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Physics World at 25

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On the cover:
Artistic interpretation of simulated particle collision data at CERN's Large Hadron Collider, as predicted in 1997.

How times have changed

Welcome to this special issue celebrating 25 years of *Physics World*

To mark the 25th anniversary of the member magazine of the Institute of Physics, which launched in October 1988 (see image above left), this special issue of *Physics World* looks back at some of the highlights in physics of the last 25 years and also forward to where the subject is going next.

We've split the bulk of the issue into five sections, each with five items (five times five being 25 of course). Two sections are retrospective, in that we unveil our choice of the top five discoveries in fundamental physics over the last 25 years along with five images from the same period that have let us "see" a physical phenomenon or effect. Two other sections examine the five biggest unanswered questions in physics and profile five people who are changing the way physics is done. Finally, we disclose the five most promising spin-offs from physics.

We also have the first of a set of fiendish physics-themed puzzles devised for you by staff at the UK's Government Communications Headquarters (GCHQ) – with the rest to be unveiled throughout October at physicsworld.com/puzzle.

Physics World would not have thrived for so long without the support of the Institute of Physics, which now has more than 50 000 members. Key to the magazine's success has been its editorial independence from the Institute, which means that *Physics World*'s editorial staff can focus, without bias, on creating interesting, informative and entertaining content to the best of their ability. *Physics World* has not stood still either: we now create audio and video content, host online lectures, publish special Web-only reports and are active in social media. All members of the Institute can also enjoy *Physics World* in digital format through our apps or via members.iop.org – with this month's issue including a set of specially made videos on the top spin-offs from physics.

Like physics itself, it is hard to imagine what *Physics World* will look like in another 25 years. But you can be sure that, in whatever format it exists, *Physics World* will be there.

Matin Durrani, Editor of *Physics World*

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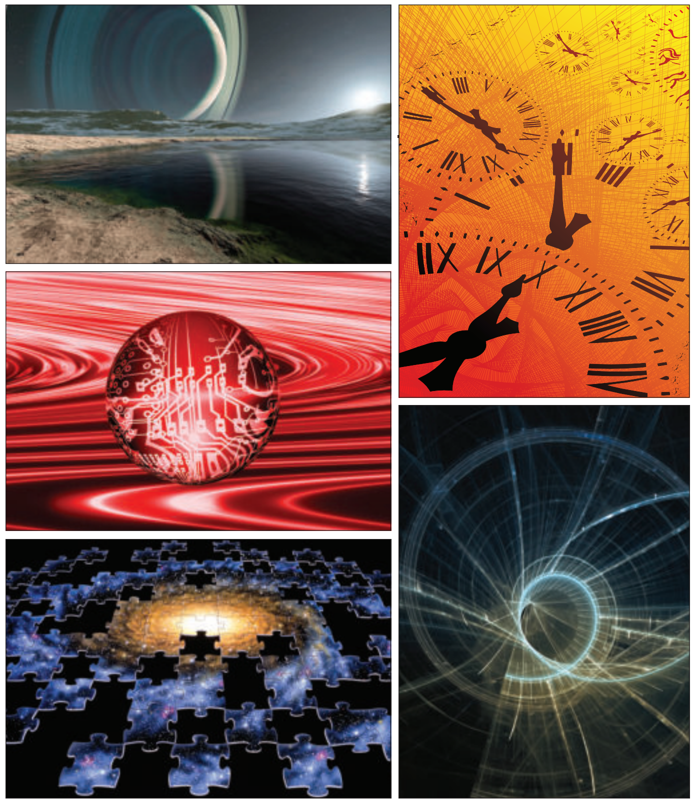
Risk-takers – our graduate careers section looks at the opportunities at physics spin-out companies 69–83



Big questions – getting to the bottom of alien life, time, quantum gravity, the dark universe and quantum computing 33–46

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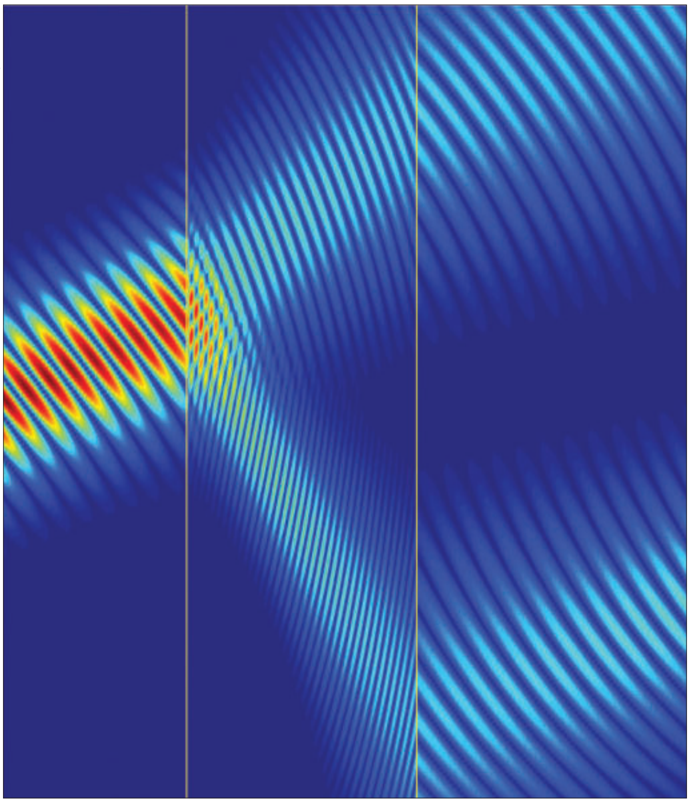
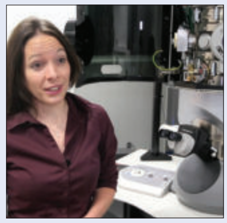
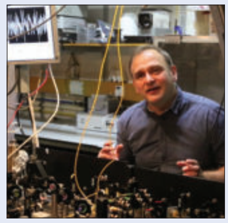
New J. Phys. **7** 220

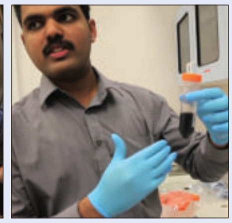


Practical matters – technological spin-offs from physics research include using negative-index metamaterials to create perfect lenses 50–53

Physics World at 25 multimedia highlights







Members of the Institute of Physics accessing *Physics World* in digital format through our apps or via members.iop.org can enjoy three short films exploring some of the most promising technologies emerging from physics research.

- "Graphene's potential to provide drinking water" takes you to the lab at the University of Manchester where graphene was first discovered in 2004 to explore its application to water purification.
- In "Quantum computing: a revolution in bits" you will visit the University of Sussex to see how the computers of tomorrow could harness the spooky effects of quantum mechanics.
- "Building the perfect lens with metamaterials" transports you to Imperial College London to discover how a theorized "perfect" microscope could boost nanotechnology and the biosciences.

The issue also has a feast of other multimedia, including a pick of the best video explanations from our popular 100 Second Science series. You can listen as well to audio snippets from some of the high-profile physicists featured in the issue, including Neil Turok, who talks passionately about the need to nurture scientific talent in Africa.

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Quanta

For the record

If you are playing for big stakes, very possibly you're not going to win

John Ellis *from King's College London quoted in the* Guardian

Ellis was commenting on the lack of evidence of supersymmetric particles at CERN's Large Hadron Collider.

It blows my mind that some smart people would suggest it

Physicist **Elon Musk** *quoted in* Businessweek

Musk, the brains behind PayPal and SpaceX, says that space solar power is a "dumb idea" and that if anyone had a vested interest in it, it would be him.

Oxygen is sparse, temperatures are extremely low and the wind is fierce, and they have long shifts

Ezequiel Triester *from the University of Concepción quoted on* SciDevNet

In August around 250 employees at the Atacama Large Millimeter/submillimeter Array in Chile went on strike for 17 days following a pay dispute, with the union that represents them calling for a 15% pay increase as well as "special bonuses".

That is truly a daft question, particles are not pets!

Particle physicist **Tom Kibble** *quoted in the* Guardian

Kibble, who worked on the theory behind the Higgs boson and is now emeritus professor at Imperial College London, rebuffed the paper after being asked what his favourite particle is.

It's conclave glass, it's basic physics

Office worker **Richard Hughes** *quoted in the* Times

Hughes was commenting on a new skyscraper – dubbed the Walkie Talkie – that is currently being built in London. At certain times of day, the building's shape focuses light from the Sun, which resulted in a car's roof being melted.

It's the adults who are afraid of science and maths and engineering

Rosemarie Truglio, *senior vice-president of curriculum and content at the Sesame Workshop, quoted in the* New York Times

The popular TV show *Sesame Street*, produced by the Sesame Workshop, has been teaching maths, science and engineering concepts in its shows and on its new website.

Seen and heard

Thomas Legrave

A barrel of laughs

Physics can be quite a serious endeavour, which is why making physics funny is never easy. We should know: we've tried hard enough over the years with this page of *Physics World*. We therefore winced when CERN announced that it was going to stage its first ever official stand-up comedy night dubbed LHComedy. Held at CERN's Globe of Science and Innovation in Geneva, the free event featured six CERN scientists – Sam Gregson (pictured), Alex Brown, Benjamin Frisch, Claire Lee, Hugo Day and Clara Nellist – but it seems that Belgian comedian Lieven Scheire, who began (but did not finish) a degree in physics at the University of Ghent, stole the show. "I love CERN, it's the most famous experiment of the EU," he said as he opened his 30-minute set. "Apart from Greece, of course." Gregson told *Physics World* that the evening was a "fantastic success" adding that the live event garnered more than 10 000 online viewers – more than watched the discovery of the Higgs boson being announced in July 2012. "Everyone went away happy, having laughed and learned," he says. Just like reading Quanta then.

Frampton: the movie

Over the last 25 years, *Physics World* has kept an eye out for some of the unusual, intriguing and just plain bizarre human-interest stories in physics. Nothing, however, has quite beaten the tale that we first reported in early 2012 about Paul Frampton – the 69-year-old British-born US-based theoretical physicist who ended up in prison after being arrested at Buenos Aires airport with 2 kg of cocaine in his luggage. Frampton was in Argentina after thinking he had struck up a correspondence on the Internet with Czech-born lingerie model Denise Milani. When he arrived, Milani was nowhere to be seen and Frampton was apparently asked by someone else to carry a suitcase for Milani, which contained the drugs. Despite protesting his innocence, Frampton was sentenced in November 2012 to 56 months in jail, which he is currently spending under house arrest. But as if to underline the old adage that truth is stranger than fiction, Frampton's story could now be made into a movie. In fact, according to the *Hollywood Reporter*, Fox Searchlight has already asked Steve Zaillian and Garrett Basch from the US film-production company Film Rites to produce it. Fox Searchlight and the producers are seeking a writer to adapt the story – but the more pertinent question for us is who could play Frampton? Answers please.

An astronomical proposal

Amateur astronomer David Osario has come up with an unusual way of proposing to his long-term girlfriend and primary-school teacher Saydi Rodriguez. The romantic gesture involved Osario using a special printer at his work to write the words "Will you marry me?" onto a small custom-made telescope eyepiece, just 8 mm in diameter, before taking his bride-to-be to the David Dunlap Observatory in Toronto for a spot of star gazing. Eyepiece in hand, he installed it onto his personal telescope in a corner of the observatory's car park, lining up the question in the centre of the Moon before asking Rodriguez to a look. "I wanted the proposal to be romantic, with a hint of geeky," Osario told the *Telegraph*.

Mattel

Mars: the pink planet?

It is one year since NASA's Curiosity rover landed on the red planet and to mark that milestone, Mattel has collaborated with the US space agency to bring out a "Mars Explorer" Barbie. The new toy, costing $12.99, is packaged in what Mattel says is a "stylish space suit with pink reflective accents, helmet, space pack and signature pink space boots". Coming a couple of years after Barbie first appeared as a computer engineer, we are pleased that sexist stereotypes are slowly disappearing, but some bloggers were more concerned that the doll's apparel was not realistic: Barbie's uncovered hands would basically burn up in the Martian atmosphere. Another gaffe is that it doesn't have the NASA logo either.

Frontiers

In brief

Laser imaging spots brain cancer

Researchers in the US have developed a new imaging technique to distinguish tumours from healthy tissue in the brain. The technique is based on a particular type of Raman scattering and has been developed by researchers in the US, who believe it could prove more successful than either magnetic-resonance imaging or fluorescence-guided surgery. The method uses stimulated Raman-scattering microscopy, which uses two lasers with a frequency difference tuned to match specific vibrational signatures. As long as the user knows what they are looking for, this technique can generate much stronger, faster images than those produced using normal Raman-scattering microscopy. It could boost the success rate for the complete surgical removal of brain tumours by distinguishing between protein-rich tumours and healthy tissue, which has equal amounts of proteins and lipids (*Science Translational Medicine* **5** 201ra119).

Artificial muscles lift heavy loads

Human-like artificial muscles that can extend to five times their original length while lifting loads 80 times their own weight have been developed by researchers in Singapore. Made from polymers, the artificial muscles mimic the operation of their natural counterparts by contracting and expanding rapidly in response to electrical stimuli. The core of the breakthrough comes in the use of dielectric elastomers to form the muscles. Although the muscles were originally designed to convert electrical energy into mechanical energy, they can also work the other way by generating and storing energy harvested from mechanical movements. This development is a first for robotics and could pave the way towards a new generation of more efficient, greener and cheaper robots.

Chlorine has graphene covered

Researchers in the US have developed a new way to p-dope graphene that does not sacrifice its excellent electronic properties too much – something that has proved to be a challenge until now. The team succeeded in p-doping the graphene with chlorine using a plasma-based surface-functionalization technique. The chlorine covers more than 45% of the surface of the graphene sample – a better proportion than with any other graphene-doping material. The resulting material, which now contains a band gap, could be ideal for making all-graphene integrated circuits on a chip, radio-frequency transistors and nanoelectronic circuit interconnects (*ACS Nano* 10.1021/nn4026756).

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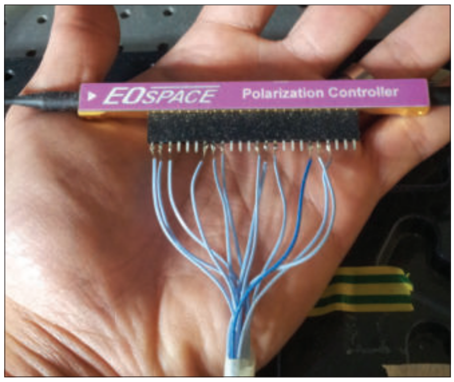
Quantum cryptography gets mobile



Anthony Laing

Mobile safety Palm-sized quantum cryptography.

The first practical way of carrying out quantum cryptography using a mobile phone has been developed by physicists. Quantum cryptography, which lets messages be sent with absolute secrecy, is currently limited to banks and other organizations that can afford to have expensive and extremely sensitive quantum-optical components at both ends of a communications link. The new method can be carried out instead using potentially inexpensive electronics that could be integrated within a single chip.

The technique is based on the principle of quantum key distribution (QKD), which allows two parties – Alice and Bob – to exchange an encryption key, secure in the knowledge that it will not have been read by an eavesdropper (Eve). This guarantee is possible because the key is transmitted in terms of quantum bits (qubits) of information, which change irrevocably if intercepted, thus revealing the actions of Eve.

Developed by Anthony Laing and colleagues at the University of Bristol and the Nokia Research Centre in Cambridge, UK (arXiv:1308.3436) the system uses a variant of QKD called reference frame independent QKD (rfiQKD). It solves one big restriction with conventional QKD methods: they only work if Alice and Bob measure the properties of photon qubits relative to a fixed reference frame.

The advantage of rfiQKD is that it allows for some twisting and turning – even if this relative motion is unknown. The technique works by having Alice and Bob each compute a specific combination of observables whereby the effect of the twisting angle cancels itself out. According to Laing, this "angle independent" value can be thought of as the purity of the quantum state exchanged by Alice and Bob. When it falls below a certain threshold, the pair is alerted to Eve's spying presence.

In the new system, Alice acts as a "server" performing all the delicate measurements required for the rfiQKD, while Bob acts as the "client" and uses a portable device. First, Alice creates a very weak pulse of light that is sent to Bob (through an optical fibre) who passes it through an attenuator, which outputs a single photon. Bob sets the polarization of the photon and sends it back to Alice who then measures its polarization. They both then compare their measurements using a conventional link, allowing them to extract both the cryptography key and the purity of the link.

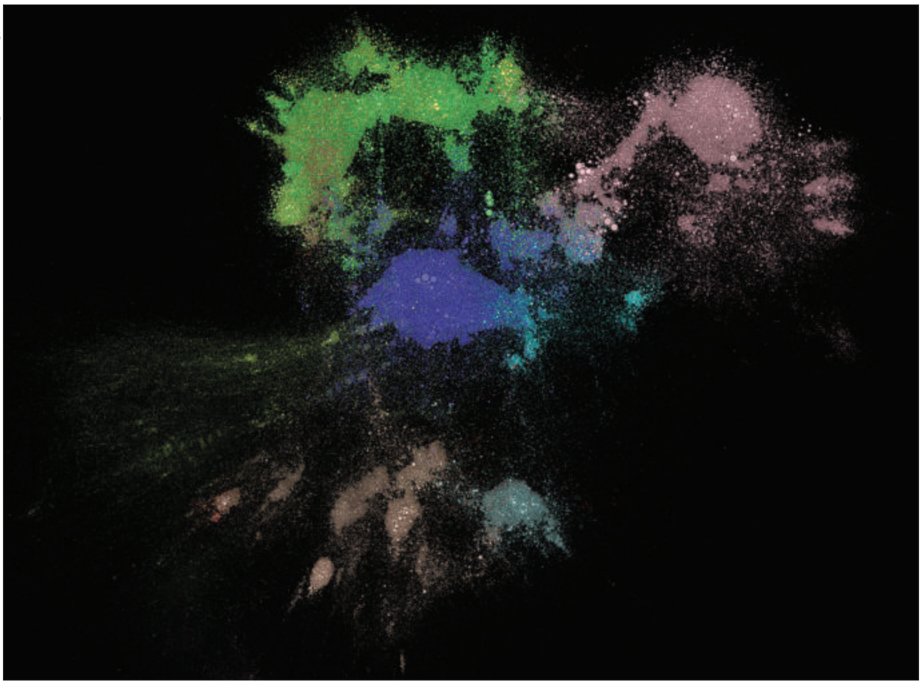
Positrons are in excess

Researchers working on Europe's PAMELA satellite have published new data concerning a mysterious excess of positrons that permeate outer space. Launched in 2006 to examine the nature of antiparticles in cosmic rays, PAMELA's first results two years later revealed an unexpected rise in the ratio of positrons to electrons above an energy of about 10 GeV. Basic theoretical calculations, in contrast, suggested that the positron fraction should decrease.

Theorists have since put forward several explanations for the positron excess – including the possibility that it arises from annihilating dark-matter particles that may generate electrons and positrons as well as pulsars. Another suggestion – that the PAMELA team may have misunderstood its experiment – now seems unlikely after physicists using NASA's Fermi Gamma-ray Space Telescope confirmed that they too had detected a rise in the positron fraction at energies of 20–100 GeV. The positron excess was also seen in data from the Alpha Magnetic Spectrometer experiment aboard the International Space Station in April this year.

The latest PAMELA data (*Phys. Rev. Lett.* **111** 081102), which was obtained between July 2006 and December 2009, contain three times the number of positron events as in the previous sample, including absolute numbers of positrons, not just their fraction of the positron and electron total. Measuring absolute numbers of positrons is not easy as it requires precise estimates of the number of positrons that are lost as a result of inefficiencies in detection – unlike a measurement of the relative positron-to-electron number, for which such inefficiencies cancel out.

Damien George, Rob Knegjens



Welcome to the *arXiv* galaxy

For the past 25 years, *Physics World* has been bringing you news of all the latest physics research breakthroughs. Apart from keeping a close eye on the latest papers in scientific journals, we also forage through the *arXiv* preprint server, which has accrued almost a million articles over the past two decades, and become an indispensable tool for physicists and science journalists alike. Unfortunately, this vast repository can sometimes be hard to navigate, especially for those looking for an overview of a niche subject area. But a picture is worth a thousand words – or in this case, a million papers – thanks to a new website called *Paperscape*. Developed by physicists Damien George at the University of Cambridge in the UK and Rob Knegjens at Nikhef in the Netherlands, the website allows users to visualize the *arXiv*'s hoard in all its glory. The interactive graphic is based on a nifty algorithm that groups papers that cite each other together, but forces those that don't to repel each other. The resulting map resembles an irregularly shaped galaxy in which each "star" is a scientific paper, revealing how the various categories of research – shown in different colours in the image above – relate to each other. At its centre, demonstrating its importance across different physics sub-fields, is a Switzerland-shaped blob representing theoretical high-energy physics. The radius of each point indicates how many times the paper has been cited, allowing users to quickly assess what the most important papers in different fields are, while the brightness of a point indicates how recently the paper was published.

Star flicker is revealing

A new method of measuring the strength of gravity on the surface of a star has been developed by astronomers in the US. Surface gravity provides information about two fundamental properties of a star: its mass, which governs how the star behaves, and its diameter, which can affect estimates of the sizes of planets seen orbiting it. The new technique could therefore lead to further insights into exoplanets.

Devised by a team led by Fabienne Bastien and Keivan Stassun of Vanderbilt University, the new method, which has an accuracy of 15–25%, was chanced upon when Bastien was examining data from the Kepler space observatory. She noticed that the more a star's light flickers during a period of eight hours, the lower its surface gravity.

Bastien and Stassun think that the flickering is related to the fact that most stars have outer layers that are convective, with surfaces that boil like a pot of water on a hot stove – the hot bubbles of gas rising to the surface, while cooler ones descend. Following the Stefan–Boltzmann law, the hot bubbles are brighter, so the star's surface looks granulated, with dark areas surrounding bright ones. On a star with a high surface gravity, such as the Sun, the granules are small, producing only tiny flickers. In contrast, a low-surface-gravity star, like a puffy red giant, has large granules and therefore larger flickers.

The flicker method could lead to better estimates of the diameter of planets. This in turn could help to determine whether a far-off world is a gas giant like Jupiter, an ice giant like Neptune or a rocky planet like Earth (*Nature* **500** 427).

Innovation

Neutron study aims to improve HIV drugs

A study of a common component of HIV drugs using neutron scattering has revealed that the component is not as good at bonding as had been thought. The study highlights aspects of the drug component that could be improved to make it better at mitigating the effects of HIV – a damaging virus that replicates using a person's immune system. HIV implants genetic information into the immune system's T-cells, which then produce copies of the virus until they die. Once enough T-cells have died from churning out HIV, the person is unable to ward off other infections and they are said to be suffering from AIDS.

The best known way of tackling HIV is through antiretroviral drugs (ARVs). These consist largely of chemicals known as "reverse transcriptase inhibitors", which prevent HIV from generating its DNA in a T-cell, and "protease inhibitors", which stop an enzyme known as HIV-1 protease from chopping up newly made proteins into the right segments to construct a functional HIV. Protease inhibitors prevent this chopping by bonding to HIV-1 protease themselves, so that the enzyme cannot bond to anything else.

Scientists have previously studied how protease inhibitors bond to HIV-1 protease by using X-ray crystallography. But protease inhibitors bond to HIV-1 protease largely with hydrogen bonds and since hydrogen atoms have only one electron they are almost invisible to X-rays. Now Andrey Kovalevsky at Oak Ridge National Laboratory in Tennessee and colleagues from elsewhere in the US, the UK and France have used neutron crystallography to study the interactions between protease inhibitors and HIV-1 protease. Unlike X-rays, neutrons scatter off atomic nuclei and directly pinpoint the location and strength of hydrogen bonds.

The team performed its study on a protease inhibitor known as Amprenavir, using neutrons from the Institut Laue-Langevin (ILL) in France. Neutron beams are generally weaker than X-ray beams and therefore need larger crystals off which to scatter. However, proteins such as HIV-1 protease do not readily form large crystals, and growing them was one of the group's main challenges.

X-ray studies of the interactions between Amprenavir and HIV-1 had suggested that there were seven hydrogen bonds between the molecules but the ILL data show that there are just four, two of which are weaker than thought. By tailoring the geometry and functional groups of protease inhibitors, drug designers could make them form stronger bonds with HIV-1 protease.

News & Analysis

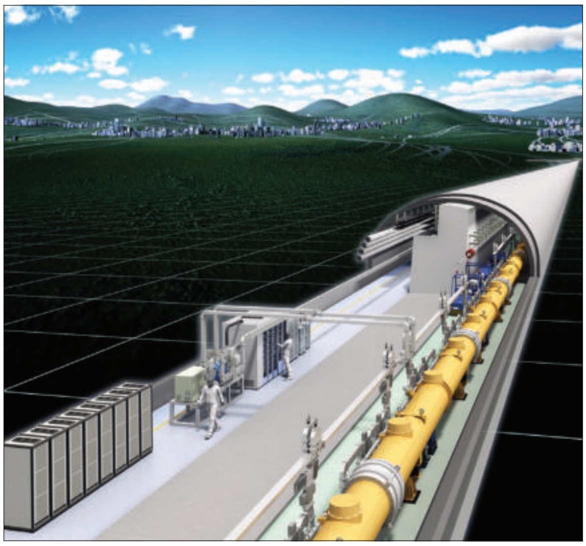
Japan looks beyond the LHC

A site in northern Japan has been selected by a panel as a possible location for the International Linear Collider, but acquiring funding for this potential successor to the Large Hadron Collider will be a long process, as **Michael Banks** reports

Visitors to Tokyo would have witnessed scenes of jubilation last month as the International Olympic Committee announced on 7 September that Japan's capital had been chosen to host the 2020 Olympic Games. Beating off stiff competition from Istanbul and Madrid, the decision to hold the world's biggest sporting event in Japan even caused a 3% rise in Japanese shares that day.

Yet for all the fanfare that the Asian powerhouse will encounter in 2020, researchers in Japan will hope that the games will not be the only big project coming in the next decade to the country's shores. They are also keen for Japan to host the planned $8bn International Linear Collider (ILC) – one option for the next big particle-physics experiment after CERN's Large Hadron Collider (LHC) – and in late August the country took a big step forward to reaching that dream when a potential site for the facility was picked. To be built possibly by the end of the 2020s, the ILC would accelerate bunches of electrons and their antimatter partners, positrons, before smashing them together at a rate of five times per second.

The eight-strong ILC Site Evaluation Committee of Japan, which includes the director-general of the KEK particle-physics lab in Tsukuba, Atsuto Suzuki, opted for the Kitakami Mountains – lying in the Iwate prefecture about 400 km north of Tokyo – as the preferred location for the ILC, if it is to be built in the country. The site has already been endorsed by Lyn Evans, who is responsible for overseeing the design of a future linear collider and who chaired a 12-strong international review committee for Japan's site decision. "[The site] is an excellent scientific choice," he says. "Our next job is to take the rather generic design for the ILC and adapt it to a detailed design fitting the local conditions."



ILC

Grand designs Japan has selected the Kitakami Mountains – lying in the Iwate prefecture about 400 km north of Tokyo – as the country's preferred location for the ILC.

Japan's stock was further boosted last month when its plans to host the ILC were backed in a joint statement from the Asia-Pacific High Energy Physics Panel – comprising particle physicists in Australia, China, India, Japan, Korea and Taiwan – and the Asian Committee for Future Accelerators, which promotes accelerator facilities in Asia, Oceania and the Middle East. The statement adds that the ILC is "the most promising electron–positron collider to achieve next-generation physics objectives".

A second chance

As no other country has yet put its name forward to host the ILC, Japan remains in the lead to host the machine. But with the host country expecting to pay around half of the $8bn cost, the bid will need strong political support. A proposal for Japan's budget next year does contain a line for ILC funding, but only to explore "collaboration". However, University of Oxford particle physicist Brian Foster, who is the Linear Collider Collaboration's regional director for Europe, thinks the ILC's appearance in the budget is "still an important signal". "It will take several years to work it out, but at least it is starting," he says.

Politicians seem enthusiastic about bringing scientists and engineers from around the world to Japan

According to Hitoshi Murayama, director of the Kavli Institute for the Physics and Mathematics of the Universe in Tokyo, who sat on the international review committee, there are about 150 people in the Japanese Congress who actively support the ILC and in July the ruling party LDP published a policy document that mentioned the ILC. However, supporting the ILC is not yet an official position of the government, with the Japanese Ministry of Education, Culture, Sports, Science and Technology waiting for a decision. "Some politicians would love to bring [the ILC] to Japan, while others worry that the rest of science funding in the country may be affected," adds Murayama. "But local governments are sold on the economic benefits, as well as the idea of building a global science city around the ILC."

If the ILC is built in the Kitakami Mountains in the north of Japan – a region that was hit by the 2011 earthquake and tsunami – some of the money from the reconstruction fund could be used to pay for the facility. In fact, one reason for Japan's desire to host a big international facility could be that in June 2005 Japan missed out on hosting the ITER fusion experimental reactor, which is currently being built in Cadarache, France, after it abandoned its bid for the facility to be built in Rokkasho in the Tōhoku region of Japan. "The politicians seem enthusiastic about bringing scientists and engineers from around the world to Japan, which they hoped ITER would do," says Murayama. "Many people now see this as Japan's second chance."

Cleaner collisions

Japan's site selection came just a little over a year after particle physicists around the world celebrated the discovery at the LHC of the Higgs boson – the missing piece of the Standard Model of particle physics –

with a mass of about 125 GeV. After spending eight or so months studying the particle, the LHC was shut down in February to undergo 18 months of upgrades and repairs that will allow it to reach 13 TeV collisions – near its full design energy of 14 TeV – when it switches back on in 2015.

The LHC will also undergo a high-luminosity upgrade that will boost its luminosity five-fold in the early 2020s. This increase will be achieved by installing "crab cavities" that cause the protons to collide head-on rather than cross at a small angle as they do now. There are also plans to give the LHC an energy upgrade later in that decade by installing 20 T magnets that would push the energy of the collider up by a factor of two.

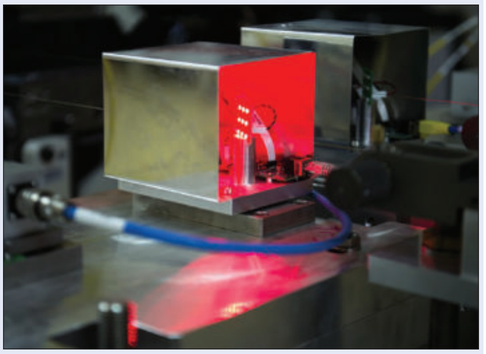
But the ILC will be even more ambitious. Based on 20 years of R&D, the collider will be about 30 km in length and will smash electrons into positrons at energies of about 250 GeV – which is enough energy to study the Higgs. The main focus of the design is the machine's superconducting accelerator technology, which will feature around 8000 1 m-long "superconducting cavities" that will accelerate the electron and positron beams to 250 GeV. As the ILC uses fundamental particles, the collisions will be much cleaner than the LHC's and scientists will be able to precisely measure the Higgs boson's properties and how it interacts with other particles. There would also be scope to upgrade the ILC to 500 GeV and ultimately 1 TeV.

Move over ILC?

The International Linear Collider (ILC) has some competition to become the next big particle-physics experiment after CERN's Large Hadron Collider (LHC). The Compact Linear Collider (CLIC), being developed mainly at CERN, would use a novel "two-beam" acceleration concept that would involve running a high-current electron beam parallel to the main beam. Radio-frequency energy is extracted from this beam and sent to accelerating structures that drive the main electron and positron beams. According to CLIC supporters, the design could achieve collision energies as high as 3 TeV for a 48 km collider – although a shorter, less-energetic collider is also possible.

Yet there are also calls to perhaps ditch linear colliders and stick with circular ones. Some physicists have proposed a new 80–100 km ring that would not only study the Higgs, but also be used in the future for a 100 TeV proton collider. Dubbed "TLEP", the facility – which could be based near Geneva like the LHC – would operate at around 350 GeV, or even 500 GeV. Most of the cost of such a machine would be in excavating the tunnel, with the accelerator itself costing about one-third of the total. Researchers are planning to complete a conceptual design study by 2017 as an input to the next review of the European strategy for particle physics.

Some are thinking outside the box regarding the next particle collider. Physicists working in the International Coherent Amplification Network (ICAN) are looking into ways to combine the beams of tens of thousands of fibre lasers – a common component in the telecommunications industry – and coherently combine them into a "superbeam". The electron beams would be collided with photons from ICAN-style lasers to produce backscattered 63 GeV gamma-ray photons. These would then be collided to produce the Higgs.



CERN

Going through the options CERN has been developing technology for the CLIC – an alternative to the ILC.

Another option for a future particle smasher is a muon collider – one that would bang together positive and negative muons. As the muon is 200 times heavier than the electron, it presents an attractive alternative because it could reach the same energy at much lower speeds and not require at least 30 km of accelerator. It would also lose far less energy through synchrotron radiation if used for circular acceleration. However, while muons have some advantages over electrons, they are unstable and have a half-life of just over 2 μs, which means they have to be accelerated and collided very quickly. In August Nobel laureate Carlo Rubbia called for a muon collider demonstrator to be built to test the technology for a muon collider that could be used as a "Higgs factory" (arXiv:1308.6612).

Evaluating times

Although the ILC is not the only game in town for the next big particle-physics experiment after the LHC (see box), Japan has, in fact, been searching for a site to host the collider since 1999. Back in 2003, 10 candidate sites were proposed, which were narrowed down to two in 2010 – the one in the Kitakami Mountains and the other in Sefuri on Kyushu, the southernmost of Japan's four main islands. In January the ILC Site Evaluation Committee of Japan began to examine the two options and plumped for the 50 km route under the Kitakami Mountains after some 300 hours of meetings. The committee noted that both sites had a "very good geology that satisfied the minimum conditions" for construction of the ILC but they varied in terms of risk and cost.

On closer comparison, the Kitakami site had the edge in terms of the risks of construction and operation, as well as cost. One main issue for the Sefuri site was that it would pass under a lake and a town. "The Sefuri site had several issues that the chosen site does not have," says Murayama. "There are active faults on parts of the proposed route, a reservoir and dam above the route that may make waterproofing an issue as well as a residential area that may make it harder or longer to obtain necessary permits."

Yet that does not mean there are no issues with the Kitakami site. The proposed route would also go under a river, with only 20 m rock below the riverbed, but the site does have the upper hand in terms of the geological conditions for tunnelling and stability. "Overall, the chosen site has a very good geological condition, and even after the earthquake on 11 March 2011 it did not 'bend' the rocks; they moved together," adds Murayama. "It looks very suitable for the ILC and we approved the chosen site unanimously." That view is backed up by Evans. "The chosen site is in very good geological condition, allowing an eventual upgrade of the energy with no active faults and a wealth of seismic data from the [March 2011] earthquake," he says.

The benefits of the Kitakami site were further boosted given that it would be near a Shinkansen railway line. However, the committee's report warns that more would need to be done in terms of integrating the foreign researchers who would work at the site, including boosting the number of international schools in the region. "Given Japan's ageing and declining population, opening up the country is a major push by politicians," says Murayama.

Astronomy

Survey hopes to pin down universe's dark secrets

Astronomers have embarked on a project to map 300 million galaxies in the southern sky over the next five years. Using a 570 megapixel camera installed at the 4 m Victor Blanco Telescope at Chile's Cerro Tololo Inter-American Observatory, the Dark Energy Survey (DES) aims to determine what is responsible for the accelerating expansion of the universe.

The DES will use four different methods to study dark energy. It will count galaxy clusters to examine the repulsive gravitational nature of dark energy as well as measure the brightness of up to 4000 supernovae to determine the speed of the universe's expansion since they exploded. The survey will also study the bending of light by measuring the shapes of 200 million galaxies. Finally, it will monitor sound waves generated in the universe's first 400 000 years to create a large-scale map of cosmic expansion over time.

"It's the quintessential next-generation dark-energy experiment – the largest galaxy survey ever made," says astrophysicist Josh Frieman from Fermilab and the University of Chicago. "The goal is starting to nail down [dark energy's] properties, which requires much larger surveys than before." Key to the survey is the telescope's 570 megapixel camera, which has a three square degree field of view and a good sensitivity to red light – an important factor when dealing with highly red-shifted galaxies. "It's an excellent telescope and an excellent astronomical site," Frieman adds "We wanted to be in the southern hemisphere to study the same sky as the South Pole Telescope, which has been surveying the cosmic microwave background and clusters of galaxies."

CTIO

Surveying the heavens
Astronomers have begun to use the 4 m Victor Blanco telescope at Chile's Cerro Tololo Inter-American Observatory to map 300 million galaxies in the southern sky.

The DES is not the only new project to probe dark energy. In February the Japanese Hyper Suprime-Cam (HSC) project will start surveying the northern sky using an 870 megapixel camera on the 8.2 m Subaru Telescope in Hawaii. "The DES is certainly a good competitor," says HSC head Satoshi Miyazaki from the National Astronomical Observatory of Japan in Mitaka. "The DES and HSC are complementary to each other. They go wider and shallower; we go narrower and deeper."

Meanwhile, in December the Extended Baryon Oscillation Spectroscopic Survey (eBOSS) – a spectrograph installed on a 2.5 m optical telescope at Apache Point Observatory in New Mexico – will begin to survey the universe's expansion history after its first three billion years. "Although our current footprint is only one tenth of the size of the DES, [eBOSS] should nevertheless be very useful to calibrate [DES's] photometric red shift," says Jean-Paul Kneib of Switzerland's École Polytechnique Fédérale de Lausanne who is eBOSS's principal investigator.

Later this decade should also see the start of the Dark Energy Spectroscopic Instrument project on Kitt Peak, Arizona, while in the 2020s the 8.4 m Large Synoptic Survey Telescope in Chile will survey the entire visible sky.

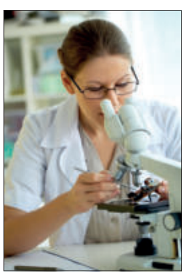
Peter Gwynne
Boston, MA

Women in physics

'Impostor syndrome' shown to drive women away from physics

Women could be shying away from top research positions in computing, physics and mathematics, because of the well-known psychological frame of mind called "impostor syndrome". That is according to a new study by sociologists at the University of Notre Dame in Indiana, who found that the effect is most felt in the theoretical sciences and that it could be compelling women to leave research for careers in science communication and teaching.

Impostor syndrome is the feeling that you have somehow fooled your peers into thinking that you are competent – and that any success you have had is down to luck and others failing to see your flaws. In the new study, Jessica Collett and Jade Avelis surveyed 461 PhD students at Notre Dame and found that many women who had left – or were planning to leave – research cited concerns about their competency and talent to succeed. Men also suffered from it, but less so than women.



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A frame of mind
A new study suggests that "impostor syndrome" may be a reason why some women leave science.

The researchers say that such women may be performing exemplary work in their job and outwardly they may not display such concerns, putting up a facade of assuredness that only adds to their distress as they worry about being "found out". Data from the study and accompanying interviews suggest that women may actively avoid situations that they think are beyond their strengths and instead pursue activities that they perceive themselves as being better suited to, such as teaching.

Why women experience impostor syndrome more than men is still a puzzle. One explanation is what Collett calls "fixed personality characteristics", which are ingrained in a person at an early age. "The other explanation for the gender difference is more social and stems from women being more likely to be uncomfortable with their success," adds Collett. "They may perceive success in certain spheres as a masculine accomplishment, or simply feel that they don't belong in a high achievement domain because of gender stereotypes."

Intriguingly, the study, which was presented in August at the annual meeting of the American Sociological Association in New York, found that US students are more likely to suffer from impostor syndrome than their visiting overseas counterparts, which implies a cultural disparity.

Gemma Lavender

People

Rubbia appointed life senator in Italy

The particle physicist and Nobel laureate Carlo Rubbia has been chosen as one of just six elite "life senators" by Italian president Giorgio Napolitano. The appointment of the former director-general of CERN to Italy's upper house is the latest in a long list of accolades for the 79 year old, who shared the 1984 Nobel Prize for Physics with Simon van der Meer for their contributions to the discovery of the fundamental particles that mediate the weak nuclear force.

Matin Durrani

Power player Nobel laureate Carlo Rubbia was announced last month as one of four new life senators in Italy.

According to the country's constitution, the Italian president may appoint up to five life senators during his or her time in office, drawing on citizens "who have honoured the nation for outstanding achievements in the social, scientific, artistic and literary fields". The chosen individuals have the same voting rights as the country's 300 or so elected senators – rights that they hold for the rest of their lives. Each month senators receive an after-tax salary of around €5000 and expenses of up to €9000.

Joining Rubbia in the upper house of parliament will be architect Renzo Piano, conductor and music director Claudio Abbado, and stem-cell researcher Elena Cattaneo. The quartet was appointed following the deaths of four life senators in just over a year – including the 103-year-old neurologist Rita Levi-Montalcini in December 2012. The four new life senators will sit alongside two existing life senators – ex-prime-minister Mario Monti and former president Carlo Azeglio Ciampi.

In a statement, President Napolitano described the new senators as "bearers of truly exceptional CVs and talents" who, he said, would provide a "special contribution, in highly significant fields, to the life of our democratic institutions". And referring to the 50-year-old Cattaneo, who is very young by the standards of most life senators and a relative unknown, he said he wanted to give a "strong signal of appreciation, and encouragement" to the many young Italians who dedicate themselves "despite the difficulties" to scientific research.

Fernando Ferroni, president of Italy's National Institute of Nuclear Physics, says that Rubbia's selection is recognition of "a character of extraordinary intelligence, superhuman energy and incredible passion for physics". According to Italian science-policy expert Renzo Rubele, a physicist at the Free University of Brussels in Belgium, Napolitano has "returned to the original spirit of the constitution" by selecting the new life senators from the world of culture rather than picking former politicians, as his predecessors tended to do.

Yet Rubele points out that the appointments have been politically controversial. Although not formally aligned with any political party, the four are, he says, like previous life senators, all "left-minded". With frequent weak majorities in the Senate meaning that life senators' votes can sometimes be decisive in determining the outcome of confidence motions and other important bills, politicians aligned with the centre-right former prime minister Silvio Berlusconi, he explains, "have been putting pressure on successive presidents either to compensate for this situation or to abstain from nominating new life senators".

Edwin Cartlidge

Particle art lights up Victorian ice well

Richard Davies

A new physics-inspired art installation has opened to the public at the London Canal Museum. Entitled *Covariance*, the work was commissioned by the Institute of Physics, which publishes *Physics World*, and was created by artist Lyndall Phelps in collaboration with Ben Still, a particle physicist from Queen Mary University of London. *Covariance* is inspired by the SuperKamiokande underground neutrino observatory in Japan and the way in which particle physicists visualize their data. The kaleidoscopic artwork is located in a Victorian ice well beneath the museum and is a reference to the subterranean location of many neutrino experiments. The artwork comprises hundreds of hand-crafted acrylic discs, each patterned with glass beads and diamantés, connected together with brass rods. Strings of these discs have been suspended from the ceiling of the ice well in concentric circles with an outer diameter of about 9 m. The artwork will be available to view until 20 October.

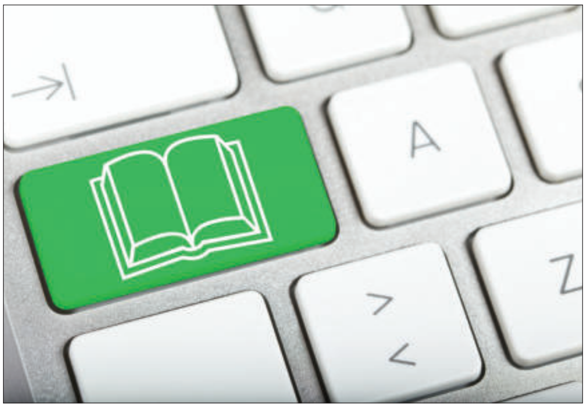
James Dacey

Publishing

UK urged to rethink open-access policy

A group of parliamentarians in the UK says the government should rethink its open-access policy for scientific publishing that was introduced in April. Members of the House of Commons' Business, Innovation and Skills (BIS) committee say in a report released last month that the government and the Research Councils UK (RCUK) – the umbrella organization for the UK's seven research councils – should reconsider their preference for "gold" open access over "green". The government opted for gold after accepting the recommendation made in a report on open access published in June 2012 by the sociologist Janet Finch along with academics, librarians, publishers and members of learned societies.

Gold open access refers to an author paying an article processing charge (APC) to publish in an open-access journal, with the finalized published paper then being made immediately available for anyone to read – and reuse – free of charge. Green open access, meanwhile, is when a paper is published in a subscription journal but after a certain embargo period, typically 12 months, the accepted manuscript is allowed to be placed in a centralized free-to-access repository. After the Finch report came out, RCUK said its policy would be to phase in gold open access starting in April 2013, estimating that around 45% of the research it funds in 2013 would be gold, with the proportion rising to three quarters by 2017.



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Going for green? A committee has suggested that the UK should backtrack from its preference for gold open access.

While the BIS committee, chaired by Adrian Bailey, says that gold is the "desirable ultimate goal" in the long term, it adds that focusing on gold during the transition to full open access is a mistake. "Almost without exception, our evidence has pointed to gaps in both the qualitative and quantitative evidence underpinning the Finch report's conclusions and recommendations," says the committee. "Most significantly a failure to examine the UK's green mandates and their efficacy."

In a statement, Finch says that many of the committee's conclusions are the same as those made in her report, including the need to have a mixture of green and gold during the transition period. However, Finch adds that she is "disappointed" not to have been invited to give evidence and that there are some "unfortunate gaps" in the MPs' report. "There are issues where the select committee appears to have misread our report, and others where we simply took a different view of the evidence and of stakeholder concerns," says Finch.

An RCUK spokesperson says that it will consider the committee's recommendations "carefully". "We continue to have a preference for open access through gold, with its more immediate benefits for society, the economy and wider research, while continuing our commitment to supporting a mixed model for both gold and green routes for open access." The RCUK will conduct a review of its open-access policy in 2014.

Michael Banks

Research

Universities hit by £2.4m fines for lack of grant reports

Several UK universities have had to return substantial sums of grant money to the country's research councils after failing to comply with the funders' terms and regulations. In total, the seven research councils in the UK that belong to the Research Councils UK (RCUK) have imposed financial sanctions of more than £2.4m during the past five years. The figures came to light following a Freedom of Information request from the *Times Higher Education*.

The Engineering and Physical Sciences Research Council (EPSRC) has levied the most fines, totalling £1 420 471, although £704 455 of that is still subject to appeal. At the other end of the scale, the Science and Technology Facilities Council and the Arts and Humanities Research Council have not issued any fines, while the Medical Research Council issued one fine for £46 985. The other three research councils have each demanded more than £300 000 back.

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Cash back Some research councils have clawed back thousands of pounds in fines after universities failed to meet the terms of grants issued to them.

One trigger of a penalty is if a university fails to meet deadlines for submitting financial reports. "If the final report or the financial expenditure statement is not received within the period allowed, the research council may recover 20% of expenditure incurred on the grant," the RCUK says on its website. If that report is not received within six months of the end of the grant, the university may lose the entire sum. "We have rigorous reporting requirements to the Department for Business, Innovation and Skills on the outcomes and impacts of the research we are funding, and we need to ensure effective and efficient use of resources," says RCUK spokesperson Katie Clark. "We can only do this accurately and efficiently when universities comply with the terms and conditions of their grants."

The biggest institution to be hit was the University of Edinburgh, which had to pay back £291 132 to EPSRC. A spokesperson for the university says that while it is pleased that the terms are met for the vast majority of its grant income, Edinburgh is "clearly concerned" that for a small number of awards the university does not meet them. Individual research councils declined to comment, but noted that they had all contributed to the joint RCUK statement.

Katia Moskvitch

People

Graphene pioneer Konstantin Novoselov goes Dutch

The 2010 Nobel-prize winner Konstantin Novoselov of the University of Manchester in the UK has taken up a part-time role at Radboud University Nijmegen in the Netherlands. Novoselov, 40, will hold a special chair in the electronic properties of novel materials at the university, which will be funded by Nijmegen's High Field Magnetic Laboratory (HFML), where the Nobel-prize winner carried out parts of his PhD research.

The Dutch physics community has welcomed the appointment, adding that it underlines the "special relationship" between Novoselov and Radboud University Nijmegen. Between 1997 and 2001, Novoselov worked at the university together with his former mentor Andre Geim, with whom he shared the 2010 Nobel prize for their work on the properties of graphene. Since its discovery in 2004, interest in this "wonder material" has rocketed – both in terms of fundamental science and potential future applications.

Novoselov, who was born and raised in Russia, says that he is honoured by the new position – which will not be paid, except for expenses – stressing that it seals a long-standing collaboration with Nijmegen. Indeed, Novoselov has visited the HFML regularly to conduct experiments and he will continue to give

On the move University of Manchester physicist Konstantin Novoselov has taken up a part-time role at Radboud University Nijmegen in the Netherlands.

occasional colloquia, although the new job will not involve any formal teaching commitments.

Nijmegen created a similar academic chair for Geim in 2010 and Novoselov has now been honoured in the same fashion. "Somehow, exact academic positions seem to be much more important to the Dutch than they are here," Novoselov told *Physics World*. "I am only interested in doing my research as much as possible, the where and how is irrelevant, frankly."

In 2001 both Novoselov and Geim left the Netherlands to take up positions at Manchester, apparently after Geim failed to find a position at several Dutch universities. Indeed, after the pair won the Nobel prize, which was for work they did in 2004 while at Manchester, both Novoselov and Geim complained that the Dutch research system was too rigid and did not give researchers space for creative fundamental research. The comments caused a storm in the Dutch media and within the Dutch research community.

Graphene theorist Carlo Beenakker of Leiden University welcomes Novoselov's appointment. "He comes to Nijmegen a lot anyway, working with graphene-theorist Michael Katsnelson, and with Geim already holding a visiting professorship, adding Novoselov seems logical," says Beenakker. "Geim and Novoselov are part of the Dutch graphene scene."

Gerard Meijer, dean of Nijmegen, adds that having Novoselov at the HFML will be "a true inspiration" for students and staff there. "To work with him is a unique opportunity that we would like to preserve." However, Jan Kees Maan, director of the HFML, who supervised Novoselov during his PhD, admits that while the appointment is welcome, it comes a little late. "I think it is healthy for a young, brilliant scientist like Novoselov to find a career elsewhere, like at Manchester," says Kees Maan, "even if in hindsight our university appears to have missed a Nobel laureate in the process."

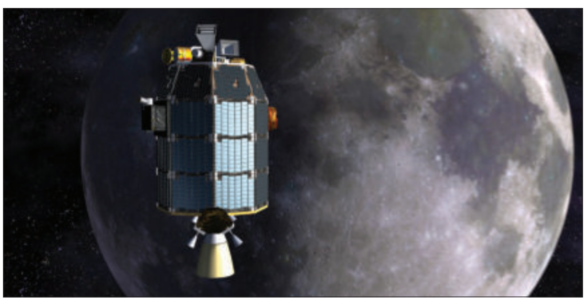
Martijn van Calmthout
Amsterdam

Astronomy

NASA's LADEE survives post-launch problem

NASA has successfully launched a mission to the Moon with the goal of gaining detailed information about the lunar atmosphere. Despite a minor glitch soon after take-off from NASA's Wallops Flight Facility in Virginia, the Lunar Atmosphere and Dust Environment Explorer (LADEE) safely began making its way to the Moon, which it will study from an almost circular orbit some 250 km above the lunar surface for a period of 160 days. The craft is set to reach its destination early this month.

LADEE will feature three scientific instruments including an ultraviolet and visible-light spectrometer that will analyse the lunar atmosphere's composition by studying its components' spectra. The mission



Fly me to the Moon LADEE will study the lunar dust from an altitude of 250 km.

also has a mass spectrometer that will monitor variations in the lunar atmosphere over the course of several orbits of the Moon at different altitudes and a lunar-dust experiment that will collect and analyse particles in the Moon's atmosphere. "A thorough understanding of these characteristics will address long-standing unknowns, and help scientists understand other planetary bodies as well," NASA said in a statement.

In addition, the mission will demonstrate the use of lasers – rather than radio waves – to communicate with Earth from altitudes higher than low-Earth orbit. Laser communication should provide the speeds necessary to transmit high-definition data and 3D video to Earth from planetary missions, such as future manned flights to Mars.

The glitch after LADEE's launch involved a shutdown of the craft's positioning system shortly after separation from its rocket. Engineers quickly determined that the problem stemmed from a system intended to protect the reaction wheels that steer and stabilize the craft. According to NASA, the fault was "selectively re-enabled".

Peter Gwynne
Boston, MA

Sidebands

China to launch Moon mission
China has announced it will send an unmanned rover to the Moon by the end of the year. Dubbed Chang'e 3, the 100 kg, six-wheeled rover will spend three months traversing the lunar landscape transmitting images and digging into the Moon's surface to test samples. China's first Chang'e probe was launched in 2007 and completed a 3D map of the Moon's surface, while Chang'e 2 – which took off in 2010 – carried out further mapping of the Moon's surface at an altitude of 100 km. Chang'e 3 is far from the end of China's interest in the Moon as the country is planning to send a manned mission to the lunar surface by 2017.

France invests in nanotech
France has announced it will extend its nanotechnology R&D programme for another five years. Nano2017 will run from 2013 until 2017 with a total funding of around €3.5bn. The French prime minister Jean-Marc Ayrault has said the government will fund an initial investment of €600m, together with €400m expected to come from the EU and €1.3bn from French–Italian semiconductor manufacturer STMicroelectronics. Research will focus on high-performance processing, next-generation imaging and non-volatile memories. The programme will involve over 100 partners including university departments, equipment manufacturers and small businesses. Nano2017 follows on from Nano2012, a similar public–private initiative launched by the then French president Jacques Chirac in 2007.

Sound pioneer Ray Dolby dies
The physicist and sound engineer Ray Dolby died on 12 September at the age of 80. Dolby helped to develop an electronic noise-reduction system, dubbed Dolby NR, which effectively eliminated the hiss that used to be heard in quieter passages in films. The speaker system was a revelation within the film industry and helped to transform cinema-going. Born on 8 January 1933 in Portland, Oregon, Dolby was raised in San Francisco before going to Stanford University in 1954 to study electrical engineering, where he worked on early prototypes of the video tape recorder. In 1961 he won a Marshall Scholarship to do a PhD in physics at the University of Cambridge. After a stint as a technical adviser to the UN in India until 1965, Dolby returned to the UK to found Dolby Laboratories, where he developed his novel noise-reduction system.

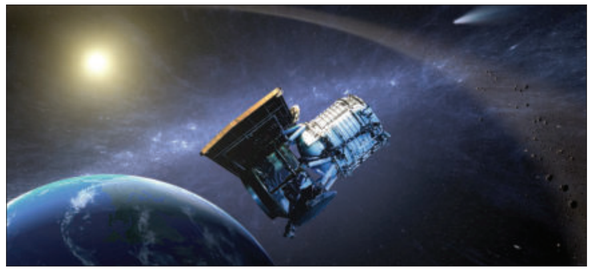
Astronomy

Infrared telescope revamped as asteroid hunter

NASA has confirmed that its dormant Wide-Field Infrared Survey Explorer (WISE) craft will be rebooted to begin a three-year mission to search for near-Earth objects (NEO) that could be on a potentially fatal collision course with Earth. The spacecraft will also identify asteroids that future missions could capture and bring back to Earth orbit for scientific study or mining.

Originally launched in late 2009, WISE used its 40 cm telescope and two infrared cameras to perform an all-sky survey at wavelengths of 3.4 μm and 4.5 μm. Before its hydrogen coolant ran out in late 2010, the telescope tirelessly made around 7500 images every day. For four months until early 2011, the spacecraft also made a survey of NEOs, detecting asteroids within 45 million kilometres of Earth's orbit.

Following congressional hearings that pressed NASA and other agencies to speed up their plans for effective asteroid detection after more than 1500 people were injured when a small asteroid exploded above Chelyabinsk in Russia, the space agency announced in August that it would now restart WISE to search for asteroids through the heat they emit. "We see the same signal regardless of whether an asteroid is bright or dark like a piece of charcoal. Therefore, with infrared, we can obtain an accurate measurement of an object's true size," James Bauer from the Jet Propulsion Laboratory told *Physics World*.


NASA/JPL-Caltech

Second life NASA has announced that WISE will now spend three years searching for asteroids.

WISE could also identify asteroids that future missions could capture and bring back to Earth's orbit for scientific study or even mining, and help US president Barack Obama's aim to send humans to an asteroid by 2025. However, according to Bauer, it is unlikely that WISE can last beyond the three-year extension as it does not have any onboard propulsion system and its orbit would then have "decayed to the point that we will not be able to keep sunlight out of the telescope anymore".

Gemma Lavender

Mexico

Pixqui puts space equipment to the test

The Mexican Space Agency (AEM) is collaborating with NASA to test a device designed for Mexico's fledgling space industry as well as other space agencies. Known as Pixqui, which means "guardian" in the pre-Hispanic language Nahuatl, the device can be put onto a NASA scientific balloon and loaded with instruments to monitor if they will function properly in a vacuum and in extreme temperatures. Pixqui was designed and constructed by a group of scientists from the National Autonomous University of Mexico (UNAM), with support from the National Council for Science and Technology and AEM.

On 19 August the AEM tested prototypes of Pixqui for a high-energy cosmic-ray telescope – the Japanese Space Agency's Extreme Universe Space Observatory (EUSO) – that is planned to be placed on the International Space Station in the next few years.


UNAM

Testing, testing Pixqui can be used to see if instruments in space missions can function in extreme temperatures.

Researchers in Mexico were responsible for building the "nervous system" for the EUSO, which consists of the electronics that transmit information between the telescope's main CPU and its systems. "The idea is to correct eventual failures in the functioning of the devices, before sending them to space," says Gustavo Medina Tanco, Pixqui project leader from the Nuclear Sciences Institute of UNAM.

Pixqui will be a boost for the development of space technology in Mexico, in particular by providing opportunities for engineers and physics students to work for the first time with other space agencies. Medina Tanco adds that Mexican universities on their own will not be able to fulfil the growing demand for the development and construction of devices that can operate in space and calls for the creation of new companies in Mexico to fill the gap.

Gabriela Frías Villegas
Mexico

Opening data up to scrutiny

New tools and technologies are increasingly allowing researchers to share their data in online repositories. **Edwin Cartlidge** looks at the benefits and the costs of "open data"

There was a time when a scientific paper was satisfyingly self-contained. In their experimental report, scientists would typically provide a complete description of the method and apparatus they had used, most of the data collected, an analysis of uncertainties, and any other information needed to repeat the experiment. Everything, in other words, that would allow another scientist to try and replicate the results or to extend the research in some way.

Today that is no longer the norm. The advent of digital technology in recent decades has led to an explosion in the amount of data that can be collected by experiments and then stored – in some cases trillions of bytes' worth. This "data deluge" has led to important discoveries, but it means that papers usually do not contain all of the data needed to underpin their conclusions. And that, argues University of Edinburgh geologist Geoffrey Boulton, who chaired a 2012 Royal Society working group looking into the matter, poses a serious threat to science. "We have lost sight of what we are doing," says Boulton, referring to the process of independent experimental verification that lies at the heart of the scientific method. "The things we do with data are really quite shocking."

However, just as modern technology has created the problem, it also offers a way out. Scientists, learned societies and governments have started to extol the virtues of "open data". This is the idea that scientists make their data available in online databases that can be reached from, or at least referenced by, the papers that they write. These data would include all the raw measurements they make, including any null results, in the form of text, images or video, as well as the "metadata" needed to interpret these measurements, and any other relevant information, such as lab notes, ideas and project plans. All this information would be made available to other scientists and, with suitable accompanying explanations, to the general public.

The 2012 Royal Society working group said it was "unequivocal that there is an imperative to publish intelligently open data when that data underlies the argument of a scientific paper". Three years earlier the US National Academies of Science had also argued for a similar course of action, recommending that "all researchers should make research data, methods and other information integral to their publicly reported results publicly accessible". This position was heeded this February by the US government when it announced a set of policy principles for ensuring public access to research publications and data.

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Free for all
Could experimental data – not scientific papers – be the way that scientists gain recognition?

The benefits of openness

However, the open-data movement is still very much in its infancy, and there remains a considerable gap between the good intentions of learned societies and the reality of life in the lab. Boulton believes that scientists have a responsibility to make their data publicly available, arguing that "to do otherwise is malpractice". But as the research system currently stands many scientists lack the motivation to put their data in the public domain, argues Paul Ginsparg of Cornell University in the US, founder of the *arXiv* preprint server. "It takes significant additional effort to archive and document data for others to use," he says. "Even the most idealistic researchers might have difficulty justifying the time investment if a publication and its attendant rewards are possible without uploading the data."

To date, the main focus of scientists' efforts to ensure their work is available to all has been making scientific research papers free to anyone to read through the principle of "open access" (see August pp22–27). Arguably, however, open data would represent a more fundamental change to the practice of modern science than open access. While the latter makes available the finished products of research, the former supplies the raw material, providing the means for detailed and precise tests of the claims made in scientific papers. It is only with this material in hand, says Boulton, that other scientists can expose fraud and data manipulation, and fully exploit research to generate new knowledge.

Indeed, Boulton believes that vast quantities of such freely available data could also help spur what has been referred to as a "fourth paradigm of science". Following the established trio of experiment, theory and simulation, this fourth element would be the identification of previously unseen relationships within data thanks to the vast processing power of modern computers. It is an approach, Boulton argues, that inverts the process of doing science as envisaged by philosopher Karl Popper – rather than hypotheses being products of the imagination that are then interrogated through experiment, they are instead formed via induction from pre-existing data. "It is now looking as though Popper was wrong," says Boulton, "and that in this new world of big data, induction might be quite a powerful process."

A template for the dissemination of open data has been put forward by an international group of scientists, librarians, publishers and funding agencies known as Force 11. Their model "executable paper" involves adding interactive features to traditional static texts, including links to primary data that allow readers to manipulate that data while reading the paper and so, at least in principle, put the stated conclusions to the test. In addition, if the authors grant permission, readers can scrutinize the computer code underlying the experiments described.

While this vision has yet to be fully realized, a number of organizations are trying to bring it about (see box). These include the commercial company Figshare set up by Mark Hahnel, who says he became frustrated at not being able to publish all of his research data while doing a PhD in stem-cell biology at Imperial College in London. He envisaged sharing his data by breaking them down into their constituent parts, such as single graphs or figures, for research, he says, "where the results were null, or didn't fit into a larger publishable story for whatever reason". Figshare provides a public, permanently available repository for individual researchers as well as universities and publishers to share their data with the wider world – with annual institutional licences covering the costs of the free service provided to individuals. Having been in operation since 2012, Figshare currently hosts around 1 million publicly available data units, says Hahnel.

Going public

While services such as Figshare simplify the process of uploading data to the Internet, researchers will in many cases still have much to do in making the fruits of their labour available to others. As the Royal Society report points out, there is a big difference between simple disclosure of data and what it calls "intelligent openness". Much of that difference lies in providing the "metadata" that allow others to interpret the output of specific experiments. These metadata include basic details such as the name of the person who created the research data, when those data were created and who paid for the research, as well as more subtle information such as how the data were acquired, how they were treated and analysed, and how they should be used.

One field that is at the forefront of open data is astronomy, with the Sloan Digital Sky Survey, for example, having provided images of hundreds of thousands of galaxies online. However, other areas of physics are less well suited to public scrutiny. Particle physics involves sharing data in large networks of distributed computers. Those data are not at all user-friendly either, since their interpretation requires the results of complex computer models that characterize the efficiency of the particle detectors.

"Unlike astronomy, which is accessible to everyone, here the metadata come in the form of a dirty great simulation," says Tony Hey, who trained in particle physics and is now in charge of Microsoft's collaboration with universities and other research organizations.

Indeed, Ginsparg thinks physicists are likely to find it tough-going to provide open data. In addition to the time needed to make data available and understandable, many researchers will probably fear being scooped if they release their data too early. Ginsparg points out that the *arXiv* server already permits any kind of data to be uploaded alongside research papers, but that there has been relatively little demand for this service so far. And then there is the question of privacy. The possibility, he says, that ostensibly anonymized data actually contain systematic patterns that reveal subjects' identity "will give researchers pause".

Opening up data

A number of organizations are providing services to make research data publicly available and usable.

Figshare (http://figshare.com) is a general-purpose online repository where individual scientists and institutions can store and share research data, and make these data citeable.

Dryad (http://datadryad.org) shares many of the features of Figshare, accepting a wide range of data formats and allowing data to be cited.

DataCite (http://datacite.org) helps researchers find and cite datasets, and facilitates links between research articles and underlying data.

Labarchives (http://labarchives.com) provides electronic lab notebooks, allowing researchers to organize and preserve their data, view lab data remotely and publish data to specific individuals or to the public.

Scientific Data (www.nature.com/scientificdata), to be launched in spring 2014, will contain articles that describe experimental and observational data sets, allowing researchers to receive credit for publicly available data.

Data must be recognized as contributing to the body of scientific knowledge

Making data pay

For many, the key to stimulating open data is to put suitable rewards in place. Alex Wade, director of scholarly communication at Microsoft and a contributor to a recent report by information providers Thomson Reuters on open data, points out that many decisions regarding university hiring and promotion and the allocation of grants are based on researchers' records of publication in high-profile journals. He would like to see such decisions also being made on the basis of data dissemination, by recording and recognizing the number of times specific data are reused by other researchers. "It would be progress to see a more diverse set of research outputs and metrics considered in measuring scholarly impact," he says. "Data must be recognized as contributing to the body of scientific knowledge."

However, such credit is likely to become meaningful to researchers only if it results in tangible benefits. Such benefits will be discussed as part of a "road map" on research data that the League of European Research Universities is due to release by around the end of the year, according to Paul Ayris, director of library services at University College London, who adds that the road map will recommend that researchers who share data should get career recognition. "I can't say what criteria academic appointment committees will use in the future," he adds, "but in my view data sharing will come to be seen as a mark of best practice within the next five to 10 years."

However, it remains to be seen just how keen universities are on open data. Boulton says that in the UK, university vice-chancellors "see more costs than benefits" and are also worried that industry might not like the idea of collaborative data being made public. Boulton, though, believes that sharing data should be seen as part of the normal scientific process. "It is a false dichotomy to say that you either do science or you handle the data," he says. "Very simply what we want is the greatest scientific bang per buck."


Accelerating universe
BEC
Quantum teleportation
5 DISCOVERIES
Neutrino mass
Higgs boson
Meg Urry
PHYSICS WORLD AT 25
5 IMAGES
The dark universe
Exploiting quantum mechanics
5 QUESTIONS
Quantum gravity
Time
Alien life

25 years of *Physics World*

To celebrate the 25th anniversary of *Physics World*, we bring you 25 tasty treats concerning the past, present and future of physics.

Five discoveries
We kick off with the five most significant discoveries in fundamental physics over the last 25 years. Narrowing down the huge list of possibilities to the five best was hard work for the *Physics World* editorial team, but we've made our call. Each has proved to be a technical *tour de force* and involved a close interplay between theory and experiment (pp25–28).

Five questions
Next up, we look at the five biggest unanswered questions in physics right now. We thought long and hard about the precise wording for the questions, and have invited five top physicists to explain the importance and significance of each. Find out more from Catherine Heymans, Adam Frank, Ray Jayawardhana, Sabine Hossenfelder and John Preskill (pp33–46).

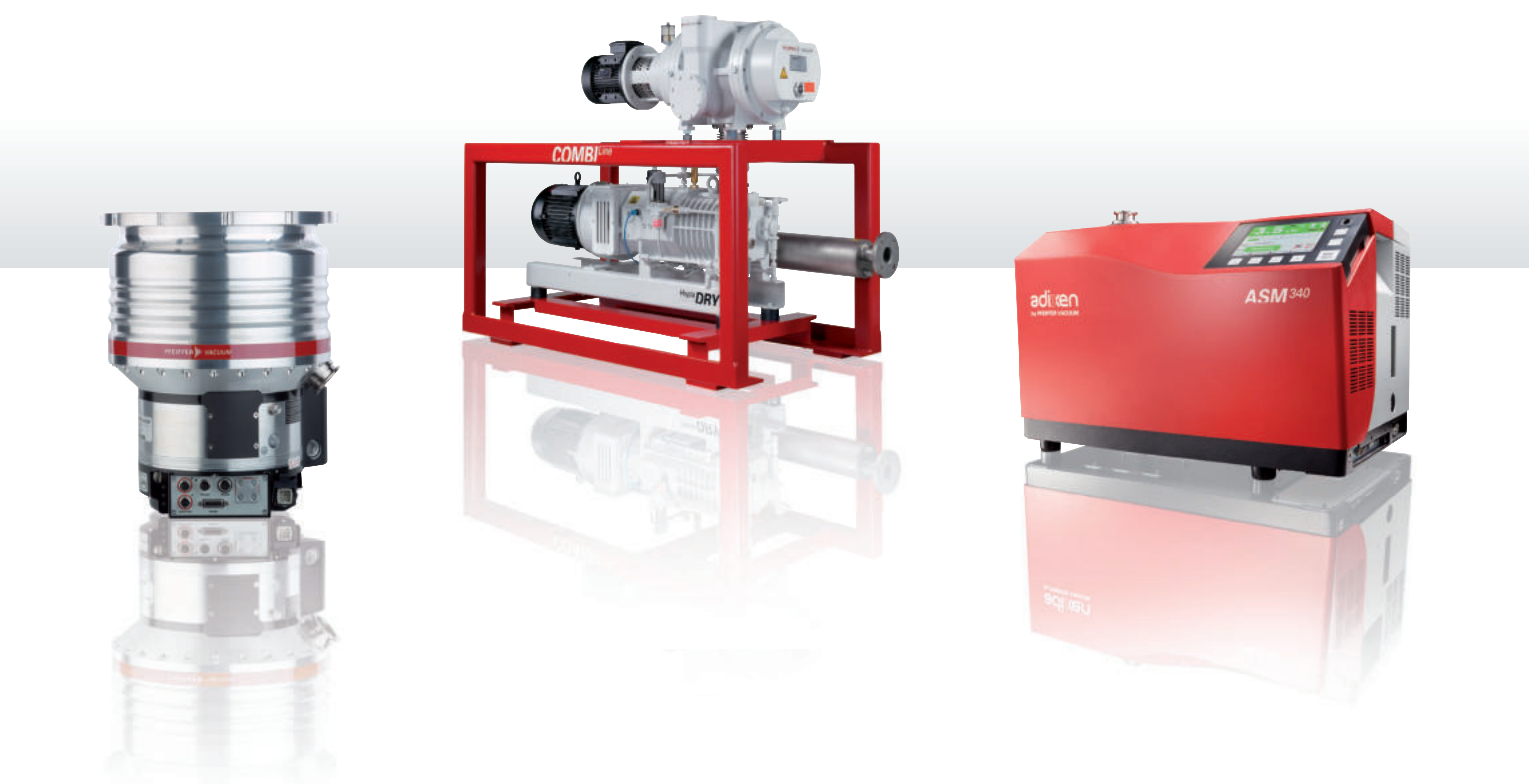
Five spin-offs
We've selected five technological spin-offs from physics research that we think will do most to change the lives of people around the world in the coming years. Predictions are, of course, easy to get wrong, but we've plumped for five spin-offs that physicists are already developing – so we reckon our forecasts will not be too far off the mark (pp50–53).

Five people
We profile five people who are representative of the way physics is changing, in that they are nurturing new talent in the developing world, building bridges with other disciplines, or making physics more welcoming to women, those from minority groups and non-scientists. Our "famous five" are by no means the only physicists contributing to these efforts, but are certainly among the leaders (pp57–65).

Five images
Interspersed between the above sections are five full-page images from the last quarter-century of physics. Each image is noteworthy for having let us "see" an important physical phenomenon or effect, which is why we haven't selected any photos of people, buildings or scientific equipment. The images are all eye-catching for sure – but they've not been picked on grounds of prettiness alone.

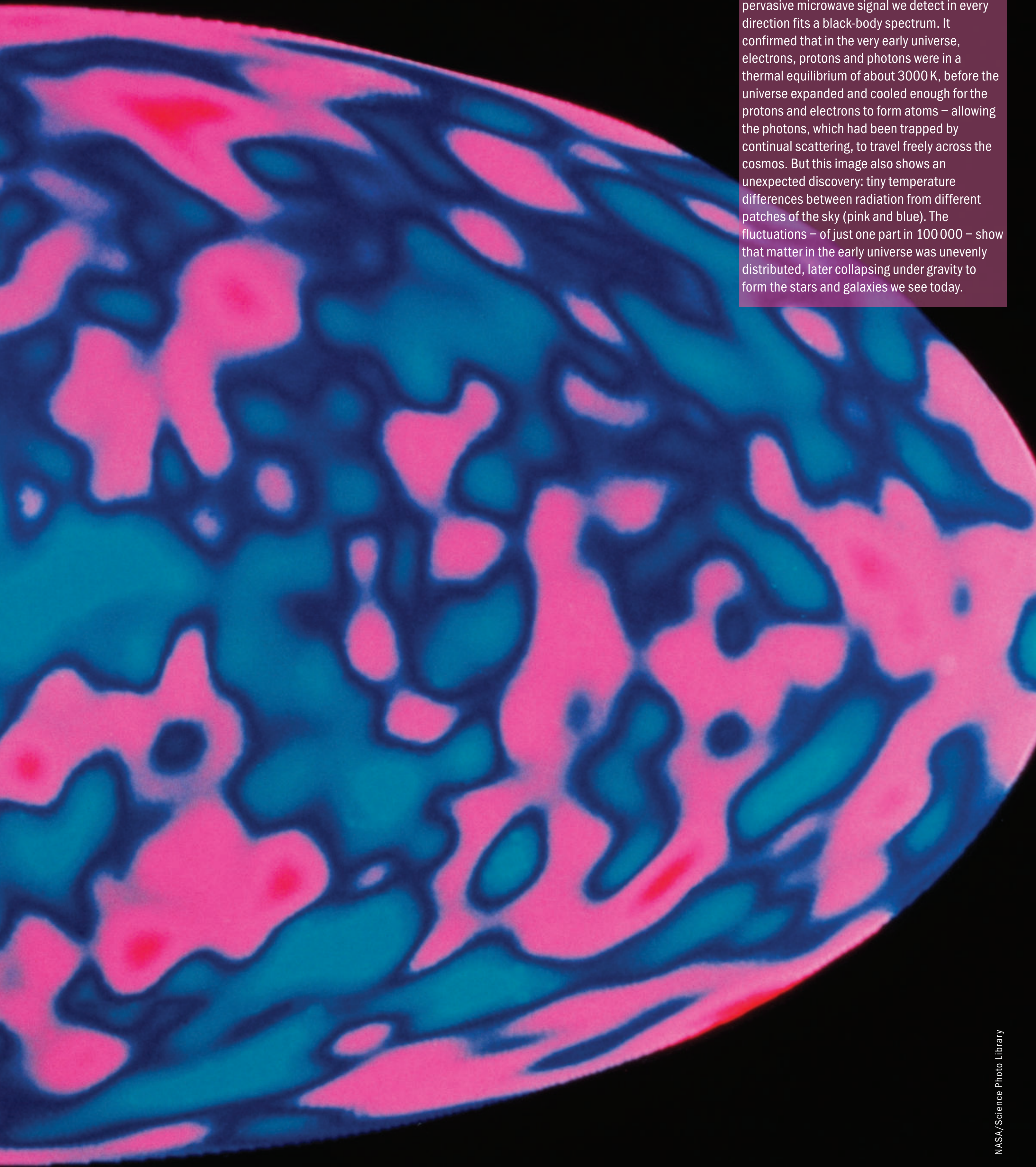
Whether you love or hate our choices, let us know what you think – and what, if anything, we've missed.

- Members of the Institute of Physics accessing *Physics World* via our apps or online at members.iop.org can also enjoy specially created video and audio content related to the issue.


COMBI
ASM 340

Oddly uneven

This map of the universe, created by NASA's COBE satellite during 1989–1993, was a double success for science. First, it showed that the pervasive microwave signal we detect in every direction fits a black-body spectrum. It confirmed that in the very early universe, electrons, protons and photons were in a thermal equilibrium of about 3000 K, before the universe expanded and cooled enough for the protons and electrons to form atoms – allowing the photons, which had been trapped by continual scattering, to travel freely across the cosmos. But this image also shows an unexpected discovery: tiny temperature differences between radiation from different patches of the sky (pink and blue). The fluctuations – of just one part in 100 000 – show that matter in the early universe was unevenly distributed, later collapsing under gravity to form the stars and galaxies we see today.



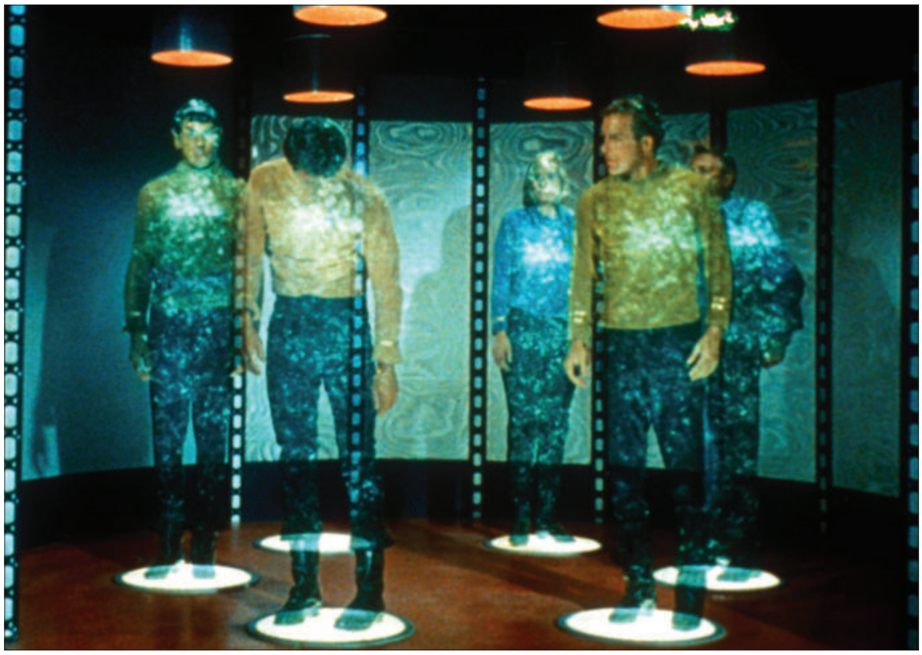
NASA/Science Photo Library

5 Discoveries

The five biggest discoveries in fundamental physics of the past 25 years

From A to B in an instant

Kicking off our choice for the top five discoveries in fundamental physics over the first 25 years of *Physics World* is **quantum teleportation**, which has made the fantasy of *Star Trek* real



Paramount Television/The Kobal Collection

Beam me up Teleportation is now possible, albeit only for quantum states so far.

Picking winners in physics is never easy or fair – as those choosing each year's Nobel laureates would no doubt agree. But selecting the five biggest discoveries in fundamental physics over the last quarter century is possibly an even tougher job. Quite simply, there have been so many eye-popping findings that our final choice is, inevitably, open to debate. Yet for *Physics World*, the following five discoveries – presented chronologically – stand out above all others as having done the most to transform our understanding of the world.

The earliest discovery on our list is teleportation, which is usually synonymous with the fictional world depicted in *Star Trek*. In fact, the word was coined as early as 1931 by the American writer Charles Fort in his book *Lo!*, which examined a variety of other-worldly phenomena. Reality eventually caught up with fiction in 1993 when an international group of scientists said that teleportation of a quantum state is entirely possible, so long as the thing being copied is destroyed.

Simply put, teleporting a quantum state involves making a precise initial measurement of a system, transmitting that information to a receiving destination and then reconstructing a perfect copy of the original state. For a long while, however, the first step in the process was considered impossible because of Heisenberg's uncertainty principle, which implied that making a perfect copy of a quantum system would alter the original system, effectively destroying the original state.

But in 1992 at a conference in Montreal, William Wootters of Williams College in the US revealed a curious theoretical result that he and Asher Peres of Technion – Israel Institute of Technology had obtained when they considered two identical but unknown quantum states, such as two photons, both either vertically or horizontally polarized. They found that if the two states had previously interacted with each other – i.e. were "entangled" – an observer could glean the maximum possible amount of information about the system from a single measurement on the pair of states, rather than from multiple measurements of the individual components, as would seem more intuitive. In other words, a property of the original states – the polarization, in the case of photons – can be estimated as best as possible.

After the talk, Wooters, Peres and four other researchers, including Charles Bennett of IBM in New York, concocted the basics of quantum teleportation. Their protocol (*Phys. Rev. Lett.* **70** 1895) allowed for an observer, Alice, to send information about an unknown quantum state to another observer, Bob, simply by passing classical information to him. This would be done by giving Alice and Bob one half each of an additional pair of entangled particles. Alice would interact the unknown quantum state with her half of the known entangled particle pair, then measure the combined quantum state, before sending the result through a classical channel to Bob. The act of measurement alters the state of Bob's half of the entangled pair and this, combined with the result of Alice's measurement, allows Bob to reconstruct the unknown quantum state.

Various groups are trying to carry out quantum teleportation to and from the ISS

In 1997 another group of researchers – led by Anton Zeilinger who was then at the University of Innsbruck (*Nature* **390** 575) – put Bennett and colleagues' ideas into practice when they teleported the polarization of a photon. This breakthrough was swiftly followed by similar efforts in a variety of other systems, including the teleportation of atomic spins, coherent light fields, nuclear spins and trapped ions.

The record distance for quantum teleportation currently stands at 21 m with single atoms and 143 km with photons. Researchers have also teleported macroscopic complex spin states between caesium atoms, and even a solid-state qubit in a computer chip. Various groups are even trying to carry out quantum teleportation to and from the International Space Station. "Beam me up Scotty!" may not be quite so far-fetched.

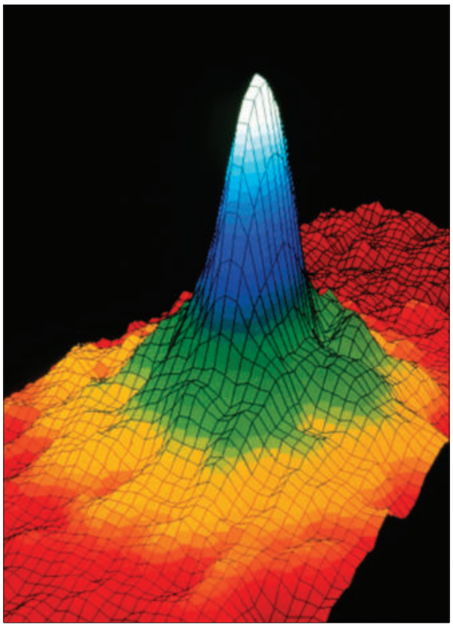
Tushna Commissariat

Unlocking a new state of matter

The creation of the world's first **Bose–Einstein condensate** in 1995 transformed atomic physics

We all have in our minds a "textbook" idea of how scientific discoveries should be made, in which visionary theorists make neat and precise predictions that are then confirmed by talented experimentalists at a particular time and place. Science rarely works like that, yet the creation in 1995 of the first Bose–Einstein condensate (BEC) from ultracold atoms came close to such perfection. More significantly, the creation of this entirely new form of matter – in which particles are locked together in their lowest quantum state – has opened up a whole new field of physics research.

The idea of a BEC dates back to 1924 when the Indian theorist Satyendra Nath Bose derived the Planck law for black-body radiation by treating photons as a gas of identical particles. He sent his ideas to Albert Einstein, who generalized Bose's theory to an ideal gas of atoms and predicted that – if the atoms were cold enough – their wavelengths would be so large that their wavefunctions would "overlap". The atoms would essentially lose their individual identities, creating a macroscopic quantum state, or superatom – a BEC. For many years, though, the idea of a BEC remained in the realms of theory and it was not until techniques for laser-cooling atoms to ultralow temperatures were developed in the 1980s that making a BEC became a possibility.



National Institute of Standards and Technology/Science Photo Library

Cool progress The density of a cloud of ultracold rubidium atoms forming a Bose–Einstein condensate. The blue and white peak shows the BEC, a cloud of a few thousand atoms some 10 μm across.

Several groups entered the race, but it was in Boulder, Colorado, at 10.54 a.m. on Monday 5 June 1995 that a team at the JILA laboratory – a joint institute of the University of Colorado and the National Institute of Standards and Technology (NIST) – created the world's first BEC. Led by JILA's Carl Wieman and NIST's Eric Cornell, the researchers produced a BEC consisting of 2000 rubidium-87 atoms that had been cooled in a magnetic trap to 170 nK using a combination of laser and evaporative cooling. Within a few months, Wolfgang Ketterle at the Massachusetts Institute of Technology also made a BEC from 500 000 sodium-23 atoms at 2 μK. The trio bagged the 2001 Nobel Prize for Physics for their efforts.

> The atoms would lose their individual identities, creating a macroscopic state, or superatom

Hundreds of groups around the world have since created BECs, which have been used for everything from slowing light to making "atom lasers" and even modelling the behaviour of black holes. Moreover, the interactions between the atoms can be finely controlled, meaning BECs can be used to simulate properties of condensed-matter systems that are extremely difficult – or impossible – to probe in real materials. Physicists now even routinely make condensate-like states from fermions, which is far trickier as these particles – unlike bosons – do not normally like occupying the same quantum state as their neighbours. And in 2010 physicists made a BEC from photons – the very particles that Bose himself had studied. The story of BECs had, it seems, come full circle.

Matin Durrani

Secrets of the supernovae

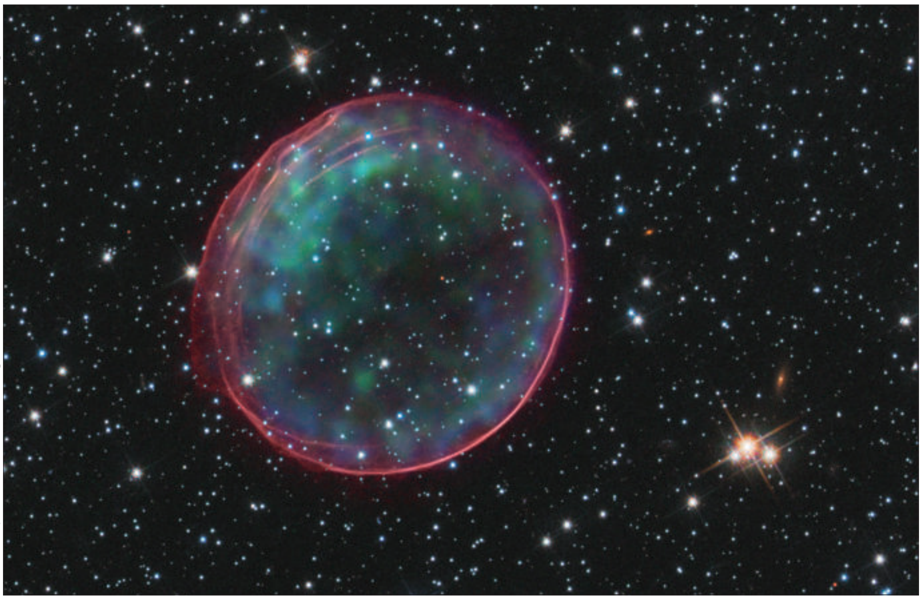
The stunning discovery of the **accelerating expansion of the universe** implied the existence of a mysterious "dark energy" pervading the cosmos

There have been countless amazing findings in astrophysics and cosmology over the last 25 years, but the discovery that the expansion of the universe is not slowing down – but is in fact speeding up – ranks above all others. That sensational finding implied that about three-quarters of the mass–energy content of the universe must consist of some weird, gravitationally repulsive substance, dubbed "dark energy", about which we still know virtually nothing. It had previously been assumed that the universe would – depending on how much matter it contains – either collapse eventually in a big crunch or go on expanding forever, albeit at an ever more gentle pace.

The discovery that the expansion of the universe is accelerating was made in the mid-1990s by two rival teams of researchers hunting for certain exploding stars, known as type 1a supernovae. These stars always blow up in the same way when they reach the same mass, which means that they can be used as "standard candles" to accurately measure distance in the universe. Although bright, such supernovae are extremely rare and the two groups – the High-Z Supernovae Search Team led by Brian Schmidt and the Supernova Cosmology Project (SCP) led by Saul Perlmutter – had to carry out painstaking surveys using ground-based telescopes and the Hubble Space Telescope to find them in sufficient numbers.

Although the two teams had expected to find that the expansion of the universe is decelerating, as more and more data piled up, it became clear that the results only made sense if the universe contains a force that pushes matter apart. But the researchers did not come to this conclusion quickly or lightly. At the time, it was still assumed that we live in a universe containing a small

X-ray: NASA/CXC/SAO/J.Hughes *et al.* Optical: NASA/ESA/Hubble Heritage Team



Cosmic conclusion The accelerating expansion of the universe becomes clear from studies of type 1a supernovae, which are dimmer – and thus farther away – than expected, leaving remnants such as this.

The results only made sense if the universe contains a force that pushes matter apart

amount of ordinary, visible matter and a heap of "dark matter" that we cannot see. Dark matter itself had taken more than 50 years to be accepted and adding dark energy seemed yet another complication, spoiling the intrinsic elegance of Einstein's simple model of the universe.

However, the evidence from the supernovae searches could not be ignored and the results from the two teams, which emerged during late 1997 and early 1998, pointed to an accelerating expansion. Although controversial, the conclusion was quickly accepted by the wider scientific community and led eventually to Perlmutter, Schmidt and the latter's High-Z co-member Adam Riess bagging the 2011 Nobel Prize for Physics. In honouring the trio, the Royal Swedish Academy of Sciences said their discovery was "as significant" as the discovery in 1992 of the minute temperature variations in the cosmic microwave background, which are the fossil remnants of the large-scale structures in today's universe. But, for us, the accelerating expansion has the edge as the implications are even more profound, pointing as they do to the composition and fate of the cosmos.

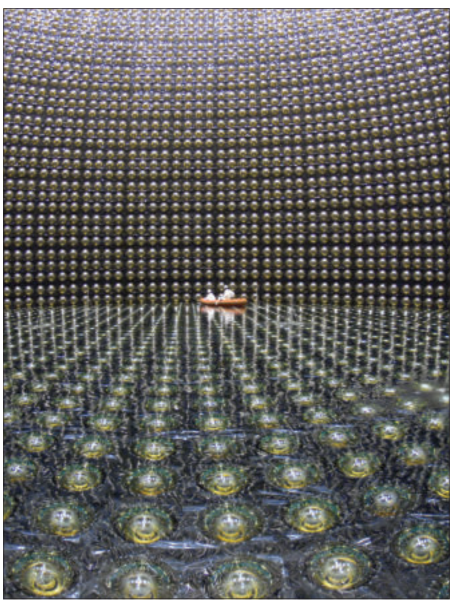
Matin Durrani

The ghosts of matter weigh in

The 1998 finding that **neutrinos have mass** laid to rest one of the biggest puzzles in physics

Once described by physicist Frederick Reines as "the most tiny quantity of reality ever imagined by a human being", neutrinos have long perplexed both experimental and theoretical physicists. Apart from being fiendishly hard to detect, theory suggested these particles are massless, whereas observational evidence hinted at the opposite. So in 1998, when the Super-Kamiokande experiment in Japan obtained the first convincing evidence that neutrinos do indeed have mass, what had been one of the most fundamental puzzles in particle physics was finally settled.

Produced by neutrons undergoing beta decay, neutrinos are chargeless particles that interact with matter via the weak force. Their story began in 1930 when only two particles – the electron and the proton – were known, and discrepancies arose in the study of beta decays that seemed to break the law of energy conservation. Wolfgang Pauli hypothesized the existence of the neutrino as a "desperate remedy", although he dubbed the particle a "neutron" and only



Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo

All-seeing eyes The Super-Kamiokande detector lies 1 km underground in the Mozumi mine in Japan.

later was it christened by Enrico Fermi as "neutrino" or "little neutral one".

Since neutrinos react so weakly with matter, it was thought nearly impossible to detect them – in fact, Pauli bet a case of champagne that it would never be done.

Neutrinos have long perplexed both experimental and theoretical physicists

Happily, he was proved wrong when in 1956 Reines, along with Clyde Cowan, detected antineutrinos emitted by a nuclear reactor, for which the pair went on to win the 1995 Nobel Prize for Physics. Then in 1957 Italian physicist Bruno Pontecorvo suggested that multiple types, or "flavours", of neutrinos exist and that they can change, or "oscillate", from one to another. Pontecorvo's ideas were confirmed in 1962 when scientists at Brookhaven National Laboratory (BNL) observed the existence of both Pauli's electron neutrino and also the muon neutrino. A third type of neutrino – the tau – was hypothesized in 1975 and was finally detected in 2000.

But a big problem revealed itself in 1964, when Raymond Davis and John Bahcall, also at the BNL, were surprised to find that their solar-neutrino experiment detected only about 30% of the neutrinos predicted by theory. This discrepancy could only be explained if neutrinos were oscillating between flavours as they travel from the Sun to the Earth – and Davis' experiment had detected only a third as it was sensitive mainly to electron neutrinos. Unfortunately, if oscillation was occurring, it meant that neutrinos have mass, which was at odds with the Standard Model of particle physics.

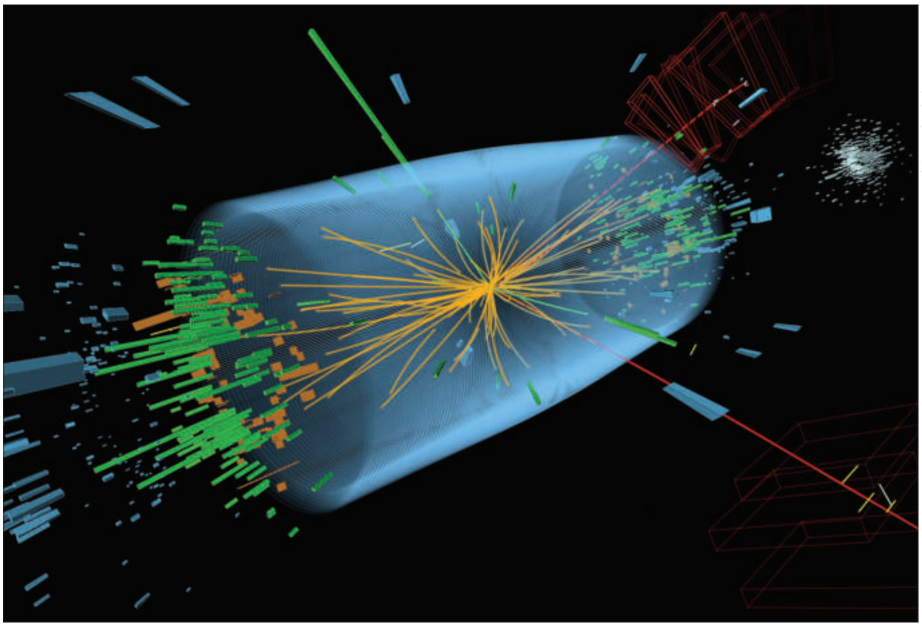
The breakthrough came from the giant Super-Kamiokande detector in 1998, when researchers found that the ratio of electron to muon neutrinos coming from opposite sides of the Earth were different. This finding meant that these neutrinos – created when cosmic rays interact with nuclei in the upper atmosphere – were changing flavour as they passed through the Earth. This showed for the first time that neutrinos must have mass, albeit only about 0.1 eV.

Any doubt about that finding was laid to rest this year when researchers at the T2K (Tokai to Kamioka) experiment in Japan fired a beam of muon neutrinos 295 km through the ground to Super-Kamiokande. There they detected electron neutrinos with a statistical significance greater than 5σ, the precise values of which are, however, still unknown. The challenge now is to pin down each neutrino's mass.

Tushna Commissariat

The particle with mass appeal

The discovery of the **Higgs boson** has been an epic tale of ingenuity, hard work and perseverance


CERN/CMS Collaboration

Found at last Cornering the elusive Higgs boson at the Large Hadron Collider.

It is not often that a topic in physics – particularly particle physics – trends on *Twitter*. But that is exactly what happened on 4 July 2012, when physicists working on the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN announced that they had discovered a "Higgs-like particle" with a mass of about 125 GeV/c^2. Almost half a century since Peter Higgs – and independently Robert Brout, François Englert and others – had published papers that describe a mechanism by which certain particles could get mass, the elusive particle had been found.

The Higgs boson and its associated field explain how electroweak symmetry was broken just after the Big Bang to give these elementary particles the property of mass. However, the Standard Model does not predict the mass of the Higgs. Successive experimental programmes at CERN's Large Electron–Positron collider and Fermilab's Tevatron tried to measure the particle's mass and, although many tantalizing hints popped up over the past dozen years, a conclusive result evaded researchers.

Proposed in 1983 and approved for construction in 1994, the LHC is the world's highest-energy particle accelerator and was fired up on 10 September 2008 – when a beam of protons was successfully steered around the 27 km circular tunnel for the first time. Unfortunately, all operations were stopped nine days later because of a serious fault between two superconducting bending magnets. Repairing the resulting damage and installing additional safety features took over a year and it was not until 19 November 2009 that proton beams were successfully circulated again, with the first proton–proton collisions being recorded four days later at an injection energy of 450 GeV per beam.

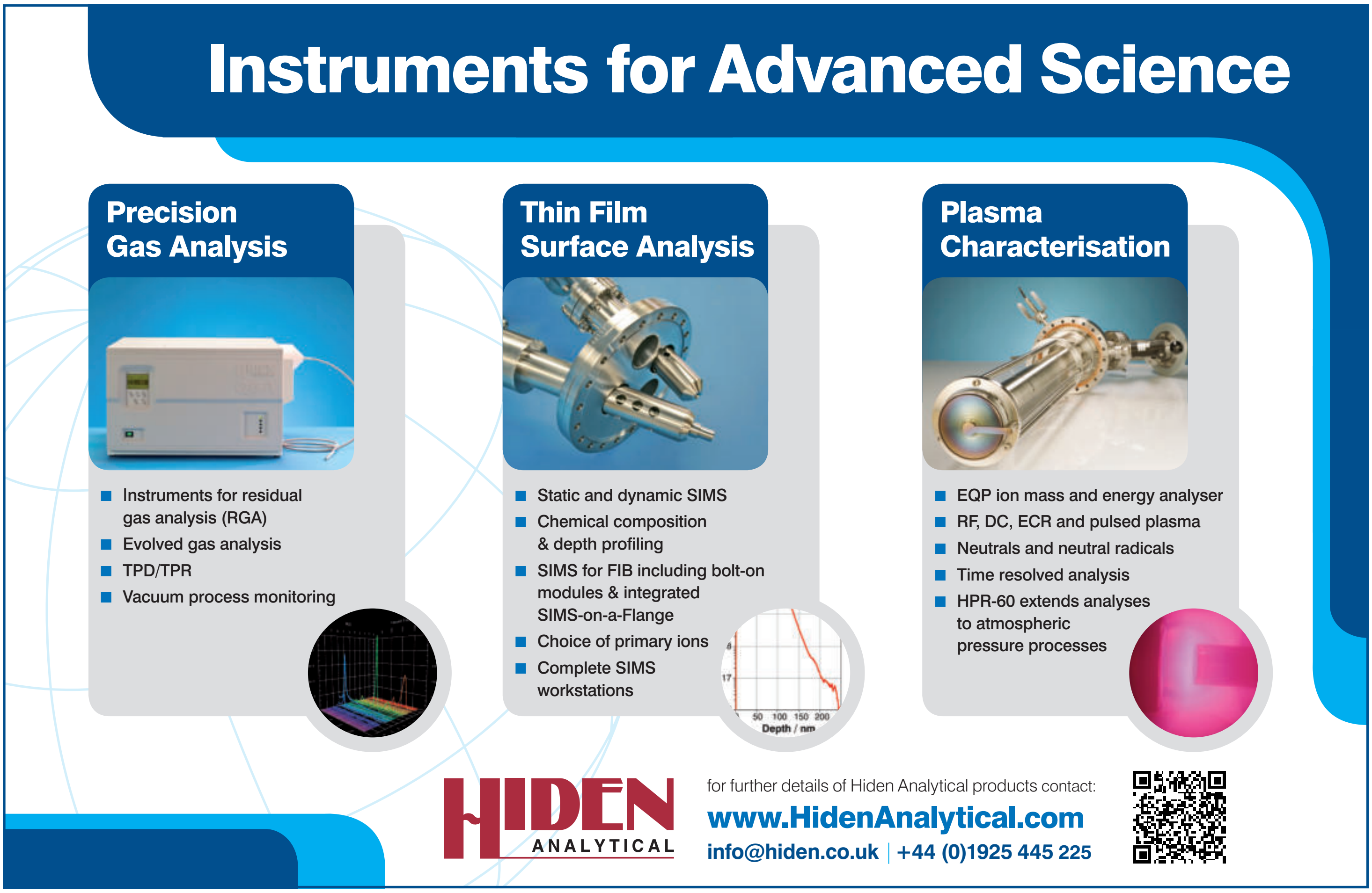
Over the next 30 months, the accelerator proved more than its worth, producing 10 times more data than expected, allowing both ATLAS and CMS to home in on the Higgs last July.

For the better part of a month in summer 2012, particle-physics fever – aptly nicknamed Higgsteria – swept the globe after a CERN meeting was announced and a press conference called. Rumours abounded in the days before the meeting, including a tantalizing leaked video that only served to further drum up excitement for the big reveal. On 4 July camera crews, reporters and researchers from the world over flocked to the Geneva lab where the announcement was made, with millions of others watching a live webcast of the meeting. When both CERN experiments reported measurements of the Higgs' mass at confidence levels of 5σ – the golden standard for a discovery in particle physics – the discovery graced the front pages of newspapers worldwide.

> For a month in summer 2012, particle-physics fever swept the globe

The search for the Higgs was successful thanks to the combined efforts of a huge number of theoretical and experimental physicists and engineers from all over the world, as well as the enormous amount of power of the LHC Computing Grid, which churns through the petabytes of data produced by the LHC each year. In completing the Standard Model search for the predicted particle, the discovery of the Higgs boson is not only the most important physics breakthrough of the 21st century, but also one of the biggest human endeavours of all time.

Tushna Commissariat


Instruments for Advanced Science
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Instruments for residual gas analysis (RGA)
Evolved gas analysis
TPD/TPR
Vacuum process monitoring
Thin Film Surface Analysis
Static and dynamic SIMS
Chemical composition & depth profiling
SIMS for FIB including bolt-on modules & integrated SIMS-on-a-Flange
Choice of primary ions
Complete SIMS workstations
Depth / nm
Plasma Characterisation
EQP ion mass and energy analyser
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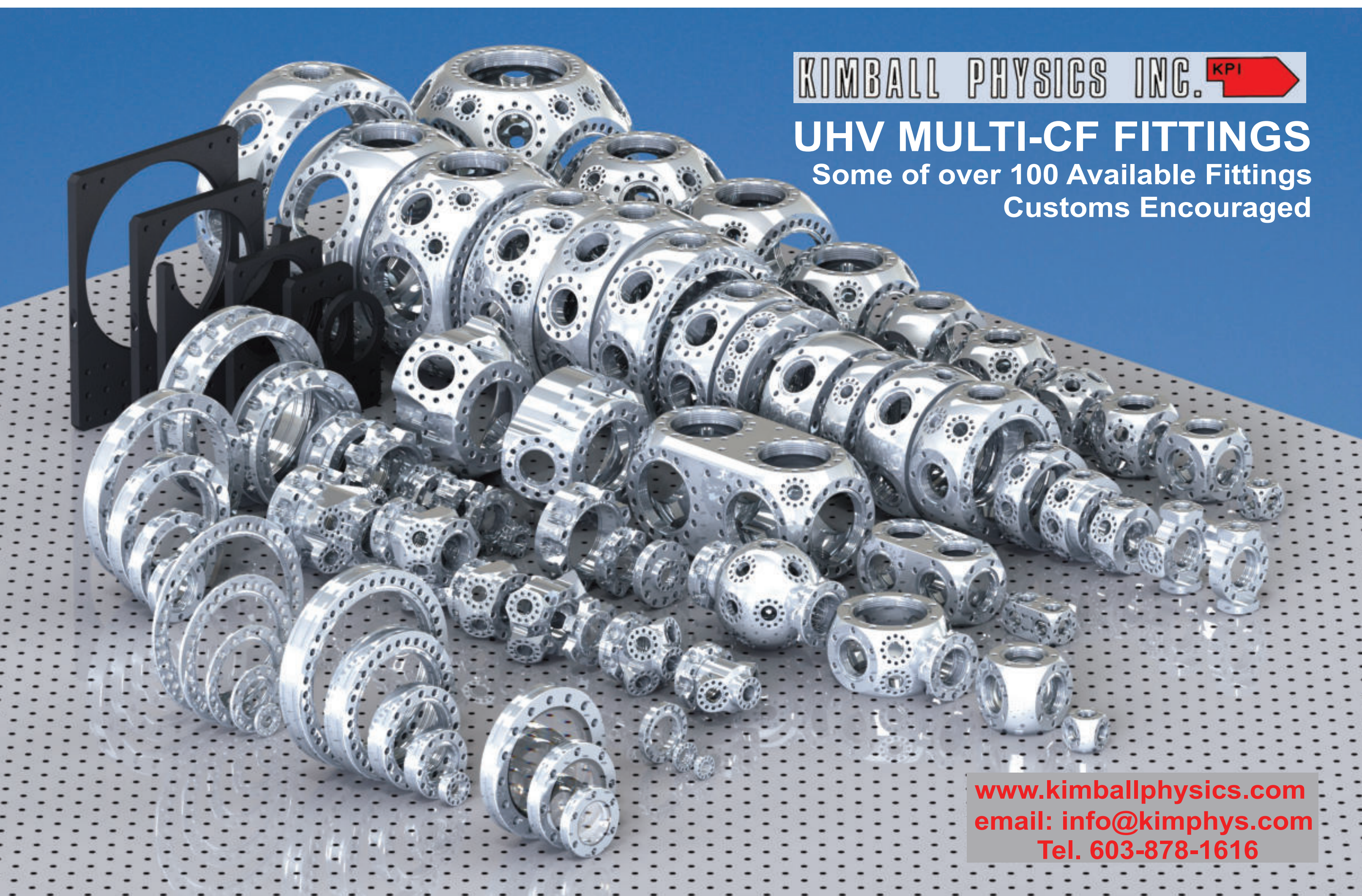
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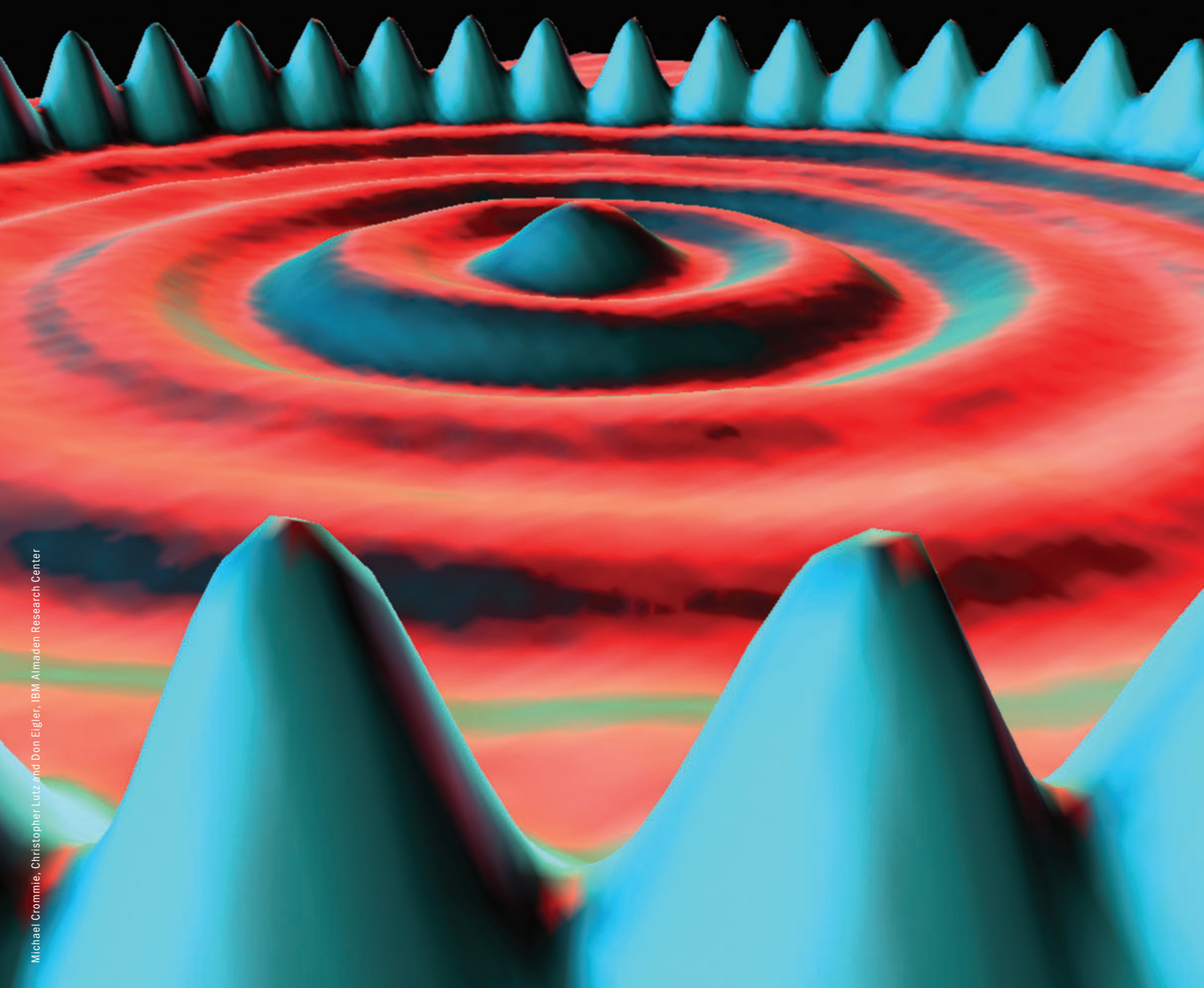
All penned in

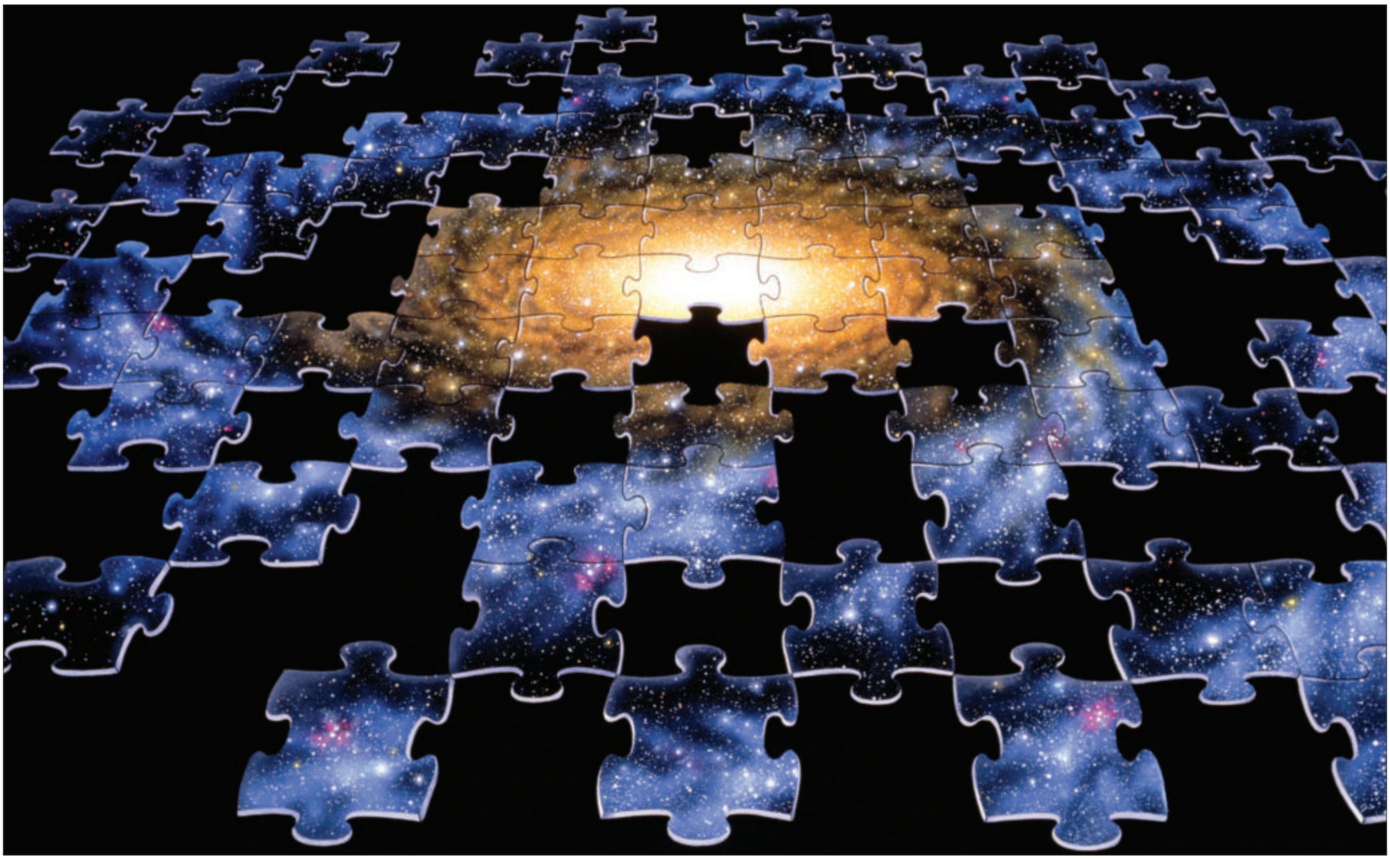
When electrons are confined to a small length scale approaching their de Broglie wavelength, their behaviour is dominated by quantum-mechanical effects. Here, electrons (red) are restricted from moving perpendicularly to the surface of a copper crystal by the intrinsic energy barriers above and below the surface. The electrons can, however, move in the plane of the surface, but some of them are trapped within a ring of 48 copper atoms (blue) of radius 71.3 Å that "corral" the electrons within this fixed boundary. Just as electrons confined in atoms exist only with quantized amounts of energy, so the electrons here can only have discrete amounts of energy. Particles within a "box" such as this exist as standing waves of electron density – the more ripples, the higher the energy. This image – taken by researchers at IBM in 1993 using a scanning tunnelling microscope – was the first time they were ever visualized.



Michael Crommie, Christopher Lutz and Don Eigler, IBM Almaden Research Center

5 Questions

The five biggest unanswered questions in physics right now



Lynette Cook/Science Photo Library

What is the nature of the dark universe?

Just over 95% of our universe comes in the shrouded form of dark energy and matter that we can neither explain nor directly detect. **Catherine Heymans** explores this enigma and describes where we will look next in our search for darkness

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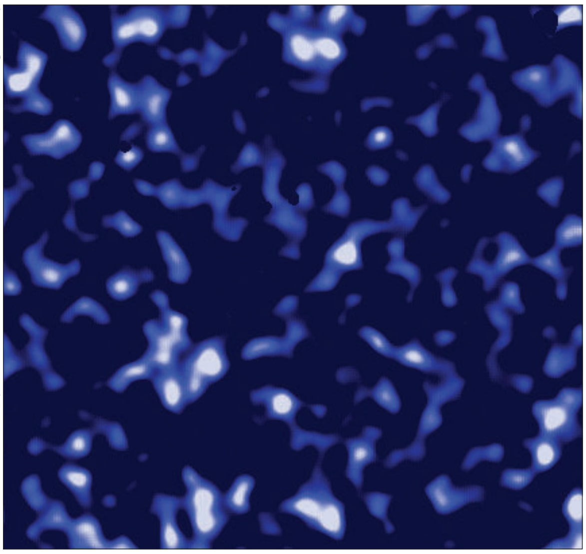
This year the Planck space mission released exquisite observations of the early universe, providing the strongest evidence yet that the universe we live in is very dark indeed. Its precise results show that our universe is composed of 26.8% dark matter and 68.3% dark energy, while less than 5% is made up of the stuff we are familiar with on Earth. With their long-standing quest to make these precision measurements essentially now concluded, cosmologists are rapidly turning their attention to a much bigger and further-reaching question: what is the exact nature of this dark universe?

Dark matter is exactly what it says on the tin: it is dark and comprised of a mysterious substance that does not emit or absorb light. We only know it exists because of its gravitational effects on the normal matter that we can see. Dark energy is less well described by its label, being an invisible source of energy that drives the post-Big-Bang expansion of the universe to mysteriously accelerate. Together, these two dark entities play out a cosmic battle of epic proportions. While the gravity of dark matter slowly pulls structures in the universe together, dark energy fuels the universe's accelerating expansion, making it ever



Van Waerbeke, Heymans, Canada–France–Hawaii Telescope Lensing Survey

Dark cosmic web The distortion of light from about 10 million galaxies, which is bent as it passes clumps of dark matter, has shown that dark matter in the universe is distributed as a network of gigantic dense regions (white), separated by a vast emptiness.

harder for those dark-matter structures to grow.

It is widely believed that to truly understand the dark universe, we will need to invoke some new physics that will forever change our cosmic view. As the conclusion of this dark quest could be so far reaching, astronomers are approaching the task with care, using a series of independent and meticulous observations. Efforts include the Canada–France–Hawaii Telescope Lensing Survey, which has directly mapped out the invisible cosmic web of dark matter by observing how its mass bends space and time, lensing the light of very distant galaxies. Projects such as the Sloan Digital Sky Survey are accurately charting the locations of billions of galaxies, which closely trace the distribution of dark matter because this gravitationally attractive substance dictates where and when galaxies form. Galaxies also carry with them a signal imprinted in the distribution of normal matter just after the Big Bang that can be seen in how galaxies cluster in the cosmos today.

Capturing dark matter

Astronomers have put their theories of dark matter to the test, finding that a very wide variety of observations all agree with a single theory, termed the "concordant cosmology". This overwhelming body of evidence supports the theory that dark matter is made up of weakly interacting matter particles (WIMPs), and the challenge is now on for particle physicists to go out and catch or create one.

To truly understand the dark universe, we will need to invoke some new physics that will forever change our cosmic view

Several attempts have already been made to trap a dark-matter particle, but any hints of success have so far been controversial and open to interpretation. The next major leap in the search for a fleeting glimpse of a dark-matter particle in flight is taking shape not in space but nearly 1.5 km under the Black Hills of South Dakota. The LUX-ZEPLIN experiment will use nine tonnes of liquid xenon as its dark butterfly net. The hope is that a few of the trillions of WIMPs that pass through the Earth every second will be caught crashing into some of the xenon particles. How successful this new experiment will be in its quest to uncover the nature of dark matter will depend on just how much of a wimp the dark-matter particle turns out to be. An unquestionable direct detection of a dark-matter particle would be one of the most significant discoveries of this century, finally confirming Fritz Zwicky's theory, which was ridiculed when he proposed it in 1933.

Exposing dark energy

While the astronomical community is now fairly united in postulating the existence of an invisible dark-matter particle, the same cannot be said about its support for the simplest explanation for dark energy. Observations that the expansion of our universe is accelerating are most easily explained by considering the extra energy associated with the vacuum that permeates the universe. According to quantum theory, empty space is filled with a swarm of virtual particles with a wide range of masses that can briefly pop in and out of existence. As mass and energy are equivalent, the growing vacuum within an expanding universe acts like a bank of unlimited energy, inflating the whole universe at an accelerated speed.

Unfortunately, there is a problem with this simple and elegant vacuum solution to the nature of dark energy. Particle physicists can make a theoretical estimate for the energy of a vacuum and they find that it is 120 orders of magnitude larger than the dark energy that the Planck results show. This wild discrepancy has opened up a wide range of exciting new dark-energy theories including exotic models such as a multiverse that resembles the middle of an Aero chocolate bar. Perhaps our universe is one Aero bubble being pulled by our neighbouring Aero-bubble universe?

Many cosmologists believe that the dark-energy phenomenon indicates that we need to look beyond Einstein's theory of general relativity. By observing how dark-matter structures change over cosmic time, we can investigate how dark energy evolves and test gravity for the first time on cosmological scales. Just as Einstein revolutionized our understanding of Newtonian gravity, confirmed through observations of the solar system, so new observations of gravity on cosmological scales may bring about another revolution in our understanding of gravity.

Two major new international projects will lead our quest to discover what the dark-matter particle is and why the expansion of our universe is apparently accelerating. The Euclid satellite, due to launch in 2020, will image the full dark sky from above the Earth, while the Large Synoptic Survey Telescope, due to see first light in 2019, will image the full Southern sky from a mountain top in Chile. Both of these projects will chart the distant universe with exquisite precision, utilizing a diverse range of cosmological tools to map out the evolution of dark-matter structures and document the expansion and curvature of space and time from 10 billion years ago to the present day. Exciting times are ahead for our understanding of the fundamental physics that govern the dark side of the universe. ■

What is time?

People have been asking this question for centuries, and despite some advances in our understanding, it is likely to puzzle us for many years to come, says **Adam Frank**

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The problem of time is one of the oldest conundrums we have, and the fact that our lives are finite makes it the most intimate and personally pressing "deep" mystery about reality. Physicists from Newton onward have, in some cases, directly addressed issues concerning time that were once the domain of philosophers. But the science of physics – charged as it is with embracing the whole of physical reality – has added its own perspectives (and paradoxes) to questions about time, its structure and its fundamental reality. The result is that there is no single problem of time in our science. Instead, there are many interwoven problems that may require more than one conceptual revolution to resolve.

The poles of debate over time in western thinking were laid down by two Greek philosophers, Parmenides and Heraclitus, around the 5th century BC. The tradition established by Parmenides claimed that time, as a measure of change, is an illusion, and that reality, at its most fundamental level, is timeless and eternal. In contrast, Heraclitus and his followers claimed that nothing exists beyond time and that change – relentless in its advance – is the only fixed feature of reality. Debate about the fundamental nature of time in physics takes place within the shadow of these ancient distinctions. Even today, you will find physicists at both the Parmenidean and Heraclitan ends of the spectrum – and pretty much everywhere in-between.

One early proponent of a "middle way" between Parmenides and Heraclitus was Isaac Newton. The development of Newtonian mechanics established the modern paradigm for scientific inquiry and in doing so split the difference, in some sense, between the two ancient views on time. While the differential equations of Newton's dynamics treat time as a parameter that flows at a constant rate everywhere in the universe, these equations represent laws that are themselves eternal and exist outside of time. After Newton, the prospect of discovering additional timeless "laws of Nature" became a siren call of inspiration for all of science, marking its special place among the modes of human inquiry.

Newton's own laws were, of course, found to be valid only in the limits that speeds are less than that of light and length scales are larger than those associated with quantization. But however much the rise of relativity and quantum mechanics changed our views of Newton's universe, their development did not alter his essential idea that at least one aspect of reality – the laws of physics – exists beyond time.

Within our search for timeless laws, physics has brought us to a number of essential realizations (and open questions) about temporality. One of the most obvious and still unresolved of these questions is the famous "arrow of time". All established fundamental laws governing the dynamics of particles – the most elementary of physical objects – are time-reversible. Nothing in Newton's equations of point-mass dynamics or Schrödinger's equations for the wave function can tell us which direction the hands on the clock should turn. The macroscopic world, however, brooks no such indecision. Scrambling eggs and stirring cream into coffee make it clear that an arrow of time from past to future is an essential component of reality.

Back to the beginning

As a physical principle, questions concerning the "arrow of time" appear in the language of dynamical (differential) equations that govern physical processes. As such, it is not something the Greeks would have recognized. It was only with the advance of thermodynamics (and, later, statistical mechanics) that

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Research at the frontiers of physics embraces an astonishing range of possible natures of time, which demonstrates both how far we've come and how far we still have to go

this dilemma was resolved, after a fashion, by averaging over the micro-states associated with each macro-state of many particles. Thus a new quantity associated with large systems – entropy – entered the lexicon as a stand-in for time in the macroscopic world.

Thinking in terms of entropy, however, only pushes the problem of time's arrow backward. Once the entropy (in other words, disorder) is maximized, a system reaches equilibrium and each moment will look, essentially, like the next – bar the occasional fluctuation. Thus physicists must become cosmologists to ask why we live in a universe where entropy was initially low enough to allow evolution, and therefore change, to continue. The discovery that our universe began in a Big Bang meant that this cosmological arrow of time had to be pushed back to a question of cosmic initial conditions. But as Roger Penrose, Sean Carroll and other theorists have argued, low-entropy initial conditions within the classic Big Bang scenario are extremely unlikely.

Questions about the universe's initial conditions bring us to the search for that most fundamental of fundamental theories: quantum gravity. Efforts to quantize the classical space–time of general relativity are discussed elsewhere in this issue (see pp42–43), but one important consequence of such research has been to push theorists to new frontiers in our understanding of time. For example, consider the troubling fact that when you cast Schrödinger's equation in a form appropriate to the space–time of general relativity, you end up with an equation in which time does not appear. This time-free expression is known as the Wheeler–DeWitt equation, and it presents us with a set of "cosmological" quantum states for the universe without any way of evolving between those states.

Does the Wheeler–DeWitt equation mean that Parmenides was right, and time is merely an illusion? The question is far from settled, but many of those working on quantum gravity argue that the time and space we are familiar with cannot be fundamental. Instead, they insist that time and space must be built from something more essential – something with quite different properties from our usual notions of locality and temporal progression. In its modern setting, the question "Is time real?" is phrased in terms of time emerging from some deeper set of principles.

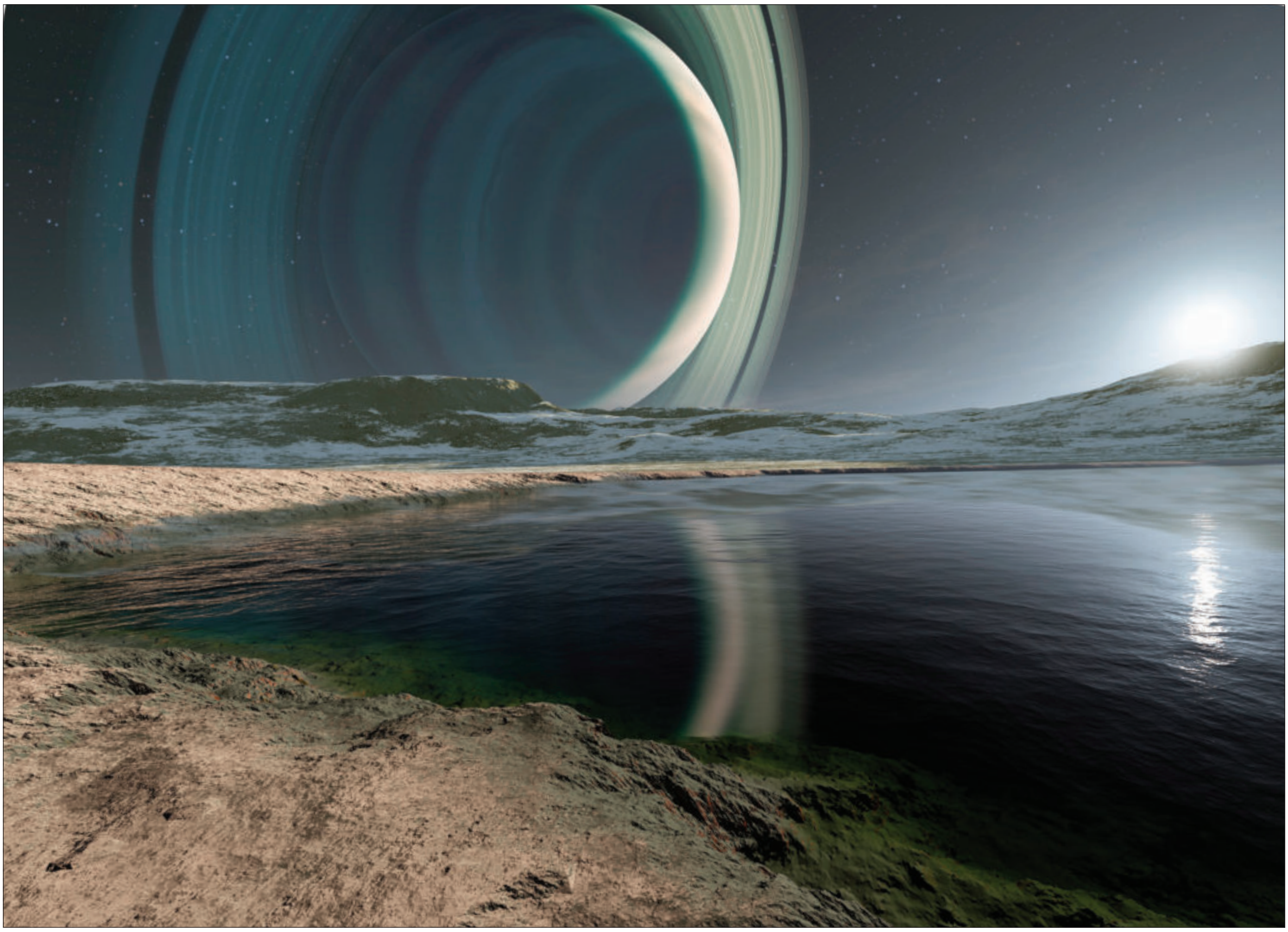
For other researchers, however, the paths taken in the search for quantum gravity pose troubling questions. Andreas Albrecht, for example, has noted that moving from the Wheeler–DeWitt equations to the time-bound world we experience introduces a new puzzle, which he terms the "clock ambiguity". As Albrecht has demonstrated, there is no straightforward way to choose which part of the new quantum-compatible theory should act as a clock, and which should be called "space". Making such a choice, in effect, de-unifies space–time, and Albrecht has found that different, arbitrary, choices for what plays the role of a clock can lead to entirely different sets of physical laws.

A plea for time's reality

An even more strident criticism of current approaches comes from Lee Smolin, who has argued that the centuries-old emphasis on timeless laws represents a conceptual stumbling block. In Smolin's view, the drive for eternal laws to describe reality as a whole has backed fundamental physics into a corner where it is forced to consider "potential" realities, as is the case for multiverse theories and their infinite and possibly unobservable other universes, rather than the one we experience. Smolin also takes a bold step into the Heraclitan domain by arguing that time is the bedrock of reality and cannot be considered emergent. According to this argument, even physical laws must be bound within time and can, therefore, change.

Research at the frontiers of physics embraces an astonishing range of possible natures of time, which demonstrates both how far we've come and how far we still have to go. Time has proven to be a remarkably durable mystery in physics. We should expect it to remain so, just as we should expect it to continue provoking our most creative scientific responses – at least for the time being. ■

Is life on Earth unique?


Detlev Van Ravenswaay/Science Photo Library

From finding unusual creatures on Earth to spying life's building blocks beyond our solar system, **Ray Jayawardhana** examines what we know about the nature of life's uniqueness, and the possibility of its existence in faraway realms such as extrasolar planets

Talk about going down a rabbit hole. There I was bent nearly in half, not quite on my knees, crawling through a narrow tunnel barely four feet tall that sloped down at a steep angle. Donning blue-grey overalls, waterproof boots and a hard hat with a miner's lamp, I trod carefully to avoid catching myself on the sharp bits of rock protruding from all sides of the poorly lit, claustrophobic cavity. The sweltering heat and stifling humidity made breathing a chore, but I was not going to complain. It was a privilege to join Tullis Onstott and Maggie Lau of Princeton University, and Tom Krieft of the New Mexico Institute of Mining and Technology, on this scientific adventure. Nearly two kilometres underground, we were deep inside an active gold mine located near Johannesburg, South Africa. Our mission: to collect samples of ground water seeping through cracks in the bedrock, which Onstott's team would later examine for living organisms that thrive where the Sun never shines.

In deep places of the Earth such as these, Onstott's team and others have identified varieties of bacteria that challenge what we thought we knew about biology. Rather than relying directly or indirectly on photosynthesis, they instead feed off hydrogen gas and exist in underground ecosystems that have been totally disconnected from the biological cycles on the Earth's surface for possibly tens of thousands of years. In 2011 Gaetan Borgonie from the University of Ghent in Belgium and his colleagues spotted roundworms (nematodes) living kilometres below ground level in several South African mines – the first multicellular organisms to be recovered from such depths. These discoveries have extended the

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Eye Of Science/Science Photo Library

Tiny hints Extremophiles can survive conditions lethal to most life forms on Earth. This tardigrade, for example, can survive at temperatures near absolute zero, at pressures six times those on the deepest ocean floor, and even in the vacuum of space under cosmic radiation. Their existence could give clues to life on other worlds.

biosphere of our planet considerably – and added to its biomass. But more interesting still, they might even provide clues to the biology of the early Earth before the evolution of photosynthesis, or to the nature of life on other worlds that have a different atmospheric make-up from our own.

Extreme beings

Organisms found in the deep subsurface of the Earth are among the many so-called "extremophiles" that scientists have come across over the past few decades. Others include microbes that live close to volcanic vents on the ocean floor, or on salt flats near the Red Sea. Yet more are found beneath the permafrost of the Canadian Arctic, within parched soils of the Atacama Desert in South America and even at the edges of the stratosphere. The very existence of these creatures affirms that life is a hardy phenomenon, capable of adapting to a remarkable range of environmental conditions.

Still, despite their magnificent and bewildering variety, all of these organisms are intimately connected to each other: they share the same biochemistry, inhabit the same evolutionary tree and trace their origins to a common ancestor that probably existed over three billion years ago. But to date, scientists have not uncovered a "shadow biosphere" on Earth, comprised of a radically different sort of life. Nor have they found compelling evidence of extraterrestrial life – yet.

What researchers have done is to confirm that the ingredients of life, as well as potential habitats, exist beyond the Earth and are ubiquitous in our cosmic neighbourhood. Laboratory measurements show that amino acids – building blocks of proteins – are common in meteorites and comets. Some carbon-rich meteorites even contain components of DNA called nucleobases. Astronomical spectroscopy at optical, infrared and radio wavelengths has revealed a number of complex organic molecules in interstellar gas clouds – the birth sites of stars and their planetary retinue.

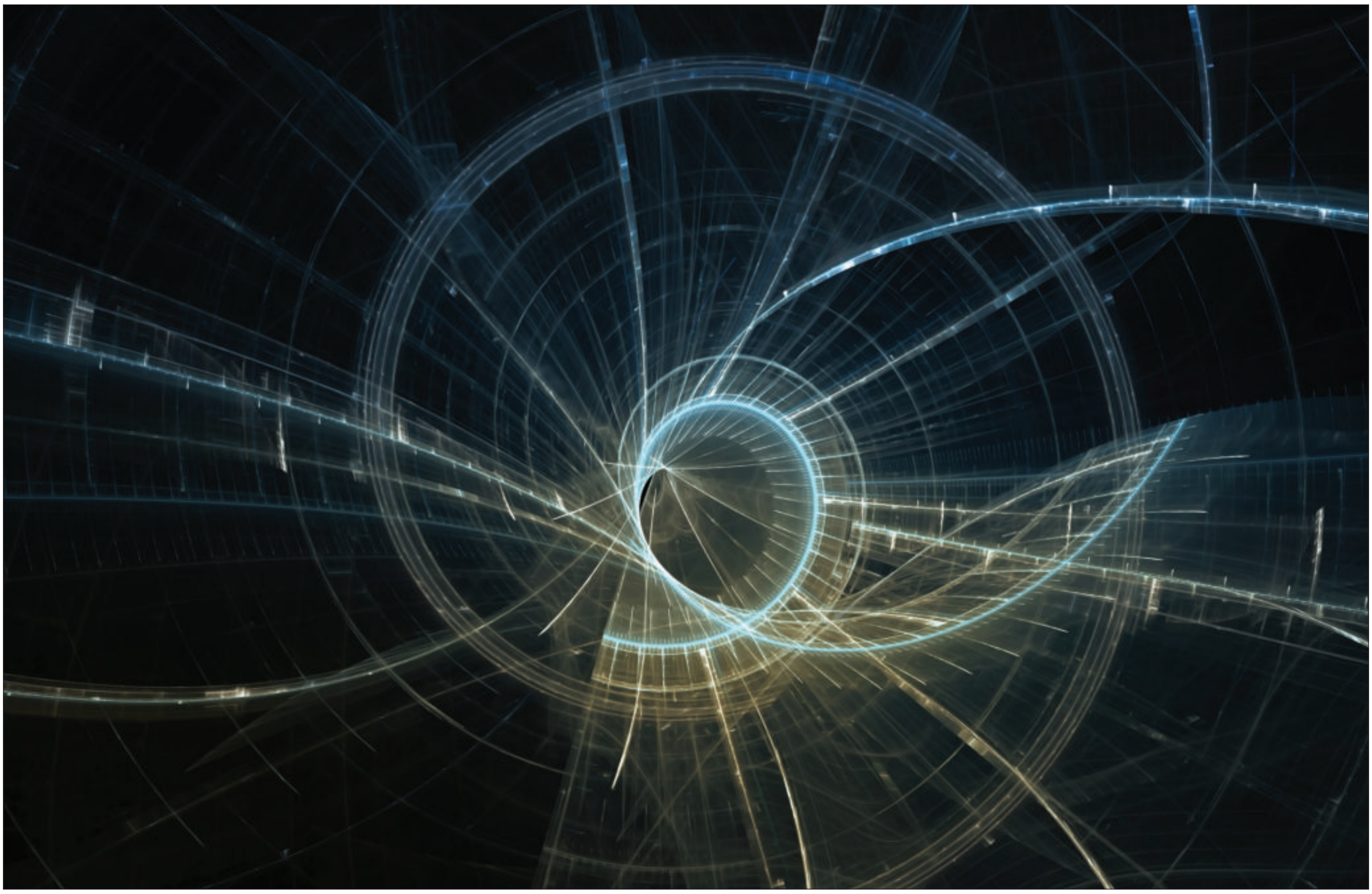
Closer to home, our neighbouring world Mars remains a prime target in the search for life beyond Earth, with growing evidence of past water flows raising the prospect of habitability sometime in its history. Likewise, the big moons of Jupiter and Saturn, especially those that might harbour subsurface oceans, continue to intrigue us.

Beyond our solar system

In recent memory, the most dramatic development in the quest to understand our place in the universe has been the identification of thousands of planets orbiting stars other than the Sun, known as extrasolar planets, or exoplanets. Using ground-based telescopes and spacecraft such as NASA's Kepler observatory, astronomers commonly find such alien worlds by measuring a star's wobble as unseen planets tug on it, or by registering a star's periodic dip in brightness as a planet transits in front of it. That is a big change from merely 20 years ago, when we were certain of just one planetary system – our own. The pace of discovery has been astounding and the incredible diversity of worlds has surprised us many times over.

What is more, thanks to a suite of remarkable new instruments, we have taken the temperature of distant planets, espied water in their atmospheres and even captured the first direct pictures of alien worlds. A number of "super-Earths" have been found already – those more massive than Earth but less so than our ice giants Uranus and Neptune – and astronomers expect to find Earth-sized planets by the dozen within the next few years. Some of these will likely be in the so-called habitable zone, where the temperatures are just right for liquid water. That will inevitably bring questions about alien life to the fore. But detection will not come easy. It will take a new generation of telescopes to pin down molecules that we associate with life – such as oxygen, ozone, methane, water and carbon dioxide – in the atmosphere of a distant terrestrial world. Even if and when we succeed in identifying such telltale signs of life, we probably will not know for a while what sort of creatures might inhabit that world.

The Earth is special among its siblings in the solar system as the only planet with surface oceans and life on a planetary scale. However, it seems absurd, if not arrogant, to think that ours is the only life-bearing world in the galaxy, given *hundreds of billions* of other suns, the veritable cornucopia of planets and the apparent abundance of life's ingredients. It may be that life is fairly common, but "intelligent" species are not. In any case, as the history of science has proven time and again, generalizing from a single instance often leads to misguided, if not dangerous, conclusions. So we will have to find at least one other example of life elsewhere before we can discern what is and is not unique about life on this precious bit of reformed cosmic debris.



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Can we unify quantum mechanics and gravity?

The incompatibility of general relativity and quantum mechanics is perhaps the most important open problem in theoretical physics. **Sabine Hossenfelder** describes how physicists are working to unite these two perspectives in a theory of quantum gravity

Sabine Hossenfelder is an assistant professor of high-energy physics at the Nordic Institute for Theoretical Physics (Nordita), Sweden, and writes the popular blog *Backreaction*, e-mail hossi@nordita.org

If you know one thing about quantum mechanics, it is probably that quantum matter can be both here and there at the same time – it can be in a superposition. And if you know one thing about gravity, it is probably that matter attracts other matter – it has a gravitational field. So it seems that the gravitational field of quantum matter should also be both here and there at the same time. However, Albert Einstein's general relativity, which describes gravity, is a classical theory. It has taught us a great many lessons and can do many things, but one thing it cannot do is describe gravitational fields in quantum superpositions. For this we need a quantized version of general relativity – a theory of quantum gravity.

And if you know one thing about quantum gravity, it is probably that no-one knows how it works.

We do, however, have requirements for the successful theory of quantum gravity.

What do we want from quantum gravity?

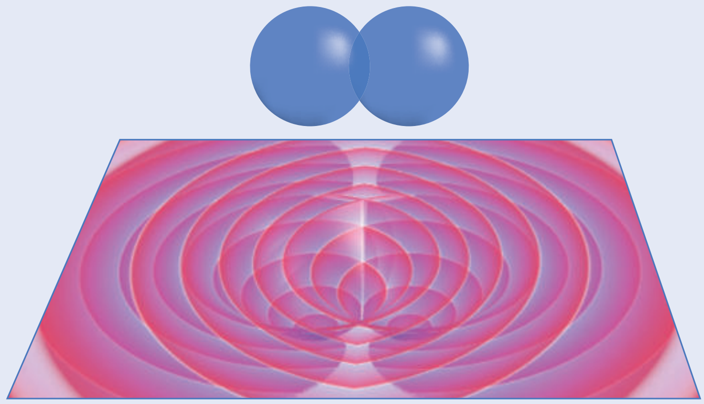
To begin with, a theory of quantum gravity should tell us how quantum matter gravitates, especially if gravity is strong. As long as gravity is weak, we could get away with quantizing it in the same way that we quantize other interactions. But this weak-field quantization stops making sense when gravity is strong, such as when highly energetic particles collide at energies so high that the particles themselves have a strong gravitational interaction.

Quantum gravity should also tell us what happened in the very early universe. According to general relativity, our universe started in a singularity. This unphysical result indicates that we need a more fundamental description of space and time back then. Since gravity was strong in the early universe, quantum effects of gravity cannot be neglected when describing this phase.

General relativity also predicts singularities when matter collapses into black holes, which leads to what is known as the black hole information loss paradox. It concerns the fact that black holes emit thermal radiation because of quantum effects, not including quantum gravitational effects. But when the black hole has completely evaporated, all that is left is thermal radiation, regardless of what formed the black hole. Information is destroyed in this irreversible process, but since irreversible processes cannot happen in quantum mechanics as we know it, this represents an inconsistency. Quantum gravity should explain what happens to the information in black holes.

Along with solving these thorny problems, the successful theory of quantum gravity must also be able to reproduce all achievements of general relativity and the Standard Model of particle physics. And it must make testable predictions that give us confidence that we have the right description of nature.

Why combine quantum mechanics and gravity?



S Hossenfelder

Quantum mechanics tells us that particles can exist in quantum superpositions, and general relativity tells us that particles have a gravitational field. But what is the gravitational field of a quantum superposition? This seemingly simple question is one we cannot currently answer. To do so we need to develop a theory of quantum gravity.

What have we learned so far?

Physicists are working on several approaches to quantum gravity: string theory and loop quantum gravity; causal dynamical triangulation and asymptotically safe gravity; causal sets; group field theory; emergent and induced gravity; and a few other comparably small research agendas. String theory currently has the highest score in addressing the above requirements, followed by loop quantum gravity and asymptotically safe gravity.

From the outside, research on any of these approaches to quantum gravity must be like watching the construction of a tunnel. For a long time, nothing much happens, except that occasionally a tool goes in and rubble comes out. But step inside and you will see a hive of activity. Recently, a lot of progress has been made in each of the approaches – progress that has considerably advanced our understanding of the problem. In the end though, a tunnel is only useful once a breakthrough is made.

While no breakthrough has yet been made, we are learning. We have learned that specific properties of quantum gravity appear in several of the approaches, if in different manifestations. The best known example may be holography – the encoding of information contained in a volume on the boundary of that volume. The existence of a minimal length scale is another such property that appears in different approaches. It seems that, ultimately, quantum gravitational fluctuations prevent us from resolving structures arbitrarily well. A more recent discovery is that the dimension of space–time seems to become smaller on short distances, a surprising behaviour that has also been found in different approaches.

I have little doubt that we will be able to unify quantum mechanics and gravity; some of my colleagues might even argue that we have already done so. But we are not looking for *a* theory of quantum gravity. We are looking for *the* theory of quantum gravity – the theory that describes the world around us. Making connections with observation is thus not only important, but also necessary for quantum gravity to be scientific.

What is next?

So far, we do not have any experimental evidence for quantum gravity. But during the last decade it has become clear that it is technologically possible, even in the absence of a fully fledged theory, to search for evidence of general properties expected of quantum gravity – like the ones named above, and more still, such as violations of certain symmetries. This can be done, and has been successfully done in some cases already, through the use of phenomenological models. Such models parameterize effects and make connections with observations. Observations can then be used to learn what properties the yet-to-be-found theory can have and which it cannot have. I think that this experimental guidance is essential to constructing the theory of quantum gravity, and is the route to making progress.

Since gravity is really a consequence of space–time being curved, we are looking for a theory of the quantum nature of space and time itself. It is the most fundamental of the currently open questions in the sense that it concerns the most basic ingredients of our theories. Next to revolutionizing our understanding of space, time and matter, quantum gravity will likely also significantly advance other areas. The nature of time and its uni-directional arrow are puzzles deeply interlinked with quantum gravity, and so is the physics of the early universe. Moreover, I believe we will learn a lesson about quantization that has the potential to improve our ability to manipulate quantum matter.

The tunnel's construction site might not look like much, but rest assured: once a breakthrough is made, you will see heavy traffic on the new route.

Mehau Kulyk/Science Photo Library

Can we exploit the weirdness of quantum mechanics?

Harnessing quantum entanglement will be the key to realizing large-scale quantum computers that solve hard problems, argues **John Preskill**

Quantum theory is over a century old, yet physicists continue to be perplexed and delighted by the weirdness of the quantum world. Whereas the laws of classical physics successfully explain the phenomena we experience every day, atoms and other tiny objects obey quantum laws that sometimes seem to defy common sense, baffling our feeble human minds. In the 21st century, we hope to put this weirdness to work by building quantum computers capable of performing amazing tasks.

To appreciate how the classical and quantum worlds differ, it is helpful to recall how information gets encoded and processed by physical systems. Just as digital information can be expressed in terms of bits, information carried by quantum systems can be expressed in terms of indivisible units called quantum bits, or "qubits". A qubit is just a quantum system with two distinguishable states, and it can be realized physically in many possible ways; for example, by the spin of a single electron. But to get to the crux of how qubits differ from classical bits, let us view them more abstractly.

Boxing clever

We can picture a bit as a box with a ball inside that can be coloured either red or green. The box has a single door we can open to find out the ball's colour. A qubit is also such a box, but with two doors marked 1 and 2. Whenever we open the box, we must choose either door 1 or door 2; we cannot open both. However, opening a door not only reveals the colour inside but also unavoidably disturbs what is inside.

If we put a red ball in door 1 and later open door 2, the ball that comes out has a random colour: red with

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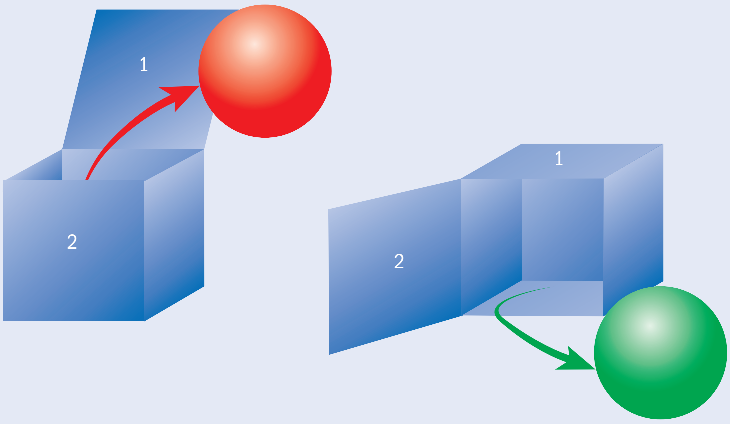
Curious affair



A qubit can be viewed as a box containing a ball that is either red or green, the colour of which can be viewed by opening either of two doors (1 and 2). Strangely, we cannot predict what will happen when we observe the colour through, say, door 2, even though we know exactly how the box was prepared, for example, by opening door 1.

probability ½ and green with probability ½. Although we often use probability to describe classical systems, the randomness exhibited by quantum systems is different. If a classical box has a ball inside and we do not know the ball's colour with certainty, we assign probabilities to the two possible colours, reflecting our incomplete knowledge. But for the quantum box, we may be powerless to predict what will happen when we observe the colour through door 2, even though we have complete knowledge of how the box was prepared (for example, by opening door 1).

The deepest differences between classical and quantum information can be fully appreciated only if we consider systems with more than one part. So consider two qubits: Alice's in London and Bob's in New York. This qubit pair can be prepared in a state such that if Alice opens either door of her box in London she sees a random colour, and the same is true for Bob in New York. So neither party acquires any information by measuring his or her qubit. Instead, information is hidden in *correlations* between what Alice sees when she opens a door in London and what Bob sees when he opens a door in New York – in this particular state Alice and Bob are guaranteed to find the same colour if they both open the same door. There are four distinguishable ways in which boxes in London and New York could be perfectly correlated – Alice and Bob could see either the same colour or different colours when both open door 1 or both open door 2. By choosing one of those four ways, we have stored two bits in the boxes.

The technology for controlling quantum systems is advancing rapidly, fuelling the hope that in a few decades human civilization will enter an age of quantum supremacy

Classical systems can also be correlated, of course, but this is different. What's strange is that the information is completely inaccessible locally; it is entirely stored in the correlations. Though the whole system is in some definite state, the parts of the system are not. That is "quantum entanglement".

Stranger and stranger

Entanglement gets stranger still for systems with many parts. Picture a 100-page book. If the book were classical, then by reading one page we could learn 1% of the content of the book. But a highly entangled quantum book is different. Looking at any one page we see only random gibberish, learning almost nothing about the content of the book. That is because information does not reside on the individual pages; instead it is recorded in the correlations among the pages. Only by performing a complex collective observation on many pages at once can we discern the differences between one highly entangled book and another.

For a highly entangled state of a few hundred qubits, the correlations among the qubits are so complex that describing them completely using classical information would require an unthinkable number of bits – more in fact than the number of atoms in the visible universe. This extravagant complexity of the quantum world points toward a highly plausible but unproven conjecture: classical systems cannot in general simulate quantum systems efficiently. If true, this statement has extraordinary implications. It means that by building highly controllable, many-qubit quantum systems, we should be able to perform some information-processing tasks far faster than would be feasible if we lived in a classical – rather than a quantum – world.

The technology for controlling quantum systems is advancing rapidly, fuelling the hope that in a few decades human civilization will enter an age of quantum supremacy, in which quantum computers solve problems that are beyond the reach of classical digital computers, such as factoring large numbers and simulating the physics of complex molecules. But to realize that dream, we must overcome a formidable obstacle: that of "decoherence", which ordinarily makes large quantum systems behave classically. Entanglement among the qubits in a quantum computer is the source of its power, but entanglement between the computer and its unobserved environment is our enemy, driving decoherence.

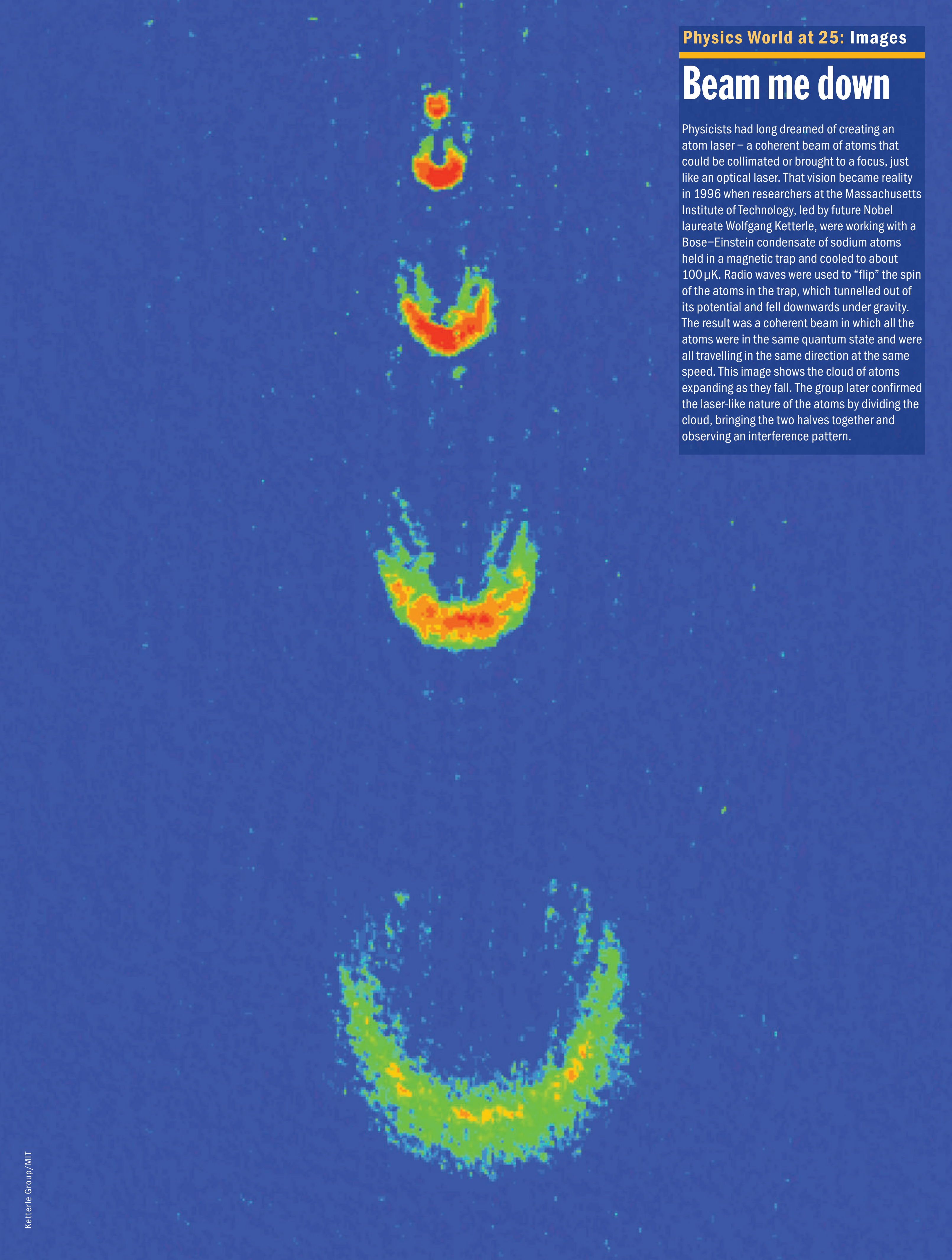
In a classical computer an error occurs if interactions with the environment flip a bit. But a qubit is more delicate – it suffers an error if any information at all about its state leaks to the environment. That is decoherence. So for a quantum computer to work effectively, the information it processes must be perfectly concealed from the outside world until the computation is completed and the result is announced.

What weapon shall we wield to battle decoherence? Entanglement! The best way to resist decoherence is to encode information in highly entangled states. The state stored in the computer is like an entangled quantum book. The environment, interacting with the pages one at a time, acquires no information about the content of the book, because the information resides not in the individual pages but rather in the correlations among the pages. This principle, dubbed "quantum error correction", will guide the design of future quantum computing hardware and software.

Today's scientists and engineers are fortunate to live in an age of emerging quantum technologies. Indeed, our imaginations are poorly equipped to anticipate the many potential rewards to be gained by manipulating highly entangled quantum states. We should expect the unexpected. ■

Beam me down

Physicists had long dreamed of creating an atom laser – a coherent beam of atoms that could be collimated or brought to a focus, just like an optical laser. That vision became reality in 1996 when researchers at the Massachusetts Institute of Technology, led by future Nobel laureate Wolfgang Ketterle, were working with a Bose–Einstein condensate of sodium atoms held in a magnetic trap and cooled to about 100 μK. Radio waves were used to "flip" the spin of the atoms in the trap, which tunnelled out of its potential and fell downwards under gravity. The result was a coherent beam in which all the atoms were in the same quantum state and were all travelling in the same direction at the same speed. This image shows the cloud of atoms expanding as they fall. The group later confirmed the laser-like nature of the atoms by dividing the cloud, bringing the two halves together and observing an interference pattern.



Ketterle Group/MIT

Five spin-offs from physics research with the potential to change our lives

Physics for our future

From lasers and semiconductors to X-rays and the Web, physicists can be credited with seeding numerous technologies that have changed how we live. **Hamish Johnston** presents five spin-offs from physics research that we predict will most alter our everyday lives over the next 25 years

Hamish Johnston is editor of *physicsworld.com*

Predicting the future is a mug's game, which is why most physicists prefer not to shout too loudly about the possible benefits of their research, even if there is a growing demand from funding agencies to do so. Grandiose, utopian predictions that never materialize always look faintly ridiculous in years to come – have you seen anyone recently flying to work on a nuclear-powered jet-pack?

But with this being the 25th anniversary of *Physics World*, it is only right that we should set ourselves up for a fall by picking the five physics spin-offs we expect to make the biggest difference to humanity over the next few decades. And while there are plenty of spin-offs that will aid science, our five choices are those that will, we feel, do most to improve the everyday lives of ordinary people around the world.

Of course, we expect to get a few of them wrong. And there are bound to be one or two seemingly mundane discoveries that we have missed, yet will catapult to fame and fortune in the next few years. So without further ado, let's begin with our first choice – a medical treatment that today can only be done at 40 or so facilities worldwide but that, we reckon, will soon be found at every major hospital around the globe.

A better beam

That treatment is hadron therapy, which exploits the fact that beams of protons and other hadrons can almost magically penetrate human tissue before releasing their energy at a well-defined depth. Hadron beams can therefore kill tumour cells while sparing healthy tissue, making them ideal for treating certain cancers – notably the potentially lethal eye cancer ocular melanoma – because the patient suffers less and the success rate is higher. Gamma rays, X-rays or electrons, in contrast, tend to dump their energy over a much greater volume.

Particle therapy has emerged as a by-product of high-energy physics – in fact, the first treatment took place at the Lawrence Berkeley National Laboratory in 1954 – but making it more widely available is a challenge. The snag is that the accelerators currently used to create beams of protons and other heavy ions are large and expensive, and the gantries that steer the beam across a tumour are the size of a small house. But one solution that could put particle therapy within the reach of most hospitals is laser-driven acceleration, which involves firing a very short yet intense laser pulse into a jet of gas, thin foil or thicker target.

Particle therapy has emerged as a by-product of high-energy physics, but making it more widely available is challenging

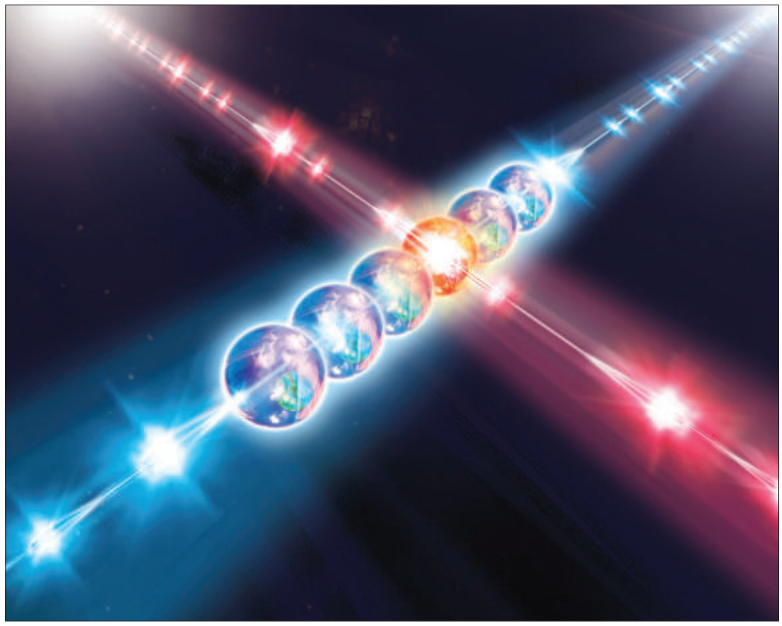
As the intense pulse travels through the target, it rips nearby electrons away from the positive nuclei, thus creating a huge electric field gradient in its wake. This field has a large accelerating potential that can be thousands of times that of a conventional accelerator. A laser-driven hadron accelerator can therefore, in principle, be relatively compact. Table-top lasers have already been used to accelerate protons to tens of mega-electron-volts, approaching the 70 MeV needed to treat ocular cancer. However, we need to find ways of boosting their energy to 200–300 MeV to kill tumours lying deeper within the body.

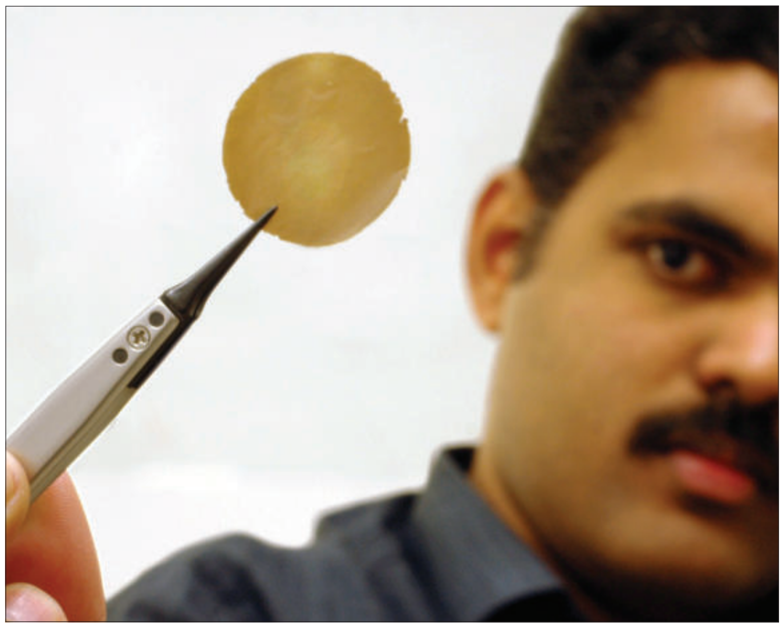
Commercially available laser systems that can deliver such energies should be available in about 10 years, although it will probably take a further decade or so before they become routinely used to treat patients in hospitals. One problem with laser acceleration is that it delivers particles in pulses, rather than as a continuous beam. Techniques will therefore have to be devised to ensure the pulses are intense and numerous enough that patients get enough of a dose without having to lie perfectly still for long periods. In fact, the pulses could be a virtue as the magnets needed to scan the proton beam across a treatment area would then not have to be as big.

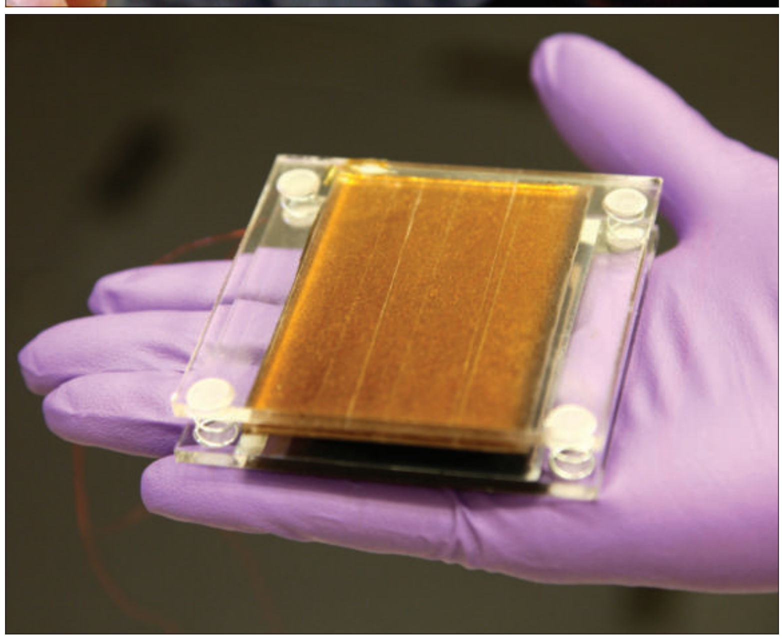
And if lasers do not bring hadron therapy to every hospital, there are other options, such as fixed-field alternating gradient accelerators. They are being developed at Daresbury Laboratory and elsewhere, and could also lead to compact devices suitable for cancer treatment.

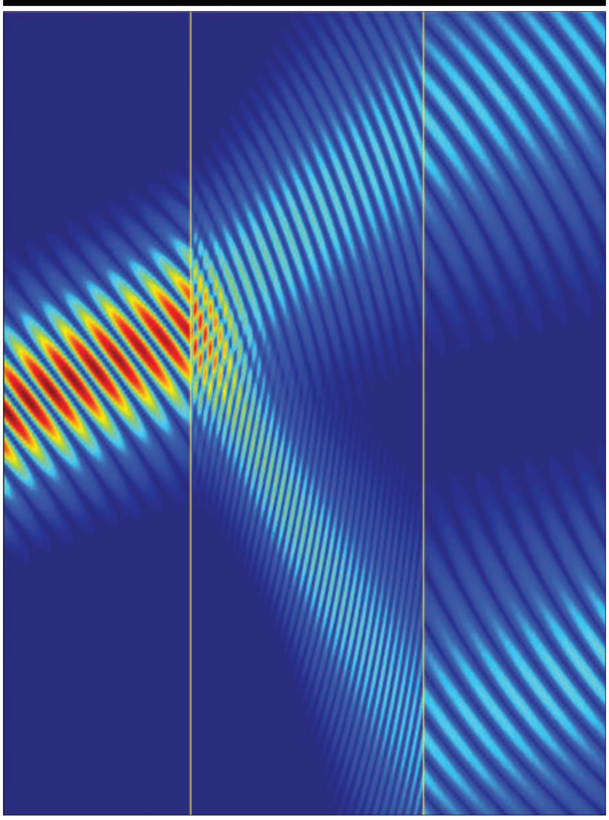
Some like it thin

While laser-driven hadron therapy is likely to be of most benefit to people in rich nations, our next spin-off could have massive implications for those in the developing world. It involves a material that was first isolated just nine years ago by Andre Geim and Konstantin Novoselov at the University of Manchester. That substance is, of course, graphene. Much of the hype surrounding this 2D honeycomb of carbon atoms has focused on its extraordinary electronic properties – who could resist the lure of an ultrathin bendable smartphone? But we think that another of graphene's physical properties could be more important still. It turns out that despite being just one atom thick graphene appears to be completely impervious









Clockwise from top left: National Cancer Institute/Science Photo Library; IQOQI/H Ritsch; University of Manchester; Georgia Institute of Technology; I Shadrivov/*New J. Phys.* **7** 220

Opportunity knocks Physics with the potential to do good. Clockwise from top left: a beam of protons irradiating a tumour; conceptualization of a quantum simulator; a graphene water filter; a triboelectric generator; a computer simulation of a superlens material.

Superlens-powered “nanoscopes” look set to fundamentally alter how we view the very small

to almost every liquid and gas. By drilling holes of the appropriate size in graphene – or creating membranes of graphene flakes stuck together with just the right sized gaps between flakes – the material can be used as a selective filter.

In 2012 Geim and colleagues found that membranes made from millions of flakes of graphene oxide that had been stuck together allow water to easily pass through – yet the membranes are impervious to every other liquid or gas tested. Indeed, water was found to flow through the membrane 10 billion times faster than helium, which itself is rather good at diffusing through solids.

The application of such graphene membranes is obvious: they could be the ultimate water purifiers and could someday create drinking water from the sea. But such graphene-based membranes could have other applications as well, such as separating molecular species in a mixture, shielding people from dangerous toxins or making more efficient electricity-generating fuel cells.

But while cheap and effective water purification could be an early spin-off from research into graphene, this “wonder material” could have many other applications in biology and medicine too. One promising idea is to read the base sequences of DNA by drawing these protein chains through tiny nanometre-sized holes drilled into graphene, the electrical properties of which change depending on which base happens to be in the pore at any one time. Such graphene “nanopores” could even be engineered to mimic the plethora of pores inside living cells or to craft artificial systems that recreate the incredible filtering abilities of the cell wall.

Being strong, flexible and – as far as we know – biocompatible, graphene could also be used as the basis of new kinds of prosthetic limbs. Earlier this year, for example, physicists in Germany showed that graphene transistors can generate an electrical signal in response to changes in the concentrations of ions that occur when cultured nerve cells fire. Work like this could help us to build artificial limbs that are wired directly into the human nervous system using graphene electronics as the interface.

Quantum calculations

Strengthening the links between complicated, messy biology and the neat reductionist world of physics is the basis for our next revolutionary spin-off. For the past decade or so, the new discipline of quantum information has grown by leaps and bounds. Ultra-secure quantum-cryptography systems are already being used by banks and other institutions keen on secrecy. Physicists can transmit quantum information a hundred or so kilometres through the air, and there are serious proposals to make a quantum link between ground and satellites in space.

The possibilities of quantum computers, however, are even more intriguing. Such devices, which would exploit superposition, entanglement and other quantum phenomena to perform super-fast calculations, have the potential for some amazing feats. But there is one particular thing that a quantum computer can do much better than a conventional computer – and that is to solve the Schrödinger equation for systems as large as a molecule, without resorting to the messy approximations that are usually needed to describe even the simplest molecules.

This would involve taking a collection of quantum bits, or “qubits” – say trapped ions – and manipulating both their internal properties and the interactions between them to simulate the atoms, and the forces between them, in a molecule. In the case of ions, this manipulation could be done by adjusting electric and magnetic fields applied to the ions or by shining laser light on them. Researchers would need about 100 qubits to do quantum simulations that can compete with today’s supercomputers. Although today’s best systems have tens of qubits, our control over the quantum world is improving so rapidly that working “quantum simulators” could be with us in a decade or so.

Algorithms for such simulators have, in fact, already been developed for calculating chemical reaction rates and how proteins fold. If put into practice, they could help with the design of new drugs by allowing chemists to calculate more accurately the properties of candidate molecules and slash the time it takes to determine which would work best. Quantum simulators could also be used to understand the process by which DNA protects itself from the gene-damaging glare of sunlight, which could help prevent skin and other cancers.

Simulators could even help us to understand how photosynthesis occurs and thereby let us build artificial systems that mimic the efficient energy harvesting of plants or serve as new sources of sustainable energy. Quantum simulations would also help chemists get a better handle on how enzymes work, which could be a boon to the chemical industry. Indeed, quantum simulation looks set to be one of the most important tools that physicists have created for the rest of science.

Seeing more clearly

Our next big spin-off could also boost our understanding of biological processes by giving us a new way of seeing with light. Light is, of course, a wonderful thing as it can be guided and focused using simple lenses and fibres, capturing images of objects that are either too small or too far away to be seen with the naked eye. Moreover, many atomic and molecular transitions occur at optical wavelengths, which is why light – from the infrared to the ultraviolet – lies at the heart of a vast range of spectroscopic techniques.

But there is one major drawback to light as a probe of atoms and molecules: light of a certain wavelength cannot be used to discern an object smaller than about half that wavelength. Even for ultraviolet light, this “diffraction limit” is about 50 nm, or roughly the size of a large protein molecule. Electron microscopy can get round this resolution problem because the wavelengths of electrons can be much shorter than light. But it usually requires samples to be prepared in a way that can alter them, which is a problem for fragile biological systems.

Over the past decade or so, however, physicists have devised a way of getting around the diffraction limit and obtaining images of objects that are much smaller than optical wavelengths. The technique does not involve the familiar "far-field" light that is scattered or transmitted by an object and observed some distance away from it. Instead, it exploits the "near-field" or "evanescent" light that contains detailed sub-wavelength information about an object.

This light, which decays exponentially over a distance shorter than the wavelength of the light itself, cannot be gathered and focused using conventional optics. But in 2000 John Pendry of Imperial College London predicted that artificially engineered metamaterials with a refractive index of less than zero could be used to create a "superlens" that could gather and focus the evanescent light before combining it with the far-field light to create an image of the object. If the lens were "perfect" and gathered *all* the light, it could be used to create an image with infinite resolution. But even if only some of the light were captured, a superlens could still probe distances significantly below the diffraction limit.

The challenge with making negative-index metamaterials is that the index of refraction has both an electric and a magnetic component, both of which have to be less than zero. And, while the first rudimentary superlens-powered "nanoscopes" have already been made using metamaterials with the appropriate electrical components, making a material with the right magnetic response seems to have stalled over the past few years. Still, we think such nanoscopes look set to fundamentally alter how we view the very small – from protein folding and DNA replication to seeing how viruses invade healthy cells. So perhaps the superlens will find a cure for the common cold at last.

Power on the go

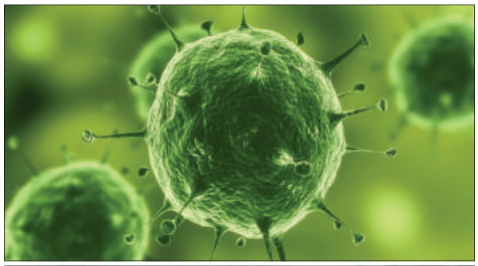
Our final spin-off concerns energy – and specifically the stuff that powers the growing number of smartphones, tablets and other portable devices that we use while on the move in our daily lives. These are mostly run by lithium-ion batteries, but boosting battery capacity has proven very difficult. If we are moving, however, why not harvest some of that kinetic energy to power all our gadgets? Harvesting is most efficient when it harnesses repetitive motion such as walking, and the best estimate for the maximum rate at which mechanical energy can be converted to electrical energy – without impeding the walker – is 11 W. That, coincidentally, is about the same as today's ubiquitous USB charger.

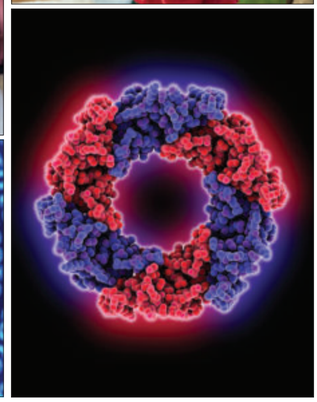
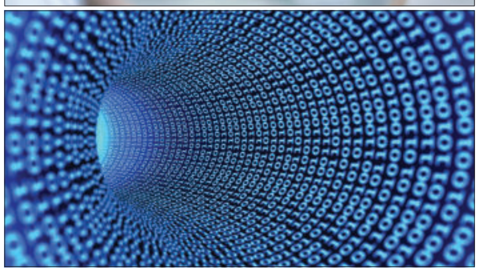
Researchers have already made a device – designed to be fitted into a shoe – that can fully charge a mobile phone in about 10 hours. While most of us do not regularly walk for such long periods, a phone user could at the very least keep their phone battery topped up using such a system. The "shoe charger" has been built by a team led by Zhong Lin Wang at the Georgia Institute of Technology, who is an advocate of energy harvesting from triboelectricity – commonly known as static electricity.

Normally the bane of engineers working in fields as diverse as aeronautics, microelectronics and textiles, triboelectricity is generated when two different materials (one electron-loving and the other electron-repelling) are rubbed together and then moved apart. The result is two oppositely-charged surfaces that create a voltage that drives a current. But triboelectric generators do not just have to be fitted into shoes. A jacket, for example, could produce 10–20 W from human motion – while a triboelectric flag flapping in the breeze could harvest 30–50 W.

But who would want a triboelectric flag and clothes? The most immediate beneficiaries are sure to be infantry soldiers, who are currently burdened by massive battery packs weighing up to 10 kg that they need to power a myriad of electronic devices from night-vision goggles to GPS and communications systems. Triboelectric systems could also be used to power the growing number of medical implants and prosthetics that currently run only on batteries.

While all of these innovations have come from blue-sky research, they will probably come to fruition in very different ways. Laser-driven proton therapy will be developed by large teams of physicists, cancer specialists and medical-equipment makers, whereas the first commercial shoe charger could be created in someone's garage. And to make a difference in our lives, all of these concepts must survive the "valley of death": the gap between making a scientific discovery and turning it into a practical product. We are confident that at least some of our top five will make it across. ■



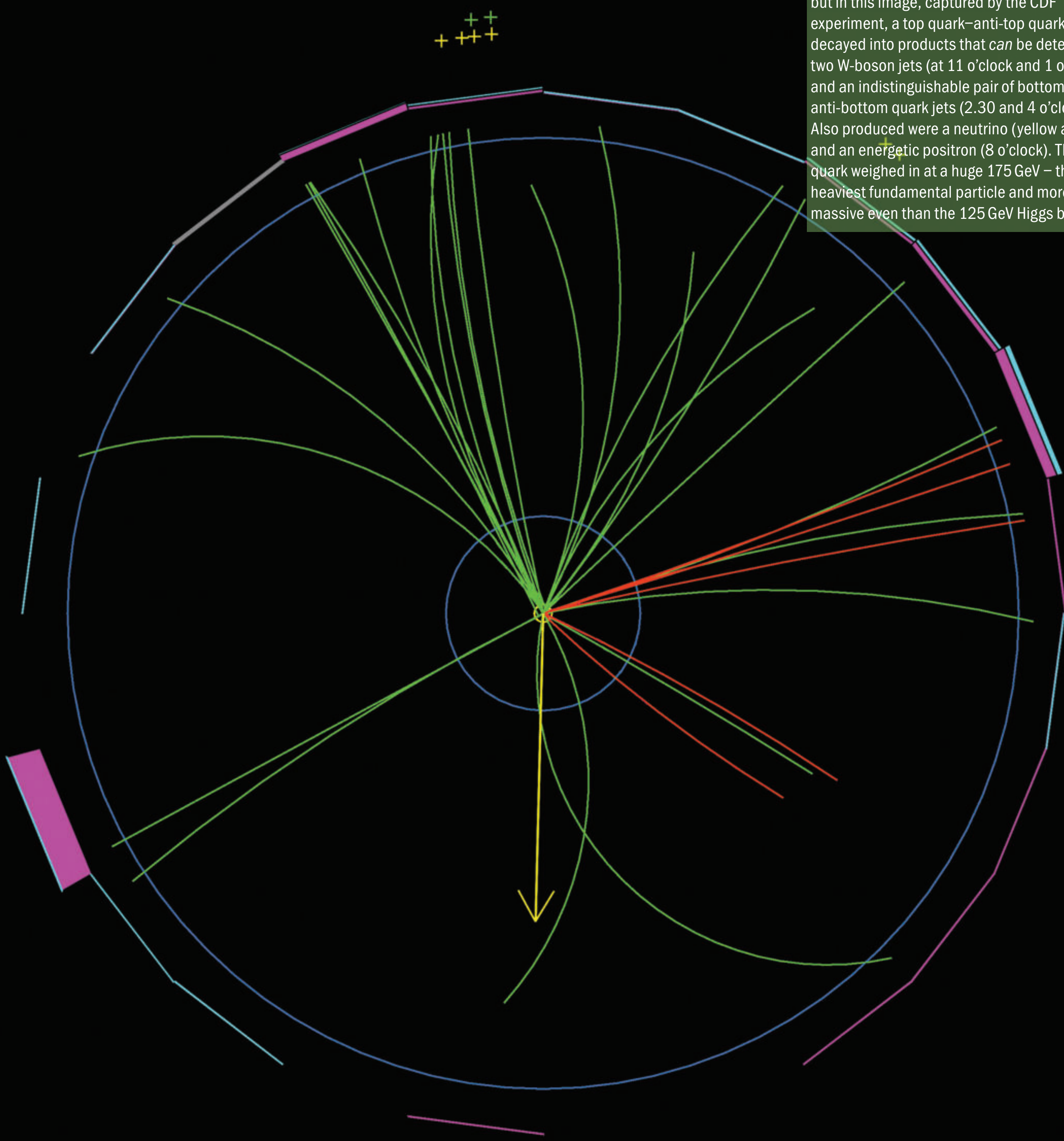




Physics for all
Clockwise from top left: compact laser-driven accelerators will improve cancer treatment; graphene filters will extend access to clean water; superlenses will allow us to watch the chemistry of life in action; quantum simulators will help us harness the Sun's energy by mimicking photosynthesis; and energy harvesting will keep our electronic gadgets working while we are on the go.

Clockwise from top left: SuperStock; iStockphoto; Laguna Design/Science Photo Library; iStockphoto; Shutterstock

First to the top

1995 was a year to remember for Fermilab in the US as it was then that the top quark – the sixth and final quark to be discovered – was finally snared at the Tevatron collider by smashing protons and antiprotons together. The top quark has a lifetime of only about 10^{-24} s and so disappears too quickly to be observed directly, but in this image, captured by the CDF experiment, a top quark–anti-top quark pair has decayed into products that *can* be detected: two W-boson jets (at 11 o'clock and 1 o'clock) and an indistinguishable pair of bottom and anti-bottom quark jets (2.30 and 4 o'clock). Also produced were a neutrino (yellow arrow) and an energetic positron (8 o'clock). The top quark weighed in at a huge 175 GeV – the heaviest fundamental particle and more massive even than the 125 GeV Higgs boson.



Fermilab/Science Photo Library

5 People

Five people who are changing how we do physics

Nurturing the next Einsteins

Neil Turok wants to change how advanced scientific training is done worldwide, and he believes that Africa can play a vital role in shifting entrenched views

AIMS South Africa

For the cosmologist Neil Turok, Africa represents "the world's greatest untapped pool of scientific and technical talent". He should know: the director of Canada's Perimeter Institute for Theoretical Physics was born in South Africa, and credits his political-activist parents with giving him a "very strong sense of commitment and obligation" to improving education for people across the continent. Indeed, Turok's parents convinced him to found the African Institute for Mathematical Sciences (AIMS), which has trained some 460 postgraduates in advanced mathematics since its inception in 2003.

Each year, AIMS brings 50–60 postgraduates from more than two dozen African countries to its campuses in South Africa, Ghana and Senegal to learn how mathematics can be used to solve scientific problems. The year-long MSc programme begins by boosting students' skills and filling in the sometimes huge gaps in their previous education. "These are bright people but they have not always been through good universities," Turok explains, adding that AIMS seeks to "shock" students out of what he calls an "undergraduate way of thinking".

Rather than sitting through conventional lectures, AIMS students learn to think on their feet. This is not easy, Turok says, with some students becoming "very unhappy" and questioning why they are there. "But after about two months, they get it – 'this is about me thinking'," he says.

AIMS students are also exposed to a wide range of cutting-edge research via three-week survey courses. The idea is to help students make an informed decision about topics they want to pursue in their PhDs.

Morenikeji Deborah Akinlotan from Nigeria is about to embark on a PhD in biomathematics because of her experience at AIMS: "I discovered that mathematics is not only extremely useful in all spheres of life, but also that I can actually apply mathematics in medical-related projects."

Of course, African students are not the only ones who need to shed their "undergraduate thinking" and Turok believes that every university in the world ought to run similar year-long programmes. He argues that they let students think about what they want to specialize in rather than just plunging into a PhD. Governments have also become short-sighted, he adds, concentrating only on economically relevant science and engineering. "The focus should be on developing students as independent and innovative thinkers – that is the most valuable thing a university can do."

"My experience in founding AIMS has convinced me that Africa is the ideal place to reinvent advanced education. The students are more motivated than anywhere else because they have such adversity in their lives. They are also more diverse, and the energy you get from students in Africa is quite extraordinary." When Turok arrived at the Perimeter Institute in 2008 he set up the Perimeter Scholars International MSc programme, which, much like AIMS, exposes students to a wide range of theoretical physics.

Turok says that although AIMS is only a decade old, it has already benefited Africa. While about 30% of its alumni have chosen to pursue further study or careers outside of Africa, others are taking leading academic, industrial and government roles across the continent and all have made a strong commitment to contribute to its prosperity. The institute is also expanding, with new facilities planned for Cameroon, Tanzania and Benin.

> Africa is the ideal place to reinvent advanced education

So far, AIMS has succeeded in attracting both funding and volunteer lecturers. However, Turok believes that AIMS's ultimate success will be in changing cultural attitudes about Africa. Before AIMS was established, he says, "the international development community had overlooked advanced training in Africa, mostly focusing on primary school". But Turok thinks it is vital to have people in government who can think for themselves and plan and structure an economy. "Above all, you need role models," he says. "You have to create a situation where the brightest African students are succeeding in higher education and getting advanced degrees."

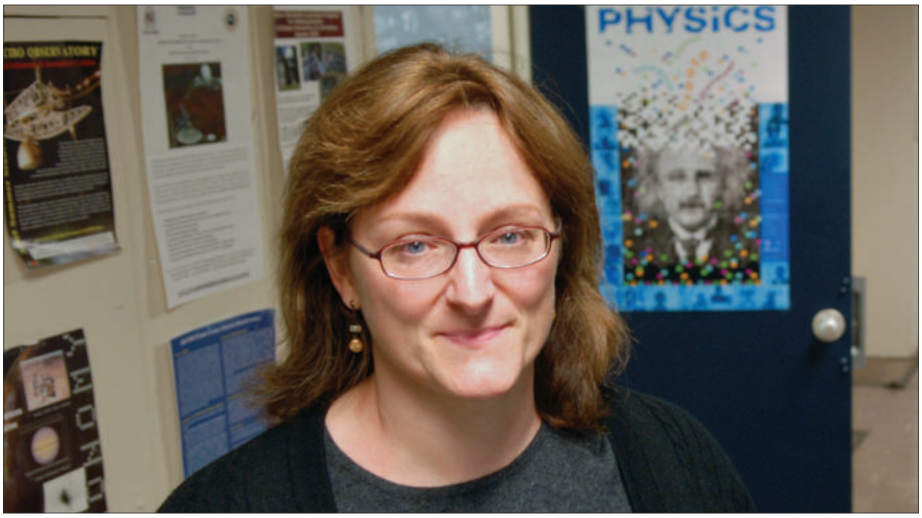
Trust Chibawara, who is from Zimbabwe and attended AIMS in 2007, was one such student. "I was far better equipped for making my future decisions after AIMS,"he says. "AIMS taught me, most importantly, that I can learn, that I can attempt anything I put my mind to and be very successful."

In 2008 Turok said that he wanted the next Einstein to be African, and the goal of creating 15 campuses across the continent is an important part of the AIMS Next Einstein Initiative. "Theoretical physics has always been the pinnacle of human achievement and seeing Africans do theoretical physics will do much to undermine racism," he says. "An individual can do incredible things."

Hamish Johnston

Under a limitless sky

A veteran of the fight for equal opportunities for women in science, **Meg Urry** is now turning her attention to an even bigger problem



Michael Marsland/Yale University

Two decades ago, the US physics and astronomy communities looked pretty similar: about 10% of faculty members were female, and almost everyone was white. Since then, the picture has changed – but only in astronomy, and only for women, who now make up around 15% of tenured faculty and, by some estimates, nearly 40% of new hires in US astronomy departments. Physics, meanwhile, is stuck at around 10%, and in both fields the figures for under-represented minorities have barely budged.

This asymmetric pattern of change is both troubling and galvanizing for Meg Urry, the Yale University astrophysicist and incoming president of the American Astronomical Society (AAS). Following her election in February this year, Urry – a longtime advocate for women in science – announced that increasing participation among minorities would be a major goal of her presidency. "In the past two decades we've seen a revolution in the participation of women in astronomy," she wrote. "We have yet to see comparable gains in the participation of under-represented minorities, or the sense among all members that they are fully welcome. This has been a priority for the AAS for some time, and I intend to add my voice to this issue."

Urry's voice matters not only because of her role in astronomy's gender "revolution" but also because of her status as a researcher. Until recently, she was the chair of Yale's physics department, having become its first ever tenured female faculty member when she was hired in 2001. Before that, she spent 14 years at the Space Telescope Science Institute (STScI) in Maryland, US, where her achievements included a study of active galactic nuclei that has been cited nearly 2000 times.

Urry's scientific accomplishments have boosted what she calls her "second career" as a proponent of women's participation in science. This career began in earnest in 1992, when Urry and an STScI colleague, Laura Danly, organized the first Women in Astronomy conference. One outcome of it was the Baltimore Charter, which identified problems such as sexual harassment and discriminatory hiring in astronomy and recommended ways of addressing them. But the conference also did something that Urry believes was even more important: it brought 150 women astronomers together in the same room. "We all were looking around and going, 'Oh my God, I didn't realize there were so many!'," she recalls. "It created networks, it created a sense that we were well beyond critical mass and I think all those things combined to create a community where everyone lifted everyone else."

Fixing the leaky pipe

Urry acknowledges that boosting the participation of minorities in physics and astronomy is "a slightly different problem". One reason is that whereas women are under-represented in these fields by "factors of a few", for some minority groups, she says, "it's an order of magnitude problem". African-Americans and Latinos, for example, receive fewer than 3% of the physics PhDs awarded in the US each year despite making up almost 30% of the population. Being part of such a small group can be isolating, says Hakeem Oluseyi, an astrophysicist at the Florida Institute of Technology and an officer of the National Society of Black Physicists. "You feel like your entire race is going to be judged on your behaviour," he says. To combat that perception, Oluseyi adds, "You need a critical mass. If you accept students one or two at a time, you'll have people dropping out."

Efforts to achieve critical mass often focus on the education "pipeline" that takes students from secondary school up to PhD level. Jenni Dyer, who leads the diversity programme at the Institute of Physics, which publishes *Physics World*, says that in the UK, the percentage of black science students is extremely low even at secondary school. For that reason, she says, her team concentrates on getting students interested early in their education. But in the US, Urry says, the pipeline for African-Americans and Latinos also has a significant "leak" at the end of their undergraduate years, since many aspiring minority scientists attend poorly funded (often formerly all-black) institutions that do not prepare them well for postgraduate study. Oluseyi, who graduated from Mississippi's historically black Tougaloo College, recalls that he faced a steep learning curve when he went to Stanford University for his PhD. He credits his success in part to his African-American PhD supervisor, the late Art Walker, and to a Stanford programme that accepted students like him and let them catch up by taking advanced undergraduate courses.

By excluding people from physics we have dumbed it down

Supporting programmes like that might be one way for the AAS to help boost minority participation, Urry speculates. But whichever part of the pipeline she decides to tackle, she believes that fixing the leaks is vital. "Personally, I am driven by the issue of justice and fairness," she says. "But there is also no evidence whatsoever to believe that women or people of colour or gay people or handicapped people are less competent at physics. So, on the assumption that everyone has a similar distribution of ability, by excluding these people from the profession we have dumbed it down." And that, Urry concludes, is "something that in the modern day, when so many problems are technical and scientific in nature, we just can't afford to do".

Margaret Harris

Sharing the tools of the trade

Physicists are increasingly collaborating with scientists from other fields, but few have taken this concept as far as **Albert-László Barabási**

Northeastern University

Albert-László Barabási wants to set the record straight. "I consider myself a physicist," he says, and it is easy to see why. Born in Transylvania to a Hungarian family, he studied physics at the University of Bucharest in Romania and is now a professor of physics at Northeastern University in Boston, US. But at the same time, the versatile Barabási is also a lecturer at Harvard Medical School, and holds appointments in Northeastern's biology department and its College of Computer and Information Science. "I may have chosen my topics of enquiry a bit more freely from the traditional physics canon," he admits.

Barabási made his name in 1999 when, with Réka Albert of Pennsylvania State University, he used tools from statistical mechanics to develop a theory describing the origins of "scale-free networks" (*Science* **286** 509). These are networks that are held together by a few highly connected nodes, called hubs, like Google on the Web or very popular individuals in social networks. Since then, Barabási has continued to develop and apply these techniques to networks in fields as diverse as biology, computer science, economics and human behaviour. Gene Stanley, a physicist at Boston University who has made major contributions to complexity research, says that showing that many networks in the real world can be described as scale-free – and recognizing that this property is ubiquitous – is Barabási's biggest accomplishment. But Stanley adds that Barabási has "done something which some people do *not* do. He's stuck with it – he's stayed with the field he helped to develop".

Beyond tradition

Barabási has, for example, set up a collaboration between Northeastern's Center for Complex Network Research, which he directs, and Harvard Medical School. One focus of the group's work is to treat the cell not just as a bag of genes that have a mutation, but as a bag of interacting components. In Barabási's eyes, this gene network is the kind of complex problem that Ludwig Boltzmann faced in the 1870s and 1880s when he developed thermodynamics from statistical principles, translating microscopic randomness into macroscopic behaviour.

In Barabási's view, being a physicist means using the techniques of physics to inquire into the world around us – and while that world is made up of stars and subatomic particles, it also includes social and biological systems. In the past, Barabási explains, there have not been enough data for physicists to apply their tools to these complex systems. However, "big data" now offers a deluge of information about the real-time behaviour of many complex systems, and these resources can enrich physics. Indeed, Barabási is critical of the concept of "traditional physics". "Traditional physics is the physics that isn't worth studying, isn't it?" he asks with a glint in his eye. "Because it is already traditional and we know everything about it."

Branching out into research areas untouched by "traditional physics" does have its pitfalls, however. Although Barabási's work on human behaviour and mobility is arguably among his most interesting to date, he recently pulled the plug on it after becoming uneasy with the way certain organizations, such as the US National Security Agency, have used his findings. He refuses to be drawn on specifics, but says that, in general, scientists "occasionally have to step back and ask ourselves why we do certain things and whether there are proper safeguards for how the research is being applied". Barabási believes that in this particular case, the safeguards have failed. "My personal answer was to scale back that part of research and also to think a bit deeper about what our responsibilities as scientists are in this domain," he says.

> It is essential for the boundaries of physics to change

The need for change

Despite these risks, Barabási thinks it is essential for the boundaries of physics to change. In the past, he notes, the subject suffered when it failed to accommodate new directions of research. "For a long time, physics departments short-sightedly believed that astrophysics and astronomy were not physics," he says. "They are struggling to bring astrophysicists back now that they are becoming very exciting and making major discoveries."

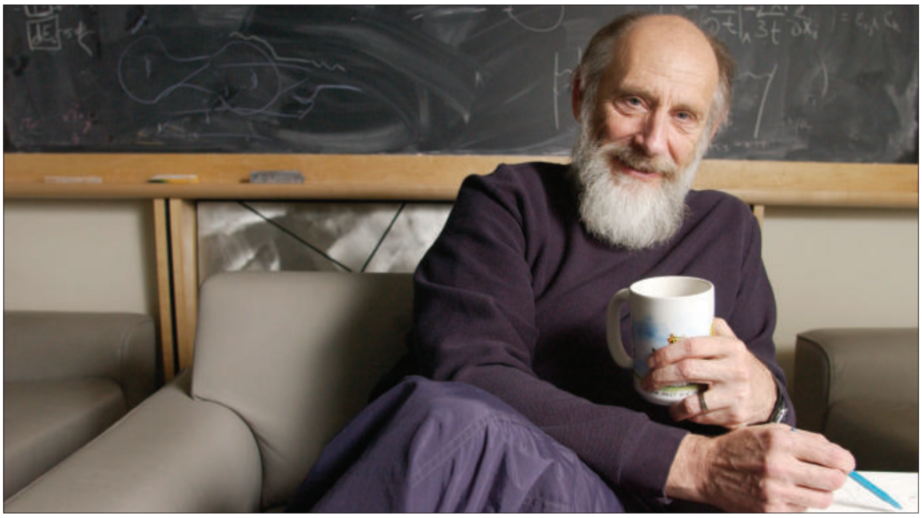
Barabási's affinity with these outcast astronomers of the past triggered in him some mixed feelings earlier this year when one of his papers knocked the astronomer Subrahmanyan Chandrasekhar off his perch as the author of the most-cited paper in *Reviews of Modern Physics*. "I have always been a fan of Chandrasekhar who himself was actually an outsider in physics," he says. "Had there been any person that I would *not* want to dethrone, it would have been him."

Barabási believes that physics still has a tendency to exclude those who are perceived as outsiders. When he and his colleagues in the other departments hire someone, he says, they do not ask that person whether they have a PhD in that subject. "[Instead] we ask them what they can bring to the department and how exciting their research is." In contrast, he adds, "I can't remember one single hiring in a physics department that didn't ask, 'Is this candidate a physicist?'" If physics does not adapt, it risks becoming "an insular enterprise" that will be left behind by other fields, Barabási warns.

Louise Mayor

A new kind of outreach

Leonard Susskind is bringing a "theoretical minimum" of real physics to people all over the world through his online courses



Linda A Cicero/Stanford News Service

One evening a week, Leonard Susskind goes back to basics. In a lecture theatre at Stanford University in California, US, he talks about classical mechanics, quantum theory, relativity and various other topics typical of degree-level physics. But the 100 or so people in the audience do not want a qualification – they are there simply because they enjoy learning.

"I thought I would try it out," says Susskind, speaking on the phone in his easy New York accent. "And I found it a lot of fun, very stimulating, and very different from teaching a regular university class. People have no interest in degrees, no interest in getting a grade, no interest in getting tested. It's a very nice way to teach people."

At 73, Susskind has enjoyed a long career at the forefront of theoretical physics. He is famous for his work on black holes – particularly his "war" with the British theorist Stephen Hawking over the fate of information contained inside them – and for his pioneering work on string theory. Today, as director of the Stanford Institute for Theoretical Physics, he is still very active in research, but that has not deterred him from a burgeoning side project: teaching physics to lay-people.

Of course, outreach is a popular occupation among physicists, as the proliferation of science-as-entertainment events and pop-science books testifies. But Susskind's project is more formal and has a slightly different purpose. In fact, he says his idea came from meeting people who are frustrated to find that the level of physics explanation in pop-science media often falls short of their expectations. "There's a subset of people who have enough technical background to know that they're not understanding," says Susskind. "They have no venue for learning physics in a real way. Textbooks are dry, textbooks are boring, and to learn completely by themselves is not fun."

Come one, come all

Seeing room for a new type of physics teaching, Susskind started delivering courses he called the Theoretical Minimum. The "minimum" should not imply that the courses are easy. Rather, the term means that Susskind spends the minimum amount of time on a certain topic (for example, classical mechanics) to proceed to the next (for example, quantum mechanics).

"You know, a lot of people from my generation learned quantum field theory from a little skinny book by a [German] gentleman named [Franz] Mandl," Susskind explains. "It was the only way to get into the subject at the time, because there were no good textbooks. And I have a very distinct memory of having learned easily and quickly from that. I always wanted to try to reproduce that in other subjects, where you really reduce it to the bare minimum."

Material in the Theoretical Minimum courses was first published in a well-received book of the same name this year, but undoubtedly most students are learning from videos of the lectures. These are available to watch free online via the course website (http://theoreticalminimum.com) and on *YouTube*, where the first lecture on classical mechanics has garnered more than 100 000 views so far.

In the sheer number of people it reaches, Susskind's project is part of a growing trend for so-called massive open online courses, or MOOCs. Similar to distance-learning courses in decades gone by, MOOCs offer university-level education online to those who might otherwise have no access to it. In recent years, MOOC enrollees have skyrocketed. EdX, a MOOC provider run between Harvard University and the Massachusetts Institute of Technology in the US, has registered more than 1.1 million users since it started up last year. "You have simply a better selection and variety of courses for people to take, and definitely there are more people taking them," says Dan O'Connell, associate director of communications at EdX.

> I get huge amounts of e-mail, mostly from outside the US

Many universities are looking to further their reach by offering MOOCs through companies such as EdX. But they have not been without criticism. Opponents of MOOCs point to the very high drop-out rates, and believe that they can encourage students to forgo university itself in favour of a (usually) free and flexible online-learning programme. O'Connell, however, points out that data collected through MOOCs can help improve actual university courses.

Making connections

Susskind is largely oblivious to these arguments – indeed, he did not know what a MOOC was until *Physics World* contacted him for an interview – although he agrees that there is no substitute for on-campus learning. He has no particular goal for the Theoretical Minimum courses, explaining that he simply finds it fun teaching physics to a diverse set of people, who, he claims, are "more responsive" than those studying for degrees. "Some of these people become my friends," he adds.

The most gratifying aspect of the project, though, is the response he has had from those watching his courses online. "Once I put the lectures out there, I started getting huge amounts of e-mail, most from outside the US," he says. "Pakistan, Iran, China."

"Every time I open my e-mail there's another five messages thanking me for putting [the videos] out there, telling me about themselves," he continues. "Lots of kids telling me they're 15 or 16 years old and they want to be physicists. They don't have anybody that can teach them."

Jon Cartwright

Exploring the Zooniverse

An early pioneer of "citizen science", **Chris Lintott** has helped to create a whole host of projects that are changing how science is done


University of Oxford

The task was simple but painstaking: to identify the shapes of over a million galaxies from images taken from the Sloan Digital Sky Survey. To help with the arduous task, in 2007 the astronomer Chris Lintott – together with astrophysicist Kevin Schawinski, both from the University of Oxford – set up a website called *Galaxy Zoo* that presented users with images of galaxies to classify. The pair hoped to initially get around 50 local amateur astronomers to help out, calculating that it could take around five years to trawl through the complete data set.

It took just three weeks – not because the amateur astronomers were unexpectedly quick but because thousands of people from all over the world flocked to the site to offer their help as extra pairs of eyes. At its peak, more than 70 000 galaxies were being analysed per hour, and in the first year of the site 50 million galaxies were classified by 150 000 people, who together made *Galaxy Zoo* the world's largest database of galaxy shapes.

The instant success of *Galaxy Zoo* led to a plethora of similar "citizen-science" initiatives and Lintott is the driving force behind the resulting "Zooniverse". Set up in 2009, this collection of online citizen science now boasts around 20 separate projects with tasks that range from searching for planets outside our solar system by analysing data from NASA's Kepler spacecraft to helping marine scientists better understand whale communication. "I am surprised by how successful it has all been," Lintott told *Physics World*. "And how many other people can say they have discovered a new planet in their spare time?"

The citizen scientist

Modern citizen science dates back to the late 1990s when the University of California, Berkeley released SETI@home – a computer program that analysed radio signals from the Arecibo radio telescope in Puerto Rico to look for signs of intelligent life in the universe. The program ran in the background on idle computers using each machine's processing power when it was not needed. However, SETI@home only involved users installing the software; they did not analyse any data.

That all changed in August 2006 when NASA set up Stardust@home, which allowed volunteers to examine images taken by the space agency's Stardust probe for evidence of tiny interstellar dust impacts in a set of aerogel blocks that the probe exposed in space. At its peak, some 20 000 users participated in Stardust@home and it was this project that inspired Lintott to set up a similar endeavour to analyse galaxy types, recognizing that in both tasks humans can easily outpace computer algorithms, which find it difficult to recognize patterns. So, in *Galaxy Zoo*'s case, when it comes to deciding whether a galaxy is elliptical or spiral – and, if spiral, whether it is rotating in a clockwise or anticlockwise direction – there is nothing better than the human eye.

Four years on from its first project, Zooniverse is now a roaring success, with more than 860 000 volunteers taking part and more than 50 published papers – all based on the work of Zooniverse's users, or "zooites". In many cases, Lintott says that Zooniverse projects stemmed from requests from other scientists about how to get the public to help them analyse their data. Although he admits that such crowdsourcing fits some areas of science better than others, Lintott says that more scientists should think about how their research can be used as part of a citizen science project. "If you have a pile of data, work with us and get people to help out," adds Lintott, who in February became the main presenter of the BBC TV programme *The Sky at Night* following the death of the show's long-running presenter Patrick Moore.

> If you have a pile of data, work with us and get people to help out

Demystifying science

Someone who has adopted Lintott's approach is Michael Doser, a particle physicist at CERN, who is working on an experiment called AEgIS that investigates how hydrogen and antihydrogen respond to gravity. The experiment works by plotting the trajectory of particles on a photographic emulsion plate, and it is currently only operating with protons and antiprotons, which are too light to measure the effect of gravity. Doser has just created software to test whether crowdsourcing could benefit the experiment by letting users – rather than computer algorithms – trace the direction of particle tracks. "I have been following Zooniverse with envy and admiration," says Doser. "The Zooniverse projects not only share the fascination of doing science, but also unlock the deep desire to participate in science of many people who do not have the chance to do so in their daily work."

Doser adds that such projects have helped to "demystify" science. "Contrary to conventional outreach, citizen science treats the public as an equal partner," he says. "Involving citizens seems to me a powerful route to increasing scientific literacy." More than that, citizen science is also making scientists rethink how they work with their data and fostering a new class of budding amateur scientists. "You find that people get really drawn in, start analysing the results and even reading new papers that come up on *arXiv*," says Lintott. "You could say they have a career as a citizen scientist."

Michael Banks

Next month in Physics World

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Animal magic
Inspired by the visual system of the humble locust, researchers are developing technologies that could one day lead to more accurate braking and collision sensors in cars

Awesome analogy?
How bouncing oil droplets could be the first macroscale example of the weird quantum phenomenon of wave–particle duality

Geological revolution
Researchers have found that variations in the Earth's orbital cycles leave fingerprints in sediment cores that let them date geological events such as glaciations to the nearest five thousand years or so

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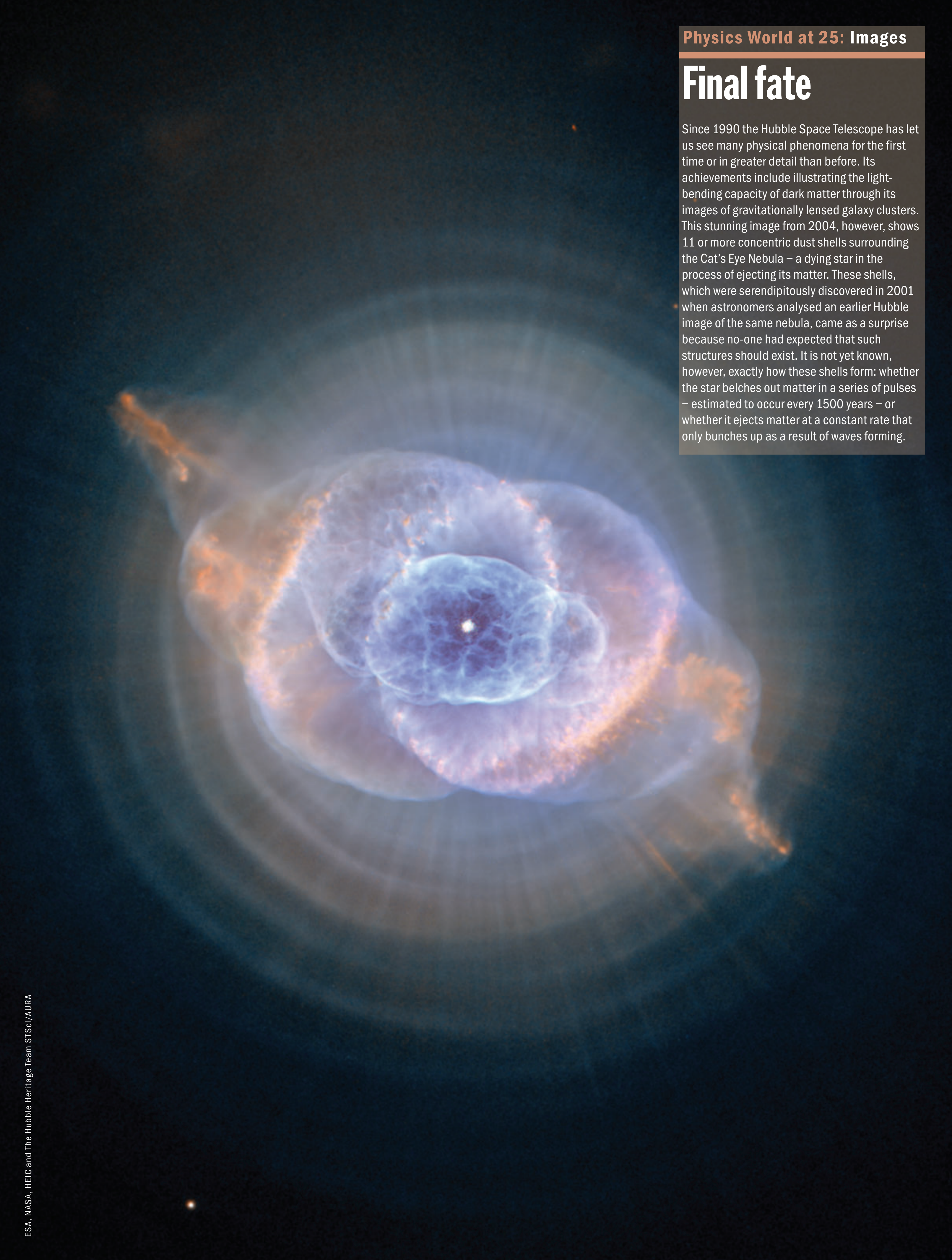
Final fate

Since 1990 the Hubble Space Telescope has let us see many physical phenomena for the first time or in greater detail than before. Its achievements include illustrating the light-bending capacity of dark matter through its images of gravitationally lensed galaxy clusters. This stunning image from 2004, however, shows 11 or more concentric dust shells surrounding the Cat's Eye Nebula – a dying star in the process of ejecting its matter. These shells, which were serendipitously discovered in 2001 when astronomers analysed an earlier Hubble image of the same nebula, came as a surprise because no-one had expected that such structures should exist. It is not yet known, however, exactly how these shells form: whether the star belches out matter in a series of pulses – estimated to occur every 1500 years – or whether it ejects matter at a constant rate that only bunches up as a result of waves forming.



ESA, NASA, HEIC and The Hubble Heritage Team STScI/AURA

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October 2013

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Risky business

Joining a physics spin-out can be a leap of faith

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A fresh spin on physics

University spin-out firms offer physicists the chance to apply their knowledge in a commercial setting, but the path to success for founders and their employees has its ups and downs, as **Margaret Harris** reports

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Full power Working for a spin-out can be an opportunity for you to develop a lot of different skills at once.

When Will Reeves embarked on a PhD in fibre optics at the University of Bath in 1999, his career path seemed assured. The communications industry was booming, companies around the world were eagerly hoovering up graduates with relevant skills, and with a telecoms-friendly PhD to add to his undergraduate degree in physics, Reeves figured it would be easy to find a job in industrial research at a large firm such as Nortel Networks. The economy, however, had other ideas. By the time he completed his PhD in 2003, the telecoms industry had gone into free fall, shedding thousands of jobs in the UK alone. "Companies were making loads of redundancies and there weren't any jobs at all in what I'd trained for," he recalls.

Fortunately, Reeves had a plan B. As an undergraduate at Bath, he had done a year's industrial placement at Sharp Laboratories of Europe, where he worked on liquid-crystal displays and learned some basic clean-room techniques. On the strength of that experience, he says, he got an interview in 2003 at a small but fast-growing firm called Plastic Logic, which had been founded a little over two years earlier by researchers from the University of Cambridge's Cavendish Laboratory. At the time, Plastic Logic was still trying to transform its founders' novel work on plastic electronics into a marketable device, and Reeves was initially hired to develop techniques for measuring the performance of different components. A decade on, however, both the company and Reeves' role within it have transformed almost beyond recognition. "It's been quite a rollercoaster, and there have been times when we have been close to closing," he says. "But I think actually [the telecoms crash] was a blessing in disguise because I've enjoyed this more than I would have enjoyed working in fibre optics."

The physics of spin

Companies like Plastic Logic, which are founded in order to commercialize university-based research, are known as "spin-outs", and they offer many different kinds of benefits. For physicists like Reeves, whose interests include both pure and commercial research, they are an attractive career option. For their academic founders, they are a way of getting good ideas out of the lab by drawing on resources and expertise from the commercial sphere. And of course, for universities and the sceptical politicians who fund them, spin-outs are a welcome sign that money spent on research can produce tangible benefits in the form of new products and jobs.

But as Reeves and others involved in spin-outs emphasize, such companies are not suited to everyone. Joining a young, untested company is risky, especially in the early years, when spin-outs are always in danger of running out of cash unless they can raise more money. As Kevin Arthur, chief executive of the solar-technology spin-out Oxford PV (see case study opposite) observes, "That's something that really focuses your mind, and you've got to like that level of risk." On the academic side, too, the spin-out route does not always make sense. "We all think from time to time that we have good ideas, but there are some pretty harsh things that go on commercially that have nothing to do with the goodness of the idea," says Graham Cross, a physicist at Durham University whose spin-out firm, Farfield, initially struggled to turn a promising technology into a marketable product.

> Spin-out firms are an attractive career option and a way of getting good ideas out of the lab

Physicists interested in working at spin-outs (or founding them) may also be at a disadvantage due to the simple fact that physics departments do not spawn as many spin-outs as their counterparts in the life sciences or engineering. And with some notable exceptions – including Oxford Instruments, which was spun out in 1959 and is now part of the FTSE 250 index of large UK companies – not many physics spin-outs grow big enough to employ large numbers of people. In 2009 Junfu Zhang, an economist at Clark University in Massachusetts, US, studied 903 academic entrepreneurs who had received funding from venture-capital companies, which invest in spin-outs with a strong potential for growth (see box on p72). Of these high-growth spin-outs, Zhang found that fewer than 5% had founders who identified themselves as members of a physics department. In contrast, 45% came from engineering departments, while another 40% worked in the medical or biological sciences.

Russell Cowburn, a physicist who has founded spin-outs at both Durham and

Cambridge universities, says that the low number of physics spin-outs is partly due to the nature of the field. "Quite often what physicists come up with is a new type of device, and then you're immediately hitting this problem of scale where it can only be brought to market if you sell a billion of them," he explains. Many biotech spin-outs, he adds, avoid this problem by developing a new treatment or process and then licensing it to a larger firm.

Another possible reason for physics' low profile in the spin-out world is that there used to be a stigma associated with getting involved in commercial ventures. Brian Tanner, a Durham physicist who founded a company called Bede Scientific Instruments in 1978, remembers his university's then-vice-chancellor telling him, "Well, if you really want to do this, young man, that's okay – but we thought you had a good career ahead of you." Such official discouragement is rare to non-existent these days, but Henry Snaith, the academic founder of Oxford PV, believes that in some quarters, old attitudes die hard. "There's a certain branch of academic scientists – physicists, mathematicians, chemists – who consider that interacting with industry is inferior to doing pure science," he says. "They think we should just be concentrating on finding out new phenomena and understanding things, and not be so worried about real-world problems."

Lingering traces of anti-industry sentiment aside, however, the raw statistics probably give a misleading impression of physicists' entrepreneurial opportunities. Because physics can be applied to many different areas, physicists are often involved in firms that do not, on the face of it, appear to have a strong connection to the subject. A good example is Sphere Fluidics, which was spun out of Cambridge's chemistry department in 2010. The company was founded to commercialize a technique for rapidly analysing single cells encased within tiny droplets and, in June 2013, it won the life-sciences category of a pan-European spin-out competition. However, the firm's chairman Andrew Mackintosh – a physicist by training, and a former chief executive of Oxford Instruments – argues that Sphere Fluidics actually has a strong link to physics. Although the firm employs chemists to create the microdroplets and biochemists to understand the processes taking place within them, the technique for manipulating and measuring the droplets relies on optical instrumentation – and that, Mackintosh says, requires physicists. "You have to put really sophisticated teams together very early on in the life of these companies," he says. "In many, many spin-outs, there'll be a lot of physics underneath, because it's about measurement and instrumentation."

Risks and rewards

This need for a physicist's skills is a positive sign for students and recent graduates interested in joining a spin-out firm. There are, however, some caveats. At their inception, spin-outs are usually little more than one- or two-person operations, and slower-growing, revenue-funded firms often remain so for years. During this earliest phase, therefore, companies will only hire new employees to do work that the founders cannot. Moreover, employment contracts are likely to be short-term, stretching only as far as the spin-out's current round of funding permits. Marcus Swann, a former postdoctoral researcher in Cross's group at Durham, notes ruefully that when he joined Farfield as its fourth employee, he imagined that working there might offer more long-term stability than the "serial postdoc" phase of early-career academia (see October 2012 pp54–57). In the event, he says, "I've been employed for 13 years now but there hasn't been any certainty over it. At a spin-out you've got no idea what's going to happen – there's absolutely no guarantee it's going to last more than a year."

Yet there are rewards in getting involved early. While life at a spin-out is not, in Tanner's words, "just a matter of swanning off with a million quid and becoming very rich", early employees of successful spin-outs can nevertheless make a fair amount of money. To attract talent, many spin-outs offer

Case study: Oxford PV

While there is no such thing as a "typical" spin-out, the story (so far) of Oxford PV nevertheless includes some characteristic features. Based on research performed by University of Oxford physicist Henry Snaith, the firm's core product is a type of solar photovoltaic (PV) cell that can be printed onto glass. It was spun out of Oxford in 2010 with the help of the university's technology-transfer company, Isis Innovation, which funded its initial round of patents and brought in an experienced chief executive, Kevin Arthur, from the semiconductor industry.

Since then, the firm has raised more than £4m, including a total of £350 000 from the Technology Strategy Board (an organization funded by the UK government) and £3.45m from investment syndicates, including venture capital. Currently, scientists and technicians at its premises in a university-linked "business incubator" north of Oxford are working to improve the efficiency of the underlying solar-cell technology and to demonstrate that durable solar-PV glass can be produced on a commercial scale. One of Snaith's former postdocs, Ed Crossland, joined the firm earlier this year as a senior research scientist, and the company plans to hire five new technologists before the end of 2013. In the future, Oxford PV hopes to license its product to manufacturers that can incorporate its energy-generating glass into the windows of skyscrapers, making it a ubiquitous feature of modern "green" architecture.

"I do solar-cell research because I believe that it's the source of energy we need for the future. In some sense, it doesn't matter which PV technology is successful as long as one of them is, but if no-one tries to push it, it's not going to happen. My motivation is to try to get the technology out there."
Henry Snaith, physicist and chief scientific officer

"With a technical staff of 10–15 there's not enough hands to do everything we want to do, so I'm still in the lab pretty much every day, whether it's with my hands wet in the fume hoods or just overseeing what's going on."
Ed Crossland, senior research scientist

"I really feel with this company we're in the right place at the right time with the right technology. We're constantly announcing updates to Henry's technology and we're just pushing at an open door with the construction industry, because they really want to have an energy-generating coating that they can apply to their existing materials."
Kevin Arthur, chief executive


Henry Snaith


Ed Crossland


Kevin Arthur

All images: Douglas Fry

Start me up: three ways of funding a spin-out

Sales

Companies that make high-value, low-sales-volume goods, such as scientific instruments, can sometimes grow "organically" by using the profits from each sale to develop new products and refine existing ones. This allows founders to maintain control over their company and its future direction, but it is unlikely to provide enough money for the company to do everything it wants to do or hire everyone it wants to hire. "I made some small profit out of it [the first microscope I sold], but I was working like a dog," says Ahmet Oral, a physicist at Turkey's Sabancı University and founder of the Anglo-Turkish firm NanoMagnetics Instruments. After finishing his "day job", he says, "I was going back home and working until two, three, even four in the morning, nonstop, for about six months or so. It was hard."

Seed money

A variety of organizations, including governments, private philanthropic groups and international bodies such as the EU provide small-to-medium-sized grants for spin-outs and other early-stage companies. Although the application process for such grants is competitive, and the funds available are generally not on the same scale as business-angel or venture-capital funding (see right), they can be vital in a spin-out's earliest stages and come with fewer strings attached. Examples in the UK include the Technology Strategy Board, the Royal Society Enterprise Fund, university-based groups such as the University Challenge Seed Fund and so-called "translational" research grants from the Engineering and Physical Sciences Research Council, although each of these organizations has different goals and rules for how monies are used. A spin-out's parent university can also be an important source of early support by offering cheap lab space within the department or at a separate "business incubator" and by funding patent applications via the technology-transfer office.

Business angels and venture capital

At the deep-pocketed end of the funding spectrum, business angels and venture capital (VC) firms provide money in exchange for a share of the business and – especially in the case of venture capital – a say in how it is run. The principal difference between them is that angels are investing their own money, while VC firms are managing funds from a large pool of investors. However, business angels also tend to invest in businesses earlier and to provide smaller amounts of money, typically around £100 000, to help a spin-out get through the difficult early period. In contrast, "most venture capitalists, even early-stage ones, won't come in at less than a £1–1.5m equity investment", says Brian Tanner, dean of knowledge transfer at Durham University. "The cost of due diligence [for their investors] is sufficiently high that they want to put in cash of that sort of quantum to make it worth their while." In order to attract that kind of money, Tanner adds, companies need a proper management team as well as an idea or product with a strong potential for growth.

All images: iStockphoto

early employees a stake in the company, and someone who helps transform a company from a start-up to a major player usually ends up with what Cowburn delicately terms "very interesting share options".

But even spin-outs with more modest outcomes have their attractions. Farfield was sold to a Swedish instrumentation company in 2010, and the future of its core technology is now uncertain. Nevertheless, Swann says that working there has given him a huge range of experiences that he would not have had if he had stayed in academia or gone to work for a bigger firm. In addition to scientific tasks such as computer modelling and developing measurement techniques, he says, he has also been involved in product development, customer support, sales and marketing, and participated in scientific collaborations with researchers in the petroleum and pharmaceutical industries. "There's no area of the company's existence where I haven't had some good visibility," he says. "From that point of view, it's been a tremendous learning experience. I don't feel constrained by my scientific background any more." Tanner, whose first spin-out fell victim to the credit crunch of 2008 and was subsequently sold to a larger company, agrees. "I don't know of anyone who's been in that early-stage business environment being out of work for long," he says.

What it takes

All of the people interviewed for this article agreed that working at a spin-out requires a love of variety. For example, on the day that Reeves spoke to *Physics World* about his work at Plastic Logic, he had spent the morning repairing a laser cutting machine, but said that other typical tasks include computer programming, meeting clients and even creative work such as designing sample content for the company's electronic displays.

Another thing that came up frequently was an appetite – or at least a tolerance – for responsibility as well as risk. "If you join a spin-out, you are by definition going to be a key player in that company," says Swann. "It's difficult to say 'no' because you know that if you don't do it, it doesn't get done." Scientists at a spin-out also have a responsibility to stay focused on the company's product rather than pursuing interesting tangents, says Ed Crossland, who did a postdoc in Snaith's group at the University of Oxford and is now a senior research scientist at Oxford PV.

> If you join a spin-out, you are by definition going to be a key player in that company

Scientific skills are important, too, and for that reason, opportunities at spin-outs are more extensive for those with physics PhDs than they are for BSc graduates. "To any graduate thinking of doing research in a start-up company, I'd say they should do it with the mind of working for one or two years to gain experience," says Snaith. "But if they really want to progress in research in industry, they should then come back [to university] and do a PhD." Cowburn suggests that undergraduates who want to get some spin-out experience should approach companies about doing a specific piece of work, such as software programming or designing a circuit, rather than seeking a traditional, training-based internship.

Regardless of their level of experience, however, prospective employees should emphasize that they have certain skills because they are a quick learner, not because it is the only thing they can do. "Being attractive to an employer means you're smart – you're not just an expert in doing one particular thing," says Crossland. "You need to be a problem solver who can apply your skills and talents to whatever problem the company might have."

Ultimately, Mackintosh believes that spin-outs are exciting places for physicists to work. "If you're prepared for a lively ride, you have no idea where that company can go," says Mackintosh. "Even if that company folds, the experience you gain allows you to go do the same thing in another company – probably a lot better than you did it the first time."

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Developing novel high power near infrared and visible lasers. Experience of ultrashort pulse generation, frequency doubling together with an appreciation of mechanical and electronics engineering would be advantageous. (Ref LE 06)

CO2 Laser Engineer
Designing mid to high power sealed RF excited infrared lasers. Knowledge of gas discharge chemistry, RF matching networks and opto-mechanical design principles would be an added advantage. (Ref LE 07)

The company offers a lively environment, an excellent benefits package and competitive salaries commensurate with experience. Dual career paths in engineering and management and recognition for design excellence allow talented engineers to realize their earnings potential.

ROFIN is one of the world's leading designers and manufacturers of industrial lasers for machining and marking applications. For more company information view ROFIN's Internet site at www.rofin-sinar.com. The company offers a lively environment, an excellent benefits package and competitive salaries commensurate with experience. Interested candidates should apply in writing quoting the relevant reference given above, with a full C.V. to: Personnel Department, Rofin-Sinar UK Ltd., York Way, Willerby, Kingston upon Hull HU10 6HD.

SHARP

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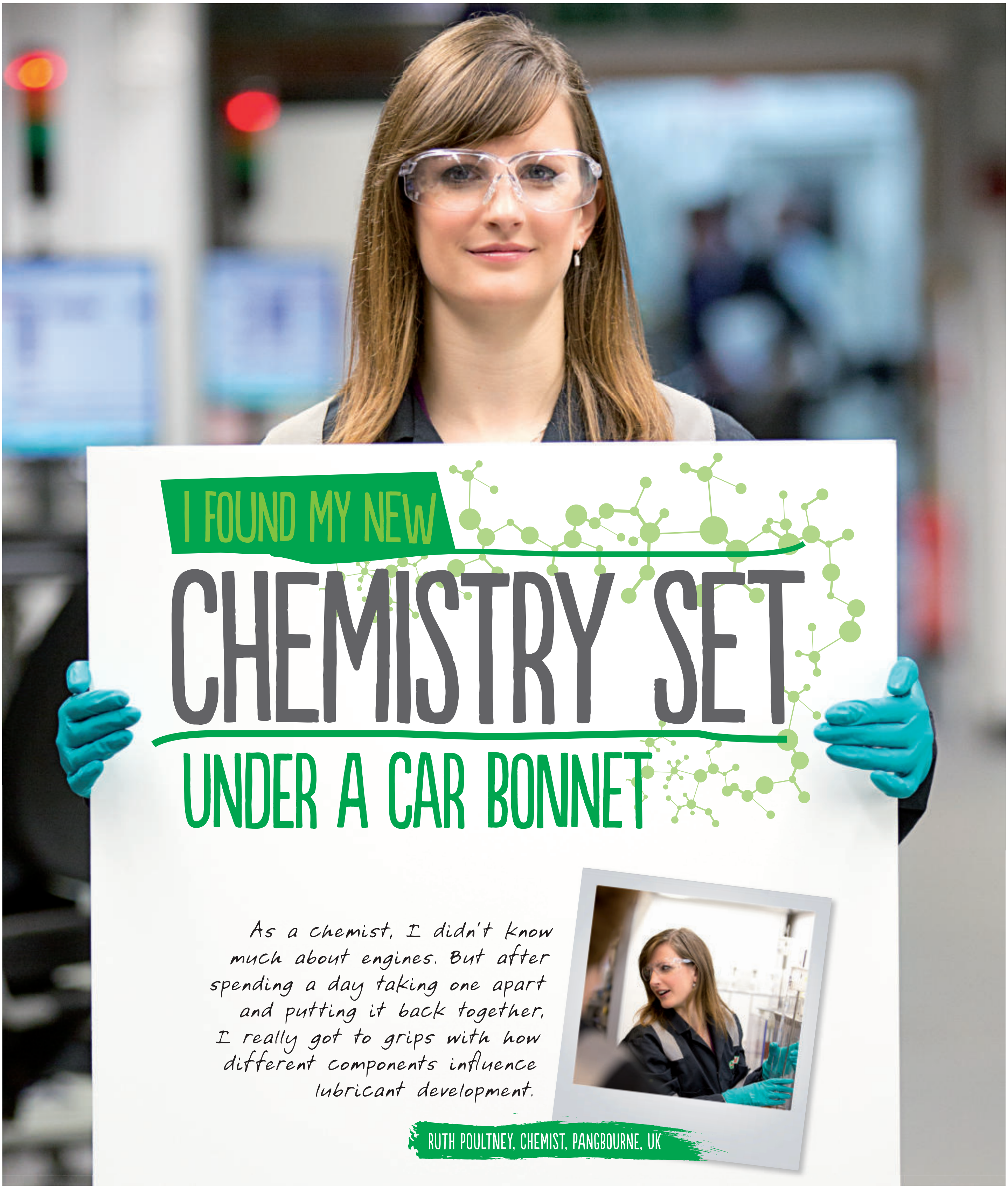
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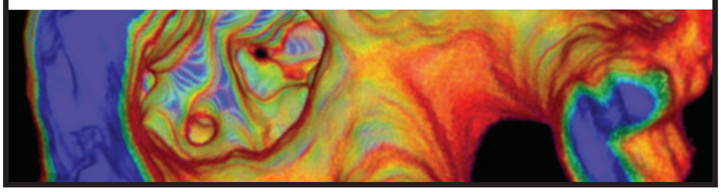
UNDER A CAR BONNET
As a chemist, I didn't know much about engines. But after spending a day taking one apart and putting it back together, I really got to grips with how different components influence lubricant development.
RUTH POULTNEY, CHEMIST, PANGBOURNE, UK



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Penn
University *of* Pennsylvania

Nano Clusters Hiring

The School of Engineering and Applied Science (SEAS) at the University of Pennsylvania seeks to build interdisciplinary faculty clusters of eminence at the forefront of nanotechnology. The newly opened Krishna P. Singh Center for Nanotechnology is a $100M facility integrating state-of-the-art nanocharacterization and nanofabrication facilities. This second phase seeks numerous hires who will comprehensively span forefront measurement, novel phenomena, innovative devices, and integrated systems. Successful candidates will be expected to couple with existing resources to synergistically build new areas of international impact.

Broad themes of interest include:

- Emerging fields at the interface of nano and biotechnology,
- Advanced nanoprobes pushing the frontiers of multi modal interactions, in-situ control and/or ultra fast dynamics;
- Coupled phenomena providing new paradigms, particularly under extreme environments including ultrafast time scales, ultra-small dimensions and intense energy fluxes;
- Design and fabrication of multifunctional devices that exploit such coupled phenomena for novel applications;
- Integrated systems for application in nano-enabled computation, energy technologies and nanomanufacturing.

Candidates will be expected to robustly utilize and further contribute to the development of experimental capabilities in the Singh Center, as well as to acquire and develop their own innovative experimental platforms. Read more about the Singh Center at http://www.nano.upenn.edu/. Candidates will also be expected to advance our creative educational programs at both the undergraduate and graduate level. Applicants with industrial experience or collaborations, and track records that include successful translational research programs and technology transfer are particularly encouraged and should highlight thes accomplishments in their application.

Appointments in this second round of hiring will be at the Associate or Full Professor level and applicants must have research and educational track records to merit an appointment with tenure. Successful candidates will be invited to participate in recruiting future faculty at all levels to further contribute to this long-term cluster hiring initiative, which builds on Penn's exemplary record in interdisciplinary research that integrates knowledge at the forefront of discovery.

Applicants should submit their applications electronically at
http://www.nano.upenn.edu/about/hiring-initiative/

Information about the School of Engineering and Applied Sciences is available at http://www.seas.upenn.edu/.

The University of Pennsylvania values diversity and seeks talented students, faculty and staff from diverse backgrounds and does not discriminate on the basis of race, color, sex, sexual orientation, gender identity, religion, creed, national or ethnic origin, citizenship status, age, disability, veteran status or any other legally protected class status in its employment practices.

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for gyrotron-based dynamic nuclear polarization.

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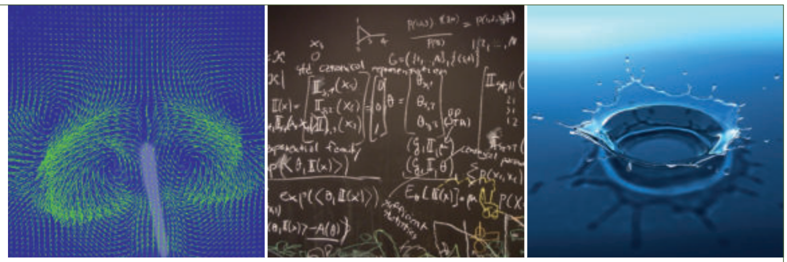
Other: optical spin pumping, electrochemistry.

Contract can be renewed up to 4 years.

Contact: **jean-philippe.ansermet@epfl.ch.**



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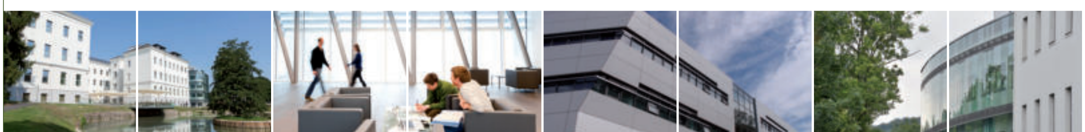
IST Austria invites applications for **tenured** and **tenure-track leaders** of **independent research groups** in following fields: **Physics** | **Chemistry** | **Biology** | **Neuroscience** | **Earth Science** | **Mathematics** | **Computer Science** | **Interdisciplinary Areas**

The Institute is dedicated to basic research and graduate education in the natural and formal sciences. The successful candidates will receive a substantial annual research budget, are expected to apply for external research grants and to participate in the Graduate School.

Deadline for receiving Assistant Professor applications: November 15, 2013
Open call for Professor applications
Further information and online application: **www.ist.ac.at/professor-applications**

IST Austria values diversity and is committed to equality. Female researchers are encouraged to apply.



IST AUSTRIA
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RICE

Faculty Position in Theoretical Cold Atom Physics, Rice University

The Department of Physics and Astronomy at Rice University invites applications for a tenure-track Assistant Professor position in theoretical physics. Applicants are expected to have expertise in ultra-cold atom physics, with a focus on connections to condensed matter physics. This position will complement and extend our existing experimental and theoretical strength in both ultra-cold atom and condensed matter physics (for information on the existing efforts, see http://physics.rice.edu/). A PhD in physics or related field is required.

Applicants should send a dossier that includes a curriculum vitae, statements of research and teaching interests, a list of publications, and two or three selected reprints, in a single PDF file to vcall@rice.edu or to R. G. Hulet or Han Pu, Co-Chairs, Faculty Search Committee, Dept. of Physics and Astronomy – MS 61, Rice University, 6100 Main Street, Houston, TX 77005. Applicants should also arrange for at least three letters of recommendation to be sent by email or post.

Applications will be accepted until the position is filled, but only those received by November 30, 2013 will be assured full consideration. The appointment is expected to start in July, 2014.

Rice University is an affirmative action/equal opportunity employer; women and under-represented minorities are strongly encouraged to apply.

Dr. Linda Douw, Branco Weiss fellow since 2013

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Can you crack the code?

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There is a word missing from the above. What is it? Give the answer in its encrypted form at physicsworld.com/puzzle.

In celebration of *Physics World*'s 25th birthday, we asked staff at the UK's Government Communications Headquarters (GCHQ) to create a set of physics-themed puzzles that will challenge even the brainiest of *Physics World* readers.

The puzzle above is the first in a series of five, and every Tuesday this month, another will appear online at physicsworld.com/puzzle. We've ranked them in order of difficulty, so they only get harder from here on in!

A big thank you to the puzzle creators Colin, Nick and Pete, whose full identities cannot be revealed.

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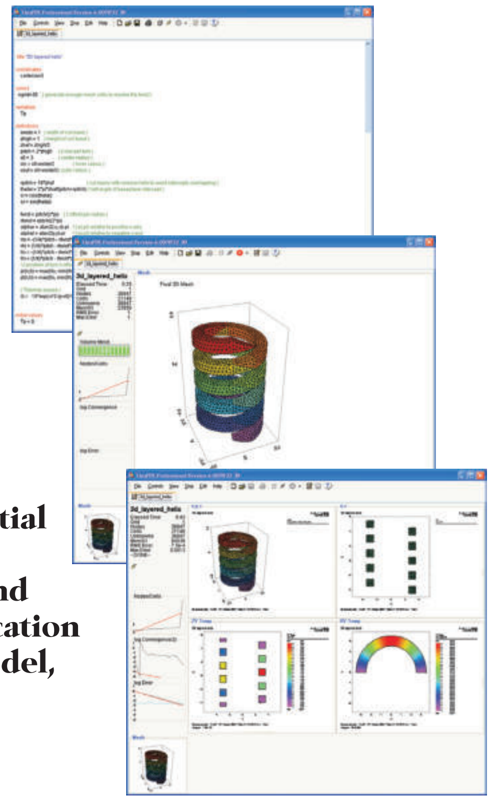

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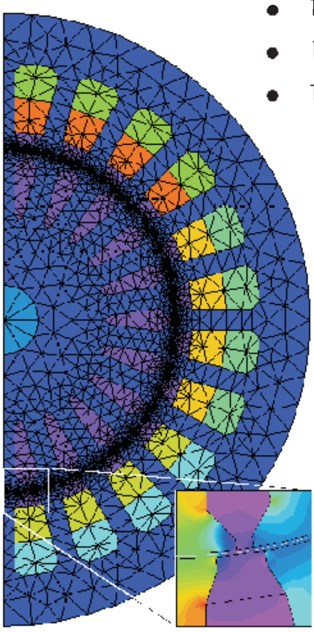

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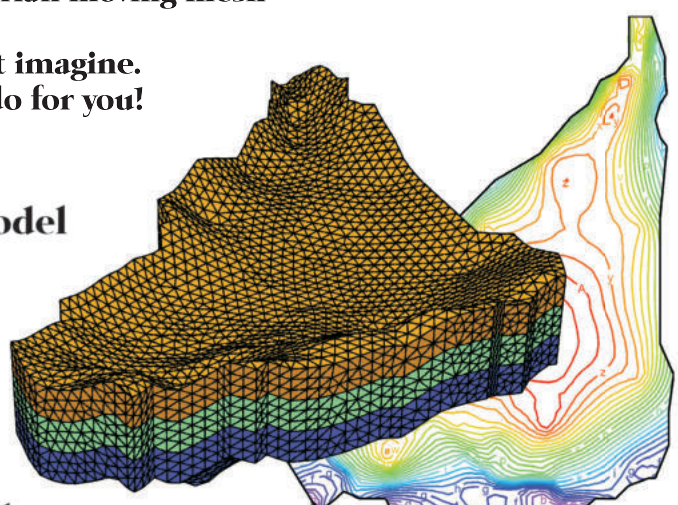

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