# physicsworld

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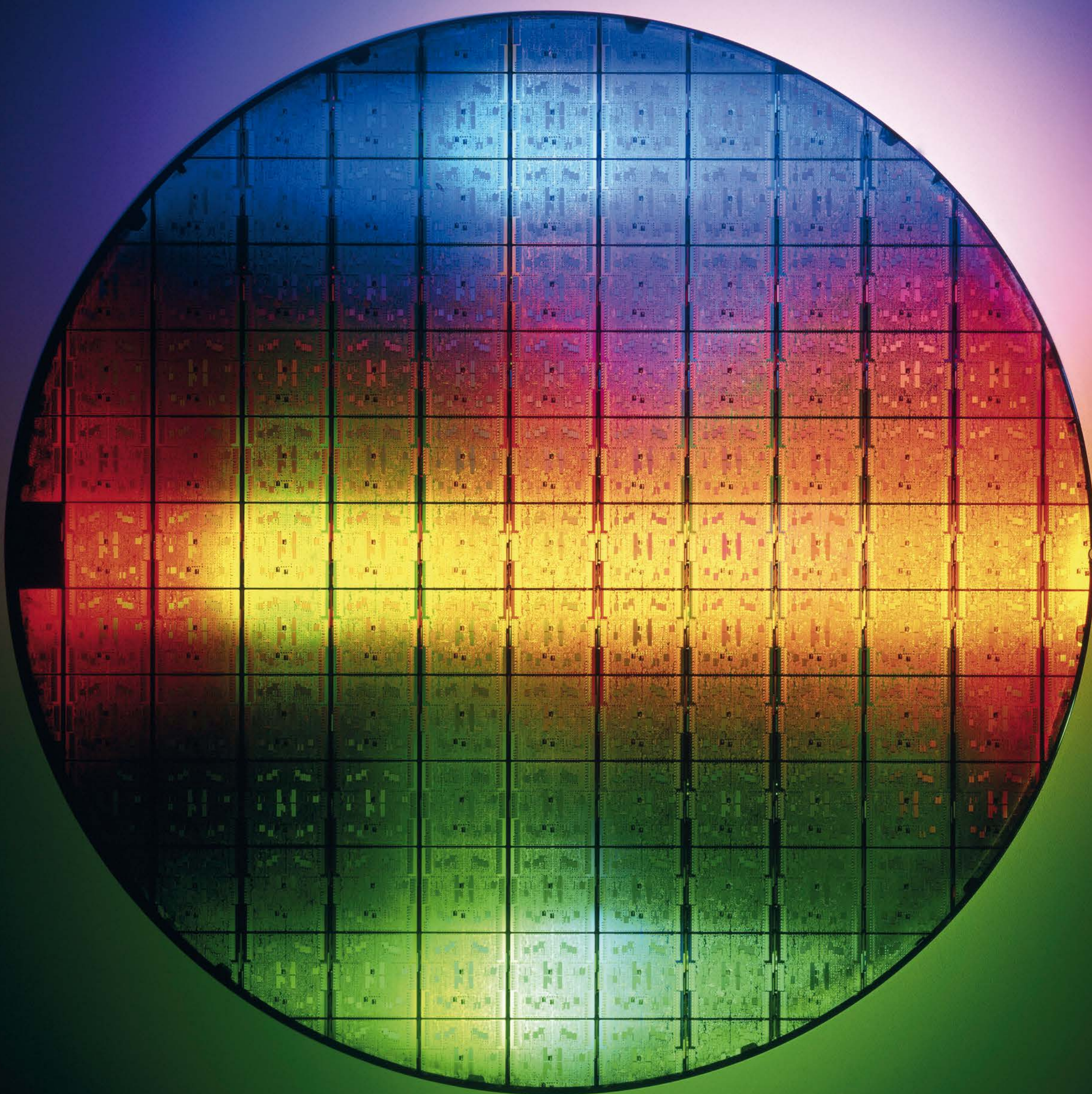
## What's the matter with condensed matter?

How we can communicate the excitement of solid-state physics



**Crystal conundrum** Zircons, plate tectonics and the mystery of life

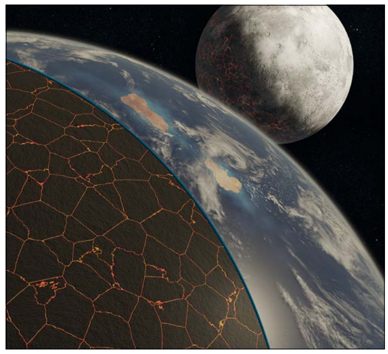
**Physicists needed** Where your skills are most wanted in the workplace

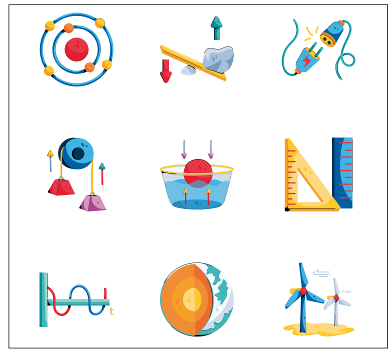
**Sounds fantastic** How to clap your hands in the best possible way

physicsworld

*Physics World* editors discuss their highlights of the October issue

AUDIO







# Features



**On the cover**
How we can communicate the excitement of solid-state physics 28 (Alfred Pasieka/Science Photo Library)

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# Quanta

## For the record

### Nobody gets to determine what you love or how you love it

*Astrophysicist* **Sarafina El-Badry Nance** *from the University of California, Berkeley, quoted in the* Guardian

Nance says she will "probably always live" with impostor syndrome and that it is systems and institutions that inform these feelings of non-belonging.

### The BBC no longer commissions such programmes, misjudging the intelligence of its audience

*Physicist and broadcaster* **Jim Al-Khalili** *quoted in the* Times

Al-Khalili was commenting on plans to discontinue BBC Four as a broadcast channel, which is home to many of his science documentaries.

### If we don't have a challenge, the brightest people will go elsewhere

**Sergo Jindariani**, *a detector physicist at Fermilab, quoted in* Scientific American

After years spent languishing in obscurity, proposals for a muon collider are regaining momentum among particle physicists.

### What we have done here is the most global, the most diverse, the most expansive project

*Physicist and artist* **Samuel Peralta** *quoted in the* Guardian

Peralta is behind the Lunar Codex, a project that sends art to the Moon via "nanofiche" files that are left on the lunar surface in time capsules.

### I can only now confidently say that I can rap about particle physics and people can bop their heads to it

*UK rapper* **Antoine Gittens-Jackson a.k.a Consensus** *quoted in* Symmetry

Consensus has teamed up with physicists to produce a second album called *ConScience*.

### I can't say I'm too eager to repeat that again

*Engineer* **Stuart Pearson** *from Delft University of Technology in the Netherlands quoted in* Nature

Pearson was commenting on the demise of Twitter, now rebranded as X, adding that he is not quite ready to build a following elsewhere.

## Seen and heard

### Nuclear effects

Many physicists will have enjoyed this year's Hollywood blockbuster. We're not talking about *Barbie*, but the biopic *Oppenheimer*, directed by Christopher Nolan (see review on pp37–38). In particular, many would have appreciated the film's visual effects, such as the detonation of the first atomic bomb. Nolan claims however, that no computer-generated imagery (CGI) was used to create these scenes. To check if Nolan is telling the truth, independent filmmaker William Baker and colleagues had a go at recreating the effects without using CGI. With just a few simple ingredients, such as water and pigment powder, they managed to get impressively near to the close-up scene of burning fuel as well as the nuclear explosion itself. "I think we figured out exactly how Nolan's team did these shots," Baker concludes.

### Salt taffy mechanics

Salt-water taffy is a sweet treat common in most US beach resorts. It's made by boiling table sugar, water, oil, corn syrup, colours and flavourings, before the mixture is cooled and stretched – either by hand or machine – to aerate the candy and break down larger oil droplets. From a physics point of view, the sweet is a viscoelastic material – which means that it's somewhere between a viscous liquid and an elastic solid. Researchers have now discovered that's because the air bubbles and the oil droplets determine the taffy's mechanical properties (*Physics of Fluids* **35** 093106). "Oil droplets and air bubbles are like rubber balls and when deformed in the taffy, they tend to return to their original, spherical shape because of surface tension," says Okinawa Institute of Science and Technology researcher San To Chan. "Emulsification and aeration make taffy more elastic, hence, chewier." That still doesn't explain though how you stop it from sticking to the roof of your mouth.

### The perfect throw

If you want to be a hot shot at basketball, it helps to be good at "free throws". They involve standing unopposed 4.6 m from the basket and trying to launch the ball up in the air and through the hoop. Researchers have now used motion-capture technology to study why some players seem better than others at free throws. By defining a proficient shooter as someone who is on target 70% or more of the time, the study involved 34 men with at least four years of basketball playing experience each. The players attempted 10 free throws and their motions were captured by nine high-speed cameras. Proficient shooters, it turns out, have more control over their body motion than weaker players, with shot success associated with a higher ball release height and players having a more upright body position at the moment of releasing the ball (*Front. Sports Act. Living* **5** 1208915).


Chris Thorogood

### The perfect catch

Carnivorous pitcher plants consist of hollow, cup-like structures that capture and then digest unsuspecting prey. Found mostly in the tropics, especially south-east Asia, pitcher plants have a slippery rim at the top called a "peristome" that is covered in small ridges that collect water. This liquid film causes the prey to skid, like an aquaplaning car, and fall into a pleasant pool of digestive juices at the bottom of the pitcher. One mystery about these plants is why they come in such a range of different shapes and sizes. Researchers from the University of Oxford's Botanic Gardens – working with Oxford mathematicians – examined what effect the shape and size had on the type of prey pitchers captured. After all, a more elaborate structure comes at a greater energy cost than having just a simple design that could do the same job. They discovered that variations in peristome geometries have a huge effect on the nature and quantity of material the plant can catch (*Proc. Natl Acad. Sci.* **120** e2306268120). Highly flared peristomes, for example, seem to be particularly suited to capturing walking insects such as ants. "We were able to show that in an optimal structure, the cost of production might be offset by the extra prey that can be caught," says mathematician Derek Moulton.

# Research updates

# 'Demon' quasiparticle spotted

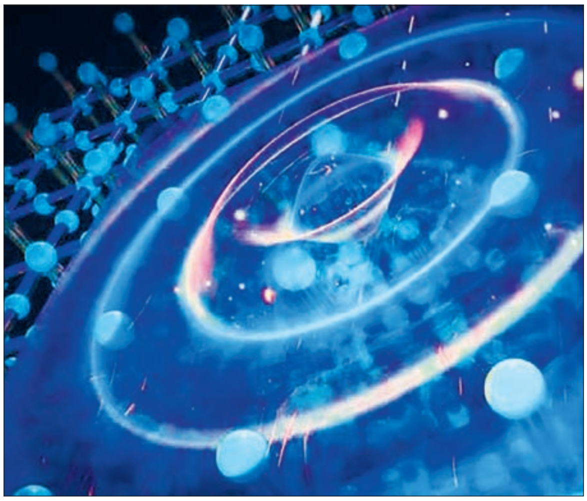
Almost 70 years after it was first proposed, researchers have observed Pines' demon unexpectedly after bombarding exotic metal with electrons, as **Edwin Cartlidge** reports

For nearly seven decades, a plasmon known as Pines' demon has remained a purely hypothetical feature of solid-state systems. Massless, neutral and unable to interact with light, this unusual quasiparticle is thought to play a key role in certain superconductors and semimetals. Now scientists in the US and Japan say they have finally detected it while using specialized electron spectroscopy to study the material strontium ruthenate (*Nature* **621** 66).

Plasmons were proposed by the physicists David Pines and David Bohm in 1952 as quanta of collective electron density fluctuations in a plasma. Plasmons, phonons and other quantized fluctuations are called quasiparticles because they share properties with fundamental particles such as photons. But unlike phonons, their frequency does not tend to zero when they have no momentum. That's because finite energy is needed to overcome the Coulomb attraction between electrons and ions in a plasma to get oscillations going, which entails a finite oscillation frequency (at zero momentum).

In 1956 Pines hypothesized the existence of a plasmon which, like sound, would require no initial burst of energy. He dubbed the new quasiparticle a demon in honour of James Clerk Maxwell's famous thermodynamic demon. Pines' demon forms when electrons in different bands of a metal move out of phase with one another such that they keep the overall charge static. In effect, a demon is the collective motion of neutral quasiparticles whose charge is screened by electrons from another band.

However, this long-standing prediction has been hard to confirm experimentally. With the two electron currents out of phase with one another, they cancel out and eliminate long-range Coulomb interactions. That precludes any signature from the demon in the metal's dielectric properties, meaning that the quasiparticle does not interact with light. Now, Peter Abbamonte of the University of Illinois Urbana-Champaign (UIUC) in the US, and colleagues have demonstrated how this difficulty can be overcome using a non-standard technique to study the metal strontium ruthenate. Rather than setting out to find Pines' demon, however, they were instead exploring strontium ruthenate's electronic properties in order to use the material as a kind of surrogate for high-temperature superconductors, which have similar properties.



The Grainger College of Engineering/University of Illinois Urbana-Champaign

**Hell of a result** Researchers have discovered Pines' demon, a collection of electrons in a metal that behaves like a massless wave.

The technique they used is known as electron energy-loss spectroscopy. This involves firing a beam of electrons with a well-known, narrow range of energies and recording how much energy is lost at which momenta after the electrons pass through a target material. The technique is well-suited to studying plasmons because electrons are very sensitive to fluctuations in charge density. Using millimetre-sized single crystals of strontium ruthenate, the researchers recorded different spectra using low- and high-energy electrons. In the latter case they found energy loss peaking at around 1.2 eV, which they identify as an interaction with a typical (charged) plasmon. On the other hand, at lower energies they observed an oscillation with a tiny energy gap – less than 8 meV – at zero momentum.

This second feature, they say, is an acoustic mode with a velocity about 100 times that of sound, which is far too high to be associated with phonons. At the same time, however, the velocity of the mode is about three orders of magnitude lower than that of a surface plasmon. Yet the figure is within 10% of that predicted by UIUC theorist Edwin Huang for a quasiparticle made up of two electron bands in strontium ruthenate oscillating out of phase with one another – a Pines' demon.

To make sure they had found the demon, the researchers checked its neutrality by examining how its intensity varied with momentum – seen as variations in the electron scattering angle. They worked out that the intensity of a conventional plasmon should vary inversely with momentum raised to the power of five. They say that the intensity of neutral plasmon should also vary inversely with momentum, but with a smaller power. That is what they found – establishing that the new quasiparticle was characterized by an inverse power of just 1.83.

They argue that the demon could be better understood by carrying out additional experiments with a scanning transmission electron microscope and also by developing a hydrodynamic theory of the quasiparticle. But Abbamonte adds that such studies need not be limited to strontium ruthenate, explaining that the demon ought to be present in other metals with sufficiently different electron bands – including some superconductors, such as magnesium diboride or those based on iron. "It shouldn't be a rare or esoteric effect," he says.

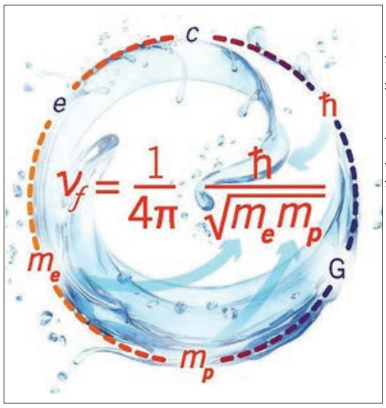
Biological physics

# Evolution may explain values of the fundamental constants

The values of the fundamental physical constants might not have been fixed at the universe's outset but instead have changed over time through a process akin to biological evolution. That is the hypothesis of a physicist in the UK, who has shown that life-friendly limits on fluid viscosity and diffusion impose constraints on the constants' values. Having found that those constraints go beyond the requirements of stellar nucleosynthesis, he conjectures that the conditions needed for fluid motion in and among living cells could have emerged later on in cosmic history (*Sci. Adv.* **9** eadh902).

The values of many physical constants appear just right for the existence of life. While some suggest this is evidence of design, Kostya Trachenko at Queen Mary University of London thinks that the universe's physical "traits" could independently emerge, and become entrenched, through a gradual process of evolution.

In 2020, Trachenko and Vadim Brazhkin established that a fluid's viscosity reaches a minimum at the temperature marking its transition from liquid to gas. By modelling that transition, they were able to express the "kinematic viscosity" – the ratio of viscosity to density – in terms of Planck's constant ($\hbar$), molecular mass and electron mass ($m_e$).




thehackneycollective.com

**The only constant is change** Could "life-friendly" limits on fluid viscosity and diffusion impose constraints on the values of fundamental constants?

Trachenko has now explored the implications of that work for the existence of life. Fluid flow is essential for the working of cells and he wanted to work out the constraints that such processes place on the values of the fundamental constants. In addition to kinematic viscosity, which governs pulsed blood flow and other time-varying phenomena, Trachenko also considered the dynamic viscosity of steady flow and diffusion constants. Using the Navier–Stokes equation and other elements of classical fluid dynamics, he showed that these three parameters could be cast in terms of $m_e$, the proton mass ($m_p$) and $\hbar$ (with the dynamic viscosity and diffusion constant also featuring the electron charge, $e$).

Trachenko found that the three parameters depend on the fundamental constants in different ways. As such, he says, combining the limiting expressions for life in each case – minima for the two viscosities and a maximum for diffusion – yields a "bio-friendly window" within which the constants have to exist. This, he claims, is an unexpected result given the complexity and variety of the biological processes involved.

Fred Adams of the University of Michigan in the US praises Trachenko's "novel" approach but cautions that it may not yield unique limits, arguing that current biological theory is insufficient to work out the full range of allowed viscosities.

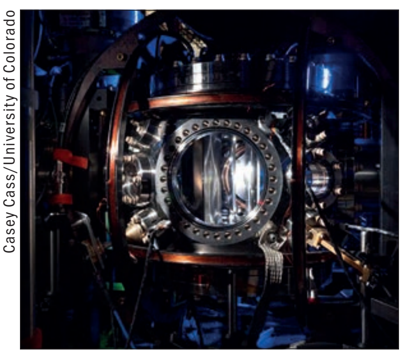
**Edwin Cartlidge**

Nuclear physics

# Electron electric dipole moment measured to unprecedented precision

**Physicists at the University of Colorado, Boulder, US have determined the shape of the electron's charge distribution to unprecedented precision. Led by Eric Cornell and Jun Ye, the team found that any imbalance in this charge distribution – the electron's electric dipole moment, or eEDM – must be less than $4.1 \times 10^{-30}$ *e* cm, with an uncertainty of $2.1 \times 10^{-30}$ *e* cm (*Science* 381 46).**

**To measure the eEDM, the researchers detect how an electron wobbles in an external magnetic and electric field. This wobble, or precession, is similar to the rotation of a gyroscope in a gravitational field. When an electron is placed inside a magnetic field, it will precess at a specific frequency thanks to its magnetic moment. If the electron also has an EDM, applying an electric field will change this rate of precession: if the electron is orientated in one direction with respect to the electric field, the frequency of precession will speed up; if it's "pointing" in the other direction, the rate will slow down.**



Casey Cass/University of Colorado

**In a spin** The researchers measured the electron electric dipole moment in hafnium fluoride ions confined within an ion trap.

**Rather than study an electron on its own, the researchers monitor the precession frequency of an electron inside hafnium fluoride molecular ions ($HfF^+$). The internal electric field of these ions makes the frequency difference much larger, and by confining the ions in a trap, the researchers were able to measure the precession of the electron for up to three seconds. Indeed, the researchers had such good control over the molecules that they were able to measure the precession frequency to a precision of tens of μHz.**

**After 620 hours of data collection, they deduced the upper limit on the electron EDM to $4.1 \times 10^{-30}$ *e* cm – some 37 times smaller than their own previous measurement and 2.4 times smaller than the previous best limit. The new limit contradicts predictions for the eEDM made by some extensions to the Standard Model of particle physics such as split supersymmetry and spin-10 grand unified theory, although previous limits on the dipole moment had already disagreed with those theories.**

**Stefan Popa**

Environment

# The 'wild boar paradox' of radioactive meat solved

A team of chemists and radiation experts in Germany and Austria have come up with an explanation for why radiation levels in wild boar have remained constant for the past 30 years, even though levels ought to be falling. After analysing the ratio of caesium isotopes in samples of wild boar meat from 11 districts of Bavaria, Germany, the team says that this "wild boar paradox" could be due to the global fallout from nuclear weapons tests. Though the exact ecological mechanism for the ongoing contamination remains unclear, the researchers say it is further evidence that decades-old nuclear tests continue to have a significant impact on the environment (*Environ. Sci. Technol.* **57** 13601).

Following years of nuclear weapons tests as well as nuclear accidents such as Chornobyl that showered the globe with fission products such as caesium-137 ($^{137}$Cs), many countries responded to the health risks by adopting regulations that limit the amount of $^{137}$Cs in foodstuffs. In Europe, the limit is 600 Bequerels (Bq) per kilogram; in Japan, it is 100 Bq/kg.

iStock/Balint-Erlaki

**A pig deal**
Wild boar in some central European forests exhibit persistently high levels of radioactive contamination.

But while food testing and other forms of surveillance provide useful information about levels of $^{137}$Cs contamination, they are silent on its source. This is because "reactor-$^{137}$Cs" and "weapons-$^{137}$Cs" are indistinguishable, with the same chemistry and the same 30-year half-life.

To identify the source of radioactive caesium in Bavarian wild boar meat, the researchers examined a caesium isotope with a much longer half-life: $^{135}$Cs. Because $^{135}$Xe – parent nuclide of $^{135}$Cs – has a large cross-section for thermal neutron capture, the high neutron flux density within a reactor core tends to transmute it into other substances, limiting $^{135}$Cs production. In contrast, the neutron flux during nuclear explosions is intense but brief, meaning that more $^{135}$Xe "survives" to decay into $^{135}$Cs. Hence, a nuclear explosion yields a relatively high $^{135}$Cs/$^{137}$Cs ratio, whereas a reactor yields a low ratio.

Following the Chornobyl disaster, levels of $^{137}$Cs in Bavaria's surface soil ranged from $10^2$ to $10^5$ Bq/m, and concentrations in local wild boar meat exceeded the regulatory limit by one to two orders of magnitude. Yet since then the decline of $^{137}$Cs in wild boar has in some locations been slower than the half-life of $^{137}$Cs. This is often attributed to the boars' tendency to eat underground fungi such as deer truffles, which can act as a repository for $^{137}$Cs.

About 25% of their wild boar meat samples contained enough weapons-$^{137}$Cs that they would have exceeded the European regulatory limit even if Chornobyl hadn't happened. This result suggests that there are, in effect, two separate downward-migrating caesium "fronts" contaminating the boars' winter food supply: one from atmospheric nuclear weapons tests, which peaked in 1964, and one from Chornobyl 22 years later.

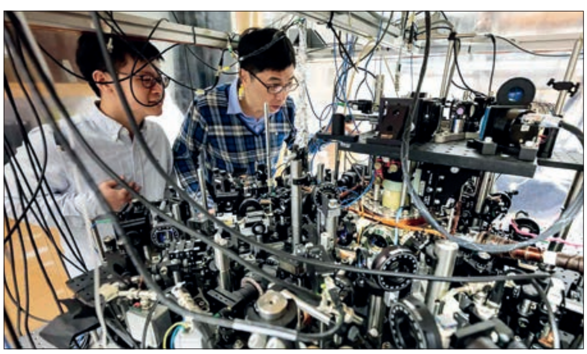
**Margaret Harris**

Atomic physics

# Quantum superchemistry emerges in the laboratory

Researchers at the University of Chicago, US, have spotted the first experimental evidence of "quantum superchemistry" in a gas of caesium molecules. The result paves the way for an enhanced degree of control over chemical reactions (*Nat. Phys* doi:10.1038/s41567-023-02139-8).

To achieve the feat, Cheng Chin and colleagues created a Bose-Einstein Condensate (BEC) of caesium atoms and then used an applied magnetic field and a so-called Feshbach resonance to tune the strength of the interactions between the atoms. This process converts the atomic BEC to a molecular BEC. The team monitored the dynamics of the molecule-creating reaction at the resonance, then continued monitoring after the magnetic field was turned off. At this point, the researchers imaged the unpaired atoms and newly-created molecules independently.



John Zich/University of Chicago

**Quick reactions**
Cheng Chin (right) and postdoctoral researcher Zhendong Zhang and colleagues have observed the first evidence of quantum superchemistry.

When the researchers analysed their data, they found that molecule formation accelerated at the value of the magnetic field that corresponded to the Feshbach resonance. The observed reactions quickly reached an equilibrium and were followed by coherent oscillations between atoms and molecules as pairs formed and broke. When the magnetic field was switched off, the reactions slowly decayed. Notably, a reaction known as three-body recombination, in which three caesium atoms come together to form $Cs_2$ and Cs, was especially favoured.

The researchers also analysed the influence of particle numbers on the reaction dynamics and found that it fitted well with a quantum field model. In particular, they saw evidence of the so-called Bose enhancement – the tell-tale sign of quantum-accelerated reactions – in the faster oscillations that occurred at higher sample densities. According to Chin, these experimental results match theoretical predictions. Although the experiment was performed with two-atom molecules, the team now plan to handle larger and more complex molecules.

**Martijn Boerkamp**

Nuclear physics

# Newly-observed oxygen-28 nucleus fails 'double magic' test

**Scientists in Japan have become the first to observe the super-heavy oxygen isotopes oxygen-27 ($^{27}$O) and oxygen-28 ($^{28}$O). It was thought that $^{28}$O could be stable, or "doubly magic", but experiments at RIKEN's Radioactive Isotope Beam Factory (RIBF) in Wako, on the outskirts of Tokyo, have now shown that not to be the case (*Nature* 620 965).**

**Magic numbers in nuclear physics refers to a situation in which an atom's nucleons are arranged in such a way as to make its nucleus unusually stable. For example, $^{16}$O has eight neutrons and eight protons, with two neutrons filling its first shell, and the next six neutrons filling the second shell. The shells for protons and neutrons act independently of each other, so the same stacking procedure within shells also works for the protons in $^{16}$O.**

**When both neutrons and protons are magic numbers, as in $^{16}$O, the nucleus is termed "doubly magic". This situation is extremely rare and among naturally-occurring nuclei, there are only four others besides $^{16}$O that meet the criteria: helium-4, calcium-40, calcium-48 and lead-208. In exotic nuclei, which are either artificially generated or exist for only very short times, the list is similarly short, with only seven candidates for double magic status.**

**The team had good theoretical reasons to expect $^{28}$O to also be doubly magic. "For $^{28}$O, it has eight protons and twenty neutrons," says Takashi Nakamura, a physicist at the Tokyo Institute of Technology. "The 20 neutrons have three shells: the first shell has two seats, the second shell has six seats, and the third shell has 12 seats. With that the shells are closed with 20 neutrons."**


RIKEN

**Where the magic happens**
The Radioactive Isotope Beam Factory at RIKEN in Wako, Japan, provided the ion beam used to create the first oxygen-28 atoms.

**To find out, Nakamura and colleagues used RIBF to accelerate a beam of calcium-48 ($^{48}$Ca) atoms to 70% the speed of light and directed it at a thick target made of beryllium. The beryllium nuclei strip protons and neutrons from $^{48}$Ca to turn it into fluorine-29 ($^{29}$F). In the final step, the $^{29}$F, which is still moving at 60% of the speed of light, impinges on a proton. The resulting collision removes a proton from the nucleus, leaving $^{28}$O.**

**However, $^{28}$O turned out not to doubly magic. Though the proton levels were filled, as expected, the energy gap between the final two neutron shell orbitals was weak, allowing mixing between these two shells. "This kind of shell erosion sometimes happens for neutron-rich nuclei, but it was not at all obvious for $^{28}$O as the protons still fill the normal seats of eight," says Nakamura, who adds that the result should make it possible to improve theories about isotopes with large neutron/proton ratios and when evaluating the properties of neutron stars.**

**Kevin Jackson**

Materials

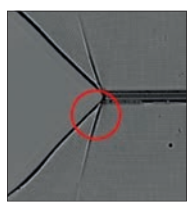
# Supersonic cracks break classical speed limit

Tensile cracks in brittle elastic materials can spread faster than the speed of sound – and faster than the laws of classical fracture mechanics say is possible. The new fracture mode was discovered by a team from the Hebrew University of Jerusalem, Israel, who say that their observations indicate the presence of "supershear" dynamics that are governed by different principles than those guiding classical cracks (*Science* **381** 415).

Materials fail when cracks form and propagate within them. Classical fracture mechanics says that these tensile cracks should move in a way that dissipates the elastic energy that builds up within a point-like zone at their tips. One consequence of this is that a classical tensile crack cannot travel faster than the Rayleigh wave speed, which is related to the material's shear-wave velocity and how much it deforms under a load (its Poisson ratio).

Jay Fineberg and colleagues have now found that some cracks do not obey this rule. Instead, they smoothly accelerate to near-supersonic speeds. They studied brittle gels that are "neo-Hookean", meaning that they have a nonlinear relationship between applied stress and strain. Using soft materials like these slows the speed of crack propagation by about three orders of magnitude, allowing the team to observe crack dynamics with fast, high-resolution cameras while making precise, real-time measurements on the strain fields surrounding the crack tips. Such measurements would have been impossible in a material such as glass, Fineberg stresses.

When they uniformly stretched sheets of the material and introduced a small cut to create an initial crack, the velocities of the cracks hit speeds never previously documented, with the fastest moving about 30% faster than the speed of sound. These observations contradict earlier studies, both theoretical and experimental, showing that cracks cannot propagate faster than sound. This is because sound speed reflects how quickly mechanical energy can move from one part of a material to another – something that must occur for it to crack.


Meng Wang, Hebrew University

**Cracking work**
A team from the Hebrew University of Jerusalem, Israel, has found the velocities of cracks in stretched sheets hit speeds never previously documented.

Notably, the new mode of tensile fracture does not occur randomly. Instead, it is triggered at critical strain levels that depend on the material. Such effects had been suggested theoretically nearly two decades ago. "We are only just at the beginning of understanding the effects we have observed," says Fineberg.

**Isabelle Dumé**

# News & Analysis

# UK rejoins Horizon Europe at last

Researchers are pleased the UK is back in the EU's flagship Horizon Europe programme, but concerns remain that the country is out of the Euratom nuclear initiative, as **Michael Allen** reports

The UK government announced last month that it will rejoin the €95bn Horizon Europe research framework. The agreement between the UK and the European Commission (EC) means that UK researchers can now apply for grants from the scheme. The UK also announced that it will associate to Copernicus, the EU's €9bn Earth Observation programme, paying around €2.6bn a year to associate with both Horizon and Copernicus.

The deal has been welcomed by UK scientists, who have long expressed dismay at not being a member of the world's largest research and innovation funding programme. "This is wonderful news," says Carsten Welsch, an accelerator physicist from the University of Liverpool. "The best science and innovation comes from international collaboration and it is great that UK experts can now play a leading role once again."

While pushing to rejoin Horizon Europe, UK researchers have often stated that Horizon Europe is about much more than just finance, such as the research collaborations it enables. Welsch, for example, lost a major EU grant last year. "After some challenging years where uncertainty made real progress difficult, association with Horizon will boost interdisciplinary research," he says. "I look forward to embracing the many opportunities the Horizon programme offers."

The agreement has also been welcomed by scientific bodies in the UK. "As the Institute of Physics (IOP) has long highlighted, Horizon association brings unparalleled opportunities backed by funding for collaboration – it is best for science, best for business and innovation, and best for the UK," says IOP group chief executive Tom Grinyer.

Before Brexit, the UK had been a full and highly successful member of previous EU research programmes, receiving more money from the programme than it put in. The UK's participation in Horizon Europe, which runs from 2021 to 2027, was agreed at the end of 2020 as part of the post-Brexit trade deal between the UK and EU. Associate membership stalled, however, and became a bargaining chip in disagreements over Northern Ireland, which were resolved in March with the Windsor Framework.

In recent months, the UK's association with Horizon Europe has been held up by negotiations on the UK's financial contribution to the research programme given it has missed more than two years of the seven-year programme.

As an associate member of Horizon Europe, Britain will now join other non-EU nations, including Israel, New Zealand, Norway, Switzerland and Ukraine. Yet it will no longer be able to take out more money than it pays in, meaning the UK could lose access to extra funding. The EC says that UK participation in Horizon Europe will begin from 1 January 2024. But because the UK government says it will not pay for the programme between 2021 and 2023 – the time the UK was a member – the agreement must now be approved by the European Council before it is adopted.

iStock/narvikk

**Back in the club**
The UK will join Horizon Europe and the EU's Copernicus Earth-observation programme but not the Euratom nuclear initiative.

## Fusion issues

The UK government also announced, however, that it would not be joining the Euratom programme. The body, through Fusion 4 Energy, is responsible for managing the EU's contribution to the ITER fusion reactor project in France.

Pulling out of Euratom means that the UK now ceases its direct involvement in ITER. According to a Fusion 4 Energy spokesperson, this will not affect ITER finances as the UK has not been contributing to the EU budget since 2021.

The UK Atomic Energy Authority (UKAEA) says it will "look into other strategies" to rejoin ITER. "We remain hopeful that UK nationals can continue to contribute to ITER, just as we have done with JET, the predecessor of ITER," notes a UKAEA spokesperson.

That view is backed by Laban Coblentz, head of communications for ITER. "We still trust that the UK will have a continuing strong interest in the ITER project," he says. "Now that the overall negotiation on Horizon has been completed, we expect that it will be possible to collectively seek ways to achieve these objectives."

The UK will now implement its own fusion energy strategy, funded with some £650m per year until 2027. Ian Chapman, UKAEA chief executive, welcomes the move and the "clarity" and "certainty" it provides to the sector. "The government's commitment to an ambitious alternative R&D programme will be hugely important in sustaining the UK's position as a leader in fusion R&D as well as developing an industrial capability to deliver future fusion power plants," he says.

**Michael Allen** is a science writer based in the UK, with additional reporting from **Michael Banks**, news editor of *Physics World*

Space

# India celebrates lunar and solar space success

The Indian space agency, ISRO, successfully launched the country's first mission to the Sun last month. The Aditya-L1 mission took off from the Satish Dhawan Space Centre in Sriharikota in the state of Andhra Pradesh on 2 September via a PSLV rocket. Named after Surya – the Hindu god of the Sun who is also known as Aditya – the craft carries seven scientific instruments including spectrometers and particle analysers. It will use these to study solar activity, such as coronal mass ejections, and the effect the Sun can have on space weather on Earth.

"Congratulations to our scientists and engineers at [ISRO] for the successful launch of India's first solar mission, Aditya-L1," said India's prime minister Narendra Modi on Twitter. "Our tireless scientific efforts will continue in order to develop a better understanding of the universe for the welfare of entire humanity." The craft is now making its way to Lagrange point 1 – a point in space about 1.5 million kilometres from the Earth towards the Sun – where it is expected to arrive early next year. It will then carry out a series of instrument calibrations before carrying out scientific observations.


ISRO

**Here comes the Sun**
India's Aditya-L1 mission will study solar activity, such as coronal mass ejections, and the effect the Sun can have on space weather on Earth.

The launch of Aditya -L1 came just weeks after another success for India as the nation became the fourth to achieve a soft landing on the Moon following the US, the former Soviet Union and China. The Chandrayaan-3 craft landed at the lunar south pole on 23 August and two days later released its Pragyan rover. Pragyan traversed 100 m studying lunar rocks and soils with its five instruments that include a laser and X-ray spectrometers. As *Physics World* went to press, the lunar rover and lander were in safe mode for the lunar night. They are expected to resume observations in late September.

The launch of Aditya came just days before Japan launched an X-ray space telescope mission as well as a lunar lander called SLIM. If all goes well, SLIM would mark Japan's first soft lunar landing.

However, Russia's first lunar mission in almost half a century ended in failure on 20 August when the craft crashed into the Moon. Launched from the Vostochny Cosmodrome on 10 August, Luna 25 was supposed to land in the South Pole region of the Moon where it would have studied the lunar surface with its eight instruments that included cameras and spectrometers. The Russian space agency Roscosmos said it lost contact with the Luna 25 spacecraft as it was entering a pre-landing orbit. The agency says it will now investigate the reasons behind the crash.

**Michael Banks**

## Andromeda galaxy photograph bags Royal Observatory Greenwich prize


Marcel Drechsler, Xavier Strottner and Yann Sainty

Amateur astronomers Marcel Drechsler, Xavier Strottner and Yann Sainty have beaten thousands of amateur and professional photographers from around the world to win the 2023 Astronomy Photographer of the Year. The image – *Andromeda, Unexpected* – was taken near Nancy, France, and captures a huge plasma arc next to the Andromeda galaxy (M31), which is the closest spiral galaxy to the Milky Way. The plasma arc is the largest such structure nearest to us in the universe and scientists are now investigating the surprising discovery. "This astrophoto is as spectacular as [it is] valuable," says astrophotographer and competition judge László Francsics. "It presents Andromeda in a new way [and] raises the quality of astrophotography to a higher level." As well as winning the £10 000 top prize, the image will go on display along with other selected pictures from the competition at an exhibition at the National Maritime Museum observatory that opened last month. The award – now in its 15th year – is run by the Royal Observatory Greenwich in association with insurer Liberty Specialty Markets and *BBC Sky at Night Magazine*. The competition received more than 4000 entries from 64 countries.
**Michael Banks**

Environment

# US funds \$1.2bn pilot to remove $CO_2$ from atmosphere

**The US Department of Energy (DOE) has announced plans to build two commercial-scale pilot plants that would remove carbon dioxide from the atmosphere through direct air capture (DAC). The \$1.2bn effort represents the first phase of a 10-year, \$3.5bn programme for four carbon-dioxide removal hubs. Environmentalists, however, have criticized the plan, saying DAC technology is expensive and its adoption would give oil and coal companies cover to continue to burn fossil fuels.**

**Worldwide some 130 DAC plants have been commissioned. Once complete, the two US plants would be the world's largest, able to eventually remove over 250 times more carbon dioxide than the largest DAC plant currently operating. The US DAC programme emerged from infrastructure legislation that a bipartisan Congress passed last year, with US president Joe Biden's infrastructure co-ordinator Mitch Landrieu calling it "the largest investment in engineered carbon removal in history".**

**1PointFive, a subsidiary of Occidental Petroleum, will build one of the pilot plants in Kleberg County, Texas, while non-profit research company Battelle will build the other in Louisiana's Calcasieu Parish. According to Occidental, its Texan plant will use liquid sorbents to capture and sequester one million tonnes of carbon dioxide in saline formations each year, increasing to 30 million tonnes a year. The company has not yet indicated a schedule for starting up and reaching maximum capacity. The Louisiana plant, meanwhile, will rely on solid sorbents with similar sequestration capacities.**

Battelle

**Hot air** Two US direct air capture pilot plants will be built, one in Kleberg County, Texas and the other in Louisiana's Calcasieu Parish costing a total of £1.2bn.

**"Cutting back on our carbon emissions alone won't reverse the growing impacts of climate change; we also need to remove the $CO_2$ that we've already put in the atmosphere – which is essential to achieving a net-zero global economy by 2050," says US energy secretary Jennifer Granholm. "The DOE is laying the foundation for a direct air capture industry crucial to tackling climate change."**

**However, former US vice-president Al Gore, a prominent critic of actions responsible for climate change, labelled DAC technologies "a moral hazard". Speaking in a TED talk he gave before the announcement, he said that the technology gives fossil-fuel producers "an excuse for not ever stopping oil". Gore added that the amount of energy required for DAC would exceed that needed to prevent the emissions of carbon dioxide that the technology would remove.**

**But supporters of the technology insist that, as the amount of global carbon continues to increase, DAC can serve as an effective back-up technology for removing it. Indeed, the DOE has also announced that it intends to allocate almost \$100m for feasibility and design studies on 19 other carbon-removal projects.**

**Peter Gwynne**
Boston, MA

Diversity and inclusion

# Female PhD students miss out on chance to become inventors

Women in technical PhD programmes are given less hands-on experience in patenting and commercial science compared with their male counterparts. That is according to a new study by researchers in Denmark and the US, which finds that this lack of experience results in fewer women becoming inventors. The team says the findings have implications for diversity and inclusion in academia as well as in start-ups and larger firms (*Proc. Natl Acad. Sci.* **120** e2200684120).

The study was carried out by Mercedes Delgado from Copenhagen Business School and Fiona Murray from the Massachusetts Institute of Technology, who examined data on PhD students trained at the top 25 US universities – as ranked by patent counts – between 1995 and 2015. They found that, overall, 4% of PhD candidates file a patent as a result of their studies. But while women make up about 30% of PhD students at the 25 universities, they only make up 20.7% of new inventor PhDs. This inventor gender deficit occurs even among students working in the same lab on similar topics under the same supervisors.

iStock/Andrei-Nikolaev

**Unequal start** A study has found that female PhD students receive fewer chances to become inventors than their male counterparts.

According to the researchers, the difference between genders could be because researchers who publish many patents tend to serve as a catalyst for students to also become adept at patenting – but those supervisors tend to opt for male students. "Female PhDs have a 21% lower likelihood of [working] with advisers who are top inventors than male PhDs – and even when [they do they] are 17% less likely than their male PhD counterparts to become new inventors," says Murray.

The team proposes several steps to reverse the trend, such as placing more women with doctoral supervisors who are themselves established inventors. Another would be to support women already in faculty positions to engage in high levels of patenting, thereby increasing the pool of women inventors who can serve as doctoral advisers.

**Ian Randall**

Diversity and inclusion

# Uproar at union's harassment policy

Astronomers have voiced their concern over an update by the International Astronomical Union (IAU) to its harassment policy, which they say helps to provide a safe space for harassers. The changes to the code were announced in an e-mail sent to IAU members from its president, Debra Elmegreen, which noted that the IAU's executive committee had modified its 13-page code of conduct to include a "substantive change" to its harassment policy.

According to the revised code, it is now "a form of harassment to physically or verbally abuse or discriminate against alleged offenders of IAU's policies, or if such policies are found to have been breached, inflict (or pressure others to inflict) punishments besides those officially sanctioned". The code also states that "the physical or verbal abuse or discrimination of those who work or have worked with the alleged or sanctioned perpetrator, simply because of their scientific collaboration, is also a form of harassment and as such is covered by this policy".

After the changes were made public, some questioned the motivation behind the modification and the wording itself, pointing out, for example, that it is not clear what the IAU means by the word "discriminate". Some astronomers worry that it is now a policy violation to refuse to work with an astronomer who has been found guilty of harassment or that someone organizing an IAU conference, say, now cannot refuse an alleged harasser from sitting on an organizing committee.

"The additions are dreadful, both in terms of their wording and in terms of the message they send – that the IAU is going out of its way to provide a safe space for harassers and their enablers," Anna Watts, an astrophysicist at the University of Amsterdam, told *Physics World*. "The current wording, for example, would preclude a victim of harassment that occurred at an IAU event, even if that harassment were confirmed and sanctioned by the IAU, from reporting the incident to the perpetrator's home institution or collaboration since this would be 'pressuring for additional punishment'."

iStock/SDI Productions

**Cause for concern** Researchers claim that the International Astronomical Union's updated code of conduct could offer a safe space for harassers.

In protest at the policy changes, Emma Chapman, an astrophysicist at the University of Nottingham, penned a letter to Elmegreen, which has been seen by *Physics World*. "The first sentence [of the changed harassment code] does serve in its ambiguity to add a layer of protection to a proven harasser," she writes. "I can easily see situations where an ally refuses to share a stage with a harasser and they are then subjected to a complaints process by the harasser." Chapman adds that she does not believe that the intentions of the committee were malicious but more that "the way their words could be twisted were not properly considered".

On 18 August, however, the IAU sent another e-mail to members, seemingly doubling down on the policy changes. The IAU says that the code of conduct applies only to IAU-related activities and that it is to "help and to foster professional respect and fair treatment for all".

"The new wording in the code of conduct says that it is harassment to physically or verbally abuse or discriminate against people who are merely *alleged* to have breached the IAU Code of Conduct at an IAU activity," notes Elmegreen. "The statement has no bearing on whom people choose to work with or associate with, including at IAU events." The IAU says it will now be considering feedback from scientists who have written to it about the code.

**Michael Banks**

People

## Campus mourns slain nanoscientist

**Tributes have poured into the University of North Carolina (UNC), Chapel Hill, following the death of nanoscientist Zijie Yan on 28 August. PhD student Tailei Qi, a member of Yan's group, has been charged with first-degree murder and possession of a firearm on educational property in connection with the incident.**

**The shooting occurred in the early afternoon and the university was locked down for several hours as a result. In the aftermath, UNC quickly went into grief mode. The campus community took a moment of silence two days after the shooting, when bells in the university's campanile were rung in Yan's memory. Later that day, thousands of students and staff attended a candlelight vigil in Yan's honour.**

**"[Yan] was a beloved colleague, mentor and friend to many on our campus," said UNC chancellor Kevin Guskiewicz. In a statement, the chair of Yan's department, Theo Dingemans, noted that Yan was a "great colleague" and an "outstanding professor, researcher and mentor" to the department and to the university. "He was very kind and soft-spoken but also a great listener with a wonderful sense of humour," Dingemans added. "Zijie would've wanted us to move forward in educating students and conducting research, and we will honour his legacy by doing just that."**

**Yan held a PhD in materials engineering from Rensselaer Polytechnic Institute and was an assistant professor at Clarkson University before joining UNC in 2019. His group's research involves the use of holographic optical tweezers to manipulate nanoparticles using shaped laser beams.**

**Qi, the PhD student charged with Yan's murder, joined Yan's group last year. He has a BSc in physics from Wuhan University and an MSc in materials science from Louisiana State University. No reason for the shooting has emerged. However, Qi had complained on X (formerly Twitter) about bullying.**

**Peter Gwynne**
Boston, MA

# Science goes on in war-torn Ukraine

Scientists in Ukraine are still in survival mode following Russia's invasion of the country, but as **Ethan van Woerkom** finds out, they are finding ways to continue their science

During the opening salvos of the Russian invasion of Ukraine, which began on 24 February 2022, academics across Europe quickly took to university mailing lists to discuss how to help their colleagues in Ukraine. While some Ukrainians managed to move to safer places across the continent, others decided to stay at home. Some 18 months on from the start of the conflict, Ukrainian cities such as Kyiv and Kharkiv are still being attacked, but a semblance of stability is beginning to emerge.

With Ukraine starting to see successes on the battlefield, some displaced researchers are slowly coming back to their home institutes. One of those is astrophysicist Oleksiy Golubov from Kharkiv National University (KhNU) – one of the country's leading institutions. He left Ukraine when war broke out, moving first to the Astronomical Calculation Institute in Heidelberg, Germany, and then the Poznan Observatory in Poland. But in July he decided to return home (see box opposite). "I moved back to Ukraine largely because I felt that I was not in the right place," he says.

Golubov's research group, however, still faces major problems. A significant number of colleagues entered military service and some have sadly died. They include Mykhailo Lesiuta, one of Golubov's first students, who joined the army in 2022 and was killed fighting in Donetsk on 11 December 2022, aged 25. While student numbers entering physics at KhNU have recovered to pre-war levels, those students are scattered, working from across Ukraine and Europe.

The scars left by the Russian army as it advanced to the outskirts of Kharkiv in the first days of the war are still noticeable. The KhNU's School of Physics and Technology, one of four distinct physics schools at the university, was completely destroyed on 11 March 2022 by Russian shelling. "We only just repaired this building before the war began," says Golubov. "We cannot have laboratory classes for our students as the laboratories are destroyed."

Oleksiy Golubov

**Shelled**
The School of Physics and Technology at Kharkiv National University was destroyed on 11 March 2022 by Russian shelling.

Other KhNU facilities, such as the School of Physics and the Astronomical Institute, avoided structural damage but scores of windows were broken when the adjacent district administration building was hit on 1 March 2022 by two Russian missiles. The strike killed 29 people. One of Golubov's students was in the building. "She was not harmed, but it was very close," he says.

KhNU's Astronomical Institute operates an observational station in Chuhuiv, 70 km south-east of Kharkiv. It includes a 70 cm optical telescope – which is used for asteroid photometry studies – as well as UTR-2, the largest telescope in the world for radio waves with decametre wavelengths. When Russian forces were pushed out of the region in April this year, astronomers discovered that the station has been ransacked and mined with explosives. "They could not steal the big telescopes, but they took away the CCD cameras – one of the most expensive parts of the telescopes," says Golubov. However, UTR-2's control room has been destroyed beyond repair and CCD cameras were later found riddled with bullet holes.

While foreign aid such as grants and collaborations initially targeted Ukrainian researchers with temporary positions abroad, there are now calls to support researchers in the country (see box below). Indeed, a survey released in July revealed that 70% of Ukrainian scientists are in a worse financial position than in the first two months of the war, with only a third now having enough money for food.

Ukraine still faces significant human, material, monetary and security challenges that are preventing researchers from doing research or teaching students. Golubov's funding situation is similarly precarious. His grant from the Ukrainian National Research Foundation recently ended and his position at KhNU has been reduced, resulting in his income falling by 80%. "If I did not have some savings, I am not sure if I could survive," he says.

### Occupied territories

Dozens of other universities or institutes in Ukraine continue to be occupied by Russian forces, however. Indeed, some have been in Russian hands since 2014 following the annexation of Crimea and the war in the Donbas, which led 26 higher-education institutions to be relocated to other parts of Ukraine. One of

### #ScienceForUkraine – providing support for Ukrainian researchers

#ScienceForUkraine is a community group of volunteer researchers and students from institutes in Europe and around the world who are supporting the Ukrainian academic community. They say help is possible in three different ways. One is to provide resident research opportunities to Ukrainian researchers abroad. The second is to create paid remote research positions, allowing Ukrainian scientists to work alongside international researchers while staying at their home institutions. The final approach is to fund research groups in Ukraine directly. Even small things, such as facilitating experiments, sharing article submission fees or sponsoring academic travel, can make a difference. Programmes that support researchers from Ukraine can be found at www.scienceforukraine.eu, including a £200 000 IOP Benevolent Fund that has already helped 31 Ukrainian physicists, with funds still available for applicants.

those affected is Melitopol State Pedagogical University (MSPU), which is an occupied university in southern Ukraine. Founded exactly a century ago, before the war it hosted several modern laboratories and trained some 2000 teachers each year.

Katerina – who does not want to reveal her full name for fear of reprisal – was in Melitopol in March 2022 when war broke out. “In the first days, when we did not know what was happening in the university, the work of the university almost stopped,” she told *Physics World*. “A month later, we started working remotely and resumed the educational process.”

Teachers were called to return to work face-to-face and soon it became impossible to live under occupation. “Over half of my colleagues did not co-operate with the occupiers,” she says. “Then Russian soldiers came with machine guns and forced them to write applications for employment at a new Russian university.”

Katerina decided to flee Ukraine and her journey took her across five countries. She now lives and works elsewhere in Europe but the events of the past 18 months have left a deep wound. “[The occupation] was a shock. I couldn’t give lectures. It was very difficult for me to communicate with students because I did not know how to encourage them,” she says. “For seven months after the start of the full-scale war in Ukraine, I could not write a single scientific paper.” Occupying forces took over MSPU, merged it, renamed it and appointed new leadership. The university continues to educate its students online, both in free and occupied territories.

Part of that “freedom” has been provided by the Internet, which continues to play a key role for Ukrainian researchers and teachers. The Ukrainian Online Physics School was set up in July 2022 by teachers in Kherson and Kharkiv distraught to see that displaced children had become deprived of a quality physics education. The school now educates displaced 13–17-year-olds and, over the past year, has held online physics classes three hours a week, three times a week.

The school has received support from Alexey Boyarsky, a cosmologist from the University of Leiden in the Netherlands, who helped initiate the project. Boyarsky and colleagues have also helped to supply battery packs so that teachers can continue lessons during blackouts, as well as terminals to access SpaceX’s Starlink satellite constellation, which provides Internet in the country.

Despite the hardship, some sort of normality is starting to return. In August the Lviv Data Science Summer School 2023 was held in-person at the Ukrainian Catholic University, organized with aid from the non-profit US-based Simons Foundation and the US National Academy of Sciences.

“Lectures were held underground so even in the case of an alarm we could continue,” says Oleksii Ignatenko – a mathematician from the university, who co-organized the event. Still, there were interruptions. “One night was quite disturbing, with alarms at 4 a.m., so lecturers had to go to the shelter,” he says, though insisting that, despite these issues, the school was a “huge success”.

Ukrainian science is still in peril and the country will need peace for it to return to pre-war levels. Yet researchers in Ukraine are trying to stay positive, hoping that international organizations and individuals can help Ukrainian science to either slow its decay or even reverse it. The most important action anyone can take to help, it turns out, costs nothing. “I would ask people not to ignore what is happening in Ukraine,” says Golubov. “These are lives of real people who are suffering under Russian occupation.”

**Ethan van Woerkom** is a science writer based in Amsterdam

## Oleksiy Golubov – returning home to build a “Ukrainian Boulder”

Oleksiy Golubov completed his studies at Kharkiv National University (KhNU) in 2008 before carrying out a PhD on galactic dynamics at the University of Heidelberg, Germany, which he completed in 2012. After a postdoc at the University of Colorado Boulder, US, Golubov returned to KhNU in 2014. Once the Russian invasion of Ukraine began in early 2022, however, eight of the 10 members of Golubov’s research group left Kharkiv, moving within Ukraine or fleeing to elsewhere in Europe.

As Golubov is unfit for military service due to a paralysed left hand, he was exempt from the ban on men aged 18–60 leaving the country. Eventually, he managed to travel, and spent time as a visiting researcher at the Astronomical Calculation Institute at the University of Heidelberg and the Poznan Observatory in Poland. “My motivation was that all work was done online anyway,” he says. “In Europe I had a more stable situation, an Internet connection, no air alarms.”

While Golubov and his parents could leave Kharkiv, his godfather was less fortunate, getting trapped in occupied territory for months. Golubov’s research institute continued to function online, and he taught four courses over the following academic year. He managed to keep up his research and recently published a reconstructed orbit of the first iron meteorite instrumentally captured during its fall.

But the past 18 months have been far from easy for Golubov, who sank into a deep depression. “The conditions for my work were perfect – I had accommodation, I had good problems to work on and my colleagues and advisers were super motivating,” he says. “[But] I did almost nothing useful, I did not know what to start with.”

Shortly after Ukrainian forces pushed back and liberated Kharkiv, his godfather’s house was destroyed by Russian shelling along with most of Golubov’s possessions, which had been stored there temporarily. “My PhD hat from Germany, all my memories and, most unpleasantly, my library where I had hundreds of books, mostly about physics, mathematics, astronomy [were destroyed].”

Yet Golubov is trying to stay upbeat. Since 2022 he has written more than 1000 Wikipedia articles in Ukrainian about astronomy and his home city of Melitopol. “[It] is the city of my childhood, the city of my dreams,” he says. “I want to move to Melitopol and turn it into a Ukrainian Boulder, a Ukrainian Heidelberg. All my work in Kharkiv, Europe and America [is about] gaining enough experience to be able to go to Melitopol and work there fully independently.”


Oleksiy Golubov

**Back where he belongs** Physicist Oleksiy Golubov moved to Germany and then Poland when war broke out but has now returned to Ukraine.

# Comment

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**Physics World**
No.2 The Distillery, Glassfields, Avon Street, Bristol
BS2 0GR, UK
Tel +44 (0)117 929 7481
E-mail pwld@ioppublishing.org
Web physicsworld.com
LinkedIn physics-world
Facebook facebook.com/physicsworld

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**Institute of Physics**
37 Caledonian Road, London N1 9BU, UK
Tel +44 (0)20 7470 4800
E-mail membership@iop.org
Web www.iop.org



# European success

**The UK's agreement to rejoin the EU's Horizon research programme is welcome news**

Like many scientists, I've always thought the UK's decision in 2016 to leave the European Union was a big mistake. Admittedly, the EU has its flaws, being far from nimble in its decision making, remote from ordinary voters, and too keen to overstretch its powers. The UK also has a tradition of wanting to do things its own way. But the EU's Horizon research programme has been a huge success story, especially for the UK, which always won a big slice of the money on offer.

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That's why the UK government's decision last month to rejoin Horizon is great news and has been widely welcomed (see pp10). The UK had been locked out for almost three years, first caught up in a political ding-dong with the EU over the status of Northern Ireland within the Single Market and then in haggles over the price of rejoining. The country's absence led to significant uncertainty, with some top scientists missing out on money and others reluctant to move to Britain, preferring to further their careers elsewhere.

Researchers in the UK can now apply for European Research Council grants and co-ordinate academic–industrial consortia, with the UK's participation officially starting in January 2024. But the UK will only be an "associate" member, meaning it doesn't have a say in major decisions, putting the country in a weaker position than when it was in the EU. What's worse, the UK is not rejoining the Euratom fusion-research programme, meaning it is not officially part of the ITER project being built in southern France.

I'm surprised more has not been made of the UK's withdrawal from ITER. Of course, ITER is far from perfect: there's been mismanagement and the project's been far more costly than first imagined. The hope is that the UK will – somehow – become an associate member of ITER, but who knows how long that will take. In the meantime, the country will have to focus on the STEP prototype power reactor spearheaded by the Culham Centre for Fusion Energy, which is also home to several private fusion start-ups.

The UK should now turn its attention to rejoining the Erasmus+ student-exchange programme. Students in Northern Ireland are able to apply to Erasmus+ but the UK-wide Turing scheme – billed as a replacement for Erasmus+ – has not been a huge success, with problems over the size and timeliness of payments. Science is all about international co-operation with counterparts in other countries and it's daft that British students are missing out.

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

# Transactions Magnetic attraction

**James McKenzie** explains why magnetism is so important for physics-based businesses


**Super science** The vast numbers of hard disks in data-storage centres that underpin "cloud computing" rely entirely on the physics of magnets.

In 2022 I stood for election to the magnetism group of the Institute of Physics (IOP) as I always think the best way to be involved in anything is simply to get stuck in. I'd only joined the group the year before after starting to work at a company specializing in permanent magnetic materials. Despite not knowing much about the group, I was – to my surprise – elected.

The magnetism group is one of the IOP's larger special-interest groups and, among other things, runs a successful and widely attended annual conference, which this year was held in Manchester in April. The meeting covered topics stretching from spintronics, 2D physics, domain walls and dynamics to vortices, skyrmions, topological physics and intelligent computing. It also spanned a wide range of materials from biological and organic systems to spin ices, superconductors and magnetocalorics.

But the IOP's magnetism group isn't the only UK outfit involved in this field: there's also the UK Magnetics Society (UKMagSoc), of which the company I work for is a corporate member. UKMagSoc's activities overlap to some extent with those of the IOP, but the society is more focused on the application and commercialization of magnets, such as electrical machines, instruments and hard disks. The society does, though, have individual members as well – in fact, in June I attended a joint IOP/MagSoc event at the IOP's headquarters in London, where speakers spelled out the challenges over the next five to 10 years in a range of magnetic materials and devices.

## Future challenges

For a newcomer like myself, the meeting was a really helpful overview of magnetics and I finally found out from a talk by Thorsten Hesjedal from the University of Oxford what a skyrmion really is. It's a whirling, nanometre-sized topological defect in a thin magnetic film, which could provide a new form of computer memory. Skyrmions could, I learned, be particularly useful out in space where conventional computer memory can easily get corrupted by cosmic radiation.

There were also some excellent talks of direct interest to my day job on various aspects of motor design and electrical machines by John Reeve from drive manufacturer FluxSys Ltd, by Dean Evans of motor and generator firm NEMA, and by Juliette Soulard of the Warwick Manufacturing Group. Particularly interesting to me was a lecture by Robert Hicken, a condensed-matter physicist from the University of Exeter. He examined the challenges of keeping up with the ever-increasing demand for data storage, a topic I reported on in December 2020.

Now you've certainly heard of Moore's law, which – as I mentioned in another recent article – states that the number of transistors on a microchip doubles about every two years. It is named in honour of the late Gordon Moore, the co-founder of Intel who came up with the concept in 1965. However, Hicken introduced a related concept that was new to me, which is that the density of data storage on magnetic media (such as hard drives) should increase at a rate of about 40% per year.

Known as "Kryder's law", it's named after Mark Kryder – a former chief technology officer at disk-drive manufacturer Seagate. Kryder, who has a PhD in physics, first mentioned the notion in an article in *Scientific American* in 2005. Sadly, Kryder's law has been rather less successful than Moore's law because the growth in storage density on magnetic materials rose by only 15% in the five years ending in 2014.

Even if Kryder's bold prediction didn't hold true, the demand for data storage will certainly rise in the long term and companies like Seagate, Toshiba and Western Digital – who together make 80% of all hard-disk drives (HDDs) in the world – will be doing all they can meet the huge demand. Worth


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**Mega deal** Sales of hard-disk drives peaked in 2010 but more than 250 million units were still shipped in 2022.

$35bn per year in 2021 according to a report from Future Market Insights, the data-storage market is set to grow to $80bn by 2029.

A staggering 259 million HDDs were shipped in 2021, with most going into data centres. With 44% of the market, Seagate is currently the largest manufacturer of HDDs – in fact, its technology facility in Northern Ireland alone makes almost 30% of the global supply of read/write heads. The company also seems to be leading the storage-density race thanks to its work on "heat-assisted magnetic recording" (HAMR). It's allowed Seagate to boost the storage density of its hard disks to more than $2 \times 10^{12}$ bytes (2 TB) per square inch, with the bits written via a laser and a plasmonic near-field transducer integrated into the read/write head.

Some 21 years after the idea was conceived, the first HAMR HDDs have recently started shipping with a massive 32 TB capacity (10 platters of 3.2 TB each). Seagate's road-map suggests we will end up with 120 TB drives with this HAMR technology by the end of the decade, with more than 10 TB data storage per disk. This will mostly be down to major improvements in magnetic media and growth technology plus associated alignment challenges.

## Smaller, brighter, better

Today each hard-disk track – of which there are about a million per inch – contains bits of information recorded into tiny areas just 42 nm wide (roughly six to eight magnetic grains) and 10 nm long (barely two to three grains). But if we are to meet growth targets, these tracks will have to get much, much smaller. Single bit-patterned magnetic media will be required to achieve the end goal of more than 8 TB of data per square inch using a technology called heated dot magnetic recording (HDMR).

As Hicken went on to explain, boosting storage densities is not as simple as just making bits as small as possible: you also have to ensure that data can be written on to the drives quickly enough and that they are thermally stable too. Companies, in other words, face a trilemma of conflicting requirements that are a challenge to solve. Thankfully, they have other solutions up their sleeve. Optical techniques in particular could push HDDs beyond current limits with "all-optical" disk writing and switching.

So if you thought hard disks were boring objects locked away in shed-like data centres, it's time to think again. They hide a huge amount of cutting-edge physics and engineering and we can expect many more exciting developments if we are to reach the 120 TB per HDD and keep up with the demand for "cloud" storage. If there's another joint IOP/UKMagSoc event next year, I strongly urge you attend.

**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

# Critical Point Quantum investment

**Robert P Crease** finds out from Susannah Glickman why people ploughed so much money into quantum computers before the technology had even been properly developed


iStock/ipopba

**Money for nothing** Why was so much invested in quantum computers before they even existed?

"What a relief," said Susannah Glickman. A PhD student at Columbia University in New York, she had just successfully defended her dissertation on the history of quantum computing, and had morphed into Dr Susannah Glickman. Her thesis, as she wrote in the introduction, explored "how quantum computing went from the theoretical fringes to a brick and mortar set of institutions".

I'm guessing, but I imagine hers is the first PhD in the history of quantum computing. Most historians who study technology generally investigate the origin and development of something in the past, be it telephones, engines or medical devices. But Glickman's thesis – entitled "Histories, Tech, and a New Central Planning" – explores how and why the US invested tens of billions of dollars, launched various federal policies and programmes, and indeed created entire industries devoted to a technology whose applications lay entirely in the future.

As an undergraduate at Reed College in Portland, Oregon, Glickman did a joint degree in mathematics and anthropology. For her undergraduate project in 2015 she worked with a maths professor writing algorithms for quantum computers. But she was baffled that anyone would want to write algorithms for devices that did not yet exist – and may never even do so. When she posed that question to her supervisor, he couldn't give her a satisfactory answer.

## Turning speculation into solutions

Glickman began her PhD at Columbia in 2016, still brooding about the fact that an entirely speculative technology could inspire such a huge industrial infrastructure and such far-reaching federal programmes and initiatives – the "central planning" of her title. The answer, she discovered during the course of her thesis, comes in two parts.

The first is the notion – strongly promoted by scientists and politicians alike – that the development of all technology follows a "natural course" and any nation that ignores this fact will endanger its global power and security. As Glickman describes in her dissertation, this narrative was used to push America's development of semiconductors, which in the 1970s were said to be vital to keep the US ahead in the Cold War. Later, in the 1980s, they were needed to staunch the country's decline relative to Japan, and in the 1990s it was to support encryption devices.

The narrative that investing in technology is good for the national interests had, in other words, a long track record of success. Hardly surprising, then, that those with a vested interest in quantum computers used the familiarity and persuasiveness of this narrative to give these devices the hard sell too. In doing so, they had to challenge the more neo-liberal idea that any technology should be left to develop at its own pace.

Glickman's template for this process is the semiconductor industry's use of Moore's law, which is named in honour of Gordon Moore. As the co-founder of tech giant Intel, he famously predicted in 1965 that the density of transistors on a microprocessor would double every year (a figure later revised to every two years). Clever public relations extrapolated what was essentially a rule of thumb into an iron "law" demonstrating the inevitability of smaller and smaller computer chips. Woe to the US, it seemed, if it did not invest heavily in the technology. The resulting massive investments, Glickman showed, made that extrapolation self-fulfilling. Her dissertation treated the development of quantum computing as the same basic process, but on steroids.

The second part of Glickman's answer has to do with the extraordinary claims of what quantum computers would do in the future. Such devices, their backers said, would solve hitherto insoluble problems like protein folding and optimizing nitrogen fixation. They would crack most encryption methods, and would develop uncrackable ones. Richard Feynman, John Wheeler and other prominent physicists who spoke about quantum computing's potential seemed to ratify the promises, helping to convince federal administrators to take them seriously. Quantum computing, writes Glickman, was held up as "revolutionary, era-defining".

Glickman's dissertation does not take a stand on whether these narratives or promises are true or false. Rather, her aim is to describe their role in creating the political, economic and industrial environment in which a massive infrastructure, political programmes and planning, and plentiful funding sprang up around a still-speculative technology.

In her research, Glickman was startled by how obsessed quantum computer advocates are with its history, often saving boxes of photographs, stacks of notes, and caches of e-mails. "I knew the historians would come knocking," said one of her interview subjects.


Susannah Glickman

**Tech investigator** Susannah Glickman says that studying quantum computing has made her a different kind of historian.

AUDIO Susannah Glickman talks to *Physics World*'s Matin Durrani in more detail about her investigations

From my experience, that's in sharp contrast to other kinds of scientists, who keep only reprints, trash all their e-mails, and view history as last year's journals. But quantum computing practitioners were, Glickman writes, if anything "too excited about documenting their own histories," for such documentation can distort and disguise history, obscure ambiguities, erase dead ends, and encourage over-the-top claims.

One promoter of quantum computers told Glickman a holy-grail-like story about how the history of technology began with fire and has culminated with quantum computing. Another related a metaphysical tale of how just as the quantum world is the ultimate reality and the classical world derivative, so quantum computing is the natural way and classical computing its imperfect predecessor.

### The critical point

Glickman's PhD was also unusual in that the committee before whom she had to defend it consisted of an anthropologist and three historians who specialized in US history, political theory and business. This diversity was due to the fact that her dissertation was not a straightforward story about technology developing in its own special ether, but was as much about US history, political economy, industrial competition, philosophies and myths. "I had to adapt to the subject matter," she told me. "Studying quantum computing made me a different kind of historian."

Glickman is now an assistant professor in the history department at Stony Brook University, where she is working on an interdisciplinary project lying at the intersection of liberal arts and quantum and AI technologies. But the thoroughness of Glickman's PhD made me wonder whether most historians haven't been overlooking these features in past technologies. Her dissertation on the history of a future technology suggests that historians of past technologies will have to become different too.

**Robert P Crease** is a professor in the Department of Philosophy, Stony Brook University, US; e-mail robert.crease@stonybrook.edu; www.robertpcrease.com; his latest book is *The Leak* (2022 MIT Press)

# Building an inclusive community

**Alex Belsley, Marija Radulovic, Angela Stephen** and **Carrie Weidner** say that diversity and inclusion considerations must be at the forefront of rapidly developing fields such as quantum technologies

Daniel Marchant

**Discussion points** Creating a truly inclusive and diverse subject requires continuous effort, reflection and adjustment.

Creating inclusive and equitable environments in the lab and at scientific conferences is crucial if we are to foster equal opportunities for all. This involves addressing many issues such as ensuring there is a gender balance within the subject, removing language barriers and making the events accessible for individuals with disabilities. Despite progress in recent years, there remain many challenges facing physics – including in quantum technologies. Quantum technology is a burgeoning field where developments are occurring at a breath-taking rate, but we must ensure that progress does not come at the expense of cultivating a safe environment.

Such thoughts were on our minds as the organizers of BQIT (Bristol Quantum Information Technologies) workshop – an annual meeting that has been running for the past 10 years. Recently, a particular focus at the conference has been addressing issues in equity, diversity and inclusion. That's why, since 2019 BQIT has featured panel discussions on topics such as tackling implicit bias; the impact of working conditions in academia on mental health; the effect of the COVID-19 pandemic on research; and ways in which institutions can help fight pandemic burnout and impostor syndrome.

In April, some 200 participants met at the University of Bristol for BQIT where the diversity and inclusion session, which we organized together with Alex Clark and BQIT chair Holly Caskie, was for the first time transformed into an interactive workshop. Following an introductory talk from Caroline Clark, participants were divided into groups, which included people at various stages of their career to promote diverse perspectives. Each group also had help from facilitators from the University of Bristol's equity, diversity and inclusion team.

Although the groups debated the issues facing those in quantum technologies, our discussions touched on topics that are also relevant to many other areas of physics.

One major concern in physics is the large gender imbalance, which is caused in part from a lack of diversity in applicants and unconscious selection bias. Delegates discussed how interventions such as "blind" interviews and redefining success metrics beyond gender balance can help. Another problem concerns language barriers, which often results in a bias against non-native English speakers. This issue can be tackled by focusing on effective communication and recognizing that science ability is not limited by language proficiency. Accommodating individuals with disabilities requires accessible buildings, laboratories and equipment, including technologies such as remote experiment control.

If we are to create a more inclusive community, we also must pay particular attention to people who have caring responsibilities, who are neurodivergent or who come from minority groups. It's vital to strike a balance between career aspirations and caring responsibilities, which means we have to clearly communicate expectations and requirements, create suitable job roles, and promote a supportive work environment. In the case of neurodiversity, one solution is to use anonymous questionnaires to help tailor workspace adjustments, while another involves cultivating socially cohesive groups to foster understanding and support. Creating an inclusive academic culture also requires us to address personal biases and learn more about the problems at hand. We also need to use techniques such as creating agile working practices, offering leadership training and creating physically inclusive workspaces.

The trouble in such a fast-moving field as quantum technology is that people end up being expected to work long hours, which can lead to a significant imbalance between work and personal life. This is especially taxing for those with fixed-term contracts, given the added pressure of traditional productivity metrics and the constant push to publish papers. That's why we need to train supervisors in pastoral support and mental health. Unnecessary pressure can also be alleviated with robust support networks and clear expectations. Universities should also encourage staff to strike a good work/life balance and to take holidays. Flexibility is vital, especially for experimentalists who spend long hours in the lab, so we must employ arrangements that allow individuals to compensate for extended work hours with time off.

**On conferences**

We know that conferences are vital for researchers to collaborate and share knowledge, but they must be held at safe, accessible and welcoming venues. Meetings should feature a diverse array of participants, encourage a broad range of perspectives, and empower under-represented groups. Alternative formats like table-based poster sessions and hybrid events are useful for addressing accessibility challenges, provided that technological barriers are managed.

Conferences should also provide comprehensive support for attendees, including help with delegate fees, visas, accommodation and transport costs and even childcare facilities and on-site prayer and reflection rooms. We can also encourage people to interact in a respectful way through, for example, having pronoun badges, running structured engagement opportunities, and organizing an array of session types.

If we are to build a diverse field, we also need to examine why people from under-represented groups find it hard to progress in their careers or leave physics altogether. Encouraging physicists to stay in the field means making sure they have enough money to live on, they have a good work/life balance and that we are able to be accommodating of different responsibilities that many individuals face. A kind, inclusive culture that celebrates teamwork is one that embraces diverse perspectives and allows talent to flourish.

We call on those in senior positions in the quantum community to consider these issues and find ways to implement solutions. Future BQIT meetings will aim to implement these suggestions as best we can. The path to a truly inclusive and diverse community, especially in new and rapidly developing fields, requires continuous effort, reflection and adjustment. We now want to broaden discussions and identify further challenges within quantum technologies. Our long-term vision is a quantum community where individuals from all backgrounds have equitable access to opportunities, where diverse perspectives are highlighted and where a wealth of experiences and a range of viewpoints can drive collaboration. We believe we can get there.

**Alex Belsley, Marija Radulovic, Angela Stephen, Carrie Weidner** are based in the Quantum Engineering Technology Laboratories at the University of Bristol e-mail: c.weidner@bristol.ac.uk

# 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

## Oppenheimer omissions

In reply to the reaction from members of the *Physics World* editorial team to the film *Oppenheimer* (online 3 August, see also pp39).

It was interesting to see the various star ratings that the *Physics World* editors gave to the movie. Certainly, I rated it very highly, as did many of my colleagues who watched the film too. We were all born around 1940 and it is my belief that stories about the atomic bomb, its testing and possible use resonate more with those of us who were adults through the Cold War than people from later generations.

As a South Australian, I also want to mention a notable local connection to the first bomb, which is perhaps not that well known. While at the University of Birmingham in the UK, the physicist Mark Oliphant (1901–2000), who was originally from Adelaide, was part of the influential MAUD committee, which in 1941 told the British government that an atomic bomb was feasible and should be built. Oliphant later worked on the Manhattan Project itself.

The film could not by necessity cover all the history, but it is sobering to note that there may not have been such a dynamic bomb programme in the US were it not for Oliphant's urging. After the Second World War, Oliphant returned to South Australia, which has large remote areas that were used for testing of the British nuclear bomb. In recent years, the conduct of these tests has been seen in a different and not entirely complimentary light.

**Geoff Jansen**
Adelaide, Australia

I enjoyed the movie *Oppenheimer*, but readers should be aware that it contains fiction as well as fact. It includes, for example, a fictional meeting between Robert Oppenheimer and Albert Einstein, where they discuss the design of the atomic bomb. There are also doubts whether Oppenheimer really did speak words from the Hindu scripture *Bhagavad Gita* after watching the Trinity bomb test in 1945.

But the film's most disturbing historical distortion is the scene at the University of Cambridge in the mid-1920s, where Oppenheimer is shown trying to poison his tutor Patrick Blackett by leaving him a poisoned apple. That incident did happen (though there is doubt about which poison was used) – but the scene mistakenly shows Blackett introducing Oppenheimer to Niels Bohr. In fact, as Abraham Pais's 1991 book *Niels Bohr's Times* makes clear, it was Ernest Rutherford – head of the Cavendish Laboratory at the time – who introduced Oppenheimer to Bohr.

I am not clear why the director Christopher Nolan exchanged Rutherford for Blackett yet decided to include the genuine dialogue between Bohr and Oppenheimer from Pais's book. In a film that prides itself on including so many historical figures, this deliberate distortion of the truth for dramatic purposes seems to me unacceptable. Readers might be interested in a recent article in *Business Insider* by the US nuclear historian Alex Wellerstein, which describes what else is right and wrong in the film (tinyurl.com/4dyw2kpr).

**Andrew Robinson**
London, UK

I read with interest your article "*Oppenheimer*: the movie" (September p17), which lists some of the many physicists who appear in the film. I was surprised, however, that Rudolf Peierls and Otto Frisch were not included.

In 1940 these two physicists, who were then working in the physics department at the University of Birmingham, produced all the theory and calculations for an atomic bomb to be constructed. They also issued the famous "Frisch–Peierls memorandum" outlining the feasibility of atomic weapons. A few years later the theory and calculations were passed to Oppenheimer's team, who developed the atomic bomb at the Manhattan Project, with two devices subsequently being detonated over Japan.

**Richard Hampton**
Birmingham, UK

● See pp37–38 for Andrew Glester's review of *Oppenheimer*.

> It is my belief that stories about the atomic bomb, its testing and possible use resonate more with those of us who were adults through the Cold War

## A boffin speaks

In reply to the Quanta article about the campaign by the Institute of Physics (IOP) to "Bin the boffin", which included projecting the message onto the offices of the *Daily Star* newspaper (August p3).

In my comic-reading days, the best stories always included a boffin – a person with vision, deep knowledge, imagination, charm and influence, who could either destroy or save the world with equal ease. Such incredible characters inspired me, as a child with an open, inquiring mind, to attempt to emulate them and reach the top of the boffin tree. My journey proved to be full of joy and satisfaction and, on the rare occasions I have been called a boffin, my chest has always swelled with pride, satisfaction and gratitude.

The IOP campaign to "Bin the boffin" is in danger of destroying our heritage, history and culture. As an established, fulfilled, happy boffin, I suggest a laser beam projected on the front of IOP headquarters, perhaps carrying a rolling promotion of some fascinating books on our wonderful subject. A good inclusion would be the inspirational story of the early days of radar, radio astronomy and quantum optics as set out by R Hanbury Brown in his aptly titled book *Boffin*.

**Peter Wright**
London, UK

**James Pritchard, senior communications manager at the IOP, replies:**
The IOP launched the "Bin the boffin" campaign because we believe the media should call time on the tired and clichéd habit of calling any scientist, expert or pundit a "boffin". Young people in particular said it put them off science and many thought the word referred only to male scientists.

Many journalists agree – the *Daily Mirror* has already confirmed it won't be using the word – and we are continuing to engage with other titles to ensure their style guides use more accurate and inclusive language and images when writing about physicists. Rachel Youngman, the IOP's deputy chief executive, will be writing in a forthcoming issue of *Physics World* about the IOP's campaigns and why we've been proactively seeking to engage on the issues the physics community cares about.

## Thinking by numbers

In reply to the Critical Point article by Robert P Crease about the new *Nuclear Now* documentary movie by Oliver Stone (August pp17–18).

Crease mentions the public's fear of radiation and the way that anti-nuclear propaganda promotes the notion that low levels of radiation are dangerous. As well as the obvious factors that reinforce this idea, a major sticking point is the tendency of people to think qualitatively rather than quantitatively. Sadly, this is even true of philosophers of science, as evidenced by the many works in the field that lack a single mathematical equation.

I was once involved in a discussion about nuclear power at a Café Scientifique when someone in the audience proclaimed: "I don't care how low radiation levels are, it's still dangerous." Yet radiation of some sort is all around us – in fact, physicists doing sensitive low-background experiments have to hide in underground labs to get away from the radiation we all experience in everyday life.

In a world where we're encouraged to think qualitatively, engaging with the quantitative does not come naturally. That's true even at a time like now when it is so important to be able to compare the various threats we face. Encouraging more students to do lab work would surely help.

**Jim Grozier**
Brighton, UK

## Think how to think

In reply to the Critical Point by Robert P Crease about how to write fitting memorials for scientists who have died (September p20).

Crease's welcome piece on memorializing scientists rather assumes that we all know "how to think like a scientist" (to borrow the title of the opinion piece by James Kakalios on the facing page). But do we? All scientists recognize the excitement of science, but this is not what the textbooks usually tell us. And non-scientists rarely (in my experience) know that imagination is crucial to doing science at all well.

Science magazines should encourage the scientific community into a more realistic and helpful view of what the scientific method actually is. Given that both incompleteness and fallibility are guaranteed, why should we attend to scientists? I think that scientists really do know "how to think like a scientist" but only in the sense that cyclists "know" how to cycle. The knowledge is tacit and is no good for challenging the science sceptics, for which other methods are needed.

**Chris Jeynes**
University of Surrey, UK

● Robert P Crease's latest IOP Publishing book *Philosophy of Physics: a New Introduction* discusses many aspects of how scientists think (tinyurl.com/bdh4pp52).

## Ballet pioneer

In reply to the careers article about the quantum physicist and ballet dancer Merritt Moore (June pp58–61).

While it was heartwarming to read the remarkable story of physicist and ballet dancer Merritt Moore, it isn't strictly correct to say her career path is "unique". Another person who has a foot in both camps is Robin Canup, assistant vice president at the Southwest Research Institute in the US. A leading researcher in hydrodynamical simulations of lunar-forming impacts, she was previously principal ballerina at Boulder Ballet in Colorado, US.

**Jane Clark**
Risca, Newport, Wales

## Blow your trombone

In reply to the Lateral Thoughts by cartoonist Eugenia Viti and her physicist brother Ivan Viti, which asked for other examples of limits approaching infinity in our day-to-day life (August p48).

Surely, a trumpet in which the number of valves approaches infinity is a trombone? That's not a sentence I ever expected to type.

**David Simpson**
Medway Hospital, UK


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# What's the matter with condensed matter?

From the macroscopic to the microscopic physical properties of the world around us, condensed-matter and materials-science research have a huge impact on daily life. And yet, as **James Kakalios** highlights, the field remains on the periphery of popular-physics outreach – especially compared to astronomy and big science

**James Kakalios** is the Taylor Distinguished Professor in the School of Physics and Astronomy at the University of Minnesota and the author of several popular science books, including *The Physics of Everyday Things*

In 2022 we celebrated the 75th anniversary of the development of the first transistor and today it is estimated that there are more than three billion trillion of these devices in use around the world. Without the semiconductor transistor, there would be no mobile phones (smart or otherwise) and no personal computers either. Indeed, most of the devices you'd find in a doctor's office or hospital (just think of the data processing necessary to generate an MRI image) wouldn't exist, and you'd be hard-pressed to get your car to start each morning.

Solid-state and semiconductor physics, it's fair to say, have transformed the world we live in. Promising research in quantum computation and graphene-based devices suggests that solid-state physics will continue to have a large impact on our daily life. That's why it's surprising, to me at least, that there is so little public engagement and outreach centred on condensed-matter physics.

Visit the science section devoted to physics in any bookstore and you'll find the shelves groaning under the weight of books on a variety of topics in astronomy and cosmology – everything from string theory and dark matter to black holes and gravitational waves – as well as books on particle physics and quantum mechanics. But there are significantly fewer popular-science books describing solid-state and materials-science research.

Let me be clear: I am not saying that there shouldn't be popular science books, news articles and television programmes devoted to astronomy or particle physics. The accomplishments of the Large Hadron Collider (LHC), Laser Interferometer Gravitational-Wave Observatory (LIGO) and the James Webb Space Telescope (JWST), to name just a few, are truly inspiring and should be widely shared with the general public. These projects and similar ones deserve all the attention from the press and the Nobel prize committee that they have received.

What I am suggesting, however, is that there may be a risk for these fields, and physics in general, if these are the only physics-research updates and results that the public encounters.

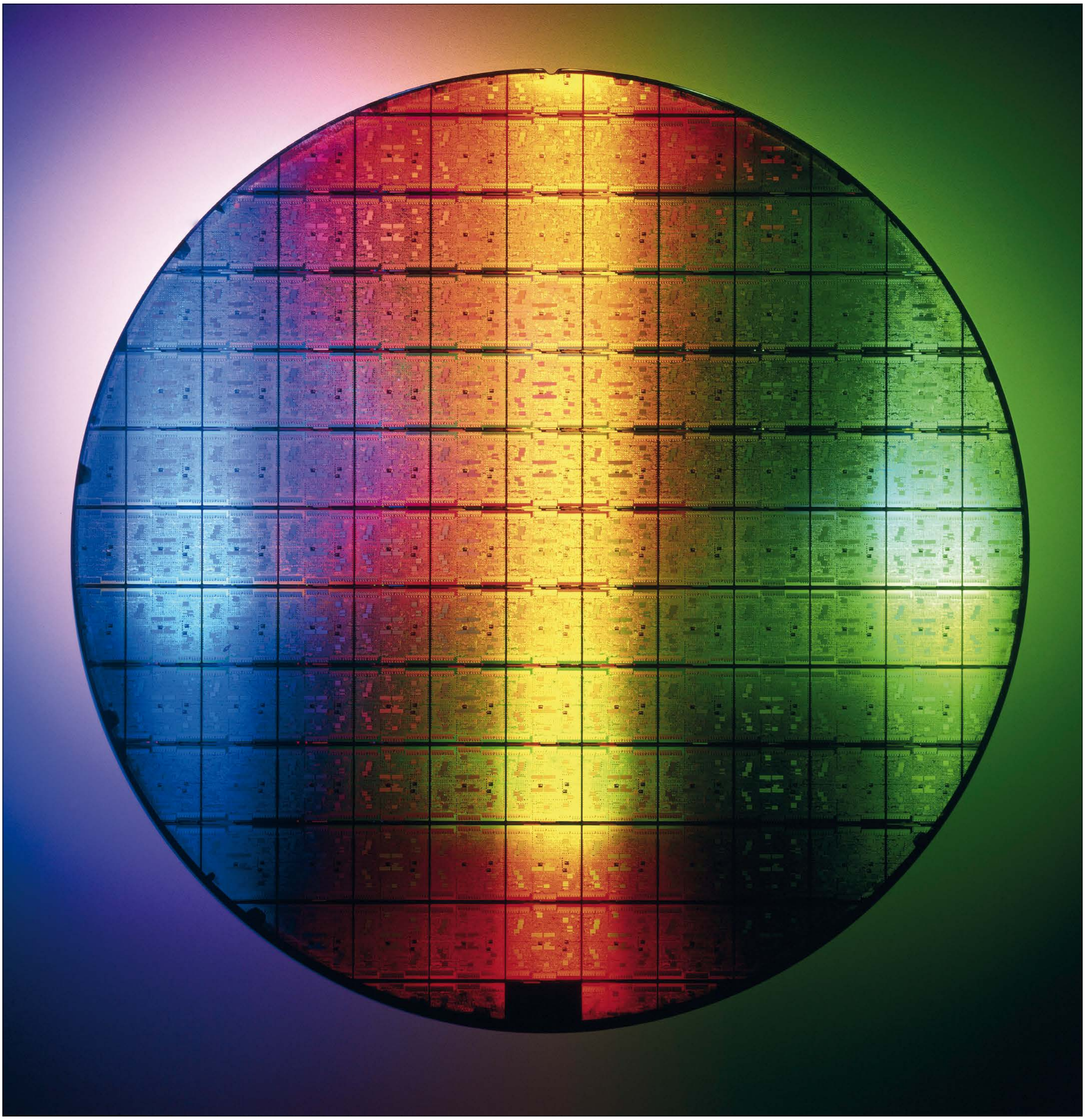
> Between the Higgs boson and the Big Bang, between the subatomic and astrophysical scales, lies another regime – the human scale – where all of us, and in particular the taxpayers who help fund our research, reside

### Public POV

Just under a decade ago, a number of focus groups and surveys of the public's attitudes towards science were commissioned by ScienceCounts, a not-for-profit outfit supported by the American Physical Society (APS), the American Association for the Advancement of Science (AAAS) and many other science organizations. The good news: people had a high regard for science in general, and scientists in particular. The bad news: only 25% of those surveyed believed that government funding of science research was necessary.

The alarming aspect of this study is that many people could not readily cite any personal benefit from government-funded scientific research. If the public and their elected representatives do not see how scientific research benefits their daily lives, then we risk the public deciding that the appropriate science funding level should be comparable to public arts funding.

The elucidation and comprehension of the laws of nature that govern the universe, and account for how it originated and continues to evolve, is truly one of the greatest accomplishments of humankind. Similarly, the identification of the quantum of excitation of the Higgs' field and the development and confirmation of the Standard Model of particle physics is a monumental advance in our understanding of the world. But between the Higgs boson and the Big Bang, between the subatomic and astrophysical scales, lies another regime – the human scale – where all of us, and in particular the taxpayers who help fund our research, reside.



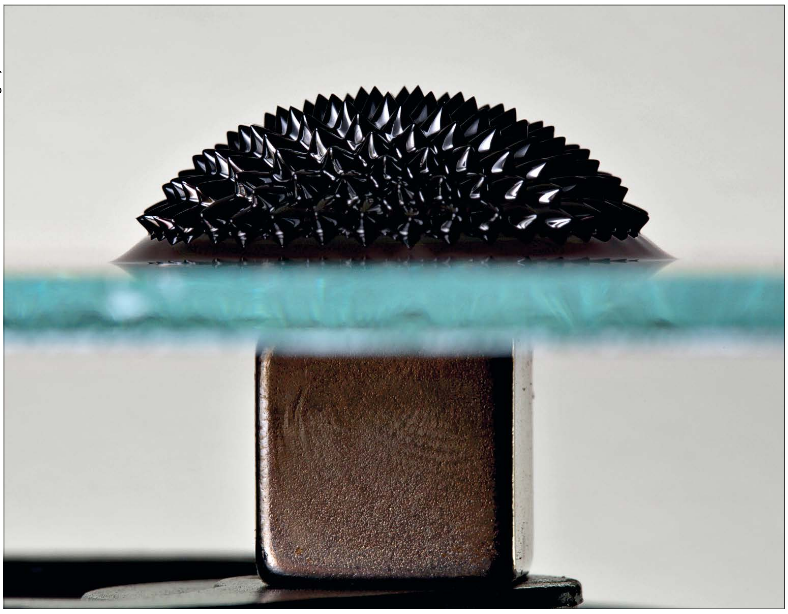
Alfred Pasieka/Science Photo Library

**Condensed matter everywhere** Semiconductor wafers are divided up into blocks to make the integrated circuits, or chips, used in electronic devices. Hundreds of thousands of transistors can be fitted on a single chip and connected by conducting pathways.

To be sure, research in particle physics and astrophysics has led to substantial technological applications – from the development of the World Wide Web and medical imaging to GPS navigation and satellite communications. These have had a great impact on society, but the applications were not the goals of this research. The main goal of condensed-matter research, on the other hand, is to understand the fundamental principles underlying the properties and behaviours of materials, so that these properties may be controlled and manipulated for desired ends.

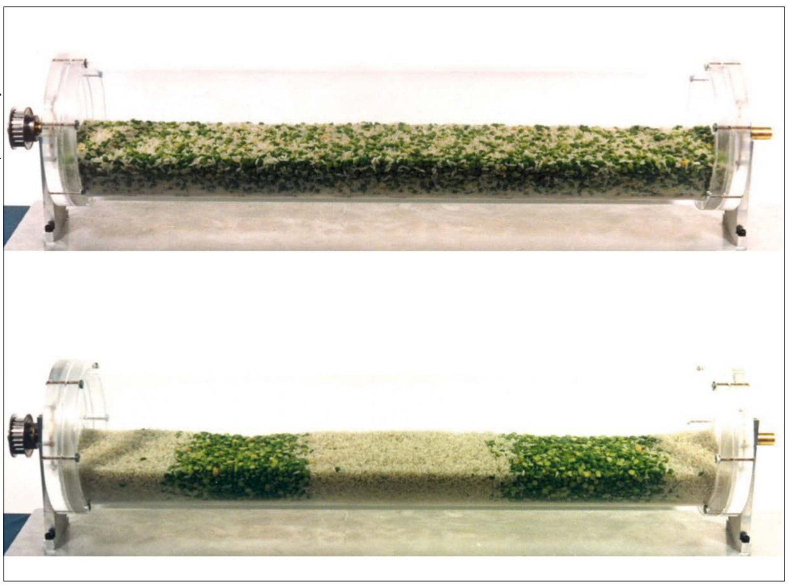
A central motivation behind the study of thermoelectric materials – solid-state semiconductors that transform heat into electric power or produce cold from an applied voltage – for example, is to be able to fabricate devices with improved efficiency and practical use. Similarly, there is much interest in rare-earth magnets, which could improve the effectiveness of wind turbines (used as permanent magnet-generator systems) and jet engines. Many laboratories, using different approaches, are working to develop a quantum computer but all of them employ solid-state devices as the basis of their qubits.

The success of condensed-matter physics teaches us that to understand the world around us we cannot rely solely on the techniques of particle physics or astrophysics. As Nobel-prize-winning physicist Philip Anderson explained in his excellent 1972 essay “More is different” (*Science* **177** 393), simply knowing the properties and interactions of fundamental particles (and even, I would add, the mechanisms by which stars, planets and galaxies



**Energetic applications** Ferrofluid on a reflective glass plate, with a rare-earth magnet underneath. Rare-earth magnets could improve the effectiveness of wind turbines and jet engines.

James Kakalios/University of Minnesota



**Grains of truth** Axial segregation demonstrated with a 50/50 mixture of uncooked rice and split peas. Studies of granular media are not merely academic, as the storage and transport of powders and grains is fundamental to the pharmaceutical, construction and agricultural industries. (Reproduced from *American Journal of Physics* **73** 8, with the permission of the American Association of Physics Teachers)

form and evolve) is insufficient to understanding physics on the human scale. As Anderson put it, "there are more levels of organization between human ethology [the study of behaviour and social organization] and DNA than there are between DNA and quantum electrodynamics, and each level can require a whole new conceptual structure."

### Attention-grabbing science

In the early part of the 20th century, the development of quantum mechanics meant that we could get a better understanding of the electronic properties of solids – whether they are metals, insulators or semiconductors. The macroscopic properties of solid-state systems could be understood through the behaviour of individual electrons, yielding transformative devices such as the transistor and the light-emitting diode.

By the second half of the last century, phenomena such as magnetism and superconductivity were recognized as manifestations of emergent collective behaviours, arising from interactions between electrons. The role of interactions is central to understanding these so-called "quantum materials", perfectly illustrating Anderson's thesis. Nothing in the Standard Model can account for superconductivity or magnetism, nor how these two phenomena can coexist in iron pnictides materials.

Similarly, interactions between individual particles can yield fascinating phenomena in soft-condensed-matter systems such as sandpiles (*Am J. Phys*. **73** 8). Here, the only relevant forces are gravity and friction, yet granular media can exhibit properties that appear counterintuitive. For example, while most materials become denser under pressure, sand can become less dense, which is why your footprints on wet sand will appear dry.

Another interesting phenomenon is that when a mixture of large and small sand particles is rotated about the long axis of a horizontal cylinder, the mixture will segregate into alternating bands of large and small sand particles like rings on a finger – a phenomenon termed "axial segregation". The width of each band is much larger than the diameter of each sand grain and is a striking illustration of how local interactions can give rise to macroscopic ordering.

I feel that my father (who was a taxi driver) would have been interested to learn that the same physics that governs axial segregation also accounts for the spontaneous formation of traffic jams, as a fundamental instability of highway flow. Studies of granular media are not merely academic, as the storage and transport of powders and grains is fundamental to the pharmaceutical, construction and agricultural industries.

I concede that in capturing the public's attention, astrophysics and particle physics have an important competitive advantage – the tools and fruits of their research generate striking visual images that readily spark one's interest. Personally, I never tire of viewing photos from the Hubble, James Webb or other space-based telescopes. Images of the detectors at the LHC are similarly remarkable – in particular because they demonstrate that humanity is able to build machines of such scale and complexity, and moreover that these machines work.

Back in early July someone on Twitter (now referred to as X) posted an image of the Cathedral of Santa Maria del Fiore cathedral in Florence, Italy, and asked whether "humanity would ever produce something like this again?" I assumed that by "something" the poster meant "of similar scale and grandeur". Consequently, I replied: "Good news – we have!" and embedded an image of the ATLAS detector at the LHC. But when it comes to condensed-matter physics, however, an image of a microcomputer – which to a large extent enables the research advances in astrophysics and high energy physics – would be a picture of a literal black box.

### Materials matter

So what advice would I give to my colleagues in condensed-matter and materials-science research who wish

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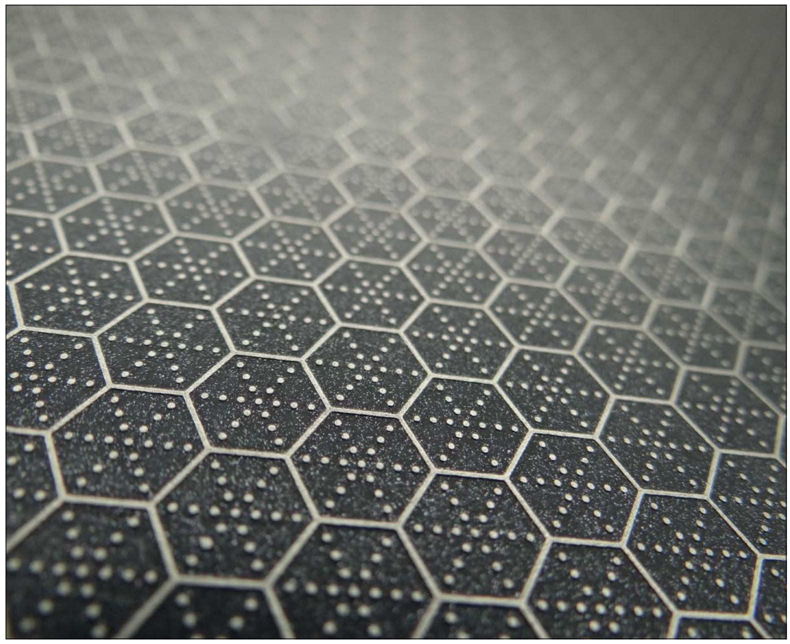

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**Similar but different** The molecules $CH_4$ and $CF_4$ are structurally and electronically similar, but when linked into long-chain polymers the former yields petroleum (left) while the latter produces Teflon (right) – both useful materials, for very different reasons.

to engage the public with our field? One advantage we have is that the results of our research are readily apparent to the public. From the moment we awake to the close of the day, people around the world are surrounded by the materials and products of our research.

This point is ably exploited by Mark Miodownik, a professor of materials and society at University College London in his 2014 popular science book *Stuff Matters: Exploring the Marvellous Materials that Shape our Man-Made World*. The prize-winning book is one of the few popular-science books that highlights materials research, and was *Physics World*'s 2014 Book of the Year. In it, Miodownik uses the framing device of a photograph of himself siting at a table on his rooftop, drinking a cup of tea. Each chapter then discusses the history and science behind a material present in this photo – steel, glass, porcelain, paper and plastic.

In his 2019 follow-up popular science book, *Liquid: the Delightful and Dangerous Substances that Flow Through our Lives*, Miodownik describes the fascinating science of fluids. This time, each chapter focuses on a liquid he encounters while on a transatlantic flight from the UK to the US – from the contents of the drinks cart to the jet fuel, from liquid soap in the toilets to the ink in ballpoint pens.

Other books – including physicists Sidney Perkowitz's *Universal Foam: From Cappuccino to the Cosmos* and Diandra Leslie-Pelecky's *The Physics of NASCAR: How to Make Steel + Gas + Rubber = Speed*; as well as websites such as Nanoscale Views and FunSize Physics – also bring home the implicit message that we are surrounded by materials physics. Whether the interacting elements are electrons, macroscopic grains of sand or mesoscopic structures – the molecules $CH_4$ and $CF_4$ are structurally and electronically similar, but when linked into long-chain polymers the former yields petroleum while the latter produces Teflon (*MRS Bulletin* **37** 1079) – Anderson's argument that "more is different" holds.

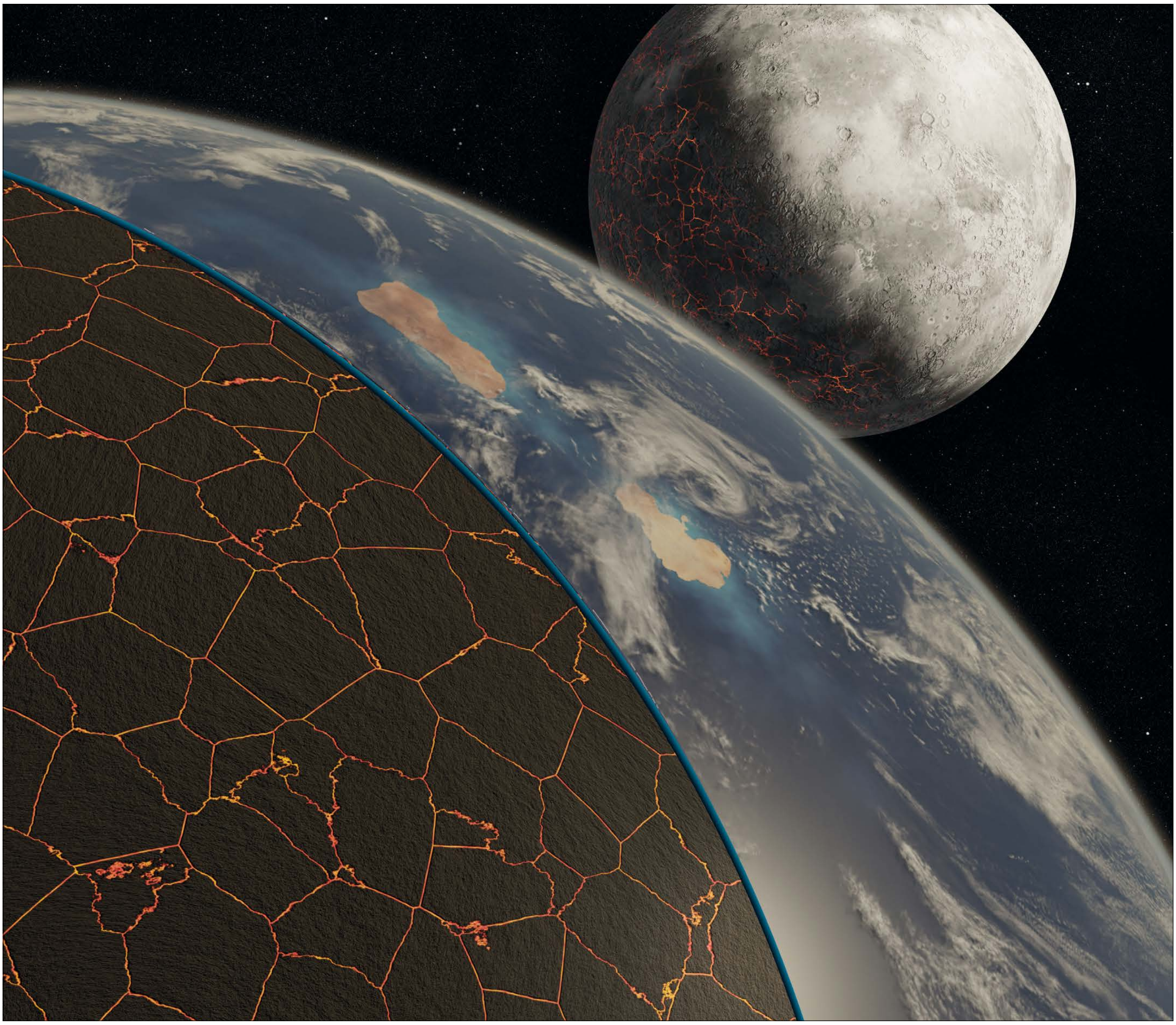
### Universal and relatable

Concepts from condensed-matter physics have been applied to situations that nearly anyone can relate to. A recent paper by Pablo Gottheil of Leipzig University and colleagues connects the physics of jamming of granular systems to the conditions under which cancer cells can metastasize and move away from their tumour of origin to other parts of the body (*Phys. Rev. X* **13** 031003). While one must, of course, avoid over-promising, one can legitimately argue that fundamental research in disordered materials can be both inspiring and practical.

The very nature of big-science projects such as the LHC, LIGO and the JWST requires many scientists and engineers working together to address particular research goals – be it observing the Higgs boson or determining whether gravitational waves exist. In contrast, advances in condensed-matter physics usually take place with many scientists working mostly independently on a broad range of research problems. Some of these studies require large facilities such as high-magnetic field labs or neutron scattering sources – but the collaborations in condensed-matter physics are orders of magnitude smaller than in particle physics. This enables a nimbleness and flexibility that our field has exploited to great benefit.

Ultimately, as scientists, we study the subjects we do because they interest us – we should share that interest with others. Science communication need not involve the very latest research advances. For example, whenever I give a public lecture, I try to find a reason to show scanning tunnelling micrographs (STM), as most of the audience is unaware that we can routinely image surfaces with atomic-level resolution. I then point out that the same physics underlying an STM also operates in the tunnelling diodes and other devices found in their smart phones and computers.

As the television networks used to say when promoting a series of reruns: if you haven't seen it before, it's new to you. To my fellow condensed-matter and materials science colleagues, I encourage each of you to share your research far and wide, and engage with the public as often as you can. As the transistor demonstrates, little things can have a big impact on all of our lives.



University of Rochester/illustration by Michael Osadciw

# A tectonic shift for life?

Magnetic data locked in ancient crystals suggest that life may have emerged long before the Earth's tectonic plates started moving. If the finding holds true, it would overturn the conventional notion that tectonic shifts were a pre-requisite for life, as **James Dacey** explains

The ground beneath our feet may appear solid and stationary. But throughout Earth's history, the relatively thin veneer covering our planet has been repeatedly squeezed, cracked and resculpted by tectonic forces. Plate tectonics can move continents, build mountain ranges, and trigger earthquakes and volcanoes when pent up energy is suddenly released.

But while tectonics can destroy life indiscriminately at a local level, it is also vital for sustaining habitable conditions across the Earth's surface. That's because carbon-rich materials are recycled back into the Earth's interior at "subduction zones" – regions where one plate is thrust under another – in a process that helps to regulate the carbon cycle. Meanwhile, water vapour and gases released through volcanic activity help to stabilize the Earth's climate and atmospheric conditions.

We only need to look at the noxious atmosphere of Venus – with its dense carbon dioxide and sulphuric acid clouds – to see what can happen on a rocky planet without plate tectonics. That's why many geoscientists therefore

**James Dacey** is a multimedia journalist based in Madrid

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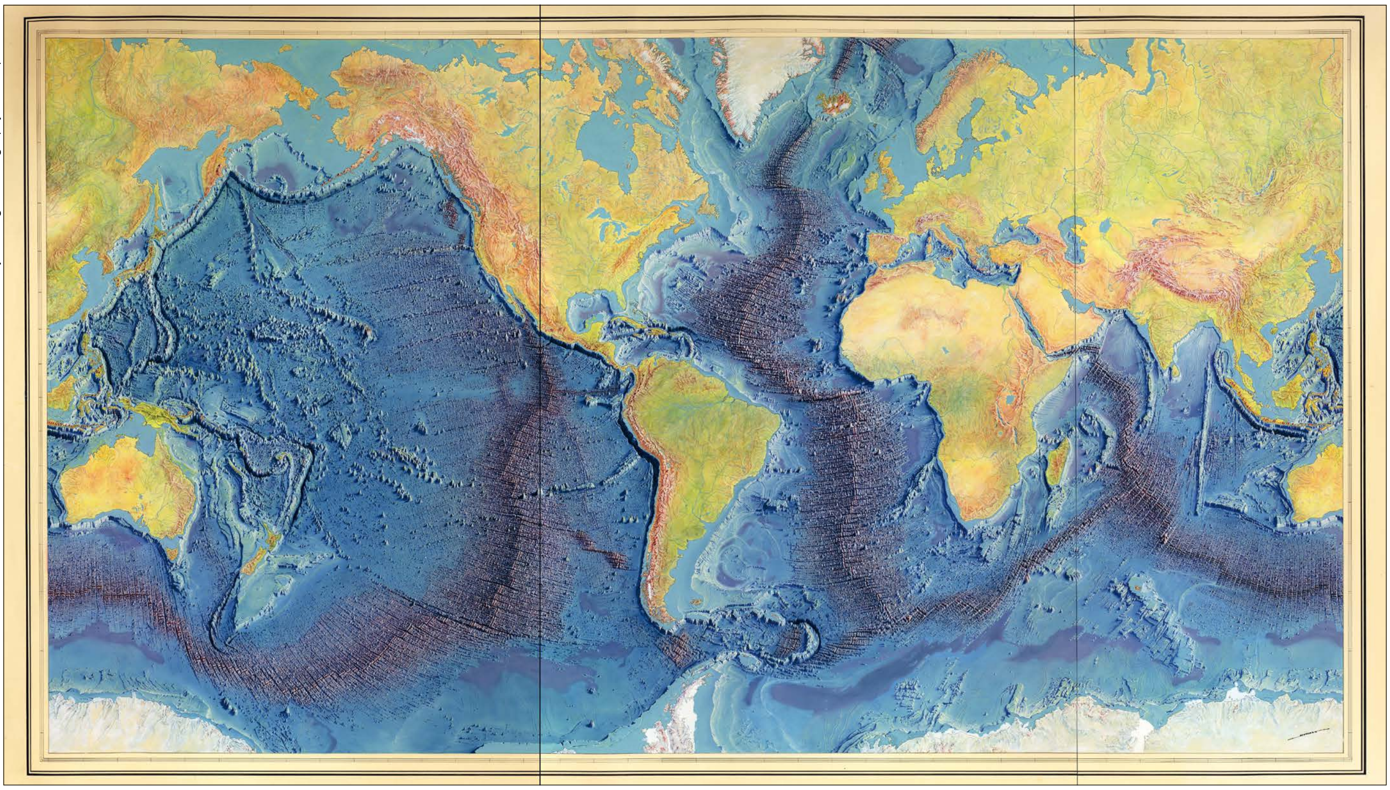


**Rifts and ridges**
The world ocean floor map created by Marie Tharp and Bruce Heezen in expeditions sponsored by the Lamont-Doherty Geological Observatory, hand-painted by Heinrich C Berann and published in 1977.

assumed that plate tectonics must have existed by the time life emerged, during the first billion years of Earth history. Plate tectonics, in essence, was considered a key pre-requisite for life.

But new findings by an international research team indicate that life could have preceded plate tectonics – and that life could have come first by some margin. If the work holds true, our young planet may have experienced a prolonged period without moveable plates, under a more rudimentary form of tectonics known as a "stagnant lid". Such a scenario, if confirmed, would transform our understanding of how life emerges and survives – and potentially help in the search for life beyond our planet.

## On shaky ground

The notion of plate tectonics may be widely accepted today, but it was controversial for many years. The story began in 1912 when the German scientist Alfred Wegener proposed the idea of "continental drift". He suggested that today's continents were once part of a much larger supercontinent but later drifted to their current positions on the Earth's surface. In his book *The Origin of Continents and Oceans*, Wegener famously noted how the coastlines of South America and Africa fit together like a jigsaw and described how similar fossils crop up in entirely different parts of the world.

Wegener's idea was initially met with scepticism, mainly because researchers were unsure what might have made the plates move. An answer began to emerge in the mid-20th century when a map produced in 1953 by the US geologist and cartographer Marie Tharp revealed the existence of a mid-ocean ridge spanning the entire Atlantic Ocean and running parallel to continental coastlines. Featuring a huge valley in its centre, Tharp argued this indicated that the ocean floor was expanding.

A full theory for sea-floor spreading was subsequently proposed by US geologist Harry Hess in 1962. He suggested that oceanic crust is being continuously formed at mid-ocean ridges, where molten material from the Earth's interior wells up to the surface as part of a convection cell, before it solidifies into new ocean floor. This fresh crust is then shunted horizontally in both directions by subsequent upwelling magma.

Meanwhile, where oceanic plates border continents, older sections of oceanic crust are thrust underneath the less-dense continental crust at oceanic trenches, and recycled back into the Earth's interior. In fact, the sinking tip of the plate also contributes to sea-floor spreading by dragging the rest of the plate behind while it plummets into the abyss.

Evidence for sea-floor spreading arrived in 1963 when British geologists Frederick Vine and Drummond Matthews looked at measurements of the Earth's magnetic field taken by a research ship travelling across a ridge in the Indian Ocean. They noticed the field was not uniform, but had anomalies that ran in stripes parallel to the ridge – and virtually symmetrically on either side of it – spanning the ocean floor. They said the stripes arise because magnetic minerals within the newly forming sea floor tend to align with the Earth's magnetic field while the rock is solidifying. New stripes are formed each time the Earth's magnetic field flips – a phenomenon that has occurred many times during the Earth history when the north pole suddenly becomes the south pole.

To use an analogy, the moving sea floor is rather like an old-fashioned cassette tape, recording each reversal of the geomagnetic field. Each reversal can be dated via fossil studies and radiometric testing of basalts drilled from the ocean floor, to chart a history of the magnetic field. These days, the existence of plate tectonics is now almost universally accepted.

But there is much less agreement over when plate tectonics first began. Part of the issue is that the Earth formed roughly 4.54 billion years ago and today virtually all oceanic crust older than 200 million years has been recycled back into the Earth. Our long-term archive of Earth history is, in other words, contained within hidden rock formations in the continents.

But even there, the few accessible rocks that do remain from the first billion years have been significantly altered by heat, chemistry, physical weathering and extreme pressures. That's why no-one's sure when plate tectonics started, with estimates ranging from more than 4 billion years ago to just 700 million years ago. It's a huge and unsatisfactory uncertainty.

What's more curious is that the earliest undisputed fossil evidence of life dates back 3.5–3.4 billion years, with signatures of life in sedimentary rocks indicating that life may have existed 3.95 billion years ago. So could life have emerged hundreds of millions of years before plate tectonics was even a thing? With so few original rocks surviving from this period, geologists are often stranded in the realms of speculation.

## Zircons: time capsules from Earth's fiery beginnings

Fortunately, geoscientists have a secret weapon to obtain snapshots of conditions on early Earth. Say hello to zircons – chemically stable mineral fragments ($ZrSiO_4$) that are found in a variety of colours and geological settings. The beauty of zircons for geoscientists is that they remain largely unaffected by changes in their host rock. They're like a time capsule of that long-distant period.

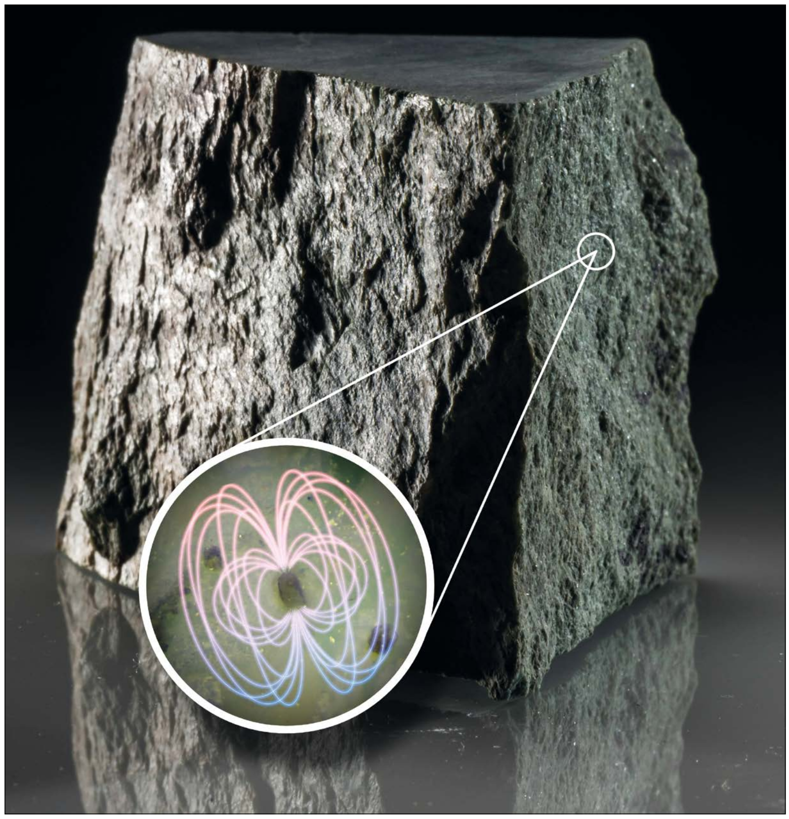
In particular, scientists have recently been studying ancient zircons that crystallized within granite rocks formed during the Earth's first 600 million years. During this period, known as the Hadean eon, our planet was a hellish place, likely shrouded in an atmosphere rich in carbon dioxide and frequently bombarded by extraterrestrial bodies. One of them probably created the Moon.

Despite the lack of a crust, however, it appears that solid rocks must have been forming because a limited number survive today. Intact rocks as old as 4 billion years exist in the Acasta Gneiss Complex of north-west Canada, and the oldest known materials of Earth origin are 4.4 billion-year-old zircon crystals found in the Jack Hills in Australia (*Nature Geoscience* **10** 457). They are housed in much newer, "meta-sedimentary" rocks.

In this new research (*Nature* **618** 531), researchers studied Jack Hills zircons spanning the period 3.9–3.3 billion years ago, as well as zircons from the same period found in the Barberton Greenstone Belt of South Africa. Led by John Tarduno from the University of Rochester in the US, the researchers were initially interested in what the zircons might reveal about the state of the Earth's magnetic field during that period. It was only later that they realized their findings had far broader implications.

Zircon crystals from both the Australian and South African sites were found to contain inclusions of an iron-rich mineral called magnetite, which were magnetized by the Earth's field at the time they formed. Even though billions of years have since passed, this information about Earth's ancient magnetic field has remained locked in the zircon crystals all this time. In fact, because the Earth's magnetic field is a dipole – with a field strength varying with latitude – measuring the strength of remnant magnetization among zircon's magnetite content can reveal the latitude at which it formed.

The next challenge was to date the zircon samples.



University of Rochester / photo by J Adam Fenster / illustration by Michael Osadciw

**Time crystals** Researchers from the University of Rochester in the US have used zircons collected from sandstone samples collected in Australia and South Africa (pictured) to show that the magnetization strength on Earth remained nearly constant between 3.9 and 3.4 billion years ago. As the strength of the Earth's field varies with latitude, both sets of zircon crystals must therefore have formed at unchanging latitudes. Plate tectonics, in other words, had not yet started – even though life already existed, challenging conventional wisdom.

Conveniently, the crystal structure of zircon also incorporates uranium, which gradually decays into lead at a known rate. The researchers could therefore work out the age of the zircon crystal from the ratio of uranium to lead, which Tarduno's team measured using a selective high-resolution ion microprobe, or SHRIMP.

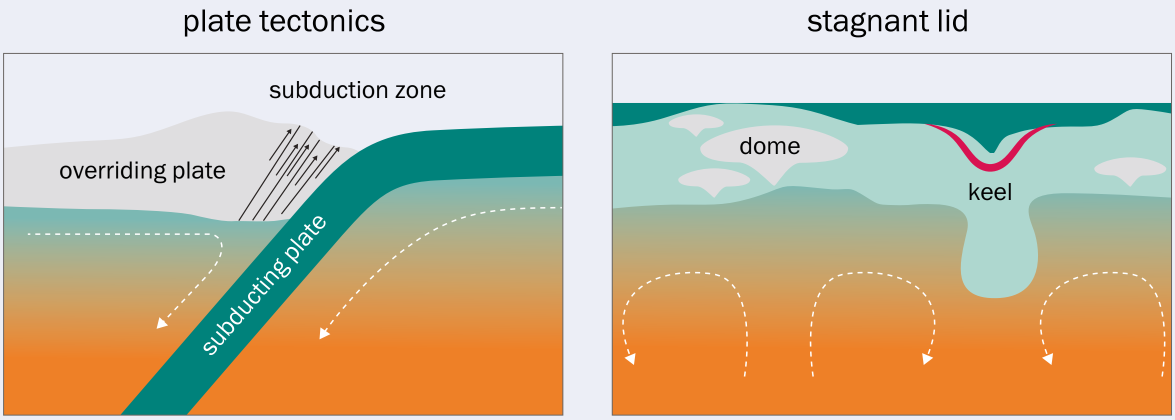
If plate tectonics had existed during the 600 million years covered in this study, then you'd expect the zircon crystals to have formed at a variety of latitudes as the plates move around. That in turn would mean that zircon crystals would have a range of magnetization strengths depending on how old they are. To their surprise, however, Tarduno and team discovered something very different.

At both the Australian and South African sites, the magnetization strength remained nearly constant between 3.9 and 3.4 billion years ago. This suggests that both sets of zircons were forming at unchanging latitudes. In other words, plate tectonics had not yet started. Part of the reason for this conclusion, explain the researchers, is that, on average, plates during the last 600 million years have moved at least 8500 km in latitude. And during this recent period, there has never been an example of two plates remaining at constant latitude simultaneously.

In other words, plate tectonics had not yet started. The researchers conclude that the Earth likely had a more rudimentary variety of tectonics, which still included some chemical recycling and fracturing of solid rock at

This simmering, stagnant form of tectonics may have created a "Goldilocks situation" that would have been just right for primordial life, free from the dramatic shifts in environmental conditions that can occur in fully fledged plate tectonics

**1 Shift of focus**




The movement of tectonic plates is vital for sustaining habitable conditions across the Earth's surface because it recycles carbon-rich materials back into the Earth's interior at "subduction zones", where one "subducting" plate is thrust under an "over-riding" plate. However, life could have preceded plate tectonics, although there may instead have been a more rudimentary form of tectonics known as a "stagnant lid", in which plumes of material emerged from the deep to form granite domes, which sat alongside "keels" formed by sinking denser volcanic rock.

the Earth's surface.

The crucial difference between today's plate tectonics and this "stagnant lid" form of tectonics is that the latter does not include plates moving horizontally across the surface, which allows for heat to be efficiently released. Instead, Earth would have been a festering world with no continental crust, populated by isolated regions of thick oceanic crust separated by areas of upwelling magma (figure 1). "Maybe stagnant lid is an unfortunate name as people might think that nothing is going on," says Tarduno. "But what you do have is plumes of material coming up that can heat the bottom of this primordial crust and lithosphere."

Towards the end of the study period (3.4–3.3 billion years ago), the magnetization observed in the zircon crystals starts to strengthen, which Tarduno suggests could indicate the onset of plate tectonics. The reason is that huge slabs of crust descending into Earth's interior at subduction zones result in the mantle cooling quicker. In turn, this process can strengthen the efficiency of convection in the outer core – resulting in a stronger geomagnetic field.

### A 'Goldilocks situation' for early life?

If basic life were already present nearly half a billion years before tectonics, as implied by this study, it raises interesting questions about how life might survive in a plate-tectonic-less world. A weaker magnetic field from this stagnant-lid phase would have left the Earth's surface more exposed to cosmic radiation, which our current strong field shields us from. Energetic protons in the solar wind would then have collided with atmospheric particles, charging and energizing them so that they can escape into space – in principle, stripping an entire planet of its water.

But Tarduno says that even the relatively weak magnetic field strength observed in this new study would have provided some shielding. In fact, he suggests this simmering, stagnant form of tectonics may have created a "Goldilocks situation" that would have been just right for primordial life, free from the dramatic shifts in environmental conditions that can occur in fully fledged plate tectonics.

It's a tantalizing idea because stagnant lid forms of tectonics are thought to be common throughout our solar system, existing on Venus, Mercury and in a less dynamic form on Mars.

To develop the research, Tarduno's team now plans to study zircons of similar ages from other locations, to give a wider range of data points. "Our approach is different from previous work because we have an indicator of motion," he says. "All arguments about plate tectonics from this time in Earth history have been based on geochemistry – not on the principal indicator of what plate tectonics is."

Peter Cawood, an earth scientist at Monash University in Australia, who was not involved in this *Nature* study, says that further understanding of early Earth may come from places in our solar system whose surfaces have not been repeatedly recycled by plate tectonics. "Mars, the Moon and meteorites provide a more extensive record of their early history," he says. "Samples from these bodies, and in particular the potential for sample-return missions from Mars, may provide important new insights into processes that acted on the early Earth."

Giant leaps on that front may occur via the Mars Sample Return Mission, scheduled to launch in 2027. But Cawood reckons that perhaps a more critical question for the development of initial life is when exactly water – a prerequisite for life – first appeared on Earth. "Previous work on the Jack Hills zircons, using oxygen isotopes, suggests that there has been water since at least 4400 million years ago," he says.

For Cawood, this research could potentially help with the search for life within our solar system and beyond – and even our concept of what life looks like. "If life on Earth developed during this stagnant lid phase, then perhaps this also occurred on Mars. If Earth had remained in a stagnant lid phase and life had continued to evolve it would certainly look different from the biosphere we have today. So, to paraphrase Spock speaking to Kirk – 'it's life Jim, but not as we know it'."

# Beyond the bomb

**Andrew Glester** reviews the film *Oppenheimer*, written and directed by Christopher Nolan

**Oppenheimer**
*dir. Christopher Nolan*
2023 Universal Pictures

When Christopher Nolan (*Interstellar*, *Memento*, *TENET*) makes a film about J Robert Oppenheimer, the father of the atomic bomb, you expect it to be spectacular. With a runtime of three hours, the simply titled *Oppenheimer* is expansive in every aspect. Indeed, new film stock had to be made to shoot the black-and-white sequences for gigantic IMAX screens.

From sequences that visualize quantum physics to those depicting the titular character's mental state soon after the devastating explosions of atomic bombs – not to mention the actual Trinity test – the film is a visual masterpiece. But much of it is dialogue-based, with the drama coming from political machinations, in a world dealing with the fallout of the Second World War.

I first saw *Oppenheimer* in the IMAX at the Science Museum in London and then for a second time in a small, seaside cinema in Devon, UK. On an ordinary cinema screen, it is staggering. On an IMAX, it is visceral. This is no surprise as Nolan is an expert of IMAX and although this film, with its concentration on politics, is closer to *The West Wing* than *Interstellar*, in his hands, the immense format leads to total immersion in the world and its characters. Add an exceptional performance by Cillian Murphy in the role of Oppenheimer and a typically Nolan time-bending narrative, and it is no wonder that audiences have flocked to IMAX screens to take it all in.

Nolan's films rarely follow a straight story arc. Narratively, there are two main strands: the early-career scientist Oppenheimer, and the embattled, politics-laden administrator of the 1950s. Between them is the story's fulcrum – the atomic bomb development in Los Alamos, New Mexico. In the former, Oppenheimer's focus, and that of the film, is physics. Patrick Blackett, Niels Bohr, Isidor Rabi and Werner Heisenberg all feature. Later, everything turns to politics, just as Oppenheimer's career did, as he sought to use his notoriety as the father of the atomic bomb to try to influence nuclear policy in the US.

This political strand centres around trial-like proceedings that were held when Lewis Strauss (played by Robert Downey Jr, another formidable performance), chair of the Atomic Energy Commission, sought to remove Oppenheimer's security clearance in 1954. Unusually, the whole film script – which includes not just the dialogue but also the stage directions, actions, expressions and so on – was written in the first person to aid those reading it to feel the intense focus of the film on Oppenheimer the man. Apart from Oppenheimer and Strauss, other key physicists such as Ernest Lawrence (Josh Hartnett), Edward Teller (Benny Safdie) and Hans Bethe (Gustaf Skarsgård) play key roles.

The film also focuses on key figures from Oppenheimer's personal life, including his long-time partner Jean Tatlock (Florence Pugh) and his wife Kitty (Emily Blunt). The latter was a fascinating character, and Blunt does a wonderful job in portraying this complex woman. A scientist herself, Kitty was a trained biologist and chemist and prior to meeting Oppenheimer, she worked at the Caltech X-ray lab, with physicist Charles Lauritsen, on experimental cancer therapy. Later, at Los Alamos, Kitty worked in the health group, conducting blood tests to assess the danger of radiation. None of this is included in the film, which instead only focuses on the pair's passionate and often tumultuous relationship. In a film with so few female scientists represented, this seems to be an unfortunate omission.

Nolan uses a mixture of colour and black-and-white film to illustrate the two perspectives. The subjective, where we are seeing the world from Oppenheimer's perspective, is in colour. The objective, largely in terms of how he is seen by Strauss, is in black and white. As with *Interstellar*, physics and storytelling collide and use one another in key aspects of the narrative.

The film begins by immersing the audience deeply in the most significant fundamental physics discoveries of the time – from nuclear and particle physics to quantum mechanics, which was a radical new way to consider the world around us. In a scene that Nolan has likened to Luke Skywalker meeting Obi Wan Kenobi in *Star Wars*, a young Oppenheimer meets the celebrated Bohr. In a later period, an older Oppenheimer meets his acquaintance Albert Einstein at the Institute for Advanced Study in Princeton, when the former moved there to serve as director from 1947 until 1966.

**Dramatic arc** Emily Blunt plays Kitty Oppenheimer in a role that reveals the complexity, but not the scientific work, of Robert Oppenheimer's wife.

Alongside these scenes, we are treated to visualizations of waveforms and particle behaviour, giving the audience a sense of what it might feel like to consider matter in this way. Visually, this metaphor continues throughout the film and, ultimately, to the destruction of that matter.

We never see the true devastation of the two atomic bombs dropped on the Japanese cities of Nagasaki and Hiroshima, but Nolan visualizes the horror through Oppenheimer's imagination in an aurally and visually hard-hitting thread that runs throughout the film. In one of the film's most jarring scenes, as the scientists and others at Los Alamos "celebrate" the dropping of atomic bombs (and thus the end of the Second World War with Japan's surrender), Oppenheimer envisions the horrifying impact of the bombs on people, all while giving a celebratory speech. This signifies his early misgivings despite his work on making the atomic bomb a reality.

Murphy's face – gaunt and haunted – fills the screen and his likeness to Oppenheimer is striking as we see him try to come to terms with what he must create (in the earlier timeline) and has successfully created (in the later). It is, however, impossible to know for sure what Oppenheimer truly felt about his role in the Manhattan Project. Asked by CBS in 1965 whether dropping the atomic bomb was necessary, he concluded "I have not a very good answer to this question." This uncertainty is core to the *Oppenheimer* script. The big questions of the film are left for the audience to decide. Nolan is not a didactic storyteller.

*Oppenheimer* does not end with the dropping of the bombs – in fact much of the weight of his story comes after the fact. In the 1950s the Republican senator Joseph McCarthy led a campaign against leftist members of the American community, with many of them losing their jobs under accusations of being members of the Communist Party. In many cases, they were not. This McCarthyism was meted upon Oppenheimer, and Nolan's film sees the politicians, especially Strauss, trying to bring him down.

One effect of the interwoven timelines is that we are confronted with people celebrating a man for his role in the mass killing of civilians and vilifying him for having left-wing sentiments. It's a rare moment where there are clear good guys and bad guys, but for the most part Nolan's characters are flawed and troubled.

In that courtroom-esque drama, the politicians are trying to remove Oppenheimer from their plans to build an even more monstrous weapon – the hydrogen bomb. Oppenheimer was aware that the Second World War was effectively over at the time the two atomic bombs were dropped on Japan – the Nazis had already surrendered and the Japanese were close to beaten.

After that, Oppenheimer was of the firm opinion that there was no justification, and no military target big enough, to justify the hydrogen bomb. His fear stemmed from the realization that humanity – or at least the politicians among us – would use any bomb they have built, no matter how big. Those politicians effectively use his left-leaning political views to remove him, and his objections, from the project.

The big questions of the film are left for the audience to decide. Nolan is not a didactic storyteller

The argument for nuclear weapons is that they form a deterrent. Whether the deterrent has worked or not is an open question. The people of Ukraine might have a different point of view from that of Vladimir Putin, for example. War certainly has not stopped. In an ideal world, these bombs would never have been made but, as the film makes clear, this is not realistic. The discovery of the immense power of the atom could not have been kept secret. That simply is not how science works. Whether there was ever a need to use it on people is quite another question.

One physics detail explored in the film is Teller's calculations that the detonation of the atomic bomb might set off a chain reaction that would ignite the entire Earth's atmosphere. Teller theorized that temperatures created by a nuclear fission bomb might be so extreme that they would fuse hydrogen atoms together, as in the heart of our Sun. If true, this might have caused a chain reaction that would engulf the planet, vaporize the oceans and extinguish all life. The scientists at Los Alamos knew that there was a negligible, but non-zero possibility the bomb would set alight the atmosphere in an uncontrollable runaway effect. They, and the politicians and generals in charge, still pressed the button.

"Are you saying there's a chance we destroy the world?" General Groves (Matt Damon) asks Oppenheimer. In creating this film, Christopher Nolan asks that question anew.

**Andrew Glester** hosts the *Physics World Stories* and *The Cosmic Shed* podcasts. He is also a lecturer in wildlife film and media, and science communication at the University of the West of England

## *Oppenheimer* the movie: *Physics World* writers give their verdict

### Matin Durrani: rating 4/5

Jo Hansford Photography

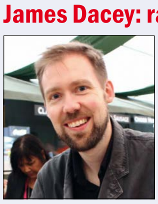
There have been some great science-based movies over the years. But there have also been some real stinkers. Thankfully, *Oppenheimer* falls into the former camp. I was relieved to find it is largely historically accurate and although a few factual distortions creep in, they aren't huge. The moral quandaries faced by Robert Oppenheimer and the other physicists on the Manhattan project are handled well – this is no glorification of the bomb.

The movie also does a great job at presenting the tensions surrounding the removal of Oppenheimer's security clearance after the Second World War and the subsequent downfall of Lewis Strauss, the chair of the Atomic Energy Commission who sought Oppenheimer's fall from grace. It's also beautifully filmed, especially the scenes on location in Los Alamos in New Mexico.

Stand-out performances for me are, obviously, Cillian Murphy as Oppenheimer and Robert Downey Jr as Strauss. It was also a delight to see a huge roll-call of physicists appearing on screen, including Werner Heisenberg, Niels Bohr, Isidor Rabi, Patrick Blackett, Ernest Lawrence, Edward Teller and Hans Bethe: who'd have thought there would ever be a Hollywood movie with them all in. My only quibble is the downplaying of Leo Szilard, who first came up with the idea of a nuclear chain reaction. I also felt the appearance of Albert Einstein, played by Tom Conti, was weak and unnecessary (and I couldn't help recall his performance as the Greek boatman Costas in the 1980s rom-com *Shirley Valentine*).

This is a movie that's definitely worth watching.

### James Dacey: rating 3/5



To sum up Robert Oppenheimer's attitude to nuclear weapons, you might land on the word "conflicted". That's also how I feel about this film.

Cillian Murphy is mesmerizing in the titular role. Slumped in a cinema seat eating popcorn, it's easy to take for granted all the versions of Oppenheimer he is playing, often in the same scene through the deftest change of facial expression. The genius. The Communist sympathizer. The vanity. The doubt. The guilt.

The film is also visually stunning. Director Christopher Nolan's choice to shoot on large-format IMAX film with Panavision cameras results in a clarity and depth of field that turns even the drabbest administrative buildings into a visual treat. I enjoyed the alternation between colour and black-and-white scenes, which helped distinguish Oppenheimer's life story from historical detail.

But ultimately, I expected the film to leave more of a lasting impression. It's slightly unfair to compare a film with a TV series, but I felt far more engaged with the characters and plot of the 2019 HBO series *Chernobyl*. That show – also a melting pot of 20th-century nuclear apocalypse, science and politics – perfectly captured the moment in history and created a deep sense of unease.

Perhaps the enormity of destruction at Hiroshima and Nagasaki created a disconnect in my mind. But after the drama and jaw-dropping visuals of the Trinity Test in the New Mexico desert, the final twists and turns involving the political "baddie" Lewis Strauss (Robert Downey Jr) feel a tad trivial. Perhaps the film is a victim of its determination to cram in as much historical detail as possible. One reviewer in the *New Yorker* referred to it as a "movie-length *Wikipedia* article". That's a bit harsh, but I sort of know what they mean.

### Hamish Johnston: rating 5/5

We decided to see *Oppenheimer* on a rainy Sunday afternoon in Bristol but much to our surprise the first two cinemas we tried were sold out. We managed to get tickets at the Odeon, where there was only a sprinkling of empty seats in the first few rows. I was gobsmacked that at least three Bristol cinemas were packed with people eager to see a film about a physicist. Indeed, we had seen *Barbie* the week before in a venue with more empty seats.

Exactly how J Robert Oppenheimer has seeped into the zeitgeist is beyond my understanding of popular culture. And I still can't believe that the theoretical physicist has been twinned with a plastic doll to create the *Barbenheimer* phenomenon (check out the illustration for Anthony Lane's review in the *New Yorker* for a particularly good mashup).

What I do know is that *Oppenheimer* is a fantastic film that I thoroughly enjoyed. How joyful it was to watch a rip-roaring tale with physics at its heart – and to see so many Nobel laureates portrayed on the silver screen.

*Oppenheimer* is not easy to watch because it requires the viewer's full concentration. So its popularity suggests that people's attention spans are not shortening as a result of apps like TikTok. I hope that this will encourage Hollywood to delve into the lives of other physicists. The remarkable story of Marie Curie would be a great place to start.

### Michael Banks: rating 5/5

I think *Oppenheimer* is a masterpiece.

When I discovered the film would run for three hours, I questioned whether a dialogue-heavy film could capture my attention for that long. But it did. That is mostly thanks to the incredible cinematography and performances not to mention the film's mesmerizing score by Swedish composer Ludwig Göransson, which adds to the movie's pacing and intensity.

The fun aspect of the film is playing "famous physicist bingo" – even Richard Feynman has the occasional cameo playing the bongos. But this is a serious movie and by the end *Oppenheimer* leaves you wrestling with the moral implications that advancing science can bring.

### Kate Gardner: rating 4/5

I was expecting *Oppenheimer* to be good-looking but problematic. I was right and wrong. It looks incredible, every stylistic choice adds rather than detracts. And it does have some problems, but on the whole I was blown away.

Robert Oppenheimer is not presented as good or bad – he is complicated, tormented by the choices his life has led him to. Cillian Murphy does an amazing job of portraying Oppenheimer's fractured mental state throughout his life, as well as convincing me of his intelligence, egotism and charisma.

Similarly, the film does not shy from the moral ambiguity of the Manhattan Project. We see not only scientists refusing to join it, but individuals and groups within the project wrestling with their consciences, trying to make themselves heard as the terrible potential of the atomic bomb becomes clear. Christopher Nolan brilliantly depicts the reactions of everyone at Los Alamos to both the Trinity test and the news that the bomb has been dropped on Hiroshima – the combination of jubilation and horror of those scenes will stay with me for a very long time.

The one glaring omission from the film is in fact 19 000 omissions – the number of people, mostly Indigenous, who lived near the Trinity test site in New Mexico. *Oppenheimer* implies the area was empty, side-stepping the thorny truth that local residents were not warned about the test at all – not even given a false story to prevent them from drinking the toxic rainwater that fell for the next few days. Did Oppenheimer feel guilt about the radiation exposure and ensuing high rates of deadly cancer among his Los Alamos neighbours? We may never know.

# Our colourful world

**Michael Banks** and his son **Henry** review *Can You Get Rainbows in Space?* by Sheila Kanani, illustrated by Liz Kay

Liz Kay

**Curtains of light** This picture book explains how the aurora is created by solar winds (left) and how observing the universe is done using wavelengths from across the electromagnetic spectrum (right).

**Can You Get Rainbows in Space?**
*Sheila Kanani, illustrated by Liz Kay*
2023 Puffin Books 128pp £14.99hb

Kids have an insatiable appetite for knowledge and love to ask questions, sometimes to the exasperation of parents and carers. Why is the sky blue? Why do leaves change colour from green to orange? Why is blood red, but our veins blue?

If you know someone young who is curious about the world around them, then *Can You Get Rainbows in Space?*, a new children's book about light and colour, could be for them. Written by planetary scientist Sheila Kanani and illustrated by Liz Kay, it is a compendium of space, science and light, told through the colours of the rainbow from red to violet and beyond.

After introducing what is meant by colour and light, each chapter focuses on a particular colour of the rainbow. Featuring fun scientific facts and trivia, every page has been nicely designed with attractive illustrations so it doesn't feel too dense and keeps children interested.

Examples of the trivia include the fact that humans tend to avoid blue food because of the colour's association with mould, and that carrots started out white before turning other colours such as purple and orange thanks to farming.

But *Can You Get Rainbows in Space?* does not just look at the six distinct visible colours. The latter chapters go beyond the rainbow to examine ultraviolet, infrared and fluorescent light, as well as what the symbolism of the rainbow represents.

I gave the book to my seven-year-old son Henry, to gauge his thoughts. He often comes home from school telling me his favourite fact of the day. "Did you know that cats can see really well in low light" was one such recent example. So this book sounded like it would be right up his street – presented at a level at which he would be able to understand the concepts and take something from it.

Despite being more than 100 pages, Henry devoured the contents over just four sittings, which is perhaps the best indicator of how much the book piqued his interest.

The following are his thoughts, edited for clarity.

"This book is about the colours of the rainbow. Each colour is given around 10 pages that contain loads of exciting scientific facts as well as details about all sorts of different things.

"I really like the facts – such as, if I put my hand on the top of a fire, the temperature could be between 500 and 1000 °C, and yellow or orange. But some super-hot fires can be even hotter, around 1000 to 3000 °C, and are blue in colour.

"Another fun fact is that flamingos are pink because of what they eat. My favourite fact is that the Sun isn't actually yellow, but green (if you measure the energy of the Sun from space)!

"I like how the pages in each chapter are the same colour it is describing and how each page is full of fun pictures that make you want to read the facts and find out more.

"This is a fun book for children who love to find things out. Five stars."

There you go: *Can You Get Rainbows in Space?* gets the thumbs up from Henry and the thumbs up from me for providing a necessary resource that parents and carers can refer to when they find themselves on the receiving end of countless questions about the colours we see in the natural world.

**Michael Banks** is news editor of *Physics World* and **Henry** is his son

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# Graduate Careers

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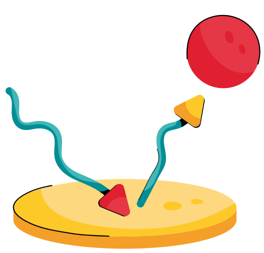
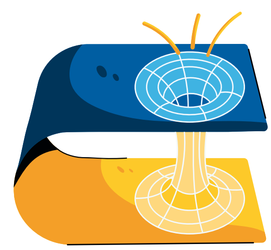




## Physics everywhere

Jobs that require physics skills are on the rise

# The demand for physics skills in the UK workplace

The growth of physics-based roles in sectors such as green energy and data science is fuelling the need for employees with physics expertise. **Sharon Ann Holgate** explores the findings of a recent report from the Institute of Physics into the labour market for physics skills in the UK and Ireland

iStock/RgStudio

**Quantifying physics** The new report *Physics in Demand* assesses many aspects of the jobs market for physics graduates, from skill prevalence and salaries to regional specialist industries across the UK and Ireland. One finding is that airline pilots and flight engineers are the highest-paid occupations that require physics skills.

If you are an early-career physicist, or about to graduate with a degree in physics, then I have some good news for you. There is a substantial and growing need for employees with physics skills and knowledge in the UK and Ireland. But as well as requiring physics expertise, most roles generally call for additional transferable skills that will enable candidates to successfully apply physics within the workplace.

Additionally, employers value physics know-how not only in its own right, but also as a foundation for solving complex problems in areas outside science. These are some of the main findings of a 2022 report *Physics in Demand: the Labour Market for Physics Skills in the UK and Ireland* produced for the Institute of Physics (IOP) by labour-market analytics specialists Emsi Burning Glass.

## Increasing opportunities

By combining market research, analysis and data expertise, the *Physics in Demand* report finds that one in 20 jobs requires physics skills – quantitatively speaking, that is 1.85 million jobs in 2020 across the UK and Ireland – with demand increasing over the decade between 2010 and 2020. The fastest-growing are roles as scientists, which are up 24% since 2010, with demand for physical scientists within that group rising by 40%. The slowest-growing are teaching positions, which only exhibited 6% growth over the same period. In terms of adding the highest volume of jobs during that decade, construction managers came out on top with 28 100 net new jobs and showing 21% growth.

The report also highlights an increasing need for physics skills and knowledge in roles not traditionally associated with the field. Physics expertise is required in many sectors, including healthcare, the public and regulatory sector, teaching, engineering, construction and manufacturing. Within higher-skilled jobs, increasing opportunities are opening up in data science, software engineering, computer science and quantitative analysis. Demand is also increasing for physics skills in the business, financial and digital sectors. As the report puts it: "The analytical rigour associated with physics gives physics-trained professionals competitive advantages in taking on these roles, distilling their complex problems and identifying how to solve them."

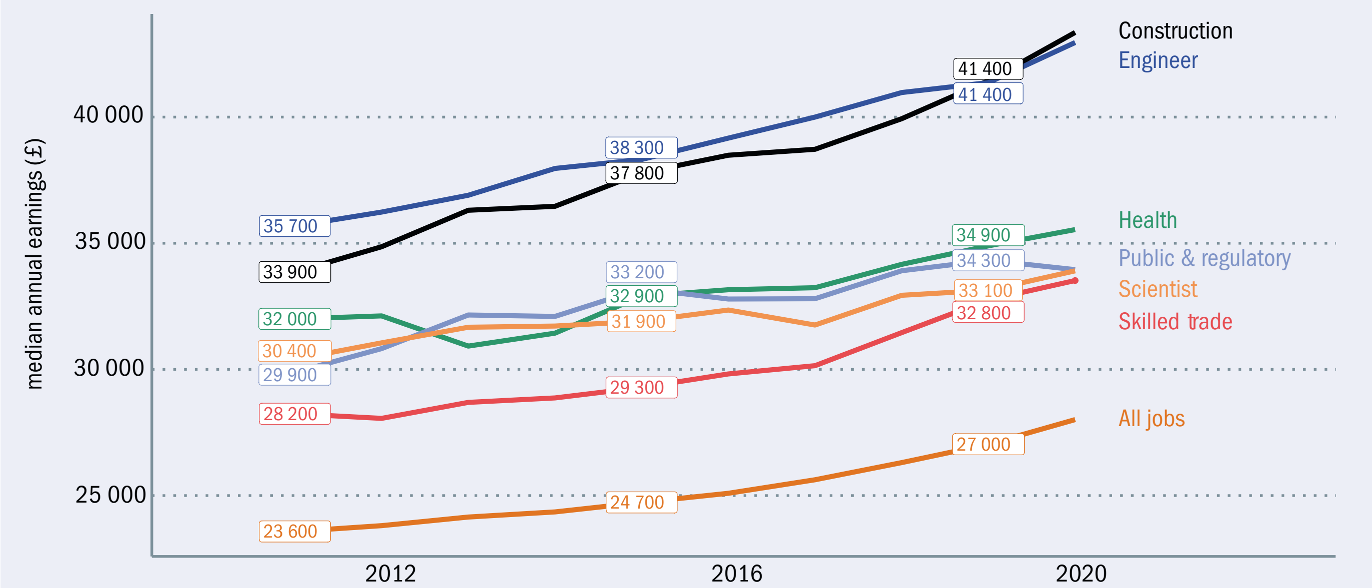
One of the biggest scientific challenges for the immediate future is within the global energy sector, with the push towards net-zero emissions. As the report stresses, physics is fundamental to that quest, and will likely hold the solutions for many of the questions around clean and sustainable energy, and how to use existing materials in new ways.

In addition, physics will be needed to develop new tools and therapies to improve health outcomes, and in analysing big data to help inform complex political and business decisions. Discussions with employers while compiling the report highlighted that growth is expected in the numbers of physics-centric roles in photonics engineering, quantum technologies, nuclear fusion and transport electrification.

## Focusing in

The report is useful for physicists because it aims to identify the specific demand for physics skills in the workplace, which is often hidden in a broader desire from employers and policymakers to boost skills in science, technology, engineering and mathematics (STEM) subjects more

## Earning trends




Institute of Physics, based on data from Emsi Burning Glass 2021.2 and ONS ASHE

Median salaries of occupations in the UK that require physics skills, from 2011 to 2020. Airline pilots and flight engineers are the highest paid – median salary of £97 400 – followed by electrical engineers (£52 200), construction managers (£48 600) and research and development managers (£46 700). As well as being the highest-paid group in the UK, construction has seen the strongest growth in median earnings: 28% since 2011, compared to 19% for all jobs. By contrast, health (11%) and scientist (12%) have seen the slowest growth.

widely. The study found that outside academia, there are relatively few roles that are solely and explicitly "physics jobs". But jobs requiring a distinct physics knowledge, or an ability to apply physics, cover a wide range of sectors. In fact, the report identifies 35 different occupations that require a high level of physics know-how, with the median earnings across these occupations being £38 123 in 2020.

These physics-related roles include engineers spanning the design, civil, electrical, electronics, flight, heating, IT, mechanical, production, quality control and refrigeration sectors. Other jobs include production managers in the construction industry and managers in R&D; senior officers in the fire, ambulance and prison services; health and safety officers; environmental health professionals; aircraft pilots; and even conservation professionals.

The report highlights that earnings for physics-related occupations are also trending upwards, with construction and engineering roles the fastest growing, reaching median pay of approximately £43 000 as of 2020. The highest-paid physics-based jobs overall are airline pilots and flight engineers, who both have a median salary of £97 400. The next highest paid are electrical engineers at £52 200, construction managers at £48 600, then managers in research and development roles who have median salaries of £46 700. At the other end of the scale, the salaries for health-related roles and scientist positions saw the slowest growth over the decade to 2020.

Earnings for physics-related occupations are also trending upwards, with construction and engineering roles the fastest growing

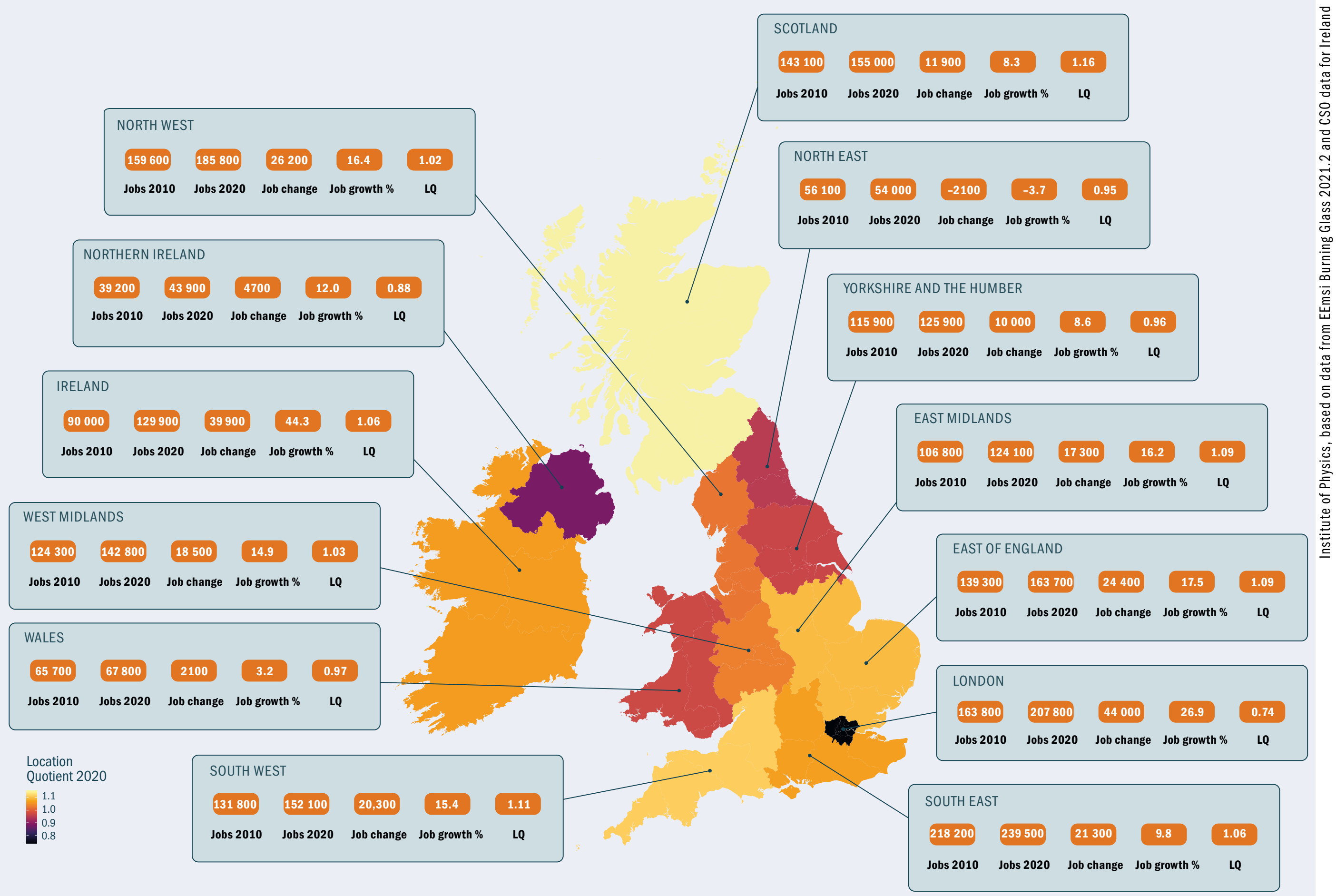
### Regional variations

When analysing the geographic concentration of physics work in the UK and Ireland, the report finds that "physics plays a vital role in the skills mix of all nations and regions". But physics roles are found to be clustered around specific industrial hotspots. With previous studies (see "There's no place like home" *Physics World* October 2019) showing many physics graduates wish to remain living in the area in which they grew up or studied, understanding which regions have the highest concentrations of physics-based job opportunities is particularly useful.

Although the labour market demand for physics skills is "large enough to be significant everywhere", the report shows that Scotland has the greatest concentration of physics-based roles –16% more than in the UK and Ireland overall, and growing by 8% in the decade from 2010 to 2020. Indeed, Scotland's main industrial sector of oil and gas, together with associated industries, provides twice as many jobs for physics-trained workers in the north-east of Scotland, compared with the UK and Ireland-wide average. Cumbria, in England's north-west, has the second-most concentrated amount of job offerings, in this case mainly within nuclear energy and shipbuilding. The north-west England region as a whole – where there is a focus on transport manufacturing and civil engineering – has seen 16% job growth in the 10 years to 2020.

When looking at growth in numbers of physics roles from 2010 to 2020 for all regions, the Republic of Ireland – which has a focus on the air transport sector, similar

## Earning trends




This map sets out the pattern of physics-demanding roles across the nine regions of England, plus Scotland, Wales, Northern Ireland and the Republic of Ireland. The map is coloured according to the Location Quotient (LQ), a metric used in economic geography to understand relative specialization, where an LQ of 1 represents the number of jobs that would be predicted given the overall trend, and values over 1 demonstrate concentration and specialization. The map also highlights the key statistics for each region or country.

to London – saw the quickest growth at 44%, while London's demand grew second fastest at 27%. For scientific research and development, both east England and south-east England are hotspots, with the former showing 18% physics job growth and the latter 10%. Growth of 16% was seen in the East Midlands, which has a focus on transport equipment manufacturing. South-west England – where defence and manufacturing of aircraft, spacecraft and domestic appliances dominates – and the West Midlands – which is a centre for heavy industry – both showed 15% growth.

In Northern Ireland, whose top industries include transport-equipment manufacturing and civil engineering, the figure was 12%. Meanwhile in Yorkshire and the Humber – where specialized construction, and machinery repair and installation are the leading industries – it was 9%. Wales – where manufacturing of transport and energy-supply equipment dominates, had slower growth of 3%. Bucking this upward trend in growth is north-east England, a centre for heavy industry and infrastructure, which has witnessed a 4% decline in physics jobs.

### Keeping up with employers' requirements

The study also looks at how the specific demands of employers are changing and converging around certain roles – including the mix of transferable skills that are required, and how well these demands are being met by current applicants. In terms of what employers are looking for, it turns out that very specific physics knowledge is required for some roles, such as those within sensor-development or gravitational-wave detection. But for other positions, such as data scientist, broader physics skills are needed that can also be held by graduates in mathematics, computer science or other related subjects.

Similarly, although new and emerging technologies are fuelling the need for a workforce with very specific physics skills, this skillset must be complemented with a broad knowledge base of fundamental physics. In certain roles, particularly in those applied for by graduates, the physics skills required will be put to use for scien-

**The report's authors found a consensus on the need to match technical physics skills with transferable skills**

## Measuring skills shortage


The *Physics in Demand* report uses online job adverts to identify where employers are finding it hard to fill vacancies. Most job postings are online for around one month. The top quartile of posting durations starts around the 40-day mark; at this point employers are consciously leaving postings open for longer. For this reason, the report uses the share of postings with duration over 40 days as an indicator of skills shortage. Pay can be another, albeit weaker, indicator of skills shortage. Using the prevalence of high-duration postings as the skills-shortage metric reveals that some but not all are in the highly paid category. This chart shows the median advertised salary and high duration density for jobs posted 2019–2021. The size of the dot indicates volume of job postings.

tific research. Physics skills are also valued in sectors such as business and finance, including for driving new technology start-up businesses forward.

But applicants need to possess more than just physics skills. After analysing more than 50 million unique job postings and speaking to senior decision-makers from 14 organizations that require workers with physics knowledge, the report's authors found a consensus on the need to match technical physics skills with transferable skills.

The most frequently requested transferable skill is communication, which is stated as a requirement in almost one-third of roles within business and finance, and in the public and regulatory sector. Meanwhile, innovation skills are sought after for 15% of science, 14% of digital, 10% of teaching and 8% of business and finance roles. Research skills are stipulated for 28% of scientists and in 14% of business and finance roles. (For advice on developing your soft skills see "16 key skills and attributes for a successful career in physics" *Physics World* October 2022.)

Some roles are cited by employers as hard to recruit for, although a lack of candidates with the desired mixtures of skills is not universal. The report states that in June 2021, more than 8500 job postings had been online for "significantly longer than average, with the largest number being engineering roles, but significant numbers found too seeking science skills in digital or business and finance". According to the report, "job postings which are left online for longer are indicative of difficulties in finding the right talent" although, it adds, there may have been reasons other than skills shortage for job postings being active for longer than 40 days.

There were close to 9000 active vacancies at the time *Physics in Demand* was written, and the report stresses that developments in technology and in the economy of the UK and Ireland will continue to create new job opportunities for physics graduates, both within and outside of physics' traditional domains. This demand and the need to fill it is noted by Tom Grinyer, chief executive of the IOP.

"Physics skills support nearly two million jobs and underpin productive industries in every part of the UK and Ireland," he says. "However, there is an acute shortage of physics skills in our economy, with IOP research showing two-thirds of physics-powered businesses have had to pause or delay much-needed R&D investment because of skills shortages. At the same time, demand is growing for highly skilled roles – the number of jobs for physical scientists grew by 40% between 2010 and 2020."

Essentially, the overall picture for those graduating with a degree in physics is a positive one. There is a high and increasing demand for your talents in the current UK and Ireland labour market, as we attempt to meet the needs of science, commerce and society.

**Sharon Ann Holgate** is a freelance science writer and broadcaster who has written extensively on careers issues. Her latest book *Communicating Science Clearly: a Self-Help Guide For Students and Researchers* (CRC Press) will be published in November 2023

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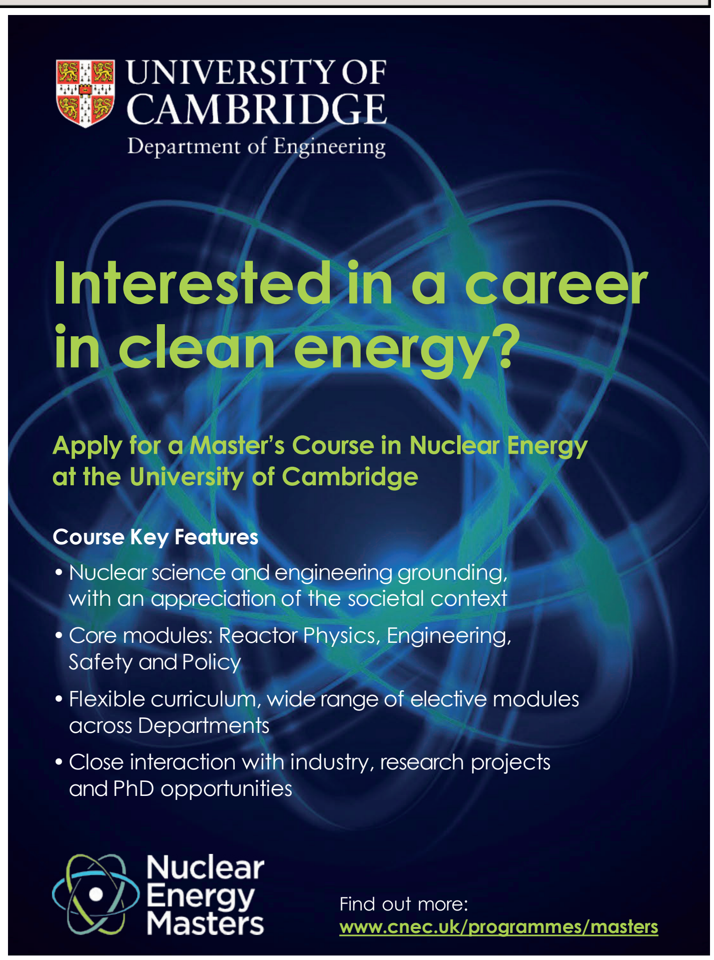
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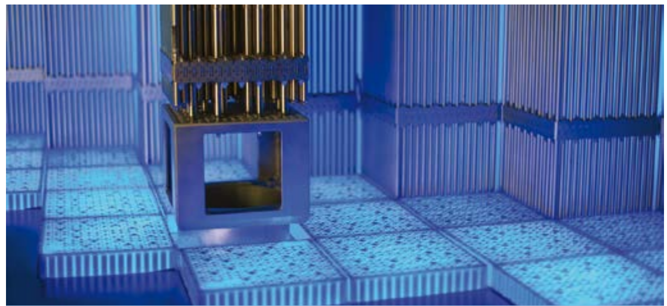

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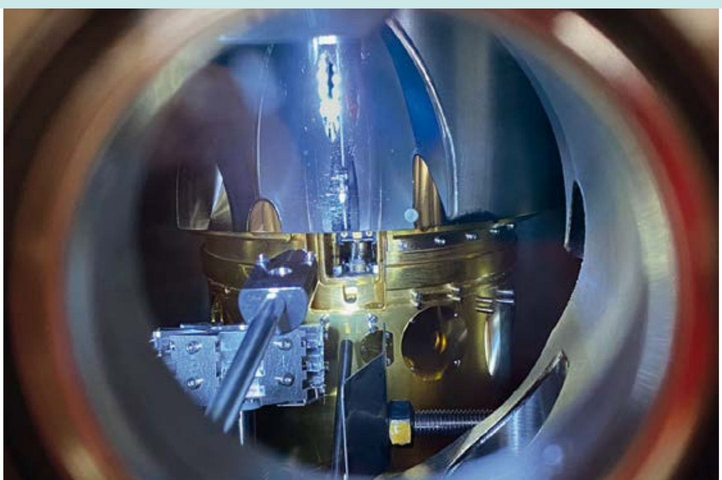

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# Put your hands together

Whether it's at a concert, play or lecture, we love to show our appreciation by clapping our hands. **Laura Hiscott** hears from two researchers who know how to make great applause

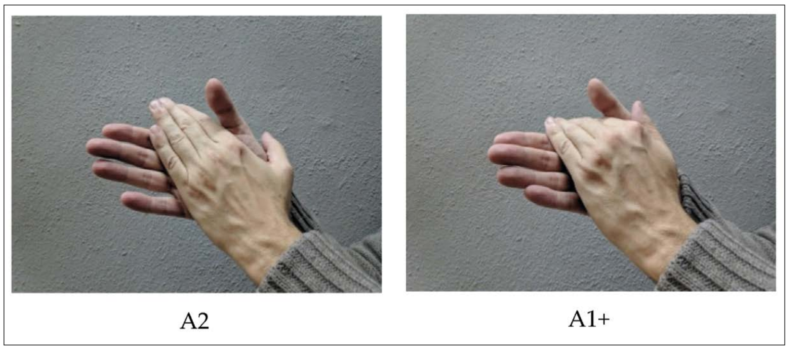
It might be hard to imagine yourself in ancient Rome, but if you were dropped into the audience of a play 2000 years ago, you'd probably know what to do when it finished – start clapping. Making a sound by putting your hands together is in fact such a long-standing practice that no-one knows quite when or how it started. Clapping certainly seems to have been well established when the Romans were around.

Some people have even made a profession of it, notably the "claqueurs" of 19th-century France, who received money and free tickets in return for particularly zealous applause. But I wonder if any of these entrepreneurs ever considered the physics of their trade. Imagine if they tested various clapping techniques to find out which would please their client most. After all, there's more than one way to crash two hands into each other, so which is best?

It's a question that inspired Nikolaos Papadakis and Georgios Stavroulakis – two engineers at the Technical University of Crete – to investigate. While teaching acoustics, Papadakis found that his students often wanted to know how they could measure sound without using any expensive equipment. For acoustic measurements like these, you generally need a short but loud sound source – and there's nothing cheaper than a handclap.

To see how well handclap measurements fared against those made with expensive acoustic kit, the researchers got a group of 24 students to perform single handclaps at various venues in no fewer than 11 different hand configurations. Each of these was defined by a unique combination of the angle at which the hands are held to one another and how much the fingers of one hand overlap with the fingers or palm of the other.

Although it might be a bit late to help the claqueurs, the results are in (*Acoustics* **2** 224). The loudest configuration, generating an average sound pressure of 85.2 dB, is one in which the hands are held at about 45 degrees to one another and the palms partially overlap (A2 in the figure). Meanwhile, there is one mode of clapping that produces particularly low tones. This involves keeping the hands at 45 degrees, but with the palms fully overlapped and slightly domed to enclose a pocket of air (A1+ in the figure).





**Hear, hear** The loudest claps occur when you hold your hands at about 45 degrees to one another with palms partially overlapped (A2), while the lowest tones occur with the hands at 45 degrees but with palms fully overlapped (A1+).

While both flat and domed handclaps disturb the air and create pressure waves that our ears detect as sounds, they do so in slightly different ways. As two flat hands collide, the air between them is forced out increasingly quickly, ultimately exceeding the speed of sound. This creates an abrupt pressure change, resulting in shock waves that make up a large part of the noise we hear.

With cupped palms, meanwhile, there is usually a gap left around the thumbs, so not all the air is expelled. This makes for slightly gentler pressure changes that do not create much of a shock wave, but which produce what's known as a Helmholtz resonance.

"In general, a Helmholtz resonator is a container of gas with an open hole," says Papadakis. "At the Helmholtz resonance, a volume of air in and near the open hole vibrates because of the 'springiness' of the air inside. This vibration creates sound at sufficiently low frequencies that other handclap configurations cannot produce at such volume."

The loudest configuration is one in which the hands are held at about 45 degrees to one another and the palms partially overlap

This is the same phenomenon underlying the hum you get from blowing across a bottletop, as well as that uncanny "sound of the sea" in a seashell. In the latter case, environmental fluctuations in sound pressure enter the shell and bounce off its hard inner surfaces, with resonant frequencies getting amplified in the enclosed pocket of air to mimic the whooshing of ocean waves.

As poetic as it might be to use a seashell, you can actually recreate this effect using just your hands. If you put your domed palms together, leaving a gap where your thumbs overlap, and hold this gap to your ear, you may well hear that familiar hiss. You can even play around with varying how domed your hands are and hear a noticeable change in frequency as you do. When you clap your hands together into this shape, you generate a brief, loud pulse at these resonances.

So, equipped with these insights, has Papadakis changed the way he claps? "Surprisingly, yes!" he says. "Especially at concerts that I have really enjoyed, I prefer to do the domed handclap with the Helmholtz resonance. This is probably because I can more easily distinguish the sound of my own handclap among the overall sound of clapping, and because the richer frequency content with more volume in the low-frequency range expresses my enthusiasm better."

As for me, I have found myself trying out the different handclaps while I've been writing this article (apologies to my co-workers) and I've already noticed myself applauding more consciously at concerts. Who knows? Maybe if I cultivate a suitably conspicuous clap I'll convince someone to give me free tickets. Taylor Swift, can you hear me?

**Laura Hiscott** is a freelance science journalist

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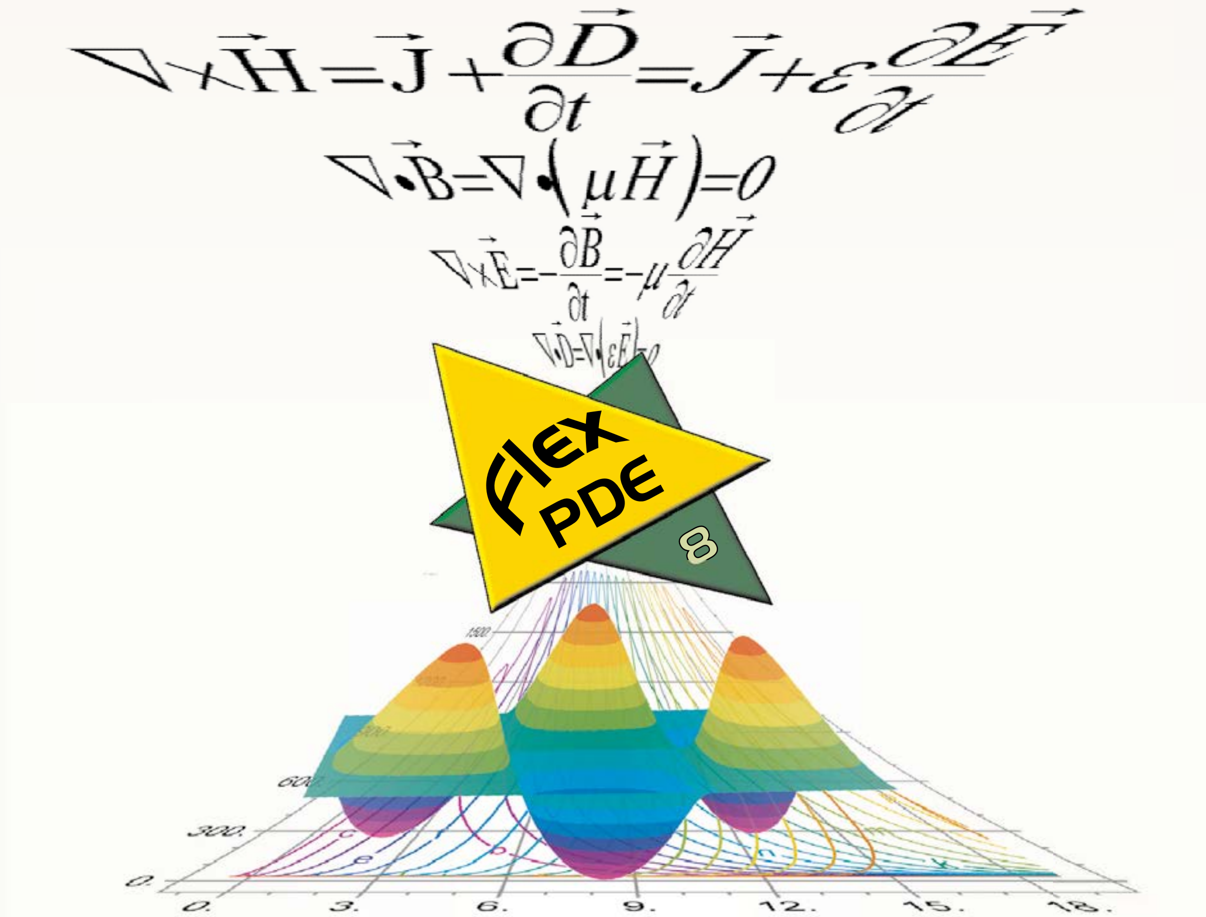


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