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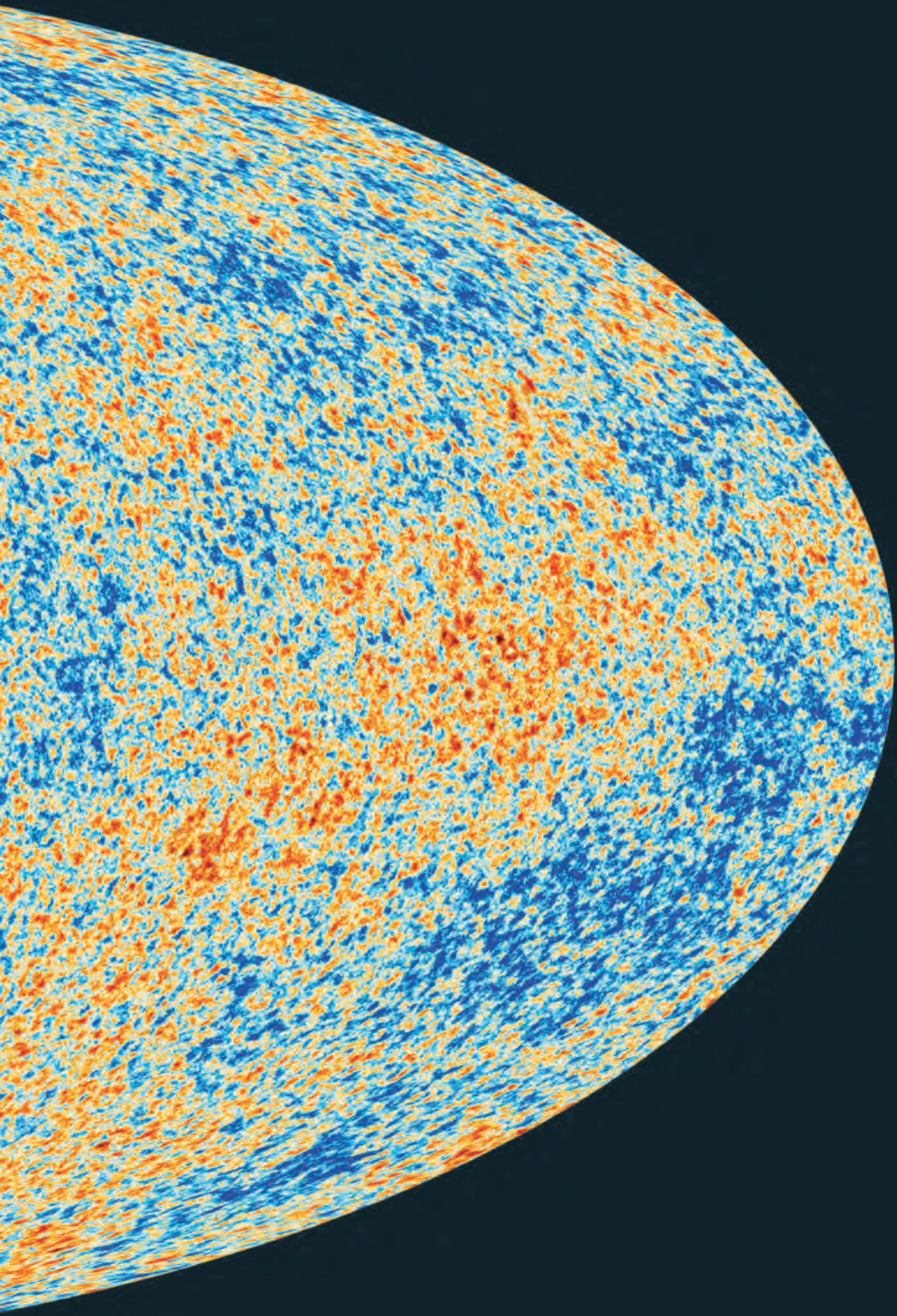

Planck perspectives
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CERN

Multimedia
The digital version of *Physics World* this month includes three great videos:
- Inside the NA62 experiment (p6)
- George Smoot on cosmology (p24)
- What quantum computers can do (p38)

Quanta

For the record

We will never make a washing machine based on the Higgs boson

CERN director of research **Sergio Bertolucci** *quoted in the* Financial Times

Bertolucci says that while CERN has contributed to the development of the Internet and magnetic resonance imaging, it is impossible to know now if the Higgs boson will have practical applications.

MOOCs seem to be reinforcing the advantages of the "haves" rather than educating the "have-nots"

Ezekiel Emanuel *from the University of Pennsylvania writing in* Nature

A survey of some 35 000 students who have completed free Web-based video courses, known as massive open online courses (MOOCs), found that 83% of them already had a two- or four-year postgraduate degree.

Nobody wants to turn off a spacecraft in orbit

Charles Sobeck, *deputy project manager of NASA's Kepler spacecraft, quoted in the* New York Times

Plans are afoot to use the force of the Sun's radiation to help the Kepler exoplanet hunter to point precisely at other stars after a critical wheel on the probe became stuck, leaving the telescope ailing in space.

The future of our economy essentially rests on an investment in students

University of Manchester physicist **Brian Cox** *quoted in the* Guardian

Cox was bemoaning press reports that the UK government was looking to cut science spending in the next two years.

I did actually dress up on a couple of occasions, but not at home

SpaceX founder and physicist **Elon Musk** *in an interview with the American Physical Society*

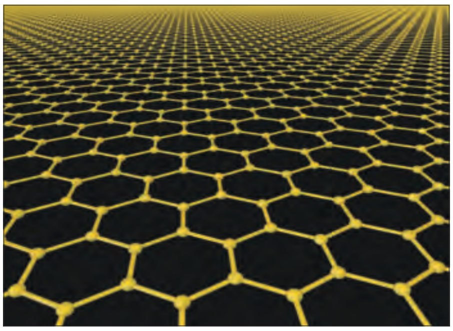
Musk says that he was, in his youth, a big fan of the fantasy table-top role-playing game Dungeons and Dragons, which involved him attending tournaments in his native South Africa.

This is the Neil Armstrong of the plant world

NASA planetary scientist **Chris McKay** *quoted on* Forbes.com

NASA is planning to grow seeds – in a specially housed container – on the Moon.

Seen and heard


Shutterstock/billdayone

Making graphene desirable

Just when you thought that graphene couldn't possibly have any more practical applications, it looks like the "wonder material" could be used to develop "stronger, safer and more desirable" condoms. Thanks to a £62 000 grant from the Bill & Melinda Gates Foundation, scientists at the University of Manchester will face up to the stiff challenge of developing new "composite nanomaterials for next-generation condoms, containing graphene" that could help stop the spread of HIV and Aids. "People have wondered when graphene will be used in our daily life," says Manchester physicist Aravind Vijayaraghavan who is leading the project. "If this is successful, we might have a use for graphene that will literally touch our everyday lives in the most intimate way." News of the project came just a day before the industrial-graphene producer Applied Graphene Materials was listed on the UK stock market, with its share price doubling within two days.

One from the archives

A previously lost black-and-white documentary film depicting the 1955 discovery of mendelevium – or element 101 – at the Lawrence Berkeley National Laboratory in the US has been discovered in a cardboard box of dusty films that were set to be thrown out. Claude Lyneis, who was deputy director of the lab's nuclear-science division before retiring three years ago, unearthed the 16 mm film in the meeting area at the lab's 88-Inch Cyclotron. With the lab not having a suitable projector to play the 60-year-old clip, Lyneis coughed up $140 on *eBay* to acquire one. To identify the main players in the 18-minute film, which has no sound or explanations, Lyneis talked to colleagues and read relevant original papers. He then cut the film down to just over three minutes to make it "*YouTube* viewable" and wrote and performed a voice-over for the film, which features scientists loading gold foil laced with einsteinium into a cyclotron. Lyneis told *Physics World* that he is now looking for funding to digitize some other films he discovered in the same dusty box. He is also seeking an institution that would be interested in archiving them.

Telling the story of radar

Still on the history of physics, comedian Eddie Izzard is set to play the Scottish physicist Robert Watson-Watt in a new BBC factual drama *Castles in the Sky*. To be aired later this year, the one-off TV film will tell the 1930s story of the race to invent radar, which was led by Watson-Watt and a team of British scientists including Arnold Wilkins. The scientists eventually showed that it was possible to detect aircraft by bouncing radio waves from them – a key achievement that contributed towards Britain's victory in the Battle of Britain in 1940. "I feel very privileged to be playing the role of Robert Watson-Watt," Izzard said in a statement. "Hopefully our production will allow him, along with Arnold 'Skip' Wilkins and their team, to finally take their places in the pantheon of British greats of the Second World War, as the inventors of radar."


iStockphoto/edfuentesg

Foaming at the mouth

Remember that university "joke" when someone sneaks up behind you and then taps the top of your beer bottle with theirs, causing a foamy mess to erupt from your bottle only for their beer not to foam at all? Well, at least you can now take some solace in a possible explanation for it. Researchers from Spain and France claim that when a bottle is struck from above, it causes a compression wave to travel down the glass that triggers a low-pressure "rarefaction wave", which travels upwards to the open surface of the liquid. This wave allows carbon dioxide to form relatively large "mother" bubbles, which implode, creating large numbers of very small "daughter" bubbles. These expand rapidly, turning much of the liquid into a buoyant foam that rushes upwards. So why doesn't the prankster's bottle foam too? "If you hit the bottle from below, you first trigger a compression wave and then a somewhat less intense expansion one, which is not very efficient in terms of driving bubble implosion," Javier Rodríguez-Rodríguez from Carlos III University of Madrid told *Physics World*.

Frontiers

In brief

Long-life nanodiamond nitrogen vacancies
A team of researchers in the US has achieved spin coherence times of more than 200 μs in nitrogen vacancy (NV) centres in tiny "nanodiamonds", shattering the previous record for this material. The NV centre in a nanodiamond could be ideal for use in future quantum computing and nanoscale sensing technologies. But most nanodiamonds available today contain a high density of paramagnetic impurities, making the electron spins in NV centres so fragile that they cannot be held for more than a few microseconds. The new nanodiamonds were developed using a top-down fabrication technique that uses a self-assembling porous metal mask and reactive ion etching process to give extremely pure nanocrystals devoid of paramagnetic impurities. The method could also be used to develop magnetic-resonance probes and quantum computers (*Nano Lett.* 10.1021/nl402799u).

Smallest ever FM transmitter
Researchers at Columbia University in the US have built the smallest frequency-modulated (FM) radio transmitter ever. The new device, which is based on a graphene nanomechanical system version of a common electronic component known as a voltage-controlled oscillator, generates a frequency-modulated signal of about 100 MHz. According to the team, the device is much smaller than any other radio-signal source ever made and, importantly, can be put on the same chip that is used for data processing. It could find use in a variety of applications, including sensing tiny masses and on-chip signal processing. It also represents an important first step towards the development of advanced wireless technology and ultrathin mobile phones (*Nature Nanotech.* 10.1038/nnano.2013.232).

Oldest minerals from Mars found on Earth
A meteorite recently retrieved from the Sahara Desert bears the oldest known minerals ever seen from the planet Mars, say scientists in the US, Australia and France. These minerals are 4.4 billion years old and therefore formed just 150 million years after the red planet's birth. Their age confirms earlier indications that the Martian crust formed quickly, as did the crusts of the Earth and Moon. Apart from being the first ever meteorite to come from the Martian highlands, it is also only the second example studied in the lab that originated well before the planet's climate deteriorated. The meteorite is a so-called breccia, a collage of different rock fragments (*Nature* 10.1038/nature12764).

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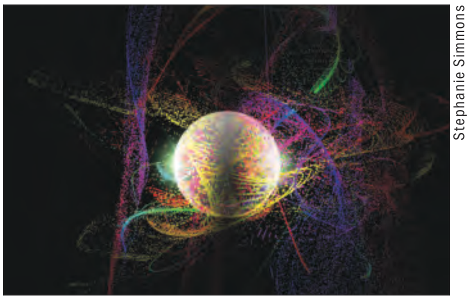
Quantum state lasts for 39 minutes


Stephanie Simmons

Endurance test Artist's impression of a "bound exciton" quantum.

Quantum states have been shown to endure in a room-temperature solid-state device for a whopping 39 min, shattering the previous record of 2 s. The feat was achieved by physicists in Canada, the UK and Germany, who used phosphorus atoms in silicon as their quantum bits – or qubits.

Whereas classical computers process bits that are either 0 or 1, quantum computers are designed to manipulate qubits, which can be 0 and 1 simultaneously. Vast numbers of operations could therefore, in principle, be carried out in parallel and render these devices far quicker than classical computers. But qubits tend to be incredibly fragile, so the information they hold is rapidly destroyed by any external noise. Cooling the qubit to near absolute zero to minimize its exposure to thermal noise can help. As working at such low temperatures is hardly practical, researchers are keen to find qubits that can operate at ambient conditions.

The new record-breaking system has been created by Mike Thewalt of Simon Fraser University and colleagues, who stored quantum information in the nuclear spins of phosphorous atoms in a silicon crystal. While this system has already been shown to retain quantum information for long times at extremely low temperatures, even at 10 K, its "coherence time" only drops to a few milliseconds.

Thewalt and colleagues took advantage of the fact that phosphorous atoms in silicon at room temperature tend to give up their electrons and become positive ions. Removing the electrons eliminates an important link between the nuclear spins and surrounding electrical noise, but it also makes the nuclear spins too well isolated to be "read" or "written". To get around this problem, the team first cooled its crystal to 4.2 K and then used laser and radio frequency pulses to put neutral phosphorous atoms into specific quantum states that were found to be coherent at room temperature for 39 min. The crystal was then cooled back down to 4.2 K before the quantum information was read out.

Although measurements reveal that the coherence time at room temperature is 39 min, team member John Morton from University College London says that under these conditions, it would be possible in principle to remove the crystal from the cryostat and carry it around the lab while the spins maintain their coherence. What's more, repeating the experiment with the sample at 4.3 K revealed a coherence time of as long as three hours (*Science* **342** 830).

Narrowest moment yet

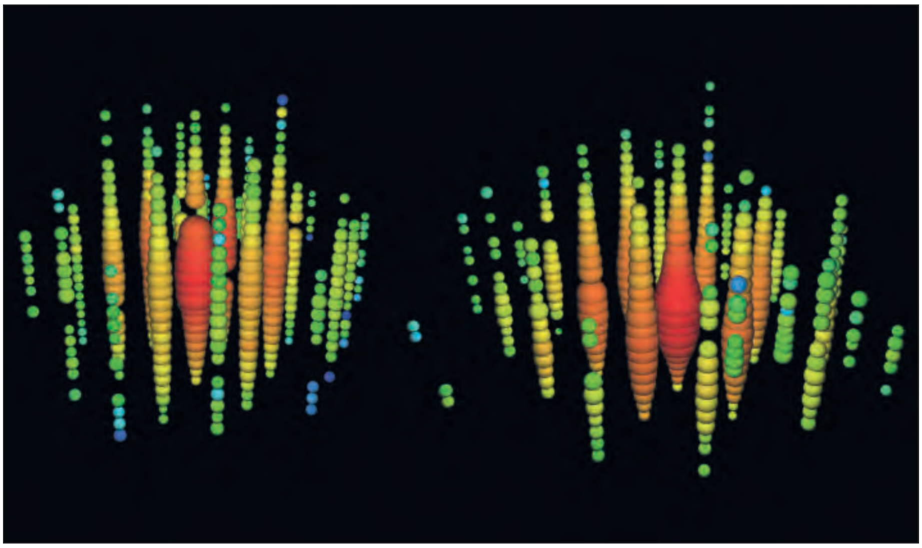
Physicists in the US and Canada have put the smallest limit yet on the size of the electric dipole moment (EDM) of the electron. The new upper limit is at most 1/12 of the previous limit set by a different experiment in 2011. According to the simplest take on the Standard Model of particle physics, the electron should have no permanent EDM because the combination of an EDM with the electron's spin magnetic moment would violate time-reversal symmetry. However, theories of physics that go beyond the Standard Model – such as supersymmetry – do predict much larger values of the EDM that could be determined experimentally.

The previous tightest limit on the EDM put it at less than $10.5 \times 10^{-28}\,e$ cm, but physicists working on the Advanced Cold Molecule EDM Experiment (ACME) in the US have set the upper limit at $8.7 \times 10^{-29}\,e$ cm, with a 90% confidence (arXiv:1310.7534).

The experiment involved sending a pulse of very cold thorium-oxide molecules through parallel electric and magnetic fields that run perpendicular to the beam. Laser pulses were then used to put the molecules into specific states such that, as the molecules travel, their spins (and EDMs) rotate about the field direction, with this precession angle being accurately measured.

If the electron has an EDM, its presence will contribute to the precession angle in proportion to the electric field near the electron. Because thorium-oxide molecules are polar, they have an extremely large EDM, and so the "effective electric field" created is huge. This helps to shift the precession angle in opposite directions by such an amount that the difference in the precession angle allows the team to determine the EDM.

IceCube Collaboration



Probing cosmic neutrinos at the South Pole

The enormous "telescope" buried deep under the ice of Antarctica – the IceCube Observatory – has made the first intentional observation of high-energy cosmic neutrinos that come from beyond the bounds of our solar system. Announced late last year, the international collaboration operating the experiment says that the detection of these chargeless, almost massless and very-high-energy particles marks the beginning of a new era in astronomy in which electromagnetic radiation is no longer the only probe of the distant universe. The colourful image above shows the signals detected in the various photomultiplier tubes that are strung along several cables in the ice and represent two of the 28 events with energies (above 30 TeV) observed in an all-sky search between May 2010 and May 2012. The shower of particles on the right is "Ernie" – it was created by the highest energy neutrino ever observed at an energy of 1.14×10^{15} eV and was detected by IceCube on 3 January 2012. On the left is "Bert", at an estimated energy of 1.04 PeV (*Science* **342** 1242856).

● This research won the 2013 *Physics World* Breakthrough of the Year award (see p7).

Locust eardrum is a tiny frequency analyser

Locusts have a highly integrated and miniaturized hearing system that bears little resemblance to either the human ear or an electronic microphone. That is the conclusion of researchers in the UK who have studied how the insects detect and process sounds.

Daniel Robert at the University of Bristol and colleagues have used a laser Doppler vibrometer to analyse how a locust's eardrum membrane responded to incoming sound waves produced by a loudspeaker. The membrane is kidney-shaped and has two points on its inner surface where mechanoreceptor cells – neurones that respond to mechanical stress – are attached in two different groups (*J. R. Soc. Interface* **11** 20130857).

The researchers scanned the laser over the surface of the membrane, measuring tiny picometre-scale out-of-plane vibrations induced by the sound waves. They found that for low-frequency sounds, the membrane vibrated in such a way that both groups of cells were mechanically excited. But high-frequency sounds managed to excite one group only – meaning that the eardrum effectively behaved like an efficient frequency analyser. The team also found that waves caused by low-frequency sounds travel completely across the membrane, where low-frequency-sensitive neurons attach to the membrane. But high-frequency waves will only travel half that distance, stopping at the attachment point of high-frequency neurons.

As well as confirming that locusts can distinguish between high and low frequencies, the team also found that the membrane has internal fluid-filled chambers, which can dampen sound depending on its frequency. Moreover, the shape of the membrane amplifies the energy density of the wave by as much as 56 000 times as it travels – something so far only observed in locusts.

Such energy localization has so far only been observed in locusts. However, the team's analysis suggests that the process is remarkably simple and it is possible that the same mechanism might also exist in mammalian ears. If that is the case, it would be an exciting new function of the mammalian ear.

Innovation

Viruses breathe new life into batteries

Research into lithium–air batteries, which may in the future power electric cars and other electronic devices, has just received a boost – from a virus. Scientists at the Massachusetts Institute of Technology (MIT) in the US have shown that using genetically modified viruses greatly increases the surface area of nanowires that work as electrodes in a battery's cathode, thereby improving the battery's charge-storage capacity.

A typical battery consists of a cathode, an anode (normally made of lithium), an ion conductor (or an "electrolyte") through which charged ions flow easily, and a separator to keep the two ends apart. The lithium–air battery, which has started to show promise in recent years, instead oxidizes lithium at the anode using a lightweight "air cathode" that replaces the much heavier metal-oxide cathodes used today.

While the batteries hold much potential, so far traditional electrochemical capacitors perform much better. Another drawback of lithium–air batteries is that they can only be charged and discharged a limited number of times before they start losing their charge-storing capacity. The batteries' electrodes also need to be made from more durable and long-lasting materials.

Now, Dahyun Oh, a graduate student at MIT, and colleagues have found that a solution could lie in increasing the surface area of the wire that acts as the electrode, which would increase the area where electrochemical activity takes place during the charging or discharging of the battery. The researchers also found that they could use a rod-shaped virus called M13 to grow the electrode materials made up of manganese-oxide wires (*Nature Comms* **4** 2756). The virus is able to capture molecules of metals from water and bind them into various structural shapes. The scientists created an array of nanowires, each measuring about 80 nm across, wrapped with tiny amounts of nanoparticles of precious metal such as palladium or gold.

According to the team, its virus-crafted nanowires showed improved performance in lithium–air batteries because the virus-built structures have a rough, spiky surface, which greatly increases their surface area. In addition, the viruses produced a 3D structure of cross-linked wires instead of isolated wires, thus giving the electrode greater stability.

Although the research is still in its early stages and such bio-batteries are not yet commercially available, the group does have a functional prototype that was tested through 50 cycles of charging and discharging.

News & Analysis

CERN gears up for new experiments

CERN's Large Hadron Collider is not due to switch back on until 2015, but several new experiments at the lab, including NA62, will start up this year. **Hamish Johnston** reports

This year will be a fallow one for the Large Hadron Collider (LHC). The accelerator and its experiments are still being upgraded and the 27 km circumference collider is not due to restart until 2015. However, all is not quiet at the CERN particle-physics lab near Geneva: the accelerators that feed protons into the LHC – the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) will both be fired up in the second half of 2014, which means that lots of experiments at CERN should be taking data this year, including some that are entirely new (see box).

One new experiment firing up is the rather prosaically named NA62 and physicists working on it are now in the final stages of installing their 270 m long experiment on the SPS. The SPS itself has a circumference of 7 km and all of its experiments are in CERN's "North Area", from which NA62 takes part of its name (62 being simply an incremental experiment number). The NA62 collaboration is small by CERN standards but it still comprises about 150 physicists at 20 institutes worldwide. Their primary aim is to make an extremely precise measurement of the probability that a positively charged kaon will decay to a positively charged pion plus a neutrino/antineutrino pair.

The decay probability might seem an arcane value to measure, but as collaboration member John Fry of the University of Liverpool in the UK explains, the decay itself is "one of the few ways open to us to actually challenge the Standard Model of particle physics". Unfortunately, measuring the decay is far from easy. "This is a very rare process and the probability that it happens is about one in 10 billion," explains CERN's Giuseppe Ruggiero, who is physics co-ordinator of NA62.

Challenging the Standard Model is also what the experiments on the LHC are trying to do, but NA62 is taking a very different approach. Instead of smashing protons together at very high energies and looking for hints of new physics in the vast numbers of particles that fly off in all directions, NA62 is looking for evidence of tiny quantum fluctuations in a very specific decay process.

CERN

Powering up The NA62 experiment will join some other experiments at CERN that are switching on this year.

A kaon comprises an up quark and an anti-strange quark. The up quark is a "spectator" that does not take part in the decay, while the anti-strange quark is transformed into an anti-down quark. According to the Standard Model, this occurs via a quantum loop and the probability of the transition has been calculated to a high degree of precision.

However, hitherto unknown particles not predicted by the Standard Model could also contribute to the quantum loop. These particles could, for example, be "sparticles" that are predicted to exist by supersymmetric models of particle physics. Rather than revealing themselves in the final products of the decay, these particles would appear as quantum fluctuations and then contribute to the quantum loop before vanishing. These fluctuations could cause a significant deviation from the Standard Model decay rate – and measuring that discrepancy is the primary goal of NA62.

> Kaon decay is one of the few ways open to us to actually challenge the Standard Model of particle physics

Detecting decays

The NA62 experiment begins by smashing a very intense beam of 400 GeV protons from the SPS into a beryllium target that is 40 cm long. This collision creates a mixed beam of about 800 million charged particles per second. Most of these particles are pions and protons, with just 6% being the kaons of interest.

The beam is then sent through a Cherenkov detector called KTAG, which identifies individual kaons by the Cherenkov radiation they create. Although all the particles in the beam have the same momentum, protons, pions and kaons have different masses and so are travelling at different velocities. They therefore create Cherenkov radiation at different angles, and by measuring these trajectories, KTAG can identify individual kaons and give each one a "time stamp" that allows a kaon to be followed through the rest of the experiment.

The kaons next encounter the Gigatracker, which is a silicon pixel detector that measures the momentum of each kaon to a very high precision. This precision is needed to match the "mother" kaon to the "daughter" pion that it decays to. The kaons then drift through a 65 m section of the experiment where about 10% of them will decay. At this point the attention shifts to measuring the momentum of the daughter pions, which is done using a device dubbed the Straw Tracker. It has more than 7000 narrow drift tubes that are arranged into modules containing rows at right angles to each other.

Finally, a second Cherenkov detector called RICH measures the speed of each pion. This value allows the physicists to confirm that they were actually tracking a daughter pion rather than a daughter muon, which are produced in much greater numbers. There are in addition several other detectors that measure the decay products to ensure that only events associated with the desired decay channel are captured.

Beyond the Standard Model

The NA62 collaboration expects to see about two decay events in the eight weeks that it plans to run in late 2014. The experiment will then run continually for a further three years, which should yield a total of about 100 events. If the measured decay rate from that predicted by the Standard Model differs by a factor of two, NA62 will be able to measure this with a statistical uncertainty of 5σ, which is the gold standard of a discovery in particle physics. In other words, by the end of 2017, NA62 could discover physics beyond the Standard Model, something that its much bigger sister experiments on the LHC – ATLAS and CMS – have so far not managed to do.

In addition to its primary goal, NA62 will also be seeking evidence of "flavour violation" by looking for kaons that decay to final states that cannot occur in the Standard Model. The collaboration will also be making a very precise comparison of two similar kaon decay processes – one into an electron and neutrino and the other into a muon and neutrino. The ratio of the decay rates of these two processes is sensitive to physics beyond the Standard Model.

"After years of construction everything is coming together, the software is coming together and the students are getting the physics programme ready and soon we will be ready to ask our questions to nature," says Augusto Ceccucci of CERN who is spokesperson for NA62.

● You can watch a *Physics World* video about the NA62 experiment on *physicsworld.com* or in the digital edition of the magazine

A year of new start-ups

In addition to NA62 many other projects will also be starting up at CERN this year. They include new experiments studying the properties of antimatter, both of which will exploit CERN's existing Antiproton Decelerator (AD). This facility fires protons from the Proton Synchrotron into a block of metal to create high-energy antiprotons, which are then slowed down before being used. CERN's antiprotons should be available once again from 1 August and the AD's four existing experiments – ACE, ALPHA, ASACUSA and ATRAP – are all expected to make use of them.

One of the new experiments on the AD is AEGIS, which is the first designed specifically to measure Earth's gravitational pull on antimatter. This will be done by measuring the vertical distance a beam of antihydrogen atoms falls as it travels a set horizontal distance. Discovering even the tiniest of differences between the gravitational behaviour of matter and antimatter could shed light on mysteries such as why there is so little antimatter in the universe. But creating antihydrogen, which consists of an antiproton and a positron, is no mean feat and the AEGIS team will spend most of its time in 2014 fine-tuning its antihydrogen generator and its beam-creation set-up.

Also running for the first time at the AD is an antiproton experiment called BASE, which aims to make the most precise measurement ever of the magnetic moment of the antiproton. By trapping a single antiproton using magnetic and electric fields, BASE physicists aim to improve the current experimental value of the magnetic moment by several orders of magnitude. By making the same measurements on protons, BASE could reveal a tiny difference in their values of their magnetic moments. Such a difference would imply that CPT symmetry – a fundamental symmetry of nature as far as we know – is violated and this would point to physics beyond the Standard Model.

Meanwhile, over at CERN's Super Proton Synchrotron, existing experiments such as the Common Muon and Proton Apparatus for Structure and Spectroscopy will be up and running in 2014.

Breakthrough of the year

Cosmic neutrinos bag *Physics World* award

The 2013 *Physics World* breakthrough of the year has been awarded to the IceCube South Pole Neutrino Observatory for making the first observations of high-energy cosmic neutrinos, ushering in an era of "neutrino astronomy". Despite the many challenges of doing science in such a remote and inhospitable environment, the $275m IceCube South Pole Neutrino Observatory managed to spot extremely high-energy neutrinos that originate from far beyond the solar system.

IceCube uses a huge 1 km^3 volume of ice as a giant particle detector that is filled with strings of photomultiplier tubes that detect the faint Cherenkov light given off by fast-moving charged particles created when a neutrino collides with a nucleus in the ice. A big surprise came in 2010, even before the detector was fully commissioned, with the measurement of a shower of particles created by an extremely high-energy cosmic neutrino – dubbed Ernie. What was unexpected about Ernie – and about 20 other similar neutrinos that have been recorded since – is that a large portion of the energy, some 10^{15} eV, of the neutrino, was deposited in the detector. This allowed the team to determine minimum values of the energies of these neutrinos to within about 15%.

Chad Carpenter, IceCube/NSF

Tip of the IceCube Work on detecting cosmic neutrinos has won this year's *Physics World* Breakthrough of the Year award.

"The success of IceCube builds on the efforts of hundreds of collaborators around the world – from the design to physics analysis," says Olga Botner at Uppsala University, who is IceCube's spokesperson. "The Breakthrough of the Year award is a superb way to ultimately honour these efforts."

Nine other achievements in 2013 are highly commended by *Physics World*: the creation of the first pear-shaped nucleus; creating "molecules" of light; making the most precise measurement ever of the cosmic microwave background radiation; taking the first direct images of atomic orbitals; storing quantum information for up to 39 minutes in a solid-state device at room temperature; making the first carbon-nanotube computer; the first measurements of the B-mode polarization in the cosmic microwave background radiation; creating the first Bose–Einstein condensate to be cooled using just lasers; and the first measurement of Hofstadter's butterfly in a solid-state system.

All 10 winners were chosen using four main criteria – fundamental importance of research; significant advance in knowledge; strong connection between theory and experiment; and general interest to all physicists.

Hamish Johnston

● To read the full top 10 go to *physicsworld.com*

Publishing

Particle-physics open-access pact finally starts up

A collaboration of funding agencies and particle-physics labs from 24 nations around the world has reached an agreement with libraries and publishers that will see some 5000 papers a year in particle physics becoming immediately free to read online upon publication. As of 1 January this year, members belonging to the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) can make their work open access in 10 participating journals. It is estimated that around 60% of all papers in particle physics will as a result become open access this year.

The deal between SCOAP^3 and 11 publishers – including Elsevier and Springer as well as IOP Publishing, which publishes *Physics World* – will see articles in 10 different journals becoming free to read online. Around half of the journals – including Elsevier's *Physics Letters B* – publish all of their content from SCOAP^3 members and so will become fully open-access journals.

It is estimated that the move will cost around €5m per year. The cash will come from libraries, library consortia, research institutions and funding agencies, which will now redirect the money that would have been used to pay for journal subscriptions to a central pot that scientists can use to pay the fees charged by journals to make a paper immediately open access. Examples of such "article processing charges" (APCs) are $1800 to publish in Elsevier's *Physics Letters B* and £1200 to publish in the *New Journal of Physics*, which is jointly published by IOP Publishing and the German Physical Society. Publishers in turn will reduce their subscription fees, where those exist, to account for this conversion to open access.

Shutterstock/Maksim Kabakou

Done deal Some 5000 papers a year in particle physics will become immediately free to read online following an agreement between publishers and funders.

"For the very first time we have a worldwide set of libraries and funding agencies who have agreed to jointly contribute for a global transition of a set of journals to open access," Salvatore Mele, interim project manager of SCOAP^3 and head of open access at CERN told *Physics World*. "The fact that it is now possible might be an inspiration to others as several funding agencies and governments are releasing reports that encourage the re-use of subscription funds for achieving open access."

An agreement between SCOAP^3 and publishers has been a long time coming. Talks had been going on for over five years before the project was officially launched at CERN in October 2012. In June 2013 the consortium was hit when the American Physical Society pulled out of the deal, meaning that *Physical Review C* and *Physical Review D* are no longer participating in SCOAP^3.

Michael Banks

● See "The reality of open access", August 2013 pp22–27

Sculpture unveiled in tribute to Irish physicist

A sculpture celebrating the life and work of Ernest Walton – Ireland's only Nobel laureate in science – was unveiled by the Irish Minister for Education and Skills, Ruairí Quinn, at Trinity College Dublin in November 2013. The artwork, entitled "Apples and atoms", was created by artist Eilís O'Connell and features a stack of mirror-polished spheres, increasing in size as they rise upward, appearing to defy gravity. Next to the spheres are specially planted native Irish apple trees that refer to Walton's keen interest in growing fruit trees. Born in 1903, Walton studied mathematics and physics at Trinity in 1926 before completing a Master's degree in physics a year later. He went on to obtain a PhD in physics in 1934 under the supervision of Ernest Rutherford at the University of Cambridge before returning to Trinity, where he remained until retirement in 1974. Walton, who died in 1995, is best known for sharing the 1951 Nobel Prize for Physics with John Cockcroft for their work on the transmutation of atomic nuclei using accelerated particle beams.

Michael Banks

People

BP chief scientist nominated for senior energy role

The Obama administration has nominated BP's chief scientist Ellen Williams to be director of the Advanced Research Projects Agency-Energy (ARPA-E), which was created in 2007 to fund "high-risk, high-reward" research into novel energy technologies that are too early for investment by the private sector. The post at the agency, which is funded by the Department of Energy (DOE), became vacant after engineer Arun Majumdar stepped down in April. Williams' nomination is expected to be approved by the Senate in the next few months.

Williams, who did both a BSc and PhD in chemistry from the California Institute of Technology, has been based at the University of Maryland since 1981. She took a leave of absence from Maryland's physics department in January 2010 to take up her post as BP chief scientist where she has focused on energy efficiency. "It is not too much to say that the future of civilization depends on maintaining access to abundant and relatively low-cost energy," Williams told a meeting at the Massachusetts Institute of Technology (MIT) in October 2012.

Energy leader Ellen Williams from the University of Maryland has been nominated to become the director of the US Advanced Research Projects Agency-Energy.

Since nominees for government positions traditionally refuse interviews with the press until they have testified, *Physics World* was unable to get comment from Williams. However, colleagues have applauded the administration's choice. "I was very happy to hear of Williams' nomination," says Rajarshi Roy, director of the University of Maryland's Institute for Physical Science and Technology. "She has been superbly effective at getting people to work together and has an extremely broad and deep understanding of relevant issues."

Meanwhile, the Obama administration has announced that physicist Marc Kastner, dean of the School of Science at MIT, has been nominated as director of the DOE's Office of Science. If Kastner's nomination is approved, he will run an organization that oversees the entire breadth of DOE's scientific activities outside nuclear weapons, including research into climate change, accelerator physics, fusion and the human genome project.

Like Williams, Kastner has wide experience in experimental physics and management of a broad range of sciences. MIT president Rafael Reif says that Kastner is "a brilliant physicist and a highly effective manager" whose appointment is "an inspired choice". "Through his leadership of MIT's School of Science, [Kastner] has an unrivalled grasp of the nation's scientific enterprise and a record of attracting exceptional talent," says Reif.

The Obama administration has also nominated Stanford University engineer Franklin Orr, director of the Precourt Institute of Energy, as the DOE's undersecretary for science and energy. This is a new position created by US energy secretary Ernest Moniz that involves integrating basic science, applied research, and technology demonstration.

Peter Gwynne
Boston, MA

Funding

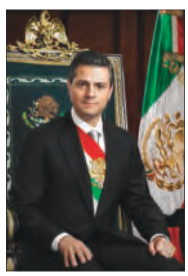
Mexican science budget boosted by 12% increase

The Mexican Congress has announced that this year's budget for science, technology and innovation is set to grow by 12% to 82 billion pesos ($6.3bn). The budget boost is part of the National Development Plan, introduced by Mexican president Enrique Peña Nieto, which aims to invest 1% of Mexico's gross domestic product (GDP) in science, technology and innovation by the end of 2018.

According to Irazema González Martínez, secretary of the science and technology commission of the Mexican Congress, the increase in the science and technology budget is a breakthrough. "For several years, Mexico has not invested enough in science, technology and innovation and, as a result, the growth potential of the economy is inferior to that of other countries," she says. "That has to change if Mexico wants to be competitive comparable to other emerging economies".

The 2014 budget, approved by the Mexican Congress, includes a 20% rise in funds for the National Council for Science and Technology (CONACYT), to $2.4bn. This extra cash will be used to improve existing programmes, such as grants for postgraduate students and Mexico's National System of Researchers, which provides an additional salary to top performing researchers in the country. It will also fund scientific projects that address specific national problems such as disaster mitigation, climate change, sustainable development, security and health.

This year CONACYT will in addition start a programme called "fellowships for young researchers", which will create 500 new permanent science positions, allowing young scientists to work in universities and science centres. "The creation of these positions is very important. It is the first time it has been done and it will allow talented young researchers to stay in the country and to work in their fields of expertise," says physicist Julia Tagüeña, who is director of scientific development at CONACYT. "This is a great opportunity for Mexican science".



Supporting science Mexican president Enrique Peña Nieto has pledged to invest 1% of the country's GDP in science, technology and innovation by the end of 2018.

But physicist Alejandro Frank, who is a former director of the Nuclear Sciences Institute of the National Autonomous University of Mexico (UNAM), says that while the increase in the budget is a good sign, it will take years to see whether it has had a positive impact. "The Mexican scientific community has to share the responsibility with the government to assure the success of the new enterprises," he says. "It is important that scientists show the importance of science and technology by creating interesting projects that address social problems relevant to the whole country."

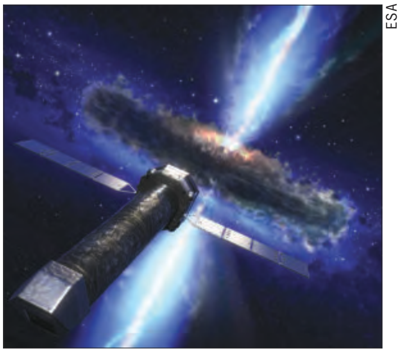
Gabriela Frías Villegas
Mexico City

Astronomy

ESA has large hopes for hot universe

The European Space Agency (ESA) has chosen the "hot and energetic universe" as the theme for its next "large-class" mission, known as L2. Scheduled for launch in 2028, L2 will be the second mission in ESA's Cosmic Vision science programme, following the JUICE mission to Jupiter and its moons, which is slated to take off in 2022 . L2 will seek to understand how and why ordinary matter assembles into galaxies and galactic clusters, as well as how black holes grow and influence their surroundings.

A total of 32 proposals were received and assessed by ESA's senior survey committee and, following an "extensive interaction" with the scientific community, the hot and energetic theme was recommended to Alvaro Giménez Cañete, ESA's director of science and robotic exploration. ESA will now issue a call for missions to address this theme, with the current leading contender being the Advanced Telescope for High Energy Astrophysics (ATHENA) project. ATHENA is an X-ray telescope proposed by an international collaboration led by Kirpal Nandra, director of the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching, Germany.



ESA

X-ray vision The "hot and energetic universe" has been chosen as the theme for ESA's next large-class probe, for which the Advanced Telescope for High Energy Astrophysics is a leading contender.

ATHENA is expected to carry two instruments. The X-ray Integral Field Unit will accurately determine the temperature, velocity, turbulence and chemical composition of hot gas, while the Wide Field Imager will perform surveys of the X-ray universe and conduct a census of black holes that were forming when the first galaxies and stars were developing. "ATHENA will certainly be the leading contender and may perhaps be the only one proposed," Nandra told *Physics World*. "We are very pleased that ESA has stepped up and recognized this opportunity to take worldwide leadership in high-energy astrophysics in the 2020s."

ESA has also announced that "the gravitational universe" will be the focus of its L3 mission, scheduled for launch in 2034. The frontrunner for this mission is currently the Evolved Laser Interferometer Space Antenna (eLISA) project, which is due to launch a proof-of-concept, known as LISA Pathfinder, in 2015.

"It is very frustrating that, although LISA Pathfinder will fly in mid-2015, ESA has decided that this timeframe was too close for comfort to commit to the L2 launch slot in 2028," says Imperial College London astrophysicist Timothy Sumner, who is a co-investigator on the LISA Pathfinder mission. "Of course we would have preferred the earlier launch slot, not only to gain maximum benefit from LISA Pathfinder, but also from a personal viewpoint for the older team members who would then see eLISA through to completion."

Andrew Williams

People

Physicist and philanthropist Fred Kavli dies at 86

The Norwegian-born physicist and philanthropist Fred Kavli has died aged 86. Kavli, one of physics' biggest benefactors, set up the Kavli Foundation in 2000 to endow research institutes at leading universities worldwide. Today, there are 17 such institutes around the world dedicated to astronomy, nanotechnology, neuroscience and theoretical physics. Kavli died at his home in Santa Barbara a year after contracting cholangiocarcinoma, a rare form of cancer.

Kavli was born in 1927 on a small farm in Eresfjord, Norway. He chose to study physics at the Norwegian Institute of Technology (now known as the Norwegian University of Science and Technology) in Trondheim. After he graduated in 1955, Kavli applied for a visa to work in the US. A year later, with visa in hand, Kavli travelled to California, where he became chief engineer of a small firm that designed and manufactured sensors for the Atlas missile – the US's first successful intercontinental ballistic missile.

Two years later, Kavli founded his own business, becoming head of the Kavlico Corporation, which grew into one of the world's largest suppliers of sensors for aeronautic, automotive and other industrial applications. He remained chief executive and sole shareholder of the company until it was sold in 2000.

Michael Mariant

Generous benefactor Fred Kavli, founder and chairman of the Kavli Foundation, has died aged 86.

It was then that Kavli turned his focus to philanthropy. He established the Kavli Foundation, which aims to "advance science for the benefit of humanity, promoting public understanding of scientific research, and supporting scientists and their work". The first institute funded – the Kavli Institute for Theoretical Physics – was created at the University of California, Santa Barbara in 2002, and has now been joined by 10 other institutes in the US, one in Japan, two in China and one each in the Netherlands, Norway and the UK. "I realized that I wanted to use the fruits of a lifetime of hard work in an efficient way for the long-term benefit of humanity by supporting basic science," Kavli told *Physics World* in 2007.

In 2008 Kavli enlarged the foundation's activities, setting up the $1m Kavli Prize, which is awarded every two years in three subjects: astronomy, neuroscience and nanotechnology. University of Cambridge astrophysicist Martin Rees told *Physics World* that he first got to know Kavli through the latter's "generous" backing for the Kavli Institute for Cosmology at Cambridge, as well as through his support for the Royal Society. "[Kavli] believed fervently in the value and potential of fundamental science," says Rees. "His foundation – now a permanent memorial to his vision – succeeded because he chose excellent advisers and staff, and also because he had a genuinely global vision."

Michael Banks

Space science

China's lunar rover begins journey

China has successfully sent a rover to the Moon – the country's first attempt to land on another body. Chang'e-3 was launched on 2 December 2013 from the Xichang Satellite Launch Center in Sichuan province by an enhanced Long March-3B rocket. It was carrying the Jade Rabbit rover, which is expected to travel around 10 km over the surface of the Moon for a period of three months. In ancient Chinese mythology, Chang'e is the Chinese goddess of the Moon and Jade Rabbit was her pet.

Chang'e-3 hovered around 100 m above the surface of the Moon in the Sinus Iridum crater and then slowly landed on the surface before releasing Jade Rabbit. During the whole landing process, the European Space Agency offered help in accurate positioning.

Around 1.5 m long, 1 m wide, 1.1 m high and weighing 140 kg, Jade Rabbit carries a camera, radar and infrared and X-ray spectrometers. Jade Rabbit will now survey the Moon's surface and geological structure, looking for natural resources and taking 3D images. It will also measure infrared spectra and analyse the lunar soil. "The radar below the rover can detect the soil structure 30 m deep and subsurface structure 100 m deep," adds Ouyang Ziyuan, chief scientist and senior adviser of China's lunar orbiter project. The probe is also carrying a telescope and an ultraviolet camera to observe the universe and the plasma sphere around the Earth.

Run rabbit, run
China's Jade Rabbit lunar rover will spend three months on the Moon and will travel around 10 km.

Chang'e-3 follows on from China's two successful lunar orbiters – Chang'e-1 and Chang'e-2, which launched in 2007 and 2010 respectively. Chang'e-3 is expected to pave the way for a manned mission to the Moon before 2020. "The technical experience gained by Chang'e-3 will be very valuable," adds Ouyang.

Jiao Li
Beijing

NASA launches MAVEN probe to Mars

NASA has launched a mission to Mars that will investigate how the planet lost its liquid water and how solar radiation is slowly eroding its atmosphere. The mission – Mars Atmosphere and Volatile Evolution (MAVEN) – was launched from Cape Canaveral Air Force Station Florida by an Atlas V Centaur rocket.

Costing $671m, MAVEN will spend 10 months travelling to Mars, arriving at the red planet in September. When the probe gets there, it will be put in a highly elliptical orbit in the Martian atmosphere, being 100 km from the planet's surface at its closest approach and 80 000 km away at its most distant. MAVEN, which took 10 years to design and build, will carry eight instruments including a spectrometer, a magnetometer and a spectrograph.

MAVEN will use its instruments to measure the current rate of atmospheric loss – a process that began about four billion years ago when Mars's protective magnetic field mysteriously disappeared – to understand how the planet transitioned from a warm, wet planet to a dry desert. The information gathered by MAVEN is also expected to help scientists grasp when conditions on Mars might have been most suitable for life to evolve.

Mars bound
NASA's MAVEN prove will study how Mars is losing its thin atmosphere.

MAVEN's launch comes a month after the Indian Space Research Organisation sent its country's first craft to Mars that will also study's the red planet's atmosphere. Dubbed Mangalyaan, the probe will arrive at the red planet in September, just two days after MAVEN. "Some of the measurements that [Mangalyaan will] make are similar to those that MAVEN will carry out and that's not a bad thing," Jeffrey Plescia, a Mars researcher at Johns Hopkins University in the US, told *Physics World*. "The interaction between the solar wind and the Martian exosphere is a dynamic system that varies in both space and time. Having two spacecraft at different locations will provide a much better 3D perspective on the processes and rates."

Michael Banks

Sidebands

Europe heads for Horizon 2020

The European Commission (EC) has kicked off its seven year €80bn Horizon 2020 programme with a round of competition for funding worth some €15bn in the next two years. This year some €7.8bn will be available, with around €3bn for grants including €1.7bn for the European Research Council and €800m for Marie Skłodowska-Curie fellowships for younger researchers. Meanwhile, "industrial leadership" will get some €1.8bn to support areas such as nanotechnology, advanced manufacturing, robotics, biotechnologies and space while €2.8bn will go on projects that address Horizon 2020's seven "societal challenges", which include health, energy, transport and the environment.

Cash for UK doctoral centres

The UK government has announced a £350m programme to train more than 3500 postgraduate students in engineering and physical sciences. The cash will fund 70 new Centres for Doctoral Training (CDT), which will be spread across 24 universities in the UK. Positions are funded for four years and in addition to carrying out research, students will also develop technical and transferable skills that are much sought after by business and academia. CDTs were established in 2009 with an initial 54 centres. Within four years they have trained around 2000 PhD students.

ICTP co-founder dies

The Italian physicist Paolo Budinich, who co-founded the International Centre for Theoretical Physics (ICTP) in Trieste, Italy, died on 14 November 2013 at the age of 97. Budinich was born on the Croatian island Veli Lošinj in 1916 and raised in Trieste. He graduated in physics from Pisa's Scuola Normale Superiore in 1939 before joining the Italian navy where he worked as a physics teacher training cadets. After the Second World War, he returned to physics, working in Göttingen, Zurich and then Trieste. Together with the Nobel laureate Abdus Salam, Budinich developed the idea for the ICTP in 1960, convincing the Italian government to support it and nominating Trieste as a candidate to host the centre. This was approved in 1962 when the International Atomic Energy Agency endorsed the ICTP's creation. Budinich was deputy director of the centre until 1978 and a year later he became founding director of Trieste's International School for Advanced Studies, until 1986.

Women in physics

Study finds women are under-represented in journals

Female physicists are less likely to author papers, have their research cited or participate in international collaborations than their male colleagues, according to a study of peer-reviewed journal papers published between 2008 and 2012. The analysis, which is the first to examine contemporary differences in research output between genders across all sciences, including physics, highlights the continuing under-representation of women in scientific publishing (*Nature* **504** 211).

Led by Cassidy Sugimoto, a specialist in scientometrics from Indiana University Bloomington, US, the researchers analysed 5.5 million papers in the Thomson Reuters Web of Science database, of which more than 120 000 were in physics and astronomy. They were able to work out the sex of 65.2% of the 27 million different authors in the database using a catalogue of names of known gender compiled from sources including the US Social Security Administration. In each paper, the proportions of female and male authors were then calculated and averaged over each discipline and country.

Shutterstock/wavebreakmedia

Cause for concern A study of 5.5 million scientific papers found that women receive fewer citations than their male counterparts and are less likely to work in international collaborations.

The analysis reveals that female scientists are 3.5–5 times less likely to author papers than male researchers. The study also found that, overall, female scientists occupying the prestigious first and last spots in a list of authors receive fewer citations than their male counterparts and are less likely to work in international collaborations. "This has critical implications for women in terms of receipt of citations, as well as access to world-class resources and star collaborators," says Sugimoto.

Although the lower overall number of female scientists partly accounts for the disparity in publication output, it fails to explain the lower citation rates and differences in collaborations that the researchers observed. Sugimoto admits that the study is purely descriptive but says that the systematic nature of the findings points to a universal gender bias across the sciences. "This research should encourage investigations of the factors responsible and what we can do to eliminate them," says Sugimoto. "Funding incentives that support and encourage international collaboration for women in fields where they are under-represented may be one potential avenue for future investigation."

Allison Shaw, a biologist and specialist in gender in science from the Australian National University in Canberra, says that cross-cultural comparisons like this are crucial for improving our understanding of the causes of gender disparity in science. "By highlighting the specific ways gender biases occur, studies like this make it possible for us as individuals to counteract the inherent biases that we, men and women alike, all have," she says.

Jude Dineley

Space

Europe launches a Swarm of satellites

Three identical satellites are now orbiting our planet as part of a mission to unlock the secrets of how the Earth's protective magnetic field is generated and why it changes over time. The €236m Swarm craft were launched by the European Space Agency (ESA) on 22 November 2013 from the Plesetsk Cosmodrome, 800 km north of Moscow. The satellites will spend the next four years identifying and measuring magnetic signals from the Earth's core, crust, mantle, oceans, ionosphere and magnetosphere as well as monitoring the near-Earth electromagnetic environment and the influence of the solar wind on our planet.

The mission comes at an important time in the history of the Earth's magnetic field as it shows signs of significant weakening, leading some to believe that a polarity reversal – a sudden switch between north and south – could be under way. On average, polarity reversals happen every 250 000 years, but the last one was nearly 800 000 years ago. ESA's Rune Floberghagen, head of the Swarm mission, describes the project as "unique", saying that previous magnetic field research projects used only one satellite. "We have a constellation of three satellites and this is a great improvement," he says, adding that the quality of scientific instruments is better and more varied than previous missions.

Eyes in the sky ESA's Swarm mission, consisting of three identical satellites, will study the Earth's magnetic field in unprecedented detail.

ESA

Each satellite features an array of instruments including a magnetometer, accelerometer and a GPS receiver, weighs 473 kg and is 9.1 m long. It is expected that two of the satellites will remain together and be put into an orbit of around 460 km, which will slowly decay to 300 km. The third satellite, meanwhile, will be on a completely different orbit at 530 km, with both sets of satellites crossing paths once per orbit. Floberghagen says the satellite constellation will not only allow the magnetic field to be measured in 3D but will also lets its variation with time to be determined, making "4D measurements" possible. Floberghagen adds that the constellation will also test how the geomagnetic field changes between night and day, as at any given time, the partner satellites would be in sunlight and the solitary satellite in darkness, or vice versa.

Data collection from the project is expected to begin in March and Floberghagen says it will be freely available not only to academic scientists, but also to commercial scientists. While Swarm is currently funded for four years, data will be collected for as long as the instruments on the satellites remain operational, which could possibly be for an additional six years.

Ned Stafford
Hamburg

Keeping serendipity alive

As lead editor of *Physical Review Letters*, **Pierre Meystre**, from the University of Arizona at Tucson, tells Jon Cartwright about the challenges facing one of the most influential physics journals

What is your research background?
My PhD was in quantum optics, which I did at the Swiss Federal Institute of Technology in Lausanne in 1974. After finishing a postdoc in the US in 1977, I then moved to the Max Planck Institute of Quantum Optics in Garching, Germany, where I worked on micromasers and cavity quantum electro dynamics. I then joined the University of Arizona in 1986, where I have been ever since, to work on laser cooling, atom optics and Bose–Einstein condensation. I now work in quantum optomechanics, which is nice because it combines everything together.

How is your new role as lead editor for *Physical Review Letters* (*PRL*) different from your previous role as an editor?
The main difference is that I don't have to review papers or manage the review process. Instead, I have to be a cheerleader for the journal, and act as a bridge between the editors and working scientists. I also help develop a vision for the future and think about how we can do things better. So it's more a "chairman of the board" type of position.

Does your new role afford you time for research?
Formally I'm hired by the American Physical Society (APS), which publishes *PRL*, as a consultant for 14 hours a week. The idea is that I will be able to continue my research as normal, and so far it seems to work.

Can you give an example of how you might make *PRL* better?
When I started out in this business, we received a journal in the mail and we would read it, or at least its table of contents. But today I just use a search engine to find the papers I need. That's enormously efficient, but it's also sad, because we don't have this wonderful aspect of stumbling upon an article by accident. Serendipity is very important in research. The question is how do we promote that? One idea is to implement something like what *Amazon* does, and have promotions saying "People who looked at this paper also liked…"

Journal chief Pierre Meystre.

Serendipity is very important in research. The question is how do we promote that?

Might you not end up doing the opposite, and promote homogenization?
Yes, so we don't want to do exactly what *Amazon* does. This method might help a researcher find other relevant papers for their research, but it will not necessarily help serendipity. I don't claim to have all the answers, but one of the reasons I took this job is because I think it's a great problem.

Is there still a place for *PRL* given the growth of open access, and the dominance of the *arXiv* server?
Open access is a huge issue with major financial implications – but it's also way above my pay grade. Regarding *arXiv*, *PRL* is obviously much more selective, because it vets articles through a rigorous peer-review process – indeed, I have had a lot of my own papers rejected by *PRL* including one rejected since I became lead editor! We want *PRL* to be the place for all the best papers in physics.

How do you ensure that you don't just accept papers that are in "fashionable" areas of research?
I think *PRL* is in a stronger position than other prestigious journals, such as *Nature* and *Science*, because we accept quite a few more papers, and because we make it a point of pride to publish in all areas of physics. So in a sense, we are less subject to the fashion of the day. But that doesn't completely solve the problem. For instance, if you reject a paper without external review, as we sometimes must – in the last year alone, we received over 12 000 manuscripts – there's always a level of arbitrariness. There are excellent and not very good papers but in the middle there's a large grey zone. How do you deal with emerging fields? How do you deal with papers that are controversial? We have to be open to new ideas.

Have there been any recent papers that straddled the grey zone?
We recently published a paper that used a D-Wave quantum computer to solve a famous mathematics problem known as the "party problem" (*Phys. Rev. Lett.* **111** 130505). Whether that machine is a quantum computer is a subject of debate, so there was a lot of hand-wringing involved in deciding what to do. In the end, we decided to go ahead. It was an example where I thought it was appropriate to take a chance. It may be right, it may be wrong – but if it's wrong, it's wrong in an interesting way. We will all have learned something.

But doesn't letting more papers in send the quality down?
It is indeed an issue: how do we establish and maintain standards? If I talk to my colleagues, they say, "Yeah, we have to tighten standards; we have to cut the number of papers published and select only the very best." Until you reject their paper! It's just human nature. So we have to do it fairly and consistently, in a way that does not discourage people.

What's your favourite *PRL* paper?
The early papers on laser cooling by William Phillips, Claude Cohen-Tannoudji and Steven Chu, were really quite a shock (*Phys. Rev. Lett.* **55** 48; **61** 169; **61** 826). Naively, you think when you put something in light, it will heat up. But these guys were saying no – it can cool down enormously. When I started in this business my colleagues told me that atomic physics was dead. But atomic physics is now probably one of the most exciting fields in physics. So things that seem dead may well just be asleep, we need to keep that in mind.

Comment

physicsworld

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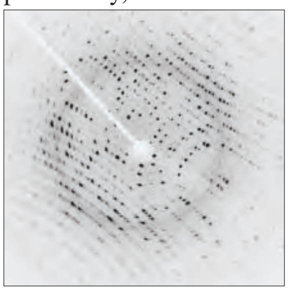
The crystal ball

Crystallography takes centre stage in this anniversary year

The coming year will be commemorated by many as the centenary of the start of the First World War, in which some nine million people went on to lose their lives. But 2014 is also the 100th anniversary of a much more positive event that reflected the dramatic pace of scientific research in the first few years of the 20th century. For it was 100 years ago that the German physicist Max von Laue was awarded the 1914 Nobel Prize for Physics for his discovery, two years previously, of the diffraction of X-rays by crystals. His discovery was the latest in a string of big breakthroughs for physicists, which included Niels Bohr's model of the atom (in 1913), Ernest Rutherford's discovery of the nucleus (1911) and Albert Einstein's *annus mirabilis* of 1905.



To increase awareness of crystallography and promote the benefits it brings, the United Nations Education, Scientific and Cultural Organisation (UNESCO) and the International Union of Crystallography have designated 2014 as the International Year of Crystallography. Rather strangely, they also want this year to commemorate the 400th anniversary of "[Johannes] Kepler's observation in 1611 of the symmetrical form of ice crystals, which began the wider study of the role of symmetry in matter". A full programme of events has been lined up, although the crystallography community will have much to do to avoid anniversary ennui following international years in physics (2005), astronomy (2009) and chemistry (2011). The 2015 International Year of Light will have even more to live up to.

Sharing your thoughts

An expanded Feedback section now includes comments from social media

Physics World notched up its 25th anniversary last year as the member magazine of the Institute of Physics, which you can now read both in print and in digital format. But *Physics World* has expanded well beyond being just a monthly magazine in recent times, to include an active website, regular focus issues on key technologies such as optics and lasers, special reports on different countries (our latest, on Brazil, is due out in April), as well as audio and video content. We also use social media to bring this material to wider attention – in fact, more than 270 000 people "like" *Physics World* on *Facebook*.

The rise of social media means there are now many more ways for people to comment on material we've published. So to bring you a flavour of the debate, we have expanded the Feedback section of *Physics World*. It continues to contain letters to the editor and an edited selection of comments from stories on *physicsworld.com*, but the section now also has, for example, Tweets on our content, posts to our *Facebook* page, and comments on our podcasts and videos. Although much social-media chatter is just hot air, there are some genuinely insightful, thoughtful and amusing comments being made, which we're handpicking for your enjoyment. We hope that these comments will encourage you to explore content from *Physics World* beyond the pages of this magazine that you may have missed.

Harming physics business

Immigration policies in the UK are making it increasingly difficult for hi-tech physics companies to do business, warns **Jeremy Good**

The Solvay conferences that were held in Europe in the 1930s were famous for getting together leading scientists – including Bohr, Einstein, Dirac and Fermi – to puzzle over the big questions of the day. Since then, scientists have enjoyed the ability to travel freely to speak at conferences or visit colleagues in other countries. Such international collaborations have long been a boon for science, improving our collective knowledge, expanding research capabilities and boosting economies.

Any world-leading science team must attract the best minds to stay at the forefront of science. Indeed, in a recent BBC discussion in which I was involved, UK government minister Matthew Hancock agreed when he noted that "the UK wants to be a magnet for the best scientists". Companies too must entice the world's best scientists to come and see what they are doing to make and encourage sales. Critical to these aims is a sensible visa and immigration policy.

At the moment the UK's immigration and visa policy is clearly not letting the country become a "magnet for the best scientists". While most academics can still travel widely, many governments worldwide, including the UK, are very restrictive, both for visitor visas and work permits. This harms us as a country and it restricts scientists from around the world who could benefit from our work.

Science-based businesses often work in niche areas. This means they must sell to relevant institutions around the world and recruit the best people, wherever they are from. Cryogenic Ltd is such a company. We employ 75 specialists from around the world and make low-temperature research equipment and superconducting magnets, with around 90–95% of all our sales being exports. Only a few companies in the world do what we do and, like many specialist science companies, we face three extremely frustrating challenges: securing visas for our clients to visit; having our clients poorly treated on arrival; and recruiting people from abroad. All of these could be improved by more sensible government policies.

iStockphoto/Bet_Noire

Travel policy Hi-tech physics-based industries rely on the free movement of scientists around the world.

Frustrating challenges

The first issue companies like ours face is when customers visit. In our experience, we have seen reputable scientists being denied visas, which has caused embarrassment and occasionally lost us business. Last year, for example, we invited a respected physicist from North Africa, who was educated at the University of Paris, to visit us and see our products, but he was refused a three-day visa for no apparent reason.

Our attempts to find out why or get reconsideration were futile. In this case we did get the order, but it was considerably more difficult for both sides. Interestingly, we got permission to build and export the equipment, so there was clearly no reason not to do business with him. But even where visas are granted, respected scientists from the developing world often have to wait months for permission to visit us. And if a customs inspection is needed before shipment, then expensive systems sit in warehouses, often delayed. This affects turnover and cash flow.

The second challenge is that customers with visas still have trouble getting into the country. These are often the most distinguished scientists from their part of the world, here on official business, to spend money with UK companies. A couple of years ago we had visitors from Japan who had placed substantial orders each year. They had flown from Holland and on arrival at Heathrow they were made to stand and wait for three hours to see a border agent. I was told that their welcome in Holland was a lot more civilized. In another example, a customer from India was interrogated for three hours before he was allowed in, despite the fact that his papers were in order, showing that he was travelling on Indian government business. Treating people in this way is absolutely unacceptable.

The final issue is that of work permits. To be the best company you need to hire the best talent worldwide. Our employees must have a high level of expertise in very specific areas. But this is also difficult. We once waited over a year to get a permit to employ a low-temperature specialist who at the time was working in Paris. Two years later, when we applied for an extension, we were told his application would not be considered until it was an "emergency", which in practice meant that it was within a week or two of expiry. We heard nothing and, following legal advice, we continued to employ him while the application was considered. It was not until weeks *after* he was supposed to leave the country that I received a call on a Saturday afternoon telling me he could stay.

All these problems mean that we are losing good people. Until recently I employed an expert in nanotechnology and atomic force microscopy. After seven years in the UK, he finally had no confidence that he would be given leave to remain, so he took his expertise to Germany where he hoped for a better welcome. I guess this is a triumph for the government's quest to reduce immigration, but it is no triumph for me. I will struggle to replace him with somebody of similar experience and ability.

A way forward

The difficulty companies have in welcoming the world's best is in no-one's interest. This is, of course, not just a UK problem as other countries that have also created difficult immigration policies are also doing great harm to science-based academia and industry. Yet a solution is surely not beyond the wits of our politicians. If we must be "tough on immigration", we should develop a separate system for the people we want and need to attract, with clear rules. Business visas must also be produced in a timely and professional manner.

I often use the analogy of Manchester United Football Club, which has become one of the world's best football teams by recruiting the top players from around the world. I would be interested to know why employing the world's best footballers is more important than employing the world's best scientists.

Jeremy Good is chief executive of Cryogenic Ltd, e-mail jeremy@cryogenic.co.uk

Critical Point Moving the goalposts

A new book about string theory offers a surprising way to explain philosophy of science, says **Robert P Crease**

Shutterstock/Krivosheev Vitaly

Game on Some say that the scientific method is like a football goal.

Many physicists have a high respect for string theory – in fact, the string theorist Ed Witten is often regarded as the greatest theorist alive. Yet critics, of whom there are many, call string theory an unscientific sham, arguing that it has no experimentally testable predictions and, barring a miracle, will have none for decades. For this reason, some physicists, such as Robert Ehrlich, have compared and contrasted the scientific status of string theory and intelligent design (*Physics in Perspective* **8** 83).

But in *String Theory and the Scientific Method*, Richard Dawid – a physicist and philosopher from the University of Vienna – confronts these contradictory feelings head-on. Dawid seeks to amend orthodox philosophy of science, arguing that physicists can be on solid ground when drawn to a theory for reasons *other* than mere testability. He makes three arguments, and in the style of orthodox philosophy of science gives them acronyms: there may be no alternatives to the theory (NAA, for No Alternatives Argument), the theory may bring unexpected coherence or clarity (UCA), and its research programme may be analogous to others that have succeeded (the Meta-Inductive Argument or MIA).

Dawid makes other claims, such as that string theory is a plausible candidate for a final theory. But it was his amendments that grabbed my attention, for they allow me to illustrate two different approaches to the philosophy of science.

The game of science

The orthodox or "Anglo-American" approach (so-called because it was developed by British and American philosophers) regards the scientific method as starting with facts, moving to a theoretical level that can make predictions, and then – through experimental verifications – delivering facts to start anew. In his classic book *A Philosopher Looks at Science*, John Kemeny illustrates this approach – also called the deductive-nomological (DN) model – with a football-goal-like diagram. Induction (turning data points into generalizations) is like a post that rises from up the field of play (or "world of facts"). The post connects with a crossbar (the theoretical realm), which leads to a prediction – the verification of which returns via the other goalpost to the ground. Science's strength depends on its regular earthly contact. As science is endless, Kemeny says, "we may expect this cyclic process to continue indefinitely".

This orthodox approach emphasizes prediction and verification, but marginalizes other aspects of science, such as how discoverers reason and the context of discovery. To use another sporting analogy, it views science as about scoring; it focuses on scoring strategies and not on such things as how the game evolves, the attitude of its players, or its social role. To be scientific is to adopt optimal scoring strategies.

A contrasting approach – some branches of which are called Science Studies, while others are dubbed Continental because they were inspired by Continental thinkers – views science as a process of making sense of the world, but with a broader perspective to sense-making than prediction and discovery. Here, the scientific process involves scientists using existing concepts to understand what they discover in the lab. Anything truly puzzling – a new kind of particle or dark energy, say – requires scientists to revise and transform the concepts they've inherited in the light of the new discovery and everything else they already know. Developing a new theory is thus not like picking and choosing a wallpaper, but an interpretive process. Science is less a matter of testing lucky theoretical guesses than a continual reinterpretation that makes explicit what scientists already understand, partly but imperfectly, in the light of new discoveries.

This alternative approach does not begin by formulating optimal scoring strategies but by understanding what is happening in actual games. It respects both the special character of science and its connection with everyday life. Scientists are people, not robots, so how does scientific engagement with the world differ from, or intensify, everyday experience? Why did human beings opt to play this particular game, and what stance does the game require of its players? This approach sees scoring strategies as springing from this game, rather than dictating it. To be scientific is to bring nature into better focus – and there's much more to this process than confirming theories.

The critical point

Partisans of the two approaches are generally unsympathetic to each other. I've read Anglo-American philosophers declare that the alternative approaches are grounded in subjective fictions. Meanwhile, a Continental colleague refers to Anglo-American philosophy as "the Fox News Network of the philosophical world", satisfied with staying inside its bubble where "scientific reasoning leading to confirmation" determines what's real, and snickering at other views.

Dawid's book is remarkable in that, probably inadvertently, it combines aspects of both approaches. His philosophical training is Anglo-American, which disposes him to try to formulate a revised form of "the scientific method" that's similar to the old one, but with amendments. We might call his approach a "Modified Orthodox Response" (MOR) that does whatever tinkering is needed to keep the orthodox approach from being blatantly out of touch with scientific practice. Yet his heart is with those whose understanding of science is informed by a more robust and experiential sense of scientific practice. The physics game he's playing is going on just fine – even though it is missing a goalpost and has a *very* long crossbar that vanishes off the horizon. He's disturbed enough by the mismatch between what his philosophical tradition tells him and the physics that he knows to try to reinterpret the former. Dawid wants to amend the scoring strategies of physics, not by improving their logic, but by adapting them to what he knows as a player to be happening on the field.

I call this progress in philosophy of science!

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Feedback

Letters and comments that appear here may have been edited.
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Fighting 'morality plays' with science

In reply to Robert P Crease's article "Deciding with science" (Critical Point, November 2013 pp19–20, http://ow.ly/rthNV).

I think Crease's remedies for distortions of science by politicians, members of the media and other interest groups need to go deeper. The stories told by opponents – Crease's term "morality plays" is a good name for them – work because they hook into genuine fears or grievances. Big industries have power, and they use it to influence governments. Many industries are not widely trusted: the nuclear industry because of its habit of secrecy, agribusiness for the aggressive way it pushed genetically modified organisms (GMOs), and so on. When these products are criticized, the usual industry response is denial, and their public-relations departments go into overdrive.

Bad science from opponents does need to be challenged, but so do vested interests when they tell less than the full truth. Climate change is a bit different, because in this case the opposition is the vested interests themselves, led by free-market believers and supported by big corporates such as fossil-fuel companies. Also, it is more personal, because to accept that climate change is real means accepting that lifestyles have to change. The issues are bigger than just a poor understanding of science.

Richard Riggs
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This piece makes some excellent points, although I think the situation is even more complex than outlined. While Crease describes some typical populist misconceptions that certainly contribute to confused public discussion, he seems less concerned with the manipulation of public opinion by economic interests that can afford to purchase the veneer of scientific legitimacy. For example, if the debate on GMOs were simply about potential benefits and risks to society, then how do you explain large companies pouring huge sums into campaigns to fight simple ingredient-labelling laws?

Many in the public – quite justifiably, I think – view the current efforts of these companies not as attempts to scientifically establish the societal efficacy of GMOs, but as attempts to obtain monopoly control over a commodity required by the entire world population. Certainly better education in scientific literacy for the public is required for more reasonable public policy debate. But so is better exposure of the practices of large corporations that hide manipulative practices under the veneer of scientific legitimacy – a practice that does as much to create misunderstanding of science as any folk tale.

kyoung21b
via *physicsworld.com*

I am very pleased to see *Physics World* address this question and agree that it is not easily or quickly solved. For some time now, I have been trying to understand how the layperson can understand scientific issues. I have my own views on many issues, such as global warming and genetic modification, but even though I am a scientist, I cannot claim to have waded through all the scientific publications to form or even validate my viewpoint.

My first justification for having a particular viewpoint would have to be scientific consensus. If, for example, the Intergovernmental Panel on Climate Change makes a judgment, then its position would be the one I regard as being the closest to the truth. However, it would be a stretch to imagine that scientists are somehow blessed with greater integrity or honesty than the general populace. Hence, the acceptance of the wisdom of any particular scientific group has to rely on a belief that the scientific standards of peer review, open debate and duplication of results are, on the whole, some kind of guarantee of impartiality. It is often the case that individual scientists cleave strongly to particular claims, but there is always someone who is equally ardent about an opposing belief; the scientific process should, over time, sort out the truth of the matter.

As humans, we have evolved to base decisions on what we personally experience

Where I become uncomfortable is when big money is involved, and the field is far from my own ("Big Pharma" immediately springs to mind). Do I believe that the scientific process will win out? I think so, in the long run, but in the shorter term, maybe not – and perhaps not before much damage has been done.

My life has been spent in the sciences and engineering, but how is someone without that kind of immersion to make good judgements? Given that I cannot claim anything remotely close to infallibility, it is hard to point the finger at laypeople and accuse them of "not getting it". How can I persuade them that there really is a majority of scientists attesting to the reality of climate change (and by "majority", I mean 97%, not just 51%)? How to convince them that the earth is older than 6000 years? Why is good old common sense insufficient?

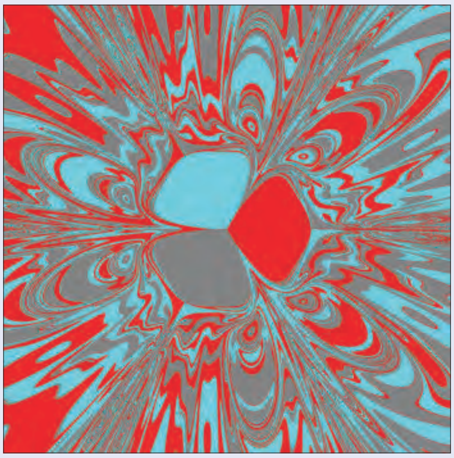
I have sometimes witnessed other scientists being very dismissive of others who do not accept their scientific beliefs, but I think that we have to be much more understanding of how non-scientists get their beliefs and information. As humans, we have evolved to base decisions on what we personally experience. That is why a few anecdotes are much more powerful than a raft of statistics. "Smoking is not really bad – I don't know anyone who has died from it" is much easier to believe than a sheaf of numbers compiled by people you don't know using methods and language you don't understand (regression coefficients, blind tests, double-blind tests, chi-squared values).

Clearly, we as scientists need to keep hammering home the messages of science, but first we need to critically evaluate how our own beliefs are formed. If we can do that, then we may be able to be convincing. We have to hold the press to task, to write carefully argued advice to our representatives, to be proactive in giving talks to our communities. Will all that be enough? I don't know.

jwlamb
via *physicsworld.com*

This whole issue is becoming of increasing concern to me as well, and I appreciate both jwlamb's comments and the article in general. It was certainly bad enough years ago when creationism seemed to be the only social problem scientists had to deal with. But today's paparazzi, the effect of big money, the tendency to live in media "bubbles" (sort of like the "disciplinary" effect in science), and the general emotional reaction to rapid change are really starting to have serious

The psychedelic pendulum



Phys. Rev. Lett. **111** 194101

The image at left depicts the chaotic pattern generated by motion of a pendulum with three fixed-point attractors ("Chaos reigns in unexpected places", 20 November 2013, http://ow.ly/rtiji).

A few years ago this would be described as GROOVY! Cool physics, yes.
Chris Orien Blake
via *Facebook*

It is mind-boggling that there are still meaningful experiments done with a pendulum. Any 7th grader could get their hands on one.
Daniel Melendez
via *Facebook*

effects on education, public policy and the wellbeing of individuals and the economy as well as science. This would be a bad time for another "dark age" of political and spiritual feudalism to begin.
ASIWEL
via *physicsworld.com*

Neutrino peculiarities

In reply to the *physicsworld.com* news story "IceCube finds cosmic neutrinos at the South Pole" (21 November 2013, http://ow.ly/rtkfa), which described the neutrinos detected as "chargeless, almost massless and very high energy".

Can somebody explain this? If $E = mc^2$, then would not "very high energy" imply something more than "almost massless"? What am I missing?
MicroTech
via *physicsworld.com*

Those aren't redundant descriptions. All neutrinos are "almost massless." We know that because (a) we have measured their flavour mixing, which can't happen if the mass is identically zero, and (b) cosmological data constrains the most massive neutrino to have $m < 0.3\,\text{eV}$ (that is, less than 10^{-6} times the electron mass). The neutrinos detected by IceCube are "very high energy" because of the way they have configured their detector to "select" particular events. The neutrinos produced in beta decay, in contrast, are low energy (a few mega-electronvolts).
kelseymh
via *physicsworld.com*

$E_0 = m_0c^2$ is the rest energy of a particle, where m_0 is the particle's rest mass. The full energy of a particle is its rest energy plus kinetic energy, $E = E_0 + T$. So there is no contradiction. Also, you can write the total energy as $E = mc^2$, but in this case m is not the particle's rest mass, but its rest mass multiplied by the Lorentz factor, γ, so $E = \gamma m_0c^2$. But when talking about the mass of a particle, we are normally talking about its rest mass, and that is very small for neutrinos.
tinash
via *physicsworld.com*

You can also understand how something can be both almost massless and very high energy just by screwing around with the equation. If $E = mc^2$, then $m = E/c^2$, which (given the value of c^2) is likely to be a vanishingly small amount, while c^2 (which we know to be rather large) is equal to E/m.
dan001
via *physicsworld.com*

More on stereo vision

In reply to correspondence about viewing stereograms (Features, August 2013 p35–39 and Feedback, November 2013 p27).

Unlike Charles Beton, I found that the stereograms published with the original article "fused" more readily than did the later ones, which were spaced further apart. I think that, if one is trying to see the 3D effect and concentrate on it without any special viewing device, it is more natural for the eyes to converge as they would in normal viewing rather than having them looking straight ahead at images separated by the interpupillary distance as if they were infinitely distant.

In my experience of having used stereo pictures of large molecules for many years, I have certainly found it more relaxing to use stereo-viewing glasses with lenses at the interpupillary distance and the pictures separated by the same distance or slightly less. With red/green anaglyphs viewed through red and green filters but without lenses, the two images are made as nearly as possible on top of each other, so that your two eyes converge and focus at the same distance (see e.g. D C Phillips and A C T North 1978 *Protein Structure*, Carolina Biology Readers).

When using stereo viewing systems for serious research with computer displays, it is preferable to have the two images presented alternately to the two eyes (M R Harris, A J Geddes and A C T North 1985 A liquid crystal stereo-viewer for molecular graphics *J. Mol. Graphics* **3** 121) as is done in modern 3D TV systems. Interestingly, some people who suffer from a weak or lazy eye find they can see in 3D with such systems, as the weak eye is left on its own when the strong eye's image is obscured.

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Physics party prank

In reply to the *physicsworld.com* blog post "Why do beer bottles foam when struck on top?" (25 November 2013, http://ow.ly/rtkUj; see also p3), which described recent research on this intriguing phenomenon.

Interesting, but what kind of idiot would ever do this?

Ian Harrison
(@itrharrison) via *Twitter*

I've totes been sciencing at parties!

Claire Lee
(@claire_lee) via *Twitter*

Nice to see at least some physicists are tackling the big challenges facing society!

William Ferguson
via *Facebook*

Well, we did ask...

In reply to the *physicsworld.com* video "What are the big unanswered questions in nuclear physics?" (25 November 2013, http://ow.ly/rtl7A).

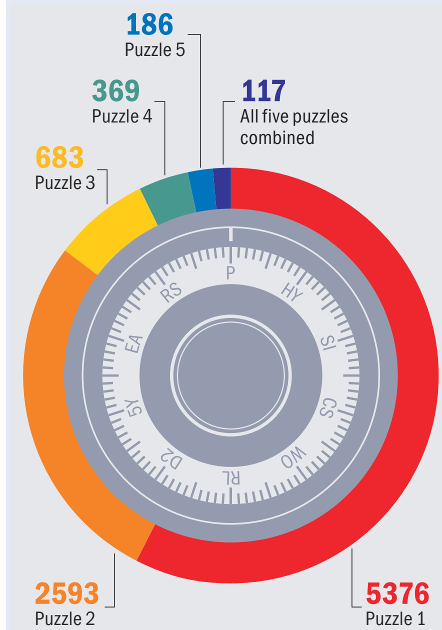
What about "How the hell do you turn this off?" and "Should that be leaking?" Or maybe "If we're trying to get rid of nuclear weapons, why aren't we using safer technologies?"

Des Brambley
via *Facebook*

I'm sure it's something like "Why are we spending money trying to harness fusion when there are little girls in sub-Saharan Africa who can't read?" Not too dissimilar to the question asked of one of the head physicists at CERN when they announced they'd found the Higgs boson!

Mark Hernen
via *Facebook*

Physics World at 25 puzzles



Answers to the Physics World at 25 puzzles
(October 2013 p88, December 2013 p17 and physicsworld.com/puzzle)

The infographic above shows the number of correct answers for each of *Physics World*'s five anniversary puzzles, which were created for us by the British intelligence agency GCHQ. Data were collected using an answer-checking box for each puzzle online at physicsworld.com/puzzle.

The series of challenges piqued the interest of many *Physics World* readers and elicited more than 1000 comments online as people debated the best approaches to solving them. We have revealed the answers below, but in case the answers alone are not enough to make you shout "Eureka!", we will post the full worked-through, multiple-step solutions at physicsworld.com/puzzle on 2 January.

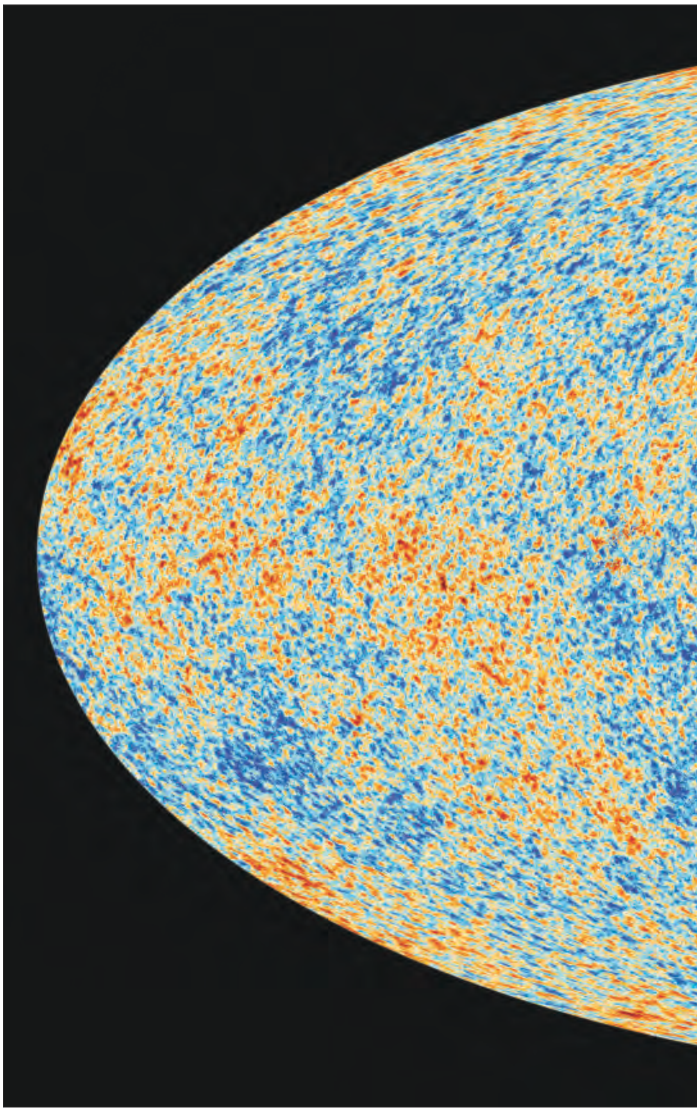
Puzzle 1: KEPLER
Puzzle 2: 13910
Puzzle 3: ORIGIN
Puzzle 4: PESTO
Puzzle 5: REINESRHEOLOGYRUTHERFORD or REINESRHEOLOGYRUTHER
Bonus print-only puzzle: TEVATRON

Quiz of the year 2013

Answers to quiz of the year 2013
(December 2013 p48)

1. Internal gravitational field **2.** Apollo-era rocket engine **3.** Ettore Majorana **4.** Extra-Low-Energy Antiproton ring **5.** GoCompare.com **6.** Mars rover Curiosity **7.** A solar panel **8.** Paul Frampton **9.** Muon g-2 **10.** F **11.** A **12.** C **13.** D **14.** E **15.** B **16.** E **17.** D **18.** C **19.** A **20.** B **21.** A **22.** C **23.** B **24.** C **25.** C

Planck perspectives



The Planck mission has produced a map of the cosmic microwave background at higher resolution than ever before. **Peter Coles** explains its implications for our understanding of the universe

Peter Coles is a professor of theoretical astrophysics, specializing in cosmology, at the University of Sussex, UK, e-mail p.coles@sussex.ac.uk

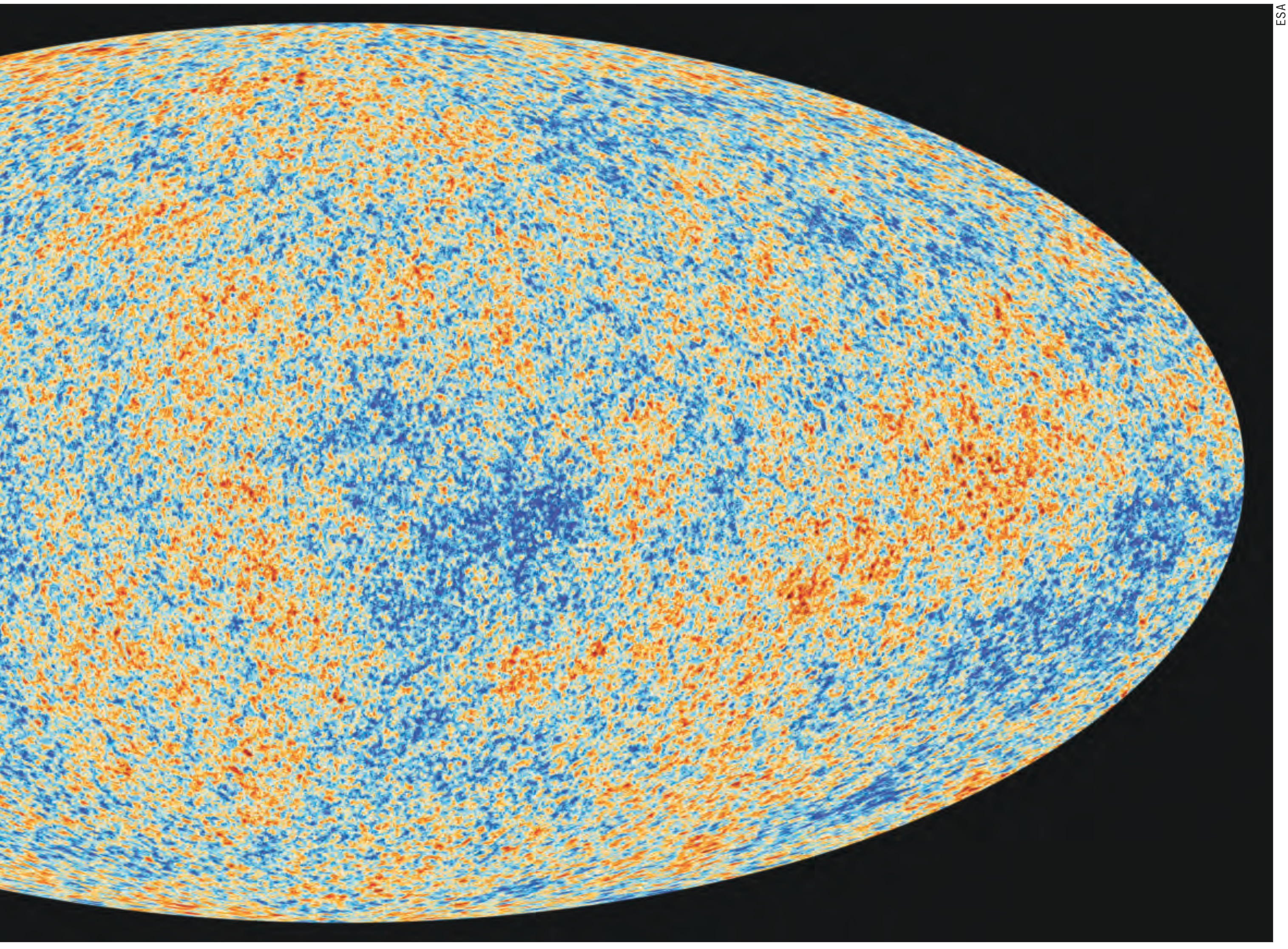
On Saturday 19 October 2013 the instruments and cooling systems on the European Space Agency's Planck spacecraft were switched off, marking the end of the scientific part of the Planck mission, after more than four years of mapping the cosmic microwave background. A day later, in preparation for a final shutdown command, a piece of software was uploaded that would prevent the spacecraft systems from ever being switched on again so that the onboard transmitter would never cause interference with any future probes. At this point Planck had already been "parked" indefinitely in a "disposal" orbit, far from the Earth–Moon system, having been nudged off its perch at the 2nd Lagrangian Point (L2) in August 2013 by a complicated series of spacecraft manoeuvres. These preliminaries having been completed, on 24 October 2013, at 12.00 GMT, a final instruction was successfully transmitted that shut down Planck for good. The Planck spacecraft will continue to orbit silently in the Sun's gravitational field for the foreseeable future.

But although this is the end of the Planck mission, it is by no means the end of the Planck era. Vast amounts of data still need to be fully analysed and key science results are still in the pipeline. The numerous maps, catalogues and other data products will be a priceless legacy to this generation of cosmologists, and no doubt many future generations. Nevertheless, this seems a good time to step back a little and try to form some sort of perspective on what the mission might mean for cosmology in the longer term. In this article, I'll try to do this by reflecting on what Planck was actually all about, asking what we have really learned from it, pondering what its scientific legacy might be, and suggesting what might come after it.

What was Planck?

The serendipitous detection of the cosmic microwave background (CMB) radiation in the 1960s provided the first direct evidence that the universe began in a hot Big Bang and led to its discoverers, Arno Penzias and Robert Wilson, being awarded the Nobel Prize for Physics in 1978. In the early days of CMB science, however, all that was known about the radiation was that its temperature is about three degrees above absolute zero, that it is of roughly black-body form (consistent with having been produced in thermal equilibrium with matter), and that it is approximately uniform in all directions on the sky. Theorists realized that the current low temperature is the result of the expansion of the universe and that the black-body radiation had actually been produced at a much higher temperature, at a time when the universe was filled with a plasma of ionized material that scattered radiation very effectively and was therefore opaque.

As the universe expanded and cooled, it would have undergone a relatively sharp transition when electrons and ions would have combined to form atoms, at which point the universe became transparent to radiation. This transition mirrors the behaviour of a star like the Sun, in which the matter temperature falls off with distance from its centre. Inside a star the matter is ionized and opaque; outside it is neutral and transparent. The sharp change in the optical properties of stellar matter happens at a temperature of a few thousand degrees, which is why stars have a well-defined surface temperature of that order. The CMB was produced when the entire universe was at a similar temperature to that of the surface of a star.


ESA

Planck's all-sky map
The most precise picture yet of the cosmic microwave background – the oldest light in the universe, which set off towards us 13.8bn years ago.

Looking out over cosmological distances we see back to this epoch; we can't see further because beyond the "last scattering surface", the universe is opaque (figure 1).

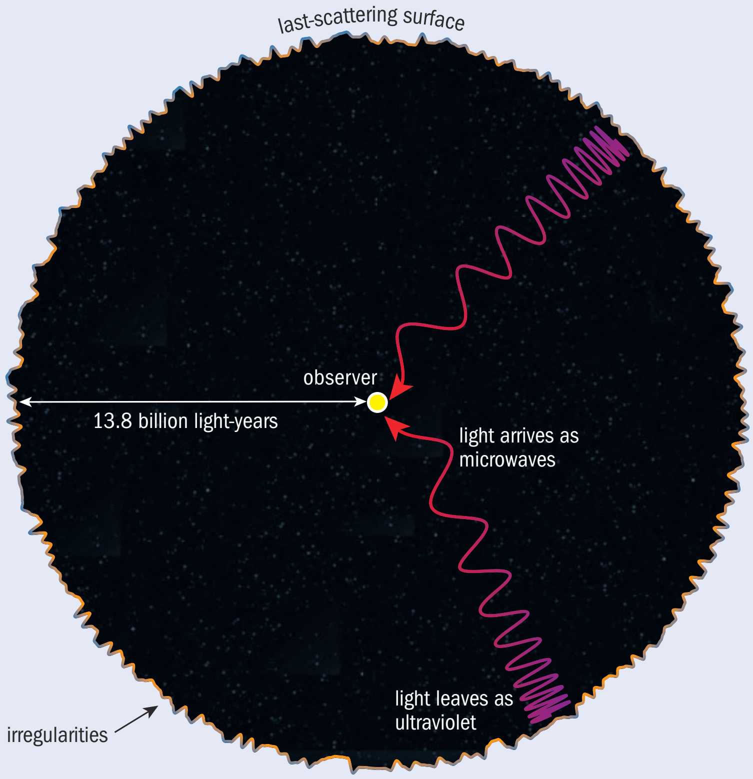
Just as astrophysicists can probe the opaque interior structure of stars by studying oscillations in the surface layers – a technique called stellar seismology – so cosmologists can probe the physics of the early universe using variations in the temperature of the CMB across the sky produced by oscillations in the primordial plasma. These oscillations are of a similar form in both cases – acoustic waves (although the wavelength is much longer in the cosmological setting than in the case of a star).

The basic theoretical framework of the Big Bang assumes the Cosmological Principle – that the universe is homogenous and isotropic. Even the most cursory observation tells us, however, that the universe is not like that, but rather lumpy, which means that any satisfactory cosmological model must explain where all the lumps came from. Our basic explanation for the lumps has not changed since the late 1960s: small initial irregularities in the distribution of matter got progressively amplified by the action of gravity as the universe expanded, eventually forming the rich cosmic web of structure we see today. These initial perturbations should manifest themselves as the variations theorists expect to see in the temperature of the CMB.

The simplest way of thinking about the initial perturbations is to consider the name Big Bang. The existence of a "bang" requires there to be acoustic waves, which are variations in the density and pressure of the medium supporting them. In the absence of such variations there cannot really be a "bang"; a completely uniform universe would really have been born in a Big Silence. If our view of how cosmic structure forms is correct, these primordial acoustic waves must have existed, therefore the universe must have been born in a bang.

The predicted "ripples" in the temperature of the CMB were not discovered until the early 1990s, when their large-scale variation was detected by the Differential Microwave Radiometer instrument on the Cosmic Background Explorer (COBE), a discovery that led to the award of the Nobel Prize for Physics to John Mather and George Smoot in 2006. COBE only detected the low-frequency part of the "sound" of the Big Bang – those acoustic waves with physical wavelengths that correspond to patches of sky larger than 10° or so. However, it led to the development of many other studies, such as the balloon-

1 Gazing back in time



Current cosmological theory tells us that about 380 000 years after the Big Bang, matter went from being an opaque plasma of ions and electrons to a transparent gas of atoms. This allowed the photons, which until then had been continually scattered, to travel through the now-transparent universe. Having existed at ultraviolet wavelengths when the temperature was 3000 K (purple), those photons reaching us now have microwave wavelengths corresponding to a temperature of 3 K (red), because over the 13.8bn years between then and now, the expansion of the universe has red-shifted the photons. The furthest back in time we can currently see is the location at which photons were no longer scattered in the opaque plasma, which is called the last scattering surface.

borne Boomerang and Maxima experiments, which sought to obtain more information about the higher-frequency content so as to map the CMB sky with greater angular resolution. Then, starting in 2003, a team of researchers used data from the Wilkinson Microwave Anisotropy Probe (WMAP) to map the whole sky over a wider range of microwave frequencies, establishing in the process a nearly complete spectrum of the sound of the Big Bang (figure 2).

Although it was in its planning stages before WMAP, Planck can be seen as a natural successor to WMAP by being more sensitive and having an improved angular resolution, which enabled it to see even shorter-wavelength acoustic ripples than WMAP could. It also had a wider range of receivers that made it better able to distinguish between the true CMB and other sources of radiation from, for example, our own galaxy, that might pollute the cosmic signal.

As it turned out, Planck was well up to the task of measuring the CMB spectrum over a huge dynamic range, providing results that were broadly compatible with WMAP but extending to much shorter wavelengths (figures 3 and 4).

So what are the main results from Planck? There are too many to discuss them all in detail – the science release in January 2013 resulted in more than 30 publications (see http://ow.ly/rqW3x) and different people will consider different things important. Here is a brief discussion of the three topics that interest me the most.

Cosmology by numbers

Cosmology is an unusual subject in many ways, not least because it appears to be done *backwards* compared with other branches of physics: instead of setting the initial conditions for an experiment and seeing how it develops, we have to infer how the great cosmic experiment that is our universe started from what we can observe it to have produced. The reason for this is that the Big Bang theory is incomplete. Based on our poor current understanding of how matter behaves at the high temperatures and densities we think occurred much earlier than the plasma phase, researchers are simply unable to predict from first principles precisely how the universe began. Indeed, the equations we use fall apart entirely at the very beginning because of the existence of an initial "singularity" at which the density and temperature become infinite.

This difficulty means that, although we can derive a system of equations, based on Einstein's theory of general relativity, to describe the universe's evolution in general terms, this system has a family of solutions corresponding to different initial conditions. We have no way of knowing which, if any, of these solutions corresponds to the universe we happen to live in. We are therefore unable to proceed by reason alone and are forced to seek observational clues.

Fortunately, it turns out that we can describe the entire family of possible Big Bang universes in a relatively simple way using a set of (dimensionless) parameters that, at least in principle, we can measure observationally. Many of these parameters can be determined more or less directly from the CMB. For example, the "matter" density is expressed via a parameter called Ω_m, which includes both the ordinary baryonic matter from which atoms are made as well as neutrinos and the exotic dark matter that seems to be required by various astrophysical observations. We often need to consider these components separately but for the following discussion it suffices to lump them all together.

Another dimensionless parameter, called Ω_Λ, describes a dark-energy component whose origin we don't understand at all but which, in its simplest incarnation, is related to the cosmological constant term, Λ, introduced by Einstein into his general theory of relativity, way back in 1916.

In this theory of gravity, the matter and dark energy expressed by the previous two parameters determine the curvature of space–time, expressed by another parameter, k. This parameter governs not only the geometry of the universe but also its dynamical evolution. If the curvature is zero then space is "flat" (i.e. Euclidean); in this case $\Omega_m + \Omega_\Lambda = 1$ so that, in the absence of a cosmological constant, the density of matter $\Omega_m = 1$.

In a more general case, the curvature can be either positive (corresponding to a closed spatial geometry, such as a 3D version of the surface of a sphere) or negative (an "open" universe with a hyperbolic geometry such as that of a 3D "saddle", which is admittedly rather hard to visualize).

Again looking at the case in which $\Omega_\Lambda = 0$, the future evolution of the universe is entirely determined by Ω_m. If $\Omega_m > 1$ then its current expansion will decelerate, eventually halt and go into reverse; such a universe will recollapse in a Big Crunch. If $\Omega_m < 1$ the expansion will continue forever. A dark-energy or cosmological-constant contribution acts to accelerate the expansion of the universe, so models with a large value of Ω_Λ typically experience runaway expansion in the future.

There are more parameters than these of course. There is also the Hubble constant, which describes the current expansion rate of the universe, and others relating to, for example, the densities of different types of matter. Minimal versions of the Big Bang model have about half a dozen free parameters, but extended versions have many more, not all of which are independent. I don't have space to discuss all of them, however, so in the following I'll just focus on these basic ones.

The existence of free parameters means that the theory is a bit of a moving target; they represent a barrier to direct testing of the theory because they can be tweaked to accommodate new measurements. However, the more precisely we can estimate their values the more we can reduce this wiggle room and subject the overarching framework to critical tests.

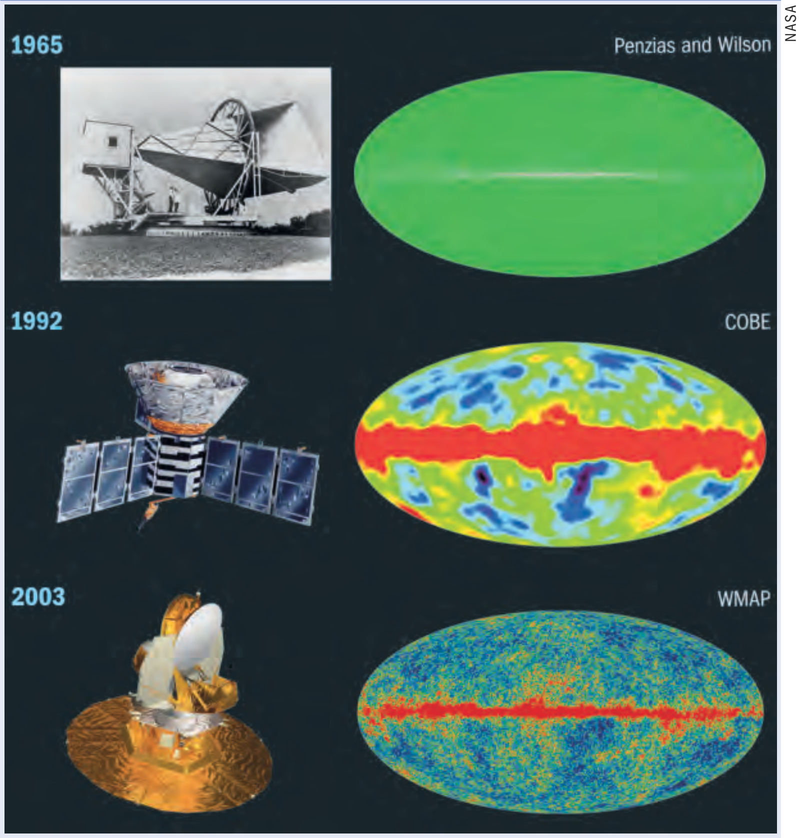
In 1994 George Ellis and I wrote a review article for *Nature* (**370** 609) in which we tried to weigh up all the available evidence about Ω_m. This parameter basically measures the mean density of the universe and it is possible to estimate this in many ways, including galaxy clustering, galaxy and cluster dynamics, large-scale galaxy motions and gravitational lensing. Many of these techniques were in their infancy at the time but, based on the available evidence, we concluded that the value of Ω_m was between about 0.2 and 0.4.

This verdict was somewhat controversial because of a theoretical predilection for a picture of the early universe, known as cosmic inflation, in which the expansion of the universe expands by an enormous factor, perhaps 10^{60}, very soon after the Big Bang. This stretches the universe so that it is expected to appear very flat; k is driven towards zero to very high accuracy. At the time there wasn't much direct evidence for a cosmological constant, and in the absence of this, a flat universe would require $\Omega_m = 1$. As it turns out, the subsequent development of these techniques has not changed our basic conclusion that $\Omega_m =$ 0.2–0.4. The last 15 years or so have, however, seen two stunning observational developments that we did not foresee at all.

Beginning in the late 1990s, two major programmes, the Supernova Cosmology Project led by Saul Perlmutter and the High-z Supernova Search Team led by Adam Riess and Brian Schmidt, exploited the behaviour of a particular kind of exploding star, type Ia supernovae, to probe the geometry and dynamical evolution of the universe. The measurements indicate that distant high-redshift supernovae are systematically fainter than one would expect (based on extrapolation from similar nearby low-redshift sources) if the universe were decelerating. The results are sensitive to a complicated combination of Ω_m and Ω_Λ but they strongly favour accelerating-world models and thus suggest the presence of a non-zero cosmological constant, or some form of dark energy. The leaders of these supernova studies were awarded the Nobel Prize for Physics in 2012.

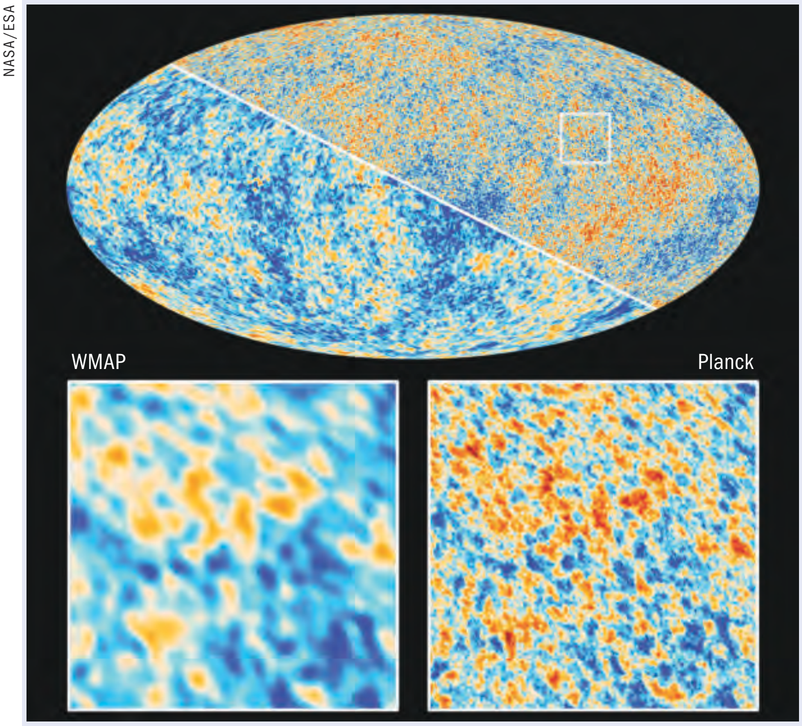
The supernova searches were a fitting prelude to the stunning results that emerged from WMAP in 2003. The CMB is perhaps the ultimate vehicle for classical cosmology. When you look back to a period when the universe was only a few hundred thousand years old, you are looking across most of the observable universe. This enormous baseline makes it possible to carry out exquisitely accurate surveying. The observed spectrum of the temperature variations displays peaks and troughs that contain fantastically detailed information about the basic cosmological parameters described above (and many more). Earlier CMB experiments, especially WMAP, established a basic framework called the concordance cosmology. Planck not only confirmed this picture but made it much more precise, pinning down the free parameters to unprecedented accuracy (figure 5).

2 Increasing resolve



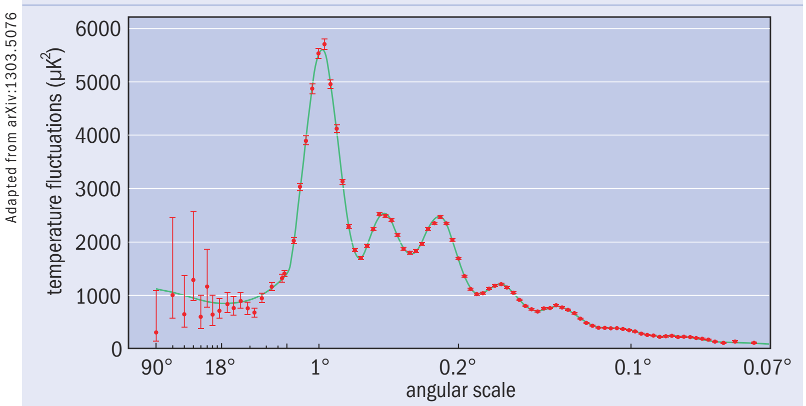
Increasingly high-resolution maps of the cosmic microwave background since its discovery. The band across the centre of each map is not part of the microwave background, but is foreground contamination from our own galaxy, the Milky Way, which also emits at microwave frequencies. Blue regions are colder than average and red regions hotter.

3 Resolving the ripples



The map from Planck is much higher resolution than the WMAP image. There is more than an order of magnitude more information in the Planck map than its precursor.

4 Primordial pulse



The power spectrum of the cosmic microwave background as seen by Planck. The plot shows the relative strength of the acoustic oscillations in the primordial plasma, i.e. how loud the Big Bang was as a function of wavelength of these waves, with long wavelengths on the left and short wavelengths to the right. The peaks occur at specific wavelengths in much the same way as they would in the sound spectrum produced by a musical instrument. In the cosmological context their position and amplitude depends on the matter content and geometry of the universe as specified by the various cosmological parameters described in the main text.

The increasing precision of cosmological-parameter estimates has tightened up the theoretical slack in the Big Bang model, but not without generating a certain amount of tension. Combining the CMB measurements with other data (such as the supernovae or measurements of large-scale structures) does seem to move the best-fit values slightly away from where they would sit if derived from the CMB alone. However, the statistical evidence for discordance among the parameters – for major departures from the standard Big Bang model – remains marginal, at least for the time being.

The confirmation and refinement of the concordance cosmology is a great achievement, on a par with the establishment of the Standard Model of particle physics. But there is more to cosmology than increasing the precision of cosmological-parameter estimates. We also need to ask if we can discover evidence of anything outside our standard view of the cosmos.

Non-Gaussianity

One important topic is the "non-Gaussianity" of the CMB, because the simplest theories of cosmological inflation predict the generation of small-amplitude irregularities in the early universe that imprint themselves upon the observed radiation pattern. These irregularities are essentially in the form of acoustic waves, so in a very real sense it is inflation that put the "bang" in Big Bang and was thereby responsible for creating galaxies and the large-scale structure of the universe. In the standard cosmological model, these acoustic waves form a statistically homogeneous and isotropic random field. Technically, this means that the perturbations have probability distributions that are invariant under translations and rotations in 3D space. Such fluctuations appear in inflationary cosmology in a manner essentially identical to the zero-point fluctuations that arise from the quantized harmonic oscillator problem and that are well known to be described by Gaussian statistics.

According to the theory of cosmological inflation, the dynamics of the early universe were dominated by a hypothetical scalar field called the *inflaton*. Assuming the fluctuations are small in amplitude, the scalar field evolves according to the same sort of dynamical equation that also describes, for example, a massive body falling through the air. Eventually such a body reaches a terminal velocity, which is defined by the balance between gravity and air resistance (drag) but is independent of how high and at what speed it started falling. The problem is that if you want to know where a body moving at terminal velocity started falling from, you're stumped: all dynamical memory of the initial conditions is lost when terminal velocity is reached.

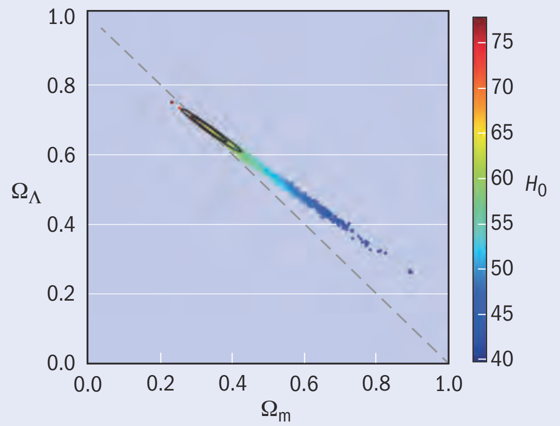
The problem for early-universe cosmologists is similar. In the context of cosmology there is a "slow-rolling" regime in the evolution of the inflaton field that is analogous to drag-limited motion of a falling body; in such a regime the universe enters a near-exponential phase of accelerated expansion, which causes it to inflate. In this phase the small-amplitude Gaussian quantum fluctuations in the scalar field become CMB fluctuations, which are Gaussian to a very high precision. If everything we measure is consistent with having been generated during a simple slow-rolling inflationary regime, then there is no way of recovering any information about what happened beforehand because nothing we can observe today will remember it. The early universe will remain a closed book forever. On the other hand, if inflationary dynamics were a bit more complicated (such as if there were multiple scalar fields rather than just a single inflaton) the fluctuations need not be so accurately Gaussian.

Before Planck, all statistical studies of CMB fluctuations had generated results consistent with Gaussian fluctuations. One of the most important things that the Planck collaboration has been looking for is evidence of non-Gaussianity that could be indicative of primordial physics more elaborate than that involved in the simplest inflationary models described by the slow-rolling solution.

Because we don't know *a priori* whether any of these ideas are correct, we cosmologists encode the level of non-Gaussianity in a parameter called f_{NL} and have designed sophisticated statistical tests to estimate it from observed data. By far the most precise measurements of this quantity have come from Planck; the value is $f_{NL} = 2.7 \pm 5.8$ which, within the error bars, is clearly consistent with zero. If this limit doesn't look impressive, note that f_{NL} is defined as a quadratic correction to an assumed Gaussian component. In essence we are modelling the CMB in the form $a + bx + cx^2$, and we already know a (the mean temperature) and b (the amplitude of the Gaussian component) and want to measure the value of c (which is f_{NL}), which represents the size of a non-Gaussian contribution. The typical temperature fluctuations seen on the CMB sky are about one part in 10^5 of the mean temperature (about 2.73 K); quadratic terms are therefore of an order 10^{-10}, so the upper limit on the level of non-Gaussianity allowed by Planck really is minuscule; it is Gaussian to a few parts in a hundred thousand. This is one of the reasons why some people have described the best-fitting model emerging from Planck as the Maximally Boring universe.

Perhaps this is a signal that we are approaching the limit of what we can learn about inflation in particular, or even the early universe in general, using the traditional techniques of observational cosmology?

5 Composition of the cosmos



Estimates of the matter-density parameter, Ω_m, and the dark-matter parameter, Ω_Λ, from Planck. Combining data sets such as these with results from other missions allows cosmologists to obtain values for these parameters, which describe the composition of the universe. The values also depend on the Hubble constant, H_0, and must lie on the dashed grey line on which the two parameters sum to equal 1. The latest estimates, taking into account the Planck data, indicate that the universe is composed of 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy.

Cosmic anomalies

Although Planck seems to have closed the window on the possibility of probing the early universe using non-Gaussianity (by not finding any), it has left another window very firmly open. As well as providing the strong basis for the concordance cosmological model discussed above, the WMAP data also provided some tantalizing hints of anomalous behaviour in the CMB sky that can't be accounted for by the standard cosmology.

One way of looking at how cosmology works is to think of it as an enormous exercise in data compression: Planck's raw map of the CMB sky consists of millions of pixels each measured at nine different wavelengths. From this, one can extract the spectrum shown in figure 3, which consists of a few dozen data points plotted on a graph, and from the spectrum we can extract a handful of very precise parameter estimates. This data compression is possible because the data are assumed to be described by a statistically homogeneous and isotropic Gaussian random field, which means that the spectrum contains all the relevant information in the map. All other degrees of freedom in the data are irrelevant (or "non-informative") for cosmology.

This compression scheme only works, however, if the underlying assumption is correct. As I have explained, upper limits on the particular form of non-Gaussianity described by f_{NL} are consistent with this assumption but there could be other departures that we don't know how to characterize. These would be missed by the standard analysis pipeline, so it's important to check the data rigorously with as many tools as possible to check we haven't discarded any important clues.

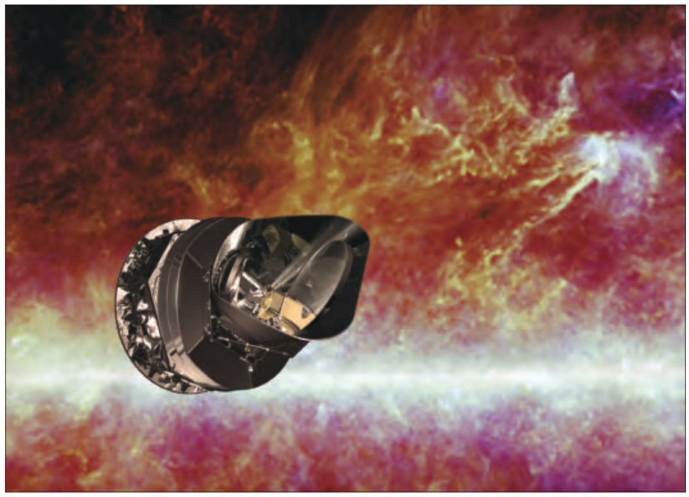
The possible anomalies detected by WMAP included a curious "cold spot" that appears to be colder than one would expect on the basis of Gaussian statistics. WMAP also revealed an unexpected alignment between fluctuation patterns on large angular scales, chiefly between the quadrupole (90°) and octupole (45°) modes corresponding to the first two points on the left of figure 2. And finally, there was a marked asymmetry in statistical properties of the observed CMB between the hemispheres north and south of the ecliptic plane.

Opinions about these WMAP anomalies differ among cosmologists, with many thinking that they are just systematic artefacts of the experimental procedure but others convinced that they may provide clues to physics beyond the standard model (such as deviations from the cosmological principle). Intriguingly, all the anomalies found by WMAP are also present in the Planck data; there remains no consensus on their significance.

What next?

In summary, what Planck has done is to confirm and render more precise a standard view of cosmology that already existed rather than provide dramatic and

This is one of the reasons why some people have described the best-fitting model emerging from Planck as the Maximally Boring universe



All-sky surveyor The Planck telescope may have been shut down but there is still plenty to learn from the data that it produced during its lifetime.

revolutionary new insights. It has increased the precision of cosmological-parameter estimates and in so doing has given us a detailed quantitative description of the geometry, expansion rate and energy budget of the universe. It has provided strong evidence to support the simplest theory of cosmological inflation and also, by placing strong constraints on the level of primordial non-Gaussianity, excluded more exotic variants of the inflationary idea. It has also confirmed the existence of various anomalies found by WMAP though not really confirmed whether they provide significant evidence of physics beyond the standard model of cosmology.

So what comes next? The most obvious answer to that question is CMB polarization. The analyses of Planck data published so far focus exclusively on the variation in temperature (effectively the intensity) of the CMB across the sky. However, theory predicts that the radiation field should be partially polarized as a consequence of scattering from electrons in the primordial plasma. Measuring the polarization of the CMB is a formidable technical challenge, which explains why it will take the Planck collaboration much longer to analyse the data than in the case of the intensity alone, but promises rich rewards if it can be done. Among other things, the polarization of the radiation field depends in a particular way on the existence of primordial gravitational waves, a key prediction of inflationary theories.

The first polarization data from Planck will not be available until later this year at the earliest, but such is the importance of this aspect of the CMB that there are already missions planned as successors to Planck, such as one from the European Space Agency called PRISM.

Although we have learned a very great deal from Planck and other complementary studies, there is still a great deal about the state of the universe that we misunderstand at a fundamental level. In particular we want to know if dark matter and dark energy are real or just manifestations of something wrong with the applicability of general relativity on cosmological scales. Only time, and more data, will tell. ■

Technology whose time has come

Joshua Pearce describes how physicists can help bring simple, affordable and life-changing devices to people and laboratories all over the world, using the concept of open-source appropriate technology

Several years ago, I was teaching introductory physics lab courses at a small university. As is common at many universities, much of the equipment there was outdated, and the experiments – one of which actually included watching ice melt – left a lot to be desired in terms of igniting my students' enthusiasm for the wonders of physics.

At the same time, as part of my own research on solar energy, I had just begun taking a serious look at the concept of appropriate technology (AT). This term comes from the world of economic development, and it refers to technology that can be easily and economically constructed using materials and techniques that are readily available to local craftspeople. In academic studies and early work by the World Health Organization (WHO), AT has been shown to play a central role in the alleviation of poverty in the developing world. Yet research and development on these technologies generally receives only modest support from institutions in richer countries. One reason for this lack of support is that the operation of many AT devices depends on relatively well-understood science. In fact, it depends on the sort of science that is accessible to pretty much anybody – including my introductory physics students.

This was my eureka moment. My budget for the labs was small, but since one of the key tenets of AT is that people living on $1 per day should be able

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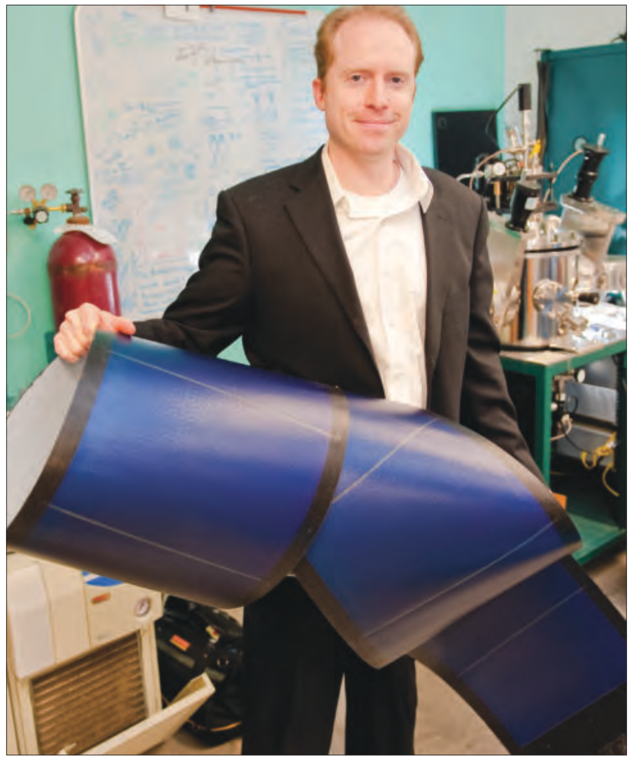

Low-tech and hi-tech Open-source appropriate technology can be simple and elegant, such as this student-designed solar-powered water-purification cone (above). Contaminated water sitting in the black base is evaporated and condenses on the sides and then runs down to a clean water reservoir. (Designs printable on a RepRap are available at www.thingiverse.com/thing:119674). More complex up-to-date technology, such as this thin-film solar cell deposited on flexible stainless steel (right) can also be appropriate in some cases. Photovoltaic cells are a sustainable source of energy, capable of powering everything from the lights in a hut to major science centres.

to afford to use it, cost was not a barrier. I therefore designed a class project in which students had to develop an appropriate technology, build it and finally design a physics lab experiment around it. They worked in teams, brought the equipment (largely scavenged) to class and then traded experiments with their peers. We did several "round robin" sessions so that everyone got to investigate several physical phenomena. Some students who were interested in mechanical properties built a bicycle-powered table saw. Another group put together a vertical-axis flexible-blade windmill. Many students explored basic thermodynamics and heat transfer by constructing a plethora of individual-scale or village-scale solar-powered devices, such as water pasteurizers, dehydrators, ovens and stills.

This project-based assignment motivated students to learn physics by offering them a chance to make concrete contributions to sustainable development. And it worked: the sense of exploration and excitement in the room was palpable, and the class's average scores on an exam after the project were significantly higher than the average achieved in exams before the project.

A history of the AT movement

I was not the first person to stumble on the idea of mixing physics and AT. In 1980 Peter Logan – an applied physicist then based at the Papua New Guinea University of Technology – suggested that physics could play a major role in sustainable development by contributing to the interdisciplinary field of appropriate technology. Logan's paper (*Physics in Technology* **11** 187) followed a period of explosive growth in appropriate technology; in the 1960s and 1970s, groups such as the WHO made it part of their programme to eliminate poverty. Unfortunately, in the years that followed, the concept of AT went into decline as large development projects (such as dam building) generally became the internationally favoured solution to poverty. These monster projects had their own problems, since much of the funding ended up being "recycled" back to wealthy countries at the expense of poorer ones, but AT was viewed as too cumbersome and difficult to scale. How could you get water-pump designs that worked in Africa to remote villages in Peru where people were experiencing identical problems with their water supplies? If only there was some form of global, interconnected communication system for people to share good ideas!

In its early years, the AT effort was perhaps ahead of its time. Now, however, the Internet has made it relevant again. Reinvented as open-source appropriate technology (OSAT), the modern form of AT focuses on technologies that promote sustainable development and are designed in the same fashion as free and open-source software (FOSS). A typical FOSS program grants users the right to use, copy, study, change and improve its design, and it facilitates this by making its source code readily available ("open source"). The open-source paradigm normally also includes a viral component, such as requiring users to share improvements with the community under the same open/free terms that applied to the original program. These viral qualities help open-source

Open-source technologies develop quickly by encouraging contributions and recognizing good work technologies develop quickly, since they enable massive global teams to work together. Above all, the open-source movement treats its users as developers by encouraging contributions, recognizing good work through peer approval and helping superior code propagate through the software "ecosystem".

These same principles also apply to OSAT hardware. Such hardware can be simple and elegant, as with the treadle pump (shown on p33) and a device that uses ultraviolet light from the Sun to purify water (see photo on p36). However, it can also encompass complex and state-of-the-art devices such as LEDs and photovoltaic cells on flexible substrates. In fact, even hi-tech devices such as mobile phones can sometimes be used in "appropriate" ways. For example, Bangladesh's national "Village Phone" programme, which primarily targets women living in remote areas, works like an owner-operated payphone. To cover the initial costs of the phone, borrowers take out a $200 loan from the Grameen Bank, a Nobel Peace Prize-winning organization that specializes in this type of "microfinance". They then subscribe to a related telecoms firm, Grameenphone, and are trained on how to operate the phone and how to develop a business by charging others – such as small farmers, who need to determine the best local city to take their produce to on a given day – to use it. With OSAT, the conflict is not between hi-tech and low-tech, but between appropriate tech and inappropriate tech. The most important feature of any OSAT device is that it must take into account any limitations imposed by the cultural, economic, educational and environmental resources of the local community.

Open-source 3D-printed scientific equipment

A number of designs for scientific equipment are available online. For example, some of my work on solar water purification requires heat exchangers, which needed very expensive prototyping with laser welding. We were able to build a digitally controlled laser welding system, using printed parts and open-source plans, for less than the price of a single heat-exchanger prototype. We also used a script in OpenSCAD to make a chemical oxygen demand analyser (see photo, right). This analyser runs on a simple version of an open-source Arduino Uno microcontroller and all the black components were synthesized using a RepRap 3D printer. We have shown that it is as accurate as commercial models but costs two orders of magnitude less.

Michigan Tech

Printable lab equipment A student tests the 3D-printed analyser.

If your research takes place on the nanoscale, you might be interested to hear that the University of Münster in Germany has developed an open-source scanning tunnelling microscope for a fraction of the cost of commercial systems. If your work requires optics, you might consider using a RepRap to print components from the open-source optics library (www.thingiverse.com/jpearce/collections/open-source-optics). This library contains free designs to build a research-grade Michelson interferometer or a hand-held spectrometer, along with many other tools. And physics teachers, take note: a basic optics lab set-up for an entire class costs only about £300 to print, compared with a retail cost of about £9000. I have documented dozens of other examples in my book *The Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs* (2014 Elsevier).

Fully formed

One particularly interesting recent area of OSAT development is "distributed additive manufacturing", which uses 3D printing to make everything from solar-distillation devices to hand-cranked generators. Broadly speaking, 3D printers work by taking in a filament of the working material (a popular one is a plastic called ABS, which is used in making LEGO bricks), heating it and then extruding it through a nozzle to produce a single 2D layer. By raising the printer's vertical axis and repeating the process many times, it is possible to construct a 3D object layer by layer (see September 2013 pp25–29).

Although some commercial 3D printers cost thousands of pounds, there is an open-source 3D printer known as a RepRap – the name is short for "self-replicating rapid prototyper" – that can be built for less than £400 and is capable of printing around 50% of its own components (http://reprap.org). RepRaps use computer-aided designs that can be shared over the Internet as easily as photographs. Hundreds of RepRap-friendly designs for OSAT devices exist already, including "recyclebots" that turn waste plastic into 3D printer filament. It is also worth noting that components of many scientific instruments can be made using RepRaps – a fact that could reshape the landscape of science education and research in developed countries as well as developing ones (see box above).

There is plenty of research left to do in this area, including improving local availability of feedstock for polymers and other materials (including ceramics and metal); increasing the maximum size of printed parts; improving the material properties of the printed objects; and using renewable-energy systems to power the production. My collaborators and I have already started working on solar-powered 3D printers that fit in a suitcase. However, more work is still needed to extend existing 3D printing technology before a complete, village-level OSAT fabrication process will become a reality.

Getting involved

Physicists have a good track record of opening up science for the common good. We have been sharing our open-access e-prints on *arXiv* for more than 20 years, long before "open access" became a buzzword. Given this background, I think it is time for physicists to take a serious look at OSAT.

If you are already doing research that could directly contribute to sustainable development, I suggest you start sharing your work on *Appropedia* (http://appropedia.org). This advertising-free website works like *Wikipedia* – anyone is allowed to create and modify content directly from their Web browser – and it has become the primary site for collaborative solutions in sustainability, poverty reduction and international development. On it, you will find project examples, descriptions of best practice,

Sunlight is the best disinfectant SODIS is a simple, low-cost method of disinfecting drinking water using the Sun. When transparent soda bottles filled with biologically contaminated water are placed in sunlight for six hours the combination of solar heat and ultraviolet light sterilizes the water and makes it safe to drink. Here it is being used in Indonesia.

"how tos", ideas, designs, observations, experimental data, deployment logs and much more. Most of the projects on there have been created by development workers and students, and many of them would benefit from the analytical minds of physicists. In addition, *Appropedia* would welcome summaries of your latest results on technical topics related to the site's mission. And of course, if you need field partners to help test some of your ideas, there are some perfect collaboration opportunities just waiting to happen.

But even if your research is not directly related to appropriate technology, you can still contribute to OSAT by making your own designs for customized lab equipment into open-source hardware. These contributions can include the bill of materials and instructions for operating equipment you have already made; or you can design new tools, which can be 3D printed. A good program for doing this is OpenSCAD – a free, open-source application that uses a script containing details of an object's geometric parameters as its input. If you can already program a computer, you will be able to easily learn OpenSCAD. OpenSCAD is extremely powerful as it enables designs to be fully parametric, meaning that changes can be made simply by adjusting the value of user-defined variables. Another useful customizing tool can be found in the *Thingiverse* (www.thingiverse.com), one of many digital repositories of free printable designs. This repository includes an application that converts OpenSCAD scripts into easily manipulated designs that anyone can use.

By sharing equipment designs with the open-source community, you will help other groups lower their laboratory costs and make your equipment accessible to researchers in the developing world. Moreover, you will also benefit directly when members of the international open-source community hack your equipment to improve it and then share the new, enhanced design with everyone. With OSAT, we all win. ■

Questioning quantum speed

The promised speed of a quantum computer is usually explained in terms of its ability to make many calculations in parallel. But, as **Philip Ball** reports, many quantum theorists reject this idea and point to other explanations entirely

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In the 1980s, University of Oxford physicist David Deutsch had an insight that would spawn an entirely new goal for physicists. He argued that a computer that manipulates information according to quantum rules rather than classical physics might work much faster than conventional machines. Subsequent studies confirmed that idea, although the rudimentary experiments on quantum computing have so far used only a handful of quantum bits. But even though the awesome speed that Deutsch forecast has not yet been unleashed, that power is evidently available in principle from quantum physics.

When he began thinking about these ideas, Deutsch was a committed proponent of the "many worlds" interpretation of quantum mechanics, which holds that every possible state of a quantum wavefunction is realized in parallel universes. Deutsch argued that the quantum speed-up comes from the fact that in effect a quantum computer performs many calculations at the same time in these "other worlds", whereas a classical computer has only one world in which to work. He called this "quantum parallelism".

The many-worlds interpretation of quantum theory was derived from Hugh Everett's ideas in the 1950s, but it remains controversial to this day and is rejected by many quantum theorists. All the same, Deutsch's notion of quantum parallelism has stuck – the standard explanation in popular descriptions of quantum-computing speed-up is still that massively parallel computation takes place, whether or not it involves other universes.

The common proposition for how a quantum computer works is that its quantum bits (qubits) can be placed in superposition states, encoding not just a binary 1 or 0 but any combination of the two. This means that, while the superposition is sustained, the quantum computer can juggle simultaneously with many more potential "solutions" to a computational problem than can a classical machine, accounting for its remarkable speed.

It's a nice intuitive picture – but is it true? "I don't believe it for a minute," says quantum theorist Christopher Fuchs of Raytheon BBN Technologies, a US-based company that is currently developing real quantum processors from superconducting circuits. "The source of the speed-up is something of an entirely different character," he argues.

He isn't alone. Several other quantum physicists take issue with the "parallelism" picture, saying that at best it is only a crude representation, and perhaps a total misrepresentation. "I agree that this is not at all the right way to explain what is going on, though I've been guilty of doing it myself," says David Poulin of the Université de Sherbrooke in Quebec, Canada.

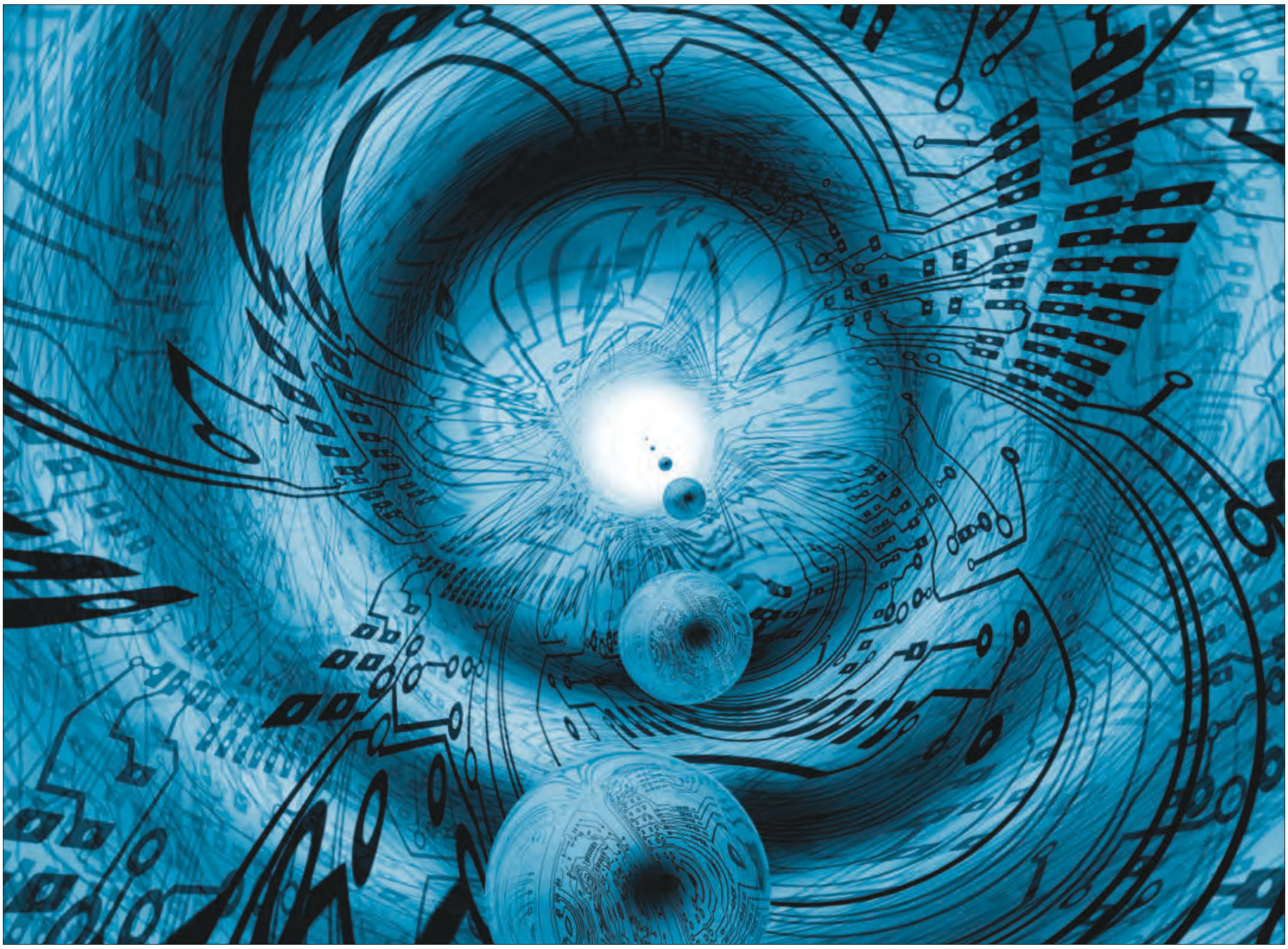
Other explanations for how quantum computers achieve their speed-up have been around for some time. But none is universally accepted, and most apply only to certain realizations of quantum computing. And perhaps because they lack the neatness and intuitive appeal of parallelism, they are given little air time in popular accounts. In fact, some researchers feel that the origin of quantum speed-up is still an entirely open question. According to Maarten van den Nest of the Max Planck Institute of Quantum Optics in Garching, Germany, "understanding the essential features of quantum physics accounting for this increased power is a fundamental but largely unsolved problem".

None of the explanations for how quantum computers achieve speed-up is universally accepted

Only one universe

Deutsch's original formulation of quantum computing was located squarely within the many-worlds picture. He was convinced that a consideration of this behaviour "places an intolerable strain on all interpretations of quantum theory other than Everett's". That view was strongly challenged by physicist Andrew Steane, also at Oxford, who in 2000 posted a preprint on the *arXiv* server with the combative title "A quantum computer only needs one universe" (arXiv:quant-ph/0003084; later published as *Stud. Hist. Phil. Sci. B – Stud. Hist. Phil. Mod. Phys.* **34** 469). "Quantum superposition does not permit quantum computers to 'perform many computations simultaneously'," Steane argued. "Quantum computation is therefore not well described by interpretations of quantum mechanics that invoke the concept of vast numbers of parallel universes."

This argument has been sharpened by a theoretical demonstration that a quantum computation does not in general have access to all the possible states of the quantum variables (called the Hilbert space). Poulin and colleagues showed two years ago that, unless the timescales are truly astronomical, the volume of Hilbert space physically accessible to a quantum system is only a tiny fraction of the entire set.



Mehau Kulyk/Science Photo Library

Other-worldly Do quantum computers achieve speed-up by performing calculations in many parallel universes?

While Deutsch didn't suggest that quantum parallelism requires access to *all* of Hilbert space – every possible quantum state of a wavefunction – Poulin's work shows that a quantum system is able to explore much less of it than might be imagined.

For Steane and many other quantum theorists, the real key to quantum speed-up was instead the phenomenon of entanglement – the ability to place two qubits in co-dependent states, in which a measurement performed on one of them instantly fixes the state of the other one. So, for example, if two entangled spins are anticorrelated, a measurement revealing one of them to be "up" compels the other to be "down".

Ever since entanglement was first highlighted by Albert Einstein and his co-workers in 1935, it has been seen as perhaps the central "weirdness" of quantum theory. The weird thing about it is that as soon as one of the qubits is measured, the second qubit assumes its correlated value *immediately*, faster even than information could be sent between the two qubits via a light signal. In Einstein's view, in which faster-than-light communication is forbidden by special relativity, this "non-local" influence showed that quantum theory was incomplete and must be underpinned by a deeper layer of reality. His idea was that each quantum entity is described by "hidden variables" that already have specific values before they are measured. But subsequent theory and experiment has shown that entanglement is indeed a genuinely non-local effect, and incompatible with hidden variables.

As Steane wrote in his paper, a quantum computation "uses entanglement to generate and manipulate a physical representation of the correlations between logical entities, without the need to completely represent the logical entities themselves". In other words, the computer uses the entangled relationships between qubits to manipulate them together rather than one by one – doing only what is necessary, without extraneous intermediate steps.

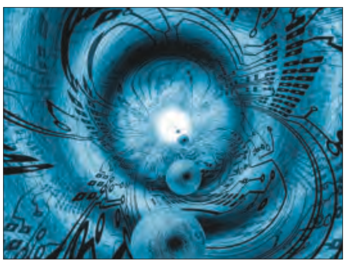
Therefore, says Fuchs, "Quantum computers can skip steps that would have to have been taken on a classical computer. Computational steps somehow 'count for more' on a quantum computer with respect to the necessary classical steps. That's a completely different idea than parallelism." Although Steane feels his argument remains valid today, he admits that "it is an issue of interpretation that cannot be settled by an experiment or a mathematical proof of some kind".

Meanwhile, Dan Browne of University College London suggests that quantum-computational speed-up is more about the *interference* that is possible between quantum states than it is about entanglement. Quantum interference is familiar from the double-slit experiment for quantum particles. It is subtly different from classical wave interference, and arises from correlations between the probabilities of particles' positions that make the joint probability differ from the sum of the individual ones. Entanglement is one facet of interference, because it too involves correlations, but it's possible to have interference without entanglement.

Casting doubt on entanglement

For a long time it was widely believed that entanglement could indeed account for the rapidity of quantum computation. That view was cast in doubt, however, by a paper written last year by Van den Nest (*Phys. Rev. Lett.* **110** 060504), in which he outlined a scheme by which quantum computation could be carried out using an amount of entanglement that, by many standard measures, could be arbitrarily small. "Even when the amount of entanglement present in the computation turns out to be very small," says Van den Nest, "the computation may still be just as powerful as a fully fledged quantum computer that uses lots of entanglement."

However, he adds, "Asking how large the entanglement must be to yield useful quantum computations is too vague a question to be meaningful, since there are many non-equivalent ways of quantifying it." It may even turn out, Van den Nest says, "that entanglement plays no decisive role for quantum speed-ups in the first place". Indeed, work done 15 years ago by Daniel Gottesman (now at the Perimeter Institute in Waterloo, Canada) that formed his PhD thesis at the California Institute of Technology, has long shown that it is certainly not a sufficient ingredient. "High amounts of entanglement do not guarantee speed-ups," Van den Nest says.



One oddity of quantum experiments is that their outcomes can depend on the order in which you make the measurements

Gottesman's thesis contained a theoretical technique he developed for studying a class of quantum logic gates that are commonly known as the Clifford group. With this technique, known as the "stabilizer formalism", many of the current quantum information-processing algorithms can be constructed from the Clifford group, in particular those designed to correct errors that develop in the computation. "Quantum circuits built using the Clifford group are able to make very entangled states, or states consisting of large superpositions, and can cause widespread interference between different branches of the wavefunction," Gottesman explains.

Despite that, the stabilizer formalism shows that there is an efficient classical algorithm that can simulate the gates in the Clifford group. In other words, at least for this class of quantum gates, neither entanglement nor interference guarantees any advantage over classical circuits. "Therefore, Clifford group gates cannot give you an exponential speed-up over classical computation," says Gottesman.

Out of context

Robert Raussendorf of the University of British Columbia in Vancouver, Canada, suggests that we are currently more clueless than ever about where the quantum speed-up comes from. If it's not from the vastness of Hilbert space (of which Deutsch's many-worlds view was one expression), not from entanglement and not interference, then what? "As far as I am aware, right now it's pretty silent in the theatre where this question is played out – that's because the main candidates are all dead," Raussendorf says.

But he says that recently a new candidate has appeared on the scene, called "contextuality" – a notion that goes back to work done in 1967 by Simon Kochen and Ernst Specker, which examined hidden-variable theories in a manner analogous to that published the previous year by the Northern Irish physicist John Bell. Bell's theorem helped to prove that the existence of hidden variables is not compatible with the non-local effects that are apparently manifested by entangled states. This led to the now widely accepted belief that hidden variables do not exist.

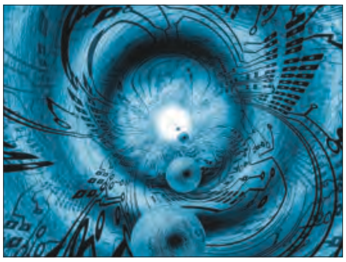
Kochen and Specker, meanwhile, considered the implications of hidden variables for the issue of experimental context. One oddity of quantum experiments is that their outcomes can depend on the order in which you make the measurements of the variables – for example, whether you measure a particle's position or momentum first. In other words, there's a dependence on the context of measurement. In contrast, outcomes in classical experiments are non-contextual: you get the same result regardless of the order of measurements. Kochen and Specker showed that any hidden-variables theory is incompatible with the contextuality that we see in quantum mechanics.

Recently, Joseph Emerson of the University of Waterloo in Canada and his colleagues have argued that, rather than the non-locality of entanglement, it could be the contextuality of quantum physics that supplies the hidden resource needed for at least some forms of quantum speed-up. "Contextuality is the first speed-up candidate about which I am excited," says Raussendorf.

The myth of quantum spice

Some feel that this debate about the "how" of quantum computation is a red herring. "Researchers attending most conferences in quantum computing never mention these issues, or only in discussions over beer," says Franco Nori of the University of Michigan in the US. Most people in the field, he says, are focused on immediate practical issues, such as "how to achieve longer coherence times for entangled qubits, how to achieve more operations within each coherence time, how to couple and uncouple qubits controllably, and so on".

But for others, the problems in explaining quantum speed-up bear on the whole matter of how quantum computers are sold – sometimes literally so. That was clear in the heated debate about whether "the world's first commercial quantum computer" advertised by the Canadian company D-Wave in 2012 was a true quantum computer at all, or just a fancy box of tricks



It is very difficult to describe how a quantum computer works using everyday language

that made token nods towards quantum effects.

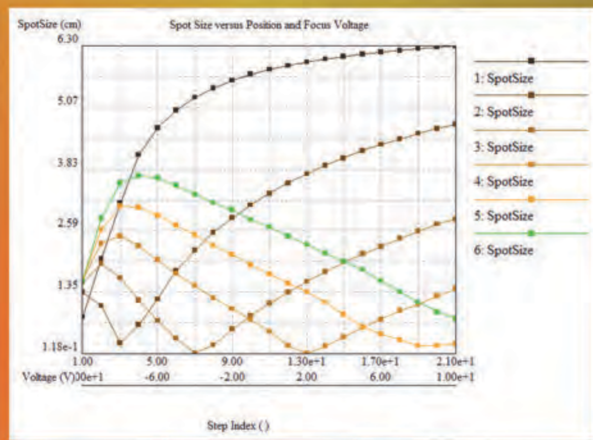
"The question has, as far as I am aware, mostly been interpreted as seeking a resource, a kind of quintessential quantum spice," says Raussendorf. "The science-fiction version of this line of thought is that quantum spice can be bought by the ounce in future computer stores, and a hundred dollars' worth allows one to do such-and-such a computation." But that's not how it is.

"It is very difficult to describe how a quantum computer works using everyday language," Browne admits. Indeed, there may never be a one-size-fits-all answer, which is perhaps why any simple account of how a quantum computer does its job is doomed to be incomplete if not misleading. "I consider it unlikely that there is a single simple concept that is capable of capturing where quantum speed-up comes from," says Van den Nest. He says there are several non-equivalent ways of viewing classical computation as being a subset of quantum computation, and in each case the "ingredient" needed to release the power of the quantum approach might be different.

This difficulty is part of the reason why it is hard to find things that quantum computers *can* do – so far, only a small number of algorithms have been proposed that are well suited to particular problems, such as factorization and searching. "There isn't a straightforward way of making use of what quantum mechanics has to offer," says Browne. "Designing good quantum algorithms is a very difficult task," Van den Nest agrees. "I believe this task could be made lighter if we were to arrive at a systematic understanding of the possible ways to move from classical to quantum computing" – in other words, if we had a better grasp of which aspect of quantum physics the advantages ultimately stem from.

But Gottesman wonders if we can ever really grasp that. "My own feeling is that quantum speed-up is a property of quantum mechanics as a whole and is not something you can definitively pinpoint the source of," he says. "If you have 'enough' of quantum mechanics available, in some sense, then you have a speed-up, and if not, you don't."

At the same time, this ambiguity could be a virtue, since it leaves space for researchers to draw inspiration from diverse views. After all, even if a quantum computer does indeed require only one universe, Deutsch's vision of a multiplicity helped him to launch the field. Critics might dismiss the idea, but not what it produced. "For the most part these debates are metaphysical," says Poulin, "but they can nonetheless be useful because thinking about these questions can lead to new methods to process quantum information." ■



William Gasarch

Mathematics and prejudice

iStockphoto/MarcelC

Natural appeal Edward Frenkel's new book looks at the beauty of mathematics such as symmetry.

Love and Math : the Heart of Hidden Reality
Edward Frenkel
2013 Basic Books
$27.99 292pp

Mathematics has been around for thousands of years, and this has given it plenty of opportunities to become very complicated. For example, seemingly disparate fields of mathematics have often, over time, become connected in surprising ways. In his book *Love and Math*, Edward Frenkel describes this process via an analogy with continents and the bridges that are built between them. This is very apt, since building a bridge between (say) North America and Europe would be very difficult, and much of the mathematics he writes about is also very difficult.

The book is partially Frenkel's autobiography: it describes how he got involved with mathematics, the problems he faced as a Jew in the old Soviet Union and his love of the subject. In order to convey this history, he also explains a great deal of mathematics, and particularly that associated with the Langlands programme, which aims to unify the different branches of the field. This mathematics is sophisticated (I will briefly present some later), yet Frenkel manages to give even relatively inexperienced readers a sense of it. In particular, he conveys that this material is interesting and important. While I was reading the book, I was also working on a fun but frankly non-important problem in mathematics. The contrast was striking!

The book – which is written in the first person – begins by describing some elementary particle physics and group theory and explaining how they relate to each other. After this comes the author's own tale. Frenkel was born in 1968 in what was then the Soviet Union, and he initially wanted to study physics. His mentor, Evgeny Evgenievich Petrov, converted him to mathematics, the subject in which he earned his PhD, but since his work is often related to physics it is not clear he really did switch. At such high levels it is hard (and not productive) to distinguish between the two.

As a young man, Frenkel was a brilliant mathematician, and if the Soviet Union had not practised a form of institutionalized antisemitism, he would have passed his exams and got into Moscow State University. But under the circumstances, such success was impossible no matter how well he performed. The examiners kept making the questions harder and harder, both in terms of their intellectual merit (he was still able to solve questions of this type) and in terms of stupid pedantics. As an example, Frenkel defined a circle as "the set of points equidistant from a point", but his examiners deemed this answer wrong since it should be "the set of *all* points equidistant from a point". Another way for Jews to be barred from school was to give them harder problems to solve. Often such problems had an easy solution that was hard to find, thus giving the appearance of fairness. (For more on this see "Jewish problems" by T Khovanova and A Radul, arXiv:1110.1556.)

Frenkel's experience was far from unique, and in his book he describes the ways in which many Jewish mathematicians, physicists and other scientists dealt with this system. Some of them met quasi-secretly and still managed to get much done, and it is tempting to wonder whether oppression got their creative juices flowing. However, this is a fallacy. We only read about those who managed to do well, and I am sure that many brilliant students were blocked from making contributions. Their biographies are not written.

At the heart of the book is Frenkel's description of the Langlands programme, which aims to build those "bridges" between different mathematical "continents". Here is an example. Let p be a natural (or "counting") number. If we restrict ourselves to the set of numbers $\{0,1,2\ldots,p-1\}$ then we can still add, subtract, and multiply if we "wrap around" back to the beginning. For example, if $p=13$, then $12+4=3$, which we denote as $12 + 4 \equiv 3 \pmod{13}$. Also note that $6 + 7 \equiv 0 \pmod{13}$, so we think of 7 as being $-6 \pmod{13}$. If p is a prime number, then we can also divide.

Now, let $f(x,y)$ be a cubic polynomial in two variables with integer coefficients, such as $f(x,y) = y^3 + y - x^3 - 2x^2$. If p is prime, we can ask how many pairs (a,b) with (a,b) included in the set $\{0,1,2 \ldots p-1\}$ exist such that $f(a,b) \equiv 0 \pmod{p}$. We denote this number as n_p. We can then form an infinite polynomial $p(x)$ where n_p is the coefficient of x^p. This infinite polynomial is then associated to a group of symmetries in the complex plane G called a modular form. The correspondence between $f(x,y)$ and its modular form is one-to-one and it preserves some properties; that is, every cubic equation maps to a modular form and every modular form maps to a cubic equation. This is an important connection.

What the Langlands programme does is essentially to take the notion of equation and generalize it, and also to take the notion of modular form and generalize that. The programme then makes conjectures about how these very general objects are related. Frenkel illustrates this connection-building process with several nice examples until, on page 222, he has a chart that connects number theory, Riemann surfaces (geometry) and quantum physics. Quantum physics? How did that get in there? Through gauge theory – a complicated notion that Frenkel (wisely) does not try to explain. However, having read the book, I now want to find out what it is.

It's a book to read to be *inspired* to learn maths

Frenkel claims that frequently, a branch of mathematics that was thought of as a pure abstraction ends up being applied to practical problems. I am often sceptical of such claims, since the (perhaps forgotten) origin of many mathematics problems is, in turn, some real-world application. However, the examples given here seem legitimate; to my eye, at least, number theory really does lack any apparent connection to the practicalities of quantum physics, yet the links are there. One is left with the impression that Frenkel and the other scholars who appear in the book (including Ed Witten, the only physicist to win a Field's Medal) are seriously brilliant people who are doing seriously brilliant work.

You do not need to know much mathematics to read this book, but you do need to like it. Depending on your level, you will get lost at some point (for me, it was the definition of a "sheaf"). However, this is not a book to read to learn maths. It's a book to read to be *inspired* to learn maths.

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Next month in Physics World

Disagreeing over big G
Physicists have attempted to measure the gravitational constant, or "big G", for over 200 years, but why is it that our results still wildly disagree?

Our wobbly galaxy
It is well known that the Milky Way rotates around a supermassive black hole at its centre, but a surprising recent discovery, which no-one can yet explain, is that it also undulates up and down

Fictional models
You don't have to model physical reality to derive a successful physical model, as James Clerk Maxwell showed with his electromagnetic field equations based on the idea of an ether of rotating vortices

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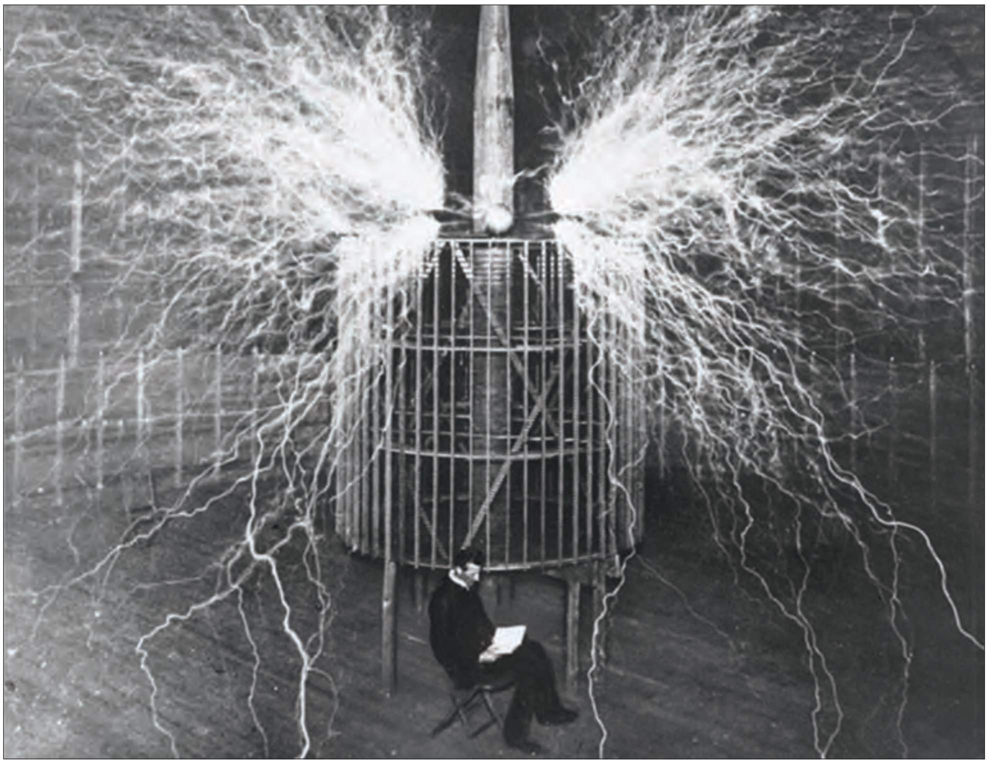
David Goodstein

Rise and fall of an electrical genius

Westinghouse



Electric effect
Nikola Tesla, in a promotional shot for Westinghouse Electric Company.

Tesla: Inventor of the Electrical Age
W Bernard Carlson
2013 Princeton University Press
£19.95/$29.95hb
520pp

The scientist and inventor Nikola Tesla was born in 1856 to Serbian parents living in the town of Smiljan, in what is now Croatia. Inspired by his mother, the young Tesla was an avid tinkerer who tried to build an airship when he was still a child. He also had an overly vivid imagination, and initially lived in the shadow of his older brother, Dane. After Dane was killed in an accident, seven-year-old Nikola was expected to follow in his father's footsteps and become a priest of the Serbian Orthodox Church. A few years later, however, Tesla fell seriously ill with cholera, and on his apparent deathbed he extracted from his father permission to pursue a technical education. He quickly got better.

Unfortunately, Tesla's subsequent history – his inventions of the two-phase electric motor and the Tesla coil (among other things), his long feud with Thomas Edison and his later slide into obscurity – is related unevenly in W Bernard Carlson's new biography. Although *Tesla: Inventor of the Electrical Age* starts out reasonably well, telling the story of Tesla's early life and early inventions, problems develop quickly.

The book's first sign of trouble follows Tesla's 1875 move to Graz, Austria. There, at the Joanneum Technical School, he received his first formal introduction to what was then known about electricity. It was in Graz that Tesla made his first attempts to invent an alternating-current (AC) motor, in contrast to the direct-current (DC) motors that were in use at the time. But Carlson's accounts of the technical details of Tesla's work are given in terms of Tesla's understanding rather than a modern view, and they are often difficult to follow in detail.

After Graz, Tesla continued his education in Prague, followed by Budapest. There he acquired a sidekick, Antal Szigeti, and had his first big idea: a rotating magnetic field in an AC motor. He and Szigeti then went to Paris, where they joined the company started by Edison, and Tesla learned the difference between his mental image of an AC motor and the problems associated with the real thing. In 1884 he moved again, this time to New York, where he worked at the Edison Machine Works. He developed an arc-lighting system there, but Edison was more interested in incandescent lighting, and the two soon parted ways.

In the years that followed, Tesla invented a series of electrical devices, including a thermoelectric motor and a pyromagnetic generator. His work attracted the attention of wealthy financiers as well as technologists; Alfred S Brown, superintendent of Western Union's New York Metropolitan District, backed him in this period, as did Charles F Peck, a lawyer from Englewood, New Jersey. With their help, Tesla developed the idea of a polyphase AC motor, which became his first big invention. He presented a lecture on his new motor to the American Institute of Electrical Engineers on 16 May 1888. It was a big hit, and afterwards he moved to Pittsburgh, where the entrepreneur and inventor George Westinghouse put him to work on improving his polyphase motor.

The Westinghouse Company built between 500 and 1000 Tesla motors, destined for use primarily in streetcars and mining machinery. Westinghouse also licensed Tesla's US patents for a polyphase AC induction motor and built huge power stations to supply these motors with electricity. Edison, for his part, built DC power stations and championed the use of DC, but Tesla's ideas were superior and won out in the end. It is curious that very little is said in this book about the epic struggle between Tesla's AC ideas and Edison's DC devices.

In any case, Tesla quit Westinghouse in 1889 and returned to New York, where Szigeti had been working all along. (As a side note, Szigeti may have been more than just Tesla's friend and assistant; Tesla had longstanding friendships with several men, Szigeti included, and Carlson speculates, without reaching a firm conclusion, that he was homosexual.) In New York, Tesla undertook to repeat the experiments of Heinrich Hertz, which had confirmed James Clerk Maxwell's prediction of electromagnetic waves. Fiddling with a Hertz-like apparatus for producing waves, he soon hit upon what became known as the Tesla coil – a machine that generated high-frequency, high-voltage signals at a low current. He began giving lectures in which he thrilled his public with high-power demonstrations of electrical effects.

Remarkably, he was seldom injured during these spectacular shows.

The apex of Tesla's career came in 1893, when the head of the effort to harness the power of Niagara Falls, Edward Dean Adams, awarded to Westinghouse the contract to build generators for the power plant. Adams' decision was influenced by Tesla's polyphase AC ideas, which he admired – albeit not enough to keep him from hedging his bets. Although Westinghouse got the power plant, its great rival, the Edison General Electric Company, was chosen to build the lines that would transmit the power to Buffalo, New York, 20 miles away.

"The success of the project at Niagara Falls," Carlson writes, "cemented Tesla's reputation as one of America's leading inventors." But after his Niagara triumph, Tesla's long descent into obscurity began, and unfortunately Carlson's book descends with him.

Tesla's principal invention of this later period was a scheme to send information and power worldwide by means of waves in the Earth: not the radio waves of his rival Guglielmo Marconi, but underground standing waves generated by huge devices. However, Tesla was never quite able to finance the construction of these devices, and in the book we learn of his increasingly desperate attempts to raise funds to support this and other "inventions" – all of them apparently unsuccessful.

It is curious that very little is said about the epic struggle between Tesla and Edison

Carlson sees Tesla's information-transmission "invention" as anticipating the World Wide Web, and says there are individuals even today investigating whether Tesla's ideas might work. But as even Carlson admits, there is a "disjunction between what Tesla thought…and how the Earth actually functions". Disjunction, indeed: this idea, like many of Tesla's schemes, was pure fantasy.

Initially, Carlson is somewhat sceptical of Tesla's wilder notions. In the end, though, he is dragged along by Tesla's magic, and the second half of his book suffers for it, sliding off into the sort of nonsense that Tesla's die-hard fans (and there are a lot of them out there) really love. This is a pity, because Tesla did have some very good ideas, especially early on. All told, this is not a very good book.

David Goodstein is a physicist emeritus at the California Institute of Technology, US, e-mail dg@caltech.edu

Web life: *Space Politics*

URL: www.spacepolitics.com

So what is this site about?

As all space scientists know, getting astronauts to the International Space Station or robots to another planet requires more than just technical know-how. It also requires money. And if you want money, it is a truth universally acknowledged that, sooner or later, you're going to need to deal with politics. This is where the *Space Politics* blog comes in. Under the tagline "Because sometimes, the most important orbit is the Beltway" – a reference to the ring road that encircles Washington, DC – it offers regularly updated, detailed information about funding, changes to mission timetables and other workings of government that relate to space exploration.

Who is behind it?

Space Politics is the work of Jeff Foust, a journalist and aerospace analyst based in Maryland, US. This isn't his only project, though: in addition he writes the blog *NewSpace Journal* (www.personalspaceflight.info), which is dedicated to the space industry's growing entrepreneurial wing, and edits a weekly online magazine called *The Space Review* (www.thespacereview.com). Oh yes, and he also freelances for other people's space-related publications and works as an aerospace analyst at a management-consultancy firm. All three of Foust's space websites are updated with remarkable regularity, and somehow, he still finds time to write a blog about his favourite baseball team, the Washington Nationals. Impressive.

Who is it aimed at?

Although Foust writes clearly in plain English, without too much jargon, you will need to be reasonably familiar with the ins and outs of House and Senate space sub-committees, Congressional Budget Office reports and NASA review panels to understand the importance of the issues that *Space Politics* covers. And as you may have guessed already, the blog is very US-centric. You won't find much detailed information here about the internal workings of the European Space Agency, JAXA or the Russian, Indian and Chinese space programmes, although Foust does occasionally report on their activities as they relate to America's.

Why should I visit?

Funding policy is one of those topics that can seem really boring – right up to the point when it starts to affect something you care about, whereupon it suddenly becomes *very* interesting. (Kind of like insurance and pensions, then.) Not many people have the patience or the interest to trawl through the minutiae of who said what in yesterday's meeting of this or that minor committee, but as Foust's blog demonstrates, this stuff can be hugely important. A good example comes from a post in November 2013 about a report by the planetary science sub-committee of the NASA Advisory Council. Among other things, this report revealed that budgetary constraints may force NASA to choose between two of its highest-profile missions: the Saturn-circling Cassini and the Mars-roving Curiosity. Ouch.

Can you give me a sample quote?

While attending a conference of the American Institute of Aeronautics and Astronautics in early autumn 2013, Foust wrote about the effects of continued budget uncertainty on the US space community. "'How many of you know what your budget is going to be next year? Raise your hand,' said Larry James, a retired Air Force lieutenant general and the new deputy director of JPL… As you might expect, effectively no-one in the audience of several hundred space professionals did. That uncertainty about civil and military space budgets as fiscal year 2014 approaches was a recurring theme at the conference yesterday, where government and industry officials emphasized the 'changing landscape' of the industry and the need for innovation. With NASA expected to at least start the fiscal year next month under a continuing resolution (CR), one that could potentially be extended for the full year (just yesterday the chairman of the House Appropriations Committee introduced a CR that runs through 15 December), plus the prospects of another round of across-the-board cuts triggered by sequestration, few at the conference expressed a lot of optimism about the agency's fiscal situation."

Between the lines: film special


NASA

In space no-one can hear you scream
The (fictional) film *Gravity* depicts a NASA mission to the Hubble Space Telescope that goes horribly wrong.

The right stuff

Physics World is arguably a little late to join the critical love-fest for *Gravity*. Alfonso Cuarón's space-adventure film opened in the US in October 2013 and, despite achieving considerable box-office success on both sides of the Atlantic, its days in cinemas may well be numbered by the time this review is published. But if it is still showing in your area, and you haven't yet seen it, take our better-late-than-never advice: go. In fact, go now. You can read the rest of this review later (it's got spoilers anyway). As the film opens, its stars – Sandra Bullock as a scientist and first-time astronaut; George Clooney as an old-school space veteran – are performing a spacewalk as they carry out a routine upgrade to the Hubble Space Telescope. But after the briefest of introductory scenes, Houston informs them that they have a problem: a huge cloud of debris from a failed Russian satellite is hurtling towards them, punching holes in everything in its path. What follows is essentially an astronaut's vision of hell, as Bullock's character – cut adrift from her damaged shuttle and out of contact with Mission Control – struggles through fire, water and a pitiless shortage of air in her efforts to return to Earth. The special effects required to create such sequences are impressive but not perfect, and for many physicist viewers, part of the fun will come from spotting moments when astronauts or pieces of debris behave in unphysical ways. But we suggest saving such analysis for a second viewing. What makes Cuarón's film great is not just its special effects, but the way he and the actors use sparse dialogue and a bleak, expansive setting to create a curiously intimate-seeming film. Bullock, in particular, is fantastic in her role as a scientific everywoman, and while it is hard to believe that the real-life NASA would send an astronaut into space who had crashed the Soyuz simulator every time, her personal journey is realistic and never overdone.

● 2013 Esperanto Filmoj/ Heyday Films/Warner Bros, http://gravitymovie.warnerbros.com

Inside the LHC

Particle Fever, a new documentary film by Mark Levinson and the theoretical physicist David Kaplan, lifts the lid on the inner workings of CERN as scientists there wrestle with the twin challenges of installing and running the Large Hadron Collider and using it to search for the Higgs boson. From a purely educational perspective, professional physicists are unlikely to learn much from this film about the theoretical and experimental science that underpins the work at CERN. However, the film does work well as a layman's introduction to concepts such as multiverse theory, supersymmetry, the Standard Model and the cosmological constant – largely as a result of the deft use of smooth graphics, coupled with clear and concise explanations from the scientists involved and jaw-dropping footage of the collider itself. But education was never the main point of a film that, above all else, is most successful as a sometimes revealing portrait of the working lives of the men and women caught in the glare of the global media spotlight. By following the inside story of six scientists – including Fabiola Gianotti and Savas Dimopoulos as well as Kaplan himself – it also provides a unique insight into the dogged tenacity required to endure the triumphs and disappointments involved in such large-scale and high-publicity experiments. As Dimopoulos says, in particle physics "jumping from failure to failure with undiminished enthusiasm is the big secret to success".

● 2013 Anthos Media, http://particlefever.com

Hawking on film

Great books often get made into mediocre films, but every so often, the reverse is true. Such is the case with *Hawking*, a candid biopic of the University of Cambridge cosmologist that stands head and shoulders above its subject's own recently published memoir (December 2013 pp32–33). Hawking is credited as one of the film's writers (the others are Ben Bowie and director Stephen Finnegan), and he provides much of its narration. Crucially, though, we also see footage from interviews with his sister Mary, his friends, students, nurses and even his ex-wife Jane. Their reminiscences combine to give us a much more complete picture of Hawking's life and personality, and the camera's sympathetic eye sees much that would be difficult to get across in words. It is one thing to read in Hawking's memoir that his first electric wheelchair "gave [him] a considerable degree of independence", but it is quite another to watch footage of him chasing his young son around the garden in it. It is also interesting to hear Peter Guzzardi, who edited Hawking's bestselling popular book *A Brief History of Time*, say that he was "really disappointed" with its first draft. The fact that Hawking was both determined and willing to completely rewrite it – despite being interrupted by a major health crisis – says much about the man whom his friend and colleague Kip Thorne calls "the most stubborn person I've ever met".

● 2013 Vertigo Films, www.hawkingfilm.com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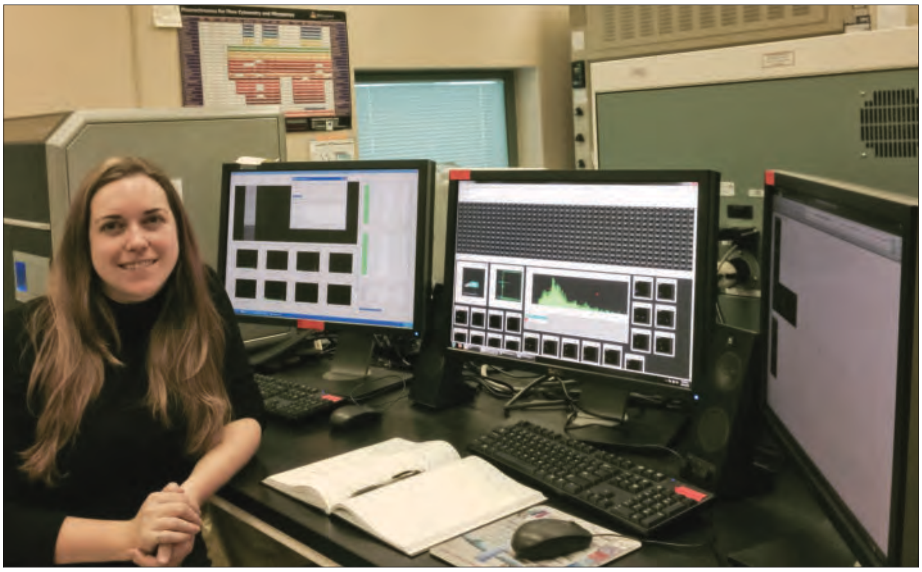
Careers

From astronauts to cancer patients

A career in radiation physics offers plenty of variety and the chance to solve problems that directly affect patient care, as **Lindsay Beaton-Green** explains



Health Canada

Caring physics Lindsay Beaton-Green enjoys being able to apply her physics training to patient care.

Exposure to ionizing radiation can happen in several different contexts. People undergoing radiotherapy treatments for cancer are exposed to such radiation, as are astronauts on lengthy spaceflights and, of course, there is always the possibility of people receiving a dose as a result of radiological or nuclear events such as the reactor meltdowns at Chernobyl and Fukushima. As a radiobiologist in Health Canada's Consumer and Clinical Radiation Protection Bureau, I have worked on projects related to all three of these contexts, building on work that I did during my PhD at Carleton University in Ottawa, Canada.

Early on, I could not have predicted that I would end up working in radiation physics. I enjoyed many different subjects at school and had an affinity for both calculus and physics, but when I was an undergraduate at Carleton, I thought that I would likely go into optical engineering. Then, as I was completing my undergraduate degree in engineering physics, I was introduced to the world of medical physics. The idea that I could work in an area of physics with strong ties to the medical field fascinated me. I loved the idea that projects could be so closely related to patient care, and when I spoke with my professors at Carleton about applying to the university's graduate programme in medical physics, they were very encouraging.

When it was time to choose what to specialize in for my graduate thesis, I was quickly persuaded to focus on radiobiology thanks to the passion and excitement of Ruth Wilkins, who became my adviser. An adjunct professor at Carleton, Wilkins is also affiliated with Health Canada, the government department responsible for public health, and for my PhD thesis project, she guided me towards a Health Canada project on radiosensitivity among men being treated for prostate cancer. Patients who are radiosensitive exhibit severe side effects long after their radiation treatments are complete and, ideally, we would like to be able to predict someone's sensitivity before they receive treatment. Tests for radiosensitivity would need to be simple enough to be completed within the pre-treatment planning time, typically 1–2 weeks, and using a blood sample instead of a biopsy would be less invasive for the patient. By using a "case-control" study, in which patients had already been identified as sensitive or not, we found measurable "endpoints" – for example, the speed of the cell cycle or the amount of stable damage – that showed new and promising results, and also helped to further validate existing results that measured similar endpoints.

A range of projects

While working on my PhD, I also became involved with other radiobiology projects at Health Canada. One such project was to analyse the blood samples of astronauts to see if they had experienced long-lasting radiation damage following long-term space flights. Exposure to cosmic radiation is a concern for astronauts because the DNA alterations caused by such radiation can produce stable, long-lasting chromosome damage, which may pose a risk to the astronaut's health. By using fluorescence microscopy and image analysis, it is possible to compare damage in the cells of astronauts before and after their flights, and use that information to make an estimate of the dose received while in flight.

Another project I worked on was related to the development and validation of rapid biodosimetry methods. In the event of a radiological emergency, rapid biodosimetry is needed to help determine who was exposed to high enough levels of radiation to require medical intervention. In order to be prepared for such an emergency, Health Canada conducts annual exercises and continues to improve on current methods, while also developing and validating faster methods that employ new technologies.

After I finished my PhD, I was lucky enough to be offered a job with Health Canada as a full-time employee. This meant that, in addition to working on other interesting projects, I have been able to continue the research I did for my PhD. At the moment, I am working to validate the results I found in different patient cohorts to find out if they are general biomarkers of patient sensitivity. To do this, we are revisiting the prostate cancer patients, as well as new patient cohorts (such as breast cancer patients) to see if the same measurable differences between the sensitive and non-sensitive patients can be found. In addition, these results still need to be tested in a predictive study, which is a long-term project that we hope to get started, and will likely involve collaborations with other radiobiology laboratories.

The need for curiosity

The aspect of medical physics I like best is that it requires you to apply many different skills. For example, my work involves a variety of sophisticated equipment, from using high-powered microscopes and flow cytometers (instruments that use laser optics, fluidics and electronics to make multiple measurements of single cells as they pass a point of interrogation), to modelling and calibrating different irradiation exposure systems such as X-ray machines and alpha-radiation exposure systems. Working with these advanced specialized technologies requires a certain amount of technical aptitude and in a field that touches on physics, engineering, biology and medicine, being able to learn new things quickly is also an asset. An understanding of programming is important, and image-analysis skills are increasingly crucial.

There are also some key general skills needed for a career in research, such as a sense of curiosity. It is important to keep asking questions, such as "What does this result imply?" or "How does it fit in with what we already know?" as well as "What's next?" and "How can I take this experimental result and use it to make a difference?" These are questions my colleagues and I ask ourselves often, and puzzling through them makes for rewarding days at the lab.

> Working with advanced specialized technologies requires technical aptitude, and being able to learn new things quickly is an asset

Research projects and method development can require long and painstaking effort, and working with patient samples also means it can be very unpredictable. Hence, patience and an ability to see the bigger picture are helpful skills, too. However, there are always new and interesting problems to solve, and with a background in physics, I feel I am able to apply my analytical skills to fun, challenging puzzles. I really enjoy the variety of projects, and there is a level of satisfaction that comes when you can combine the experimental work with the analysis and presentation of the results.

Some of my favourite moments have come from attending and presenting my work at regional and international conferences. It is exciting to find yourself surrounded by a network of scientists who are passionate and inspiring, and sometimes you encounter opportunities for interesting collaborations with other research groups. I can't emphasize enough how important it is to surround yourself with interesting people. Asking questions and getting involved with groups that have common interests has led me to many exciting opportunities and projects, and I look forward to where it will take me next.

Lindsay Beaton-Green is a radiobiologist in the Consumer and Clinical Radiation Protection Bureau at Health Canada, e-mail lindsay.beaton@hc-sc.gc.ca

Careers and people

Spotlight on: Oliver Kraft

KIT

The election of Oliver Kraft as the new president of the Materials Research Society (MRS) represents a new direction for the 40-year-old professional body. Although nearly half of the MRS's 16 400 members are based outside the US, Kraft, a researcher at Germany's Karlsruhe Institute of Technology (KIT), will be the first non-American to lead the organization since its founding in 1973.

After earning his PhD in materials science from the University of Stuttgart in 1995, Kraft spent a year at Stanford University in the US, working as a postdoctoral fellow in the laboratory of William Nix. He then returned to Stuttgart, this time as the head of a group at the Max Planck Institute for Metals Research, where his research involved investigating deformation mechanisms in thin metal layers. In 2002 he moved to his current position at the KIT, where he directs the 70-strong Institute for Applied Materials.

Movers and shakers

Five firms have received Innovation Awards from the Institute of Physics (publishers of *Physics World*). Laser-systems manufacturer **Coherent Scotland**, radiotherapy firm **Elekta**, computer-modelling specialists **Simpleware**, pipeline technologies firm **Tracerco** and wind-farm diagnostics experts **ZephIR** were honoured for developing and successfully marketing new physics-based technologies.

Canada's Perimeter Institute for Theoretical Physics has named mathematical physicist **Kevin Costello** as the first holder of its Krembil Foundation William Rowan Hamilton Chair in theoretical physics. A second new post, the Galileo Galilei Chair in theoretical physics, went to mathematician **Davide Gaiotto**.

Two US physicists who are "transforming the way science is taught" have had their efforts recognized by the Carnegie Foundation for the Advancement of Teaching. **Gintaras Duda** of Creighton University and **Steven Pollock** of the University of Colorado at Boulder were among four scholars named as the foundation's "Professors of the Year" for 2013.

The UK nanodiagnostics firm **Endomagnetics** – which was spun out from the physics departments of University College London and the University of Houston in 2007 – has won the inaugural Nanomedicine Award from the Europe-wide organization ETP Nanomedicine.

Four physicists will share the American Physical Society's 2013 John Dawson Award for Excellence in Plasma Physics Research. **John Ferron**, **Thomas Osborne** and **Philip Snyder** of the US firm General Atomics and **Howard Wilson** of the University of York, UK were honoured for their theoretical and experimental work on high-performance tokamak plasmas.

High-energy physicist **Valerie Gibson** from the University of Cambridge, UK, has won the Women in Science and Engineering (WISE) Leader Award.

Daniel Kleppner, an emeritus professor of physics at the Massachusetts Institute of Technology, US, has won the Franklin Institute's Benjamin Franklin Medal in Physics for his research on the behaviour of atoms at ultralow temperatures.

Optical physicist **Martin Lavery** of the University of Glasgow is among six UK-based researchers named as winners of the 2013 Scopus Young Researcher Award.

Mathematical physicist **Oliver Rinne** of the Albert Einstein Institute in Potsdam, Germany, has won the €10 000 von Kaven Award for Mathematics for his work on black holes.

Darach Watson of the University of Copenhagen, Denmark, has received the Lundbeck Foundation Research Prize for Young Scientists for developing a method that uses light from quasars to measure distances in the universe.

Once a physicist: Dara Ó Briain

Dara Ó Briain is an Irish comedian and television presenter

How did you get interested in physics?
When I was 14 there was a teacher in our school who decided to go off-piste on the course and start dropping in the odd thing about relativity and the shape of the universe and all that. At that age he was throwing seed onto ground that was ready to grow, and it was suddenly very exciting. At that point I discovered John Gribbin's *In Search of Schrödinger's Cat* and then found myself reading all these science popularizations. Physics got me at that age where it gets people.

How did you get from there to comedy?
I decided that what I wanted to do was be a physicist, but then I went to university and it was painfully difficult – I did theoretical physics and mathematics, so I chose as obscure and difficult an area as I could get. But you know, the problem actually wasn't that it was difficult – it was that it moved away from stuff that required any physical intuition at all. It was training me to be a mathematical physicist, and therefore I had to do a lot of Fourier transforms and different types of equations and that was a long way from the fun results that drew me in. And I suddenly found myself, by contrast, running off to stand in front of crowds and tell jokes, and the lure of that drew me away. This is what happens occasionally – you find yourself with other passions.

You've come back to physics in recent years by putting more science in your comedy. What's that been like?
As I continued in my showbiz career, physics was always at the background and an ongoing passion. It took me a while to get over the difficulty of learning how to do it professionally – the techniques you need to actually be a proper grown-up mathematical physicist – so that I could go back to the results, which are so beautiful and appealing. But I started to put more jokes about science in about 10 years ago, and I had the confidence that the audience would come with me. Around the same time, some other people – Ben Goldacre writing *Bad Science*, Robin Ince doing his gigs – also came to this kind of thing, and because of the Internet we sort of found each other a bit. I did a chat show in Dublin that I invited Ben Goldacre to be a guest on, for example. So we found ourselves fighting this sort of sceptic/rationalist battle and it began to get noticed that this was the sort of thing for which I had a passion. Initially I was asked to do an episode of *Horizon* with Brian Cox, but I was unavailable for that, so I ended up instead doing *Stargazing Live* because it was felt that, with Brian being a scientist, he would do the science and they needed a professional broadcaster doing the live TV. Everything else came from that.

Have you ever told a science joke that your audience didn't get?
Not yet, no, but I'm getting quite good at introducing them.

What's been the best thing about getting back to the scientific part of your mindset?
To be honest, it's been a complete pleasure the entire way through. I know there are some people who try to parlay a successful showbiz career into marrying a popstar (who they then divorce six months later) or hanging out with models, or whatever – I have parlayed it into hanging out with scientists and chatting about physics, and it has been just a pleasure. Recently we were filming for *Stargazing Live*, and we did a three-day filming trip that involved seeing a rocket take off, then going on a zero-gravity flight, then going in a centrifuge – so in the course of whatever number of hours, I went from zero *g* to 5 *g* – and I'm like a kid doing these things. It's great. It's been a joy.

What would be your advice to someone who's struggling their way through mathematical physics, like you did?
I would be loath to offer advice because of the slightly unusual circumstances I had: I was finding that the course was becoming very, very technical at a point where I was getting a much more visceral thrill from standing in front of an audience. That might not be the case for other people. But one thing that was interesting was that at the end of the degree, it suddenly came back around to really cool results again. When you study quantum mechanics, the quantum mechanics you study is not fun. It is all dense statistical notations for things, and relativity also seems like that for a long time – but then all of a sudden, there is a black hole. And you go "Wow, fantastic, I've actually solved the Schwartzchild solution and found a singularity!" and suddenly it seems like, great, now this makes sense. But a huge amount of it can be difficult. You cannot see the wood for the trees, all you see is trees, and the trees are just lots and lots of problem sheets about very obscure things. And that's tough. But the beautiful results are still out there, and it's just a case of bearing with it until they re-emerge.

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A short history of radar in Norwegian

When I introduce myself to a new group of students, I often tell them that, although my qualifications are all in physics, I have spent my whole working life on radar. Sometimes I also tell them that, thanks to a recent upheaval in my life, I now live in the town of Hammerfest, in the far north of Norway. Whenever that happens, my students usually have as many questions for me about the consequences of living at 71° north as they do on the lecture topic.

But this isn't the only way in which my academic interests and Arctic location come together. I am learning Norwegian, you see. This isn't a matter of picking up a few useful phrases to trot out to impress the locals during your two-week summer holiday. No, Norwegian is becoming my everyday language and I need to be proficient just to get on with life. Since I have just turned 50 I have come to the conclusion that learning Norwegian – or any other language for that matter – is a young person's game, and I salute all the foreign students at UK universities, all the speakers at international conferences and all the other people I have met who so readily and capably converse in English rather than their mother tongue.

But what does learning a new language have to do with radar? Well, from time to time I have dabbled in the murky world of electronic warfare. The whole subject of signal intercept intrigues me, and my interest also extends to the design of radar waveforms and the associated signal-processing methods employed to get useful target information out of them. Some radar waveforms are designed to be exceptionally difficult for an enemy intercept receiver to detect – what's known as Low Probability of Intercept (LPI) radar. Allied to this is the concept that even if a radar signal is detected, it should impart no useful information to the intercept receiver – Low Probability of Exploitation (LPE) radar.

Many LPI waveforms are very wideband phase or frequency modulated and/or employ frequency-hopping techniques with very long coding sequences. Some of the better coding techniques *appear* random and give rise to noise-like spectra with very low spectral power densities. A radar that sends out signals coded in this fashion can process received signals of the same type because it has a filter "matched" to the signal's waveform via an autocorrelation process. In essence, the radar can detect very weak returning signals because it "knows" what signal it sent out – and hence what to expect on reception – and this makes it possible to design the optimal filter (a matched correlator) in the receiver and thus achieve the best signal-to-noise ratio upon reception. In contrast, an intercept receiver cannot anticipate what to expect, so it cannot do the processing required to extract signals from background noise. It can only detect a signal on the basis of its peak power being somewhat above the local noise within the receiver.

Okay, that's enough radar theory for now. Let's get back to Norway. It is a myth to think of Norwegian as just one language; there are in fact two official forms of Norwegian, plus hundreds of regional (sometimes highly localized) dialects. I learned Bokmål, one of the official written forms, but now, perhaps inevitably, I find myself in an area with a quite different dialect that more closely resembles the other official form, Nynorsk.

Alta/Vardfjell/NORAP/Avinor

My mind learned to construct matched correlators that would be triggered by the appropriate word

In the early days, I had extreme difficulty in understanding what was said to me. I had to analyse each sound, piece them all together and then rake through my memory banks to see if I recognized words. This was a slow and painstaking process with unreliable results. I often confused similar-sounding words, leading to misunderstandings that were frustrating but often quite hilarious. In short, I was an intercept receiver with no correlator trying to make sense of a Low Probability of Exploitation Norwegian. At full speed, Norwegian was a total mystery and my mind treated it simply as noise.

In time, I started to recognize words. It was as if my mind had learned to construct matched correlators that would be triggered by the appropriate word. (I understand that speech recognition is described in similar terms.) But then, native Norwegians upped the ante: they responded to my increased understanding by introducing more dialect (unknown coding sequences) and by using voice intonation (frequency modulation), faster speech (wider bandwidth/higher data rates) and colloquial phrases (waveforms of unknown purpose). By golly, they know a thing or two about LPI/LPE waveforms around here!

Gradually, my mind is constructing more correlators, and I even have a few longer-sequence correlators that can recognize whole phrases in an instant. The data rate can still be problematic, with fast speech leading to missed segments, and I still need to add to the bank of correlators (expand my vocabulary). However, I can often understand slow, clear speech, since the bandwidth is low and the signal-to-noise ratio high.

In an age when scientists and engineers (including radar engineers) are turning towards the natural world for inspiration to solve technical problems, it is interesting to reflect on the parallels between signal intercept and learning a new language. Both have become a significant feature of my life. Like radar theory and Norwegian, the natural beauty of the seasons and the landscape of the far north are truly inspirational – but it takes a degree of patience to appreciate them.

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