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Volume 36 No 4 April 2023

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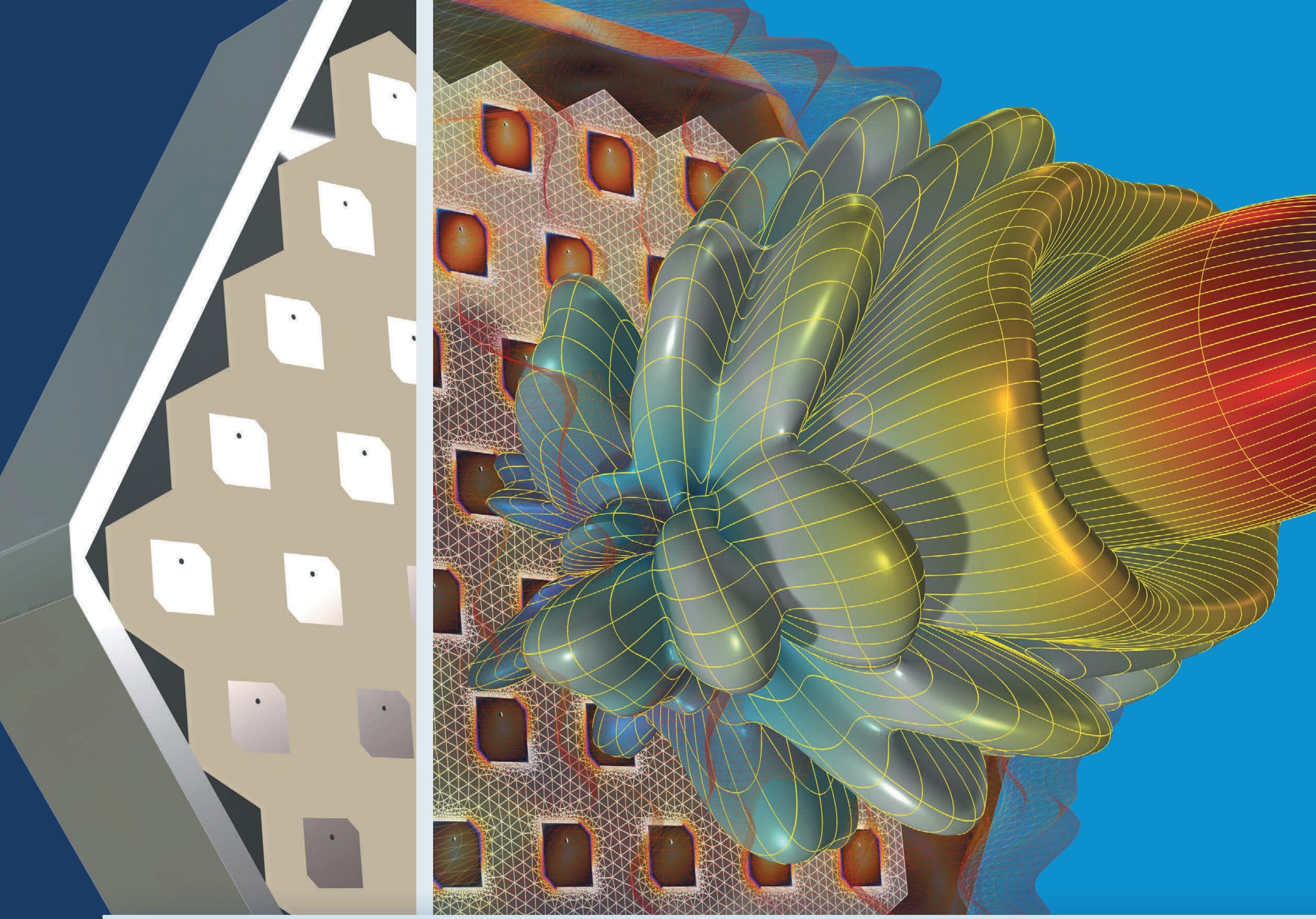
Can we use quantum computers to create music?

Cosmic insights First science results from the James Webb Space Telescope

Complex catalogue How to make a periodic table for topological materials

Please concentrate Why you should focus on this novel form of solar power



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

Cosmic secrets Early science results from the JWST
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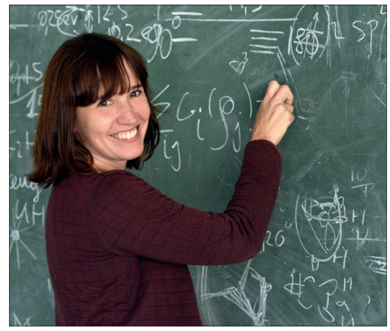

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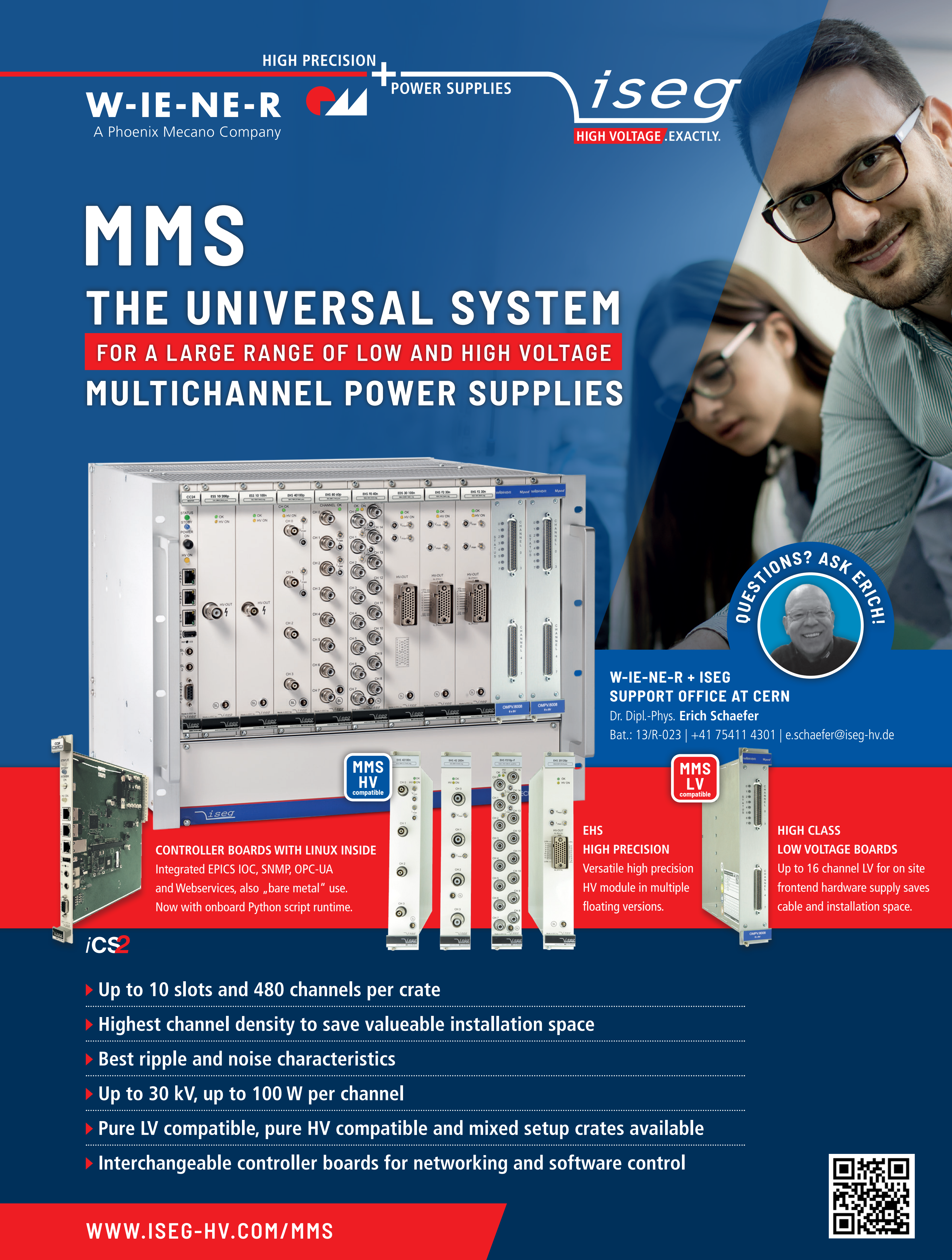
Physics World is published monthly as 12 issues per annual volume by IOP Publishing Ltd, No.2 The Distillery, Glassfields, Avon Street, Bristol, BS2 0GR, UK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Quanta

For the record

Each time we are rolling a dice

Rafael Mariano Grossi, *director-general of the International Atomic Energy Agency, in a statement*

Grossi was commenting on the Zaporizhzhia Nuclear Power Plant in Ukraine entering emergency mode in early March, for the sixth time since the start of the war in Ukraine.

It's bananas

Astrophysicist **Erica Nelson** *from the University of Colorado quoted in the* Times

Nelson was responding to the news that the James Webb Space Telescope has found giant galaxies with as many stars as the Milky Way existing much sooner after the Big Bang than scientists thought possible.

I now think it's a lot more critical and urgent to have diverse hires

Physicist **Pablo Bianucci** *from Concordia University in Canada quoted in* APS Physics

Bianucci says that before he asked his colleagues he had "no idea what the climate is like in my department for those who aren't white men".

My father would have been really proud about that

Theoretical physicist **Ronald Mallett** *from the University of Connecticut quoted in the* Guardian

Following the death of his father when Mallett was 10, the physicist has been conducting research on time travel, saying he "opened the door to its possibility".

I was fortunate to have parents who encouraged me to think anything was possible

Libby Jackson, *head of space exploration at the UK Space Agency, quoted in the* Sunday Times

Jackson says that as a teenager she e-mailed NASA to ask if she could do work shadowing and "amazingly, they said 'yes'".

I thought it was a good idea and something we needed

Kétévi Assamagan *from the US Department of Energy's Brookhaven National Laboratory quoted in* Symmetry

Assamagan has dedicated much of his career to helping physicists across Africa, including co-founding the African School of Physics.

Seen and heard


Sophie McFarland/deft productions

I'm a Barbie...role model

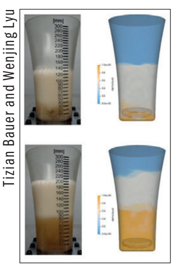
To mark International Women's Day last month, Barbie created "one-of-a-kind role model dolls" to honour seven female leaders in science, technology, engineering and medicine. They include Susan Wojcicki, chief executive of YouTube, German microbiologist Antje Boetius from the Max Planck Institute for Marine Microbiology, as well as the UK space scientist and science educator Maggie Aderin-Pocock (above). The Barbie doll inspired by Aderin-Pocock, which won't be on general sale, has a starry dress reminiscent of the night sky and comes with a telescope accessory for stargazing. Aderin-Pocock, who has just become the University of Leicester's new chancellor, says that when she heard the news of a Barbie in her honour she "danced around the living room" with her daughter. "When I was little, Barbie didn't look like me, so to have one created in my likeness is mind-boggling," says Aderin-Pocock. "It's such an honour to receive this doll that is celebrating my achievements."

Spiky structures

Winter may be over in the northern hemisphere, but have you ever wondered why icicles tend to have a rippled shape, with alternating ridges and valleys running down the length of the spiky structures? The icy mystery may now have been solved by Menno Demmenie and colleagues from the University of Amsterdam (*Phys. Rev. Applied* **19** 024005). The team built an "icicle machine" in which water is trickled in at sub-zero temperatures. If the water comes in too fast, this test found it just drips onto the floor. But if it comes in too slowly, the icicle grows up rather than down. By changing the salt content of the water and using colouring to monitor flow, the team came up with an explanation for why ripples form. When pure water was used, few ripples were seen and the icicles resembled candles. However, with salty water, the salt gets pushed out of the bulk ice and onto the surface of the icicle. This creates a film of salty water that flows along the surface of the icicle, forming the rippled structures.

No pump required

Sports-equipment manufacturer Wilson has unveiled a prototype basketball that never needs to be pumped up. Made using a 3D printer, the ball looks a bit like a spherical sieve comprising a rigid frame with lots of holes in it. The ball was manufactured in collaboration with a company called EOS and Wilson says it almost matches the "performance specifications of a regulation basketball, including its weight, size and rebound (bounce)". The ball debuted in February at a US National Basketball Association event, but apparently the league has no plans yet to use it in real games.


Tizian Bauer and Wenjing Lyu

All foam, no beer

A foamy head on a pint of beer is usually a sign of a good quality tipple. But how can you ensure that the desired amount of foam is created every time a pint is poured? Physicists in South Korea and Germany have now attempted to answer this conundrum by studying what happens when beer is rapidly forced into a glass through a hole in its base (*Physics of Fluids* **35** 023318). The hole is surrounded by a magnet and when the glass is full, a magnetic disc seals the hole. The researchers used cameras to monitor the filling process and then carried out computer simulations, which revealed that the foam is formed only in the first moments of pouring when the flow is turbulent. The researchers also discovered that warmer temperatures and higher pressures create more foam. The group says that further work could not only help to create a better foamy head, but also cut pouring time, which means you won't have to wait a second longer for your pint. We'll drink to that.


DUGALD STEWART

Research updates

‘Near-ambient’ superconductivity found

Superconductivity has been observed at temperatures up to 20 °C in a nitrogen-doped lutetium hydride, but the claims will need careful validation, as **Michael Banks** reports

Adam Fenster/University of Rochester

Hot topic Ranga Dias and colleagues at the University of Rochester have announced the discovery of a new room-temperature superconductor.

Superconductivity has been observed at 20 °C (294 K) in a nitrogen-doped lutetium hydride under a pressure of 1 GPa (10 kbar). The material was made and studied by Ranga Dias and colleagues at the University of Rochester in the US, who claim that the finding raises hopes that a material that superconducts at ambient conditions may soon be found (*Nature* **615** 244).

Being able to carry electrical current with no electrical resistance, superconductors have a wide range of applications but they need to be cooled down to low temperatures for the effect to occur. For many years, the materials with the highest superconducting transition temperatures were the copper-oxide-based “cuprates”, which superconduct at around −130 °C at ambient pressure. But then in 2015 Mikhail Eremets and colleagues at the Max Planck Institute for Chemistry and the Johannes Gutenberg University Mainz, both in Germany, observed superconductivity at –70 °C in a sample of hydrogen sulphide – albeit at pressures of about 150 GPa.

Four years later, Eremets’ team and a group led by Russell Hemley at George Washington University in the US reported superconductivity at temperatures up to about –20 °C at similar high pressures. Then in October 2020, Dias and colleagues claimed in the journal *Nature* to have discovered superconductivity at a balmy 15 °C in a hydrogen sulphide material.

Dias’s paper hit the headline and was included by *Physics World* in its Breakthroughs of the Year for 2020. The superconductor was made by adding carbon to hydrogen sulphide and then squeezing the sample to 220 GPa. Dias’s team found a maximum superconducting temperature of 15 °C occurring at about 260 GPa.

But concerns were raised over the finding, and the paper was subsequently retracted in September 2022 by editors at *Nature*. However, Dias and colleagues maintain that they stand by their results. Indeed, Dias says that the 2020 paper has since been resubmitted to *Nature* with new data that, they claim, validate the earlier work.

High hopes

Now, Dias and colleagues are back with a new material and one that superconducts at room temperature under less pressure than previous efforts. Dias’s team created it from a gaseous mixture of 99% hydrogen and 1% nitrogen that was placed in a reaction chamber with a pure sample of lutetium. The components were left to react for a couple of days at about 200 °C.

The resulting lutetium-nitrogen-hydrogen compound was initially a blue colour. But the sample turned pink as it was put under pressure, with its change of colour coinciding with the onset of superconductivity at a temperature of –102 °C and pressure of 0.5 GPa. When the researchers compressed the sample to still higher pressures, they observed a maximum superconducting transition temperature of 20 °C at a pressure of 1 GPa – the highest value ever recorded at such low pressures.

Eventually, when the material was compressed beyond 1 GPa, the sample became non-superconducting again and its colour went bright red as it turned into a metal. Given the controversial nature of their previous work, the team made various measurements to show that the phase was indeed superconducting. In particular, they recorded the electrical resistance, showing it dropped to zero at the transition temperature.

The researchers also measured the magnetic susceptibility, observing that the material expelled magnetic field lines, which is another characteristic of a superconductor. Finally, they measured the specific heat, which also showed a characteristic response at the transition temperature. While the researchers carried out X-ray scattering to determine the crystallographic structure of the sample, they could not determine the precise location of the hydrogen and nitrogen atoms, which could be resolved via neutron scattering in future studies.

Eremets, who was not involved in the new work, told *Physics World* that the superconductivity seems to be “proven comprehensively” by electrical transport, magnetic susceptibility, heat capacity and other measurements. But he admits that it will be “of paramount importance” to reproduce and confirm the current claim with additional tests. “The data of the [2020] retracted paper also looked good but the claimed [room-temperature superconductivity] has not been reproduced in careful experimental and theoretical studies,” he says.

Eremets adds that it is important that the authors “provide all necessary information and support for a smooth reproduction” of the sample and the results. “The scientific community expects that this time the synthesis will be described in great detail,” he says. “If it were not possible for other researchers to reproduce the synthesis, it would be important that authors distribute samples for validation.”

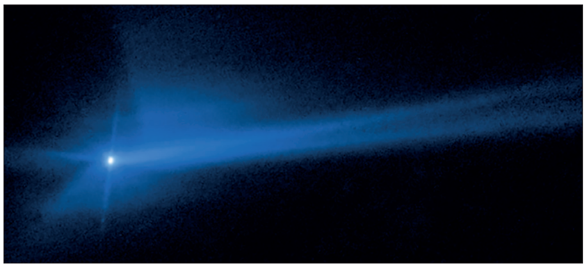
Space

DART impact ejecta gave Dimorphos an extra push

The impact of a spacecraft into the asteroid Dimorphos last year changed the asteroid's orbital period around its larger companion asteroid by 33 minutes, with much of the momentum change coming from the ejecta liberated by the impact. That is one of the findings from five new papers that have verified the amount by which the impact knocked the 177 m-wide Dimorphos from its orbit around the 850 m-wide Didymos, (*Nature* doi:10.1038/s41586-023-05805-2).

The Double Asteroid Redirection Test (DART) was a NASA spacecraft designed as a test to see if it is possible to deflect a potentially hazardous asteroid away from Earth. DART struck Dimorphos on 26 September 2022, obliterating the spacecraft and excavating a crater on the surface that led to streams of ejecta stretching away from the asteroid.

NASA had expected that Dimorphos' orbit would undergo a minimum change of about seven minutes after impact. Yet observations of the double asteroid's light curve (that tracks how the two asteroids orbit around each other, periodically eclipsing one another), as well as radar measurements, indicate that Dimorphos' orbital period around Didymos was slowed by 33 minutes.


NASA, ESA, STScI, Jian-Yang Li (PSI), Joseph DePasquale (STScI)

Impact zone
Hubble images in the hours and days after DART hit Dimorphos show the evolution of the ejecta streams from the asteroid.

"A lot of people had this assumption that we were taking two billiard balls and just crashing one into the other," says Cristina Thomas of Northern Arizona University, lead author of one of the new papers. Instead, DART was crashing into little more than a loosely consolidated rubble pile and was able to kick out plenty of material into space. "That material has its own momentum," Thomas told *Physics World*. "We refer to that as 'momentum enhancement' because it's above and beyond what we would expect from an inelastic collision."

It was this momentum enhancement that made up the difference between seven and 33 minutes in the change in orbital period. This suggests that most of the momentum change imparted on Dimorphos came not directly from DART's kinetic impact, but from the ejecta causing a recoil on the asteroid. The finding has consequences for when it may be necessary to deflect a hazardous asteroid away from Earth. The extra push from the ejecta means that it could be possible to deflect an asteroid with less time before impact than originally thought. "[It] really changes the way that we think about the scale of asteroid deflection," says Thomas.

Thomas points out, however, that DART's impact "is just one data point" and other asteroids could have different properties.

Keith Cooper

Particle physics

Nuclear reactor reconstructed in 3D using muon imaging

Scientists from France have used muon-imaging techniques to carry out a 3D reconstruction of a nuclear reactor. The researchers say that the technique, used for the first time in such a way, could be extended to non-destructively image other large objects (*Sci. Adv.* 9 eabq843).

Muons are charged subatomic particles that are around 200 times heavier than electrons. Muon radiography – or muography – creates 2D images by analysing how muons in cosmic rays penetrate objects. Depending on their energy, muons can traverse metres of rock or other materials, making them ideal for imaging thick and large structures. Indeed, the technique has previously been used to produce 2D images of nuclear reactors, pyramids and volcanoes.

Led by Sébastien Procureur from the Université Paris-Saclay and the French Alternative Energies and Atomic Energy Commission (CEA), the researchers used four telescopes to observe a decommissioned nuclear reactor in France from different angles. They then combined the different 2D images to obtain the 3D structure of the reactor using a modified tomography reconstruction algorithm that was originally developed for medical applications.

"Each image provides a measure of the density of the object, but integrated in the direction of observation," explains Procureur. "By moving the telescopes, we can access a large number of densities integrated in different directions and can then determine the local densities."

Procureur adds that while the technique will never be able to resolve small cracks in such structures, the information obtained remains inaccessible via other non-invasive methods. "Compared to medical imaging, where the volume to be imaged is much smaller and the number of available 2D images is much greater, we have shown that we can obtain relatively precise 3D information on an object that is more than 30 m long with fewer than just 30 images," he says.


Procureur *et al.*, *Sci. Adv* **9** eabq8431 (2023)

Peering inside
The G2 reactor at the French Alternative Energies and Atomic Energy Commission's site in Marcoule has been imaged using muography techniques.

The muon technique could be used to image reactors, either in operation or during their decommissioning phase. It could also help in post-accident inspections, such as those carried out after the Fukushima nuclear accident in Japan in 2011.

Isabelle Dumé

Fusion

Proton–boron fusion passes milestone

Researchers have managed to confine the exotic fuel magnetically, but doubts remain over its potential as an energy source. **Edwin Cartlidge** investigates

Physicists in the US and Japan have observed nuclear fusion between protons and boron-11 atoms in a magnetically-confined plasma for the first time. They say that the result demonstrates the potential of proton–boron fusion as a plentiful, economical source of energy. But others caution that the scientific basis for such an energy source remains largely unproven and that huge technical hurdles stand in the way of commercial power plants (*Nature Communications* **14** 955).

All forms of fusion hold the promise of near limitless, clean, baseload energy without the problems of possible meltdown and long-lived waste that plague fission. But proton–boron ($p^{11}B$) fusion brings a couple of additional virtues compared to the more mainstream reactions involving the hydrogen isotopes deuterium and tritium. Boron can be easily mined whereas tritium is rare on Earth and difficult to produce artificially. The proton–boron reactions also produce three helium atoms (alpha particles) – whose energy could in principle be directly converted into electricity – while generating no neutrons, and thereby substantially reducing the radioactive contamination of reactor components.

However, those plus points come at a price. Deuterium–tritium fusion itself requires enormous temperatures to overcome the mutual repulsion of the nuclei – around 100 million kelvin. But proton–boron reactions need far more extreme conditions still – some 1.5 billion kelvin. The authors say that the higher a plasma's temperature the more energy is usually radiated away in the form of synchrotron and bremsstrahlung radiation. This, they point out, makes it harder to generate more energy through fusion reactions than is needed to power a reactor – a major problem when a commercial plant is likely to need an energy gain of at least 50 to overcome inefficiencies in the power-generation process.

TAE Technologies

Team work Researchers in the control room of the Large Helical Device at Japan's National Institute for Fusion Science in Toki.

Richard Magee and colleagues at Californian fusion company TAE Technologies together with scientists at the National Institute for Fusion Science in Toki, Japan performed experiments on the institute's Large Helical Device (LHD). This is a stellarator with the necessary fusion fuel already in place – the protons being fired in as high-energy neutral beams while boron powder is injected into the plasma to help reduce impurities.

TAE provided the detector, which relied on a partially depleted silicon semiconductor generating a current when struck by alpha particles. It was made to avoid erroneously registering signals from X-rays and other plasma radiation by being angled away from the core plasma and having the charged alpha particles steered to it by the LHD's large magnetic field.

The team performed several dozen experimental shots in February last year. They observed fusion reactions by comparing the signal on their detector before and after turning on the neutral beams as well as carrying out some shots without any boron powder. Only when they had both neutral beams and boron powder did they get a jump in output – the exact value of which told them that they were producing about 10^{12} fusion reactions per second, which agreed with computer simulations.

This is not the first demonstration of proton–boron fusion – scientists have previously observed it using particle accelerators and powerful lasers. But the US-Japanese collaboration argues it is important to study the reaction inside a magnetically confined, thermonuclear plasma. The researchers acknowledge, however, that much more work needs to be done, but are confident that TAE will achieve energy gain in one of its devices.

Indeed, TAE claims to be well on the way to commercial fusion energy. The company has built a series of increasingly sophisticated reactors to explore field-reversed configuration fusion, which involves firing pulses of plasma into a chamber and holding them in place magnetically by rotating them. None of the devices to date have demonstrated proton–boron fusion – its current "Norman" reactor uses a hydrogen plasma – but the firm says it intends to send electricity to the grid from a pilot proton–boron power plant by the early 2030s.

Peter Norreys, a plasma physicist at the University of Oxford in the UK, says the researchers have done "a fine job" in their experiments. But he argues that proton–boron fusion is still far from rivalling deuterium–tritium reactions. One potential complication, he says, is the need for relativistic descriptions of plasma dynamics at such high temperatures. He also thinks it likely that bremsstrahlung radiation could impair plasma confinement by eroding a reactor's inner surfaces.

Scientists at the EUROfusion consortium in Garching, Germany, are also guarded. Tony Donné, Hartmut Zohm and Volker Naulin told *Physics World* that the observed reaction rate in the latest experiments is about 10 orders of magnitude too small to be useful for fusion energy (taking into account proton–boron's low power density). They have "strong doubts" that it will ever be possible to achieve the gains needed for commercial power generation.

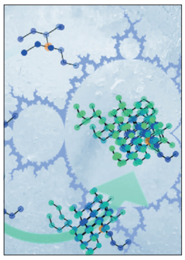
Condensed-matter physics

New type of fractal emerges in spin ices

A new type of fractal has appeared unexpectedly in a class of magnets known as spin ices. The new fractals, which were observed in clean 3D crystals of dysprosium titanate ($Dy_2Ti_2O_7$), appear to come from excitations of magnetic monopoles in the material, and could have applications in magnetocalorics, spintronics, information storage and quantum computing (*Science* 378 1218).

Fractals are ubiquitous in nature and are seen in snowflakes, networks of blood vessels, mountain landscapes and coastlines. To qualify as a fractal, an object must have a hierarchical geometric structure with a basic pattern that repeats at ever-decreasing sizes, branching off into narrower patterns that are smaller versions of the main one.

An international team says it has now discovered a new type of fractal in clean 3D spin ices, which feature disorder of magnetic moments (or spins) at low temperatures exactly the same as the proton disorder in water ice. Structurally speaking, spin ices contain rare-earth ion moments that occupy the corners of a tetrahedral pattern, and local constraints mean that these moments obey the "ice rules": two of them point into the tetrahedron and two point out of it.



Jonathan N Hallén, Cavendish Laboratory, University of Cambridge

Cool result An international team claims to have discovered a new type of fractal in clean 3D spin ices.

At temperatures just above absolute zero, the crystal spins form a magnetic fluid. Small amounts of thermal energy then cause the ice rules to break at a small number of sites, and the north and south poles making up the flipped spins separate from each other. At this point, they behave as if they were independent magnetic monopoles.

"We realized that the monopoles must be living in a fractal world, and not moving freely in three dimensions as had always been assumed," explains team member Claudio Castelnovo from the University of Cambridge, UK. The configurations of the spins create a dynamic network that branched as a fractal, and the monopoles moved along it.

To explain this behaviour, the researchers used a mathematical model that describes how monopoles hop thanks to quantum tunnelling of the magnetic spins. They found that the system sits near a critical point at which the average number of moves available to a monopole at each site is the one that generates fractal clusters. In their simulations, they mapped out the sites each monopole can reach and showed that these clusters do indeed form the fractals they predicted.

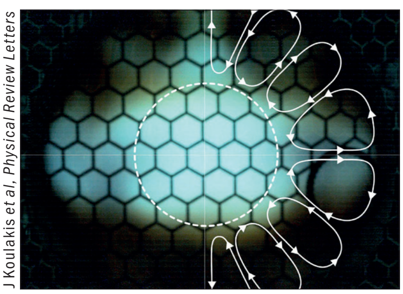
The researchers are now investigating how other properties of spin ices may be affected by the dynamical fractals. "We hope to work with experimental groups to find further evidence of this behaviour," says lead author Jonathan Nilsson Hallén from the University of Cambridge. "We are also actively searching for other systems in which similar dynamical constraints may appear, and we plan to more broadly investigate the range of effects they may give rise to."

Isabelle Dumé

Planetary science

Sound mimics gravity's role in convection within stars and planets

Sound waves have been used in the lab to mimic the role that gravity plays in driving convection in huge rotating bodies such as stars and planets. The experiment was performed by Seth Putterman and colleagues at the University of California, Los Angeles, who were able to create gravity-driven circulation patterns (*Phys. Rev. Lett.* **130** 034002).



J Koulakis *et al*, *Physical Review Letters*

Out of this world Researchers at the University of California, Los Angeles, have managed to replicate the convection patterns that are believed to exist within stars and planets.

Convection within rotating planets and stars plays an important role in the internal dynamics of these huge objects. On Earth, for example, convection in the outer core is believed to create our planet's magnetic field, while convection in the atmosphere drives weather patterns. In the Sun, convection is believed to be responsible for creating solar flares.

Some aspects of stellar and planetary convection are difficult to simulate using computers. Instead, researchers have tried to create small versions of this convection in the lab. However, it has proven challenging to create a radial force with the appropriate strength to play the role of gravity. Indeed, some researchers have gone as far as doing their experiments on the International Space Station to try to create a useful force.

Back on Earth, Putterman and colleagues' new experiment uses a rotating spherical bulb filled with a weakly ionized sulphur gas. The gas is heated using microwaves, which make the gas at the centre of the bulb warmer than the cooler and denser gas at the edge. The team then modulate the microwaves to create sound waves inside the bulb. As the sound waves pass through the gas, the density gradient creates a radial force that tends to pull the cool gas at the edge of the bulb towards the centre – just as gravity pulls a fluid towards the centre of a planet.

As the bulb rotates, the inward moving cool gas is replaced by warmer gas that moves towards the edge of the bulb. This results in the formation of a pattern of convection cells surrounding the bulb's axis of rotation. By carefully tuning their set-up, Putterman's team could generate distinctive convection patterns, featuring cells of circulating fluid that strongly mimic the patterns that are believed to exist within stars and planets.

By adapting this technique further, the team hopes that future studies could simulate gravity-driven convection with far greater accuracy than existing set-ups – helping them to better understand the vital role that convection plays in systems with large-scale circulation.

Sam Jarman

Quantum physics

Event horizon can destroy quantum states

A thought experiment reveals that black holes should annihilate nearby quantum superpositions, as **Jacklin Kwan** finds out

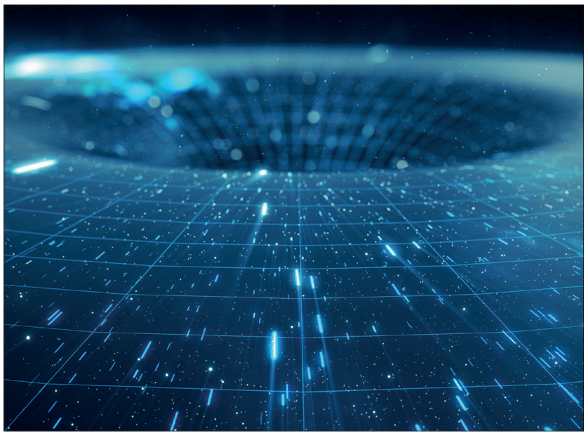
A new thought experiment suggests that the mere presence of a black hole can destroy a nearby quantum spatial superposition. Developed by physicists in the US, the experiment implies that the long-range gravitational field of the particle in the superposition will interact with the black hole's event horizon, causing the quantum superposition to decohere within finite time (arXiv:2301.00026).

Coherence is a concept in quantum mechanics that allows a system to exist in a superposition of several different quantum states at the same time. Decoherence is the process of destroying a superposition by making a measurement that puts the system into a specific state. Measurement in this case is a general term and refers to an interaction between a quantum system and its surroundings.

Superposition and other aspects of quantum mechanics can describe the behaviour of microscopic systems. However, physicists have not been able to incorporate gravity into quantum theory's description of nature. Gravity is best described by Einstein's general theory of relativity and unifying the two theories is an important aim of modern physics. This has proven very difficult because the effects of quantum gravity are only expected to be relevant at very short length scales corresponding to extremely high energies – well beyond the capabilities of current and future particle accelerators.

As real experiments cannot be done, physicists use thought experiments to try to develop a consistent theory of quantum gravity. These seek to explain the behaviour of quantum systems under extreme gravitational conditions such as those that exist at the event horizon of a black hole. This is a boundary surrounding a black hole, beyond which nothing – not even light – can escape. This implies that information can enter a black hole, but it cannot leave.

Co-author Daine Danielson, from the University of Chicago, says that the experiment considers a hidden observer behind a black hole's event horizon. The thought experiment involves a massive particle, such as an electron, that is fired at barrier that contains two slits. According to quantum mechanics, the electron will behave as a wave that diffracts through both slits simultaneously. In other words, the electron is in a coherent spatial superposition of two states, each travelling through its own slit. If the electrons strike a screen behind the slits, the two states are recombined and create an interference pattern.



Shutterstock/Rost9

Cause and effect A thought experiment suggests that the presence of a black hole can decohere a quantum superposition.

The new thought experiment describes a double-slit experiment that is conducted near to a black hole by a physicist called Alice. There is also an observer called Bob who is inside the black hole. As Alice conducts her double-slit experiment, a quantum theory of gravity requires that the massive particle interacts with the black hole via "soft gravitons". Gravitons are hypothetical carriers of the gravitational field and are analogous to photons – which are carriers of the electromagnetic field.

These soft gravitons can be absorbed by the black hole, where they can be measured by Bob – at least in principle. By making multiple measurements of soft gravitons over time, Bob should be able to deduce the state of the quantum superposition in Alice's experiment. In other words, Bob is making a measurement on Alice's experiment from beyond the black hole's event horizon, from where he is causing the spatial superposition to decohere.

But how can Bob decohere Alice's experiment if information cannot travel out of the event horizon? Indeed, doing so violates causality. Danielson and colleagues argue that this paradox can only be resolved if the black hole itself decoheres Alice's experiment before Bob can. In other words, they say, the black hole affects the quantum superposition in the same way as a classical observer.

The researchers argue that their analysis also applies to other types of horizons, such as the cosmological horizon – which defines the size of the observable universe. Such thought experiments are useful for probing the fundamental rules that a consistent theory of quantum gravity may one day have, the researchers say. "Any theory of quantum gravity, for example, must have the fundamental feature that black holes which act as quantum systems act as observers," says co-author Gautam Satishchandran from Princeton University.

Vlatko Vedral, a quantum physicist at the University of Oxford, who was not involved in the work says that the superposition is treated quantum mechanically, but the authors treat the background gravitational field – such as the black hole itself – classically. "It's not clear that an approximation like this is valid in the context they consider," he says. However, if the conclusions are correct, Vedral considers them to be profound. The thought experiment suggests that black holes can serve as a source of irreversibility – the destruction of a quantum state that can never be fully recovered. Since gravitation is infinitely long-range, it does not matter how far an experiment is from a black hole, he says, the decoherence effect that the authors calculate would be non-zero. Therefore, the creation and recombination of quantum spatial superpositions can never be fully efficient because "part of [the system] is always irreversibly lost to beyond the horizon," he says.

News & Analysis

UK urged to rejoin Horizon Europe

The Windsor Framework paves the way for the UK to join the €95bn Horizon Europe programme, but a lack of urgency from the UK government is causing concern, as **Michael Allen** reports

The European Union has confirmed that the UK can start negotiations to become an associate member of the €95bn Horizon Europe research programme once the EU and UK's agreement over the status of Northern Ireland has been ratified by the British parliament. But despite optimistic noises from Brussels, there is disquiet in the UK scientific community due to what it sees as a shift in tone on Horizon membership from the UK government and seeming reluctance to start negotiations.

The UK government has long maintained that it wishes to join Horizon Europe, which began in 2021 and is the world's largest research and innovation funding programme. Britain had been a full and highly successful member of previous EU research programmes for decades. Indeed, its ongoing participation, albeit as an associate member, had already been agreed at the end of 2020 as part of the post-Brexit trade deal between the UK and EU.

However, membership stalled and became a bargaining chip in disagreements over Northern Ireland. If it were to become an associate member of the research programme, Britain would take part in projects alongside other non-EU nations, including Israel, New Zealand, Norway, Switzerland and Ukraine.

The Windsor Framework, which concerns the flow of trade through Northern Ireland, was agreed on 27 February and opened the door for the UK to join Horizon Europe. "The European Commission had always said that the lack of an agreement around the Northern Ireland Protocol was the thing that was stopping us moving forward with the association," says Daniel Rathbone, assistant director of the Campaign for Science and Engineering (CasE). "It seems that the big political block on Horizon Europe association is now lifting."

iStock/Delpixart

Back together? The agreement over the flow of trade through Northern Ireland between the UK and the EU opens the door to the UK joining the €95bn Horizon Europe research programme.

Speaking at a press conference on 27 February, Ursula von der Leyen, president of the European Commission, said work on the UK's association with the research programme could start "immediately" once the Northern Ireland deal is implemented. She added that this was "good news for scientists and researchers in the EU and in the UK". While Rathbone is pleased to see "the enthusiasm from von der Leyen" towards Horizon Europe association, he does not feel that the UK government is showing the same level of enthusiasm. It is a feeling shared by other organisations, with representatives from across the UK and EU research and development sector signing a joint statement urging rapid progress on UK association to EU programmes, including Horizon Europe, Copernicus and Euratom.

It is a view echoed by the Institute of Physics (IOP). "The government must honour its commitment to UK science and innovation", says Tom Grinyer, the IOP's group chief executive officer. "Being frozen out of Horizon Europe has been costly to UK and European science and the physics innovations that can transform our society and economy."

Show me the money

A week before the Windsor Framework agreement was announced, CaSE revealed that the UK's former Department of Business, Energy and Industrial Strategy (BEIS) had quietly returned £1.6bn to the Treasury, which had been allocated for Horizon Europe association, or other science and innovation spending. The BEIS, which used to look after British science, was disbanded in February and replaced by a dedicated new Department for Science, Innovation and Technology.

The UK government had repeatedly stated the money would be spent on R&D, Rathbone says, but has not explained why it has been returned, beyond accounting issues – a move that has worried scientists. "[There is] no guarantee that it comes back to R&D and no real explanation as to why it's no longer available to science," he adds. According to Linda Partridge, a vice president of the Royal Society, there are reports in Whitehall that "practically every department is announcing that they do science" so they can have a claim on the money.

Since the Northern Ireland deal was unveiled, Conservative prime minister Rishi Sunak has also not publicly discussed the EU research framework. When fellow Tory MP Philip Dunne asked Sunak in parliament on 3 March if negotiations to resume association with Horizon Europe had begun, Sunak merely said that the government "will continue to work with the EU in a range of areas – not just research collaboration, but strengthening our sanctions against Russia, energy security and, crucially, illegal migration".

"It's glaringly obvious that Sunak has said nothing about [Horizon Europe association], in fact he's studiously avoided saying anything about it," says Partridge. There have also been reports that Sunak is uncertain about the benefits of the European research programme. According to the *Financial Times*, "senior colleagues" said the prime minister was

A science policy expert discusses the issues surrounding Horizon Europe

"sceptical" about the value of Horizon Europe and the cost of participation. British officials said Sunak had questioned whether the UK should route its science budget through Brussels and was considering an independent global science collaboration plan, known as "plan B".

But Rathbone says that Horizon Europe is about much more than just finance, such as the research collaborations it enables. He adds that arguments about alternatives enabling collaborations with countries outside of Europe are irrelevant. "There are a lot of countries outside Europe that have associated or would like to associate [with Horizon Europe], because they recognize the value of the programme," he says. "It helps to unlock and enable collaborations outside Europe as well as inside Europe."

Speaking to BBC Radio 4 on 6 March, the UK science minister George Freeman noted that the UK's financial contribution to the research programme will need to be negotiated. "If you have been out of the club – not by your own volition – for two years, the monies that you would have paid in for full membership over the whole seven years clearly aren't due, so we need to sit down and come up with a sensible package," Freeman explained.

It's glaringly obvious that Sunak has said nothing about [Horizon Europe association], in fact he's studiously avoided saying anything about it

Partridge agrees that there are areas that will now need negotiation. "No-one's denying that the programme has been running for a couple of years, so there will have to be financial adjustments – that's true with any agreement, you have to hammer out the details," she says. "What we would like to see is an announcement of goodwill towards the prospect and a serious roadmap for the negotiations." Rathbone, meanwhile, believes the financial issues are solvable in a relatively short period of time. "What we'd really like to see is those conversations and negotiations with the EU taking place in parallel with the final steps on the Windsor Framework, so that once that is signed off the association is ready to go," he says.

But further confusion about the UK's position emerged on 6 March when the UK government launched a 10-point strategy to make the UK a "science superpower" by 2030. Backed by an additional £370m in funding, it included plans to boost the economy and improve people's lives through investment in science, technology and innovation. However, the strategy said nothing about Horizon Europe apart from confirming that the UK would continue to finance, until the end of June, existing successful Horizon grant applicants if the UK fails to associate.

Rathbone says that while the strategy is important, the idea of the UK becoming a science superpower is "dead before it's even got going" without Horizon Europe association. "Everybody from industry to scientists wants this association [with Horizon Europe]," adds Partridge. "This foot dragging by the government is really baffling".

● The UK government published an updated National Quantum Strategy last month, which included the promise of £2.5bn funding for quantum technologies over 10 years

Michael Allen is a science writer based in Bristol

Diversity and inclusion

Science needs reform to tackle racism, says report

US educational institutions and workplaces must be pro-active in combatting racism and supporting people from minority groups. That's the conclusion of a new report from the US National Academies of Sciences, Engineering and Medicine (NASEM) that was initiated in response to the Black Lives Matter protests in 2020 that followed the murder of George Floyd.

Written by an 18-strong committee, the report surveys historic cases of discrimination and includes interviews with minority science, technology, engineering, mathematics and medicine (STEMM) professionals. The report lays out measures for leaders and managers to make STEMM more inclusive of people from Black, Indigenous, Latin, Asian-American and other communities.

Fay Cobb Payton from North Carolina State University, who co-wrote the report, says it also provides "a comprehensive vision for the future of diversity science".

iStock/elenabs

Group effort US National Academies report calls on organizations to take measures to better support minoritized individuals.

One recommendation is for STEMM centres to attract minoritized individuals and improve their sense of inclusion by integrating the principles of minority-serving institutions (MSIs). They include "historically black" colleges and universities (those set up before the Civil Rights Acts of 1964 to serve African Americans) as well as "tribal colleges and universities", run by American Indian tribes. The report adds that "predominantly white institutions" should seek sustainable partnerships with all MSIs.

The report also says that STEMM "gatekeepers" – such as university deans, administrators and lab directors who control resources, recruitment and workplace atmospheres – often cannot assess their own biases. Such gatekeepers, it adds, usually have "attitudinal biases, cognitive mechanisms and social motives that keep the white status quo intact". People in gatekeeper positions must ensure that all members of their group feel psychologically safe, the report says, and also act to "promote equal status among team members".

Susan Fiske, a social psychologist from Princeton University who co-chaired the report, told *Physics World* that despite scientists striving for objectivity in their data, they can be full of biases. "The problem is structural," she says. "The pressures on people and the positions they are in determine their behaviour."

Richard Blaustein

Careers

Women in academia migrate shorter distances than men

Female researchers who migrate for work tend to pick nearby destinations and go to fewer countries than their male counterparts. That is according to a new analysis of worldwide migration patterns, carried out by demographers in Germany and the UK. The study finds, however, that the gender gap of internationally mobile academics is closing faster than the general gender gap in science.

Led by Xinyi Zhao from the Max Planck Institute for Demographic Research in Rostock and the Leverhulme Centre for Demographic Science at the University of Oxford in the UK, the study set out to understand how migration patterns differ by gender.

It involved analysing more than 33 million research papers published between 1998 and 2017 using data from the Scopus academic database. By extracting data on institutional affiliations, the team identified "mobile" scholars as anyone whose country of affiliation changed between papers.

iStock/Delpixart

Change of direction Academics move abroad to establish new collaborations, raise their profile and boost their career but male and female researchers have different migration patterns.

Over the two decades studied, the authors found that both the number of "origin" countries (where the moving researcher came from) and "destination" nations (where the researcher ended up) increased for both male and female academics. However, the range of origin and destination countries for women remained smaller than it was for men.

The study also found that the gender gap is narrowing faster among mobile scholars across all disciplines compared to the general gender gap in science. The researchers found that between 1998 and 2017, the proportion of women in research grew from around 32% to 36%. The proportion of women among mobile academics rose more sharply, jumping from 24% to 32%.

The paper speculates that the increase in mobile female scientists could be due to women increasingly migrating independently of families. The authors also point out that many initiatives now exist to promote women and gender parity in academia, and that these programmes are also focused on drawing on overseas talent.

But despite increasing globalization, the report found that the pool of destination countries remained smaller than the pool of origin countries. In other words, researchers tend to concentrate in a smaller range of nations – particularly those in the "global north" – leading to a brain drain elsewhere. The data also showed larger gender gaps in lower-income countries, for both mobile scholars and researchers in total.

"We hope more attention can be given to female researchers from countries in the Global South to help them engage in international migration and global brain circulation," Zhao says.

Laura Hiscott

People

NASA puts UK physicist in charge of $7.8bn science programme

The UK-born physicist Nicola Fox has become head of science at NASA, one of the highest-profile positions at the US space agency. Fox takes over from Thomas Zurbuchen as NASA's associate administrator for the science mission directorate after he stepped down at the end of 2022 following six years as the agency's chief scientist.

Born in Hitchin, Hertfordshire in 1969, Fox graduated from Imperial College London with a BSc in physics in 1990. After an MSc in telematics and satellite communications from the University of Surrey, she returned to Imperial to do a PhD in space and atmospheric physics, which she completed in 1995.

Fox then moved to the US, doing a postdoc at the Goddard Space Flight Center before heading to the Applied Physics Laboratory (APL) at Johns Hopkins University in 1998. There, she studied various aspects of the geospace impact of coronal mass ejection events from the Sun.

Leading light As NASA's associate administrator for the science mission directorate, Nicola Fox is responsible for over 100 NASA missions.

NASA/Aubrey Gemignani

Fox later became chief scientist for heliophysics at APL as well as the project scientist for NASA's Parker Solar Probe, which launched in August 2018. Fox joined NASA headquarters in 2018 as director of the heliophysics division, where her portfolio also included NASA's space weather research programme.

NASA's science mission directorate has five separate divisions focusing on earth science, planetary science, heliophysics, astrophysics, and biological and physical sciences. In her new role, Fox is responsible for over 100 NASA missions as well as an annual budget of $7.8bn. She is also only the second women to hold the position after astronaut Mary Cleave who was in post from 2005 to 2007. "It's the role of a lifetime, I could not be more excited," Fox told BBC Radio 4. "You don't really dream of working for NASA, it certainly doesn't seem like it's something that could be a reality."

"As the director of our heliophysics division, Nicky was instrumental in expanding the impacts and awareness of NASA's solar exploration missions and I look forward to working with her as she brings her talents to her new role," says NASA administrator Bill Nelson.

Michael Banks

Exploiting physics to impact the economy

Anne Crean, head of science and innovation at the Institute of Physics, talks to Matin Durrani about how it is supporting research and business innovation

What is your role at the Institute of Physics (IOP)?
I lead the IOP's work to influence and deliver impact on science and innovation matters important to the physics community in the UK and Ireland. I have over 30 years executive and non-executive director experience working in business, government, membership and research and innovation organizations, including eight years at the IOP.

What role does physics play in supporting the economy?
The physics sector in the UK accounts for 11% of GDP, 10% of UK employment and performs one-third of all business research and development. Physics-based products and services are critical to advances in aerospace, defence, energy, healthcare, manufacturing, transport and space sectors as well to the photonics, quantum and semiconductor industries.

Can you highlight any examples?
The IOP Business Award winners are perfect examples. Last year, Cerca Magnetics, Zilico, Digistain and Ceryx Medical received awards for their disruptive medical innovations. Also recognized was Porotech for the development of porous semiconductors that enabled the world's first commercial indium-gallium-nitride red light-emitting diode epiwafer.

How can the IOP help the physics-based economy?
Physics is providing solutions to mitigate climate change and to tackle public-health challenges to help create a better world for the next generation. Without significant investment in R&D, infrastructure, skills and business innovation, however, the physics-based economy is at risk. It is vital that we evidence and champion the impact that physics has for policy makers and funders.

How does the IOP achieve this?
We have set out R&D blueprints to help create a thriving physics ecosystem. We are now organizing community action on topical and pressing issues as well as creating a programme of impact projects to ensure the health of physics discovery and business innovation.

Institute of Physics

Industry boost Anne Crean is keen for the physics community to submit ideas for "impact projects" supported by the Institute of Physics.

The IOP's impact projects involve community debates and evidence-gathering to influence science and technology strategies and investment

Could you explain what the impact projects are about?
The IOP's impact projects involve community debates and evidence-gathering to influence science and technology strategies and investment. They also help to create roadmaps to address sector challenges or shape policy to tackle business innovation and growth issues.

What projects did the IOP deliver last year, and what concrete outcomes were obtained?
Working with IOP members and the wider physics community, last year our impact projects influenced national strategies for the quantum and semiconductor sectors. Our quantum work culminated in a report that coincided with the launch of a trade body for quantum businesses called UK Quantum and with the UK National Quantum Technologies Programme's 2022 Quantum Showcase event. Members also formed a new IOP quantum Business Innovation and Growth (qBIG) group. It will support roadmap activities, catalyse industry–academia collaborations and represent the quantum community to national and regional policymakers.

The second impact project in 2022 was run in partnership with the Royal Academy of Engineering and set out strategy recommendations around tooling and skills. It was linked to our work with the Compound Semiconductor Catapult on a roadmap for the development of so-called "type II superlattice" infrared detectors.

What impact projects are running this year?
Our flagship project for 2023 is "physics powering the green economy", which will highlight the role that physics is playing in the environmental sector. The project will span energy production, transport, buildings and CO_2 management applications. Through roadmaps in nuclear, renewables, energy storage, hydrogen and carbon capture, usage and storage it will recommend how to accelerate our transition to net zero.

We will also be exploring how future advances in positioning, navigation and timing technologies could drive economic growth. Finally, we will be working with venture capitalist firms that are investing in physics-based businesses to better understand their interests and issues. This will hopefully influence strategies to support future investment.

How can the community propose future impact projects?
We want our members and the community to help shape the debate and stimulate our next set of impact projects. We hope to encourage submissions from across academia, business, nations and regions, and from under-represented groups in our community. This is an opportunity for the whole physics community to say what matters most and why, what science and innovation issues are important, what change is needed, and how the IOP can make a difference.

● Submissions for IOP impact projects can be made at bit.ly/3YPa3JK. The deadline is 11 May.

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

Comment

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The 2023 subscription rate for institutions is £500 per annum for the print magazine, £948 for the electronic archive, £1157 for combined print and electronic. Single issues are £46. Orders to: Subscriptions Dept, IOP Publishing, No.2 The Distillery, Glassfields, Avon Street, Bristol BS2 0GR, UK; tel +44 (0)117 929 7481; e-mail customerservices@ioppublishing.org. *Physics World* is available on an individual basis, worldwide, through membership of the Institute of Physics

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

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

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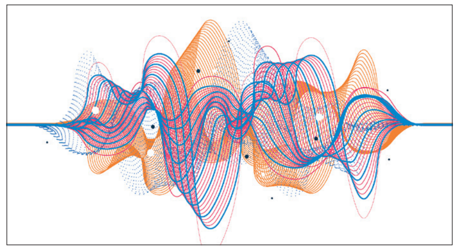
Melody makers

Attempts to use quantum computers for music are a welcome diversion

When the science writer Philip Ball told *Physics World* he had been to an event at the Goethe-Institut in London that explored how quantum computers could make music, our ears pricked up. We know that these devices hold all sorts of great promise at speeding up scientific calculations, but how exactly would you use a quantum computer to create or play tunes? Our interest deepened when Ball revealed that musical pioneers Brian Eno and Peter Gabriel had attended the London meeting too.



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As you can find out from Ball's resulting cover feature "Playing to the quantum beats" (see pp26–30), the event wasn't some kind of abstract, theoretical discussion. Instead, it contained real, live musical performances. In one, the violinist Craig Stratton played an improvised tune that was converted into quantum states that were fed into an IBM quantum computer in New York. It processed the states into a different form that was played by a synthesizer emitting saxophone sounds back in London.

In another performance, musicians wore movement-sensitive rings and gloves that let them use their hands to rotate an image on their laptop of a qubit running on the New York machine. At a moment of their choosing, they could "measure" the qubit, collapsing into a particular state, the values of which determined the parameters of artificially generated sounds. The performers could make further hand movements in response to what they heard – a musical collaboration between themselves and their devices.

It sounds pleasantly bonkers. But there's serious science behind it. The London event was held to mark the launch of a new book edited by Brazilian composer and computer scientist Eduardo Reck Miranda that, he claims, is the first book about this endeavour. Titled *Quantum Computer Music* (Springer 2022), it has chapters covering everything from "quantum keyboards" and the "sound of the Ising model" to applications of quantum annealing to music theory and making music with cellular automata.

These are early days and no-one quite knows how the field will develop (or even if quantum music will go anywhere at all). But the London event was a great example of scientists and artists genuinely collaborating to create something new. Perhaps quantum computers could one day even be applied to other forms of art. Could such devices be used to create, say, quantum-inspired drawings, paintings or sculpture?

With all the grimness and craziness in the world, applying quantum computers for art is surely a project everyone should welcome and support.

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

Let the *viva voce* live up to its name

Pruthvi Mehta wonders if the standard viva is really the best way to assess PhDs for all students

The end of my PhD on supernova neutrino interactions is approaching at an alarming rate. I expect to have submitted my thesis by the end of March and the write-up so far has been largely without any hiccups. But that hasn't stopped me from worrying about what will come soon after I submit: the PhD oral viva. For PhD students, the viva is meant to be the culmination of several years of hard work – or the "living voice" of their work, hence its name *viva voce*.

A physics PhD viva usually consists of an oral examination where an external examiner is brought in to question the student on their work and on physics in general. That person sits alongside "internal" examiners. For any PhD student nearing the end of their programme, the prospect of having to defend their thesis is a huge source of anxiety, eclipsed only by the thought of what to do after their PhD is over.

Many would expect such an important and final part of a doctoral student's journey to be rigorously planned, and often, especially on the student's end, it is. Yet having seen many of my colleagues go through the process, it is concerning how widely procedures differ from student to student even from those within the same department.

iStock/monkeybusinessimages

Under the spotlight The experience of PhD students during their oral viva examinations tends to differ widely.

Setting standards

The very concept of a several-hours-long oral examination has its faults, especially for students who are neurodivergent or have mental-health issues. Even for neurotypical students, many enter the examination room with their stomach in knots. Giving a 20-minute presentation on their research may be daunting enough for someone who has, for example, severe social anxiety – let alone undertaking a thesis defence lasting potentially several hours.

You might think then that an institution would plan ahead – yet there are many examples of the opposite. One student at Liverpool who had schizophrenia entered a viva examination room and neither the external nor internal examiners knew about this student's disorder. After a while, due to the stress of the procedure, the student understandably had an acute psychotic episode and was failed by the examiners. The student eventually passed after their disorder became known, but one has to ask how this was allowed to happen in the first place.

One of the main issues about oral vivas is that the remit of the exam is not standardized. The level of expertise of an examiner in relation to the student's field can differ greatly. For some it may be the spokesperson of the very experiment their research is on, while for others it could be someone only tenuously linked to the field. Who you get could substantially impact the variety and depth of the questions you'll face.

There is not even a standard length for vivas. I know of one former PhD student in my department who had a viva examination that was six hours long while another's test was a mere 90 minutes. This is clearly unfair, and in some cases can cause understandable resentment when the outcome or qualification at the end is just the same but the process to get there much more gruelling.

So, what can be done about it? One option would be to insist that vivas last for a fixed length of time, just as with written examinations. A more radical solution may be to scrap vivas entirely and instead validate the academic rigour of a student's thesis by using a grading system. It's an approach already used in countries such as Germany and Finland.

If that is a step too far, given that oral examinations have been in use for centuries, then perhaps we should change the very nature of the viva itself. Rather than several hours of grilling, perhaps a presentation by the student is enough followed by a few pertinent questions. This would help those whose minds go blank when in a stressful face-to-face meeting. Having a practice viva could also ease any nervousness that anxious students may have, while it should be compulsory to let examiners know if there are any mental-health issues, which could threaten the student's wellbeing during and after the exam.

Finding a voice

There are also aspects of the viva that seem to smack of institutionalized Anglocentrism, notably the insistence that exams should be carried out in English and the fact that examiners don't always appreciate that non-native English speakers can face language barriers. Of course, this isn't unique to vivas, but rather science as a whole.

Professors aren't always sympathetic or kind to international students for whom English is not their first language. I once even helped a student whose supervisor cited her English-language skills as a reason to discontinue her PhD and put her on a Master's programme instead. The stress of having to communicate your research verbally in a language that isn't your mother tongue seems to be an extra layer of pressure for an already anxiety-ridden student.

Another change could be to allow students' whose first language is not English to carry out all or some of their viva in a different language. There are experts in all fields around the world and it is lazy not to find an examiner who can converse in the student's preferred tongue.

The *viva voce* should be allowed to live up to its name – if a student's thesis defence is supposed to be its living voice, let's try not to stifle it.

Pruthvi Mehta is a contributing columnist for *Physics World* and a particle-physics PhD student at the University of Liverpool, UK

Critical Point Magnificent structures

Protecting science requires not just science, but an understanding of human behaviour too, argues **Robert P Crease**

It's the people who matter The future of science and scientific facilities depends on a better understanding of how humans behave.

In October 2022 the president of Stony Brook University, Maurie McInnis, began her "State of the university" address with a tribute to Brookhaven National Laboratory. Stony Brook, she reminded her audience, helps to manage the "bustling" lab, which is located near Stony Brook on Long Island. It provides "eureka moments" for students, she said, helping them define and realize their goals. The lab helps students make a difference, both to themselves and to the world.

These were stirring words. Still, I couldn't help being reminded of the havoc that occurred at Brookhaven 25 years ago after it was announced that there had been a non-hazardous leak from the spent fuel of the lab's research reactor. It's a dramatic and almost unbelievable story that I cover in a new book written with former Brookhaven interim director Peter Bond entitled *The Leak: Politics, Activism, and Loss of Trust at Brookhaven National Laboratory.*

Federal, state and local health environmental experts found the leak harmless. But its impact was spun way out of proportion by politicians and activists. Their loud voices, which were amplified by media commentators, unqualified "experts" and celebrities such as Alec Baldwin and Christie Brinkley, convinced many nearby residents that they were in imminent danger of meltdowns, cancer and other deadly diseases.

These concerns led not only to the reactor being closed down in 1999 but also to calls for the entire Brookhaven lab to be shut. That didn't happen, but the incident did lead to the firing of Associated Universities, Inc. (AUI) – the group of nine universities that had managed Brookhaven since it was founded in 1947. In fact, Stony Brook's partnership with the lab was a direct result of that firing, as it was chosen to replace AUI.

So why didn't all the lab's nearby residents simply accept the word of the experts – of the federal, state and local authorities who, after numerous extensive and thorough studies, concluded that the leak at Brookhaven was non-hazardous? The reason is visible in the unfolding drama portrayed in *The Leak*. Simply put, experts don't come with a stamp of approval; they become that way only after they've spoken to people who hear them as experts.

All about the acoustics

Expertise is often pictured in what one might label the "call-and-response" model. In it, somebody needs information and so seeks out and asks the appropriate authority. That authority delivers the information, and the information-seeker acts accordingly. The call-and-response model assumes that the person knows the voice is from an expert, who is responding appropriately to the person's questions.

The model works well in certain circumstances, such as when you have to fix your plumbing, mend your car or seek medical advice. But it doesn't apply in larger social contexts, such as the potential threat of a nuclear reactor in a government laboratory. If it had held true, people living near the lab would have listened to how the government experts evaluated the hazard, and accepted their judgement.

The fact that many people in the community ignored the expert voices means (according to the model) that they were responding irrationally. Those people were exposed to an entire spectrum of individuals claiming expertise and shouting different advice. Some of those individuals seemed to be responding to the concerns voiced by the neighbours, while others gave advice that sounded patronizing, irrelevant and too technical.

This situation is better modelled by an "acoustical" picture of expertise. I see this as involving a "soundscape" in which the audibility of a voice depends on where both speaker and hearer are positioned. The soundscape at Brookhaven in 1997 – and in many other public controversies – was cacophonous. But if we want effective action, we need to map that soundscape by identifying which voices are loud or soft, which are clear or staticky, and where and to whom they are speaking.

The critical point

In his book *The Great Instauration*, published in 1620, the philosopher and statesman Francis Bacon warned that science was in danger of becoming a "magnificent structure without any foundation". Humans, he said, were apt to ignore, squander and undermine the considerable beneficial powers of science unless they were able to appreciate how it operated in a way they could understand and value.

Bacon was writing before modern science, and had to try to link its promise and potential benefits with the lives of those who needed to support it. These days we live in a world dominated by science and technology but we still need to speak in an acoustical landscape to outline the links between scientific facilities and the lives of those who provide the funding and foundations.

The damage to valuable and irreplaceable scientific facilities that took place at Brookhaven could happen anywhere

In 1998 the US Department of Energy hosted a "Lessons learned" conference near its headquarters in Washington DC, attended by representatives from the agency and many US national labs. One delegate was Judy Jackson, the then-head of public affairs at Fermilab near Chicago. When she took the podium, her first slide simply read: "Brookhaven's experience: 'There but for the grace of God…'" The damage to valuable and irreplaceable scientific facilities that took place at Brookhaven could, in her view, happen anywhere.

But can we afford to let advanced, multibillion-dollar scientific facilities rely on Divine grace for their survival? The health and welfare of these facilities – their ability to define and fulfil the goals for which they were built – requires a deeper understanding of human nature, not as a tack-on but as a foundation. Why, in other words, do humans find it meaningful not just to build scientific facilities but to close them down too?

It's a question that is critical to any science-dominated university, including Stony Brook. But when educational goals become focused on technical training and scientific advance – and we ignore the study of the world in which humans live – we are in danger of undermining the very foundations on which the magnificent structures of science are built.

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Transactions Concentrate on this

James McKenzie believes that "concentrator solar power" could be the answer to our environmental woes

Modern solar cells are so good at converting sunlight into electricity that today's flat-panel photovoltaics (PVs) are cheap, efficient, long lasting and plentiful. As I mentioned last month, they economically outperform concentrator photovoltaics (CPVs), which use lenses or curved mirrors to focus the Sun's rays onto tiny solar cells. Despite showing much early promise, CPVs today seem far too complicated and expensive to succeed.

There is, though, another kind of solar power I find exciting, which uses sunlight to warm up a heat-retaining liquid. The hot fluid can be used to boil water, with the resulting steam driving a turbine to generate electricity. Known as concentrator solar power (CSP), it is only really economic at large scale, but has one huge advantage. Because the liquids in CSP can be stored, the energy can be converted into electricity even when the Sun isn't shining.

According to the US National Renewable Energy Laboratory, three main types of CSP have been tested over the years. First there are linear concentrator systems, which use long U-shaped mirrors to collect the Sun's energy. Motors actively tilt the mirrors towards the Sun, focusing sunlight onto tubes (receivers) that run the length of the mirrors. The tubes, which contain the hot fluid, are usually placed in troughs lying along the focal line of the mirror, although sometimes a single tube is placed above multiple mirrors.

Another kind of CSP uses a mirrored dish rather like a large satellite dish. To minimize costs, the dish is not one single structure but is usually made up of many smaller flat mirrors. The curved surface directs and concentrates sunlight onto a thermal receiver, which absorbs and collects the heat. The hot fluid heats a gas in a version of the classic Stirling engine, moving pistons to create mechanical power, which drives a generator.

Finally there are "power tower systems", which use a large field of flat, Sun-tracking mirrors. Known as heliostats, they focus and concentrate sunlight onto a receiver at the top of a tower. As with the other CSPs, a heat-transfer fluid heated in the receiver generates steam to drive a turbine. Most use molten salts as a heat-transfer fluid that can store energy for use at night or when it's cloudy.

BrightSource Energy

Field of dreams The Ivanpah Solar Power Facility in Nevada uses thousands of mirrors to focus sunlight onto a tank of water at the top of a tower, with the resulting steam being used to drive turbines.

Mixed fortunes

There were more than 90 CSPs in operation around the world by the end of 2021, with Spain and the US accounting for over half the globally installed capacity of 6.4 GW. Examples include the 110 MW Crescent Dunes facility in Nevada (which uses molten salt) and the 394 MW Ivanpah project in California (which runs on water). The beauty of CSPs is that they are all highly efficient. Power-tower systems (where the fluid is at 250–565 °C) can convert up to 35% of all solar energy into electricity, while dish systems (running at 550–750 °C) can be up to 34% efficient.

According to a 2021 report from the International Renewable Energy Association (IREA), the levelized cost of electricity (LCOE) – a kind of average net cost – of CSPs has fallen sharply in recent years. In the decade to 2020, the global weighted average LCOE of newly commissioned CSPs plants tumbled by 70% from $0.361/kWh to $0.107/kWh. The reductions have been driven largely by the fact that these plants can operate at ever higher temperatures, which cuts storage costs and allows them to run for longer periods.

For plants commissioned between 2016 and 2020, the IRENA report found that about four-fifths had at least four hours of storage, while 35% had eight hours or more. This trend is expected to accelerate even further with IRENA already finding that the average storage time had risen from 4.7 hours for projects commissioned in 2020 to 17.5 hours for those commissioned the following year. The average CSP project size in 2021 was a respectable 110 MW.

But CSP systems aren't perfect. They use lots of water and it's not cheap keeping the mirrors clean, which is vital if you want to keep their efficiencies high. And, of course, these systems only work well if there's lots of sunlight, which makes them impractical in many parts of the world. What's more, the cost of rival renewable sources of energy has been plummeting.

According to IRENA, the LCOE for solar PV has fallen by 88% since 2010 to $0.08/kWh, while onshore wind power has dropped by 68% during that time to $0.033/kWh and offshore wind has decreased by 60% to $0.075/kWh. Despite its recent drop in price, CSP remains much higher at $0.107/kWh. It makes CSP look uneconomic, although this headline figure includes the cost of storing the energy, which is omitted from the other LCOE numbers.

Still, for all the promise, CSPs lag far behind conventional solar PV panels, which had a total installed capacity of 957 GW in 2021. Solar PVs are simply such an easy and scalable technology, provided of course that you can store the energy in batteries. Given the huge amount of work going into developing batteries for electric vehicles, I'm sure solar PV will give CSP with thermal storage a run for its money over the next 20 years.

As the IRENA 21 report concludes: "In the absence of strong global policy support for CSP, the market remains small and the pipeline for new projects unambitious". I find that disappointing, given the remarkable fall in costs for CSP since 2010 and its ability to provide dispatchable power 24/7 in sunny areas at a reasonable price. Sadly, energy production is all about the economics – and CSP is always playing catch-up on cost.

But perhaps all is not lost. First, the batteries needed for solar PV might rocket in price as they require rare materials that might one day become costly. Second, research suggests that the heat stored in CSPs could be used to produce a range of "green fuels", such as hydrogen or ammonia. Perhaps CSPs might one day even work in partnership with their nemesis – the flat solar PV panel – to produce electricity and fuel round the clock.

James McKenzie was vice-president for business at the Institute of Physics 2016–2020, e-mail james.mckenzie@iop.org. He is writing here in a personal capacity

Feedback

Letters and comments that appear here may have been edited, and do not necessarily reflect the views of *Physics World*.

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

Hydrogen keeps it all together

In reply to the feature article "Home, green home" by Margaret Harris (November 2022 pp29–33), which describes the challenges of changing the heat supply for homes and buildings so they don't use fossil fuels anymore.

Harris gives a comprehensive and interesting account of, among other things, the pros and cons of replacing natural gas with hydrogen for domestic heating. However, the article repeats a common misconception, which is that high concentrations of hydrogen can make steel pipes brittle, thereby requiring new pipes to be installed. As a now-retired materials scientist who specialized in deformation and fracture, I hope I can reassure her (and your readers) that it is not something to worry about.

It is true that atomic hydrogen can be absorbed into the interatomic interstices in steel's crystal structure and then diffuse quickly through the metal. These hydrogen atoms – produced, say, if wet steel is ineptly welded – tend to be attracted to regions of high tensile stress, such as crack tips. Once there, the atoms can make it much easier for cracks to propagate, reducing the steel's fracture energy to very low values and turning the steel brittle.

However, the hydrogen in bottles and pipes exists in the form of diatomic molecules (H_2), which are much too big to be absorbed into these interatomic interstices. Hydrogen molecules are highly stable and do not easily decompose into individual atoms so there is little chance of anything migrating through the pipe. Sure, at pressures much higher than ever exist in gas pipes, a tiny amount of atomic hydrogen can get into the steel, which might reduce fracture toughness by 20–30%. But this by no means makes the steel "brittle", just a little less tough.

It's also worth noting that the strength of a hydrogen–hydrogen bond (432 kJ/mol) is only a shade higher than the bond between hydrogen and carbon atoms (413 kJ/mol) found in current domestic gas. It's unlikely therefore that hydrogen embrittlement would ever be a problem for sending hydrogen gas through steel pipes, given that we've been transporting domestic gas down them for years without anything going wrong. What's more, large steel cylinders of high-pressure hydrogen are a common sight in labs and they're not known for blowing up, even given the thumping they get.

Older readers might also remember that in the days before natural gas was piped ashore, our gas supply came from "coal gas" (also known as "town gas"). Produced at local and regional gasworks by reacting coal with steam before being stored in large gasometers, it was composed of roughly equal amounts of hydrogen and carbon monoxide, with a tiny bit of methane. The domestic piping system was, in other words, used to transport hydrogen a long time ago, with no ill effects. More information is on the excellent Wikipedia page "Hydrogen embrittlement" (bit.ly/3ZZySn1).

Steve Roberts
Oxford, UK

Fusion oversights

In reply to the news and analysis article "Physicists plot laser fusion path" (February p8–9), which describes how the US National Ignition Facility (NIF) demonstrated ignition late last year.

Your discussion both of the laser fusion work at NIF, and of other approaches to fusion energy, concentrates almost exclusively on the energy gain in deuterium–tritium targets. However, your coverage ignores the massive problem of how to produce, or "breed", tritium with a "breeding ratio" of at least 1, which is an essential part of any reactor system.

Apart from tritium escaping by diffusing quickly away at high temperatures, there are problems with the usually proposed method for breeding tritium, which involves reacting neutrons with lithium. In particular, the lithium has to be enriched to increase the proportion of lithium-6 isotope from its natural value of 7.5%. Given that you need a blanket of lithium (or lithium compound) roughly 100 cm deep to slow and interact with the 14 MeV neutrons, it would mean enriching several tonnes of lithium. Quite how this could be achieved (and at what cost) is rarely discussed.

Another problem concerns the beryllium that is needed to enhance the neutron flux and help with breeding. It seems that the metal, at least from some sources, might contain uranium and therefore have the potential to give serious radiological problems when subjected to a high flux of neutrons. So while it is interesting that many start-up companies are being founded around the world to tackle fusion, the danger is that any coverage of them focuses only on their approach to ignition. If the real difficulties mentioned above are ignored, investors will ultimately be very disappointed.

John Evans
Abingdon, UK

A load of old wind

In reply to Amory Lovins' letter about wind energy (October 2022 p23) and James McKenzie's Transactions column on wind-powered ships (October 2022 p21).

Physics World should be a forum for a serious discussion of energy issues. Instead, it just pushes nonsense on the wonder of renewables that defies basic physics. It's hard to know where to begin, but let me start with Lovins' letter "The power of the wind", which claims that the whole UK has never had so little wind that it was "becalmed".

That's not the point. Wind power varies as the cube of the wind speed, and most wind turbines don't give their rated power until the wind reaches 11 m/s. Low wind speeds across the country mean very little wind power. Recall the cold spell in the UK in December 2022 when, as usual, natural gas had to fill in for the absence of wind.

Then there was McKenzie's article on a new generation of wind-powered ships. There are many good reasons why wind was abandoned back in the 19th century (even for inefficient and dangerous steam ships with boilers that could blow up). In particular, a ship with square rigging is unable to go faster than the wind speed.

Sure, the large triangular sails on a ship with "fore and aft" rigging act as airfoils that produce lift so it can go faster than wind. But the lift is at an angle to the direction of travel, creating a component trying to overturn the ship. This can be counteracted by having sailors lean over the side, installing a large submerged keel to provide drag, or using a design like a catamaran that has two widely spaced hulls.

None of these options is practical for a modern cargo ship.

Peter Rez
Arizona State University, US

More finance, please

In reply to Jon Cartwright's feature "What goes up…" (February pp21–24), which describes the mathematical modelling of ultra-long financial bonds.

As a retired chartered financial planner, I was both surprised and pleased to read the article on financial bonds. It may not be physics or even science, but it does illustrate how physicists can adapt to the world of high finance. As the article explains, bonds are quite simple in principle, but can become quite complex in practice. That's because they are traded on the stock market, which means their price is determined by supply and demand, while speculation and gambling can come into play.

Historically, retail investors have used them as a hedge against volatility and risk for the key constituent of the market, namely equities. *Physics World*, in my view, should now consider a follow-up article that explains the unique importance of equities over other securities and provide the broader picture of the investment industry. In brief, equities create the growth to enable one to beat inflation, with bonds providing a hedge against investment risk.

Brian Bradley
Sixpenny Handley, Dorset, UK

Philosophical ding-dong

In reply to an analysis by Robert P Crease and Gino Elia of the philosophical implications of the 2022 Nobel Prize for Physics, which was won by Alain Aspect, John Clauser and Anton Zeilinger for their work on the fundamentals of quantum information science (December 2022 p21).

The 2022 Nobel award is indeed a delight to philosophers of science like me, but I think Crease and Elia mis-frame their discussion. They suggest that the Einstein–Podolsky–Rosen (EPR) paper of 1935 (*Phys. Rev.* **47** 777) "is unique among physics papers in that it begins by attempting to define reality" and that in it "'reality' was being approached for the first time as a testable hypothesis". Neither of these claims seems right.

First, what EPR offered was only a sufficient condition for a quantity's (not an object's) being real, not a necessary and sufficient condition, and thus obviously not a definition, whether of reality, or of a quantity's being real. Neither was it intended to be one. Introducing the sufficient condition was rather a dialectical wheeze on Albert Einstein's part: for years Niels Bohr had been dodging the thrust of Einstein's thought experiments (to show that quantum mechanics is incomplete) by suggesting that disturbance due to measurement vitiated Einstein's conclusions.

With the EPR criterion, and noting the entanglement correlations, Einstein upped the ante: now Bohr could stick to his disturbance doctrine, and thereby defend completeness, only if he accepted instantaneous action at a distance. As it was, Bohr dodged the trap, essentially by rejecting the EPR criterion, though many were not convinced by this move, including Bell.

Second, seeking to define reality is a mug's game – anything plausibly true one could say would be hopelessly bland. The true activity is saying what reality is like – and that's what the vast majority of physics publications are self-consciously seeking to contribute towards. The EPR paper is not special in this regard.

Third, that there exists a mind-independent, objective reality was not a hypothesis, nor was it the focus of this discussion. The question, again, was rather what reality is like. Einstein and John Bell were holding out for a reality describable in a detailed and uniform way by physical law, but they differed over whether it would have to include action at a distance or not. Bohr was content with a much more piecemeal reality in which no detailed laws operated fully descriptively at the microscopic level, and there was much less that could be said about how physical things were than we had previously supposed.

Historically, Crease and Elia neglect the crucial role of David Bohm's 1952 hidden-variable theory in Bell's thinking. Bell knew this theory (as did Einstein), and he showed that it explicitly contained action at a distance. He asked himself whether any theory that sought similarly to complete quantum theory – while matching its empirical predictions – would also have to include this feature. His 1964 result (*Physics* **1** 195) provided the answer to his own question. Note that Bell's 1966 paper (*Rev. Modern Phys.* **38** 447), in which he discusses Bohm and poses the crucial question, was written before, but published after, his 1964 paper.

Chris Timpson
University of Oxford, UK

Robert P Crease and Gino Elia reply: We thank Timpson for his clarifying points, but he misses the combative thrust of Bohr, Einstein and Bell's papers. Timpson is right to be suspicious of the traditional framing of the Bohr–Einstein debate as a clash between realism and anti-realism. But that's not our claim. We were saying that the Bohr–Einstein exchange was not a disagreement about the implications of quantum mechanics for reality. The EPR paper was special because it made explicitly testable a deeply held conviction about reality, putting it pointedly up for discussion in a way prior physics articles hadn't. The paper was essentially throwing down the gauntlet before Bohr, and it's hard to reconcile the brazenly polemical tone of the EPR paper's abstract and first paragraph with Timpson's third point.

Bell also threw down gauntlets, and in papers such as "Bertlmann's socks and the nature of reality" challenged people to notice that entanglement involved something wildly counterintuitive about reality that no common-sense person would agree to, but which did not seem to trouble many physicists. Bell's work deliberately opened the door for others to test one of quantum theory's most conceptually demanding implications, and reopened the conversation about its foundations.

Eddington was unequivocal

In reply to Mike Follows' review of Michael Strevens' book *The Knowledge Machine: How an Unreasonable Idea Created Modern Science* (October 2022 pp40–41).

I was disappointed that Follows refers to the famous Eddington–Dyson eclipse expedition of 1919 by stating that "although the results were equivocal, Eddington concluded that they confirmed general relativity, which demonstrates that there is an element of subjectivity in the way scientific claims are interpreted".

While the expedition is often cited by philosophers and sociologists as an example of subjective science, recent studies have found that the observations did in fact justify Eddington's conclusions. Sadly, the incorrect version of this story continues to receive more attention than the true version.

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

Moiré imaging with conductive atomic force microscopy

Introduction

Conductive AFM (C-AFM) is a technique capable of acquiring current maps with nanometre scale spatial resolution and picoamp scale resolution in current. As the flow of current is fundamental to numerous technologies from computation to energy harvesting, C-AFM has many applications not only for fundamental research but also in the refinement of devices and failure analysis. Here we exemplify the exceptional resolution of C-AFM by studying twist-controlled layered materials heterostructures.

When two rigid layers with a fixed spatial periodicity are overlaid, a moiré pattern may be observed. The symmetry of such features is dependent upon the symmetry of the overlaid layers and the periodicity is dependent upon the mismatch in period of the two features and the angle between them. Recently moiré patterns have received significant interest for their influence over the functional properties of layered materials heterostructures, namely the field of twistronics [1,2].

One prominent example of where moiré patterns have been explored in layered materials heterostructures is the case of single layer graphene (SLG) on hexagonal boron nitride (hBN), where using hBN as a substrate [3] and encapsulant [4] of SLG enables the fabrication of devices in which the effects of contaminant induced doping is suppressed, yielding state-of-the-art performance characteristics such as mobility. For SLG on hBN, a hexagonal moiré pattern is seen owing to the hexagonal symmetry and small spatial mismatch between hBN and SLG (~2%), see figure 2 b–d. Samples were fabricated by exfoliating both hBN (HQ graphene) and graphene on thermally grown SiO_2 before flakes were sequentially picked up and transferred onto pre-deposited contacts using polymeric stamps. After removing polymer residue through solvent immersion and then mechanically by performing contact mode AFM over the area of interest, samples were measured using C-AFM on the Park FX40 Automatic AFM with Multi75E probes, see figure 2e and f.

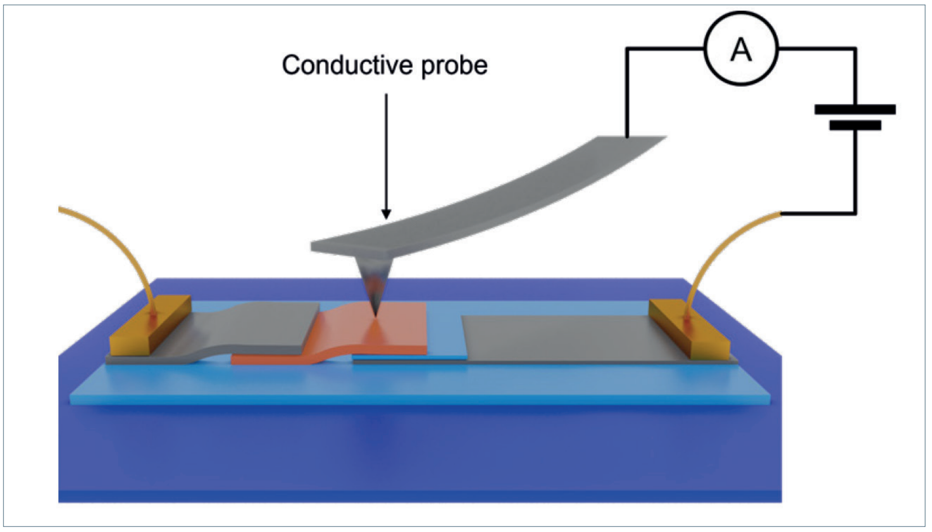

Figure 1. A simplified schematic of C-AFM, in which the interaction between the tip and sample is controlled by either contact mode or PinPoint™ AFM. In addition to extracting the topography, a map of the current at the junction between the tip and sample is also extracted.

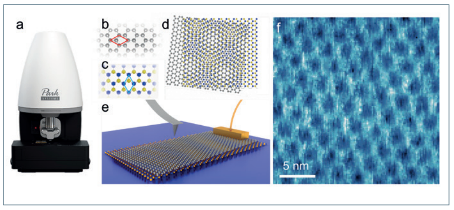

Figure 2. Using the Park Systems FX40 Automatic AFM (a), C-AFM measurements were performed in contact mode to map the morphology of moiré patterns. A heterostructure of SLG (b) on hBN (c) was produced by stacking mechanically exfoliated flakes. The similar lattice constants of hBN and SLG give rise to a moiré pattern, as depicted for a twisted heterostructure (d). With an electrode applied to the substrate and the tip-sample interaction controlled via contact mode (e), current maps acquired under constant voltage may be measured (f) which reveal a hexagonal moiré pattern due to the spatially modulated stacking registry of hBN and SLG.

Experimental and results

C-AFM utilises the same setup as contact mode AFM (with associated mechanical setpoint: SP_{Mech}) to maintain the tip in contact with the surface under constant mechanical load via a feedback loop which also allows the topography to be extracted. By applying an electrical contact to the sample and using a conductive probe, the current may be measured at the tip-sample junction and mapped spatially with sub-nanometre resolution. Such current maps of SLG/hBN (see figures 2f and 3a) reveal a hexagonal moiré pattern with areas of higher current observed for the network of walls between domains compared to the central regions where the lattices stack in a more parallel fashion [5,6]. The contrast of such features in AFM images may be optimised by optimising SP_{Mech}, the voltage applied between the tip and sample (V_{TS}), increasing the scan rate to suppress thermal drift and changing the state of the tip by applying short and controlled pulses of higher voltage. Upon optimisation of the aforementioned acquisition parameters, current maps showing nanometre scale corrugations (see figure 3a) may be taken, with extracted line profiles (see figure 3b) showing remarkable conformity.

In general, in layered materials heterostructures, the intra-layer forces arising from bonding within layers are stronger than inter-layer forces arising from van der Waals interactions. For this reason, layered materials heterostructures typically exhibit moiré patterns as the stronger intra-layer interactions yield comparatively rigid layers which are not disrupted even when small relaxations may lead to favourable inter-layer adhesion energies [7]. In some special instances, however, layered materials heterostructures may be formed between layers of the same or similar lattice constant and marginal twist angle (typically <2°) such that inter-layer interactions are sufficient to induce changes in the intra-layer structure, known as atomic reconstruction and demonstrated for the first time in 2L-MoS_2 (0°) by Weston *et al* [8,9].

We fabricated such samples using the so-called 'tear and stack' method [10], by first exfoliating 1L-MoS_2 (SPI supplies) on polydimethylsiloxane (PDMS) using scotch tape. The flake was then brought partially into contact with a freshly cleaved highly oriented pyrolytic graphite (HOPG) surface and retracted, such that the flake broke, with part left on the HOPG before the remaining 1L-MoS_2 on PDMS was aligned to the first flake and stacked on top. By breaking and restacking the same flake, the twist angle between two layers can be controlled deterministically (0° was used here). Before measuring using C-AFM, samples were annealed to 150°C for 5 minutes in air before cooling to room temperature and scanned using contact mode AFM to promote the removal of contamination from the top MoS_2 surface and buried interfaces.

The cleaned 2L-MoS_2 (0°) on HOPG was measured using C-AFM (see figure 4) with $V_{TS}=-0.5$ V and $SP_{Mech}=0.5$ V (~65 nN), with regular triangular domains observed in both the current and lateral force channels (see figure 4d and e) but not in topography (see figure 4c). Contrast between current of domains with 'AB' and 'BA' stacking registries was in good agreement with observations in the literature [8,11]. In addition to the current map, contrast was measured in the lateral force image (the deflection of the cantilever parallel to the scan direction and perpendicular to the cantilever) which implies differences in the mechanical interaction between the tip and 2L-MoS_2 across different domains.

Comparing different areas of the same 2L-MoS_2 (0°) on HOPG sample, areas of comparatively regular triangular domain morphology (see figure 4d) are observed in addition to more distorted structures (see figure 5a), which we attribute to uneven distributions of strain induced mechanically during sample fabrication. In addition to measuring the morphology of such domains, C-AFM allows the current-voltage characteristics of the junction between the tip and sample to be measured from isolated locations. By performing arrays of point current-voltage measurements across a pre-mapped region, current voltage maps from specific domains may be measured, as shown in figure 5b, to isolate the properties of specific registries and gain insights into how local variations affect the performance of completed devices.

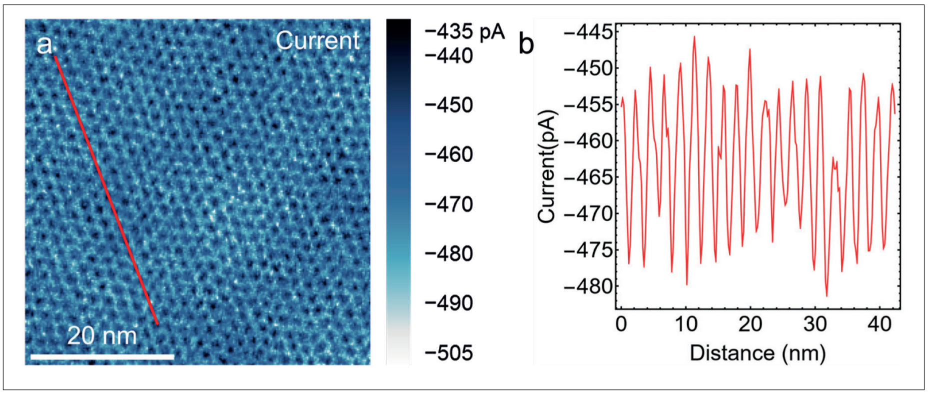

Figure 3. Using C-AFM, a current map (a) of SLG on hBN was measured with V_{TS} = -1V and SP_{Mech} = 2V (~260 nN) with Multi75E cantilevers, showing no contrast in topography but a uniform hexagonal moiré pattern in the current map, as shown in figure 2. To measure the moiré period, a line profile was taken at an angle close to the fast scan direction (b), with an extracted mean spacing of 2.20 nm between local current maxima.

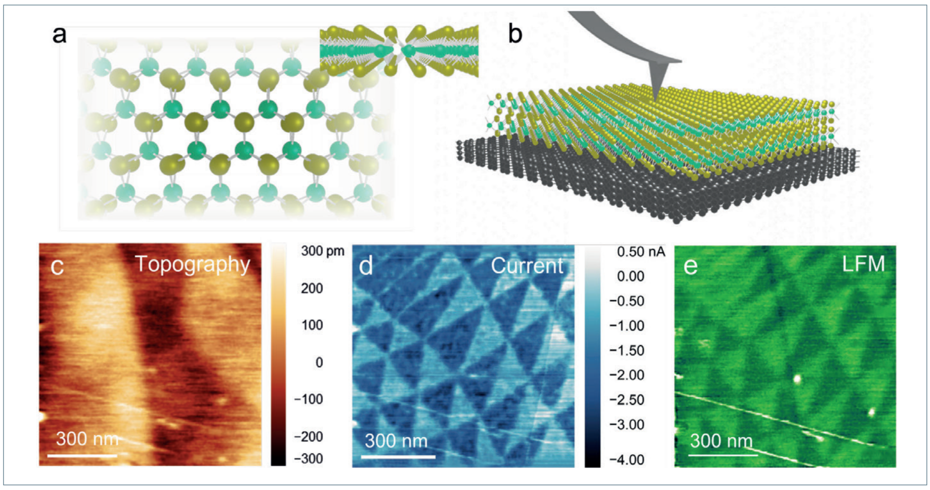

Figure 4. By deterministically breaking and re-stacking a single mechanically exfoliated 1L-MoS_2 (a) on HOPG, parallel stacked (0°) registries of 2L-MoS_2 can be studied using C-AFM. (b) While no contrast is observed in the topography channel (c), regular triangular patterns are observed in both the current map (d) and lateral force map (e) due to differing stacking registries.

Conclusion

In conclusion, we have demonstrated that C-AFM enables spatially modulated functional properties in electrically conductive samples to be measured with nanometre scale resolution and highly relevant functional properties to be measured via mapping and spectroscopy. The advantage of C-AFM is that it provides information on the electrical properties of materials at nanometre length scales which are complementary to both optical spectroscopy and device characterisation techniques, which is valuable both in exploring the fundamental properties of twisted layered materials heterostructures and in the optimisation of devices such as transistors, memristors, photodetectors and light emitting diodes.

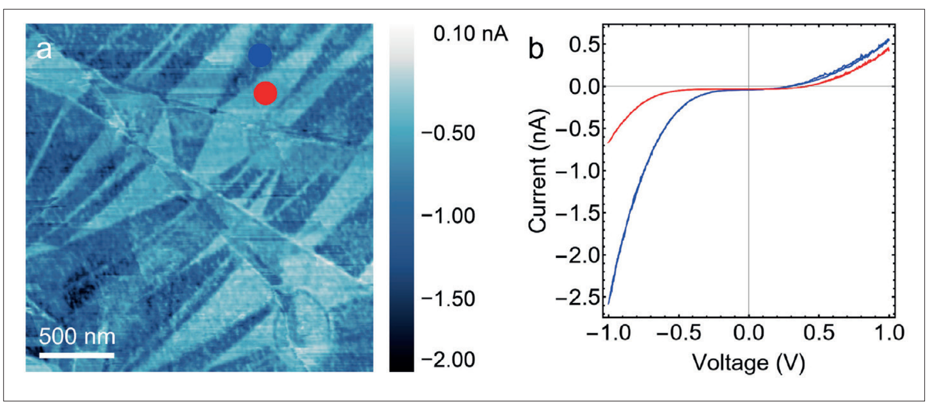

Figure 5. For the same parallel stacked 2L-MoS_2/HOPG sample shown in figure 4, a larger area current map was measured, revealing less regular distorted domains (a). By positioning the probe over specific domains, current-voltage curves may be measured (b), revealing differing characteristics over regions of high and low current contrast.

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Playing to the quantum beats

Computers and digital technology are central to the modern music industry – but what could quantum computers bring to the party? **Philip Ball** tunes in to an avant-garde band of musicians and scientists who are exploring how quantum computing can be used to make and manipulate music

Philip Ball is a science writer based in the UK, whose latest book is *The Book of Minds* (2022), e-mail p.ball@btinternet.com

The Goethe-Institut, opposite Imperial College in London, is not the kind of place you would expect to encounter cutting-edge avant-garde art. With its Neo-classical façade and a history of providing German language classes, it hardly seems the type of venue to host an event that includes musicians like Peter Gabriel and Brian Eno, along with a number of quantum physicists. But the sounds emanating from its lecture theatre last December were a far cry from the institute's traditional image: drones, bleeps and bursts of wild beats more akin to the soundtrack of an experimental underground movie.

This was, in fact, the sound of quantum computing.

The event was attended by about 150 people, who were listening to an improvised musical performance orchestrated by the Brazilian composer and computer scientist Eduardo Reck Miranda, who is based at the University of Plymouth in the UK. In one piece, Miranda and two colleagues were each using their own laptops, which were connected to a quantum computer over the Internet, to control – via hand gestures – the state of a quantum bit (qubit). When that state was measured, the result dictated the characteristics of the sounds created by synthesizers back in London.

If that sounds bizarre – well, yes it truly did.

In quantum computing, information is encoded in superposition states of entangled qubits, which allows some calculations to be carried out far more efficiently than is possible with classical machines. Although these devices are still prototypes mostly confined to the laboratories of tech giants such as IBM and Google, composers like Miranda are keen to discover what the new technology can offer them. "I want to develop machines that will help me be creative and will challenge my normal way of doing things," he says.

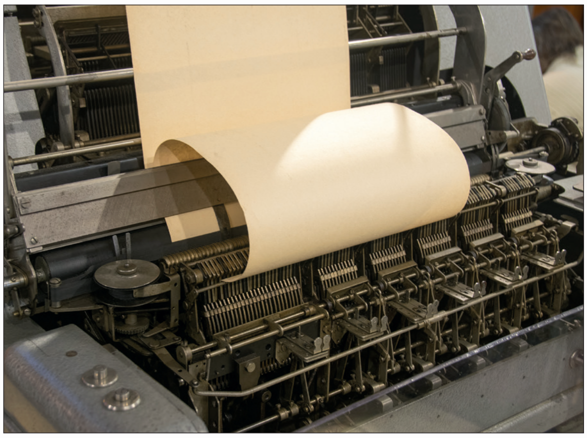
Quantum computing, Miranda believes, "promotes a different way of thinking, [which in turn] will lead to different ways of thinking about music." It's a view shared by Bob Coecke – another of Miranda's collaborators – who is a physicist at the Oxford-based quantum computing company Quantinuum. "If you change the way you look at things, and the language you use, you come out with completely new ideas," says Coecke.

Quantum music is currently a decidedly niche field – but one that is attracting some high-profile interest. Indeed the Goethe-Institut event was convened to mark the launch of a new book edited by Miranda, *Quantum Computer Music*, which claims to be the first-ever book on the subject (Springer, 2022). Coecke, meanwhile, is planning a quantum art/science mash-up in Oxford this year with Miranda and the Italian theorist Carlo Rovelli.

"I'm fascinated to know how [this music] works," said Eno after the Goethe-Institut performance in an interview with the institute. "It's difficult for me to make a judgement, because you don't know how much of those decisions were made by humans, and how much is coming out of that different kind of intelligence."

A natural partnership

The idea of using computer-like algorithms in music dates back to the 1840s, when scientist and mathematician Ada Lovelace first speculated about using Charles Babbage's Analytical Machine – a kind of steampunk calculating



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Digital transformation The notion of using quantum computers for artistic purposes is part of a tradition that stretches back to Ada Lovelace, who wondered almost two centuries ago if Babbage's Analytical Engine could be used to create music.

Goethe-Institut London/Photo: Pau Ros

Where quantum physics meets music Eduardo Miranda (left) at the Goethe-Institut in London, December 2022.

device made from intricate arrays of brass cogs and camshafts – to "compose elaborate and scientific pieces of music of any degree of complexity or extent". In some ways it was a natural partnership, for much of music itself has an algorithmic and mathematical basis, reflected by the symmetries apparent in the works of Baroque composers such as Johann Sebastian Bach.

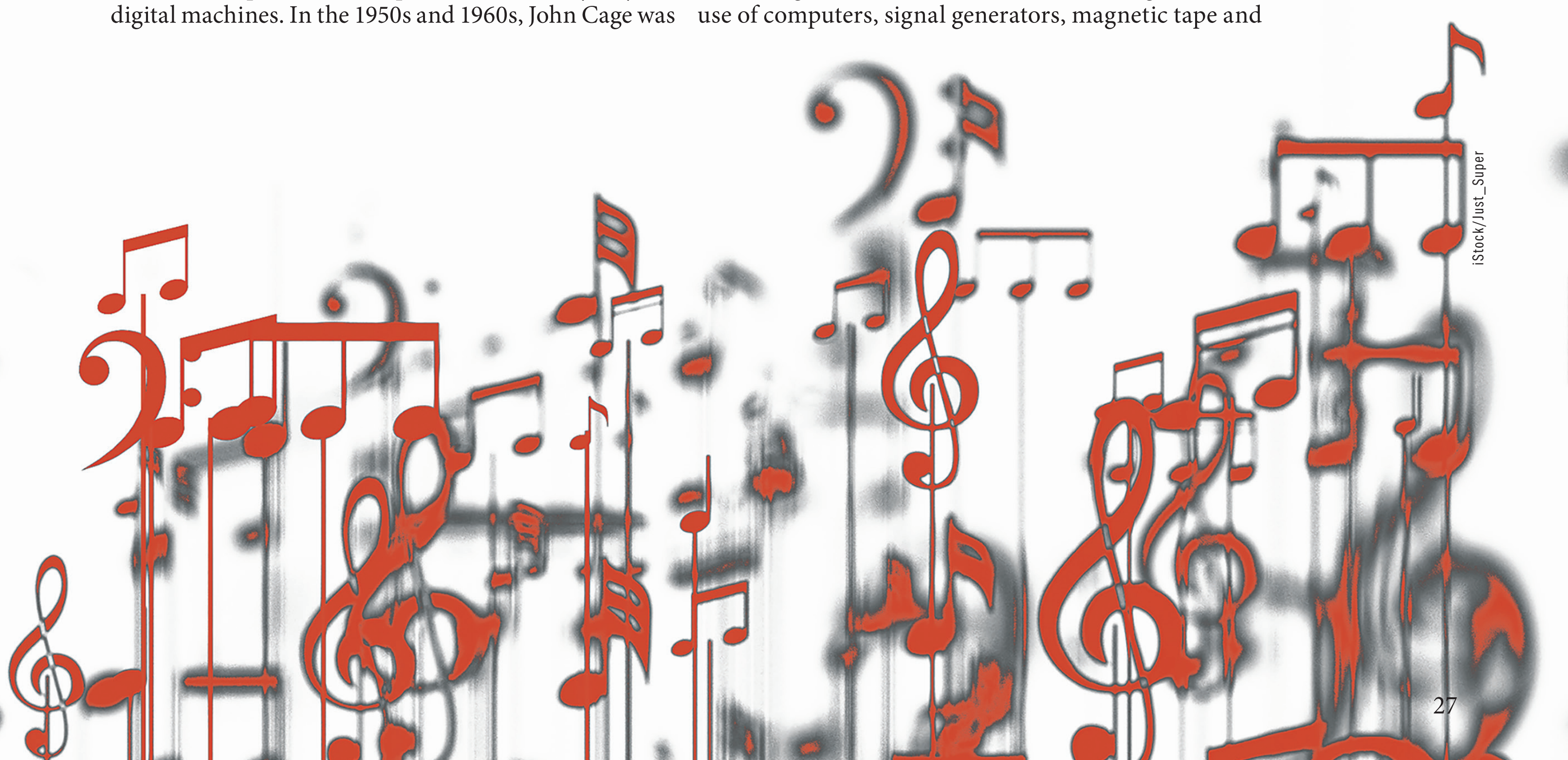
The use of chance and probability in "automated" composition became popular even earlier, in the *Musikalisches Würfelspiel* (musical dice games) of the 18th century, in which small pieces of music were assembled using dice rolls. One composition allegedly written by Mozart in 1787 may be an example of the genre. It would have been played by the performers rolling dice many times, with the number thrown on each occasion corresponding to a particular pre-written section of music. The result was a randomly stitched together composition that differed in every performance, which you can listen to at bit.ly/3HivOLk.

It was the element of randomness that attracted modern composers to computers in the early days of digital machines. In the 1950s and 1960s, John Cage was at the centre of a group of tech-loving New York-based musicians that included Yoko Ono and the late Japanese composer Toshi Ichiyanagi, whose ambiguous 1960 score *IBM for Merce Cunningham* was inspired by the punch cards of early computers. On display at the Museum of Modern Art in New York, his score is as much a work of art as an actual piece of music – how (if it all) it should be interpreted is up to any potential performer.

Cage was also one of several artists involved in the Experiments in Art and Technology collective, which included engineers from Bell Laboratories in New Jersey, where Cage would hang out to get ideas. By using chance, he explained, he hoped to avoid the trap of repeating himself in his compositions.

In the 1960s and 1970s the Greek-French composer Iannis Xenakis – a student of the French composer Olivier Messiaen – incorporated computers, algorithms and various stochastic processes into his composing methods. Meanwhile, the Paris-based IRCAM institute, founded by composer Pierre Boulez, became a hub of avant-garde music in the 1970s, making extensive use of computers, signal generators, magnetic tape and

I want to develop machines that will help me be creative and will challenge my normal way of doing things



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other electronic resources.

Digital-information technology is now central to the production and reproduction of mainstream music. Some of the signal-processing algorithms and hardware that are ubiquitous in music and video today were developed at Bell Labs – and it would be hard to imagine the modern music industry without that kind of digital tech. It was surely inevitable, then, that as quantum computers morphed over the last two decades from a theoretical proposal to real machines, musicians would be curious about what these devices might do for them.

A quantum revolution

Publicly available quantum computing resources are, however, relatively limited, so Miranda is restricted to using a seven-qubit, cryogenically-cooled IBM Quantum device housed in New York, accessed via the cloud. Miranda admits that there is nothing, so far, in the quantum algorithms he uses to craft his compositions that couldn't also be simulated with a classical computer. "For now we're doing [quantum music] in a very naïve way because the machines are limited," adds Coecke.

Still, as Miranda explains, some of the algorithms he is developing would already be computationally expensive and slow on classical devices, and hard to implement live in real time in a concert. But speed of computation is not really the main issue when it comes to using quantum physics to compose music. Currently the big appeal of quantum algorithms is, rather, as a source of randomness in musical choices.

As with some earlier computer-based music, particular parameters of the musical score, such as the pitch or duration of a note, can be assigned to random choices made by the machine. But whereas classical computers offer only a kind of algorithmically generated pseudo-randomness, quantum devices access the genuine randomness involved in the outcome of a quantum measurement. The universe, you might say, makes the choices. What's more, this can be done in real time.

Miranda imagines a composer assigning a particular algorithm to a piece of music, which is then played out via a quantum computer during a performance. In other words, the quantum computer can be remote, as it was at the London event, but simply sends its measurement results back to, say, a classical tone generator. "You set up the conditions, but you're not completely sure what it will produce until the piece is performed," Miranda says. "The performance will be unique for that particular moment."

The Goethe-Institut event showed other ways in which quantum music might work. In one piece, the British violinist Craig Stratton improvised a short tune. The pitch and duration of each note were represented as quantum states that were then sent to the IBM computer in New York. There, the device processed the states to formulate a response that was "re-musicalized" and played back in London by a tone synthesizer (in that event using a saxophone sound) moments later.

Deep-learning AI algorithms for such musical "call-and-response" improvisation have already been devised. But according to Miranda, those algorithms tend to produce mere pastiches of the music they are trained on. Quantum computers, in contrast, will probably behave "more like a partner than an imitator". Indeed the computer-generated melodic responses to Stratton's improvisations sounded little like the stimuli that provoked them, retaining just a few tantalising echoes of the initial sounds.

Stratton, who found the process intriguing, believes that quantum computers certainly have a place in the development of music. "How do we grow and develop if we don't explore other avenues?" he asks.

Bloch heads

In another piece, Miranda and his Plymouth colleagues Pete Thomas and Paulo Itaborai used various computer interfaces to manipulate "Bloch spheres". Named after the Nobel-prize-winning physicist Felix Bloch, these spheres are geometrical figures that describe the vector components of a two-level quantum system (the points on the surface being pure states and those on the inside being mixed states). At the London event, Miranda and Itaborai wore a movement-sensing ring and glove to transmit control signals by hand gestures to a laptop, while Thomas used a panel of knobs.

These signals were fed to a quantum circuit running

Goethe-Institut London/Photo: Pau Ros

That's handy By wearing a movement-sensing ring and glove, performers at the Goethe-Institut event in London were able to "measure" the qubit in an IBM quantum computer in New York, thereby "collapsing" it into an output state, the value of which determined the sound generated by three synthesizers back in London.

remotely on the IBM quantum computer, which allowed the musicians to rotate the orientation of a Bloch sphere (a visual representation of which was projected onto a screen behind the performers). At certain times the performers could choose to "measure" their qubit, thereby "collapsing" it into a definite but fundamentally unpredictable output state. (You can have a go yourself on a classical simulation of the process at bit.ly/41fXVnr).

The value of this state was then used to determine the parameters of the sound generated by three sound synthesizers assigned to each performer. "The sound that results will always be surprising," Miranda says. "We don't know what it will be until we do the measurement." The three performers then responded to what they heard with their subsequent hand movements, making the outcome a constant collaboration both between each musician and their instrument and also with each other.

Miranda calls the performance a rehearsed improvisation. "We practised it before a few times and agreed to a few things we would do, pretty much like what jazz players do," he says. On this occasion all three qubits were independent, but Miranda is keen to find ways of entangling the qubits so that each is dependent on the others – making the musicians themselves literally coupled in new ways.

A new kind of music

Harnessing quantum computing for making music is "like learning how to play a new musical instrument" says Maria Mannone, a theoretical physicist working on quantum information at the University of Palermo in Italy, who is also a composer. "We have to learn how to play the music we want, but, at the same time, the specific features of the new instrument can create constraints and suggest particular ideas."

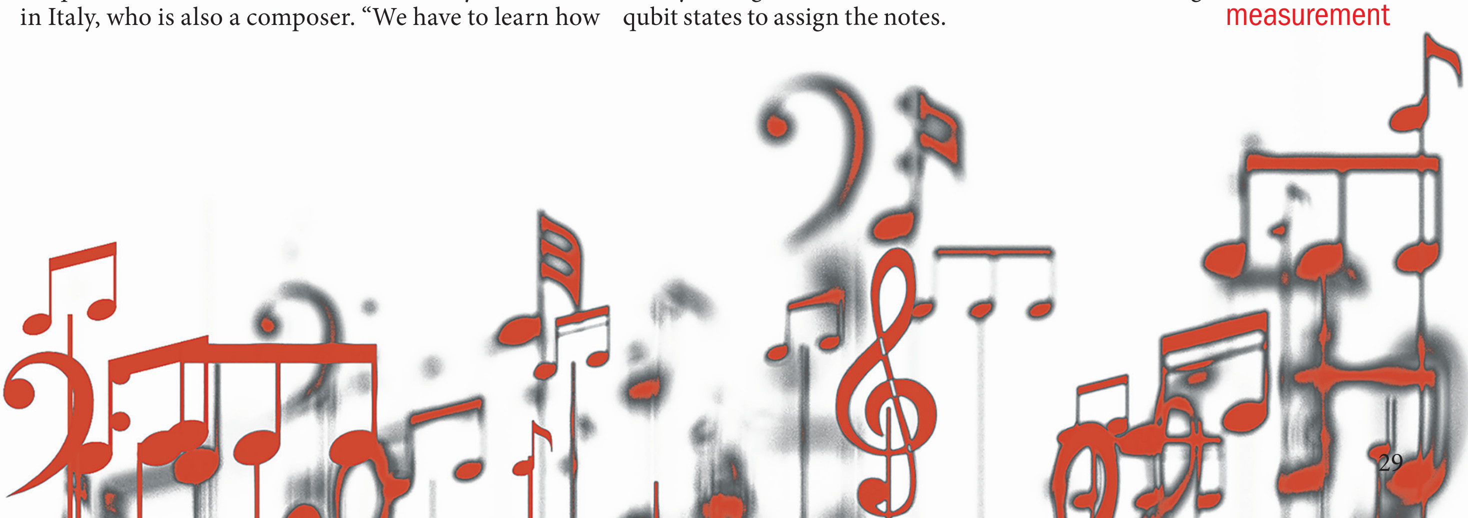
Miranda suspects that one way to exploit the possibilities is to get a quantum computer to come up with unexpected musical fragments that provide the kernels of ideas for the composer to develop, rather in the way in which AI-generated music is currently being used. "I'm trying," he says, "to get the machine to give me material that I wouldn't come up with myself – ideas that I can work with."

One of the current obstacles to the expansion of the field is the sheer unfamiliarity and technical complexity of quantum mechanics itself. Miranda's new book *Quantum Computer Music* is not a manual for the faint-hearted, being filled with wave functions and matrix algebra. Musicians will be daunted, while the physicists and engineers who understand the theory tend to have little knowledge of musical traditions.

But he hopes that user-friendly interfaces will be developed that will lower the entry barrier, just as they have for computing generally. Miranda's qubit rotations, for example, are controlled by simple hand gestures, rather like the way in which the theremin – an electronic musical instrument – is played.

Another approach is being pioneered by Jim Weaver, a quantum scientist at IBM's Yorktown Heights Research Center in New York, who has developed the Quantum Toy Piano. It's a musical tool that uses a quantum computer to generate melodies and harmonies probabilistically, using the inherent randomness of measuring qubit states to assign the notes.

The sound that results will always be surprising. We don't know what it will be until we do the measurement



Everything, especially in the sciences, can be a source of inspiration

Weaver has already developed such ideas into the Quantum Music Playground, in which a user-friendly interface allows the user to manipulate quantum states to create multi-instrument compositions. "[People] can fiddle around until the music sounds the way they'd like it to," Weaver says. "It's music of the Bloch spheres," he quips, alluding to the old notion of a cosmic "music of the celestial spheres" (the idea that the relative movements of the Sun, Moon and planets are a form of music).

This system actually runs on a classical simulation of quantum states conducted by a conventional computer, rather than a real quantum device. This is because it requires complete knowledge of the quantum state – which can't be done for a real qubit because a measurement collapses the state. Weaver, who sees the tool as educational as well as musical, hopes it can help students (and musicians) develop an intuition for quantum-computing algorithms. The work might not only change music but benefit quantum science too.

Another option for overcoming the technical barriers will be for musicians to embed themselves in the quantum research community. That's the approach taken by the American composer Spencer Topel, who in 2019 was artist-in-residence at Yale Quantum Institute, home to quantum-technology experts such as Michel Devoret and Robert Schoelkopf. During his stint at Yale, Topel created a live performance in which the music was produced from measurements of the dynamics of the superconducting quantum devices used as qubits in most current quantum computers.

Musicians could benefit from learning a bit of quantum mechanics, too. "Composers have to be knowledgeable," Mannone points out, "because everything, especially in the sciences, can be a source of inspiration." Indeed the level of knowledge required need not be so daunting. As she points out, some of those now writing quantum code for other applications "do gorgeous work while having only a basic knowledge of quantum gates and principles".

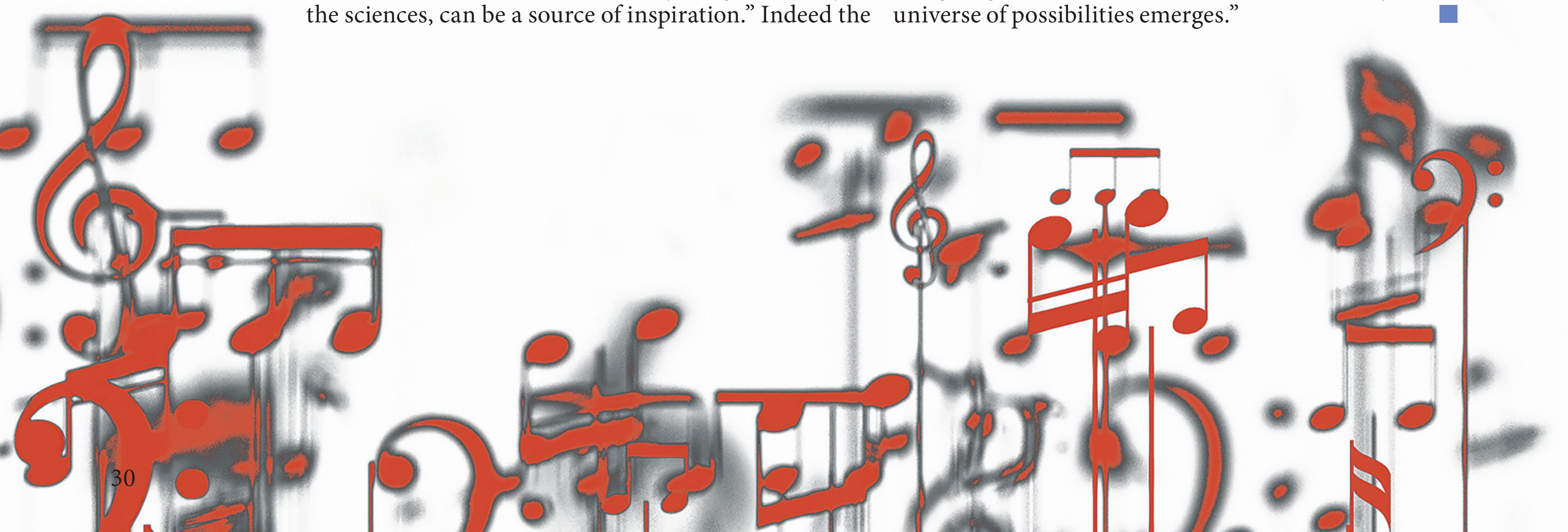
In her own work, Mannone has used quantum physics to analyse music – for example, by using a technique developed to quantify the memory of open quantum systems to measure the amounts of repetition and similarity that appear in musical compositions (*Journal of Creative Music Systems* doi.org/10.5920/jcms.975).

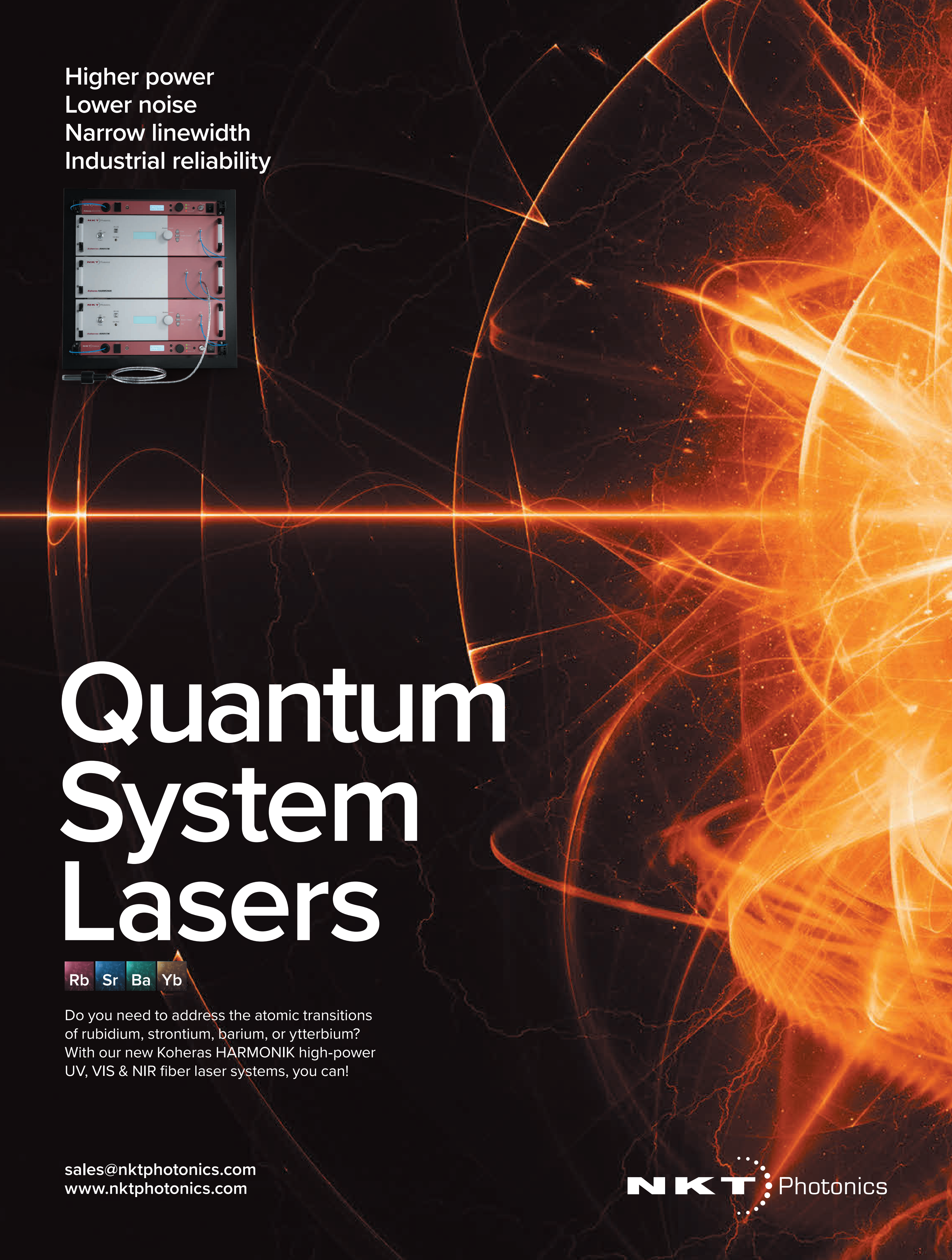
Hear all about it

If you're wondering where you might be able to hear quantum music for yourself, Miranda has his sights set on a live performance at a concert hall through a forthcoming collaboration with the London Sinfonietta. He also foresees this kind of composing infiltrating less formal settings such as clubs, perhaps via the "live coding" movement, a new performance art in which DJ-like coders write programs to control audio-visual media in an improvised and interactive way, perhaps combined with dance, poetry and music (you can listen to an example at bit.ly/3Z8hUDg).

To stimulate the growth of the community, in November 2021 Miranda collaborated with IBM Quantum and Quantinuum to host the first International Symposium on Quantum Computing and Musical Creativity. "We don't yet know what the possibilities for quantum music are," said Quantinuum's founding chief executive Ilyas Khan at the Goethe-Institut event – and it may be that as quantum music matures it will bear little resemblance to what today's pioneers are doing. "These first two to three years are experimental," he says.

Miranda hopes that it might become possible to express – in sound – quantum concepts such as entanglement and coherence that are hard to intuit intellectually. "That's the holy grail," he says. "I want to achieve this but I don't know how." But for Coecke, it's all about catalysing a switch to quantum thinking. "If you put things together in the quantum world, suddenly a new universe of possibilities emerges." ■

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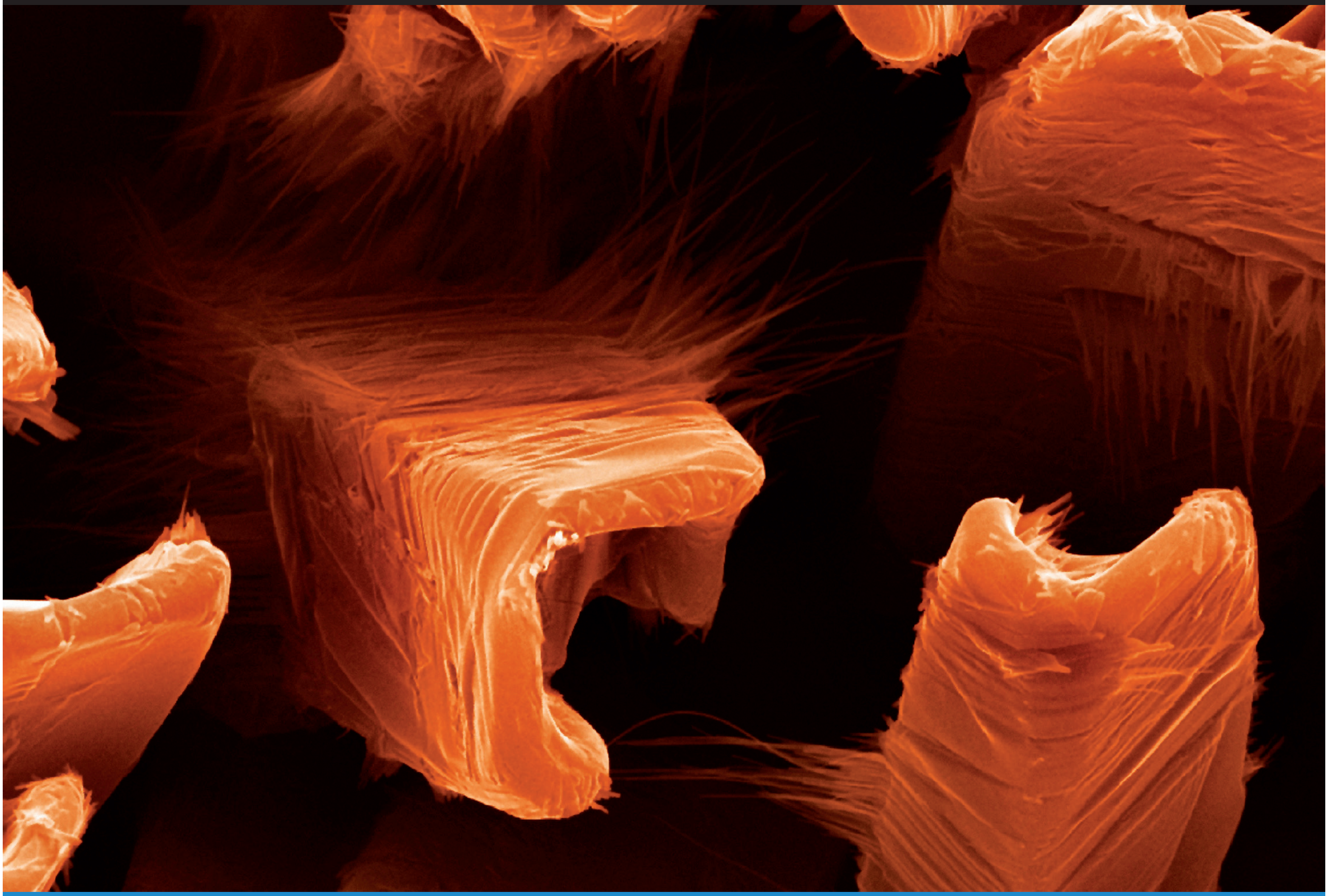
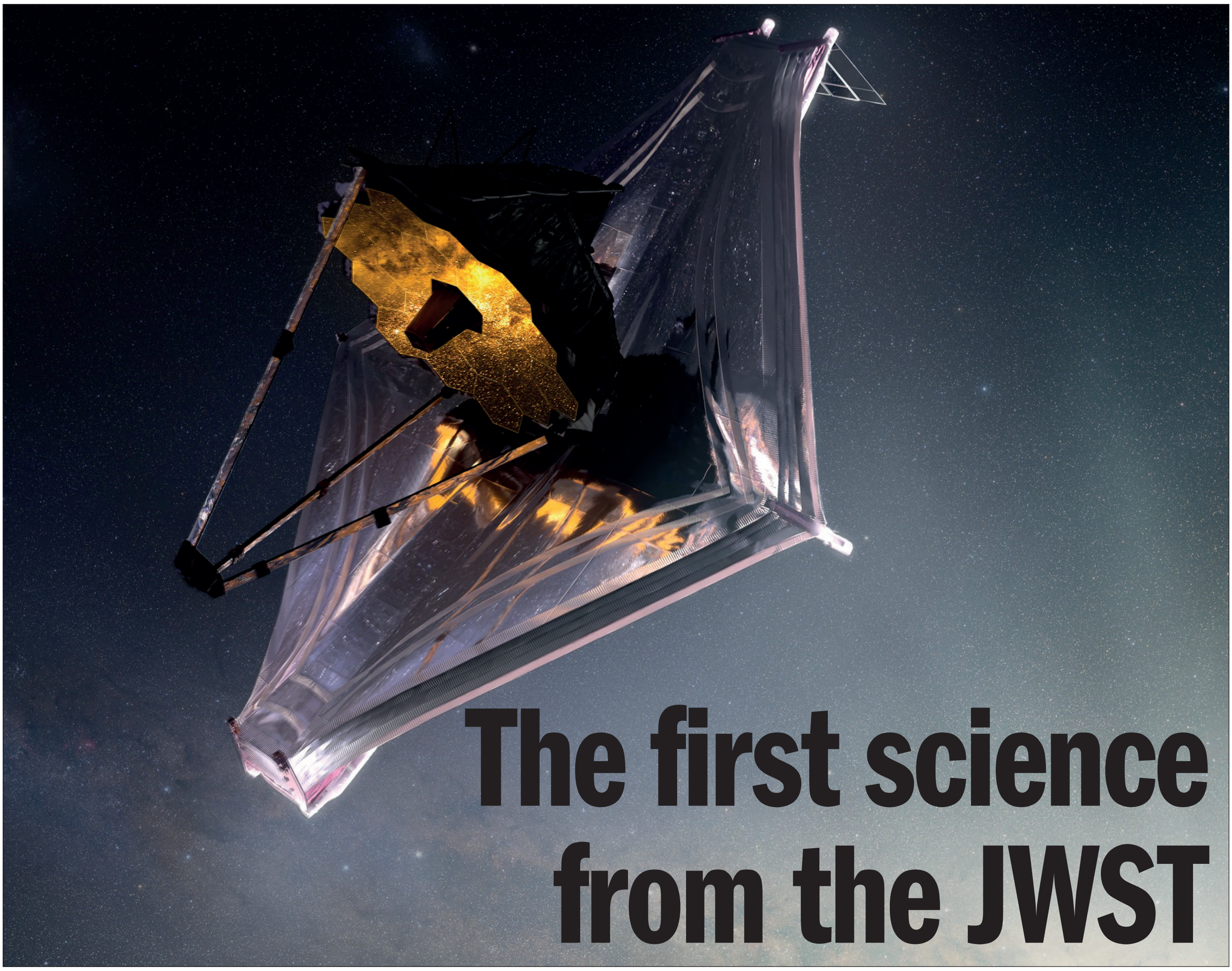



NASA-GSFC, Adriana M Gutierrez (CI Lab)

The first science from the JWST

The James Webb Space Telescope (JWST) was launched just over a year ago, and astronomers have started to unravel the secrets of the universe that this ground-breaking telescope has revealed. **Keith Cooper** picks out the highlights of the JWST's initial scientific achievements

On Christmas Day 2021, after nearly 25 years of development, NASA's James Webb Space Telescope (JWST) soared into space atop an Ariane 5 rocket. Its launch was a triumph over technological tribulations, budget and schedule overruns, and even a temporary cancellation by the US Congress. Consequently, emotions were high as the launchpad countdown neared zero.

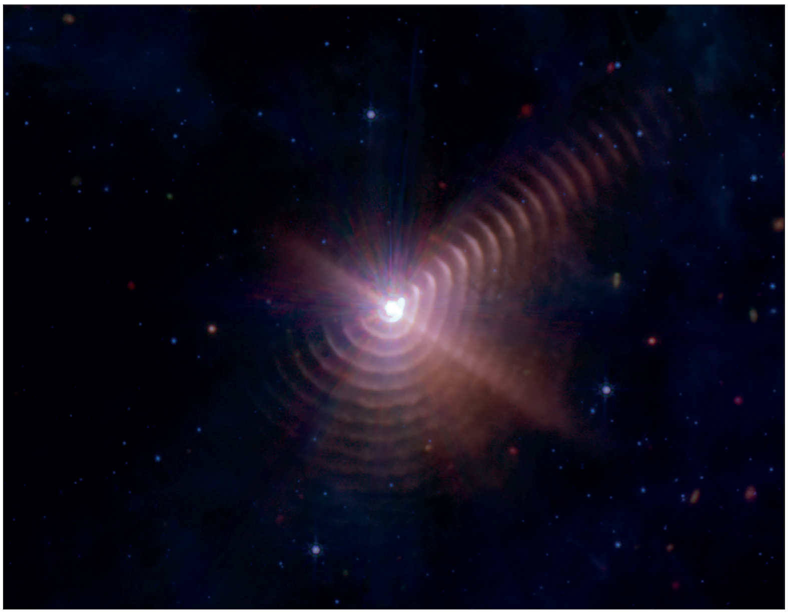
"It was tense," admits Susan Mullally, the JWST's deputy project scientist at the Space Telescope Science Institute (STScI) in Baltimore. "I couldn't believe it was real," adds Naomi Rowe-Gurney, who works as a JWST Guaranteed Time Observations postdoc at NASA's Goddard Space Flight Center, where she is supporting the Planetary Systems Team. "I was expecting another delay of some kind. I thought it was never going to launch."

A hazardous journey

The stop–start nature of the project's development came about, in part, because of the increasing complexity of the telescope, which features a segmented 6.5 m primary mirror as well as a fragile, five-layer, tennis-court-sized insulating sunshield. Both elements had to be able to unfurl like origami, after being scrunched up to fit inside the rocket faring – an unfolding that took 30 days to complete during which the telescope journeyed to Lagrange Point 2 (L2) on the opposite side of the Earth to the Sun, 1.6 million km away.

L2 is an unstable Lagrange Point, where the gravitational forces of the Earth and Sun balance the centrifugal force of a small object orbiting the Sun, but that object falls out of equilibrium around every 23 days. A telescope at this point needs to do regular course and attitude corrections using thrusters to remain in position – which the JWST is well equipped to do, with plenty of propellant on board. However, L2 is much too far away for the kind of astronaut-assisted servicing the Hubble Space Telescope (547 km above Earth) received for its faulty optics in 1993. If something had gone wrong with the JWST's mirror during its deployment, astronomers would have been left with a $10bn white elephant floating in deep space. "Those first 30 days were pretty nerve-wracking, because any problem was a single-point failure and would mean

Keith Cooper is a science journalist based in the UK. His book *The Contact Paradox: Challenging Our Assumptions in the Search for Extraterrestrial Intelligence* (Bloomsbury Sigma) is available now. Twitter @21stCenturySETI



NASA, ESA, CSA, STScI, JPL-Caltech

Bull's eye Concentric rings around the Wolf–Rayet star and O-type star system, WR 140.

If astronomers had not first modelled the pattern of scattered light leaking into the telescope so they could remove it, it would have been impossible to discern what the observations were telling us

we wouldn't have a telescope," Rowe-Gurney says.

All told, there were 344 such possible points of failure, where the telescope's intricate moving parts had to work perfectly in the cold vacuum of space. Yet work they did.

"The day when I knew this was actually going to work was when that main boom swung out, and the secondary mirror folded out, and we actually had a telescope," Rowe-Gurney says. "Even if the subsequent deployments didn't work, we could capture light and put it into the instruments."

With both mirrors deployed, the next step was to focus the 18 hexagonal beryllium segments of the primary mirror. This was accomplished in seven phases. Initially, each segment produced a different unfocused image, so the first phase was to recognize which image belonged to which hexagonal mirror. Then each mirror had to be roughly aligned so that the 18 images were all in focus. After that, the segments were further adjusted so that they began to focus on the same point.

This was followed by various degrees of fine-tuning and making sure that the focus fell within the fields of view of the different instruments. Then there was a series of corrections to ensure the segments were aligned to within 50 nm of each other. And finally, after a three-month process, the telescope was in focus.

With that all done, the next step was to calibrate its individual instruments: the Near-Infrared Camera (NIRCam), the Near-Infrared Spectrometer (NIRSpec), and MIRI, the suite of detectors that make up the Mid-Infrared Instrument. This process could only begin once MIRI had cooled to its operating temperature of just 7 K (–266 °C) in mid-April 2022, and lasted about two months.

Breaking the speed limit

To track and image objects within the solar system, which move against the seemingly fixed background of deep space, the JWST has to physically turn the spacecraft. Initially, the telescope had a tracking speed limit of 30 milliarcseconds per second (mas/s, where one arcsecond is 1/3600th of a degree) to ensure clear images.

"The speed limit was based on the motion of Mars, which approximately means anything closer to the Sun than Mars has a chance that it could be moving too fast for the telescope," says Michael Kelley of the University of Maryland.

Kelley studies the minor bodies of the solar system – asteroids and comets – which frequently come inside the orbit of Mars. The observation of comets, in particular, is sensitive to their distance from the Sun, as they react to the Sun's warmth and various gases sublimate. "A comet at 1 AU [around 150 million km] from the Sun can behave differently from when it is 3 AU from the Sun, all due to the increased amount of sunlight received," says Kelley. However, Mars is at about 1.5 AU, so with the 30 mas/s speed limit, the JWST would be restricted when trying to observe active comets inside Mars' orbit.

Fortunately, once in space, the JWST team realized that setting the speed limit at 30 mas/s was a little pessimistic. "We were testing how fast we could track, and we realized that we could actually do much faster," says Rowe-Gurney, who was involved in commissioning instruments for collecting data on moving targets and scattered light.

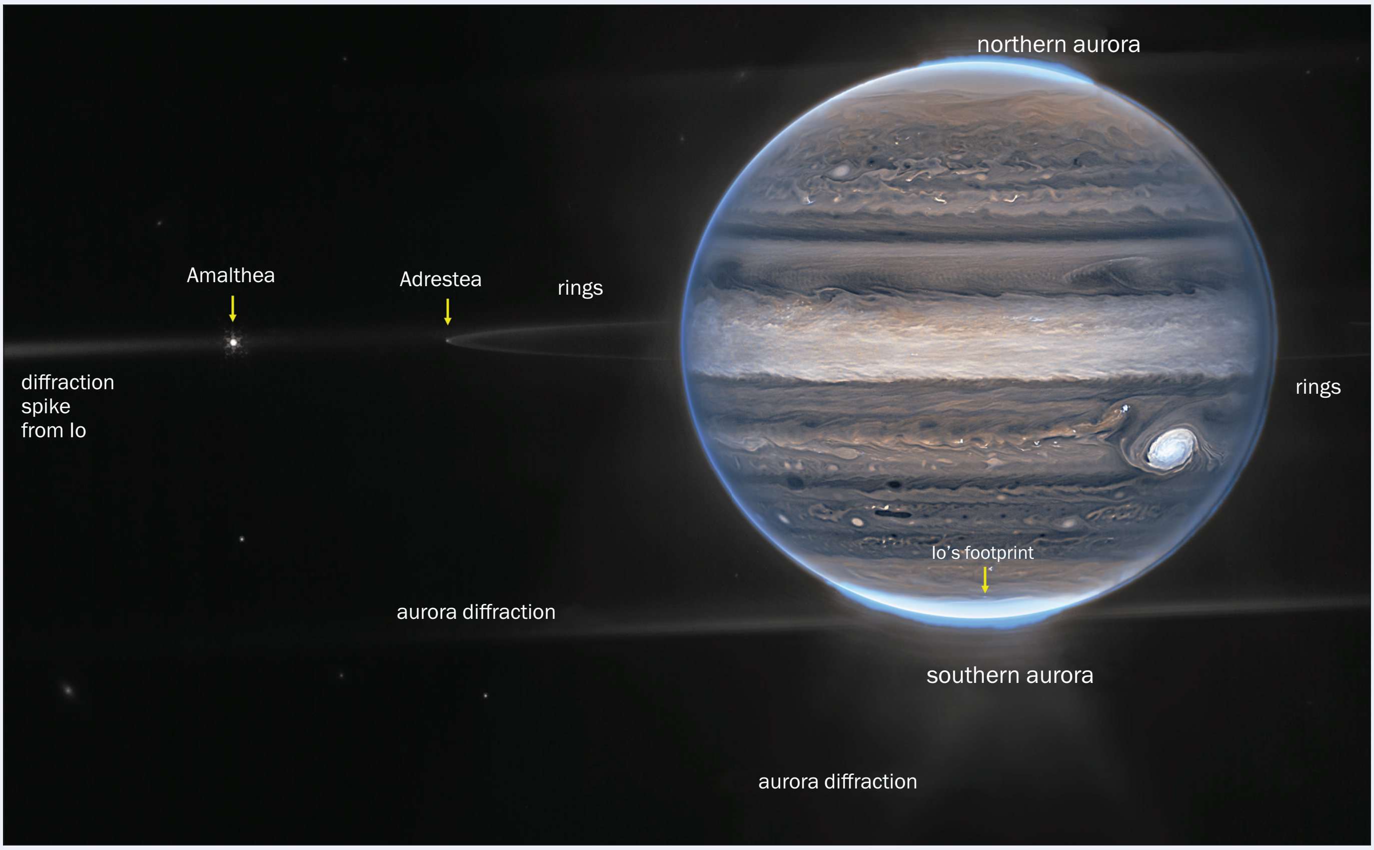
The increased tracking speed came in useful a few months later, when the JWST observed the aftermath of the Double Asteroid Redirection Test (DART) impact on the small asteroid Dimorphos, which took place 11 million km from Earth. The DART mission was *Physics World*'s Breakthrough of the Year 2022, and the JWST was able to image debris ejected from its impact by tracking three times faster than the 30 mas/s limit, keeping the asteroid in the field of view without blurring.

Indeed, the telescope has since achieved tracking speeds of up to 120 mas/s. However, the faster it goes, the lower its tracking efficiency, leading to a middle-ground compromise. "In the next year the safe tracking rate will be put up to 75 mas/s, more than doubling the current speed limit, so we'll be able to follow even more objects in the solar system without breaking the telescope," Rowe-Gurney says.

Extraneous artefacts

As well as mirror alignment, instrument calibration and tracking limits, JWST scientists needed to account for the telescope's unique imaging effects. When the JWST stares

Neighbourhood watch – solar system findings



NASA, ESA, Jupiter ERS Team; image processing by Ricardo Hueso (UPV/EHU) and Judy Schmidt

Jovian views The JWST's NIRCam image of Jupiter, revealing not only great detail in the planet's atmosphere, but also faint moons, rings and even aurorae.

Though associated with observing galaxies far, far away, the James Webb Space Telescope (JWST) has proven adept – surprisingly so – at imaging our neighbours in the solar system. Mars, Jupiter, Neptune and Uranus have had their portrait taken by the JWST thus far.

The results released to date are spell-binding. Jupiter's portrait, for instance, shows exquisite detail in the giant's tumultuous clouds. The JWST's infrared vision is able to see through to deeper layers of the Jovian atmosphere. Yet in the same shot the space telescope was also able to capture the giant planet's faint dust rings and small moons.

In the same vein, the image of the distant, blue orb that is Neptune revealed its tenuous rings with unexpected clarity. This ability to capture the bright with the dim is thanks to the JWST's high dynamic range, which is providing better results than anybody anticipated.

It's not just the planets that have been the focus of the JWST's attention in the solar system. Intriguing minor bodies have also fallen under the telescope's gaze, such as the weird objects that astronomers call "main belt comets". As with regular icy comets, these feature the characteristic tails and comae, but they have stable asteroid-like orbits within Jupiter's path.

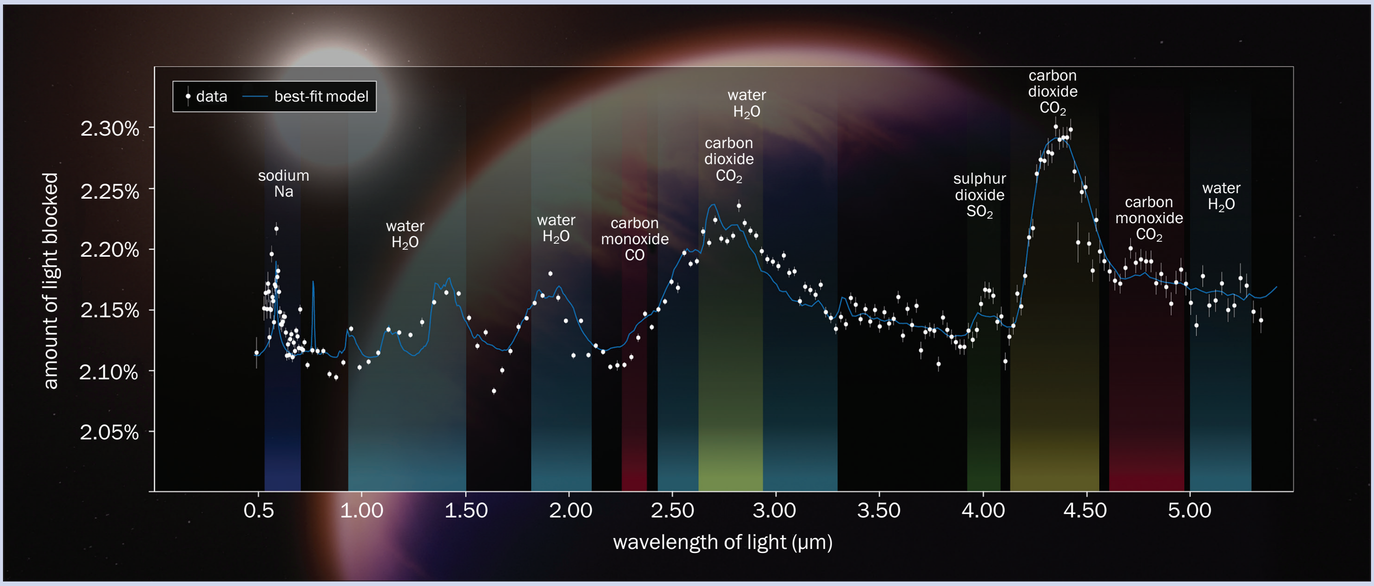
Their origins and the mechanisms that drive their pseudo-cometary behaviour are still a mystery – one that the JWST has now shed a little light on. The telescope targeted the main belt comet 238P/Read, detecting the spectral signature of outflows of water vapour, but no carbon dioxide. This is surprising because in the areas of the solar system where normal asteroids and comets formed, there would have been carbon dioxide. Either the carbon dioxide was baked out of the comet after it arrived in the Asteroid Belt, or it was never present in the first place, which could hint that 238P/Read and other main belt comets originate from a different area of the solar system.

at a bright object – a planet, a star, even a distant quasar – some of the excess light forms a diffraction pattern. This causes the "spikes" seen around foreground stars in many of the JWST's images, and although pretty, it can obscure scientific details. Fortunately, every telescope's unique diffraction pattern can be described as a point spread function, and by characterizing the shape of this for the JWST and its instruments, astronomers can remove the extraneous light from images when necessary.

A case in point was the JWST's image of a binary star system known as WR 140. Located 5000 light-years away, WR 140 features a Wolf-Rayet star and an O-type star, around 10 and 30 times the mass of the Sun respectively. An O-type star is the hottest and most massive type of star, while a Wolf-Rayet star is an O-type that is nearing the end of its life and generates powerful winds that push huge amounts of gas into space.

When first imaged by the JWST, astronomers were stunned to see 17 concentric rings, or shells, around the binary stars (see image on opposite page). These rings were initially thought to be imaging artefacts from the telescope, but after removing the point spread function, the rings could still be seen. Further investigation based on simulations showed that a binary system can produce rings of dust when stars in a highly elongated orbit come close together and their stellar winds collide, compressing the gas and forming dust. What is more, the pattern of the simulated rings precisely matched the pattern around WR 140, even down to a linear feature cutting through the rings due to enhanced infrared emission in our line

Distant relatives – exoplanets



NASA, ESA, CSA, J Olmsted (STScI)

Across the exoplanetary spectrum The transmission spectrum of the hot gas giant planet WASP-39b.

At the 241st meeting of the American Astronomical Society in January, one major announcement was the James Webb Space Telescope (JWST)'s first discovery of an exoplanet – in this case a hot, Earth-sized world transiting the nearby red dwarf star LHS 475b, 41 light-years away.

The JWST is able to characterize the atmospheres of exoplanets via a technique known as transmission spectroscopy. As the planet transits its host star, some of the star's light passes through the planet's atmosphere where it is partially absorbed by atoms and molecules that leave spectral fingerprints. While details regarding LHS 475b's atmosphere are yet to be teased out, the JWST has probed the atmosphere of another world – a hot gas giant named WASP-39b located 750 light-years away that was discovered in 2011 by the Wide Angle Search for Planets (WASP) project. The JWST has now characterized this planet in greater detail than any other outside of our solar system.

Within WASP-39b's atmosphere the JWST found carbon dioxide, carbon monoxide, hydrogen, potassium, sodium, sulphur dioxide and water vapour. The presence of sulphur dioxide is particularly interesting because it is produced when sunlight triggers chemical reactions in the atmosphere, making the discovery the first detection of photochemistry on an exoplanet.

One of the JWST's selling points was that it would also be able to shed more light on potentially habitable exoplanets – such as the rocky worlds orbiting the star TRAPPIST-1 some 40 light-years away – but we're going to have to bide our time before we have those insights. WASP-39b is a large planet with a deep atmosphere, orbiting a relatively bright star, so it's easier to observe its atmosphere than worlds orbiting cool, faint red dwarf stars such as TRAPPIST-1 or LHS 475. These exoplanets are also more difficult to characterize because of their thinner atmospheres, if they have an atmosphere at all.

Concrete findings may take several years to come, but early reconnaissance of the TRAPPIST-1 system by the JWST has so far ruled out one of the planets, TRAPPIST-1g, from having a thick hydrogen-rich atmosphere. Planet "g" is at the very outer edge of TRAPPIST-1's habitable zone, so this might mean that without a thick insulating atmosphere, TRAPPIST-1g could be too cold for life as we know it.

of sight. Like the rings of a tree trunk, the rings around WR 140 mark the stars' orbit around each other, which takes eight years.

The observations of WR 140 represent the first time a colliding wind structure around a binary star has been mapped in 3D. But if astronomers had not first modelled the pattern of scattered light leaking into the telescope so they could remove it, it would have been impossible to discern what the observations were telling us.

Astronomers' new toy

The example of WR 140 shows how vital it is to get to know the telescope while making observations. "It's something you have to think about a lot," Mullally says. "Every step of the way you're hoping to have an expert on your team who knows as much as possible either about the instrument or about how those types of observations are taken."

Accordingly, one of the motivations behind the JWST's Early Release Science (ERS) programme – where observations acquired in the first five months of science operations were made public immediately – was to help a few astronomers become familiar with the telescope and its instruments so they can bring others up to speed for later observing cycles. "It's like a new toy," says Rowe-Gurney. "There's a lot of work going into how to process and calibrate the data to make sure it's reliable."

Fortunately, the JWST is playing ball. "Instrument scientists might say they are still getting to know their instruments and how to go about removing little systematics and artefacts and things like that in your data," says Mullally, "but overall the impression I'm getting from everybody is that the telescope is performing wonderfully."

So far, there is only one caveat to the JWST's performance: the damage caused by micrometeoroid impacts. On average, the telescope's mirror is struck once a month by something large enough to affect wavefront sensing – the telescope's ability to detect errors in the alignment of its optics, which can manifest as light waves moving out of phase. This reduction in wavefront sensing can make images less sharp.

Such impacts were anticipated before launch, and were not expected to be big enough to threaten the telescope's

Clifftop nursery – star birth

NASA, ESA, CSA, and STScI, J DePasquale (STScI)

Cosmic Cliffs What looks much like craggy mountains on a moonlit evening is actually the edge of a nearby, young star-forming region, NGC 3324, in the Carina Nebula. Captured in infrared light by the Near-Infrared Camera (NIRCam) on the JWST, this image reveals previously obscured areas of star birth.

One of the first images to be released from the James Webb Space Telescope (JWST) in July 2022 was that of the "Cosmic Cliffs" – a section of the Carina star-forming nebula located about 8500 light-years away. Previously imaged by the Hubble Space Telescope, the so-called cliffs are molecular gas encircling a giant bubble that has been blown in the nebula by the stellar winds and ultraviolet light of five luminous O-type stars.

Embedded within the gaseous cliff edge are newborn stars. The JWST can track these down by identifying the polar jets and outflows of gas that are ejected as the stars form from infalling gas. In this image alone, the JWST identified 24 new outflows from young stars that are still growing.

Astronomers hope these observations will help them answer questions about what is triggering star formation in the nebula. For example, do the winds of the five O-type stars compress the gas on the edge of the Cosmic Cliffs and spark star formation that way? Or is their presence on the "knobbly" cliff tops only a coincidence, and the young stars and their outflows revealed simply because they exist in denser regions of gas that have survived the erosional onslaught of the ultraviolet radiation?

Other star-forming regions have also come under the JWST's gaze. NGC 346 in the Small Magellanic Cloud, about 200 000 light-years away, is a cosmic throwback to days gone by. It is an active star-forming nebula that contains an anomalously low abundance of heavier elements, reminiscent of conditions during the first billion years of the universe. Previously, astronomers have been able to identify high-mass stars in NGC 346, but the JWST has the resolving power to identify young stars in the nebula that measure just a tenth of the Sun's mass.

Observing the full range of stars in NGC 346 is important because it will allow astronomers to deduce the initial mass function (IMF) – that is, the distribution of masses that stars form with. In our modern universe the IMF is weighted against massive, luminous stars, but was this necessarily the case in the early universe when there were fewer heavy elements, which can affect the temperature of the molecular gas clouds from which stars form and in turn possibly influence the masses of stars? NGC 346 could provide a modern day answer, with repercussions for galaxies in the early universe.

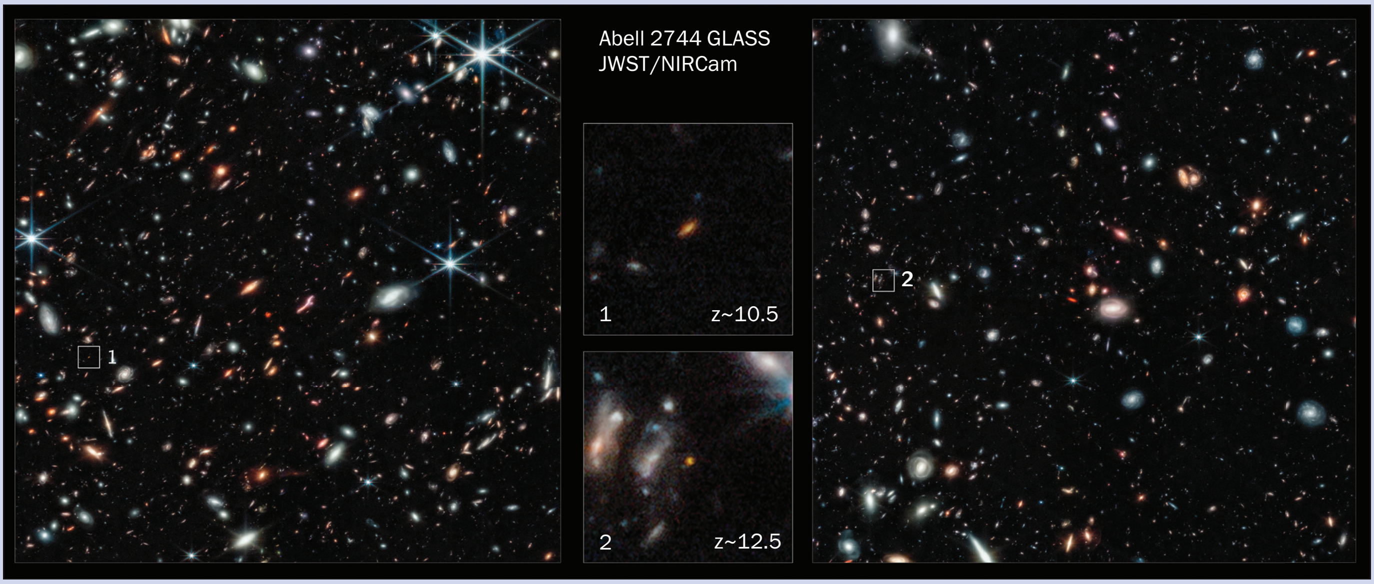
lifespan. However, by May 2022 one of the mirror segments had already received a larger-than-typical impact, leaving a wound about 30 cm across and increasing the telescope's total wavefront error from 50 nm to 59 nm. This is significant because if the wavefront error reaches 150 nm, the telescope will no longer be sensitive enough to meet its scientific targets – meaning that just 10 impacts of a similar scale would be "game over" for the JWST.

Somewhat alarmed by this prospect, NASA has convened a micrometeoroid working group to investigate the risk. The micrometeoroid population at L2 is well known; what isn't clear is the relationship between the kinetic energy of impacts and the degradation of wavefront sensing. Are such large impacts extremely rare and the JWST was simply unlucky last May? Or will the telescope experience more serious impacts at a greater frequency than predicted?

Until the working group comes up with answers, the telescope's managers are mitigating the risk by encouraging astronomers to time their observations (where possible – time-sensitive observations are exempt) so that the telescope is not pointing into the "rain" of micrometeoroids.

If this system succeeds, or the working group comes up with a reassuring answer about impact odds, the JWST should have a long life ahead of it. Thanks to its flawless launch and a journey to L2 that required minimal course corrections, the telescope has enough propellant on board to continue its mission for at least another 27 years.

Looking back in time – high-redshift galaxies



NASA, ESA, CSA, T Treu (UCLA)

Magnified A JWST image of the galaxy cluster Abell 2744, the great mass of which acts as a gravitational lens, magnifying the light of high-redshift galaxies.

One of the key science motivations behind the James Webb Space Telescope (JWST) is its ability to detect galaxies at higher redshift than ever before. Redshift is a measure of how much the wavelength of light has been stretched to longer, redder wavelengths by cosmic expansion, and the more distant a galaxy, the higher its redshift. Within days of the first release of science data from the JWST's numerous deep-space galaxy surveys, the telescope was more than proving its worth in this regard.

Indeed, at the First Science Results from the JWST conference in December 2022, there was a running joke: astronomers would refer to galaxies at, say, redshift 9 or 10 as being high redshift, then catch themselves as they realized that the JWST has now discovered galaxies at much higher redshifts. In fact, the telescope has detected galaxies with confirmed, record-breaking redshifts of 11.58, 12.63 and 12.30, smashing past the pre-JWST record of 11.1. We see these galaxies as they existed less than 400 million years after the Big Bang. The JWST has even found several galaxies at potentially even greater redshifts. These await spectroscopic confirmation, but if the initial assessment is correct then they are at redshifts of 14.3, 16.7 and even an amazing redshift 20, which would equate to seeing a galaxy as it existed just over 200 million years after the Big Bang.

By looking farther back in cosmic time than ever before, we are bound to find some surprises, and the JWST hasn't let us down. Many of these very early galaxies appear to be more luminous in ultraviolet (UV) light than our models of galaxy formation predict (of course, this light has been shifted into infrared wavelengths by the time it reaches us). UV light is produced largely by hot, young stars and therefore a galaxy's UV luminosity is a measure of star formation. The expectation was that this UV luminosity function would drop off the earlier we look into the history of the universe, since early galaxies would contain fewer stars. The JWST's UV observations therefore suggest that something fundamental about how galaxies form stars was different back then.

One possible explanation could be that the initial mass function in these early galaxies was different to what it is today, skewed more towards a greater abundance of hot, massive, UV-emitting stars. This discovery is why the JWST's observations of NGC 346 – the star-forming molecular cloud with an unusually low abundance of heavy elements akin to conditions found in the early universe (see box on p37) – are so important.

In theory, low abundances of heavy elements can support the formation of a greater amount of luminous, massive stars, and calculations suggest that an overabundance of massive stars could cause the UV luminosity to increase by as much as 2.5 times, matching what the JWST observes. Steven Finkelstein, a professor of astronomy at the University of Texas at Austin, says that this hypothesis could be tested by the JWST. "Such massive stars would have high surface temperatures, which in turn would lead to emission lines from highly ionized atoms that are detectable with JWST spectroscopy," he tells *Physics World*.

Another big question in cosmology is what brought the cosmic Dark Ages to an end, ionizing most of the neutral hydrogen gas in the early universe. The cause of this ionization would be one of the first major sources of light and radiation, and astronomers have flip-flopped between whether it was the first galaxies or quasars (active black holes).

The JWST is able to observe the host galaxies of high-redshift quasars, which is something the Hubble Space Telescope could not do. It is finding that quasars existed in the middle of over-densities of galaxies – proto-galaxy clusters, if you will – but that in general the black holes are sticking close to the Eddington limit, which is the balance between the mass of a black hole (and hence its gravity) and its luminosity. If this is correct, then it would seem that black holes in the early universe are sticking close to the rules, while stars could be breaking them – which could mean they had a more significant influence on what brought the cosmic Dark Ages to an end than expected.

If the mission's first 12 months are any indication, these 27 years should produce reams of sensational new views and data from a superb instrument, with a high likelihood of transforming astrophysics, exoplanet studies, cosmology and more. Already, two major scientific conferences – the First Science Results from the JWST meeting at the Space Telescope Science Institute in Baltimore in December 2022, and the 241st meeting of the American Astronomical Society in Seattle in January 2023 – have teased the potential of the JWST with some tantalizing new discoveries that are just the tip of the iceberg of what it's capable of. The rollercoaster ride of the JWST's launch may be over, but the real excitement is just beginning.

A periodic table for topological materials

Topological insulators are a relatively new discovery, with the first theoretical studies taking place in the 1980s. But now, a team has identified tens of thousands of these unusual materials. **Maia Vergniory** talks to Margaret Harris about the database her group has compiled

Ana Ruzi / Donostia International Physics Centerreko DIPC

Diagnosing topology Materials simulation expert Maia Vergniory.

Materials that conduct electricity on their outsides, but not their insides, were once thought to be unusual. But computational chemist Maia Vergniory and colleagues have recently proven otherwise. They have identified tens of thousands of such topological insulators and other materials with noteworthy topological properties, and have compiled their findings to create a Topological Materials Database (www.topologicalquantumchemistry.com).

Vergniory – from the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany – spoke to Margaret Harris about how the team went about this search and what the database means for the field.

What is a topological material?

The most interesting topological materials are topological insulators, which are insulating in the bulk, but conducting on the surface. In these, the conducting channels where the electronic current flows are very robust. They persist independently of some external disturbances that you can have in experiments, such as weak disorder or temperature fluctuations, and they're also independent of size. This is very interesting because it means these materials have a constant resistance, a constant conductivity. Having such tight control of the electronic current is useful for many applications.

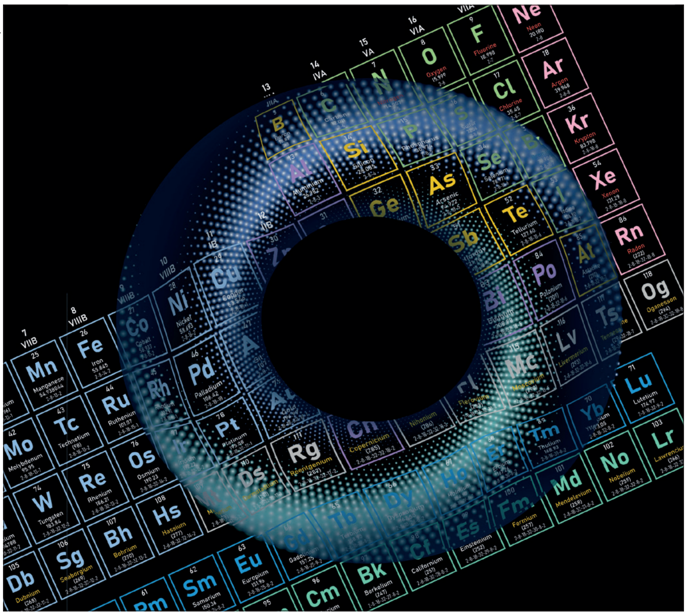
What are some examples of topological insulators?

The best-known example is probably gallium arsenide, which is a two-dimensional semiconductor that is often used in experiments on the integer quantum Hall effect. In the newer generation of topological insulators, the most prominent one is bismuth selenide, but this has not gained as much widespread attention.

Why did you and your colleagues decide to search for new topological materials?

At the time, there were just a few of them in the market, and we thought, "Okay, if we can develop a method that can calculate or

Christine Daniloff/MIT



Topological catalogue The Topological Materials Database created by Maia Vergniory and colleagues is a searchable tool containing more than 90 000 known topological materials.

diagnose topology quickly, we can see if there are materials that have more optimized properties."

One example of an optimized property is the electronic band gap. The fact that these materials are insulating in the bulk means that in the bulk, there is a range of energies where the electrons cannot pass through. This "forbidden" energy range is the electronic band gap, and electrons cannot travel in that region even though they can exist on the material's surface. The larger the material's electronic band gap is, the better a topological insulator it will be.

How did you go about looking for new topological materials?

We developed an algorithm based on a material's crystalline symmetries, which is something that was not taken into account before. The symmetry of the crystal is very important when dealing with topology because certain topological materials and some topological phases need a particular symmetry (or lack of symmetry) to exist.

For example, the integer quantum Hall effect needs no symmetries at all, but it does need one to be broken, which is time-reversal symmetry. That means the material needs to be magnetic, or we need a very large external magnetic field.

But other topological phases do need symmetries, and we managed to identify which they were. Then, once we had all the symmetries identified, we could classify them – because in the end, that is what physicists do. We classify things.

We started working on the theoretical formulation in 2017, and two years later, we published the first paper related to this theoretical formulation. But it's only now that we've finally completed everything and published it (*Science* **376** 10.1126/science.abg9094).

Who were your collaborators in this effort and how did each person contribute?

I designed (and, in part, performed) the first-principles calculations in which we considered how to simulate real materials and "diagnose" whether they had topological properties. For that, we used state-of-the-art codes and homemade codes that tell us how the material's electrons behave and how we can classify the material's topological properties.

If we know the material's crystalline symmetries, we can anticipate what the behaviour of the charge is going to be or flow

The theoretical formulation and analysis was done by Benjamin Wieder from the University of Paris-Saclay, France, and Luis Elcoro of the University of the Basque Country, Spain, because they are more hardcore theoretical physicists. They helped with analysing and classifying the topological phases. Another very important contributor and the leading guy of this project was Nicolas Regnault from the École Normale Supérieure – PSL in France; we built up the website together and took care of designing the website and the database.

We also had help from Stuart Parkin of the Max Planck Institute of Microstructure Physics and Claudia Felser at the Max Planck Institute for Chemical Physics of Solids. They are materials experts, so they could give us advice on whether a material was suitable or not. And then Andrei Bernevig from Princeton University, US, was the co-ordinator of everything. We'd been working together for several years already.

And what did you find?

What we found is that there are many, many materials that have topological properties – tens of thousands of them. We were surprised by the number!

Given how ubiquitous these topological properties turned out to be, it seems almost surprising that you were surprised. Why hadn't anyone noticed before?

I don't know why it was missed completely by the community, but it's not only those within materials science and condensed-matter physics who missed it. Quantum mechanics has existed for a century already, and these topological properties are subtle, but they are not very complex. Yet all the smart "fathers" of quantum mechanics completely missed this theoretical formulation.

Has anybody tried synthesizing these materials and checking to see whether they do indeed behave as topological insulators?

Not all of them have been checked, of course, because there are so many. But some of them have. There are new topological materials that have been created experimentally following this work, like the high-order topological insulator Bi_4Br_4.

The Topological Materials Database you and your colleagues constructed has been described as "a periodic table for topological materials". What properties determine its structure?

The topological properties are related to the electronic current, which is a global property of the material. One of the reasons physicists might not have thought about topology before is that they were very focused on local properties, rather than global ones. So in this sense, the important property is related to the localization of the charge and how the charge is defined in real space.

What we found is that if we know the material's crystalline symmetries, we can anticipate what the behaviour of the charge is going to be or flow. And that is how we could classify the topological phases.

How does the Topological Materials Database work? What do researchers do when they use it?
First, they enter the material's chemical formula. For example, if you are interested in salt, or sodium chloride, the formula is NaCl. So you put NaCl in the database and you click, and then all the properties appear. It's very simple.

So common table salt is a topological material? That's amazing. Apart from surprising people with the topological properties of familiar materials, what impact do you hope your database will have on the field?
I hope it's going to help experimentalists figure out which materials they should grow. Now that we have analysed the full spectrum of all material properties, experimentalists should be able to say, "Okay, this material is in an electron transport regime that we know is not good, but if I dope it with some electrons, then we will reach a very interesting regime." So we hope, in a sense, that it will help experimentalists to find good materials.

A lot of attention has come to topological materials recently because of a possible link to quantum computing. Is that a big motivator in your work?
It's related, but every field has different branches, and I would say our work is in a different branch. Of course, you need a topological material as a platform to develop a topological quantum computer using any of the possible qubits (quantum bits) that have been proposed, so what we did is important for that. But developing a topological quantum computer will require a lot more work on materials design because the material's dimension plays an important role. We were looking at three dimensions, and it could be that for quantum computing platforms, we'd need to focus on 2D systems.

There are other applications, though. You could use the database to find materials for solar cells, for example, or for catalysis, detectors or low-dissipation electronic devices. Beyond the super-exotic applications, these day-to-day possibilities are also very important. But our real motivation for the work was to understand the physics of topology.

What's next for you and your collaborators?
I would like to do research on organic materials. The focus in the current database is on inorganic materials because we took the Inorganic Crystal Structure Database as our starting point, but organic materials are very interesting, too. I'd also like to investigate more magnetic materials, because there are fewer magnetic materials reported in the database than non-magnetic ones. And then I want to look at materials that have chiral symmetries – that is, they are symmetric, but "handed" in that they have a left version and a right version.

Do you think there could be thousands more topological materials out there among the organic or magnetic materials?
I don't know. It depends on the size of the electronic band gap. We'll see!

Margaret Harris is an online editor of *Physics World*

Reviews

Deconstructing structures

Jess Wade reviews *Nuts and Bolts: Seven Small Inventions That Changed the World (in a Big Way)* by Roma Agrawal

Rafiq Maqbool/AP/Shutterstock

Long legacy The Indian telegraph service had simple engineering components, and lasted 163 years. Here, an employee at the central telegraph office in Mumbai, India, processes a telegram on the last day of the service in 2013.

Nuts and Bolts: Seven Small Inventions That Changed the World (in a Big Way)
Roma Agrawal
2023 Hodder & Stoughton 320pp
£22 hb

String, nail, magnet, pump: the contents of *Nuts and Bolts: Seven Small Inventions That Changed the World (in a Big Way)* reads more like a list for a visit to a hardware shop than a book about engineering. But understanding and appreciating the remarkably simple objects that enable modern life might help us to engineer new solutions to tackle some of the world's biggest challenges. From telegrams to washing machines, from the COVID-19 vaccine to the International Space Station, complicated contraptions rely on these seemingly modest components. At least, that's what engineer, physicist and author Roma Agrawal says in her latest book.

Nuts and Bolts begins with Agrawal coaxing a steel rod out of a 1000 °C furnace, sees her dismantling ornate watches with the UK's first doctor of horology (the study of mechanical time-keeping devices) and chatting to British cardiologist, writer and comedian Rohin Francis, who has an extremely popular YouTube channel called *Medlife Crisis*. But this book is about much more than simply engineering. It's about the thrill of discovery, the passion of craftspeople and the effort involved in translating an idea into reality.

Whether it's LEDs or lasers or the Large Hadron Collider at CERN, there's a lot of physics in this book, too. Having first studied physics at the University of Oxford, Agrawal later trained in structural engineering and has worked for some of the UK's largest engineering firms. Her curiosity, talent and personal experiences are woven between careful drawings and technical descriptions.

Agrawal couples precise science with exceptional storytelling, and while she diligently documents the intricacies of bicycles, cameras and heart pumps, her real enthusiasm lies in much bigger structures. Perhaps unsurprisingly, she's particularly excited by those that she played a hand in constructing. For instance, the cables of the Northumbria University Bridge and the complex configuration of bolts required to endure the fierce winds battering the spire of the Shard. Here her text is effortless and her expertise impeccable, as Agrawal herself is the main character.

Elsewhere in the book, we learn about Josephine Cochrane, an American socialite and inventor from the late-1800s who enjoyed hosting fancy dinner parties in her Chicago mansion. Like Agrawal, engineering was in Cochrane's blood: her grandfather invented the first steamboat and her father constructed mills. But Cochrane was born at a time when women were afforded little opportunity. Frustrated that her crockery was becoming chipped as it was being washed, Cochrane believed engineering could come up with a practical and efficient solution. With no formal training and little assistance – Cochrane mainly rejected the contributions of the professional (male) engineers for being subpar – in a shed in her back garden, Cochrane invented the world's first working dishwasher.

She filed her first patent in 1885, was recognized with the highest award at the World's Columbian Exposition in Chicago in 1893 and went on to set up a business that was bought by KitchenAid and became the Whirlpool Corporation. Apart from Cochrane, Agrawal also introduces readers to others of a similar ilk, including Emily Warren Roebling, who oversaw the construction of the Brooklyn Bridge; Stephanie Kwolek, who discovered the wonder material Kevlar; and Chandra Bose, who contributed to the invention of radio and made serious contributions to our understanding of the biophysics of plants.

Perhaps what I wasn't expecting was for the book to be so deeply personal, including the story of how engineering is central to Agrawal's past and critical to her present. India, where Agrawal grew up, has the largest number of engineering institutions in the world. A wheel, which Agrawal uses to explore transport and machinery, is the centre of the Indian flag. "Taar" (meaning "wire" in Hindi), the popular Indian telegraph service that relied on magnets and cables, connected three generations of Agrawal's family. Stringed instruments, including the tanpura that provided the musical accompaniment to Agrawal's Indian dance lessons, would go on to inspire C V Raman to describe the scattering of light by atoms that would win him India's first Nobel prize in science.

Before exploring the "superpowers" that lenses give humans, Agrawal shares a letter to her daughter, Zarya, who was conceived by *in vitro* fertilization (IVF) – a procedure that involves the use of a microscope to identify and combine cells that could become a baby. It would take another

> Agrawal couples precise science with exceptional storytelling, and while she diligently documents the intricacies of bicycles, cameras and heart pumps, her real enthusiasm lies in much bigger structures

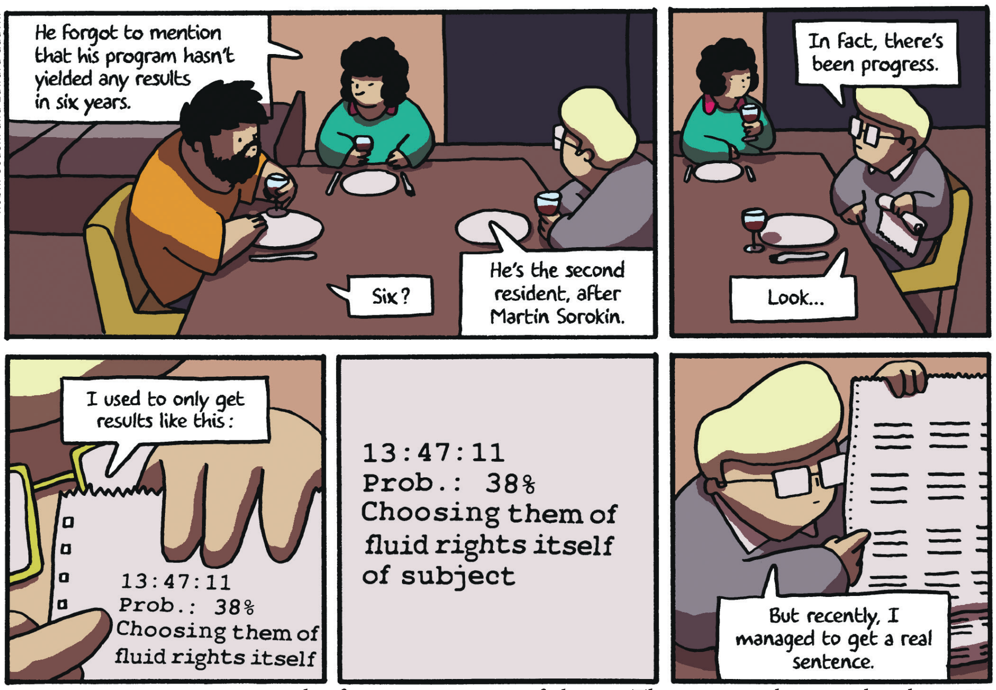
feat of engineering – a breast pump – to give Agrawal the time and strength to write this book. For Agrawal, engineering isn't just roads and bridges: it enables life itself.

So, while at first glance *Nuts and Bolts* could be any other book about engineering – there's a spring, a bike wheel and a bicycle pump on the cover – it is much more than that. With refreshing simplicity, Agrawal delivers a masterclass in providing technical content alongside historical context, uncovering hidden figures, and making innovation come to life. Her honesty, bravery and passion are evident on every page. Agrawal is not your typical structural engineer. She has the power to make seemingly inanimate objects ones of wonder and the ability to make engineering a deeply human story.

Jess Wade is a contributing columnist for *Physics World* and a research fellow at Imperial College London, UK

A tale of catastrophe and complexity

James Kakalios reviews *The Phantom Scientist* by Robin Cousin (translated by Edward Gauvin)



Robin Cousin and Edward Gauvin

Mystery masters This comic explores the possibility that one of the biggest unsolved problems in computer science may be cracked, thereby enabling solutions to previously intractable problems to be found.

The Phantom Scientist
Robin Cousin (translated by Edward Gauvin)
2023 MIT Press
128pp $24.95hb

During the first year or two of the COVID-19 pandemic, many of us spent time doing jigsaws. Some of the puzzles will have been easy, some more challenging. But they all had two things in common. First, we knew what the final picture should look like (it was right there on the box cover). And second, the only way to finish the puzzle was to try a given piece and check where it might fit.

There is no formula for solving a jigsaw puzzle. We can start by separating out edge pieces or those of a similar colour. But ultimately, trial and error is the only viable way to complete it. In the jargon of computer science, any program for solving a jigsaw puzzle is what's known as "NP" – we can check if a particular trial is the right solution, but we have no direct way to get there without guesswork.

But there are many situations where there is a formula for solving a problem. If, say, you want to find the largest value in a list of random numbers, you can write a simple computer program to look at each pair of numbers and keep the larger of the two values until you've checked them all. These are what are known as "P" problems.

They are quicker to solve than NP problems that have the same number of items (be it numbers on a list or pieces of a jigsaw puzzle). But no-one has yet proved that NP problems can never be solved using P algorithms. What's known as P ≠ NP is one of the biggest unsolved problems in computer science and plays a central role in *The Phantom Scientist* – a new graphic novel by French computer scientist Robin Cousin.

Translated into English by Edward Gauvin, Cousin's novel is an engaging mix of mystery, science fiction and complexity theory, told through artwork that is simple, uncluttered and easy to follow. It takes place at the fictitious Institute for the Study of Complex and Dynamic Systems, inspired by Cousin's experience of a real-life lab belonging to the French National Centre for Scientific Research (CNRS) in Paris.

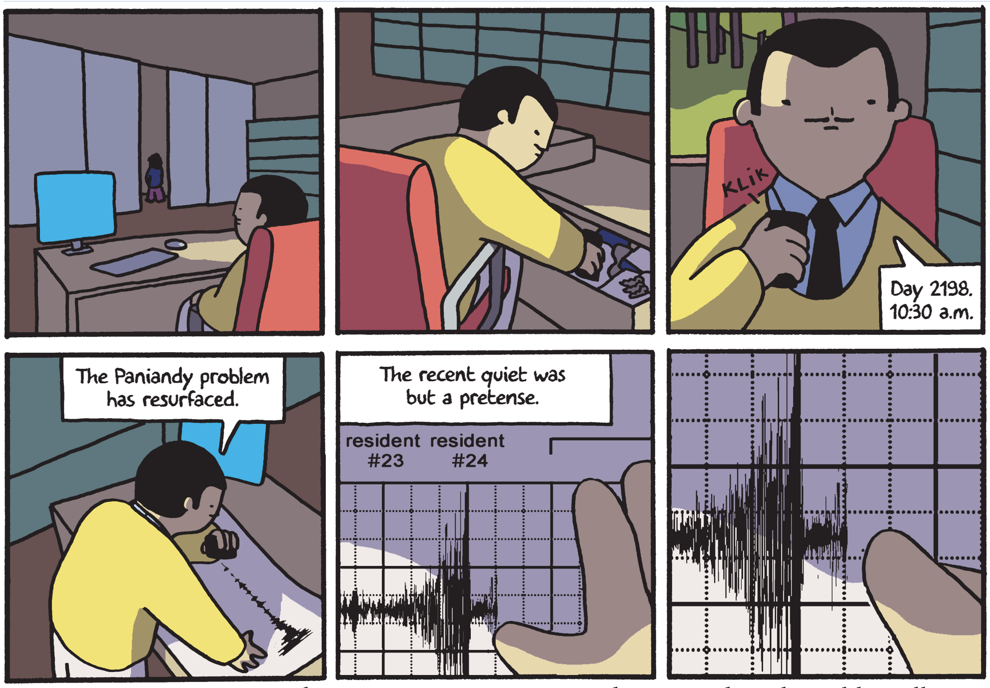
The languid, almost cinematic pace of the story pulls the reader in, creating a sense of space and time

The institute in the book is not short of space, resources or funding, having only 24 scientists (and some support staff) spread out over seven buildings in a wooded campus. As the director of the institute explains to Stephane Dousay, the 24th scientist to join: "You are free to conduct your research as you see fit. We ask only that you file regular reports." (I did say it was a science-fiction story.)

What's also unusual about the institute is that every seven years it's hit by some kind of dramatic and fatal catastrophe, which requires all researchers to leave and a new director to be appointed. It is, if you like, a living experiment in nonlinear dynamics, described by one protagonist as being "engineered to create… an instability conductive to major scientific discoveries". Or, as one outgoing director says in a video message to his successor: "Like all dynamic systems, the institute tends toward entropy and chaotic behaviour."

The story actually begins six years into the fourth incarnation of the centre with the arrival of Stephane, a physicist who studies pattern formations in budding plants. The other scientists in Stephane's building are Louise (a linguist), Vilhem (who is working on a computer program that will predict upcoming events in his life), and an occupant whom no-one has ever seen and about whom little is known.

Eventually, we learn that this mysterious researcher, the phantom scientist of the title, is reputed to have made a major advance in the study of complexity of computer algorithms. Weird things start to happen at the institute. Louise discovers notes left in the eponymous researcher's lab that suggest he's (spoiler, it is a he) developed an algorithm that enables previously intractable problems to be quickly solved. And then the bodies



Robin Cousin and Edward Gauvin

Thrilling stuff
In *The Phantom Scientist*, research breakthroughs are combined with mysterious staff disappearances.

start to pile up.

I'll say no more about the story to avoid giving the game away. However, I will note that the forest location for the campus is important as it lets Cousin show his characters doing mundane things like walking – silently and alone – from one facility to another. Or they're shown fixing dinner in their apartments or programming their computers in the lab.

The languid, almost cinematic pace of the story pulls the reader in, creating a sense of space and time that contrasts with the change in tempo as events accelerate towards the end. It also provides Cousin with an opportunity to plant clues and hidden references in the story, many of which I missed on first reading.

In fact, this is a novel that rewards rereading. It touches on everything from origami and kirigami to the Fibonacci sequence and the "sofa problem" (what's the largest area of a sofa that can be manoeuvred through a one-metre wide L-shaped hallway?). There's also a deeper point, which is that even if computer algorithms replace trial and error, we will still always need human ingenuity. As Stephane says regarding the sofa problem: "No-one's ever solved it, but I'll bet a mover could eyeball it in an instant."

James Kakalios is the Taylor Distinguished Professor of Physics at the University of Minnesota, US, and the author of *The Physics of Superheroes* and *The Physics of Everyday Things*

Careers

From student to mentor to teacher

Ellie Whitehall explains how her experiences mentoring school pupils while she was an undergraduate physics student encouraged her to train as a professional physics teacher

I first considered physics as its own branch of science when I began my GCSE studies, but I think my curiosity for the natural world was born much earlier. As a child, I distinctly remember discussing what atoms were made of at family gatherings and solving algebra with my dad for fun. I would spend hours reading about space, asking countless questions on how and why things worked, and watching the BBC show *QI* with my parents (still a family favourite).

At school I was lucky to have two specialist physics teachers, both of whom showed great passion and enthusiasm for the subject. Around the age of 15, my one and only female physics teacher told my class an anecdote that I remember to this day: during her undergraduate years some male students had boasted that girls could not achieve a first in physics. Motivated by her anger towards this comment, she worked hard and ultimately achieved the grade, proving them all wrong. I remember thinking there and then that I wanted to achieve this in my future (spoiler: I did). It is a cliché, but true: representation at school matters.

However, despite my teachers' love for physics and my aptitude for the subject, I didn't initially choose to study physics at A-level. Instead, I opted to take maths, further maths, biology and psychology. I knew I enjoyed and did well in mathematics, so taking the further option felt like a reasonable challenge. Additionally, my interests in science extended to the body and brain, which is why I opted for biology.

It was not until the summer after my GCSE exams that I realized I could combine my passions for maths and science by studying physics. Until then, I, like many others, had seen it as "the hard science", the one that many people overlook in favour of biology and chemistry. I therefore decided to replace further maths and instead study physics with greater intent, starting to love the subject content more. So much so that I applied to study it at university.

Ellie Whitehall

Role model Trainee teacher Ellie Whitehall is hoping to use her recent experiences in education to encourage more students to take up physics as a potential career.

Joining the University of Birmingham in September 2019, I was a first-year student during the early days of the COVID pandemic. Thus began 18 months of prerecorded lectures, at-home lab projects and video tutorials from my mentor in South Korea. While I mostly enjoyed the content, I missed the social aspects, such as attending events run by the university's Poynting Physical Society and in-person classes. As a result, I decided to use my free time to volunteer for the Coronavirus Tutoring Initiative – a scheme that lasted until June 2021 and paired secondary school and university students for one-to-one online tutoring. I planned and taught physics sessions for around nine months, and found myself thoroughly enjoying this first foray into teaching.

Level up

Pre-pandemic, I had also become an outreach ambassador for the university's School of Physics. Over my three years in the job, I was lucky to speak to many young people who were enthusiastic about physics and curious about university life. It was a great opportunity to share my own interests and hear their stories and experiences. Through this, I realised that I had a passion for encouraging the next generation of physicists and for providing the pastoral side of education.

From this experience, I was then asked to join the Institute of Physics (IOP) and became involved in creating their new "Levelling Up" programme, which is designed to encourage and support sixth-form students to study physics at university. The programme is especially aimed at getting more students from under-represented backgrounds to study physics and related subjects.

I formed part of a team of student mentors who met A-level students fortnightly to offer guidance and support for the university application process. The scheme ran for a year, with the same small group coming together (remotely) twice a month, allowing students to ask for advice and support at each stage of their application. We discussed everything from how to put together a good personal statement, to a typical university timetable; helping them feel confident that their applications were as strong as possible. Being part of this scheme cemented my decision to pursue a pupil-facing role in education, which allowed for both pastoral and academic involvement.

Inspired by my physics teachers and driven by my love for tutoring and mentoring, I applied for an initial teacher education course at Birmingham, which I began in September 2022. Now, almost halfway through the programme, I have taught physics at all secondary-school ages and find great joy in every lesson. To be the first person to show a class what a Van der Graaff generator does is a truly priceless moment, and one I wish to repeat for many years to come. Even seemingly smaller things, such as asking a student about their day or getting them to try answering a question even if they are unsure, are equally rewarding. These connections, which are reinforced every day, are what build an early appreciation of physics; making it more than just a lesson in a timetable and instead a way of understanding the universe.

I do sometimes struggle with impostor syndrome – I often wonder how I am responsible for all these children while only being 22 myself – but the connection with students over a subject I love, and that hopefully they will too, makes every difficult moment worth it. The IOP is also guiding me through the process, via their scholarship programme, which will provide financial support and opportunities for professional development throughout my training years. I aspire to keep teaching across the UK for as long as I can, and encourage many more students to take up physics as a potential career.


Durham University

Curious minds The "Levelling Up" programme run by the Institute of Physics, which Ellie Whitehall got involved with, is designed to prepare sixth-form students to study physics at university.

Ellie Whitehall is a trainee physics teacher pursuing a postgraduate diploma in secondary education with qualified teacher status (PGDipEd (QTS) Secondary Physics) at the University of Birmingham, UK. Twitter @EWhitehallPhys

Ask me anything: Zahra Hussaini

Zahra Hussaini is a senior software reliability engineer (SRE) at Waymo, an autonomous driving technology company that started as Google's Self-Driving Car Project. Prior to Waymo, she was a Google Search SRE, a satellite imagery software engineer, and a research assistant at the National Institute of Standards and Technology. She graduated with BS degrees in physics and mathematics from Arizona State University in 2013.


American Physical Society

What skills do you use every day in your job?

Most of my job is collaborative problem solving. SREs are software engineers that focus on the overall reliability and performance of large software systems, and we work in close collaboration with the software engineering teams that built them. I model and reason about software in the same way that I was taught to think about the natural world in my physics classes. Sometimes, this involves reading code and predicting how a scenario will play out from first principles. Other times, it's about designing and running experiments to measure how a system behaves under extreme conditions. Whatever the method, the goal is to find the edges of what the system can do and develop project ideas for how to expand its capabilities.

Technical communication is another job skill that I practised during my physics education. I'm rarely working on a problem alone, which means I need to be able to talk about complex problems and their potentially complex solutions simply and succinctly. When I'm writing project plans, I have to be clear about the assumptions and approximations I'm making; and to clearly describe the logical steps I took to reach a conclusion.

In addition to doing project work, SRE team members share the responsibility of dealing with software outages in real-time. My team runs exercises where we simulate outage scenarios and practise our responses. This part of the job combines diligently preparing for emergencies with quick, creative thinking.

What do you like best and least about your job?

What I like most about my job is the people that I work with. A healthy team culture is essential for every other part of the job. We do better work when people feel safe asking questions and sharing ideas. We build more reliable systems when we view mistakes and failures as an opportunity to learn rather than to blame. It's important to me (and to Waymo) that we build a culture that makes it easy for people to do their best work because our mission is big. We're working on autonomous driving technology that has the potential to transform lives.

My least favourite thing is that I don't get to feel like an expert as much as I'd like. SREs have a lot of breadth because we're a cross-functional team that works with many different software engineering teams. It's common to get projects that require getting up to speed in a new area quickly. It's easy to slip into feeling like I am incompetent and always playing catch up since I'm never done learning. I have to remind myself that this is a normal part of the job, and I have to balance my desire to understand everything with the need to get things done.

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

I wish I knew that it was okay to be lost. When I was younger, I felt like I needed certainty and a clear direction if I wanted to achieve anything worthwhile in my career. I wrote and rewrote 10-year plans, trying to find my future. I didn't have exposure to physics career options other than academia, so getting a PhD was an unwavering fixture of my many plans. For years, I suppressed signs telling me that a research career wasn't for me, hoping that I could find a way to stick to the plan. When I did finally decide to leave for a career in the tech industry, I had a profound feeling that I had failed. This wasn't true of course, but it took me a while to realize that and to let go of my rigid planning mentality.

I wish I knew that it was okay to explore, that there are many different paths to happiness, and that you can be good at things without them being the right thing for you. These days, my career plan has three words: follow your curiosity.

● This article was first published in the *APS Careers* guide 2023.

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Where's Wally in the multiverse?

John Berney comes to the shocking conclusion that Wally may never exist either in our universe or any other

Several years ago, I went to an astronomy conference in London where Brian Cox was the main speaker. In his talk, Cox touched on the notion of the "multiverse", reasoning that there may be an infinite number of other universes out there. What's more, he said, if something has a non-zero probability of occurring, then it must take place somewhere in one of those universes. Everything that could possibly happen, will actually happen.

If Cox is right, it means that somewhere out there is a real universe – very similar to ours – where I was too late for his lecture and never actually got to experience it. It's an intriguing notion that immediately got me thinking about *Where's Wally?* – the children's picture puzzle books where readers have to pinpoint Wally (known as Waldo in North America) in a crowd of similar-looking people.

It's fun trying to track down Wally, who is unique in that he is the only person in the book wearing a red-and-white striped jumper, bobble hat and glasses. But if Cox is right, Wally doesn't just exist; somewhere out there is an entire universe made completely of Wallys. However, the idea that there might be thousands of Wallys perturbed me, as to my mind it did not accord with common sense.

Who's the Wally now? A then record-breaking 3872 people dressed as Wally attended the 2011 Street Performance World Championship in Dublin – but could there be a universe made completely of Wallys?

I soon forgot about my Wally worries, but they all came back to me recently when I read an article (I can't remember by whom) that argued that if there were a finite number of particles in a particular universe, there would be only a finite number of ways to arrange them. In other words, every possible combination of particles must exist in an infinite number of universes.

I saw Wally appearing over the horizon again and this time I wasn't going to let him lie. Casting my mind back to my university days, I remembered being told that infinity comes in two distinct types. It can be countable (i.e. discrete) where individual elements can be mapped on a one-to-one basis to the sequence of integers. Or infinity can be uncountable (i.e. continuous) where those elements cannot be mapped to integers.

One mathematical problem that was posed early on during my undergraduate degree was to prove that no matter how small a section of real numbers is taken, it is impossible to map it to the integer set. Simply put, there are far too many real numbers. Countable infinities are big, but uncountable infinities are infinitely big, which led to the inescapable conclusion that "countable" divided by "uncountable" (if we ever get round to defining it) could only ever tend to zero.

As physicists, we are still unclear if space–time is continuous or discrete, but no such problem exists in mathematics. For example, the continuous group of co-ordinates that contains our universe (three of space and one of time; other dimensions are available) will by definition have an uncountable number of continuous possible positions within it. If we think about a dartboard, there are an uncountable number of possible locations where the dart could land. And yet the dart will definitely land on one of them, which to me suggests that something with zero probability can happen.

> The idea that there might be thousands of Wallys perturbed me, as to my mind it did not accord with common sense

Of course, the converse is also true. Imagine, for example, our dartboard divided into the complete set of points represented by co-ordinates made wholly of rational numbers (countable) and also into other points represented by irrational numbers, or a mix of the two (uncountable). All points can be hit by a dart, but the mixed positions overwhelmingly dominate and must have a probability of being hit of 1.

To return to our original question: how many combinations of a finite number of particles are possible in a universe? To answer that, consider just one of them. A single particle can sit in uncountably many places along a non-zero line of finite length, which means that the arrangement of a finite number of particles in an open space must also be uncountably infinite.

So there we have it: the number of infinite universes is countable, while the number of particle combinations within them is uncountable. Wally, in other words, is very unlikely to exist in this or any other universe, even if he could in principle. Whoever originally dreamed up the phrase "Everything that can possibly happen, will actually happen" was probably a right wally.

Finally, for all the fans of this year's big Oscar winner *Everything Everywhere All at Once*, it is not strictly necessary for everything to *exist* everywhere all at once. But then again, it might.

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