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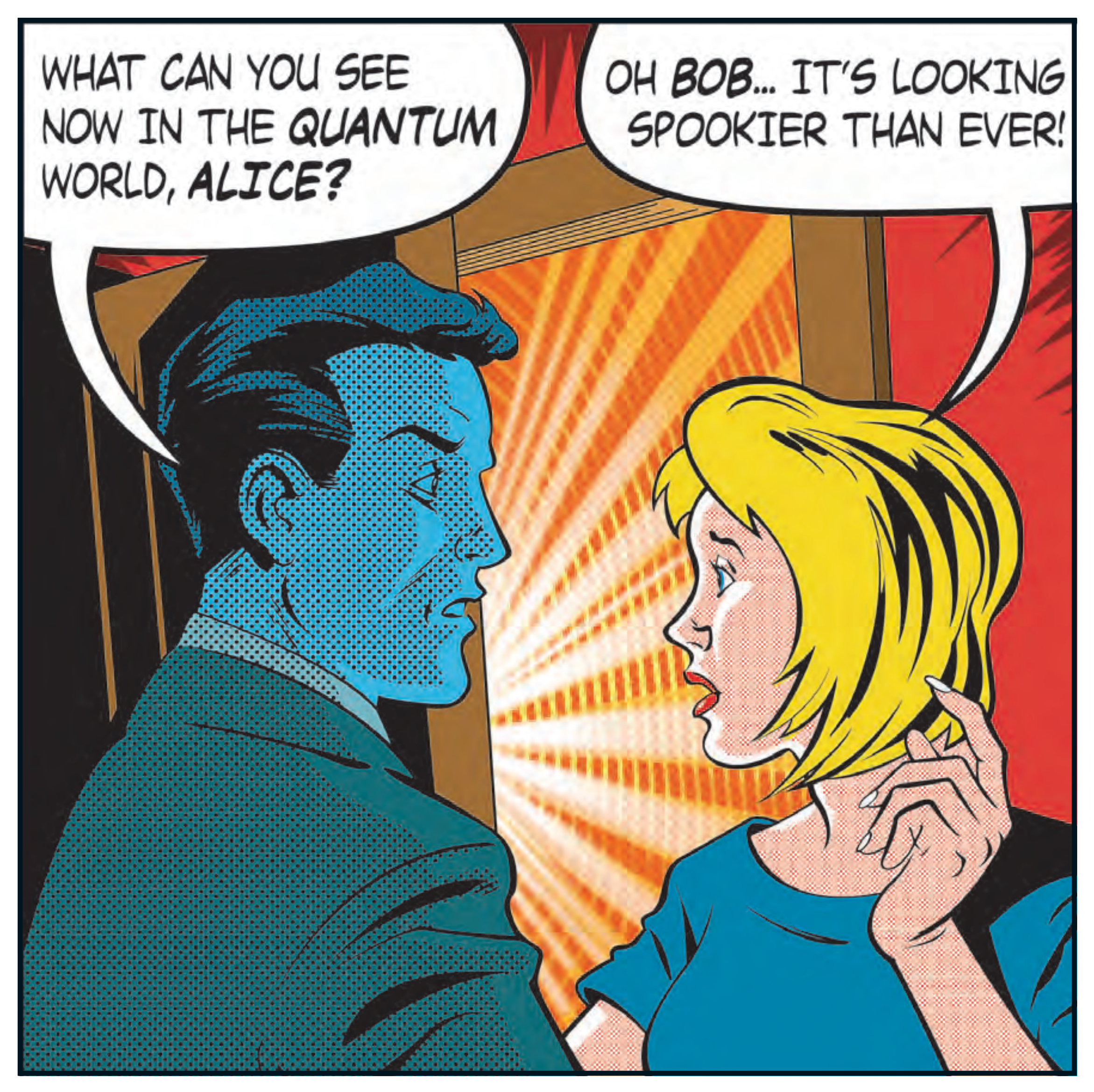

Quantum frontiers

Peering into an ever weirder world

physicsworld

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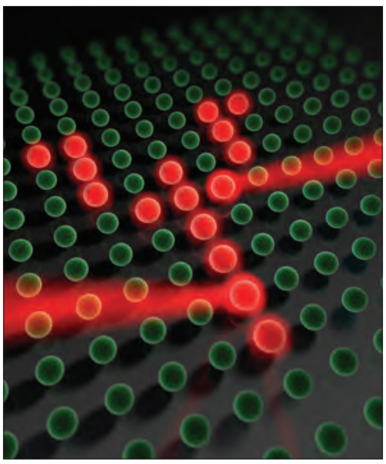
Random universe? – a quantum problem 29

I Bloch, MPQ



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Quanta

For the record

Graphene is just a bambina

University of Manchester physicist **Andre Geim** *quoted in the* Financial Times

Although graphene is expected to transform a range of industries such as electronics, aerospace and energy, Geim says it could take another 40 years before the material makes it into consumer products.

Solving string theory won't tell us how humanity was born

Harvard University physicist **Lisa Randall** *speaking to* New Scientist

Randall admits to not thinking about a theory of everything when doing research, adding that the idea we will ever get one "is a bit challenging".

It is so distressing that even Stephen Hawking gets more attention for his views on space aliens than his views on nuclear weapons

Lawrence Krauss *from Arizona State University writing in the* New York Times

Krauss warns that scientists' voices are not being heard in debates over climate change and nuclear proliferation.

I don't want everything to be clear – I want to confuse people a little so that they go away and read a book

University of Manchester physicist **Brian Cox** *quoted in the* Daily Telegraph

Cox says that he tried to get more physics into his new TV series – *Wonders of Life* – but the production team wanted the programme to be accessible to a wider audience.

Physics has been fortunate in recent years to have benefited from gifted TV presenters, firing the beauty of the subject direct into people's living rooms

Peter Knight, *president of the Institute of Physics, quoted in the* Daily Telegraph

Knight says physics has benefited from its "geek-chic" image, helped by the likes of Brian Cox.

Each wheel has its own personality

Charlie Sobeck *from NASA's Ames Research Centre, quoted in* New Scientist

NASA put its Kepler mission on standby for 10 days in January so that one of its "reaction wheels", which control the probe's motion along an axis, could recover after being overworked.

Seen and heard

Emily Baird

Stars in their eyes

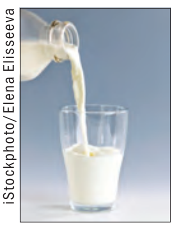
Here is one little creature that didn't make it into our recent special issue on animal physics. The dung beetle apparently uses both the Sun and the Moon to orientate itself as it rolls its balls of muck along the ground. But the big mystery in the dung-beetle world was why the insect can still navigate when the Moon is absent from the night's sky. Biologist Marie Dacke and colleagues at the University of Lund in Sweden have now shown that dung beetles actually use the Milky Way to orientate themselves. The researchers came to this surprising conclusion after putting dung beetles in the Johannesburg Planetarium in South Africa and then simulating the night sky, which showed that the insects use the light from stars to move in a straight path. So is that dung beetles sorted then? Not quite. "They still offer many more riddles waiting to be solved," Dacke reckons.

Snow patrol

You might not think the World Economic Forum in Davos would have particle physics high on its agenda, but it was the talking point at this year's annual shindig of political and business elites in the Swiss Alps. Punters at Davos were particularly drawn to CERN boss Rolf-Dieter Heuer's talk about how the lab's management structure could be applied to organizations such as the International Monetary Fund and the European Central Bank. "The international realpolitik of Davos has more in common with the quantum worlds, where subatomic particles can occupy different sates simultaneously," says Anne Richards, chief investment officer at Aberdeen Asset Management who had a three-year spell as a CERN research fellow in the 1980s. However, the rarefied Alpine air probably went a bit to Heuer's head as he offered this analogy of the Higgs boson to the Associated Press. "Suppose the Higgs boson is a special snowflake, so you have to identify the snowflakes, in a big snowstorm, in front of a background of snowfields," he mused. "That is very difficult. You need a tremendous amount of snowfall in order to identify the snowflakes." Maybe stick to those CERN management structures, Rolf.

The genius behind dark matter

It seems that US rapper GZA (also known to his fans as The Genius) has taken to physics. A founding member of hip-hop legends the Wu-Tang Clan, GZA is putting the finishing touches to his new album *Dark Matter* – a record he says is partially inspired by quantum physics. GZA (real name Gary Grice) apparently got the idea for the album on a visit to Harvard University's science centre and has even teamed up with Columbia University education expert Christopher Emdin to create "science genius battles" – a programme fusing hip-hop and science to help make physics more accessible to students. Get ready for a whole new wave of physics-based raps.



iStockphoto/Elena Elisseeva

More milk, more prizes

First came the surprising conclusion that chocolate consumption can increase a nation's chance of producing Nobel prize winners (see January p3). Now Sarah Linthwaite from Gloucestershire Royal Hospital in the UK claims that it is actually milk consumption that is the key (*Pract. Neurol.* **13** 63). Linthwaite found what she says is a positive correlation between milk consumption and the number of Nobel prizes per capita. Sweden tops the list, getting through 340 kg of milk every year per person (and has the most Nobel laureates per capita) whereas China only consumes around 25 kg per person every year (and has the fewest laureates per head). "So to improve your chances of winning Nobel prizes," the authors conclude, "you should not only eat more chocolate but perhaps drink milk too; or strive for synergy with hot chocolate."

When two become one

And finally, we couldn't resist bringing you details of Destiny's Child's latest compilation *Love Songs*, which includes the new song "Nuclear". "When the two become one on a quantum level," Beyoncé, Kelly and Michelle sing, "it's nuclear. With you here, we both heat up." Maybe it should have been a duet for Alice and Bob?

Frontiers

In brief

Diamond downsizes MRI and NMR
Magnetic-resonance-imaging technology has been shrunk to the nanoscale by two independent teams of researchers in Germany and the US, so that molecular samples just a few cubic nanometres in volume can now be detected and imaged at room temperature. Both groups used nitrogen-vacancy (NV) defects in diamonds as magnetic-field sensors to probe such minute samples. NV defects occur when two neighbouring carbon atoms in diamonds are replaced by a nitrogen atom and an empty lattice site. NV sites are capable of detecting the very weak oscillatory magnetic fields that come from the spins of protons in a sample. Apart from being able to resolve a single atom at room temperature, the technique could be used as a polarizing agent for traditional NMR and could also help the nanotechnology community image tiny devices (*Science* **339** 557; **339** 561).

'Just add water' for hydrogen on demand
Silicon nanoparticles could be used to produce hydrogen almost instantly, as they react with water, according to researchers in the US. The reaction does not require any heat, light or electricity and the hydrogen generated could be used to power small fuel cells. In essence, the technique recovers some of the energy that goes into refining the silicon and producing the nanoparticles in the first place. Thanks to their high surface-to-volume ratio, the nanoparticles should naturally generate hydrogen much more quickly than bulk silicon. The advantage of silicon is that it is abundant on our planet, has a high energy density and does not release any carbon dioxide when it reacts with water. The researchers have already successfully tested their technique in a small fuel cell that they used to power a fan (*Nano Lett.* 10.1021/nl304680w).

Stored photons interact in atom cloud
Physicists in the UK have come up with a new way of storing a handful of photons in an ultracold atomic gas, in which strong interactions between neighbouring photons can be switched on and off using microwaves. Once stored, the photons can be made to interact strongly, before being released again. An important feature of the technique is that it uses microwaves, which are also used to control some types of stationary qubit. The team believes that the technique could be used to create optical logic gates in which single photons could be processed one at a time. The method could also prove useful for connecting quantum-computing devices based on different technologies (arXiv:1207.6007v3).

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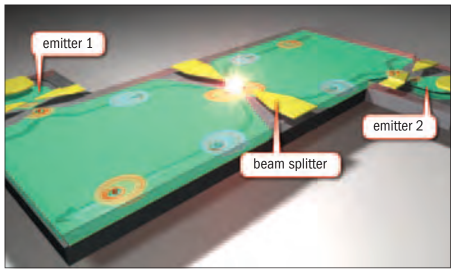
Emitting indistinguishable electrons



Coherent beams A chip off the semiconductor dot.

A new method to produce indistinguishable and coherent electrons has been developed by scientists in France. They have used it to make a small, electron-emitting chip that can produce two single electrons emitted from different sources that are in the same quantum state. This is a key step in developing electron-based quantum-information-processing techniques.

Electrons are fermions and so must obey Pauli's exclusion principle, which prevents identical fermions from occupying the same state, and so leads to anticorrelations or "antibunching". Erwann Bocquillon and Gwendal Fève at the Ecole Normale Supérieure in Paris and Lyon, along with colleagues from the Laboratory for Photonics and Nanostructures, Paris, wanted to see if indistinguishable electrons could be generated by independent sources. But as there are many electrons in any system, and they all interfere with each other and with the environment, making coherent electron beams is difficult.

The researchers' electron-emitting chip (pictured) was built using a "very clean" micron-sized bulk-semiconductor sample in which the electrons propagate in straight lines for several microns in 2D before being scattered, limiting their interactions. A strong magnetic field is then used to further restrict the movement of the electrons to only 1D so that single electrons may be guided to each of the emitters. By applying a voltage pulse to metallic electrodes deposited on top of the emitters, the researchers trigger the emission of a single electron to an electronic beamsplitter that is made up of two input and two output arms. Fève says that their sample is capable of emitting billions of single electrons per second – one electron per nanosecond.

"The two sources are perfectly synchronized such that both particles arrive simultaneously on the splitter and perfect antibunching occurs, meaning the two electrons always exit in different outputs," explains Fève. That means that the two electrons, generated by the two identical, synchronized emitters would arrive simultaneously at the two input arms of the splitter and would always emerge in two distinct outputs, obeying Pauli's principle.

But Fève is quick to point out that while the team did achieve a high degree of indistinguishability, some minimal environmental interaction did occur. The team is looking at making its sample even smaller so that the electrons travel even shorter distances, while keeping in mind the effects of temperature at such sizes (*Science* 10.1126/science.1232572).

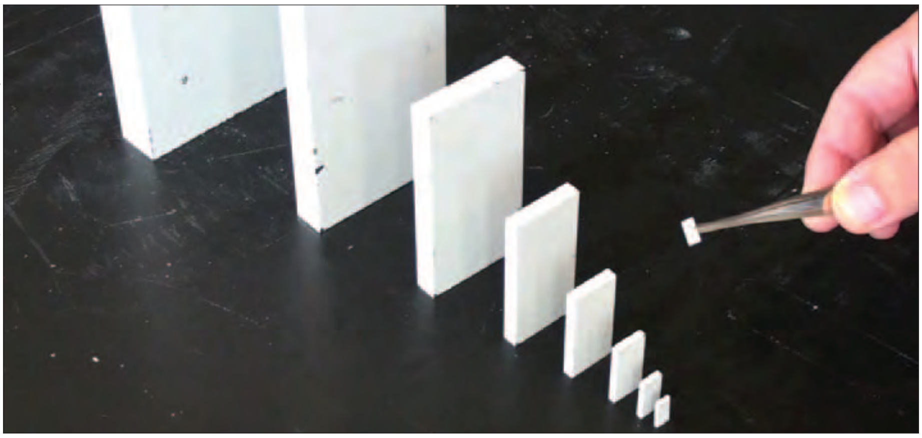
Neutrons on demand

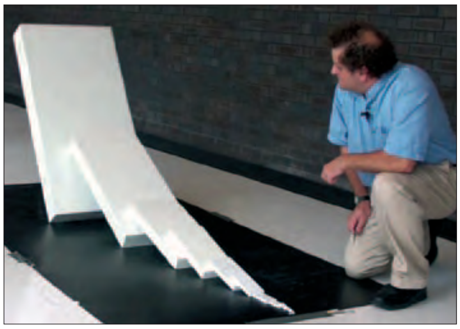
A new compact high-flux source of energetic neutrons has been built by physicists in Germany and the US. The laser-based device has the potential to be cheaper and more convenient than the large neutron facilities currently used by scientists and could be housed in university laboratories.

Built by Markus Roth of the Technische Universität Darmstadt and colleagues at Los Alamos and Sandia national laboratories, the device builds on previous research carried out at Los Alamos in 2006, which used computer simulations to show that an intense laser beam can penetrate a thin solid target, producing the necessary high-energy neutron flux. Roth's team directed extremely powerful and well-defined pulses from the Los Alamos TRIDENT laser onto a 400 nm-thick plastic target doped with deuterium atoms that was positioned 5 mm in front of a secondary target made from beryllium.

Even though the pulses delivered less than a quarter of the energy employed in previous experiments, they produced neutrons that were nearly 10 times as energetic – up to 150 MeV – and nearly 10 times as numerous. The group took the first radiographs using this beam by placing a series of tungsten, steel and plastic objects between the neutron source and a scintillating fibre array that was linked to a CCD camera.

Roth says that although his group's device produces fewer neutrons than reactors or accelerators do, it packs the neutrons into pulses – each lasting just 10^{-8} s. This makes it suitable for applications that need high temporal resolution. Roth claims that, once commercialized, the entire device would fit on a lab bench and that only the target would need shielding (*Phys. Rev. Lett.* **110** 044802).





Stephen Morris, University of Toronto

How many dominoes will topple a cathedral tower?

When a science quiz on Dutch TV last year asked its participants how many dominoes would be needed to tip over a domino as tall as the Domtoren – a 112 m-tall cathedral tower in Utrecht – mathematical physicist J M J van Leeuwen of Leiden University in the Netherlands got his thinking cap on. Starting with a standard-sized domino 4.8 cm tall, he calculated the upper limit on how much larger each successive domino could be in this game of "domino multiplication", suggesting that the maximum ratio of successive domino heights is 30% larger than the widely accepted value of 1.5. Assuming a growth factor of 1.5, the answer is 20 dominoes, but pushing the growth factor to 2, it should easily be done with just 12. Inspired by Van Leeuwen's research, the images above show Stephen Morris at the University of Toronto as he knocks over a series of 13 dominoes with a growth factor of 1.5. He claims that the energy needed to tip the first fingernail-sized domino is amplified two billion times by the end of the chain reaction – when a 45 kg block crashes to the floor. "If I had 29 dominoes," says Morris, "the last domino would be as tall as the Empire State Building." (arXiv:1301.0615)

Mobiles map the rain

Cellular communication networks can be used to accurately predict large-scale rainfall distribution patterns in real time, according to researchers in the Netherlands. The team created rainfall maps for the whole of the country using data gathered by telecom firms of the attenuation of microwave signals across 2400 network links over a four-month period. The resulting maps are largely similar to measurements taken by conventional weather-radar and rain-gauge techniques.

The research was carried out by Aart Overeem and colleagues from Wageningen University and the Royal Netherlands Meteorological Institute. The team looked at the minimum and maximum received signal power at each telephone tower in a network over 15 min periods, as microwaves are sent from one tower to the next. Signals passing through falling raindrops are partly absorbed by the water molecules and also get scattered slightly, lowering the power that reaches the receiving tower. The more raindrops in the beam's path – or the larger the drops are – the more signal power is lost.

By comparing received powers for each network link with reference values for known dry periods – and factoring in humidity and the water films that can develop on the communications antennae – the researchers were able to calculate the rainfall densities along each path. These values were then treated as point measurements at the centre of each network link and used to extrapolate the larger rain-distribution maps. In the frequencies employed in these links, attenuation caused by raindrops are the only main source of power reductions, apart from free space losses (*PNAS* 10.1073/pnas.1217961110).

Innovation

Digital files stored and retrieved using DNA

Scientists in the UK have stored about a megabyte's worth of text, images and speech into a speck of DNA and then retrieved that data back almost faultlessly. The research was carried out by Nick Goldman and colleagues at the European Bioinformatics Institute, who have stored digital information by encoding it in the four different bases that make up DNA. While the technique does not offer the convenience of random access or being rewriteable, its advantages include being highly durable and also offering an extremely high-density storage method.

The group used DNA that was produced in the lab rather than from living organisms, since the latter is vulnerable to mutation and data loss. Unfortunately, it is only possible to synthesize DNA in short strings and the shorter a string is, the lower its data storage capacity. So the team devised a coding scheme in which a fraction of each string is reserved for indexing purposes, specifying which file the string belongs to and at what point in the file it is located, allowing a single file to be made up of many strings.

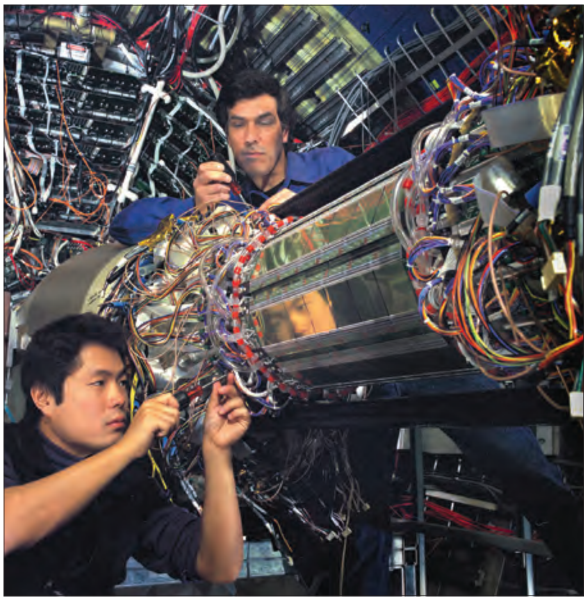
To avoid errors that occur during both writing and reading the team encoded data in trits – digits with the values 0, 1 or 2 – and stipulated that a given trit is represented by one of the three bases not used to code the trit immediately preceding it. The researchers tested their scheme by encoding five data files into single DNA sequences and then split those sequences up into roughly 150 000 individual strings, all 117 bases long. They encoded a PDF of Watson and Crick's famous double-helix paper, a Shakespearian sonnet and an audio recording of 30 s of Martin Luther King's "I have a dream" speech in MP3 format. The team then uploaded the encoded files to a private webpage to enable a company in California to synthesize the DNA.

The DNA was then sent as a tiny quantity of powder at room temperature and without specialized packaging to the European Molecular Biology Laboratory in Germany, where all five files were sequenced and decoded. Four of the files were identical copies of the originals, while the fifth required some minor adjustment to recover its full set of data.

The researchers claim to have achieved a density of 2 petabytes per gram of DNA, which could, in principle, allow at least 100 million hours of high-definition video to be stored in a teacup. Currently the technology is too expensive to be competitive for all but the most long-term archiving, but Goldman is confident that prices will come down (*Nature* **494** 77).

Nuclear physics faces loss of collider

A government panel in the US has recommended the closure of the hugely successful Relativistic Heavy Ion Collider at Brookhaven National Laboratory if funding for nuclear physics is not increased, as **Peter Gwynne** reports



Brookhaven National Laboratory

Testing times Brookhaven National Laboratory's Relativistic Heavy Ion Collider may have to close if funding for the US Department of Energy is cut.

The budgetary shortfalls that have gripped the US over the past year seem ready to claim a new victim: the nuclear-physics programme. A report released early last month, by a subpanel of the government's Nuclear Science Advisory Committee (NSAC) concluded that the country will have to close one of its three large nuclear-science facilities unless the field receives at least a small increase in government funding. It opted for the axe to fall on perhaps the best known facility – the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in New York.

The report had been commissioned last April by William Brinkman, head of the Office of Science at the Department of Energy (DOE) in response to indications that looming austerity could freeze the department's $547m annual budget for nuclear physics. The panel charged with writing the report – led by nuclear physicist Robert Tribble of Texas A&M University – considered three budget scenarios for the next five years: zero growth, annual growth at a level similar to inflation, as well as a "modest increase" of 1.6% annually above inflation.

Only under the last scenario, the panel concluded, could the country operate all three of its major nuclear-physics facilities. In addition to the 13-year-old RHIC, these are the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility in Virginia, which is undergoing a $310m upgrade, and the $615m Facility for Rare Isotope Beams (FRIB) under construction at Michigan State University (see box).

The panel concluded that CEBAF should be maintained "under all budget scenarios", owing to the amount already invested in it, which included $65m from the 2009 American Recovery and Reinvestment Act. But choosing which of the other two to sacrifice proved difficult. "If we close the RHIC now, we cede *all* collider leadership – and not just the high-energy collider – to CERN and we lose the scientific discoveries that are enabled by the recent intensity and detector upgrades at the RHIC," the report notes. "If we terminate FRIB construction, future leadership in the cornerstone area of nuclear structure and nuclear astrophysics will be ceded to Europe and Asia. In addition a window of opportunity to construct the FRIB with significant non-federal resources pledged to the project will close and is not likely to reopen."

Close call

The panel finally opted to recommend closing RHIC, which has an annual budget of $160m, but admitted that "losing any one of the components will cause severe and lasting damage to the field". Tribble later told *Physics World* that the vote was "very close", although the committee decided not to publicly reveal the actual count. The US nuclear-physics community responded swiftly to the report by vowing to fight for a budget increase, which Tribble himself will support. "I will do whatever I can to help in that regard," he says. "All panel members feel very strongly that this could be a serious problem for US nuclear physics."

Even before the report was released, the heads of the three facilities had begun collaborative efforts to counter the potential loss of a major facility. "We all appreciate that our general best interests are served by a different outcome than the cut," says Doon Gibbs, Brookhaven's interim director. Meanwhile, Robert McKeown, deputy director for science at the Jefferson lab, admits to being "relieved" that his is not the facility likely to be in jeopardy but adds that "losing any one of our facilities would be a very devastating blow to the field". Similarly, Konrad Gelbke, director of the National Superconducting Cyclotron Laboratory at Michigan State, which is overseeing planning for the FRIB, points out "huge losses to research in nuclear physics if the more stringent budget scenario is played out".

Fighting on

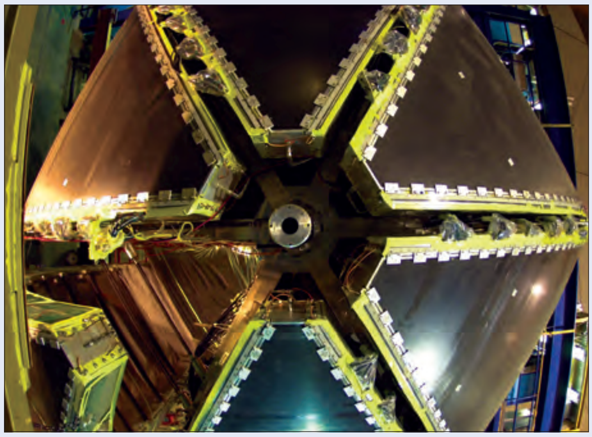
Leaders of the nuclear-physics community, however, emphasize that the DOE and the government do not have to accept the panel's recommendations. Indeed, Congress has not even determined a budget for the DOE for the current financial year. The heads of all three facilities, along with members of the nuclear-physics community and scientific societies such as the American Physical Society, have already begun a powerful effort to persuade local representatives, senators and Congress as a whole that US science will suffer in both the short and the long term without a small increase in the nuclear physics budget.

The message has certainly reached leaders at the DOE. "None of this bodes well for science at the rate

Different but related: the three US facilities battling for survival

The three major US nuclear-physics facilities under threat by budget difficulties – Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC), the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility and the Facility for Rare Isotope Beams (FRIB) under construction at Michigan State University – have different but related goals and technologies.

The RHIC is primarily designed to study the "phase diagram" of nuclear matter from almost baryon-free matter at temperatures up to four trillion degrees kelvin down to baryon-dense matter at lower temperatures. "It is by far the most powerful in the world in terms of intensity and most versatile in terms of energy," says Brookhaven's associate director Berndt Müller. Those capabilities stem largely from a series of upgrades over the past decade that have increased the collider's luminosity and the precision of its detectors. "The RHIC we have now is a new machine in many respects – in its ability to accelerate uranium to the detectors – with almost no resemblance to 10 years ago, covering science that was not envisioned when it was constructed," adds Müller. Recent discoveries include a new form of matter – a strongly coupled quark–gluon plasma – that was created by collisions of gold ions.



Thomas Jefferson National Accelerator Facility

Still running CEBAF at Jefferson Lab currently seems to be safe.

As for the FRIB, it will be complete in 2021 and be based on a high-powered superconducting linear accelerator that will be able to produce rare isotopes. The FRIB will be the world's most powerful radioactive beam facility, able to make nearly 80% of the isotopes predicted to exist for elements up to uranium.

CEBAF, meanwhile, will provide a high-intensity continuous beam of electrons using superconducting radio-frequency technology. The facility is currently undergoing a long shutdown as part of the upgrade that will double the accelerator's energy from 6 GeV to 12 GeV, with the goal of starting its new science programme in 2015. The electron beam in the upgraded facility can be split and delivered simultaneously to three different experimental halls. According to Robert McKeown, deputy director for science at the Jefferson lab, one of these halls will feature a "flagship experiment" that will use a 9 GeV photon beam to search for exotic mesons.

we're going here," Brinkman told the subpanel in Washington at a hearing, adding that it "represents permanent damage to the field". But if Congress and the Obama administration fail to avoid the looming budget cuts in the "financial sequester" – the agreement to reduce government spending across the board if the two sides cannot agree on a budget – then the cuts look more of a reality. "We didn't spend much time on sequestration," says Tribble. "If it occurs, it will be such a problem in all parts of government that it's impossible to know what the impact will be on nuclear physics."

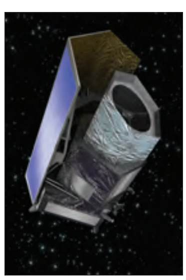
One concern is that the sequester could lead to a ban on starting any new programmes at all. That could affect the FRIB, which has not yet received the necessary "critical decision 2" go-ahead from the DOE. Even if that situation does not occur, the field could lose so much financial support that it might even have to close two machines rather than one.

Space

NASA joins Europe's dark-energy mission

NASA has signed an agreement with the European Space Agency (ESA) to collaborate on a space mission to study dark matter and dark energy. ESA's $800m Euclid mission is expected to launch in 2020 and will spend six years measuring and mapping around two billion galaxies covering more than one-third of the sky. NASA is now expected to provide around $100m towards the construction of the probe, with the space agency's involvement likely to extend the science that can be achieved.

Dark energy, which makes up around 73% of the universe, is believed to be the driving force behind the universe's expansion but is a substance about which we have almost no knowledge. Dark matter, meanwhile, accounts for a further 23% of the universe, with the rest being ordinary visible matter. "The study of dark energy was identified as an important scientific question in the 2010 Decadal Survey of Astrophysics by the National Academies of Science," NASA spokesman James Harrington told *Physics World*. "Euclid will make significant progress in understanding the nature of it."



ESA/C Carreau

Helping hands NASA is expected to provide around $100m towards the European Space Agency's $800m Euclid mission, which will study dark energy and dark matter

Euclid will be armed with two state-of-the-art instruments – an optical visual imager and a near-infrared spectrometer. For the infrared instrument NASA will now be providing 16 detectors, plus four spares, to the tune of $50m. NASA will be giving a further $50m to support the 54 US scientists who will now be joining the mission, the bulk from the Jet Propulsion Laboratory in Pasadena, California. "By providing US-made detectors for the mission and by having US scientists working on the mission, both the European and US science communities will benefit," says Harrington.

This is not the first time that NASA and ESA have worked together on a major mission, having collaborated on the Hubble and James Webb space telescopes as well as on the Cassini and Huygens missions to Saturn and the Herschel and Planck observatories. "We welcome NASA's contribution to this important endeavour, the most recent in a long history of co-operation in space science between our two agencies," says Álvaro Giménez, ESA's director of science and robotic exploration. NASA says it hopes the experience it gains on Euclid will help it with the construction of the Wide-Field Infrared Survey Telescope mission, which is planned for launch in the coming decade to study dark energy and dark matter.

Gemma Lavender

People

Steven Chu steps down as US energy secretary

The Nobel laureate Steven Chu has announced he is to resign as US energy secretary. When Chu departs, which as *Physics World* went to press was expected to be by the end of February, he will have served in the post for four years – longer than any of the 14 previous heads of the Department of Energy (DOE). Chu now plans to return to "an academic life of teaching and research" in California.

DOE

Back to the lab Nobel laureate Steven Chu says that he will now return to "an academic life of teaching and research" in California.

Politically independent, Chu received plaudits from Democrats and environmentalists during his time as energy boss, which spanned the whole of President Barack Obama's first term in office beginning in 2008. "Steve helped my administration move America towards real energy independence," Obama said in a statement. "Over the past four years we have doubled the use of renewable energy, reduced our dependence on foreign oil and put our country on a path to win the global race for clean-energy jobs."

In a letter to DOE staff, Chu noted his successes in office, such as funding the Advanced Research Projects Agency–Energy – a programme to promote and fund research and development in novel energy technologies. The agency's work in areas such as improving batteries for electric vehicles and developing manufacturing technologies for solar cells has drawn plaudits across the board, as did his "SunShot initiative" – an effort to increase US use of renewable-energy technologies – that began progress towards a goal of reducing the cost of solar power to $1 per watt. "Secretary Chu has led the energy department at a time when our nation made the single largest investment ever in clean energy and doubled its use of renewables," stated Gene Karpinski, president of the League of Conservation Voters.

Yet Chu also became a controversial figure, facing heavy criticism from Republicans, deniers of climate change and some members of the business community. Critics focused on occasional failures of Chu's initiatives, such as Solyndra – a solar-cell manufacturer that went bankrupt after receiving $535m in DOE loan guarantees – as well as A-123 Systems, an innovative battery maker that went bust before being rescued by a Chinese conglomerate.

Daniel Kish, senior vice-president of the Institute for Energy Research, a Washington DC-based non-profit corporation, asserted that the emphasis on renewables has cost jobs. "The policies and priorities of Chu's energy department have benefited our global competitors and intensified the economic pain felt by millions of unemployed Americans," he says. Chu responded to those criticisms in his letter to DOE's employees. "The truth is that only 1% of the companies we funded went bankrupt," he noted. "The test for America's policy-makers will be whether they are willing to accept a few failures in exchange for many successes."

The Obama administration will now nominate a successor, with the Democrat politicians Bill Ritter of Colorado, Jennifer Granholm of Michigan and Christine Gregoire of Washington state as top favourites. Yet there is a possibility that Chu's successor will be another scientist: theoretical physicist Ernest Moniz of the Massachusetts Institute of Technology, who served as under-secretary of energy for former US president Bill Clinton.

Peter Gwynne
Boston, MA

Quantum physics

Plans for departing Canadian space chief kept under wraps

The head of the Canadian Space Agency (CSA), Steve MacLean, quit as president last month after revealing he is planning to join a new quantum-physics venture in Waterloo. The venture will be led by Mike Lazaridis, who co-founded Research In Motion – the company behind the BlackBerry smartphone – and later set up the prestigious Perimeter Institute for Theoretical Physics, also in Waterloo.

Although details of the initiative are being kept under tight wraps, it is known that the new joint effort between Lazaridis and MacLean will be separate from the Perimeter Institute's activities, which focus on areas such as quantum gravity, quantum information and quantum fundamentals. But when asked for more details on MacLean's plans,

NASA/JSC

Back to Earth Canadian astronaut Steve MacLean has resigned as president of the Canadian Space Agency to be involved in a new quantum-physics venture in Waterloo.

a spokesperson from the Perimeter Institute declined to give any. In a statement the institute said only that it was "very pleased that the innovation and technology cluster in the Waterloo region has attracted someone of Steve MacLean's calibre" and that it looked forward "to collaborating with him and other partners who are building the quantum valley".

Information on MacLean's plans was also scarce at the University of Waterloo, which is home to the new $100m (C$160m) Mike and Ophelia Lazaridis Quantum-Nano Centre that was opened by Stephen Hawking last year, as well as at Communitech, a Waterloo-based hub that aims to commercialize technologies. Both institutions told *Physics World* they had no knowledge of the new initiative, while MacLean himself did not respond to an interview request.

MacLean received a BSc in physics in 1977 and a PhD in physics in 1983 from York University in Toronto. That year he was also selected as one of the first six Canadian astronauts, going on two missions to space in 1992 and 2006. On the 1992 flight MacLean tested a laser-vision system, a predecessor to robotic arms such as the Canadarm2 that is currently used on the International Space Station to capture spacecraft. In 2008 he was named CSA president for a five-year term.

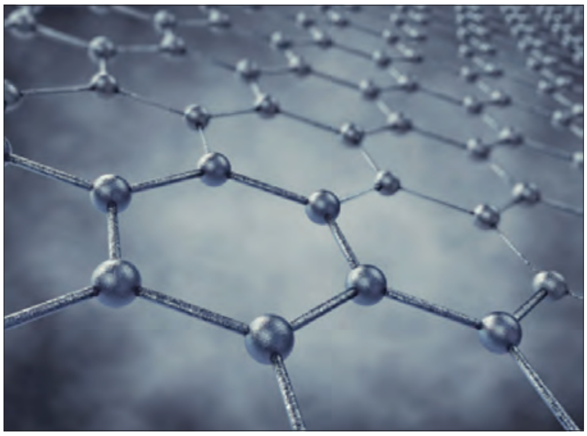
Elizabeth Howell
Toronto

Funding

Europe backs graphene research with €1bn boost

A project to commercialize graphene has been awarded €1bn over a 10-year period by the European Commission (EC). Led by theoretical physicist Jari Kinaret of Chalmers University of Technology in Sweden, the graphene project beat off four other bids for one of two huge new €1bn Future and Emerging Technologies awards – the other winning project being on brain research. The graphene project involves 126 academic and industrial research groups from 17 EU member states and will consist of 15 "packages", each representing a different application area of graphene and led by a different expert.

Half of the funding will come from the EC's Horizon 2020 programme, which promotes research and innovation in the EU, with the other half coming from national budgets or industry. The graphene project was awarded the money after gaining wide support – particularly from Neelie Kroes, the EU commissioner for digital agenda. She says the project will help create a European "graphene valley" that will connect the academic and industrial consortium.



iStockphoto/nobeastsofierce

Thin future
The 10-year graphene project will lead to the development of new techniques for the fabrication of graphene nanodevices as well as the integration of graphene-based opto-electronic devices.

Only the first 30 months of the programme have detailed goals at the moment. These include the development of different techniques for making graphene nanodevices, the design of a graphene-based receiver unit for radio signal processing and the integration of a graphene-based opto-electronic and nano-photonic device. However, Kinaret is not concerned about the lack of targets over the whole of the 10-year project. "We are doing research, not development," says Kinaret, "and a defining feature of research is uncertainty." Kinaret insists, though, that the project does have a number of detailed long-term goals, for example in electronics, optics, energy applications and composite materials.

Andre Geim from the University of Manchester, who shared the 2011 Nobel Prize for Physics with his colleague Konstantin Novoselov for their work on graphene, says that with so many potential technologies that have already been suggested for graphene, the chances are "sky high" the project will deliver something. "Graphene is my best bet for the next big technological breakthrough," says Geim. "Nevertheless, one needs to remember that it takes typically 40 years for a new material to move from academia to consumer shelves. Graphene progresses unbelievably fast, having reached industrial labs already, but our expectation should remain realistic."

News of the €1bn European award for graphene came just weeks after a report by the intellectual-property consultancy CambridgeIP noted that the US and Asia currently hold the lion's share of graphene patents, with Korean electronics giant Samsung alone filing more than 400.

Senne Starckx
Mol, Belgium

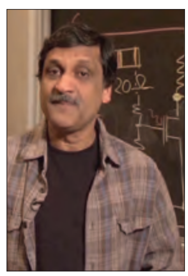
Education

Online-learning provider *edX* doubles membership

A major digital education initiative set up by Harvard University and the Massachusetts Institute of Technology (MIT) has just doubled its number of university partners and signed up its first members from outside the US. The *edX* programme, which offers free online learning, is now joined by universities in Canada, Australia, the Netherlands and Switzerland. "We have had an international student community almost from the beginning and bringing these leading international universities into *edX* will help us meet the tremendous demand we are experiencing," says *edX* president Anant Agarwal from MIT.

edX is a not-for-profit education programme offering "MOOCs", or massive open online courses. MOOCs differ from conventional online learning programmes, being free of charge, offering vast resources and not usually leading to any formal credit being awarded by the providers. Although MOOCs have existed for several years, the founders of *edX* say they are raising the bar by building an entire open-source platform that links some of the world's leading universities. A typical *edX* course consists of "learning sequences" involving videos presented by university academics, along with assessments and online interactive laboratories.

Harvard and MIT both invested $30m in *edX* early last year and were subsequently joined in the initiative by the University of California at Berkeley, the University of Texas, Wellesley College and Georgetown University. Now, these six institutions will be joined by Rice University (also in the US), McGill and Toronto universities in Canada, plus the Australian National University, Delft University of Technology in the Netherlands, and the École Polytechnique Fédérale de Lausanne in Switzerland. "Each of these schools was carefully selected for the distinct expertise and regional influence they bring to our growing family of *edX* institutions," says Agarwal.



Watch and learn
Anant Agarwal, president of *edX*, has given an exclusive video interview to *Physics World*, which can be viewed online and in our digital issue.

All six current *edX* members launched courses in 2012 and have new courses starting this spring. Among the new batch is a course on electricity and magnetism taught by Walter Lewin, an MIT physicist who already has a strong online following through earlier recorded lectures. Other existing *edX* courses include those on quantum mechanics and computing taught by Berkeley academic Umesh Vazirani, and on solid-state chemistry by MIT human-genome pioneer Eric Lander. According to *edX* spokesperson Dan O'Connell, Delft has already indicated that it will be begin offering *edX* courses from autumn, including courses on solar energy and space engineering.

James Dacey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UK

Cumbria rejects hosting nuclear-waste repository

The UK government will have to look elsewhere to store its mounting nuclear waste after plans were rejected to assess sites in Cumbria for a £12bn underground nuclear-waste repository. On 30 January seven of the 10 members of Cumbria County Council cabinet voted against a proposal to build an underground laboratory in the region that would have acted as a testbed for a full-scale storage. District councils in west Cumbria are now hoping that the veto – the second in 14 years – will be overruled by the government.

The UK has been generating nuclear waste since its first nuclear power station fired up in 1956. Since then the country has accumulated some 470 000 m^3 of waste, which could remain dangerously radioactive for up to a million years. Most of the high- and intermediate-level waste is currently in temporary above-ground storage at the Sellafield nuclear- reprocessing site in west Cumbria. The UK government, however, would like to find a permanent place to store the waste because of fears that the storage at Sellafield is deteriorating. Indeed, last year the UK's National Audit Office reported that Sellafield's storage posed an "intolerable risk" to people and the environment.

Cumbria has been seen as a possible site to permanently store the waste underground at depths of up to 1 km because of the existing nuclear facilities at Sellafield. However, some geoscientists are opposed to underground storage in the region because it is thought to contain unstable geology such as rock fractures, which can allow the spread of waste-leeching groundwater. There are also concerns that underground waste would threaten tourism at the nearby Lake District National Park.

Stuart Haszeldine, a geoscientist at the University of Edinburgh who has investigated Cumbria's suitability for underground nuclear-waste storage, told *Physics World* that he was pleased with the outcome. "It was quite unexpected to win," he says. "I didn't think Cumbria County Council would have such good judgement." Haszeldine believes that other parts of the UK would be more geologically suitable for the construction of an underground storage facility, such as around the defunct nuclear power station in Oldbury, near Bristol.


Sellafield Ltd

Risk concerns Cumbria in the UK is already home to the Sellafield nuclear reprocessing site, which closely monitors its environmental impact, but now the region's council has rejected a proposed £12bn underground nuclear-waste repository.

Many, however, are frustrated by the vote's outcome. UK energy secretary Edward Davey says it was "disappointing", adding that the decision will "not undermine prospects for new nuclear power stations". Meanwhile, council leaders from Copeland – the district that hosts Sellafield – and from neighbouring Allerdale have written to the government to ask if there is still a way that west Cumbria can be considered for long-term nuclear-waste storage.

Councillor Elaine Woodburn of Copeland told *Physics World* that more than two-thirds of Copeland residents wanted to see west Cumbria reconsidered, and that some geological experts would like to see a more detailed investigation. "The impact of hosting over 70% of this country's waste is felt economically, environmentally and socially," says Woodburn. "Whether it stays or goes, it affects us, so we need to be part of the solution. Whether [that] solution is in Copeland, I don't know; we don't have the facts to allow that decision to be taken."

Jon Cartwright

Space science

Satellite sets path for South Korean space missions

South Korea has succeeded in launching a satellite into orbit after months of delays and following two failed attempts in 2009 and 2010. The probe – dubbed the Science and Technology Satellite 2C (STSAT-2C) – took off at the end of January from the Naro Space Center, located around 480 km south of Seoul. Scientific payloads aboard the probe include an instrument to monitor radiation levels as well as an altimeter to provide precise information about the satellite's orbit.

Shortly after lift-off, the Korean ministry of education, science and technology announced that STSAT-2C had successfully deployed in a low-Earth orbit, while contact with ground stations was made 11 hours later, confirming the target orbit of 297 km by 1512 km. "[The rocket] proved that Korea has the ability to launch a space vehicle. This space technology represents the [high] standard of our country's science and technology," Yeong Hak Kim, a government official at the Korean ministry of education, science and technology, told *Physics World*.

The probe was launched by Korea's Space Launch Vehicle (KSLV-1), also known as Naro, which is a two-stage carrier rocket that, when fully loaded, stands 33 m tall and has a mass of around 140 000 kg. The first stage of the launch vehicle was designed and built by Russia's Khrunichev State Research and Production Space Center, while the second stage was developed by the Korea Aerospace Research Institute.

The project is a demonstration of South Korea's growing space prowess

The immediate scientific value of the satellite will be relatively small with the project being more of a demonstration of South Korea's growing space prowess. Indeed, North Korea's apparent success in launching a long-range rocket in January put pressure on Seoul to ensure that KSLV-1's space flight went to plan. Both countries on the Korean peninsula are now members of the exclusive group of 11 nations that have independently launched satellites from their own territory. However, South Korea will still have to make significant progress before comparisons can be drawn with other space-faring nations such as China and Japan.

Toby Brown

Asia

China signs off big science infrastructure plan

China's state council has approved a major infrastructure construction programme for science and technology over the coming two decades. Running from 2012 to 2030, the programme will aim to boost innovation in China, support major scientific breakthroughs and speed up construction of major scientific facilities. Seven areas that focus on China's strategic aims are earmarked, including energy and materials research, Earth systems and environments, as well as particle and nuclear physics.

The programme will see China building some 16 major projects, which include establishing a seafloor observatory network and carrying out a precise survey of China's resources by measuring the strength of gravity at varying locations around the country, the latter being led by Huazhong University of Science and Technology and the Chinese Academy of Sciences. The state council maintains that, rather than just being run by leading universities and institutions, all the projects should involve better collaboration and the results be openly shared.

Physicists in China have broadly welcomed the plan. "It focuses on cutting-edge research for the seven fields so this is an important plan for China," says astrophysicist Tipei Li from Tsinghua University and the Institute of High Energy Physics in Beijing. "While many other countries' research budgets are decreasing, China's budget is increasing."

The plan gives a high level of confidence in China's ability to innovate

Mi Xu, a senior adviser for the fast-reactor programme based at the China Institute of Atomic Energy in Beijing, agrees with the plan's aims. "It has given me a high level of confidence in China's ability to independently innovate," he told *Physics World*, pointing to how the country has already led the way in building a fast-neutron reactor – one that can "breed" its own fuel – located in the Fangshan District on the outskirts of Beijing (see September 2011 p9).

Meanwhile, the state council meeting in January also amended four regulations regarding the enforcement of copyright law and the protection of computer software. The changes were made in an attempt to intensify a crackdown on intellectual copyright infringement and combat the manufacture and sale of counterfeit products.

Jiao Li
Beijing

UK

NPL scoops £25m for advanced metrology centre

The National Physical Laboratory (NPL) in Teddington, UK, is to receive £25m towards the construction of an Advanced Metrology Laboratory (AML) that will contain up to 20 labs and be complete by 2017. The AML will be housed in a new building on the NPL site, with research focusing on areas such as graphene, nano-analysis and time and frequency measurements.

"The key feature of the new laboratory is the stable, high-specification environment it will provide, [such as] low magnetic field and vibration, and very stable temperature and humidity control," says Bill Nimmo, a senior research scientist at NPL. It is also hoped that the AML will foster stronger links between NPL and academia. "This arrangement will attract industry partners and funding from multiple sources," adds Nimmo.

NPL

Bigger and better The National Physical Laboratory in Teddington, UK, will build an Advanced Metrology Laboratory to develop improved time and frequency standards.

Cash for the AML is part of a UK government initiative to target investment in eight so-called "great science areas" – for which £460m has been allocated from a total £600m fund, originally announced last year. Other areas include £189m for big data and energy-efficient computing, £45m for new facilities and equipment for advanced materials research, as well as £50m for upgrades to research equipment and laboratories.

Kulvinder Singh Chadha

Sidebands

NSF director quits

Materials scientist Subra Suresh has announced his resignation as director of the US National Science Foundation (NSF). In a letter to staff he said he would be leaving at the end of this month to become president of Carnegie Mellon University. Suresh, a former dean of the Massachusetts Institute of Technology, was appointed NSF director in October 2010 for a six-year period. In the letter he said it has been an "extraordinary honour" to lead the NSF, which has a budget of around $7bn. "Despite the economic crisis and the lingering uncertainties that have ensued, NSF funding has sustained growth," he wrote. NSF deputy director Cora Marrett is expected to be named acting director until Suresh's replacement is found.

Starting bell sounds for CHIME

Construction has begun on what will be Canada's largest radio telescope. The C$11m Canadian Hydrogen Intensity-Mapping Experiment (CHIME) in Penticton, British Columbia, is the first research telescope to be built in the country in more than 30 years. CHIME boasts a 100 × 100 m collecting area, which will be filled with 2560 low-noise receivers built with components adapted from the mobile-phone industry. Signals collected by the CHIME telescope will be digitally sampled nearly one billion times per second, then processed to produce an image of the sky. Astronomers will use the telescope to map a quarter of the observable universe to help better understand the nature of dark energy.

Liangying Xu: 1920–2013

The Chinese physicist Liangying Xu, who was a fierce advocate of democracy in China, died on 28 January at the age of 92. Xu was born in the eastern Chinese province of Zhejiang on 3 May 1920 and studied physics at Zhejiang University. He later became a member of the Chinese Academy of Sciences (CAS), serving as a censor for papers that were going to be sent abroad for publication. In 1957 Xu took part in the "Hundred Flowers" campaign to speak out over the Communist Party's failings, for which he was sent to his home village where he worked on a farm and also began translating Einstein's works. Following the death of Communist party chairman Mao Zedong in 1976, banished scientists returned from the countryside and Liangying regained his job at the CAS and subsequently published a three-volume collection of Einstein's works.

Research funding

Study finds US scientists guilty of 'double dipping'

Significant numbers of US scientists have received money from more than one agency for the same or nearly identical grant applications, according to new analysis by physicist Harold Garner at Virginia Tech's Virginia Bioinformatics Institute. The analysis, which was carried out with data-mining software that is also used to detect plagiarism, estimates that the cost of this "double dipping" could have totalled around $70m over the past 10 years.

The new analysis follows a report by the US Government Accountability Office in February 2012 that suggested that there could be significant waste of funding through duplication. Garner's team focused on data from more than 850 000 grant applications that can be publicly accessed from the websites of science-related government agencies such as the National Science Foundation (NSF) and the Department of Energy (DOE). "Since our software had found plagiarism, we knew we could analyse duplication," Garner told *Physics World*.

The investigation revealed 167 pairs of very similar applications, although because the websites did not contain complete grant files, the team could not determine how similar the pairs were. However, a follow-up study by *Nature* provided documentation on 22 pairs of very similar grants. "There isn't any doubt that duplication of grant applications is going on," says Garner. "The doubt is about the intensity of it." Indeed, Garner suspects that his software could have missed many other cases of duplication.

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One for the price of two
An analysis of grant submissions carried out by Harold Garner at the Virginia Bioinformatics Institute has found examples of researchers being awarded funding from multiple sources based on the same grant application.

US research agencies are aware that there is a problem. The NSF, for example, requires notification from its grant recipients if they receive any funding for the same project from other sources. But last November, electrical engineer Craig Grimes, formerly of Pennsylvania State University, was sentenced to 41 months in prison for a series of research grant frauds that included accepting grants from the NSF and the DOE for a project on the conversion of carbon dioxide into hydrocarbons using solar energy. Meanwhile, in 2010 the NSF banned electrical engineer Guifang Li of the University of Central Florida from applying for funding for two years, after he "failed multiple times to notify the NSF of his previous Air Force funding". Li argued that, while his two proposals resembled each other, they would have produced different projects. In fact the issue of grant applications that are similar but not the same makes it difficult to judge grant applicants' motives.

Although the study does not break down instances of double dipping according to discipline, Garner points out that many physics grants involve large groups and significant funding, which means it is less vulnerable to duplication than subjects such as biomedicine that mostly involve small teams and individual investigators. Garner thinks tight budgets and the low chance of winning support are why some scientists are forced to submit identical or almost identical grant applications. "This underfunding has a number of consequences, one of which is raising the temptation for individuals to cross the line," he says.

Peter Gwynne
Boston, MA

Croatia

Reforms ignite row over how to best evaluate research

The Croatian government has adopted a draft reform proposal that aims to improve research funding, open up more posts for young scientists and strengthen how it deals with misconduct in research. Although the reforms still have to be passed by parliament before becoming law, they have already sparked fierce debate within the academic community in Croatia. Indeed, researchers in the country have been divided for several years between those demanding a move to a more meritocratic system – in which funding is linked to a researcher's publication record – and those trying to block such reforms for fear they would lead Croatia towards commercializing its science.

Most top scientists, including Croatian researchers working abroad, want science funding to depend purely on quality and excellence measured by the number of a researcher's publications and the impact those papers have. However, others say scientists in Croatia can only do better science if they have more funding and that the government should instead create a national science strategy before changing the laws.

The debate, which has been rumbling for some time, was reignited by a damning study published in January by the Institute for Social Research in Zagreb of the performance of social scientists in Croatia. It found that between 1991 and 2005 more than 60% did not publish any books, while fewer than 5% published in international journals listed in Thomson Reuters' Web of Science database.

Most top scientists want science funding to depend purely on quality and excellence

Marijan Herak, a geophysicist from the University of Zagreb, supports the proposals but complains about a lack of a proper bibliometric analysis before the writing of the draft reforms. "If our system is going to be changed – and it needs to be changed – then its inefficiency should be objectively established and documented," he says. "But this has not happened." Indeed, in January Herak undertook an as-yet-unpublished bibliometric study of the output of Croatian scientists, which – he claims – shows they fare well compared with their counterparts in other developed nations in terms, for example, of the number of publications relative to total spending on science.

Mićo Tatalović

L'Aquila scientists appeal conviction

Formal appeals are to be made by the seven researchers who were charged with manslaughter for advice they gave prior to the 2009 L'Aquila earthquake, as **Edwin Cartlidge** reports

Lawyers representing the seven scientists and engineers convicted of manslaughter for advice they gave ahead of the deadly L'Aquila earthquake in 2009 are expected to have lodged formal appeals against the verdict in the first few days of March. The researchers' conviction last October – and the six-year jail sentences handed down to each of the accused – shocked many in the scientific world and beyond, triggering warnings that many experts would now be scared to give advice for fear of prosecution. Francesco Petrelli – lawyer for convicted volcanologist Franco Barberi – said that the verdict will be "subject to a crossfire of criticisms".

The start of the appeals process comes some six weeks after the trial judge, Marco Billi, released a 943-page document explaining his reasoning for the conviction and the sentences. Largely following the argument put forward by L'Aquila's public prosecutor, Billi states that the defendants' "level of guilt is particularly high" and that this guilt is accentuated by their "conscious and uncritical" participation in a "media operation" ordered by the then head of Italy's Civil Protection Department Guido Bertolaso. The six-year prison terms imposed by Billi, which would not come into effect until the appeals process has been completed, are two years longer than those requested by the prosecutor.

The seven experts all took part in a meeting of a government advisory panel called the National Commission for the Forecast and Prevention of Major Risks that was held in L'Aquila on 31 March 2009 – six days before the quake. The meeting had been convened by Bertolaso in the wake of an ongoing "swarm" of small and medium-sized tremors over the previous few months. But Billi says he does not condemn the scientists for failing to predict the earthquake, which he adds is not possible with existing scientific knowledge. Instead, he takes issue with them for having carried out a "superficial, approximate and generic" risk analysis in the light of the swarm. That inadequate analysis, he says, had an "unequivocal reassuring effect" on the local population, leading some residents to stay indoors on the night of the quake when otherwise they would have sought refuge outside, leading to 29 deaths.


Shutterstock/Franco Volpato

Big impact Building damage in the village of Onna, near L'Aquila in Italy, caused by the April 2009 earthquake.

Billi explains that the experts were not tried on the basis of the scientific content of their statements but instead on whether they acted with due "diligence, prudence and skill". "This is not a trial against science," he writes, "but a trial against seven public officials...who carried out an evaluation of the seismic risk that violated the rules of analysis, forecast and prevention regulated by the law."

During the trial Marcello Melandri – the legal representative of geophysicist Enzo Boschi, who was another of those convicted – argued that the prosecution had not properly distinguished the responsibilities of each of the seven individuals, pointing out that many of the most controversial comments were made before the meeting by just one of the indicted – hydraulic engineer Bernardo De Bernardinis, who was then deputy head of the Civil Protection Department. Those comments included the notion that the swarm was positive because it discharged energy from the fault, which many witnesses in court said persuaded their relatives to stay inside on the night of the earthquake. But Billi backs the view of prosecutor Fabio Picuti, saying that De Bernardinis' comments amounted to the commission's "manifesto", given, he claims, their close match with other statements made during the meeting.

How can a trial against scientists' knowledge be decided without recourse to the shared canons of international science?

Alessandra Stefano, representing seismic engineer Gian Michele Calvi, says that Billi's reasoning is "very disappointing", arguing that it "does nothing but repeat the prosecution's mistaken interpretation of the facts and of the law". Petrelli, meanwhile, argues that Billi has confused the duties of the politicians and administrators with those of the scientific consultants, and failed to evaluate the "substantial difference" between the scientists' statements on seismic risk and what was said by the local television stations and newspapers.

Petrelli also maintains that Billi, in trying to show that he had not been involved in a "trial against science", has actually ended up conducting a "trial without science", in which he (wrongly in Petrelli's eyes) insisted on not examining the scientific content of the defendants' statements. "How can a trial against scientists' knowledge be decided without recourse to the shared canons of international science?" asks Petrelli.

The appeals will be heard by three judges, who, says Stefano, might reach a verdict by the end of the autumn but whose decision, she adds, is sure to be challenged in the Supreme Court by whoever loses at the appeals stage. Petrelli says that the Supreme Court is not likely to rule on the case before the end of 2015.

Meanwhile, it appears that a parallel trial against Bertolaso and Daniela Stati, who was regional councillor for civil protection at the time of the quake, will not now take place. The two had been under investigation by the prosecutors for an intercepted phone call that Bertolaso made to Stati the day before the scientists met in March 2009, in which Bertolaso referred to the "media operation" with which he wanted "to reassure the public".

Picuti and fellow prosecutor Roberta D'Avolio have now requested that the investigation against the pair be terminated. Bertolaso had claimed, when giving evidence in last year's trial, that his term "media operation" simply referred to his wish to have the scientists' deliberations made known to the media, rather than spinning the science in a pre-meditated way to reassure the public. Picuti and D'Avolio say this interpretation cannot be shown to be false beyond reasonable doubt as neither Bertolaso nor Stati offered "any causally relevant contribution to the formation of the content and outcome of the meeting". A judge must now decide whether to accept the prosecution's request, which looks set to be opposed by quake victims' relatives.

Feedback

Letters to the editor can be sent to *Physics World*, Temple Circus, Temple Way, Bristol BS1 6HG, UK, or to **pwld@iop.org**. Please include your address and a telephone number. Letters should be no more than 500 words and may be edited. Comments on articles from *physicsworld.com* can be posted on the website; an edited selection appears here

Physics in India

As a close follower of *Physics World* and an aspiring science popularizer, I found your special report on India quite timely as it reflects the enhanced efforts to promote research in this country. However, the report reflects more of the positive changes that are happening and ignores some of the serious problems that India faces in producing a high-quality talent pool at the undergraduate level.

There are many pockets of excellence in India where high-quality research is conducted. However, these centres of excellence are not involved in training undergraduates, and the institutions that do train undergraduates are not involved in research. Most Indian students therefore do not go through the process of being nurtured from an early stage by academics who are actively engaged in research, as the best Indian researchers are isolated from the country's mainstream education system.

I think a complex set of reasons are responsible for this situation. One key concern is that conducting research has been more of an exception than a norm in most Indian universities. In recent years, many initiatives have been set up to address this problem and a flood of money is now available to people who are interested in pursuing research projects. The problem is that most Indian academics have not looked at research for the better part of their careers, so whatever research they pursue is likely to be *ad hoc* and not original.

This scenario has to change if India is to do better. Undergraduate education should be introduced in all of the centres that are currently dedicated only to research. It is not just the undergraduates who stand to benefit from this; professors will benefit just as much when they are teaching curious young students.

Prem Prasad
Manipal, Karnataka, India
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I found the special report on India well planned and highly informative, especially the article on "Igniting a passion for physics among India's top students". However, I wish that the report had included a separate article on the role of informal science communications in inspiring and inculcating the spirit of inquiry among school students. In a country like India, where scientific research is mostly funded by public money, scientists ought to use the outcomes of their research for social benefit. Also, in order to attract talented students to science and thereby harness their capabilities in fostering an understanding of nature, science needs to be made attractive, accessible and comprehensible in a way that does not dilute its substance.

I am the physics curator of the National Council of Science Museums (NCSM), an autonomous organization under the Indian government's Ministry of Culture that is currently led by G S Rautela. For more than five decades now, the NCSM has acted as a bridge between members of the public and science, enhancing understanding and appreciation of science and technology through a network of 47 hands-on and interactive science museums and centres spread across the country. All NCSM units welcome people from different walks of life, including students in organized groups, families and tourists, and visitors are encouraged to get engaged with and participate in interactive science activities.


NCSM

Immersed An interactive science exhibit in India.

In addition to permanent exhibition galleries and science parks, the NCSM regularly organizes travelling exhibitions on contemporary scientific issues. One of its most remarkable activities is a specially designed "museo-bus" that brings exhibitions on scientific topics relevant to the rural population to remote villages. The NCSM has also taken on the responsibility of building science communication skills among teachers in schools, colleges and universities, and the professional development of science teachers is one of several areas identified as a target for future activities.

These initiatives – along with many others I have no room to mention here – will help to develop a "passion for physics" not only among India's top students, but also members of the wider public.

Kanchan Chowdhury
National Council of Science Museums, India
kkc_154@yahoo.co.in

Comments from *physicsworld.com*

Now hear this: the way people perceive and analyse sounds is highly nonlinear. We know this because there is a restriction (called the Gabor limit) on the accuracy of linear methods in simultaneously determining a sound's pitch and timing – and humans routinely beat it. Our report on a new study of this phenomenon ("Human hearing is highly nonlinear", 31 January) had *physicsworld.com* readers speculating about how hearing works, and what further tests might reveal.

Maybe humans beat the Gabor limit because they're using more than one process – one that does timing well but is bad at frequency analysis and another that does frequency analysis well but is bad at timing. I think it's possible to devise more tests to confirm this.

philius, Ireland

You cannot get the answer simply by using two processes. They must be correlated. Imagine using this dual analysis:

1. We analysed the frequency and we know there were three pitches, A, C# and G. But we cannot say when they occurred.

2. We analysed the timings and we know the pitches changed at 1.4 seconds and 1.8 seconds from the start of the first one. But we cannot say what the order of the pitches was.

So you see, it is a 2D problem, but the approach you suggest applies two 1D analysis techniques.

edprochak

We already know the ear is highly nonlinear in its amplitude response. Why would we expect it to be linear in any other way? Anyone who has ever played with resonant circuits understands that as you raise the Q of the circuit to get better frequency selection, the response time (hence the time to detection at a certain amplitude) increases. The two are directly related.

But that applies only to a single resonator. As I understand it, the ear has (very) many resonators, the cochlear hairs, to pick up each individual frequency. It would not surprise me to find also many resonators at the same frequency but with different Q, allowing the ear also to pick up timing differences at reasonable amplitudes. Both sets of detector would work to give the effects seen.

ajansen

physicsworld.com

Read these comments in full and add your own at physicsworld.com

I read *Physics World*'s report on India with a keen interest, but I wish it had mentioned the work of the Institute of Mathematical Sciences in Chennai (IMSc), where I earned my PhD. This is partly because the IMSc has just celebrated its golden jubilee: it was officially inaugurated in 1962, after outgrowing its origins as a series of theoretical physics seminars that met in the family home of founding director Alladi Ramakrishnan. More importantly, though, the IMSc – unlike other institutions of specialized research – is seriously concerned with the spread of basic education in its neighbourhood. The reason is a deep-rooted belief that the future of scientific research depends on quality education at all levels all over the country.

The IMSc's interest in local education shows up in the way its faculty enthusiastically engages with the education of college and university teachers by delivering more than 100 lectures each year and also organizing many workshops and courses both within and outside its campus. Its schemes for associate and visiting scholars are very similar to the ones at the Abdus Salam International Centre for Theoretical Physics, in Trieste, Italy, though they operate at a regional level. Faculty members write more than 50 articles each year on popular science and mathematics. Such a vibrant outreach programme is an essential way of serving the Indian physics community.

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Editor's note
We had to be selective about what our special report included, and we acknowledge that it focused more on the success stories in India's physics community than the problems – not least because the peaks are easier to spot and describe. *Physics World* will, however, be continuing to cover physics in India – both positives and negatives – in the future. For those who missed it, the report can be read at http://ow.ly/foCk7.

Making friends versus networking

Marc Kuchner's article on the importance to one's career of making friends, rather than merely "networking" (February pp44–45) said more about a rather strange form of networking – based on collecting signatures from strangers at a conference – than it did about how best to develop professional relationships.

I know a lot of people in my field, related fields and the wider science community. I've met some at conferences, and it does help if you remember their names and register what you have in common, as Kuchner suggests. However, contrary to Kuchner's view that online social networks are only good for superficial interactions, I have found *Twitter* immensely helpful in building and nurturing connections that extend beyond people I have met face-to-face. If I need help with a project of mutual interest, I can ask my *Twitter* contacts and will often get a response, even from people I've never met, or from people who are connected to someone I'm connected to. For example, I am the current director of the ScienceGrrl network (www.sciencegrrl.co.uk), which promotes science to girls and young women and supports those already working the field. ScienceGrrl began on *Twitter* and is largely sustained by it, and it was some time before I met my fellow ScienceGrrls in person, since we are dotted around the UK. Traditional friendship, based on personal contact and shared personal history, is not a prerequisite of initiating effective collaborative working.

People organize their online social networks in different ways. I've found that *Facebook* works best for personal contacts and conversations (my *Facebook* friends are all people I've met and liked), while *Twitter* works well for professional contacts, as people follow you largely because you Tweet on a particular subject. I divide what I broadcast to each network accordingly, but I am not impersonal, dispassionate or apolitical on *Twitter* – I would make for very dull reading if that were the case – and have made some really good friends through it. I've met most of them in person, but not all.

In summary, I don't see the friendships vs networks dichotomy that Kuchner observes. Like most people of my generation, who have changed jobs several times and are connected to wider networks via social media, I just have "people I know". I know some of these people better than others, some well enough to spend time with in person, some well enough to confide in, and a select few to whom I can truly bare my soul. There's a spectrum of friendship, populated by a diverse congregation of fabulous people who connect with me for different reasons and on a range of levels. I'd rather savour the rainbow of variety than segregate them into friends (=useful) and network (=not useful).

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Comment

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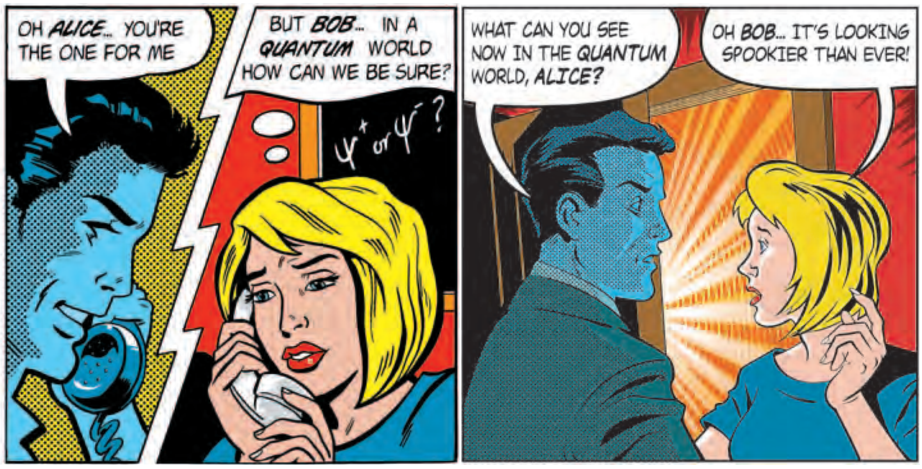


John Richardson; The Comic Stripper

Quantum frontiers

Welcome to this special issue of *Physics World* on ideas at the edge of quantum physics

Quantum mechanics, it is safe to say, is one of the most successful theories in physics. It offers explanations for everything from the behaviour of semiconductors and transistors to lasers and solar cells – and can even account for how and why stars shine. Yet many of the questions raised by quantum mechanics about the subatomic world – and of reality itself – can be mind-blowing. What's more, the quantum world keeps throwing up new surprises and shows no signs of having been fully explored.

This special issue of *Physics World* shines a light on some of the most interesting cutting-edge work at the frontiers of quantum physics. Vlatko Vedral from the University of Oxford kicks things off (pp30–32) by giving you a quick-fire reminder of the key points in quantum physics and a brief summary of the main articles in this issue. These look at the fascinating new paradigm of "weak measurement" (pp35–40), the application of quantum physics to biology (pp42–45), the use of cold atoms to simulate the quantum world (pp47–51) and the use of entanglement for completely secure satellite communication (pp52–56). Two other articles examine the impact of quantum physics on popular culture (pp25–27) and among the physics community itself (p29).

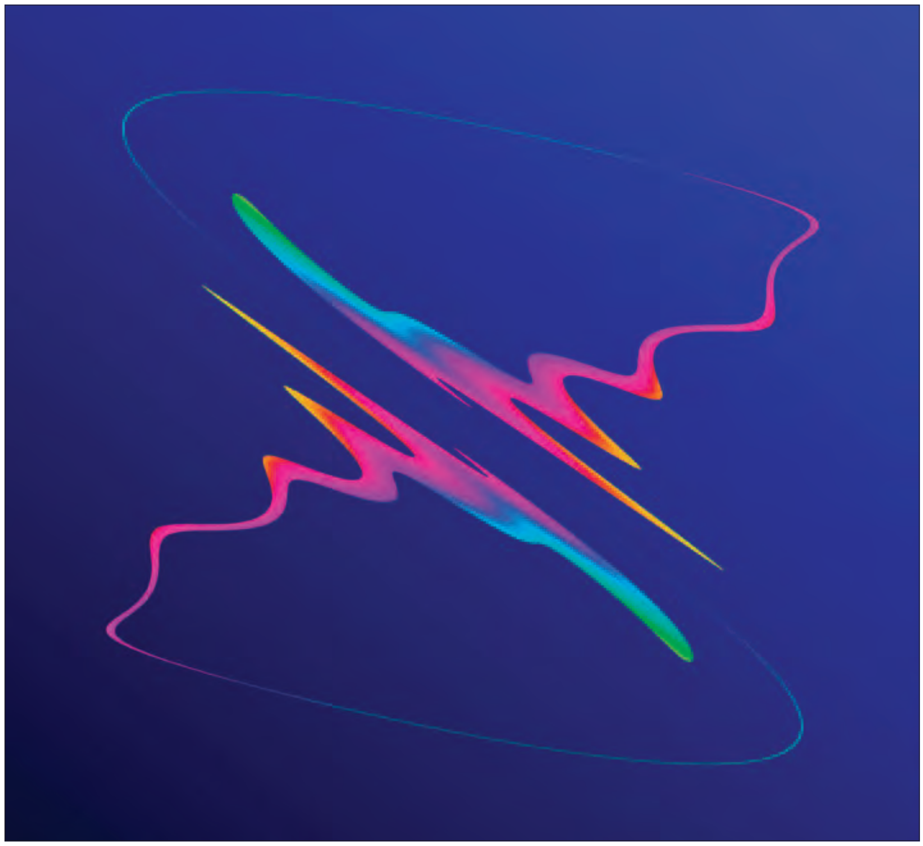
There is much, though, we have missed out for reasons of space, not least quantum computing. It is a topic we have covered before, notably in our last special issue on quantum physics exactly 15 years ago this month. It was graced with one of our most famous cover images (above left), showing Alice and Bob (the names given by convention to those sending and receiving quantum signals) in the style of pop artist Roy Lichtenstein. This month's specially commissioned cover (above right) echoes our earlier image while underlining that the mysteries of the quantum world show no sign of abating.

- If you're a member of the Institute of Physics, do check out our special quantum-related video and audio content in the digital version of *Physics World* via our apps or at members.iop.org.

We're busy right now dreaming up a selection of A-list speakers for a special *Physics World* strand in November at the Bristol Festival of Ideas (www.ideasfestival.co.uk). Meanwhile, planning is under way for our special anniversary issue in October, where we'll be revealing our pick of the 25 key people, discoveries, images, applications and questions in physics now and over the last 25 years.

Critical Point The quantum moment

Quantum mechanics, says **Robert P Crease**, has finally acquired as much cultural influence as Newtonian mechanics, though via a very different path


Eric J Heller/Science Photo Library

Abstract reality Eric J Heller is a Harvard University physicist and chemist who takes computer simulations of quantum processes and turns them into works of art, such as this piece based on a quantum chaos map.

On the outskirts of Cambridge, next door to the Lyndsey McDermott hair salon on Castle Street, is a pub called the Sir Isaac Newton. Ask those inside why it's so named and drinkers are likely to stare at you, muttering something about British greatness, history or the small fact that Newton was educated at the university down the road. But the pub's name reminds us that Newton not only is still a highly influential scientist, but remains a popular icon too. Indeed, his name has also been given to Cambridge University Library's online course catalogue, to an orbiting X-ray observatory and a unit of force, as well as a computer operating system.

But the use of Newton's name as a recognizable "brand" is only the most trivial way in which his work has influenced culture. His greatest legacy – Newtonian mechanics – has affected all human life by deepening our knowledge of the world, by expanding our ability to control it, and by reshaping how scientists and non-scientists alike experience it. The arrival of the Newtonian universe was attractive, liberating and even comforting to many of those in the 17th and 18th centuries; its promise was that the world was not the chaotic, confusing and threatening place it seemed to be – ruled by occult powers and full of enigmatic events – but was simple, elegant and intelligible. Newton's work helped human beings to understand in a new way the basic issues that human beings seek: what they could know, how they should act and what they might hope for.

The Newtonian moment

The Earth and the heavens, according to Newtonian mechanics, were not separate places made of different stuff but part of a "uni-verse" in which space and time – and the laws that govern them – are single, uniform and the same across all scales. This universe is also homogeneous. It is not ruled by ghosts or phantoms that pop up and disappear unpredictably. Everything has a distinct identity and is located at a specific place at a specific time. The Newtonian world is like a cosmic stage or billiard table, where things change only when pushed by forces. All space is alike and continuous, all directions comparable, all events caused.

This picture strongly influenced philosophers, theologians, writers, artists and even political thinkers. Indeed, the philosopher Richard Rorty once referred to "Newtonian political scientist[s]", who centre social reforms around "what human beings are like – not knowledge of what Greeks or Frenchmen or Chinese are like, but of humanity as such". Meanwhile, in 2003–2004, the New York Public Library staged an exhibition entitled "The Newtonian Moment" to showcase Newton's cultural impact and illustrate the revolution in worldview his work brought about. Writing in the exhibition's catalogue, the historian of science Mordechai Feingold declared that the name was chosen because the Enlightenment and Revolution comprised "the epoch and the manner in which Newtonian thought came to permeate European culture in all its forms".

Feingold was using the word "moment" in the way historians do, referring to special turning points in which a radically new idea recasts past conflicts and tensions to open up new possibilities for the future. These turning points are cultural paradigm shifts that change what human beings know and do, and how they interpret their experiences. Features of the Newtonian Moment include the assumption of universal continuity, certainty, predictability, sameness across scales, and the ability of scientists to "take themselves out" of measurements to see nature as it is apart from human existence.

The quantum ambush

The Newtonian Moment lasted for some 250 years until the start of the 20th century, when it was ambushed by the quantum. Many scientists initially hoped that they could find a comfortable place for the quantum on the Newtonian stage, but by 1927 it had become clear that the quantum undermined many features of the Newtonian world, raising unprecedented philosophical as well as scientific issues. "Never in the history of science," wrote the science historian Max Jammer, "has there been a theory which has had such a profound impact on human thinking as quantum mechanics".

Some scientists tried to explain what was happening by spreading word of quantum physics into ever-widening social spheres that lay beyond science itself. These popularizations encountered an enthusiastic audience. Artists, novelists, poets and journalists were fascinated by the non-Newtonian features of quantum mechanics, including discontinuity, uncertainty, unpredictability, and differences across scales and areas where scientists could not take themselves out of measurements. Quantum terms and concepts – including quantum leap, uncertainty principle, complementarity, Schrödinger's cat and parallel worlds – eventually appeared in everyday language in sparkling prose and flamboyant metaphors.

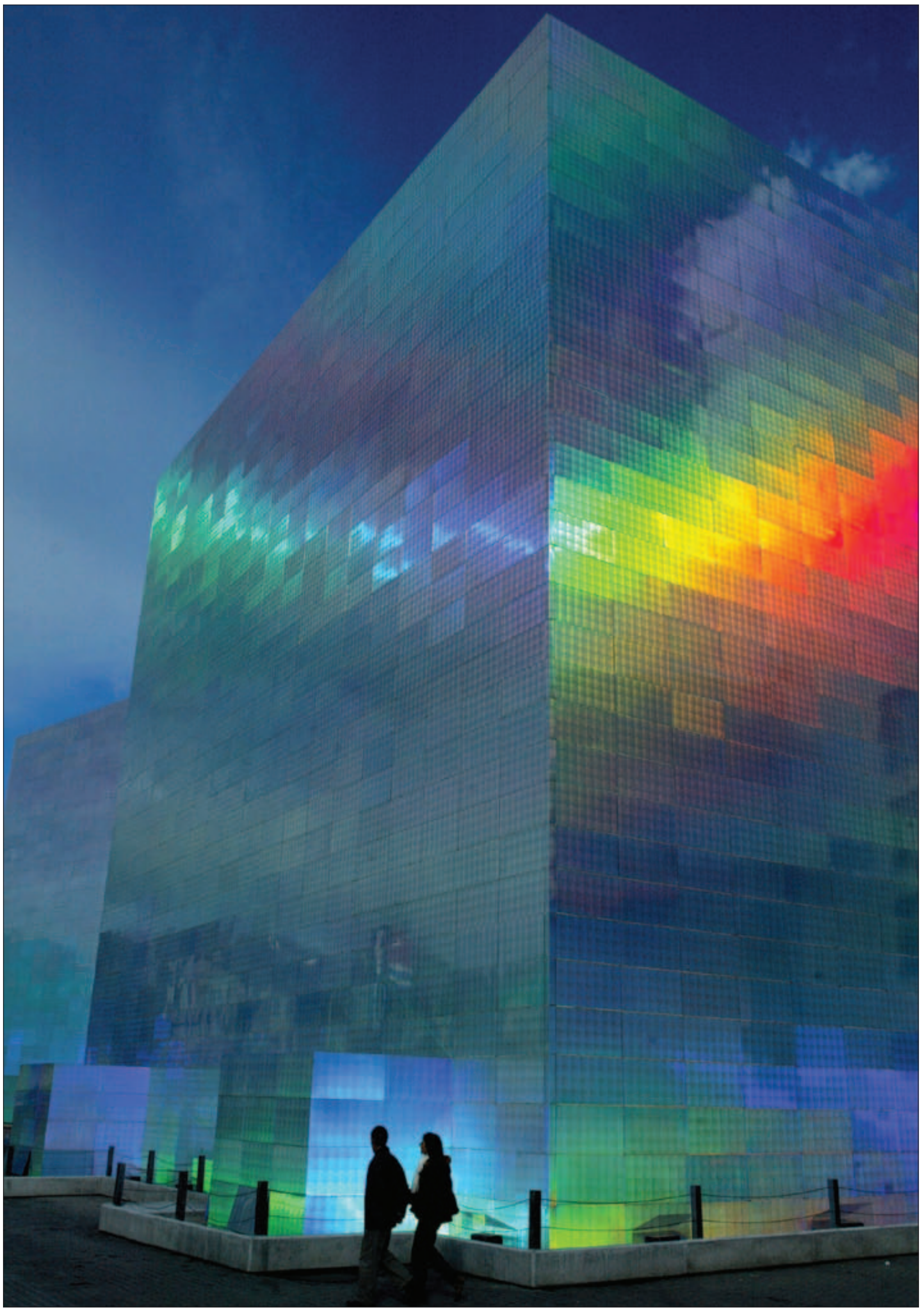
But has the cultural impact of quantum mechanics been simply to supply us with a storehouse of unusual, vivid and sometimes pretentious or even loopy images? Or has the cumulative effect been more serious, and reshaped how even non-scientists view the world?

To some extent, the quantum's impact on artists, writers and philosophers was that it helped free themselves from their own Newtonian-inspired misconceptions. A year or two after the discovery of the uncertainty principle in 1927, for instance, the writer D H Lawrence penned the following poem fragment.

I like relativity and quantum theories
Because I don't understand them.
And they make me feel as if space shifted
About like a swan that can't settle,
Refusing to sit still and be measured;
And as if the atom were an impulsive thing
Always changing its mind.

Lawrence's playfully negative remarks may suggest that his attraction is superficial: he likes relativity and quantum theories because they connect better with his experiences of the world as quixotic and immeasurable. A similar sentiment was expressed by the Austrian-Mexican artist Wolfgang Paalen in 1942 when he wrote excitedly that quantum mechanics heralds "a new order in which science will no longer pretend to a truth more absolute than that of poetry". The outcome, he continued, will be to legitimize the value of the humanities, and "science will understand the value of art as complementary to her own".

Meanwhile, in 1958 when the New York University philosopher William Barrett reviewed 20th century scientific developments, including quantum mechanics, he concluded that they paint an image of man "that bears a new, stark, more nearly naked, and more questionable aspect". We have been forced to confront our "solitary and groundless condition" not only through existentialist philosophy but also via science itself, which has triggered "a denudation, a stripping down, of this being who has now to confront himself at the centre of all his horizons".


Reuters/Vincent West

Popular physics A couple walks past "Quantum Field-X3", an installation by Japanese artist Hiro Yamagata, outside the Guggenheim Museum in Bilbao, Spain.

Such remarks suggest that humanists embraced quantum mechanics because they experienced the Newtonian universe as a cold and constricting place in which they felt defensive and marginalized – with the news of the strangeness of the quantum domain coming almost as a relief. But if this is the only reason humanists found developments of the quantum world liberating, it was surely their own doing, for they were relying far too seriously on science to begin with in understanding their own experience.

A new humanism

In 1967 the critic and novelist John Updike wrote a brief reflection on the photographs and amateur films taken in Dealey Plaza in Dallas, Texas on 22 November 1963, in the few momentous seconds when President John F Kennedy's motorcade drove through and he was hit by an assassin's bullets. The more closely and carefully the frames were examined, Updike noted, the less sense the things in them made. Who was the "umbrella man" sporting an open umbrella despite it being a sunny day? Who was the "tan-coated man" who first runs away, then is seen in "a gray Rambler driven by a Negro?" What about the blurry figure in the window *next* to the one from which the shots were fired? Were these innocent bystanders or part of a conspiracy?

"We wonder," Updike wrote, "whether a genuine mystery is being concealed here

Has the cultural impact of quantum mechanics been simply to supply us with a storehouse of unusual, vivid and sometimes pretentious or even loopy images?

or whether any similar scrutiny of a minute section of time and space would yield similar strangenesses – gaps, inconsistencies, warps and bubbles in the surface of circumstance. Perhaps, as with the elements of matter, investigation passes a threshold of common sense and enters a subatomic realm where laws are mocked, where persons have the life-span of beta particles and the transparency of neutrinos, and where a rough kind of averaging out must substitute for absolute truth."

Years later, many frames turned out to have rational explanations. The "umbrella man" was identified – to the satisfaction of all but diehard conspiracy theorists. Testifying before a Congressional committee, the man in question said he had been simply protesting against the Kennedy family's dealings with Hitler's Germany, with the black umbrella – Neville Chamberlain's trademark fashion accessory – being a symbol for Nazi appeasers. Far from heralding a breach in the rationality of the world, the umbrella man was just a heckler.

Barrett, being a philosopher, had proposed that the cultural effect of quantum mechanics was to strip us of illusions. Updike, a novelist with a keen interest in science who followed contemporary developments in physics with care, reached a different conclusion. His words above indicate that he saw the impact of quantum mechanics on culture to be deeper and more positive than Barrett had. Indeed, Updike often has his fictional characters refer to physics terms in a metaphorical way that allows them to voice their experiences more articulately.

The novelist was fully aware that when scientists look at the subatomic world frame by frame, so to speak, what they find is discontinuous and strange – its happenings random except when collectively considered. Updike also knew that most of us tend to find our lives following a similar crazy logic. Our world does not always feel smooth, continuous, reliable, law-governed, stable and substantive; close up, its palpable sensuousness is often jittery, discontinuous, chaotic, irrational, unstable and ephemeral. Reality today does not seem to have the gentle, universal continuities of the Newtonian world, but is more like that of the surface of a boiling pot of water. Using quantum language to describe everyday conditions may therefore be technically incorrect but is metaphorically apt.

In another essay, Updike wrote that "our century's revelations of unthinkable largeness and unimaginable smallness, of abysmal stretches of geological time when we were nothing, of supernumerary galaxies and indeterminate subatomic behaviour, of a kind of mad mathematical violence at the heart of matter have scorched us deeper than we know". The scorching brought about by such scientific discoveries, Updike proposed, had given birth to a "new humanism" whose "feeble, hopeless voice" is provided by the "minimal monologuists" of the Irish playwright Samuel Beckett – and which is also evident in the instantly recognizable "wire-thin, eroded figures" of the Swiss sculptor Alberto Giacometti.

The critical point

If only all human voices were as articulate as Beckett and Giacometti! Too frequently, the use of quantum language and concepts in popular culture amounts to what the physicist John Polkinghorne calls "quantum hype", or the invocation of quantum mechanics as "sufficient licence for lazy indulgence in playing with paradox in other disciplines". This is how it principally appears in things like TV programmes, cartoons, T-shirts and coffee cups.

Updike's remarks, however, suggest that quantum mechanics – a theory of awesome comprehensiveness that has yet to make an unconfirmed prediction – has does more than help to deepen our knowledge of the world and to expand our ability to manipulate it. The novelist's remarks suggest that quantum mechanics – though a modification, not a replacement, of Newtonian mechanics – has provided us with a range of novel and helpful images to interpret our experiences of the world in a new way, on a scale equal to or possibly even greater than Newtonian mechanics. Quantum physics is metaphorically appealing because it reflects the difficulty we face in describing our own experiences; quantum mechanics is strange and so are we.

Someday, indeed, the era after the Newtonian Moment may come to be known as the Quantum Moment.

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Agreeing to disagree

A recent poll has highlighted physicists' differing views over the interpretation of fundamental aspects of quantum theory, but **Maximilian Schlosshauer** argues that it might not be so bad

"If all this damned quantum jumping were really to stay," Erwin Schrödinger complained to his colleague Niels Bohr in 1926, "I should be sorry I ever got involved with quantum theory." Schrödinger, like Bohr, was a founding father of quantum theory, which had just turned our view of the world upside down. But he was not alone in his discomfort. Albert Einstein, too, spent years arguing with Bohr over whether atomic events are fundamentally random or if quantum theory really is all we can say about physical reality. Indeed, he once wrote that the theory reminded him of "the system of delusions of an exceedingly intelligent paranoiac".

Today quantum theory underlies all modern technology: from transistors, light-emitting diodes and photovoltaics, to nuclear power, magnetic-resonance imaging, lasers and atomic clocks. It is a seemingly inexhaustible source of new ideas and applications. Quantum-information science, for example, is a fresh take on information processing, and promises computers faster than anything we could currently imagine.

No-one, of course, would dispute the immense successes of quantum theory. But looking at the heart of quantum theory itself, are we any closer to agreeing what it is trying to tell us about nature? Or has nothing really changed since the 1920s?

Multiple choices

Traunkirchen in Austria is a picture-postcard village. Sitting by a pristine lake and surrounded by the snow-capped peaks of the Alps, it was the perfect setting for a conference in July 2011 on "quantum physics and the nature of reality". Together with Johannes Kofler from the Max Planck Institute of Quantum Optics and Anton Zeilinger from the University of Vienna, I polled nearly three dozen leading physicists, philosophers and mathematicians about their views on quantum theory.

The questionnaires consisted of 16 multiple-choice questions that probed the whole spectrum of fundamental questions about quantum theory. Knowing how fierce debates can be regarding the foundations of quantum theory, we knew that we should expect disagreement, but some of the results, which we recently analysed, surprised even us seasoned quantum physicists (arXiv:1301.1069).

iStockphoto/pixhook

God does not play dice Einstein disagreed that at a quantum level the universe is random.

> Quantum physics has moved from philosophy to concrete action

The respondents were sharply divided on questions that Bohr and Einstein quarrelled about. For example, when we asked whether the physical properties of objects are well defined before these properties are actually measured, half of the respondents said that sometimes they were, while the other half answered with a categorical "no". And when we asked how best to interpret the wave functions that physicists use to calculate the probabilities of their measurement results, a quarter of respondents said the wave functions are something akin to a physical property. A quarter said they are merely a representation of what we know about the object, while a third preferred a mixture of the two options.

But what surprised us most were not so much the disagreements as the precious patches of common ground that our poll brought to light. Quantum theory tells us with great accuracy how likely it is for an atom to decay at a certain time, but it does not tell us when it will actually decay – the individual event, when it happens, seems to come out of nowhere. Einstein could not accept the idea of a universe in which events truly randomly fall out one way or the other, famously declaring that "God doesn't play dice." But Einstein's reservations didn't seem to faze our respondents. A two-thirds majority declared Einstein's view wrong and randomness a fundamental concept in nature, and half thought that the randomness we see in quantum phenomena is indeed fundamental and irreducible: that there is no "hidden hand"– no gambling God – governing these events.

The challenge ahead

So what can we learn from our poll? One thing is clear: quantum physics has moved from philosophical debates to concrete action. Quantum-information science, hailed by an overwhelming majority as a breath of fresh air, is being put to use in looking at old problems from a new angle. It has helped us not only to get a better understanding of what we can do with quantum theory, but also to find new ways of understanding the theory itself. Various new interpretations based around quantum information have popped up in the last decade, and our poll shows them rivalling the traditional interpretations. And instead of just slapping an interpretation on a ready-made theory, people now try to actually derive quantum theory from simple, physical principles – a new take on the theory that a majority in our poll found useful.

Nearly 90 years after Schrödinger's exasperated cry about "this damned quantum jumping", the jumping goes on and it has got us to an awful lot of new places. In fact, two-thirds of our respondents see no limit for quantum theory's reach. They think it should be possible, in principle at least, to put not only single atoms into quantum superpositions, but also everyday objects such as a football, or even living organisms. Indeed, this is the kind of situation Schrödinger had ridiculed in his famous paradox, in which quantum theory forces a cat into an otherworldly state of dead and alive. What Schrödinger had intended as a *reductio ad absurdum* has today become just another challenge to experimentalists.

Maximilian Schlosshauer is a quantum theorist at the University of Portland in Oregon. He edited *Elegance and Enigma* – a collection of interviews with quantum physicists, e-mail schlossh@up.edu

The curious state of quantum physics

Spooky, random and incompatible with gravity – that's the old news for quantum physics. Now we can measure the state of a wavefunction without it "collapsing" and have plans to quantum-communicate with satellites in space. **Vlatko Vedral** opens this special issue of *Physics World* by bringing us up to speed with the latest mysteries of the quantum world

Vlatko Vedral is a professor of quantum information theory at the University of Oxford and the National University of Singapore, e-mail vlatko.vedral@qubit.org

In 1900 Lord Kelvin famously pronounced that "there is nothing new to be discovered in physics. All that remains is more and more precise measurement". The timing of this prediction was spectacularly bad. On 14 December of the same year Max Planck published a paper introducing the concept of quanta, thereby starting a new revolution in physics that would lead us to a completely different understanding of the world.

Over the following three decades quantum physics was fully developed, and applied to explain a wide range of phenomena. It now accounts for the basic properties of small objects such as atoms and subatomic particles, as well as the world of intermediate objects such as solids, describing, for example, their conductivity and superconductivity. Quantum physics equally applies to astronomically large objects, such as stars, explaining why and how they shine, as well as correctly predicting the size of white dwarfs. Even spiders use quantum physics when crawling up vertical walls without succumbing to gravity.

But despite the success of quantum physics, there is one thing it does not explain: gravity – the only fundamental force that is still impervious to quantization. Some people think that this means gravity is not a fundamental force after all, but a consequence of something else (and hence we might not need to quantize it). Others, most notably the University of Oxford physicist Roger Penrose, maintain that quantum physics will ultimately crush under the weight of gravity.

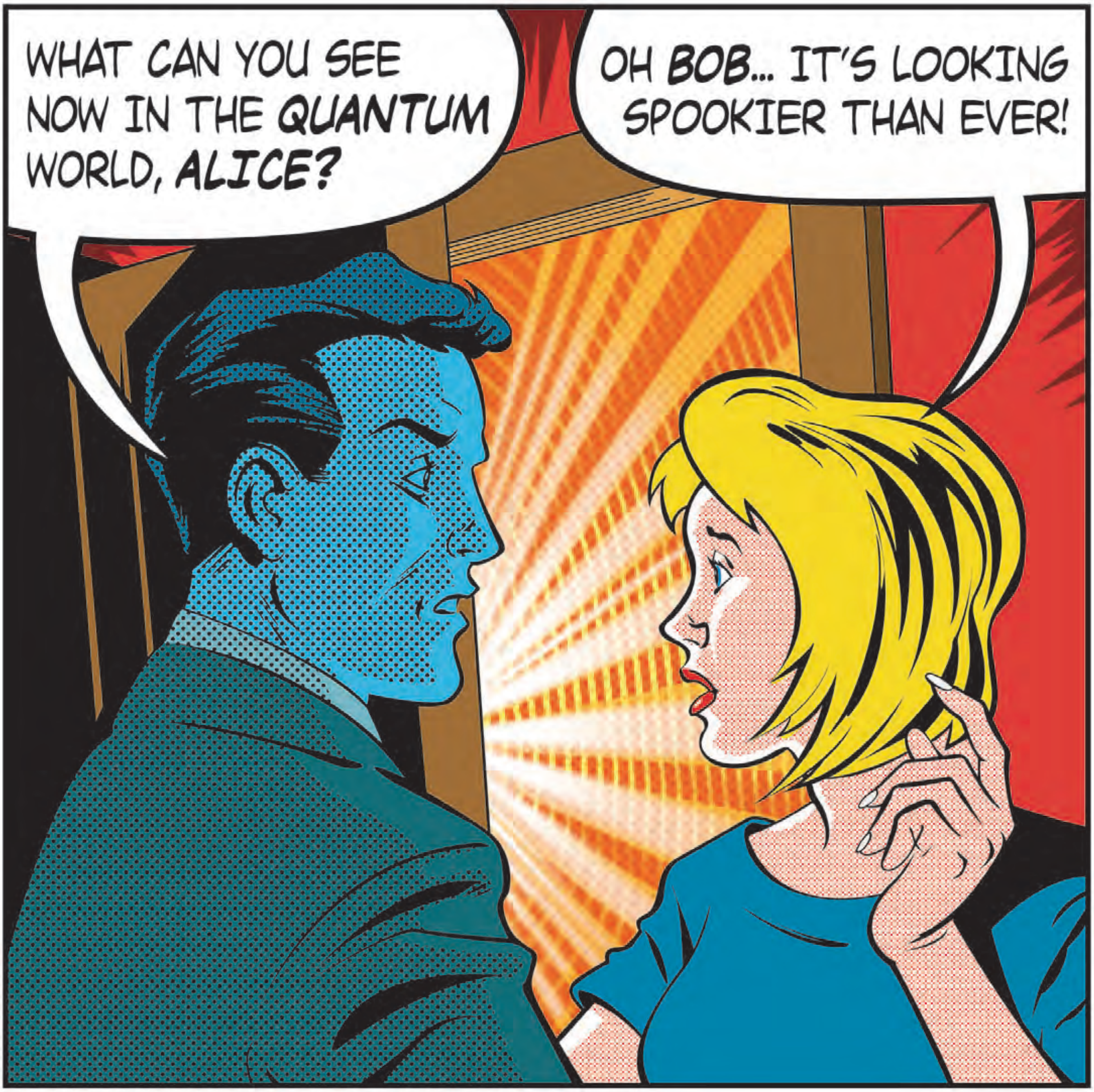
Quantum physics departs from classical physics in two key aspects. First, it acknowledges that the most fundamental events in the microscopic world are genuinely random, i.e. that there is no algorithm for predicting when an atom will emit a photon or when an incoming photon will reflect from your sunglasses. Albert Einstein, who was a determinist, complained a great deal about randomness in quantum physics, most memorably in discussions with Niels Bohr, using the now-famous catchphrase "God does not play dice". The second big departure in quantum physics is the existence of correlations – how measurements on one system give results related to measurements on another – which are independent of space and time, and connect objects into a network of interdependent entities. Erwin Schrödinger called these correlations "quantum entanglement", while Einstein complained about this aspect of quantum physics even more than about randomness, dismissing entanglement as "spooky action at a distance".

Both properties of quantum physics that Einstein disliked have, however, since been confirmed in numerous experiments. Quantum randomness is now being used in cryptography to improve the secrecy of communications and quantum entanglement provides the basis for many of the fast-developing quantum technologies. Indeed, last year's Nobel Prize for Physics went to David Wineland and Serge Haroche for making the first steps in this direction.

Behind both the randomness and the spooky action is the notion of quantum superposition, namely the fact that quantum systems can exist in many different states at the same time. However, we still do not really understand in which situations the superposition principle is valid, nor do we really understand what it would mean for a macroscopic object to be in two or more different states at the same time.

For a theory as successful as quantum physics, it is indeed curious that we are still arguing about its meaning. It seems that the macroscopic world we live in is largely governed by classical physics and it is very different from the world that quantum objects occupy. But, of course, it must be possible to derive the classical world from the quantum world. After all, large objects are collections of many atoms, each of which behaves fully quantum mechanically.

The connection between quantum and classical physics is provided through the notion of a quantum measurement. Properties of quantum systems, such as their positions and momenta, are generally indeterminate until we make a measurement. It is only by measuring, say, the position of an atom that we imprint a definitive location on it. However, this measurement at the same time makes the atom's velocity uncertain. Quantum measurements are like



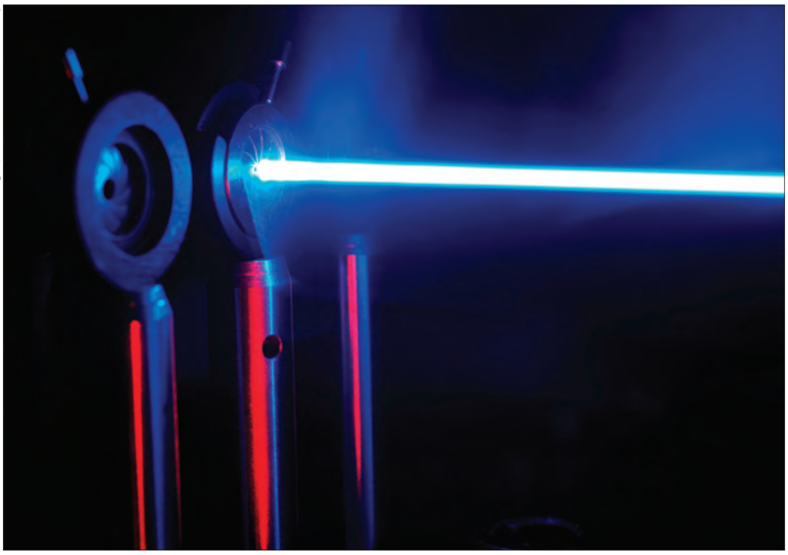
The Comic Stripper

footsteps on a dusty road – the firmer they are in establishing footprints, the more dust they raise, and this cloud of dust prevents us from seeing the footprints clearly in the future.

Curiouser and curiouser

To understand the unintuitive nature of quantum measurement we must first understand what kind of a process a measurement is. According to the standard dogma of quantum physics, quantum systems evolve differently when measured from how they evolve when they are "free", i.e. when they are left alone. Observation, in other words, affects quantum behaviour (unlike in classical physics where measuring a car's speed does not change how fast the vehicle is going). However, between the free evolution and the full measurement there is a continuum of possibilities, known by the name of weak measurements. When these were introduced in 1988 by Yakir Aharonov and colleagues, they caused a great deal of excitement. Weak measurements obtain information about the system (albeit only partial), but they do not change the state much (hence the name "weak"). This leads to the possibility of undoing the quantum measurement, at least with a high probability. "Uncollapsing the collapse" sounds like a contradiction in terms, but the key issue is that the measurement is only weak. Other quantum paradoxes can be viewed through weak measurements, as Aephraim Steinberg and colleagues explain elsewhere in this issue (pp35–40).

Even without fully understanding the picture of the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Beam me up
Entangled photons can be used for quantum teleportation, quantum computing and possibly even secure satellite communications.

world according to quantum physics, we can still use quantum systems to develop new technologies. One of the key advantages of quantum systems is their universality – in other words, every quantum system of sufficient complexity should be able to simulate efficiently every other quantum system. One of the most developed quantum simulators at present uses atoms cooled down to near absolute zero. The interactions between these cold atoms can be tuned so well in the laboratory that they can be made to interact in many different ways, allowing them to simulate the behaviour of other systems. This is useful first and foremost because some physical systems, such as high-temperature superconductors, are so complicated that it is difficult to determine their exact quantum description by measuring them directly. Simulating their behaviour with atoms lets us extract what we believe to be the essence. Moreover, we can also simulate the behaviour of systems we are not even sure exist in nature.

For example, Majorana fermions are meant to be fermionic particles (like electrons), but at the same time they are their own antiparticles (unlike electrons). At present only bosons, such as photons, are known to also be their own antiparticles so we do not really know if Majorana fermions exist. Interestingly, this does not prevent us from simulating them with cold atoms. But is our ability to simulate things that nature does not create itself a deep and fundamental property of the universe? Or is nature's way of making Majorana fermions first to make humans who then figure out how to artificially make (i.e. simulate) Majorana fermions? To paraphrase Bohr, a physicist is just a Majorana fermion's way of creating itself. Immanuel Bloch explores this fascinating topic for us on pages 47–50.

Beyond the physics lab

Quantum physics may often sound like science fiction, but surely Bohr, Einstein or any of its founders would never have believed that it might one day be possible to do quantum experiments in space. The main motive for taking quantum experiments to this new frontier is that if our future communication technology is to be fully quantum, it will involve quantum communication between quantum computers based on Earth and on satellites. The current world record in distant quantum-information processing is held by Anton Zeilinger and colleagues, who teleported a quantum bit across a distance of 143 km between the Canary Islands of La Palma and Tenerife. This terrestrial record will be smashed once we move into space – the fact that there are very few atoms around eliminates a great deal of the noise we have to face when doing experiments on Earth.

Performing quantum experiments in space will also allow us to test fundamental physics theories in regimes we have never before been able to access. That is because it will let us send signals over large distances, between platforms moving at large relative speeds, all in near-vacuum conditions. Indeed, certain tests of alternative theories to quantum physics, such as Penrose's gravitationally induced collapse, are only realistically possible in space. The problem is the measurements required are very sensitive since the effects postulated at the boundary of quantum physics and gravity are rather meagre and any other potential noise needs to be eliminated. For more on this fascinating topic of space-based quantum physics, check out the article by Brendon Higgins and Thomas Jennewein (pp52–56).

Quantum physics is also proving useful in our understanding of biology, which has traditionally been based on classical physics given that biological molecules are so large, warm and wet. After all, systems that interact strongly with their environment (and so are warm and wet) cannot behave coherently because the environment itself impedes quantum coherence. Moreover, large molecules have many more ways in which quantum coherence can be destroyed. However, we are now discovering that biology may use some of the more sophisticated quantum tricks to improve its processing. One interesting case, which Jim Al-Khalili explains, is the possibility that DNA mutations are the result of the quantum tunnelling of hydrogen (pp42–45). Other fascinating examples are bacteria implementing a quantum random walk to optimize photosynthesis, birds using entangled electrons to determine the inclination of the Earth's magnetic field and the amazing possibility that we humans and other animals can smell quantum superpositions.

Anybody's guess

So what of the future? I predict that in 2013 we will see the first implementation of quantum teleportation between satellites. We will also see the first cold-atom simulation of non-Abelian anyons (particles with a behaviour that lies somewhere between fermions and bosons). We will have more evidence that biological energy transport is fundamentally quantum mechanical. We will almost certainly still puzzle over the meaning of quantum measurement. And finally, I am convinced that another Nobel prize will be given for testing quantum-mechanical effects, most likely the existence of the Higgs boson.

My predictions will almost certainly be wrong, but even if they are, quantum physics is guaranteed to keep us tantalized for many years to come. ■

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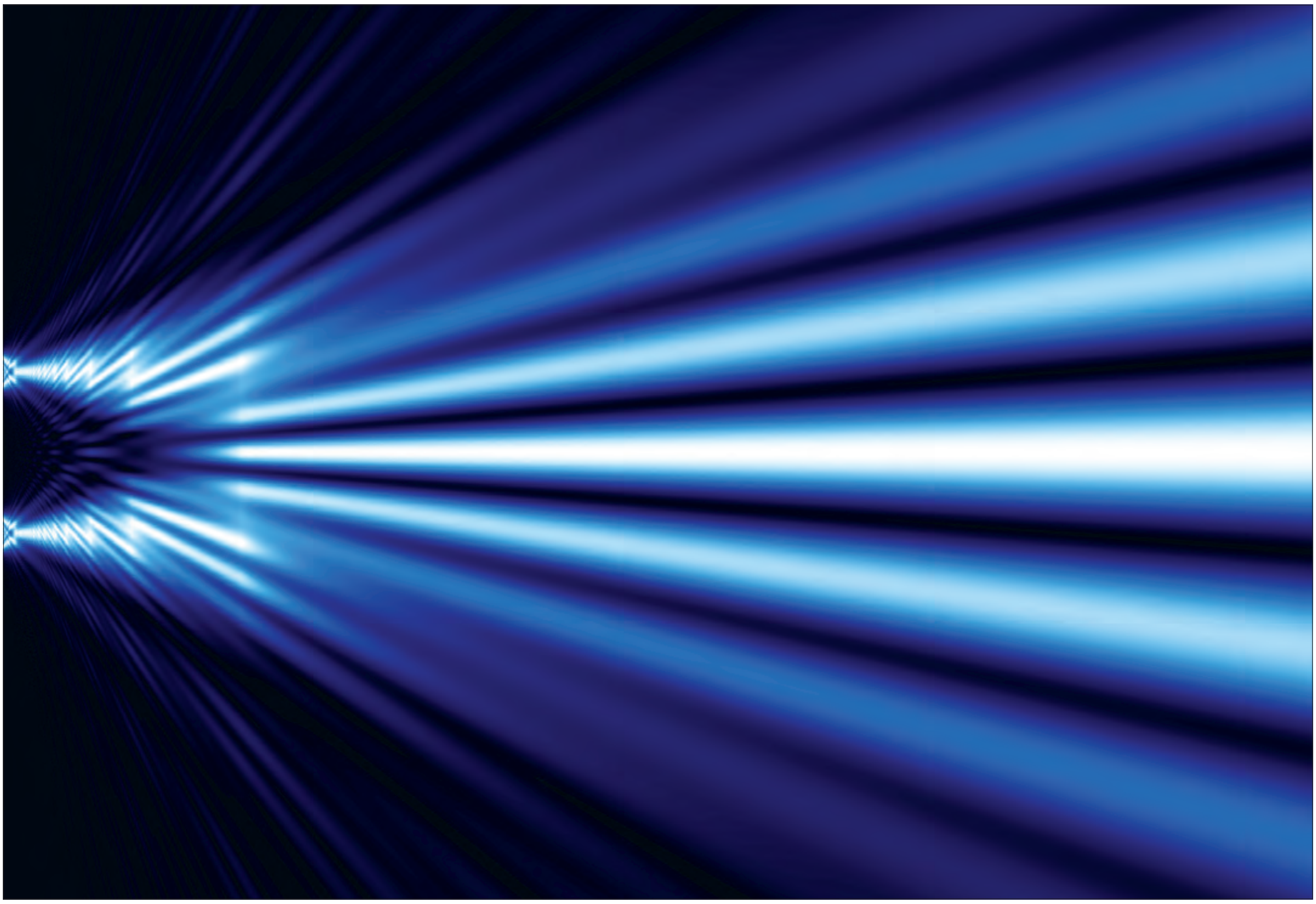

In praise of weakness

Quantum physics is being transformed by a radical new conceptual and experimental approach known as weak measurement that can do everything from tackling basic quantum mysteries to mapping the trajectories of photons in a Young's double-slit experiment. **Aephraim Steinberg**, **Amir Feizpour**, **Lee Rozema**, **Dylan Mahler** and **Alex Hayat** unveil the power of this new technique

"There is no quantum world," claimed Niels Bohr, one of the founders of quantum mechanics. This powerful theory, though it underlies so much of modern science and technology, is an abstract mathematical description that is notoriously difficult to visualize – so much so that Bohr himself felt it a mistake to even try. Of course, there are rules that let us extract from the mathematics some predictions about what will happen when we make observations or measurements. To Bohr, the only real task of physics was to make these predictions, and the hope of actually elucidating what is "really there" when no-one is looking was nonsense. We know how to predict what you will see if you look, but if you do not look, it means nothing to ask "What would have happened if I had?".

The German theorist Pascual Jordan went further. "Observations," he once wrote, "not only disturb what is to be measured, they produce it." What Jordan meant is that the wavefunction does not describe reality, but only makes statistical predictions about potential measurements. As far as the wavefunction is concerned, Schrödinger's cat is indeed "alive and dead". Only when we choose what to measure must the wavefunction "collapse" into one state or another, to use the language of the Copenhagen interpretation of quantum theory.

Over the last 20 years, however, a new set of ideas about quantum measurement has little by little been gaining a foothold in the minds of some physicists. Known as weak measurement, this novel paradigm has already been used for investigating a number of basic mysteries of quantum mechanics. At a more

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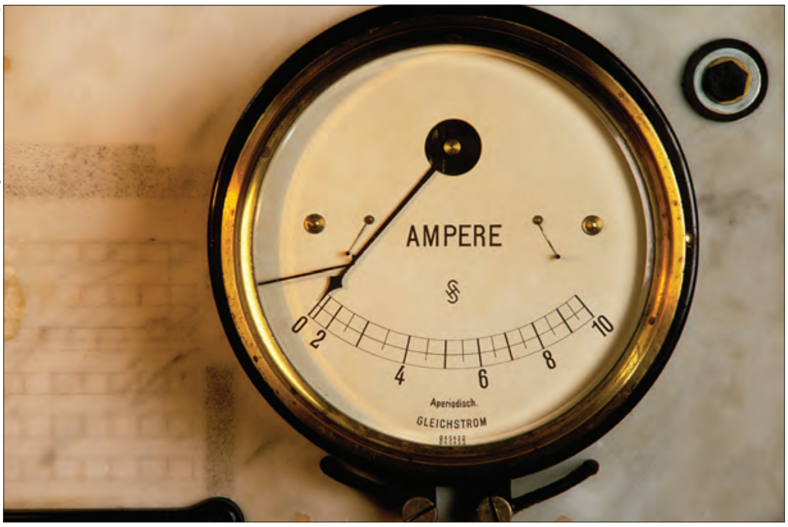

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Point and tell
Making a measurement with a classical device is simple: where the needle points provides information about the current flowing through it. The concept of measurement in quantum physics is a much more complex affair.

practical level, it has also been used to develop new methods for carrying out real-world measurements with remarkable sensitivity. Perhaps most significantly in the long run, some researchers believe that weak measurements may offer a glimmer of hope for a deeper understanding of whatever it is that lies behind the quantum state.

Quantum measurement theory

Before quantum mechanics was established, no-one seemed to feel the need for a distinct theory of measurement. A measuring device was simply a physical system like any other, and was described according to the same physical laws. When, for example, Hans Christian Ørsted discovered that current flowing in a wire caused a compass needle to move, it was natural to use this fact to build galvanometers, in which the deflection of the needle gives us some information about the current. By calibrating the device and using our knowledge of electromagnetism, we can simply deduce the size of the current from the position of the needle. There is no concept of an "ideal" measurement – every measurement has uncertainty, and may be influenced by extraneous factors. But as long as the current has had some effect on the needle then, if we are careful, we can look at the needle and extract some information about the current.

Quantum theory, however, raises some very thorny questions, such as "What exactly is a measurement?" and "When does collapse occur?". Indeed, quantum mechanics has specific axioms for how to deal with measurement, which have spawned an entire field known as quantum-measurement theory. This has, however, created a rather regrettable situation in which most people trained today in quantum mechanics think of measurement as being defined by certain mathematical rules about "projection operators" and "eigenvalues", with the things experimentalists call "measurements" being nothing more than poor cousins to this lofty theory. But physics is an experimental science. It is not the role of experiment to try to come as close as possible to some idealized theory; it is the role of theory to try to describe (with idealizations when necessary) what happens in the real world.

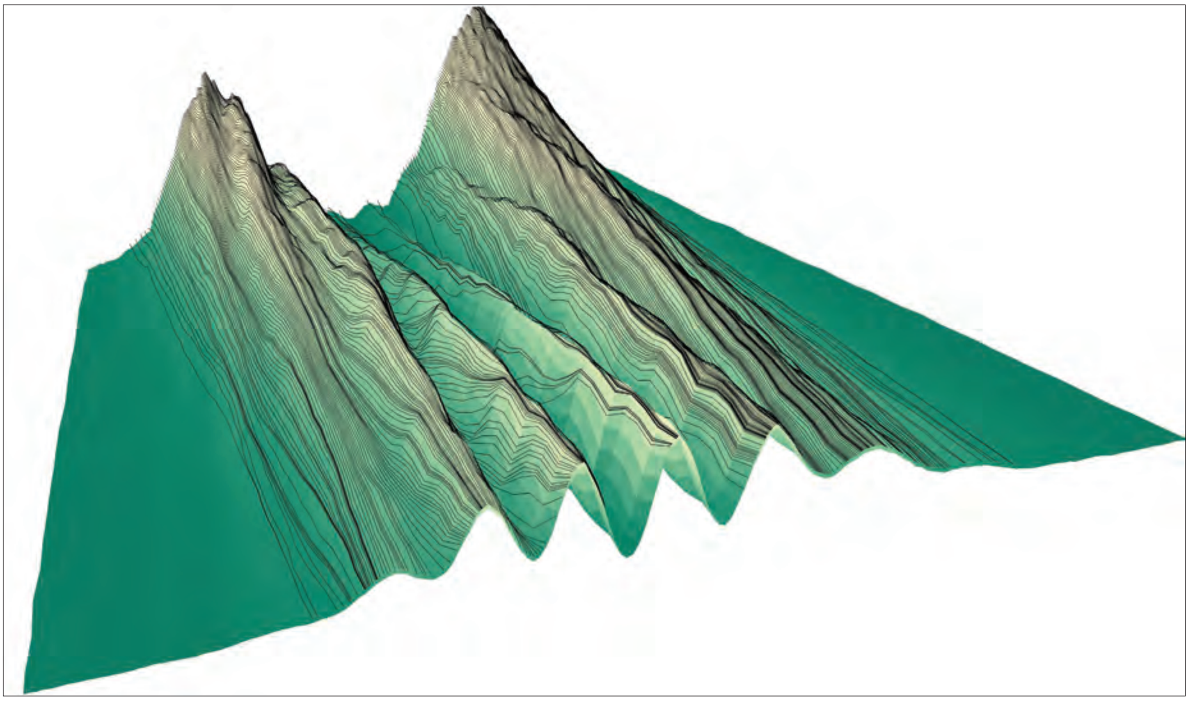
Such a theory was in fact worked out in 1932 by the Hungarian theorist John von Neumann, who conceived of a measurement as involving some interaction between two physical objects – "the system" and "the meter". When they interact, some property of the meter – say, the deflection of a galvanometer needle – will change by an amount proportional to some observable of the system, which would, in this case, be the current flowing through the wire. Von Neumann's innovation was to treat both the system and the meter fully quantum-mechanically, rather than assuming one is classical and the other quantum. (Strange as it may seem, it is perfectly possible to describe a macroscopic object such as a galvanometer needle in terms of quantum mechanics – you can, for instance, write down a "wavepacket" describing its centre of mass.) Once this step is taken, the same theory that describes the free evolution of the system can also be used to calculate its effect on the meter – and we have no need to worry about where to place some magical "quantum–classical borderline".

This leads to a wrinkle, however. If the meter itself is quantum-mechanical, then it obeys the uncertainty principle, and it is not possible to talk about exactly where its needle is pointing. And if the needle does not point at one particular mark on the dial – if it is rather spread out in some broad wavepacket – then how can we hope to read off the current? Von Neumann imagined that in a practical setting, any measuring device would be macroscopic enough that this quantum uncertainty could be arranged to be negligible. In other words, he proposed that a well-designed observation would make use of a needle that, although described by a wave packet with quantum uncertainty, had a very small uncertainty in position. Provided that this uncertainty in the pointer position was much smaller than the deflection generated through the measurement interaction, that deflection could be established reasonably accurately – thus providing us with a good idea of the value of the quantity we wished to measure.

But the small uncertainty in the position of the needle automatically means that it must have a very large momentum uncertainty. And working through the equations, one finds that this momentum uncertainty leads to what is often referred to as an "uncontrollable, irreversible disturbance", which is taken by the Copenhagen interpretation to be an indispensable by-product of measurement. In other words, we can learn a lot about one observable of a system – but only at the cost of perturbing another. This measurement disturbance is what makes it impossible to reconstruct the full history of a quantum particle – why, for example, we cannot plot the trajectory of a photon in a Young's double-slit experiment as it passes from the slit to the screen. (Actually, as explained in the box on p40, it turns out that weak measurement provides a way of plotting something much like a trajectory.)

Enter weak measurement

The idea of weak measurement was first proposed by Yakir Aharonov and co-workers in two key papers in 1988 and 1990 (*Phys. Rev. Lett.* **60** 1351 and *Phys. Rev. A* **41** 11). Their idea was to modify Von Neumann's prescription in one very simple but profound



Strength in weakness Obtained through the principle of weak measurement, this 3D plot shows where a quantum particle is most likely to be found as it passes through a Young's double-slit apparatus and exhibits wave-like behaviour. The lines overlaid on top of the 3D surface are the experimentally reconstructed average paths that the particles take through the experiment.

way. If we deliberately allow the uncertainty in the initial pointer position (and hence the uncertainty in the measurement) to be large, then although no individual measurement on a single pointer will yield much information, the disturbance arising from a measurement can be made as small as desired.

At first sight, extracting only a tiny bit of information from a measurement might seem to be a strange thing to do. But as is well known to anyone who has spent hours taking data in an undergraduate laboratory – not to mention months or years at a place like CERN – a large uncertainty on an individual measurement is not necessarily a problem. By simply averaging over enough trials, one can establish as precise a measure as one has patience for; at least until systematic errors come to dominate. Aharonov called this a weak measurement because the coupling between the system and the pointer is assumed to be too weak for us to resolve how much the pointer shifts by on just a single trial.

Under normal circumstances, the result of a weak measurement – the average shift of pointers that have interacted with many identically prepared systems – is exactly the same as the result of a traditional or "strong" measurement. It is, in other words, the "expectation value" we are all taught to calculate when we learn quantum theory. However, the low strength of the measurement offers a whole new set of insights into the quantum world by providing us with a clear operational way to talk about what systems are doing between measurements. This can be understood by considering a protocol known as post-selection (see figure 1).

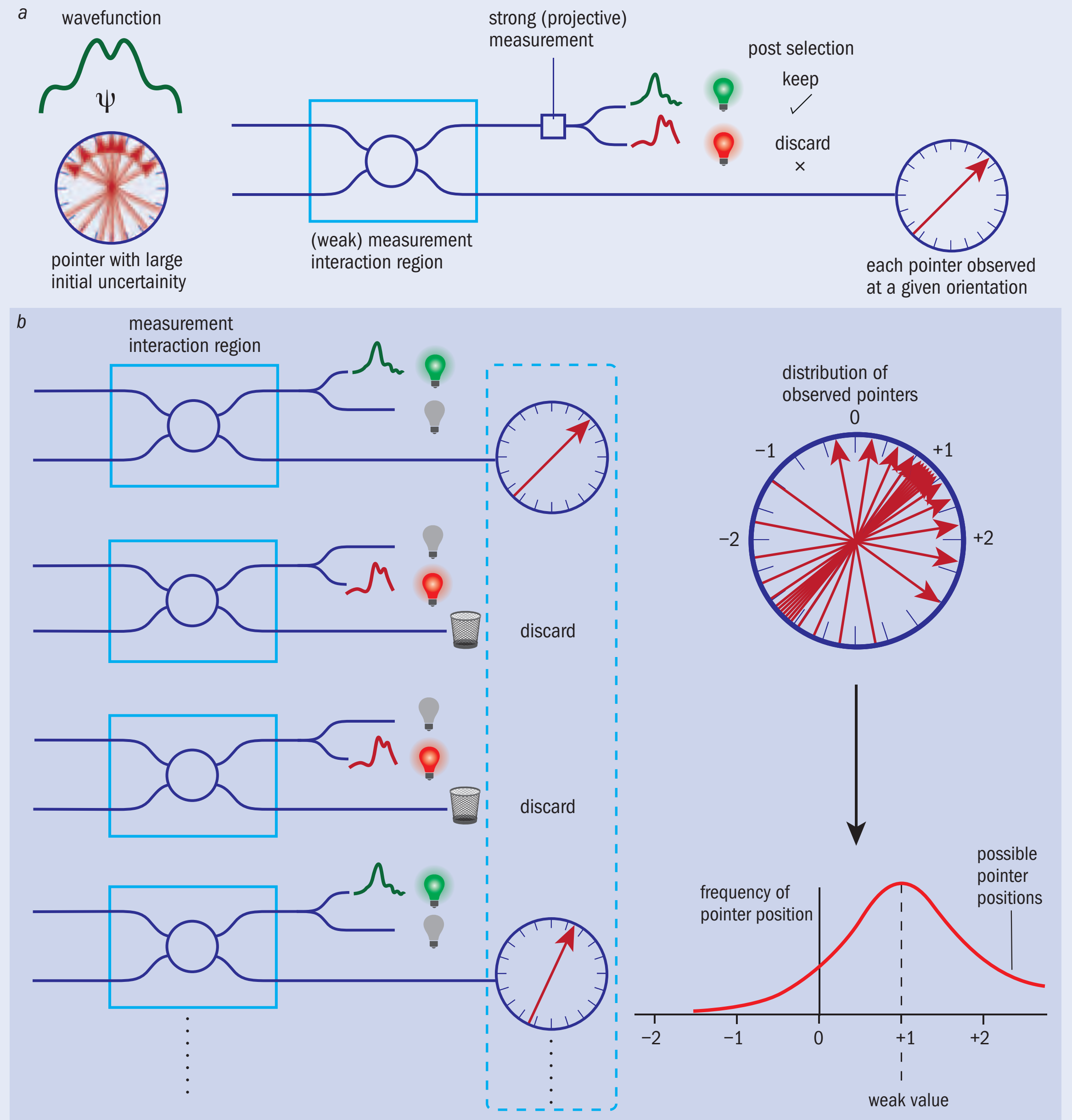
To see what post-selection is all about, let's consider a simple experiment. Suppose we start at time $t = 0$ by placing some electrons as precisely as we can at position $x = 0$. We know from Heisenberg's uncertainty principle that their velocity will be enormously uncertain, so we will have essentially no idea where an electron will be after, say, 1 second. But if we place a detector 1 metre away at $x = 1$, any given electron will always have some chance of being spotted there at $t = 1$ because the wavepacket has spread out over all space. However, when we make a measurement of where the wavepacket is, it may collapse to be at $x = 1$, or to be elsewhere.

Now suppose we take one of these electrons that appeared at $x = 1$, which is what we mean by post-selection, and ask ourselves how fast it had been travelling. Anyone with common sense would say that it must have been going at about 1 m/s, since it got from $x = 0$ to $x = 1$ in 1 s. Yet anyone well trained in quantum mechanics knows the rules: we cannot know the position and the velocity simultaneously, and the electron did not follow any specific trajectory from $x = 0$ to $x = 1$. And since we never directly measured the velocity, we have no right to ask what that value was.

To see why Bohr's followers would not accept the seemingly logical conclusion that the electron had

As anyone who has spent hours taking data in an undergraduate laboratory knows, a large uncertainty on an individual measurement is not necessarily a problem

1 Principles of post-selection



Post-selected weak measurements give physicists a whole new view of the quantum world. (*a*) They involve a system (the wavefunction) interacting with a meter (shown here by a pointer) in a "measurement interaction region". A separate measurement is made of the wavefunction once it has interacted with the pointer, which collapses the wavefunction either into the desired state (green light) or some other state (red light). (*b*) The trick in weak measurement is to repeat this process on many identically prepared systems. Each time a red light goes off, the corresponding pointer is discarded; each time a green light goes off, the pointer is kept. In this way, a collection of pointers is obtained, which all correspond to systems that ended up in the desired final state. Since the measurement was weak, there is a great uncertainty in pointer position. But since we have many pointers, we can find their *average* deflection – a number termed the "weak value".

If you do a weak enough measurement of the velocity you reduce the disturbance that the measurement makes on the position of the electron to nearly zero

been travelling at 1 m/s, imagine what would happen if you decided to measure the velocity after releasing the electron at $x = 0$ but before looking for it at $x = 1$. At the moment of this velocity measurement, you would find some random result (remember that the preparation ensured a huge velocity uncertainty). But the velocity measurement would also disturb the position – whatever velocity you find, the electron would "forget" that it had started at $x = 0$, and end up with the same small chance of appearing at $x = 1$ no matter what velocity your measurement revealed. Nothing about your measurement would suggest that the electrons that made it to $x = 1$ were any more or less likely to have been going at 1 m/s than the electrons that did not.

But if you do a weak enough measurement of the velocity – by using some appropriate device – you reduce the disturbance that the measurement makes on the position of the electron to nearly zero. So if you repeat such a measurement on many particles, some fraction of them (or "subensemble", to use the jargon) will be found at the $x = 1$ detector a second later. To ask about the velocity of the electrons in this subensemble, we can do what would be natural for any classical physicist: instead of averaging the positions of *all* the pointers, average only the subset that interacted with electrons successfully detected at $x = 1$.

The formalism of weak values provides a very simple formula for such "conditional measurements". If the system is prepared in an initial state $|i\rangle$ and later found in final state $|f\rangle$, then the average shift of pointers designed to measure some observable A will correspond to a value of $\langle f|A|i\rangle/\langle f|i\rangle$, where $\langle f|i\rangle$ is the overlap of initial and final states. If no post-selection is performed at all (i.e. if you average the shifts of all the pointers, regardless of which final state they reach), this reduces to the usual quantum-mechanical expectation value $\langle i|A|i\rangle$. Without the post-selection process, weak measurement just agrees with the standard quantum formalism; but if you do post-select, weak measurement provides something new.

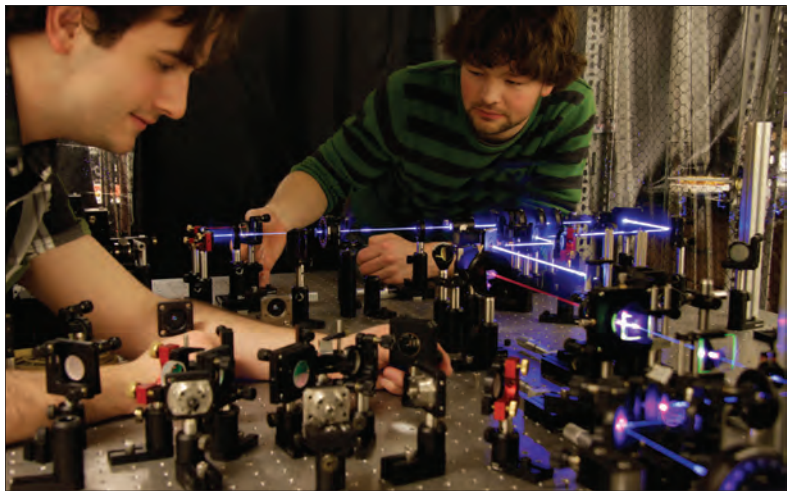
If you work this formula out for the case we have been discussing, you find that the electrons that reached $x = 1$ were indeed going at 1 m/s on average. This in no way contradicts the uncertainty principle – you cannot say precisely how fast any individual particle was travelling at any particular time. But it is striking that we now know that the average result of such a measurement will yield exactly what common sense would have suggested. What we are arguing – and this admittedly is a controversial point – is that weak measurements provide the clearest operational definition for quantities such as "the average velocity of the electrons that are going to arrive at $x = 1$". And since it does not matter how exactly you do the measurement, or what other measurements you choose to do in parallel, or even just how weak the measurement is, it is very tempting to say that this value, this hypothetical measurement result, is describing something that's "really out there", whether or not a measurement is performed. We should stress: this is for now only a temptation, albeit a tantalizing one. The question of what the "reality" behind a quantum state is – if such a question is even fair game for physics – remains a huge open problem.

Two-slit interferometers

The possibility of studying such subensembles has made weak measurements very powerful for investigating long-standing puzzles in quantum mechanics. For instance, in the famous Young's double-slit experiment, we cannot ask how any individual particle got to the screen, let alone which slit it traversed, because if we measure which slit each particle traverses, the interference pattern disappears. Richard Feynman famously called this "the only mystery" in quantum mechanics (see box on p40).

However, in 2007 Howard Wiseman at Griffith University in Brisbane, Australia, realized that because of the ability of weak measurements to describe subensembles we can ask, for instance, what the average velocity of particles reaching each point on the screen is, or what their average position was at some time before they reached that point on the screen. In fact, in this way, we can build up a set of average trajectories for the particles, each leading to one point on the final interference pattern. It is crucial to note that we cannot state that any individual particle follows any one of these trajectories. Each point on a trajectory describes only the *average* position we expect to find if we carry out thousands or millions of very uncertain measurements of position, and post-select on finding the particle at a later point on the same trajectory.

Our group at the University of Toronto has actually carried out this particle-trajectory experiment on single photons sent through an interferometer, which then combine to create an archetypal Young's double-slit interference pattern. Our photons, which all had the same wavelength, were generated in an optically pumped quantum dot before being sent down two arms of the interferometer and then being made to recombine, with their interference pattern being recorded on a CCD camera. Before the photons reached the screen, however, we sent them through a piece of calcite, which rotates their polarization by a small amount that depends on the direction the photon is travelling in. So by measuring the polarization shift, which was the basis of our weak measurement, we could calculate their direction and thus (knowing they are travelling at the speed of light) determine their velocity. The polarization of the transmitted photon in effect serves as the "pointer", carrying some information about the "system" (in this case, the photon's velocity). We in fact measured the polarization rotation at each point on the surface of the CCD, which gave us a "conditional momentum" for the particles that had reached that point. By adjusting the optics, we could repeat this measurement in a number of different planes between the double slit and the final screen. This enabled us to "connect the dots" and reconstruct a full set of trajectories (*Science* **332** 1170) as shown in figure 1.



Dylan Mahler

Practical message Dylan Mahler and Lee Rozema working on an optical table in the authors' lab at the University of Toronto, carrying out precisely the sort of experiment that theorists had suggested should be designed to define weak measurements in the first place.

Back to the uncertainty principle

Throughout this article, we have made use of the idea that any measurement of a particle must disturb it – and the more precise the measurement, the greater the disturbance. Indeed, this is often how Heisenberg's uncertainty principle is described. However, this description is flawed. The uncertainty principle proved in our textbooks says nothing about measurement disturbance but, rather, places limits on how precisely a quantum state can specify two conjugate properties such as position, x, and momentum, p,

Weak insights into interference

In the famous Bohr–Einstein debates, the fact that an interference pattern in a double-slit experiment disappears if you measure which slit the particle goes through was explained in terms of the uncertainty principle. Measuring the particle disturbs its momentum, the argument went, which washes out the interference. However, from a modern perspective, information is fundamental and what destroys the interference is knowing which slit the photon goes through – in other words, the presence of "which-path" information. In the 1990s there was a rather heated debate over whether or not a which-path measurement could be carried out without disturbing the momentum (see, for instance, *Nature* **351** 111 and **367** 626). However, in 2003 Howard Wiseman at Griffith University in Brisbane came up with a proposal to observe what really happens when a measurement is performed to tell which slit the photon traverses (*Phys. Lett. A* **311** 285) – an experiment that our group at the University of Toronto performed for real in 2007 using the principle of weak measurement. We were able to directly measure the momentum disturbance by making a weak measurement of each photon's momentum at early times, and then measuring strongly what its momentum was at the end of the experiment – the difference between the two values being the average momentum change, roughly speaking (*New J. Phys.* **9** 287).

In the original 1990s debate, the two camps had chosen very different definitions of momentum transfer, leading each to prove seemingly contradictory conclusions about its magnitude. Our experiment, by following Wiseman's proposal of weak measurement as an operational definition, was thus introducing a third notion of momentum transfer. Remarkably, the result of this experiment agreed with the most important aspects of both original proofs, in some sense resolving the controversy. Even though the different groups chose different definitions, one cannot help but think that all these definitions reveal part of a bigger story about what is really "going on" – otherwise, why should a measurement carried out using one definition satisfy theorems proved for two entirely unrelated definitions? This is just one of the open questions that those who deal with weak measurements find so fascinating.

according to Heisenberg's formula $\Delta x \Delta p \geq \hbar/2$, where $\hbar$ is Planck's constant divided by 2π. But as Masanao Ozawa from Tohoku University in Japan showed in 2003, it is also possible to calculate the minimum disturbance that a measurement must impart (*Phys. Rev. A* **67** 042105). As expected, Ozawa found that the more precise a measurement the more it must disturb the quantum particle. Surprisingly, however, the detailed values predicted by his result said that it should be possible to make a measurement with *less* disturbance than predicted by (inappropriately) applying Heisenberg's formula to the problem of measurement disturbance.

At first, it seemed unclear whether one could conceive of an experimental test of Ozawa's new relationship at all. To establish, for example, the momentum disturbance imparted by measuring position, you would need to ascertain what this momentum was before the position measurement – and then again afterwards to see by how much it had changed. And if you did this by performing traditional (strong) measurements of momentum, those measurements themselves would disturb the particle yet again, and Ozawa's formula would no longer apply. Nevertheless, two teams of researchers have recently been able to illustrate the validity of Ozawa's new relationship (and the failure of Heisenberg's formula for describing measurement disturbance). One experiment, carried out in 2012 by a team at the Vienna University of Technology (*Nature Phys.* **8** 185), relied on a tomographic-style technique suggested by Ozawa himself in 2004, while the other by our group at Toronto (*Phys. Rev. Lett.* **109** 100404) used weak measurement, as suggested by Wiseman and his co-worker Austin Lund in 2010, to directly measure the average disturbance experienced by a subensemble.

Uncertainty in the real world

Weak measurements not only provide unique tools for answering fundamental physical questions, but also open new directions in practical real-world applications by improving measurement precision. Remember that the average pointer shifts predicted for weak measurements are inversely proportional to $\langle f|i\rangle$, the overlap of the initial and final states. So if the overlap is small, the pointer shift may be extremely large – larger than could ever occur without post-selection. This idea of "weak value amplification" has in fact been used to perform several extremely sensitive measurements, including one by Onur Hosten and Paul Kwiat at the University of Illinois at Urbana-Champaign to measure the "spin Hall" effect of light (*Science* **319** 787) and another by John Howell's group at the University of Rochester in New York (*Phys. Rev. Lett.* **102** 173601), in which the angle of photons bouncing off a mirror was measured to an accuracy of 200 femtoradians.

Of course, there is a price to pay. By adjusting the overlap between initial and final states to be very small, you make the probability of a successful post-selection tiny. In other words, you throw out most of your photons. But on the rare occasions when the post-selection succeeds, you get a much larger result than you otherwise would have. (Howell's group typically detected between about 1% and 6% of photons.) Going through the maths, it turns out this is a statistical wash: under ideal conditions, the signal-to-noise ratio would be exactly the same with or without the post-selection. But conditions are not always ideal – certain kinds of "technical noise" do not vary quickly enough to be averaged away by simply accumulating more photons. In these cases, it turns out that post-selection is a good bet: in return for throwing away photons that were not helping anyway, you can amplify your signal (*Phys. Rev. Lett.* **105** 010405 and **107** 133603). In fact, measurements enhanced by weak-value amplification are now attracting growing attention in many fields including magnetometry, biosensing and spectroscopy of atomic and solid-state systems.

As often happens in physics, something that began as a quest for new ways to define answers to metaphysical questions about nature has led not only to a deeper understanding of the quantum theory itself, but even to the promise of fantastic new technologies. Future metrology techniques may be much in debt to this abstract theory of weak measurement, but one should remember that the theory itself could never have been devised without asking down-to-earth questions about how measurements are actually done in the laboratory. Weak measurements are yet another example of the continual interplay between theory and experiment that makes physics what it is. ■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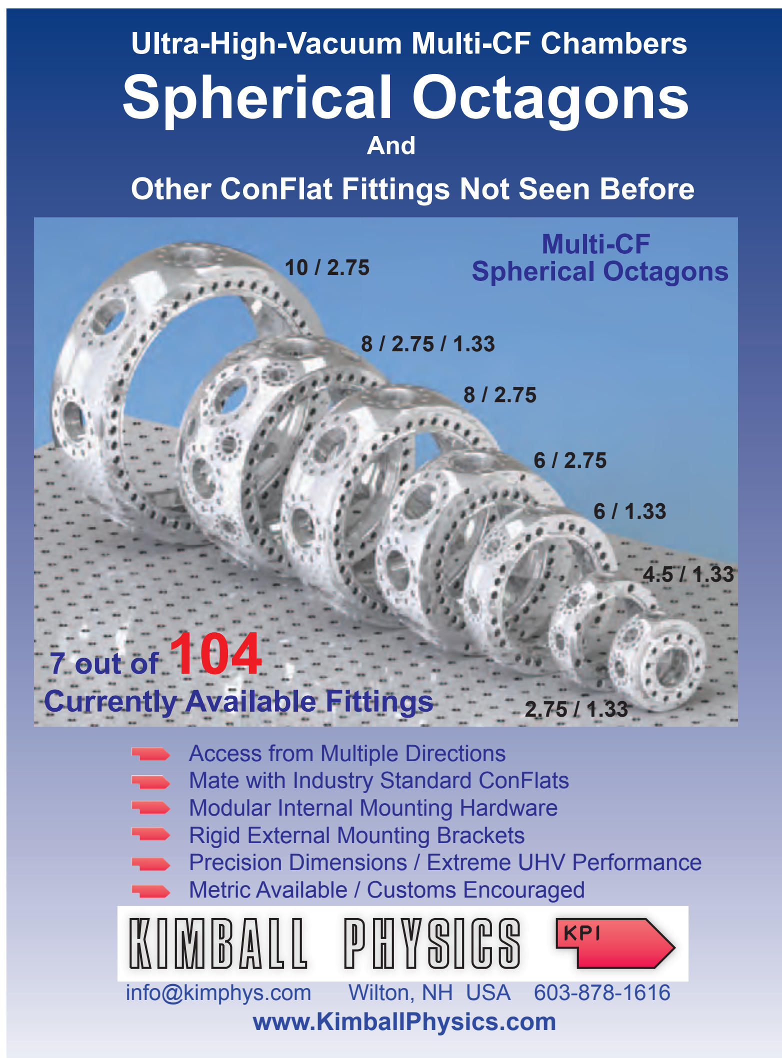
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Nature's quantum subways

Jim Al-Khalili describes the new experiments and theories exploring whether quantum tunnelling of hydrogen causes mutations in our DNA

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"Some of us should venture to embark on a synthesis of facts and theories, albeit with secondhand and incomplete knowledge of some of them – and at the risk of making fools of ourselves."

So said Erwin Schrödinger in 1943 upon his foray from quantum physics into genetics. He would soon back up these words with his hugely influential 1944 book, *What is Life?*, in which he predicted that genetic information is stored within an aperiodic crystal – an idea that would be confirmed by Francis Crick and James Watson less than a decade later when they discovered the structure of the double helix. Today, a small but increasing number of us would echo Schrödinger's sentiments, even though the case has yet to be made conclusively for a causal link between some of the weirder aspects of quantum mechanics and biology.

It is certainly true that although many examples can be found in the literature dating back half a century, there is still no widespread acceptance that quantum mechanics – that baffling yet powerful theory of the subatomic world – might play a crucial role in biological processes. Of course, biology is, at its most basic, chemistry, and chemistry is built on the rules of quantum mechanics in the way atoms and molecules behave and fit together. But biologists have (until recently) been dismissive of the counterintuitive aspects of the theory – they feel it to be unnecessary, preferring their traditional ball-and-stick models of the molecular structures of life. Likewise, physicists have been reluctant to venture into the messy and complex world of the living cell. Why should they when they can test their theories far more cleanly in the controlled environment of the physics lab, where they at least feel they have a chance of understanding what is going on? But now, experimental techniques in biology have become so sophisticated that the time is ripe for testing a few ideas familiar to quantum physicists.

Sticking together

Of all the quantum processes suggested as playing a role in biology – which include quantum coherence, superposition and entanglement – one of the least contentious and best studied is quantum tunnelling. This is the mechanism whereby a subatomic particle, such as an electron, proton or even a larger atomic nucleus, does not have enough energy to punch through a potential barrier (essentially a force field), but instead behaves as a spread-out fuzzy entity that can leak through the barrier and so occasionally find itself on the other side. This phenomenon is familiar in physics and is the mechanism responsible for radioactive decay and nuclear fusion. Quantum tunnelling is also well known in chemistry, for example in the form of hydrogen tunnelling in hydrogen-bonded dimer molecules, such as benzoic acid.

It turns out that even in biology it is now well established that electrons quantum tunnel in enzymes, allowing certain chemical processes to speed up by several orders of magnitude. But one particular question that I, and others, have been exploring over the past few years is whether quantum tunnelling of hydrogen nuclei (protons) in the form of a hydrogen bond has a role to play in one of the most important processes in molecular biology: DNA mutation. Hydrogen bonds are stronger than Van der Waals forces but weaker than ionic and covalent bonds, being a happy medium that hold certain organic molecules together. Crucially, they are strong enough to help build stable structures, but not so strong that they cannot be broken, which is why the structures can be rearranged into new configurations. The hydrogen bond is also responsible for stabilizing proteins and for modulating the speed and specificity of chemical reactions.

In physical terms, the hydrogen bond can be described as a proton trapped in a double, often asymmetric, finite potential well. The two potential minima exist because the proton is happiest being close to one or other of the two atoms at each end of the bond, with an energy barrier in the middle, which the proton can only get over classically if given sufficient energy. To understand the proton's behaviour we need to map the shape of this well, or potential energy surface, very accurately. This is no trivial matter as its shape depends on many variables. Not only is the bond typically part of a large complex structure consisting of hundreds or even thousands of atoms, it is also usually immersed in a warm bath of water molecules and other chemicals. Moreover, molecular vibrations, thermal fluctuations, chemical reactions initiated by enzymes and even UV or ionizing radiation can all affect the behaviour of the bond both directly and indirectly. In addition to all this, and what is of most interest here, is that the small mass of the proton means it is able to behave quantum-mechanically and very occasionally tunnel through the potential barrier from one well to the other (see for example the 2011 paper by Angelos Michaelides and colleagues at University College London – *Proc. Natl Acad. Sci.* **108** 6369).

This discussion is certainly relevant to DNA, which consists of two nucleotide chains wrapped around each other in a double helix. They are held together and stabilized by hydrogen bonds, which link the base pairs: adenine to thymine (A–T) and cytosine to guanine (C–G). If we consider the A–T base pair, which is held together by two hydrogen bonds, then as a result of the different possible positions of the hydrogen atoms that form the bonds, two different structures are possible. Normally, the protons form what is called the canonical (keto) structure of the base pair (figure 1), but occasionally they can be found shifted across to the opposite sides of the hydrogen bonds to form the rare tautomeric (enol) form.

After their landmark paper, which was published 60 years ago next month, Watson and Crick's interests quickly turned to the biological implications of the double-helix structure and in a follow-up paper of 1953 they suggested that spontaneous mutation – a change in the genetic code, for example from ATCAT to ATCAC – may be caused by a base taking on its higher-energy, rarer, tautomeric form. A decade later, the Swedish physicist Per-Olov Löwdin boldly proposed that the tautomeric base pair that leads to a mutation is formed through double proton transfer, with each particle quantum tunnelling through the barrier separating the two asymmetric potential wells

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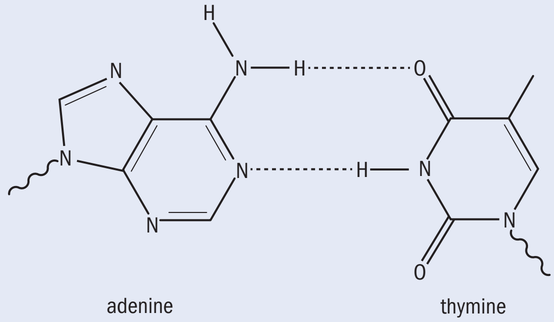
1 Base-pair mutants



One of the two base pairs comprising DNA, the adenine–thymine pair is joined together by two hydrogen bonds in the configuration shown, known as the canonical structure. Occasionally, both hydrogen nuclei (protons) in these bonds can switch allegiance and travel along the dashed lines to be close to the opposite half of the base pair, forming the tautomeric structure. Replication of the base pair while in this form leads to an error in the genetic code – a mutation.

(*Rev. Mod. Phys.* **35** 724). The protons spend most of their time in their deeper wells, but can occasionally tunnel across to the shallow well to form the tautomeric structure. A mutation can then take place only if the rarer tautomeric form remains stable during the replication process. What could happen, for example, is that an A–T base pair in DNA could turn into its tautomeric form, A*–T*. Then, when the two strands of DNA split, the tautomer of adenine will now bind to cytosine (A*–C). This would cause an error in the genetic code (because the new strand now has a C replacing a T in its sequence) and hence a mutation.

Modelling mutation

Half a century on from Löwdin's double-proton tunnelling proposal, experiments by Lorena Beese and colleagues at Duke University in the US in 2011 look to have at least confirmed the hypothesis put forward by Watson and Crick – that tautomeric forms of DNA bases can cause mutations (*Proc. Natl Acad. Sci.* **108** 17644). However, the mechanism by which canonical base pairs become tautomeric remains unconfirmed.

Many computational chemistry groups around the world have, over the past two decades, attempted to model the process of double proton transfer in the adenine–thymine base pair. (This base pair is chosen because it is simpler to model than cytosine–guanine, which is joined by three hydrogen bonds rather than two.) In recent years, a method called density functional theory (DFT) has emerged as the front-runner among the various computational methods to model the structure of large molecules and many-atom systems. In this approach, the properties of a many-electron system can be determined accurately by examining its electron density. DFT calculations are carried out by large computer codes that have become so sophisticated that non-aficionados can use them essentially as black boxes into which one feeds information about the system of interest (such as a crystal or a protein). These codes have been successfully used to tackle problems in material science, condensed-matter physics, computational chemistry and, more recently, nuclear structure and molecular biology.

This could provide information on how the tunnelling process is affected within the busy, warm environment of a living cell

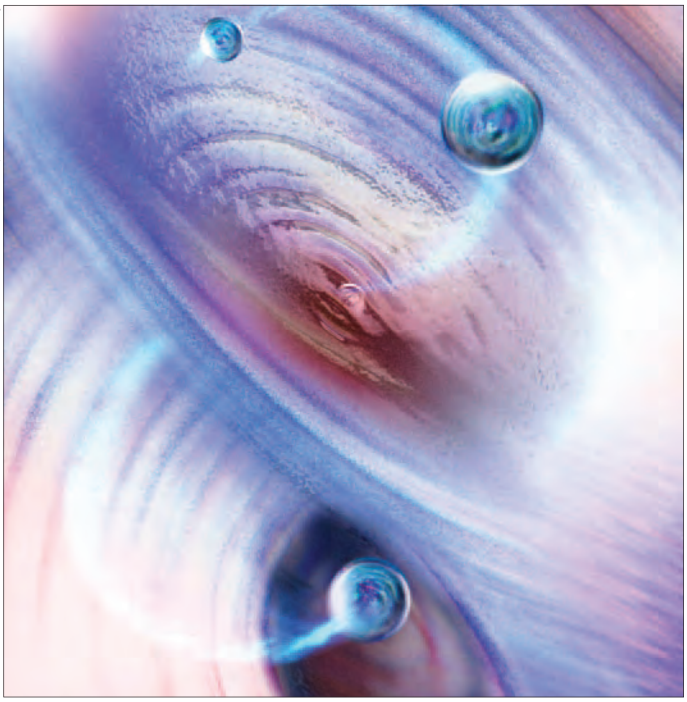
But even incorporating into the calculation the behaviour and structure of hundreds of atoms that make up a section of DNA is not likely to be sufficient to produce a realistic model. Lone DNA is an example of what is known as an "open" quantum system, whereby the surrounding environment can influence its behaviour. It is known, for example, that in the case of 5-Bromouracil – a molecule similar to adenine – the presence of water molecules completely alters the shape of the double well, making the rarer tautomeric form more energetically favourable than the canonical one, suggesting that adenine might be similarly affected inside the cell.

The approach being adopted by my PhD student, Adam Godbeer, at the University of Surrey working with theoretical chemists at University College London, led by Michaelides, involves using DFT to calculate very accurately the shape of the potential energy surface by taking into account as much of the structural information of the DNA base pair as possible, constrained as always by numerical complexity and computational power when dealing with many-body systems. This static potential energy surface is then used to calculate the time evolution of the proton tunnelling process. An added complication is the presence and influence of the external environment, for this is an open quantum system where the surrounding water molecules must also be taken into account. This leads to what is called a decoherence, or dissipative, term in the quantum-mechanical equations, which could provide information on how the tunnelling process is affected within the busy, warm environment of a living cell.

In parallel with this theoretical work, an experiment being conducted at Surrey, led by molecular biologist Johnjoe McFadden, is also attempting to pin down whether proton tunnelling plays a role in tautomeric mutagenesis. The experiment involves replacing the protons in the hydrogen bonds with their more massive isotope, deuterons, and seeing if the mutation rate changes when the heavier isotope is present. This is done by replicating short strands of DNA in deuterated water and using a powerful technique called a polymerase chain reaction to produce many copies of the strands very quickly. As the double helix splits and each strand pairs up with a new one made from the raw material available in its surroundings, use is made of the deuterium in the water for some of the hydrogen bonds. If quantum tunnelling plays a role in mutagenesis we might expect to see a drop in the mutation rate – since deuterons, with twice the mass of protons, will tunnel much more rarely.

Complicating factors

Unfortunately, I am learning that nothing is ever that straightforward in biology and – although early results point tentatively towards Löwdin's proposal being confirmed – a number of other quantum nuclear effects must be taken into account. For example, the heavier deuteron means that the vibrational frequency of the chemical bond it forms is affected.



Richard Kail/Science Photo Library

Breaking barriers Quantum tunnelling of hydrogen in DNA is one of many quantum processes in nature being explored by physicists and biologists.

Heavier atoms will (classically) lead to lower vibration frequencies or, viewed quantum mechanically, a lower zero-point energy. More energy must therefore be supplied to break the bond, which in turn lowers the measured rate. Other quantum nuclear effects, such as zero-point motion, are already known to be important in hydrogen bonds, and if a proton in a hydrogen bond is replaced by a deuteron then the structure of the bond is altered (the Ubbelohde effect), as will be the shape of the potential energy surface and hence the tunnelling probability.

The bottom line is that absolute quantitative comparisons between theory and experiment are always very difficult in complex biological systems. While it is known that an isolated nucleotide base in the lab can exist in its rare tautomeric form between 0.1% and 1% of the time, this will not be the same as the rate inside living cells where polymerase enzymes have error-correcting mechanisms that can achieve fidelities up to 1 error in 10^8 or better. This error-correcting process is of course not included in any theoretical models. In any case, it is known that mutations take place for a variety of reasons and disentangling what fraction of these might be down to quantum nuclear effects is a huge challenge.

Whether or not Löwdin's hypothesis is confirmed, his 1963 paper should at least be celebrated for a statement he makes in the very first paragraph: "The electronic and protonic structure of biologically interesting molecules and systems has to be treated by quantum chemistry. This has led to the opening of a new field, which has been called sub-molecular biology or 'quantum biology' ".

To my knowledge, that was the first ever use of the term, showing that even if we are reluctant to credit Schrödinger with first establishing the field of quantum biology, it is certainly half a century old.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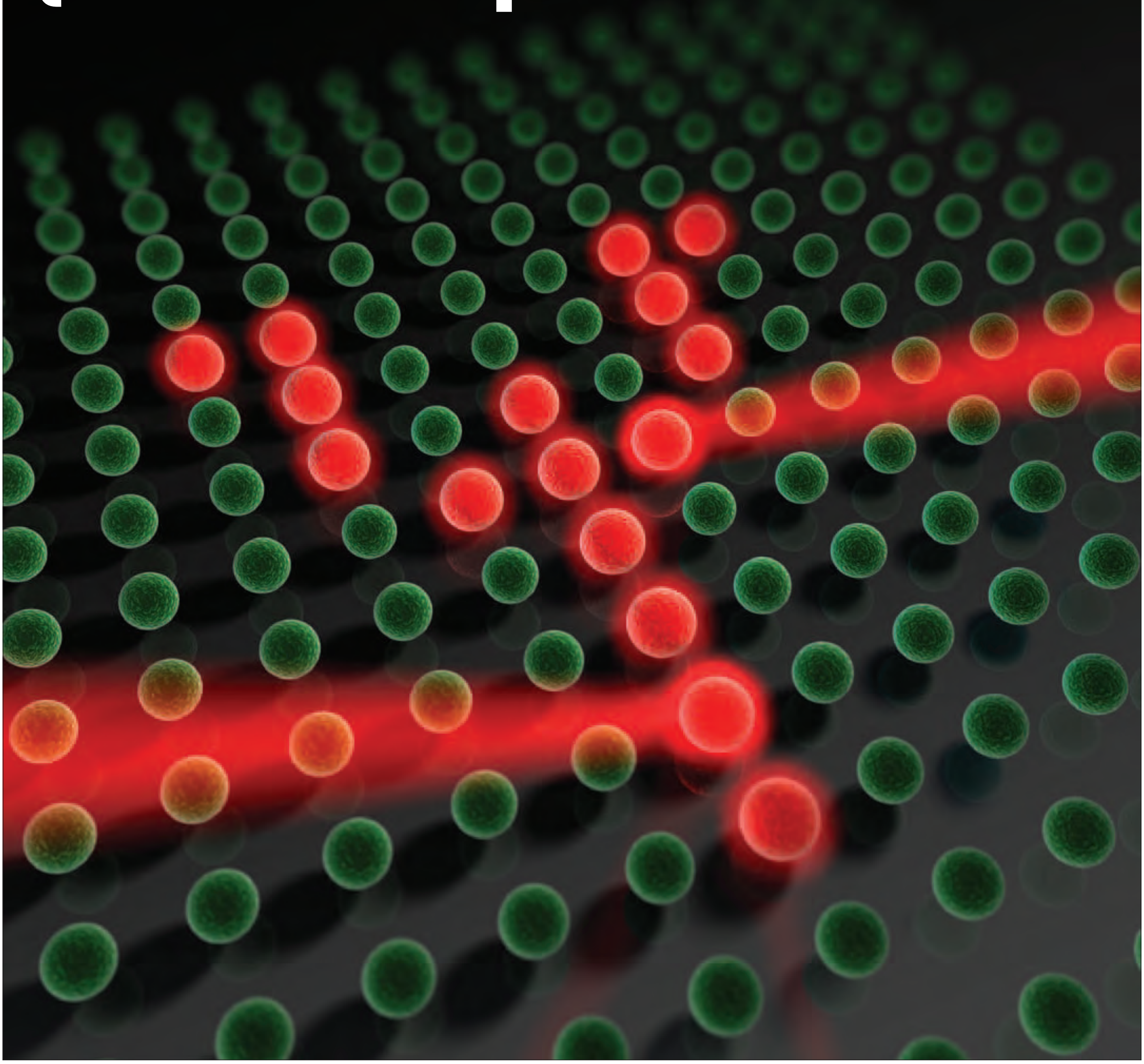
Quantum leaps for simulation



I Bloch, MPQ

Immanuel Bloch describes how recent experiments with ultracold atoms are bringing us closer to realizing Richard Feynman's dream of a universal quantum simulator

Many of the most interesting phenomena in condensed-matter physics – from high-temperature superconductivity to quantum magnetism – share one frustrating characteristic: they are extremely difficult to simulate on a computer. The reason is not hard to understand. Suppose we have a system of N spin-1/2 particles, such as electrons. In order to describe the quantum state of this system on a classical computer, we would need to store 2^N coefficients in the computer's memory. For a small system of only $N = 300$ particles, this equates to a memory size that exceeds the number of protons estimated to exist in the entire visible universe. And of course, in order to perform actual quantum-mechanical calculations on this system, we would also need to do arithmetical operations on all of these coefficients. To make matters worse, the size of the memory problem grows exponentially: adding only one more spin-1/2 particle to the problem requires you to double the size of the computer's memory.

Condensed-matter physicists have developed clever approximations and numerical methods that

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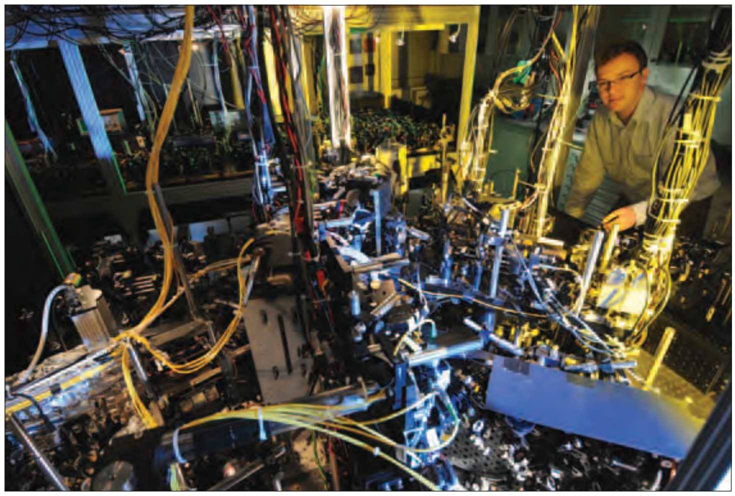
At a glance: Quantum simulation

- The idea of quantum simulation originated in a 1981 lecture by Richard Feynman, in which he suggested that simple, controllable quantum systems could be used to simulate the quantum dynamics of problems that cannot be modelled by a conventional computer
- Ultracold atoms trapped in optical lattices are a good candidate for performing such simulations, thanks to the high degree of control that experimentalists have over important parameters such as the position of the atoms and the geometry of the lattice
- Recent experiments have obtained high-resolution images of atoms trapped in these optical lattices, and also used laser beams to flip the spins of individual atoms in a controlled way
- Future experiments with ultracold atoms may enable us to simulate the effects of very high magnetic fields on real materials, and perhaps even observe new phases of matter


Thorsten Naeser, MPQ

Simulations machine Christof Weitenberg working on the experimental set-up at MPQ.

allow them to work around this fundamental problem, and in many cases these techniques have given us good answers to specific problems. However, in other systems, especially where the electrons interact strongly with each other, these approximations fail or become invalid as a result of the rapid growth of entanglement effects in many-body systems. This rapid growth can be especially severe for a system that has been pushed far from equilibrium and then allowed to evolve. But does this mean we have to give up on trying to understand how these quantum many-body problems work? Or is there another solution?

Richard Feynman certainly thought there was. In his visionary 1981 lecture "Simulating physics with computers" Feynman outlined a radically different approach to this fundamental problem: he suggested that it might be possible to use highly controllable quantum systems to simulate the quantum dynamics of other – classically intractable – problems. The idea of a "quantum simulator" was born – a "quantum machine that could imitate any quantum system, including the physical world".

As with many of Feynman's brilliant ideas, this one has taken some time to take shape in practice. Within the past few years, however, groups around the world have begun to build such quantum simulators in many different physical implementations, including Bose–Einstein condensates, degenerate Fermi gases, photons, trapped ions and arrays of superconducting qubits or quantum dots. These systems all have the virtue of being tunable, meaning that all their interactions, potentials and other parameters can be engineered to suit a certain model. Thanks to this property, there is a very good chance that we will be able to use such model systems to realize completely new forms of matter under extreme conditions that cannot be achieved in any other system – and in the process, start to investigate some previously intractable problems.

Trapped in a lattice

The root of many condensed-matter problems lies in understanding the behaviour of electrons in a solid. In the simplest approximation, such electrons can be described as moving through a periodic potential generated by the positively charged ionic cores of the atoms that make up the solid, which are arranged in a lattice structure. One way to create such a periodic potential in the laboratory is to use an "optical lattice" formed by laser beams. When the beams are superimposed on each other, their optical interference generates a pattern of regularly spaced potential wells. These wells are deep enough that atoms that have been cooled to temperatures just above absolute zero can be trapped in them, like eggs in an egg carton. These ultracold atoms then experience the lattice pattern of dark and bright regions as a perfect, defect-free, periodic potential and can move from one lattice site to the next via quantum-mechanical tunnelling.

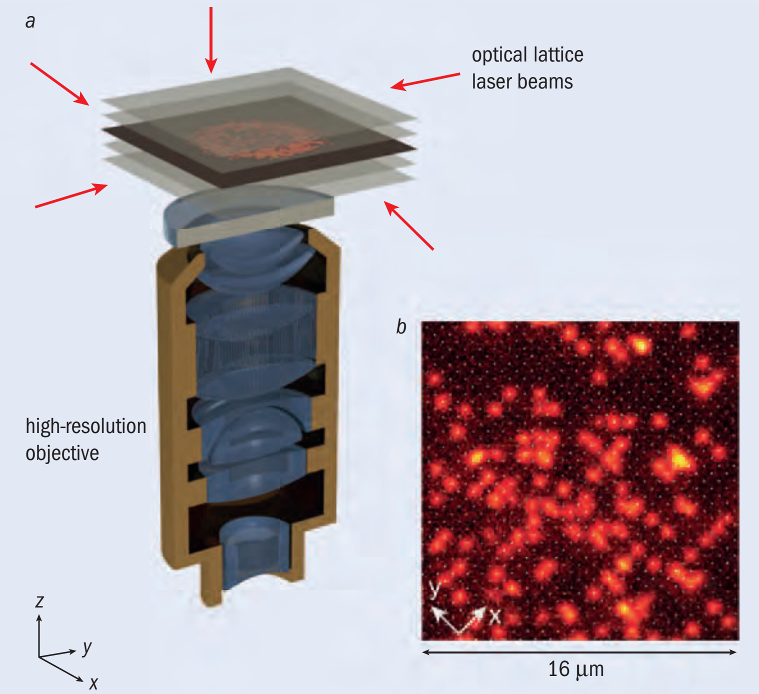
The great advantage of such a set-up is that many parameters of this periodic potential are under the complete control of the experimentalist. For example, the depth of the wells can be easily changed by adjusting the intensity of the laser beams, and the lattice's geometry can be shaped by interfering laser beams under different angles. This flexibility allows researchers to create any geometrical pattern, from a simple cubic-type lattice structure to triangular and hexagonal lattices like those found in graphene.

In recent years, the collective behaviour of interacting bosonic and fermionic atoms in such optical lattices has been a major focus of investigations with ultracold atoms. Then, in 2011, prospects for using ultracold atoms to perform quantum simulations took a dramatic step forward when two research teams (led by Markus Greiner at Harvard University and Stefan Kuhr and myself in Munich) reported that we had successfully obtained high-resolution images of individual atoms in an optical lattice. The resolution of the imaging in these so-called "quantum gas microscopes" is so good that we can discern the occupation of neighbouring lattice sites. To put that into perspective, if we had this kind of resolution in a real electronic material, we would be able to take single snapshots of the position of all the electrons in the material.

The way the experiments work is that ultracold atoms in a Bose–Einstein condensate (BEC) – an exotic state of matter in which all the component atoms share the same wavefunction, and thus behave like a single "matter wave" – are first trapped in a 2D plane. The atoms are then transferred into an egg-carton-shaped lattice potential of light, which at the same time helps to bring the atoms into an interesting, strongly interacting quantum phase. Before the atoms are imaged, the depth of the lattices is suddenly increased to stop the atoms moving and hold them tight in space. Then, a laser beam with a frequency near resonance with an atomic transition is switched on, causing the atoms to fluoresce like tiny nanoscopic light bulbs. The resulting array of nanobulbs can be imaged using a high-resolution microscope objective (figure 1).

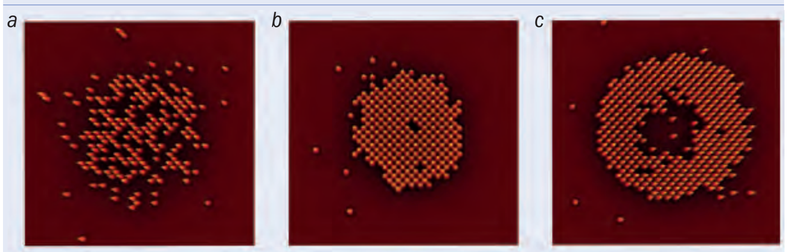
The precise moment when the first photons of the imaging laser beam are scattered off the atoms is crucial for the quantum-measurement process. Initially, the atoms are in a complicated quantum superposition state of different spatial configurations, with a many-body wavefunction $\Psi(x_1 \ldots x_N)$. The measurement process collapses this wavefunction, and the atoms are observed to be in one of many possible spatial configurations. Image-processing algorithms allow us to reconstruct the position of each individual atom in the lattice, but the particular configuration of atoms observed in a single snapshot is, of course, completely random. Only by repeating the experiment many times does it become possible to build up a histogram of the occurrences of different spatial configurations. Examples of such reconstructed particle positions for two distinct phases of matter – a BEC and a Mott insulator – can be seen in figure 2.

1 Quantum gas microscope



(*a*) Ultracold atoms trapped in a single plane of an optical lattice are imaged using a high-resolution microscope that detects the atoms' laser-induced fluorescence. (*b*) A typical image of atoms trapped in the lattice.

2 Imaging different phases of matter



Atoms in a Bose–Einstein condensate (BEC) can be described by one macroscopic wavefunction, but at the same time a BEC in a lattice exhibits large fluctuations in the number of atoms per lattice site, *n*, thanks to an uncertainty-like relationship between *n* and the wavefunction phase Φ ($\Delta n \, \Delta\Phi > 1$). In contrast, if the atoms are in a different phase of matter, known as a Mott insulator, strong repulsive interactions between the atoms destroy the coherent matter-wave field of the BEC, but they also suppress fluctuations in particle number. The result is an almost perfect ordering of atoms in the lattice, with one atom occupying every lattice site.

(*a*) Reconstructed atom positions in a BEC and (*b*–*c*) strongly interacting Mott insulators. The hole in *c* actually corresponds to a region where two atoms are occupying every central lattice site. This region appears dark because the presence of near-resonant laser light induces interactions between pairs of atoms trapped in the same lattice site, causing both atoms in the pair to escape the lattice. Hence, bright areas in the images correspond to odd-numbered lattice occupancies.

Mapping fluctuations

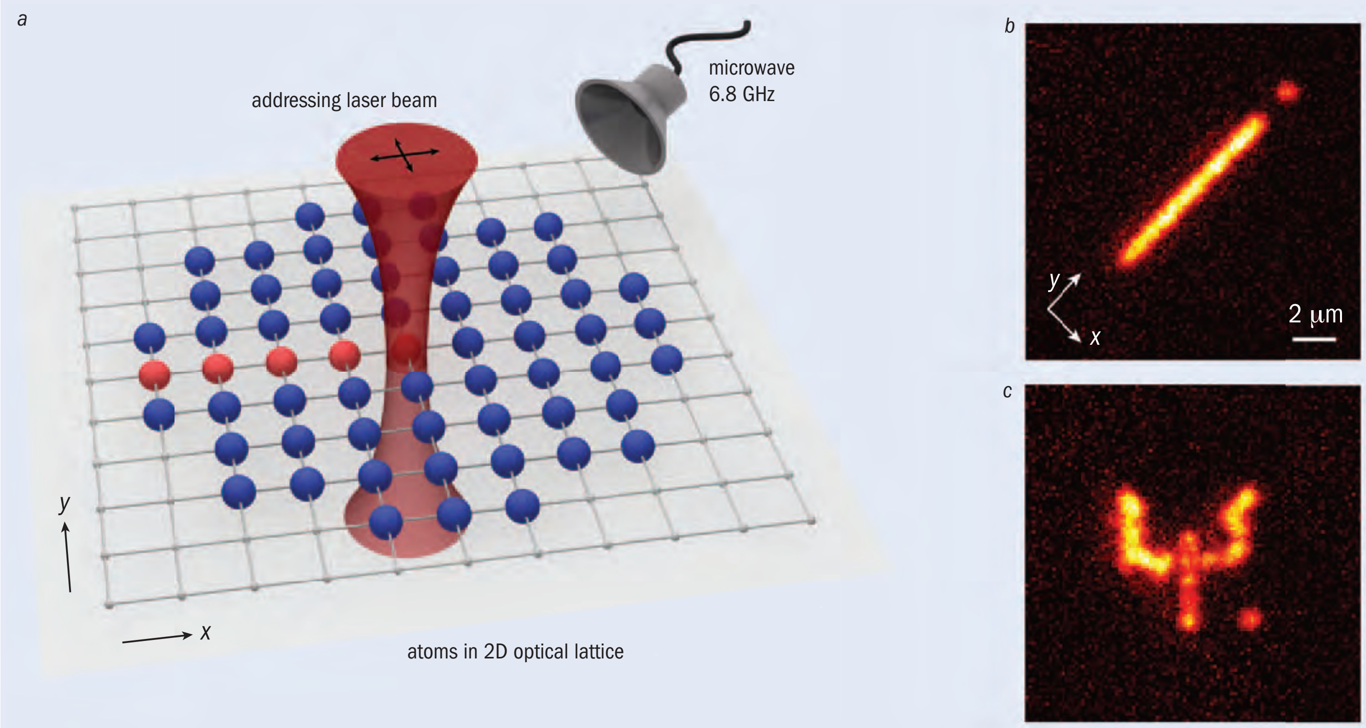
Just being able to image single atoms in a lattice is pretty exciting in itself, but it gets better. If you take a close look at the reconstructed images in figure 2 *b*–*c*, you will see some gaps, or defects, in the lattice. These "missing atoms" represent individual thermal fluctuations, and they are directly visible in a single shot of the experiment. Being able to see single thermal fluctuations in such a system gives us an extremely precise thermometer, which has allowed researchers to determine temperatures down to the 100 pK level using just a single image.

Perhaps more importantly, the "quantum gas microscope" also enables us to directly observe the zero-temperature quantum fluctuations of a many-body system. Many readers will have encountered such quantum fluctuations in the classic textbook example of a single quantum particle in the absolute ground state of a harmonic oscillator. In this simple system, the position of the particle remains undetermined within a region given by the extension of the ground state wavefunction – in sharp contrast with the behaviour of a classical particle at zero temperature, for which position and momentum would always be well defined.

A quantum many-body system also exhibits such inherent quantum fluctuations, and when they become very strong, these fluctuations can give rise to a phase transition – specifically, to a quantum phase transition that occurs even at zero temperature. Quantum gas microscopes thus offer us the chance to learn how the re-ordering of a system takes place during a phase transition, and on what timescales. This is an unparalleled glimpse into the inner workings and dynamics of many-body systems, and one that would simply not be possible in this detail for a real material.

In addition to using the phenomenal spatial resolution of quantum gas microscopes to observe single atoms, one can also perform other experiments.

3 Controlling single spins in an optical lattice



I Bloch, MPQ

(*a*) Controlling the spins of atoms in an optical lattice requires a laser beam to "address" the atoms as well as a microwave field. When this addressing laser beam is focused onto a single atom, it shifts the frequency of a transition between two spin states of the atom. If the frequency of the microwave field is set so that it is resonant with this shifted transition frequency, only the addressed atoms will have their spins flipped when the field is applied. By moving the addressing beam to different lattice sites, arbitrary spin patterns at the single-spin level can be prepared (*b–c*). Such precise control of spin patterns is a crucial first step to a number of interesting experiments, including the creation of a practical, scalable quantum computer using ultracold atoms.

For example, if we send a laser beam in the reverse direction through the high-resolution microscope objective, we can focus the beam onto single sites of the lattice and selectively flip the spin states of each atom (in other words, between different hyperfine spin states) in the microscopic array. By moving the beam along a controlled pathway, an arbitrary spin pattern can thereby be imprinted onto the gases. The spin-flipped atoms can be made visible by first removing the unaffected (non-addressed) atoms and then imaging the remaining (addressed) ones. Examples of such single-atom spin orderings can be seen in figure 3. Once these spin patterns have been prepared, they could form the initial conditions for observing interesting non-equilibrium dynamics. For example, one can track the motion of a single-particle impurity in the many-body system, observe the dynamics of domain walls between regions of different magnetization, or track the collision of two spins at energies of a few pico-electron volts. The possibilities for interesting configurations abound.

Artificial fields

Another condensed-matter problem that ultracold-atom researchers have long wanted to simulate concerns the effect of a magnetic field on the electrons in a 2D electron gas. For a single electron moving in free space, the presence of a magnetic field with a component perpendicular to the electron's direction of motion creates a Lorentz force that pulls the electron into a circular "cyclotron" orbit. If the electron is instead moving through a conductor, this same Lorentz force produces a voltage difference across the conductor – the Hall effect. But when a 2D electron gas in a very pure semiconductor at very low temperatures is exposed to a magnetic field, something more dramatic can happen: the Hall effect becomes a quantum phenomenon, with the conductance in the semiconductor equal to $\nu e^2/h$. The coefficient ν can take either integer or fractional values, and the fractional quantum Hall effect, in particular, remains a hot topic in condensed-matter research more than 30 years after its discovery. However, a severe problem exists in trying to simulate such physics with ultracold atomic gases: because atoms are neutral, they do not experience any Lorentz force in a magnetic field. One might expect that this would prevent quantum-Hall-type effects from being realized in an ultracold-atom system, but in fact there may be a way around this problem.

To understand how we might overcome such an apparently fundamental difficulty, let us take a closer look at what, on a quantum-mechanical level, the effect of a magnetic field, B, on a charged particle really is. When an electron encircles an area with an enclosed magnetic flux, its wavefunction acquires a phase shift. This is known as the Aharonov–Bohm phase, and its value is given by $\phi_{AB} = 2\pi\,\Phi/\Phi_0$ where Φ is the flux enclosed in the trajectory of the electron and Φ_0, the magnetic flux quantum, is equal to the ratio of Planck's constant to the charge on an electron. The quantum-mechanical effect of the mag-

This is an unparalleled glimpse into the inner workings and dynamics of many-body systems

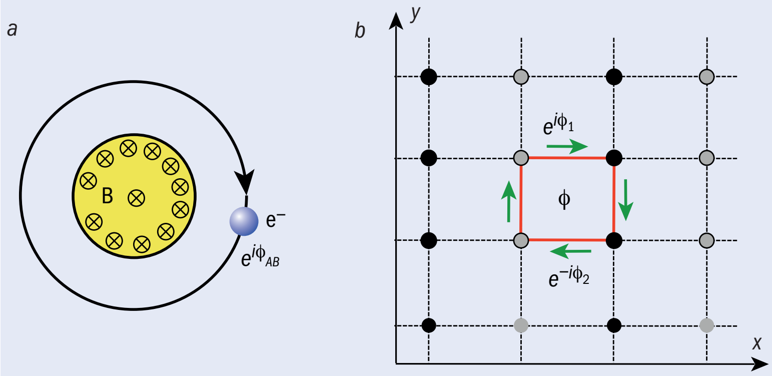
netic field on the electron is thus to introduce a phase shift ϕ on a closed-loop trajectory. Hence, if we are able to engineer such a phase shift in the wavefunction of a neutral atom by other means, we will have simulated essentially the same effect.

Several possibilities have been outlined for doing this using quantum optical control techniques. One can, for example, engineer a Hamiltonian such that when an atom, initially prepared in a single quantum state, is moved slowly in space in a way that does not induce heating (adiabatically), no quantum jumps to other energy levels occur. For a suitable choice of Hamiltonian, the particle can pick up a phase during this state evolution – the so-called Berry's phase – which depends on the geometric properties of the Hamiltonian. The Berry's phase acquired in this adiabatic state evolution then formally corresponds to the Aharonov–Bohm phase shift of a charged particle.

Another possibility is to use laser-assisted hopping of particles in an optical lattice to achieve the same net phase shift. Imagine two neighbouring lattice sites that are shifted in energy relative to each other, such that a single particle cannot move to the next site without some additional help, owing to energy conservation. Laser light tuned to the right frequency can provide this missing energy, allowing the particle to hop to the next site. Crucially, during this hopping process, the matter wave of the atoms inherits the phase of the optical wave. Laser-assisted hopping thus allows one to tune almost at will the phase shift produced when an atom hops from one lattice site to the next, and to render this phase shift position-dependent. For example, an atom hopping around a 2×2 plaquette in a lattice (figure 4) thus picks up a phase shift of $\phi=\phi_1-\phi_2$ corresponding to the Aharonov–Bohm phase shift an electron would pick up when hopping around a lattice plaquette while being exposed to a magnetic field.

The interesting thing about this second possibility is that in real materials, the achieved phase shift is limited by the strength of the applied magnetic field and is typically small. For ultracold atoms, however, such phase shifts can be tuned to any value between $\phi=0$ and π. In a real material, one would need to apply a magnetic field of several thousands of tesla – some two orders of magnitude greater than the fields generated by today's strongest research magnets – to achieve the same effect. How will matter behave under such extreme field strengths? The answer is that we don't really know – we cannot calculate it, which is why it is worth doing the simulations. Some theorists have predicted that one might encounter states that are closely related to those of the fractional quantum Hall effect in 2D electron gases. However, there is also real potential for discovering new phases of matter.

4 Realization of artificial magnetic fields



(*a*) An electron in a magnetic field *B* experiences a phase shift ϕ_{AB} caused by the Aharonov–Bohm effect as it traverses a closed loop. (*b*) A similar phase shift can be achieved for neutral atoms in an optical lattice by using a laser to make them "hop" around a 2×2 region of the lattice. Each hop along the *x*-direction imprints a phase shift ϕ_i that depends on the *y*-position of the particle. The net phase shift of the neutral atom hopping around the closed path shown is then given by $\phi=\phi_1-\phi_2$, corresponding to an "effective magnetic field".

As you might imagine, there are plenty of pathways ahead for future research. One possibility would be to extend high-resolution imaging techniques to fermionic atoms, or even to polar molecules, which have strong electric dipole moments that give rise to long-range interactions. Being able to study such interactions at high resolution might bring an intriguing new perspective to our understanding of quantum matter. Topological phases of matter with new forms of excitations, such as Majorana fermions – an elusive particle that is its own anti-particle, and has only recently been discovered in a condensed-matter setting – could be realized and probed with ultracold atoms.

Another fundamental topic that is currently much debated concerns how isolated quantum systems come into thermal equilibrium; more specifically, it would be interesting to know which observables show thermal-like behaviour after a certain evolution time. Being able to probe, with high spatial resolution, how non-local correlations in the system evolve in time would offer an exciting new way to unravel the secrets of these dynamics. One can only speculate, but I am sure Feynman would have been fascinated to see how far we have come in realizing his vision of a quantum simulator and the possibilities it offers for future research. ■

More about: Quantum simulation

2012 Nature Physics Insight: Quantum simulation *Nature Phys.* **8** 263
J Dalibard, F Gerbier, G Juzeliūnas and P Öhberg 2011 Colloquium: Artificial gauge potentials for neutral atoms *Rev. Mod. Phys.* **83** 1523
R P Feynman 1982 Simulating physics with computers *Int. J. Theor. Phys.* **21** 467
D Jaksch and P Zoller 2005 The cold atoms Hubbard toolbox *Ann. Phys.* **315** 52

The quantum space race

Sending satellites equipped with quantum technologies into space will be the first step towards a global quantum-communication network. As **Thomas Jennewein** and **Brendon Higgins** explain, these systems will also enable physicists to test fundamental physics in new regimes

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Suppose you have a photon – a single particle of light. This is a quantum system by nature, so it exists in a particular quantum state. The photon could, for example, be vertically polarized, horizontally polarized or even something in-between: a quantum superposition.

So what happens when you send your photon to a receiver at some other location? This question sounds simple but the answer can tell us some quite fundamental and startling truths about nature. In fact, when a pair of photons possesses correlations much stronger than classically allowed – entangled quantum states – the implications of what we observe in so-called "Bell tests" are enough to have spooked even Albert Einstein, and many people thereafter.

The consequences of these experimental and theoretical insights are profound as they conflict with our intuitive understanding of how the world works (see box on p54). As Richard Feynman wryly concluded: "after people read [Einstein's paper on relativity], a lot of people understood [it] in some way or other, certainly more than 12. On the other hand, I think I can safely say that nobody understands quantum mechanics".

Beyond these fundamental interests is the field of quantum communication – the science of transmitting quantum states from one place to another. Information is often transmitted by using the aforementioned vertically polarized light to represent the "0", horizontally polarized to represent the "1" and a quantum superposition to represent a combination of "0" and "1" simultaneously. Quantum communication has received significant attention in the last few years owing to the discovery of quantum cryptography.

Quantum-assured security

Quantum cryptography, or, more correctly, quantum key distribution (QKD), exploits the fundamental nature of quantum systems to change state upon measurement, allowing you to establish a common encryption key between yourself and a distant partner with the absolute certainty that if someone is eavesdropping, you will know about it. An eavesdropper would leave a trace and, if none is found, the key can be safely used to securely encode messages. These messages are sent using ordinary, classical communication channels, before being decoded by the distant party using their copy of the key. Traditional encryption techniques, in contrast, either rely on assumptions that certain mathematical operations are difficult to invert, or require the effort of a trusted courier to physically carry the key from one location to the other.

Because of this obvious and significant application, it is not just researchers tucked away in university laboratories who are interested. Several quantum-communication companies have also emerged over the last few years seeking to exploit the secure messaging that QKD allows, including ID Quantique in Switzerland, MagiQ in the US and QuintessenceLabs in Australia. Their efforts come on top of established programmes by the likes of HP, IBM, Mitsubishi, NEC, NTT and Toshiba. All of these companies – and more – are looking to develop real-world-applicable QKD devices for governments, banks and other security-focused clients.

The devices that are being built and implemented today form the seeds of what could one day become a grander *quantum* internet – interconnected networks of quantum-communication channels. These networks would permit not just quantum-secured communications, but also distributed quantum computation (several quantum computers working on the same problem in tandem) and other quantum-enhanced information technologies.

While the possibilities are exciting, quantum communication over long distances turns out to be really difficult. The culprit: transmission loss. Signals weaken in intensity when they travel long distances because photons get absorbed or scatter off molecules, with the transmission loss getting exponentially worse with distance. Classical communication can cope with the high losses experienced over long distances by using repeater devices to boost the signal. But for quantum signals this approach does not work. Quantum signals cannot be perfectly cloned, which rules out standard repeaters, and tricks such as boosting the signals by transmitting many duplicates of each quantum state at the same time would defeat the purpose of encoding information into individual quantum systems in the first place: an eavesdropper could simply pick off and examine a subset of those duplicates, which outwardly would appear to be nothing more than regular loss. As it stands, the furthest that quantum-communication signals have been sent is only a few hundred kilometres.

For applications such as quantum cryptography, that distance restriction means that your QKD system can at best allow you to securely communicate with someone just one or two cities away, which is hardly ideal in an increasingly globalized society. Moreover, in terms of physics research, it means that

Gemini Observatory

important theories can only be verified by experimental tests up to a few hundred kilometres. Frustratingly, some of the proposed effects from the interplay of quantum mechanics and relativity would be too subtle to measure on this scale. So until we can somehow surpass the tyranny of distance, such new physics cannot be tested at all.

Into the void

Fortunately for anyone involved in quantum communication, there is one environment where scattering happens to be practically absent over a very long distance: empty space.

The near-vacuum environment beyond Earth's atmosphere is ideal for low-loss optical transmission; optical diffraction is the only transmission loss worth considering. So an obvious next step to take quantum communication beyond its terrestrial limitations is to deploy a satellite fitted with a transmitter and/or receiver that can implement quantum tasks such as QKD. As a bonus, this equipment could be used to look at fundamental questions within quantum physics in a regime that has never before been explored.

The first step towards space-based quantum communication would be to place a satellite in a low-Earth orbit (LEO) – i.e. at an altitude of less than 2000 km. While a satellite in LEO can see only a small area of the Earth's surface at once, it moves with a relatively high orbital velocity of about 8 km/s, which ensures that its coverage includes all of the Earth at different,

Photons in space Quantum communication between a ground station and a satellite in space could look something like this laser guide star system at the Gemini North Observatory in Hawaii.

Bell tests

One of the most perplexing properties of quantum mechanics, entanglement is a special case of quantum superposition in which two or more particles have quantum states that are so correlated with each other they cannot be explained as separate entities. Take, for example, the so-called "singlet" state of two photons. When the polarization of one of the photons in this entangled state is measured, the result ("0" or "1") instantly tells us that the other particle will be found in the opposite state, even though we cannot predict beforehand in which state either photon will be found. Remarkably, it does not matter which measurement we perform – it is always the case that we know, instantly and with certainty, that the same measurement done subsequently on the second particle will produce the opposite outcome.

Albert Einstein, Boris Podolsky and Nathan Rosen famously thought about this strange behaviour in 1935, and concluded that if quantum mechanics is right, then it must violate at least one of two intuitive notions about the fundamental physical world – locality and realism. Locality dictates that cause and effect cannot travel faster than the speed of light (as per Einstein's relativity), while realism states that particles have well-defined properties whether they are measured or not. If one assumes the latter, then the entangled photons must somehow achieve superluminal communication such that the measurement result from one photon is transmitted instantly to update the state of the second.

However, the perfect correlations considered in such theoretical treatments cannot be tested by experiments, because any experimental set-up has imperfections. For decades it was presumed that the theoretical preconceptions held true, and quantum theory was somehow incomplete. It was not until the scenario was put into quantitative terms by the Northern Irish physicist John Bell that the possibility of experimental tests became apparent. He deduced that statistical analysis of the results of various measurements of each photon would yield a parameter that must be less than a certain value if the world followed locality *and* realism. Put into mathematical terms, Bell produced an inequality that the pair of classical preconceptions would never violate; but quantum mechanics, in principle and with sufficiently pure entangled systems, could.

In the almost five decades since Bell derived his eponymous inequality, experimental tests have, with increasing certainty, demonstrated that the joint assumption of locality and realism cannot be maintained – at least one of those must be incorrect. While work continues on Earth to finally close the various experimental loopholes all at once, the prospect of performing Bell tests using a quantum satellite raises the possibility of addressing new questions, including how well quantum mechanics holds over extreme distances, and the possible interplay of gravitation.

sometimes multiple, times in a single day.

In contrast, a satellite in a geosynchronous orbit (GSO) sits at an altitude of about 32 000 km, allowing coverage of almost 50% of the planet at all times, which means quick or even simultaneous QKD. But implementing a GSO system is more difficult and costly because such an orbit is necessarily much higher than LEO. GSO is therefore more of a long-term goal, perhaps once the economics of satellite-based quantum communication makes such an investment commercially viable. In this scenario, one could envision a constellation of quantum satellites, with several satellites communicating with each other and orbiting in a pattern that simultaneously covers all of the Earth, thereby expanding the future quantum internet to the global scale.

Whichever satellite arrangement is used, its purpose is to act as a kind of relay between two ground stations in a way that allows them to establish a secure link. This link could be accomplished in a few different ways (see box opposite).

Fundamental science in space

Several untested theories detail subtle effects that quantum states might experience over the distances, velocities and gravitation that a quantum-satellite platform could achieve. In fact, there is abundant fundamental physics at the intersection of quantum mechanics and general relativity that has never been tested, simply because we have never before had access to the relevant regimes. A quantum satellite would allow us to take the first step in testing theories over large distances, at high relative speeds and under varying gravity.

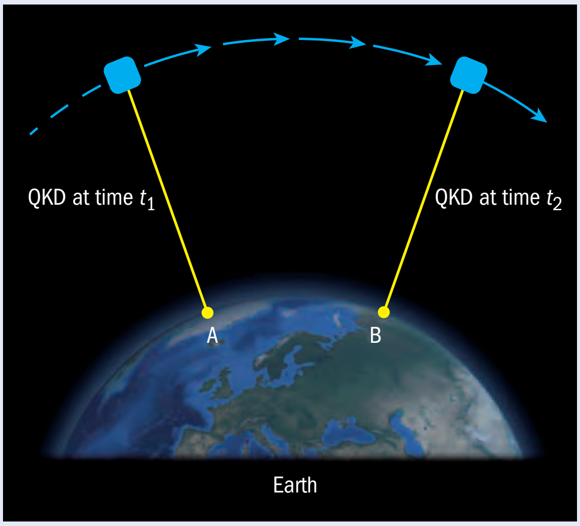
Consider this example: if a pair of entangled photons is prepared at some source location, split and then sent to two observers, the first observer to make a measurement will find one state, instantly determining in which state the other particle will be found when measured by the second observer. Special relativity, however, causes a complication in the cause-and-effect picture that we intuit: if the observers are some distance apart and moving away from each other, relativity dictates that this motion will influence the timing of the measurement events, depending on which observer you consider. In certain conditions, such as if both observers are equidistant from the source, *both* observers will conclude that their measurement was the *second* one, the first being done at the other platform. This presents a tricky puzzle for common interpretations of quantum entanglement, where the outcome of the second measurement is determined at the instant the first measurement produces a result. The puzzling question is at what point the outcome is determined, when the time-order of measurement events depends on which observer asks the question.

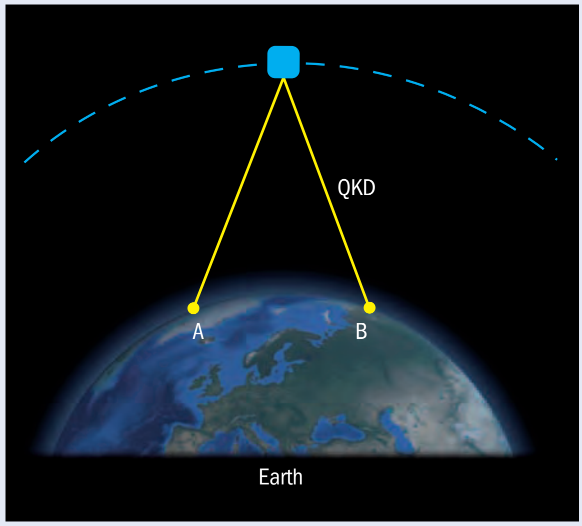
One of the hopes of investigating such questions is to finally bring the famously incompatible quantum and relativity theories to a truce, or something like it. Quantum theory (describing the behaviours of the very small) and relativity theory (describing the behaviour of the very large) have both been thoroughly demonstrated to be the most accurate and precise models of the physical world, to the extent of their applicable regimes, that humankind has ever devised. Their incompatibility is almost embarrassing.

Scientific experiments performed within new regimes have historically led to significant advancements of our knowledge and understanding of the inner workings of the universe. At present, humanity's data set of quantum knowledge comes from tests with maximum distances of hundreds of kilometres and maximum speeds of hundreds of kilometres per hour. In comparison, a LEO satellite would allow us to reach maximum distances of about 1000 km and speeds in the tens of thousands of kilometres per hour, enabling us to test a litany of potential effects and quantum behaviours that cannot be achieved on the ground.

The most clear-cut example to study is long-distance quantum entanglement, including verifying entanglement between photon pairs spanning Earth and space, checking how the quality of entanglement measurements scales with distance, as well as examining the effects of special relativity on entangled sys-

Towards global quantum communication





Global communication, such as fibre-optic broadband, could be made more robust by establishing a secure encryption key between two communicators that no-one else could possibly know. This could be done by using a satellite enabled with quantum technologies to act as a kind of relay between two ground stations to establish a secure key.

One way of doing this would be a "trusted node" approach (left), in which an orbiting satellite first establishes a key – key 1 – with station A via quantum key distribution (QKD), sending single photons one at a time either by uplink (from ground to satellite) or downlink (from satellite to ground). The satellite travels some distance and then establishes another, different, key – key 2 – with station B. (QKD itself cannot transmit existing keys, but only generate new ones.) The satellite then encodes key 1 with key 2 (encrypting it) and transmits the result over radio communications to ground station B, which uses the key it knows (key 2) to determine key 1. At this point both ground stations possess a shared secure key – key 1 – which enables them to communicate securely on the ground via the usual classical means.

This approach comes with a caveat, however: the satellite knows the secure key that the ground stations will use. If a nefarious entity were to somehow penetrate the security of the satellite, which would be no small feat given a properly designed autonomous orbiter, then the security of the communication on the ground would be vulnerable. One has to *trust* that the satellite is secure.

Fortunately, it is possible to utilize a different approach such that the satellite can act as an "untrusted node" (right). Here, an orbiting satellite generates entangled photon pairs and transmits one photon of the pair to each of the ground stations A and B simultaneously. The entanglement correlations between the photon pairs allow A and B to extract a common secret key that even the satellite does not know. The ground stations could then compare their detection statistics, independent of the source, in a manner similar to a Bell test (see box opposite), allowing them to verify that no other party gained information about the states they received – not even the satellite. (Another proposal reverses this idea, with each ground station generating and transmitting single photons that are received and entangled by the satellite, although this is considerably more technically challenging.)

Verification of the trustworthiness of the source means that no assumptions have to be made about the security of the satellite, but it does mean that the satellite needs much more complex kit, including an entangled photon source and two telescopes that can be pointed independently. These extra complications make the trusted node, by comparison, seem like a good stepping stone for testing quantum encryption with a satellite, moving towards an untrusted node approach as a long-term solution.

tems (including the moving observers scenario above). Moreover, long-distance "quantum teleportation" experiments could be conducted – the first baby steps towards realizing the famous *Star Trek* "Beam me up, Scotty" command may be only a few years away.

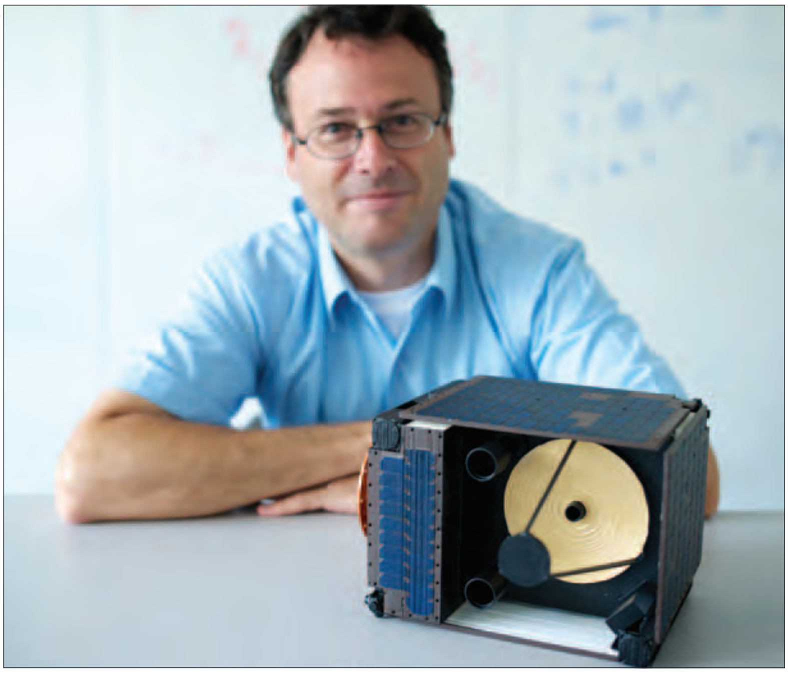
Meanwhile, back on Earth...

For these experiments to be conducted any time soon, an actual design for a satellite must be nailed down and, of course, built. As for anything of a space-faring pedigree, this encompasses a number of technical challenges that need to be resolved. First and foremost is figuring out how to successfully transmit the quantum optical signal between the satellite and the ground station, which has been studied in increasing detail by various groups worldwide. The problem that needs to be overcome is atmospheric loss – not in space, but in the region near the ground station. Other effects to contend with include atmospheric turbulence, diffraction and background noise. Our own group at the Institute for Quantum Computing (IQC) in Waterloo, Canada, has recently concluded a comprehensive theoretical study, simultaneously incorporating all of the significant effects on the signal throughput, which has helped us to determine what overall design features of the satellite and ground station systems would be suitable. We also calculated the expected performance of the quantum optical signal for QKD and fundamental science endeavours.

Another important technical challenge is to ensure that the quantum channel between the satellite and the ground station is precisely aligned as we need

The puzzling question is at what point the outcome is determined, when the time-order of measurement events depends on which observer asks the question

IQC



No small ambition
Thomas Jennewein (pictured) is leading an effort to design and implement a quantum communication satellite, a miniature model of which is shown here.

to be certain that what we actually measure corresponds to the photon states that were prepared. This means that as well as accurately pointing the transmitter and receiver at each other, timing and optical polarization must be well aligned. What makes things even more complex is that the satellite changes position as it passes overhead, so the time delay and local polarization frame are constantly changing.

The Global Positioning System (GPS) can give us timing accuracy down to 100 ns, but this will not be enough to accurately identify which of the detected photons are from the transmitted photon stream – and where within that stream they originate – rather than from some source of background noise. Experiments will be performed at night to minimize light noise, but even then there is noise inherent to the detectors, which can unintentionally "click" even in the absence of a photon. To go beyond GPS capability will require additional techniques such as high-precision time-tagging of photon detections, pulsing "beacon lasers" according to a known pseudo-random sequence to which the transmitter and receiver can synchronize, and advanced post-processing.

Aligning the photons' polarization frame with that of the detector also requires some thought – for good performance, these have to be within about 5° of each other. Again, GPS can help here, providing measurements of position and orientation that can be used to determine the correct compensation to apply. For some designs, the satellite could be rotated slowly as it passes over a ground station so that its polarization frame lines up with that on the ground. On-the-fly calibration could be done using a polarized beacon, whereby the receiver measures the polarization of the beacon and then aligns itself with that either by changing its physical orientation or by using an optical element. One other potential alignment method that we are studying at the IQC is based on analysis of the quantum signal itself.

While designing this innovative equipment, part of which we plan to send into space, we must continually keep in mind the more mundane physical constraints that we face: mass and power. We cannot expect the satellite on which we choose to house our quantum payload to carry up too much mass, or to provide too much power once it is in orbit. Many potential space-faring groups intend to install their equipment on a microsatellite, upon which mass and power are at a premium. Fortunately, designs of systems with the necessary low mass, that use low power and embedded hardware, are making rapid progress.

Quantum space race

Several research groups are pursuing the concept of a quantum satellite in friendly competition. Richard Hughes' group at Los Alamos National Laboratory in the US has been pioneering aspects of QKD on space platforms for many years, and NASA has recently indicated renewed interest. Anton Zeilinger's group at the University of Vienna in Austria has been working with the European Space Agency for several years towards deploying an entangled quantum transmitter on the International Space Station. Jian-Wei Pan's group at the University of Science and Technology of China in Hefei has been making considerable progress, with recent proof-of-concept experiments and a proposed launch date of 2016. Meanwhile, Alexander Ling's group at the National University of Singapore is preparing to launch a small "CubeSat" with an enclosed entangled photon source on board. Last but not least, researchers at the National Institute of Information and Communications Technology, Koganei, Japan, are developing their own QKD satellite demonstration.

At the IQC we are working closely with the Canadian Space Agency and industry partners to design a quantum satellite. The approach we are pursuing favours using the quantum receiver as the satellite payload, i.e. a trusted node in an "uplink" configuration (see box on p55). Compared with a "downlink" with a satellite transmitter, this configuration suffers from more photons being lost as a result of atmospheric turbulence causing the beam to slightly deviate earlier in the transmission, thus having a stronger effect on pointing losses. This reduces the rate at which a quantum key could be generated because the loss hampering the photon transmission reduces our quantum-communication bandwidth. However, there are many advantages of an uplink: a quantum receiver apparatus is quite simple, robust and standardized as compared with a quantum transmitter; and a ground transmitter means that different quantum source designs can be easily utilized whenever it is appropriate.

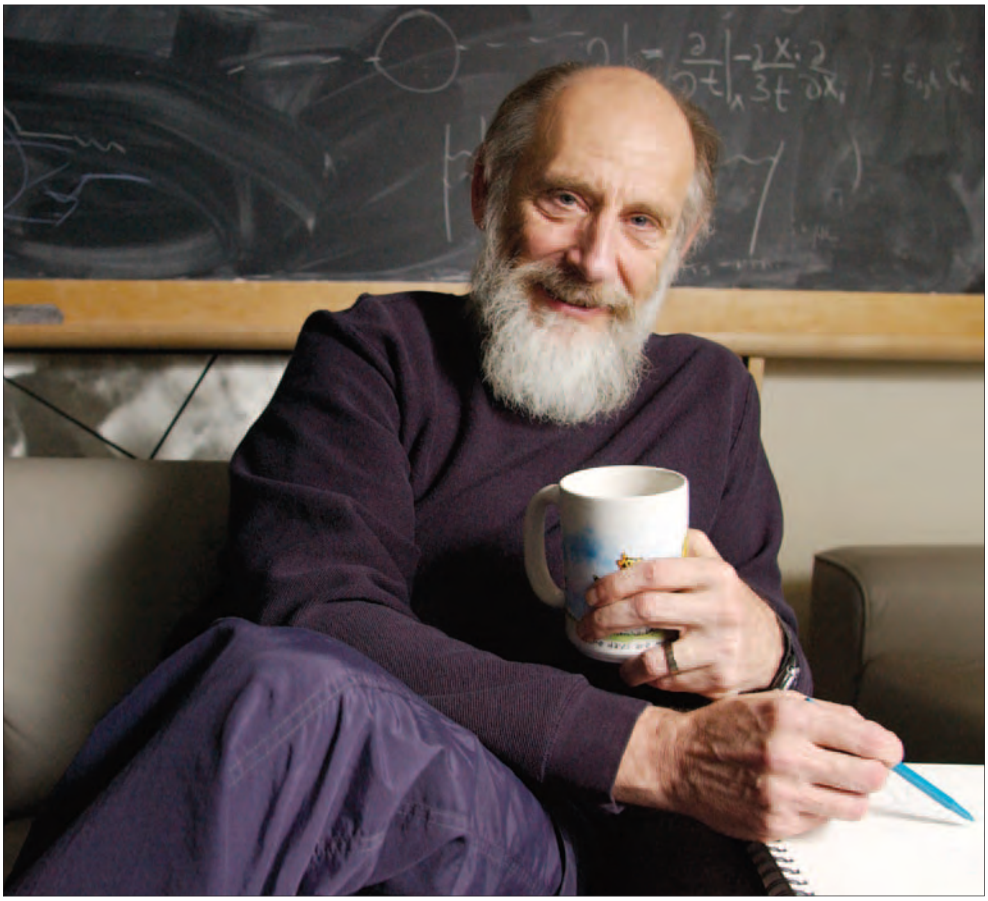
We are currently carrying out design-feasibility assessments in the laboratory, weeding out any potential problems before an actual satellite is built and sent into orbit. While it is not clear yet which group will be the first to get a fully working quantum-communication platform into space, current progress is very promising. With the prospect of global-scale quantum communications and fundamental quantum science within new, unexplored regimes, the next few years are sure to be exciting. To boldly quantum where no-one has quantumed before. ■

Reviews

Lowry Kirkby

A physics primer, with equations

Linda A Cicero/Stanford News Service



Thirst for physics
Leonard Susskind's popular series of lectures for the general public have been compiled in this book.

The Theoretical Minimum: What You Need to Know to Start Doing Physics
Leonard Susskind and George Hrabovsky
2013 Basic Books £20.00/$26.99hb 256pp

The mantra for popular-science books is to minimize the use of equations. In *The Theoretical Minimum: What You Need to Know to Start Doing Physics*, authors Leonard Susskind and George Hrabovsky have taken the opposite approach by producing a physics book for the educated general public that emphasizes the mathematics needed to solve physics problems.

When I first heard about the premise of the book, I was intrigued. Is there a group of people who want to solve physics and mathematics problems, and not simply read about the gee-whiz physics that is the standard fare of most popular-science books? To my surprise, apparently there is. *The Theoretical Minimum* is the product of a series of lectures that Susskind presented for the general public in the Stanford area – all of which can be found video-recorded on the Web – and these lectures attracted a large following of people who were, in Susskind's words "hungry to learn physics". Indeed, Hrabovsky himself was one of those people. Now president of the Madison Area Science and Technology organization, which is devoted to research and education, Hrabovsky has no formal scientific training but taught himself physics and mathematics – presumably through courses and books similar to *The Theoretical Minimum*.

This thirst for academic learning outside of a conventional university degree reminded me of the recent and rapid growth of so-called massive open online courses, or MOOCs: open-access (i.e. free) university courses that give people of any age or background the chance to learn about a subject that interests them, at their own pace (see p9). Like MOOCs, *The Theoretical Minimum* allows knowledge-lovers to get their teeth into the kind of physics and mathematics problems that one would normally face during a university degree. As Susskind puts it, it is intended for "people who once wanted to study physics, but life got in the way".

The book is written in the form of 11 short lectures that cover classical mechanics, plus a final chapter on electromagnetism. Though replete with equations, it remains very readable. Abstract concepts are well explained, usually in a couple of different ways to give the reader a good conceptual overview of the principle at hand. For example, one does not need to understand every detail of a given equation in order to comprehend its power and its use, since these are explained in the text. In addition, each lecture includes several exercises, allowing readers to put their problem-solving skills into practice. (Solutions to the exercises are posted on the Web.) The first three chapters include mathematical interludes on trigonometry, vector notation, differentiation and integration. These discussions are complete, and would serve as a good reminder for someone who is already familiar with calculus; however, they are also rather terse, and would likely be too advanced for someone who wishes to learn it for the first time.

Is this really just the minimum you need to know to start doing physics? To me, the answer is an emphatic "no": this book covers far more than the minimum. The first five chapters cover the core classical mechanics principles of motion and dynamics, including conservation of energy and momentum, while the material covered in the second half of the book (chapters 6–12) is usually considered "advanced classical mechanics". This material – which includes Lagrangian and Hamiltonian mechanics and their applications to electric and magnetic forces – is often not taught at undergraduate level in the UK since it is not part of the Core of Physics syllabus issued by the Institute of Physics. Indeed, I did not cover these subjects during my undergraduate physics degree at the University of Oxford. As such, I can attest to the readability of the book: I was able to understand what an equation that I had never seen before represents, without having to pick apart and understand every term that makes it up. In fact, I found it satisfying to finally gain a basic understanding of Lagrangian and Hamiltonian mechanics, since I had sometimes wished we had covered these subjects in my degree. I even felt like I had been partially duped during my degree after reading Susskind's comment that the Euler–Lagrange equations comprise "all of classical physics in a nutshell"!

There is, however, a flip side to my satisfaction at filling in some holes left by my undergraduate degree: I found myself wondering how much someone who has *not* had formal mathematics or physics training would really get out of *The Theoretical Minimum*. The concepts presented in it are not only advanced, but also abstract and unintuitive, and I would imagine they would be quite daunting to someone new to the subject. At the very least, they would leave newcomers scratching their heads. The book is really about explaining mathematics and abstract physics and does very little to relate these concepts back to everyday life. In addition, in many instances I thought that the explanation would benefit from a diagram or two. Susskind is one of the fathers of string theory, arguably one of the most abstract and theoretical areas of physics. However, the rest of us are not: we need a more tangible way to learn.

In summary, although this book probably offers more than many readers will have bargained for, it does provide a clear description of advanced classical physics concepts, and gives readers who want a challenge the opportunity to exercise their brain in new ways. Thanks to the breadth of accompanying information (for example, exercises and video-recorded lectures on the Web), it also enables them to learn at their own pace, and hopefully most will get some fun and satisfaction from it. If members of the general public really are pulling for these types of courses, ones that offer rigour and a challenge, I enthusiastically encourage them.

I found it satisfying to finally gain a basic understanding of Lagrangian and Hamiltonian mechanics

Lowry Kirkby is a PhD student in biophysics at the University of California, Berkeley, US, and the author of *Physics: a Student Companion* (2011 Scion Publishing), e-mail lowry.kirkby@berkeley.edu

Next month in Physics World

Blow to the head
How physical impacts from bomb blasts and in contact sports can cause disturbing long-term brain injuries on the battlefield and the playing field

Detangling DNA
60 years on from the discovery of DNA, researchers are finding that the incredibly complex knots these long molecules form – and the mechanisms by which these knots untangle – can be understood in terms of topology

Dealing with demons
James Clerk Maxwell's fictional demon was devised as a thought experiment, but some of the physicist's contemporaries actually believed it was an intelligent being that could shine a scientific light on the human soul

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Web life: *The Quantum Exchange*

the Quantum exchange

URL: www.thequantumexchange.org

So what is the site about?

The Quantum Exchange describes itself as "a Web-based repository of resources for teachers of quantum mechanics and modern physics". It is, in effect, a one-stop shop for visual aids, interactive tools and supplementary information designed to help undergraduates – and, for that matter, anyone else with a serious interest in learning more about the quantum world – understand the physics of wavefunctions, probability, spin, entanglement and other quantum fundamentals.

Who is behind it?

The site was developed by the American Association of Physics Teachers with funding from the US National Science Foundation, and is currently managed by Bruce Mason, a physicist and educator at the University of Oklahoma. It is, however, international in its scope, with links to (mostly) English-language resources created by physicists in France, Germany, Austria and the Netherlands as well as the US and UK.

What sorts of resources are included?

Videos of lectures by notable quantum physicists, *Mathematica* notebooks on energy eigenstates and Java applets that simulate wavefunction evolution all feature in the site's extensive archive. So do a few oddities, such as a fiendishly tricky quantum version of Tic Tac Toe (that's "noughts and crosses" in UK English). Many of the resources seem designed to slot into a traditional lecture-based quantum mechanics course, but others are more open-ended, and would be best used in laboratory or tutorial sessions.

Can you give some specific examples?

One of the most interesting resources in the repository is the Friedrich-Alexander-Universität Erlangen-Nürnberg's *QuantumLab*, which takes an unusually practical approach to explaining concepts such as quantum randomness, entanglement and cryptography. Rather than relying solely on diagrams, *QuantumLab* uses photographs of actual optical layouts and interactive widgets that enable students to find out what happens if (to take just one example) they change the polarization of a laser beam as it passes through various optical elements. Students who have access to an optics lab will be able to reproduce these layouts (and thus the experiments) without too much difficulty; for those who lack the right array of lasers, beam splitters and so on, a site like this is surely the next best thing. *The Quantum Exchange* also includes up-to-date links to some excellent older resources, such as the pages on laser cooling and Bose–Einstein condensation developed by physics educators at the University of Colorado in the early 2000s. Like any Web repository, it does contain a few links to resources that no longer exist, but not enough to make it frustrating.

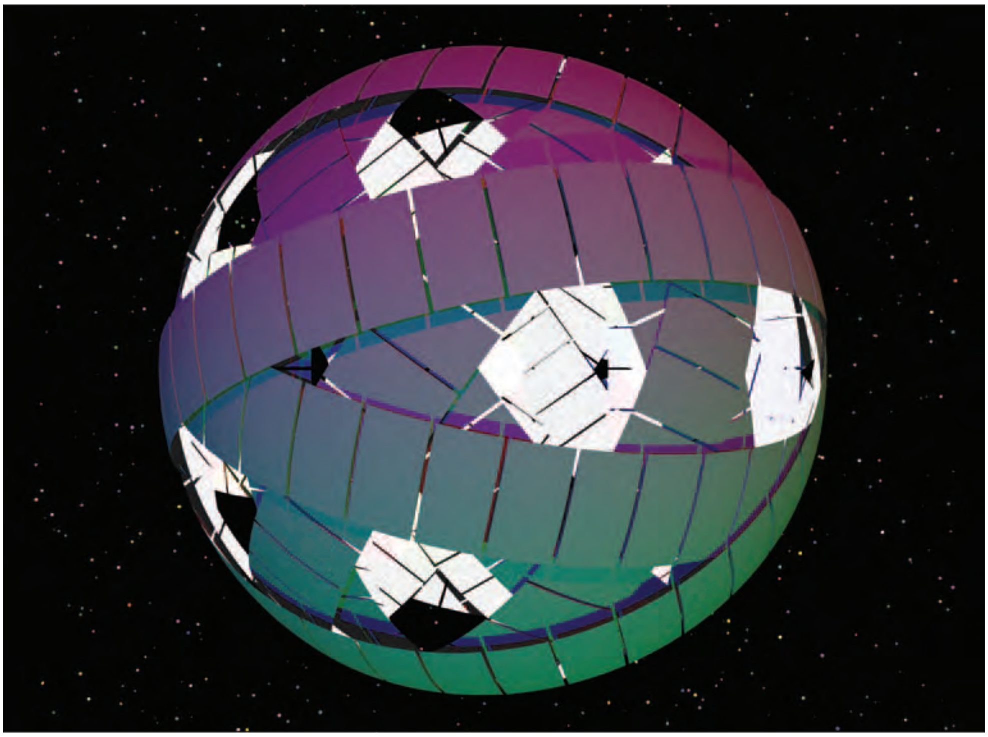
Why should I visit?

There are a lot of Internet resources that are designed to help teachers, students and members of the public understand and explore all manner of quantum phenomena – ranging from classic problems such as the "particle in a box" to the sort of cutting-edge research discussed in this special issue of *Physics World*. The principal difficulty lies in finding the right resource for a particular situation. By combining the efforts of many educators, research groups and outreach specialists – each with their own strengths and weaknesses – into a single, searchable database, *The Quantum Exchange* makes this process easier. Its centralized approach is also useful for would-be developers of new resources, who can check it to make sure their cherished projects are not reinventing someone else's wheel.

Philip Anderson

An iconoclast's career

Arnero



Ideas man
Artist's concept of Dyson rings forming a stable Dyson swarm – just one of many diverse ideas to come from Freeman Dyson.

Maverick Genius: the Pioneering Odyssey of Freeman Dyson
Phillip Schewe
2013 Thomas Dunne Books £17.49/ $27.99hb 352pp

The "maverick genius" referred to in the title of Phillip Schewe's book is Freeman Dyson: a truly great mathematical physicist, bestselling author, longest-serving member of the US military's JASON advisory group, and occupant of the "fourth chair" when the Nobel Prize for Physics was awarded for quantum electrodynamics (QED) – among many other distinctions. Indeed, a biography of Dyson was long overdue, even though his own autobiographical writings are extensive and so beautifully written that no ordinary author could match them, Schewe included.

Why, in that case, should we bother with this biography? Because, as the author makes clear, there are many Freeman Dysons, and how they developed (evolved?) into each other, and what their relationship is, are both relevant parts of his story – as is some kind of appraisal of what one is to make of the final individual.

My own contacts with Dyson have been indirect. Of course, I tried to understand the fundamental QED papers of 1949 that revised all our views of quantum field theory, and I used the techniques presented in them to help solve a puzzle in solid-state physics. Then, in 1958 I was chosen as a substitute for Dyson after he was enticed away from the University of California, Berkeley – where he had spent three summers researching condensed-matter problems with Charles Kittel – to work at General Atomics in La Jolla, California. There, for much more money than Kittel could command, Dyson helped design the safe reactor TRIGA and the Orion spaceship. (I had a marvellous summer at Berkeley, though my papers were crude compared with Dyson's.) But we did not meet until the first energy crisis, when we both attended a workshop on energy that was sponsored by the American Physical Society. Afterwards, we met at disarmament seminars at Princeton University in New Jersey, which is where I first sensed his ambiguity about conventional liberal positions on subjects such as the "Star Wars" defence initiative – most of which I hold unambiguously.

This is not an authorized biography, so Schewe did not have access to any private letters in his research. However, he is a well-known popularizer of physics (being employed in that capacity by the American Institute of Physics) and he has done a meticulous job of finding all of the relevant sources available. He has researched the course of Dyson's life in detail, beginning with his privileged and precocious childhood at Winchester and foreshortened Cambridge years, which were overshadowed by the approach of the Second World War. Dyson spent the war years doing operations research for Bomber Command, and his determinedly itinerant graduate years with Hans Bethe and Richard Feynman culminated in the great breakthrough of QED. After his relatively brief, but scientifically fertile, junior faculty years at Birmingham and Cornell, he settled permanently at the Institute for Advanced Study (IAS) at Princeton in 1953, at the age of 30.

"Settled", however, is hardly the word for it: the liberal vacations and relaxed leave policies of the IAS have enabled Dyson to become the epitome of the "have briefcase, will travel" scientist, bringing him several further careers. The one that seemed to leave the strongest impression on him was his involvement with the nuclear world and particularly the Orion project, which foreshadowed major themes of his later career. Orion was a nuclear-powered spaceship that he, Edward Teller and Ted Taylor designed in 1959 and advocated thereafter, and this experience seems to have left him with a visionary predilection for thinking the unthinkable in terms of the long-term future of the human (or other intelligent) race in space. He also became a major influence in the effort to achieve some measure of nuclear disarmament; after initially opposing the test ban treaty, as a JASON consultant he co-wrote an influential report opposing the employment of nuclear weapons in Vietnam.

Until the 1980s Dyson kept up a continuous and active career in mathematical physics, with occasional forays into broader interests such as condensed matter, biology (particularly studies on the origins of life) and astronomy. Around that time, he discovered his second métier as a writer of extraordinarily readable prose. A number of well-received essays were followed by his first autobiographical book, *Disturbing the Universe* (1979), which was nominated for the US National Book Award. Then came *Weapons and Hope* (1984), which captured the public's interest in the Reagan administration's Strategic Defense Initiative (the aforementioned "Star Wars"). He continues to publish a book every few years as well as many articles and book reviews. Partly thanks to his prolific writing, but also because he seems to have something inspiring and beautifully phrased to say for any occasion, he has become a popular lecturer and maintains a frighteningly full travel schedule. Most recently he has delighted in maintaining minority views on a number of topics such as climate, religion (his Christianity places him in the minority for his profession) and genetic modification.

Did he ever have time for a private life? Schewe's book records Dyson's claim (perhaps a dubious one) to have had two principles in his relations with women: he did not allow himself to become interested if he didn't have marriage in mind; and he intended to have six children. He proposed to his first wife, Verena – a bright, glamorous mathematician and single mother at the IAS – almost on meeting her, and wooed her by mail for over a year throughout his continual travels until (with some reluctance on her part) they married in 1950. She bore him two children before a miscarriage, but theirs was a somewhat stormy marriage, noteworthy for the fact that her thesis and mathematical notes were deliberately burned in the interest of domesticity. Both children, Esther and George, became well-known figures, she as a journalist-entrepreneur and he as an author. Dyson's second wife Imme, formerly his children's au pair, produced four more daughters. Friends of his children report that Dyson is a kindly, avuncular figure, though a rather strict father.

A more important question, though, is whether Dyson is the important world figure that Schewe makes him out to be. In his career, we can see traces of the mathematical physicist's reluctance to tackle the ambiguous or deeply puzzling question, or to go out mathematically even a little bit on a limb – something that contrasts sharply with his joyful interest in bizarre futurology. Perhaps this is the source of Dyson's dreadful misjudgment on the climate question: he sees that the possible errors are large, but does not factor in that they are likely to be large in the wrong direction, and does not credit obvious qualitative arguments from simple laws of physics.

One could wish, as in many biographies of scientists, that the scientific contributions were more critically presented and contextualized. Sometimes the hype goes too far, as when Schewe compares Dyson's popularity as the guru of QED in the 1950s with the Beatles' "conquest of America" in the 1960s. Dyson's very elegant arguments do not always have much to say about how things work in the real world, and the author makes little effort to distinguish whether they do. He did not, for one thing, participate in any of the revolutionary events that created the Standard Model. However, my own preference is for the sloppy and practical rather than elegant and precise, so I am prejudiced.

It is natural for biographers to fall a little in love with their subjects, but on balance, this book leaves the reader intrigued but a bit unsatisfied. Dyson is a superbly able man and has done so much, but what if he had focused on one career? Perhaps the career he really wanted was scotched, as Schewe suggests, by the fallout problems of Orion? In any case, he is worth reading about and marvelling at.

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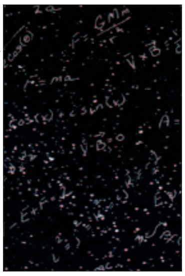
Between the lines



Princeton University Press

Hidden message
The cover of *The Universe in Zero Words* cleverly hides equations in the Milky Way.

On beyond zero

The Universe in Zero Words sounds like the title of a coffee-table book of astronomy photos. The image on its cover – a photograph of the Milky Way – does little to suggest otherwise. But the book Dana Mackenzie has actually written is a very different beast indeed. A closer look at that star-spangled cover reveals a host of equations scattered through the night sky, and inside it is an elegantly illustrated history of mathematical thought, rather than a series of nebula photos. Mackenzie's chronicle is impressive in its scope, running all the way from 1+1=2 (an expression with some surprisingly interesting properties) through to 20th-century revelations such as Lorenz's equations of chaos theory and the realization that some infinities are bigger than others. Understandably, Mackenzie, a mathematician-turned-writer, uses rather more than zero words to describe these discoveries: the book is divided into 24 semi-independent essays, each nominally based on a single equation or group of equations. Most of these expressions will be familiar to physicists, but there are also a few oddities, such as the Chern–Gauss–Bonnet equation, and even "old favourites" such as Maxwell's equations are often presented with a fresh twist. This tendency is apparent from the first few essays, which frequently give credit to ancient mathematicians who lived outside the Greco-Roman world of Euclid and Archimedes. In particular, an account of Liu Hui, a Chinese mathematician and commentator from the third century AD, enlivens the essay on the "Pythagorean" theorem – which, as Mackenzie makes clear, was not Pythagoras' invention, having been known to the Babylonians for more than a millennium before Pythagoras started teaching in the 6th century BC. This cross-cultural focus is particularly appropriate given the book's title, which refers to the Platonist idea that numbers and equations express truths about the universe that are independent of words, language or culture. What was that old proverb about books and covers, again?

● 2012 Princeton University Press £19.95/$27.95hb 224pp

Proof positive

Prove that a parallelogram with equal diagonals must be a rectangle. Show that the surface area of a sphere is exactly two-thirds that of its (closed) cylinder. Derive the equation for a hyperbola. If these instructions induce puzzlement, a vague sense of "I used to know how to do that" or even a barely suppressed twinge of panic, then *Measurement* deserves a place on your shelf. Written by Paul Lockhart, a New York-based mathematics teacher and education advocate, the book aims not only to teach mathematics, but also to instil in readers a genuine appreciation for the subject and an understanding of why it is beautiful and worth learning. In his introduction, Lockhart admits that this will not be an easy process; mathematics, he writes, is like a jungle, and "the jungle does not give up its secrets easily…I don't know of any human activity as demanding of one's imagination, intuition and ingenuity". On the other hand, mathematics is also "full of enchanting mysteries", many of which are accessible even to novices – provided they are willing to play around with ideas and also develop a high tolerance for getting stuck. To help readers build their mathematical muscles, Lockhart has peppered his book with questions and puzzles like the ones that opened this review. The solutions to some of them are worked out (or at least worked around) in the text, but most are left as an exercise for the reader, without further comment or explanation from Lockhart. In a formal textbook, such an approach would be frustrating – especially for students with problem sets due every week, who seldom have the luxury of letting it "take hours or even days for a new idea to sink in", as Lockhart advises. In the more relaxed and playful context of *Measurement*, however, it seems to work, and readers who try some of the easier puzzles will soon find themselves ready for more challenging fare. And if you do get stuck, Lockhart advises you to start working on another problem, as "it's much better to have five or six walls to bang your head against" than only one.

● 2012 Harvard University Press £20.00/$29.95hb 416pp

Einstein the inventor

Albert Einstein's early career as a clerk in the Swiss Patent Office is sometimes perceived as an aberration. Having failed to get a job as a teacher, or to have his true talents properly appreciated by the physics establishment, the story goes that he took this rather boring job only because he needed to eat, or because it allowed him time to construct a *gedankenexperiment* or two in periods of idleness. There is some truth to this: although Einstein later looked back on the patent office with fondness (calling it "that worldly cloister where I concocted my finest ideas") he left his job there as soon as he reasonably could, after obtaining an academic post at the University of Zurich. Yet Einstein's experiences of the patent office never really left him. Even after his theoretical work made him the world's most famous scientist, he maintained an avid interest in technology and practical inventions. These inventions – along with his musings and expert opinions on other people's gadgets – are the subject of *The Practical Einstein: Experiments, Patents, Inventions* by József Illy, a visiting historian at the California Institute of Technology. In this slender book readers will find some fascinating anecdotes about Einstein's lesser-known scientific results, including a refrigerator he invented with Leó Szilárd and a paper he wrote on the meanderings of rivers. Not all of these efforts were successful. For example, an experiment he conducted on molecular currents in 1915 produced a result that, in Illy's understated words, "did not stand the test of time". Similarly, Einstein's career as an impartial witness for patent disputes – which began after he had moved into academia – was marked by a number of lost cases and bungled court appearances. Even the successful and innovative Einstein–Szilárd refrigerators were preceded by Einstein's abortive efforts to develop an "ice machine" with his chemist colleague Walther Nernst. *The Practical Einstein* reads more like a series of stories than a narrative, but Illy does deserve credit for gathering the often incomplete records of Einstein's practical side into one book.

● 2012 Johns Hopkins University Press £31.50/$60.00hb 216pp

GraduateCareers

March 2013

Soft landings

The skills you didn't know you had

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The pleasure of finding things out

The ability to research a problem is one of many "soft skills" that serve physics graduates well in the job market, as **Nadya Anscombe** describes

iStockphoto/David H Lewis

Many students choose to do a physics degree because they like learning about how the world around us works. Fortunately for those about to enter the job market as new graduates, the natural curiosity that is a prerequisite for studying physics is also a prerequisite for many professions, even those that appear to have little connection with science. Finding information, sifting through it and extracting the important bits are all skills that are needed in finance, market research, politics, police work and journalism – to name just a few.

It is widely accepted that physics graduates tend to be numerate, bright and well informed about some pretty esoteric subjects. In many workplaces, though, it is their critical thinking skills that are in demand, says Peter Barham, a physicist and senior tutor at the University of Bristol who has seen hundreds of students enter the job market over the years. "Many jobs, such as patent examiner or business consultant, require someone to collate a large amount of information and act on it," he explains. "That's basically what physics is all about".

Considering the source

One aspect of finding information is, of course, having good formal research skills. During your degree, you were probably taught how to carry out simple open-ended experiments, use the library and mine various databases for information. However, many of the research skills you will find most useful in your future career are those you picked up almost without realizing it. One of these, Barham suggests, is simply being able to find the right person to talk to. "When setting assignments, we try and set questions that cannot be answered by doing a Google search," he says. "We encourage students to knock on doors and ask for advice. We also encourage them to talk to students in higher years as part of our 'parenting' system".

Being able to glean information from people is a particularly important skill for journalists. Valerie Jamieson, who is now features editor at *New Scientist* magazine, chose to study physics at the University of Glasgow because she felt it would give her skills in many areas. Today, she uses research skills she learned during her undergraduate degree and her PhD to help her find out the "very human stories" behind scientific results.

Another important – and related – skill, Jamieson says, is being able to analyse the information once she uncovers it. "In my job, I see a lot of press releases, and sometimes press releases can overblow the significance of results, which can go on to get reported," she explains. "Understanding the scientific method, how results get presented and what uncertainties mean really helps me to decide whether a story really is as significant as it is cracked up to be. It makes you better informed."

Research skills of this type are valued in the commercial world, too. For example, companies looking to hire new employees may look favourably on applicants with strong research skills – even if research as such is not part of the job description – because they tend to require less time and money to train, and will use their own initiative to start providing new ideas quickly. Graduates who have good research skills are also likely to be able to improve products and services quickly. For example, project-based work may require research skills to get a project off the ground.

Many of the skills you will find most useful you picked up almost without realizing it

Know your strengths

In the finance industry, skills such as analytical thinking and problem solving are always useful. When William Van De Pette graduated from the University of Oxford, he knew he did not want to work in physics, but he wanted a job where he could apply the skills he had learned during his physics degree. Today he is a portfolio manager at investment management group Henderson Global Investors in London. "During my degree I gained skills in research, analytical thinking and problem solving, and these are now skills I use every day in my job," Van De Pette told *Physics World*. "I often have to take maths problems and translate them into real-world solutions. For this I use problem solving strategies I learned during my undergraduate years. I also frequently have to find information by talking to people, by e-mail and by reading reports, and then make investment decisions based on what I find out."

A generalized "ability to find things out" is one of several so-called "soft skills" that students pick up during a physics degree without understanding their importance to employers, or even fully realizing that they are acquiring them at all. Two other such skills – giving presentations and accepting criticism – are explored later in this special graduate careers section, but this is far from an exhaustive list; team working, report writing, networking (see February pp44–45) and many others are also important.

To establish what skills you have used, and how and when you have used them, the careers manager of the Institute of Physics, Lindsey Farquharson, recommends that students undertake a "skills audit". Using a resource produced by the Institute ("The physicist's guide to getting the most from a physics degree"), students can establish what skills they have gained from their degree and whether they have evidence or examples to demonstrate their mastery to potential employers. By the end of the exercise, she says, they should be able to see which areas they need to work on, and which are well supported with numerous examples. Being able to demonstrate competence in these areas, she adds, could be the deciding factor between you and another candidate with the same degree.

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Dealing with criticism

Physics graduates are accustomed to receiving feedback from teachers, tutors and lecturers, but different expectations and norms prevail in the workplace. **Giles Morris** discusses how to handle criticism at work

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Entering full-time employment for the first time poses a steep learning curve, and even the best graduates are bound to make mistakes and encounter criticism. The trick is to respond positively when things go wrong, and turn things around when you get pulled up on errors.

One thing that physics graduates, in particular, should be aware of is that the hard analytical skills honed during a physics degree are best left at the door when responding to criticism. "Physicists should resist the temptation to over-analyse feedback," says Russell Coles, a human-resources consultant for the energy firm EDF and former physics teacher. "Taking an intellectually combative approach is best avoided. Emotional intelligence and the ability to take a hint will prove more valuable."

It is also good to be aware of when and where you are likely to encounter criticism. Few managers nowadays will openly criticize their staff in front of colleagues (although it still does sometimes happen), so you are most likely to come up against criticism in one-to-one meetings and annual appraisals. Other likely sources of criticism include e-mails and "track-changes" comments on reports or project documents.

If you are called into a meeting room simply to be told that you have done something wrong, you should treat the criticism as a matter of urgency. If criticism comes as part of a regularly scheduled meeting with your supervisor or line manager, it is probably a lower-grade issue, but it should still be taken seriously.

Learning lessons

Regardless of the setting or their academic background, though, many graduates are surprised to find that the criticism they receive at work is far less direct or detailed – and far more diplomatic – than the feedback they have grown accustomed to receiving in full-time education. Coles says that to some extent, this is just a part of British culture. "We don't like confrontation and don't like embarrassment," he says. "We tend to avoid the truth. We might also attempt to dilute the feedback."

Not all the differences are cultural, however. The bald truth is that new recruits are often small cogs in a big machine, and managers may not feel they have much invested in a new employee's success or failures. It is therefore possible that they will not bother to go into painstaking detail, and will expect employees to pick up on veiled clues. If a complaint has been made, managers may want or need to preserve anonymity.

As a consequence, new or relatively junior employees may feel they have to accept at face value whatever criticism is directed at them, says Simon Broomer, managing director of the career-planning firm CareerBalance. That, however, would be a mistake, Coles argues, because employees need details in order to respond effectively to criticism. "Despite having just received some bad news and although you are probably angry and in denial, you really do need to appreciate the value of what you are being told," he says. "Treat feedback as a gift."

In order to do this, Broomer suggests that employees should make a clear plan for digesting criticism and turning the situation around. First of all, he says, you should show a positive attitude. "Try to avoid being defensive, criticising or blaming others," he says. "Stay positive, demonstrating that you take the feedback seriously and are keen to improve where you can."

Criticism should be treated as a springboard for self-development

Once you have given the right impression, Broomer says, you can then dig for details by asking your manager to give specific examples of occasions when you have not done what they wanted, or behaved in a way they were not happy with. This can be a way to find out if the criticism is based on facts, or something less concrete. "Ask yourself, 'Is this an issue relating to my ability to do the job, to my attitude or my behaviour towards others?'," Broomer suggests. If a negative remark was made by someone else, he adds, you can also ask for that person to be present to discuss the issue.

Above all, Broomer thinks that criticism should be treated as a springboard for self-development. "Ask for ongoing support and coaching from your manager to help you improve," he says. If the feedback you receive indicates that you are missing skills or knowledge, he explains, you can request self-learning materials or off-site training if you believe that this will help you to acquire them. Finally, he says, the employee and manager should agree a specific time and date – ideally no more than a month away – to review progress.

The ability to take criticism on the chin and up your game in response to it may well mark you out as somebody worth promoting. "The three most important attributes I looked for when recruiting were attitude, attitude and attitude," says Coles. "Being resilient and bouncing back from a setback is powerful and can make quite an impression."

Dishing it out

Once you are on your way up the ladder of promotion, of course, the boot will be on the other foot, and you will be called upon to give criticism to others. At that point, the experience of receiving and acting on criticism will hopefully help you to do it well. Constructive and appropriate feedback is an art in itself, and one that is often in short supply in today's corporate environment. According to Coles, the key is to "be open and honest, but above all, constructive, and provide accurate feedback and pinpoint strengths as well as weaknesses".

This advice is also valid when the person you are criticizing is yourself. Peter Wilford, career coach at Gateway Career Management, is adamant about the need for regular self-assessment. "Ask yourself, 'How am I progressing? What do I need to do to reach the next level?'." If you set personal and work goals and review them regularly, Wilford says, this type of self-criticism will help you take control of your career. After all, he concludes, "It is up to you and no-one else to drive it forward."

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Medal-winning presentations

Sharon Ann Holgate examines how lessons from sports psychology can help physics graduates win over their audiences when it matters

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From announcing research results at conferences, to pitching for investment and showcasing project plans to bosses or clients, most careers involve giving presentations. Presentations can also be integral to job interviews, may count towards your degree grade and are the backbone of many science outreach activities. So whether you enjoy the experience or it fills you with dread, it is crucial to learn how to deliver the very best presentations you can in important, and often nerve-wracking, situations.

Sportspeople, too, need to perform at their best when it counts – no matter how they are feeling, who they are competing against or what internal and external pressures they are facing. Indeed, an entire discipline – sports psychology – has been developed to help sportspeople deal with these stresses, and workers in many professions have adapted aspects of these techniques to enhance their own performance. Might sports psychologists have something to offer to physics students, who need to deliver effective presentations both now and in their future careers?

The right way to practise

"Practice" is one of the most common pieces of advice given to people preparing presentations. However, there is much more you can do to prepare than simply running through the material over and over again.

Richard Keegan, a sports psychologist at Australia's University of Canberra, suggests that students should "build up, like an athlete would, from small manageable challenges to full rehearsals". He recommends rehearsing a presentation first in private, then in front of friends or relatives, and finally asking a peer group to provide a more critical audience. Try to keep any criticism or mistakes – whether in rehearsal or the final presentation – in perspective, Keegan stresses. After all, he adds, errors are "not going to result in your friends and family no longer loving you".

While practising, Keegan also suggests that students should think through worst-case scenarios and come up with a plan to deal with them. Kevin Sheridan, a postdoc at the University of Sussex and one of three UK physicists who agreed to try out the tips presented in this article, found that this advice helped him handle being interrupted with questions while delivering a presentation to his research group. "Because I had mentally rehearsed these sorts of situations, I was able to explain what I was trying to say without panic or fear," says Sheridan.

Sports psychologist Dave Smith, a senior lecturer in exercise and sport science at Manchester Metropolitan University (MMU), recommends that students try to think positively, both while practising and during the actual presentation. "Sports psychologists try to train golfers and snooker players to think positively after they mess up a shot," he explains. "If the player chastises themselves, they are likely to miss the next shot, too." If something goes wrong during a presentation, he adds, it is important to avoid panicking "because if you do, your chances of being able to sort the situation out become much less".

I think, therefore I can

Smith also advocates building confidence by imagining forthcoming presentations using an adapted form of the PETTLEP system (see box). This system was developed by some of his colleagues at MMU to provide sportspeople with a structured way of using their imagination to motivate them, improve performance, and increase their confidence. "There is a lot of evidence that some of the same neural pathways in the brain that are used when you do something are also activated when you imagine doing it. So it can help prime you for that activity," says Smith.

Natalie Whitehead, a second-year physics undergraduate at the University of Exeter, found that visualizing herself speaking in the venue helped her present her first outreach talk, which she gave to 15- and 16-year-old pupils in a local school. "It gives you a feeling for how it might turn out, so you're more prepared and more confident," she says. When she worked in an engineering consultancy before her degree, Whitehead adds, she would have found this and other advice in this article invaluable. "You didn't have much guidance," she explains. "You were just sent into client meetings and had to present your results."

However, Pete Vukusic, a physicist at Exeter who gave the Institute of Physics' Schools Lecture Tour in 2007, is more sceptical. Vukusic also played basketball at international level for the England under-15, under-17 and under-19 squads, and while he agrees that visualization is "essential for sport", in his view it is not necessarily helpful for giving academic presentations because the venue, audience responsiveness and equipment functionality are often unknown.

PETTLEP – Seven steps to imagining successful talks

Physical. Make your imagery multi-sensory, imagining how you will feel and move during your presentation, as well as thinking through the content.
Environment. Make what you imagine, and where you do your imagining, as similar as possible to the presentation location.
Task. Rather than imagining something metaphorical such as pushing a rock up a hill, imagine the tasks required to give your presentation.
Timing. Imagine delivering your presentation in real time to give an accurate sense of when you need to carry out each task.
Learning. Continually update your imagery to accommodate anything you learn, concentrating in turn on different aspects of delivering your presentation.
Emotion. Imagine the associated emotions positively so they worry you less. For example, vividly imagine being nervous, then imagine remaining calm and focused and giving a really good presentation.
Perspective. To picture both perspectives, try imagining giving your talk and also being in the audience watching yourself.

One way around this barrier is to visit a venue in advance or find pictures of it. That is part of the approach advocated by Dave Collins, who leads the Institute of Coaching and Performance at the University of Central Lancashire and is a former performance director of UK Athletics. Collins advises planning travel to the venue well ahead of time, and even trying out the journey from hotel to venue if you are staying nearby. He also recommends printing back-up copies of presentation slides on acetate overheads and saving slides on a memory stick to allow for equipment failures.

Combating nerves

On the day of the talk, Collins suggests that speakers try to distract themselves by doing "something unrelated" an hour and a half before the presentation starts. Then, at least 20 minutes before speaking, he recommends setting up and checking your slides. When it is finally your turn to talk, he says, "think about the first few words or lines you are going to say. This should kick-start you into your talk". Accepting that you may get nervous can also help you deliver a good presentation. According to Collins, "the key is to say 'Okay, I'm put out by this, but it's no worry because I know I've done everything I possibly can to perform at my best'."

Charlotte Brand, a final-year student at Exeter who regularly gives outreach talks, likes this approach. "It's really helpful to have someone say it's okay to be nervous," she says. "I think a lot of people find it very hard to accept they are going to be nervous, and that makes them more nervous and stressed."

But what if nerves do strike during your presentation? "A classic trick is to imagine the anxiety is a liquid that can drain out from your body through taps in your fingers and toes. Or think about a calming, happy place like a beach," advises Keegan. "If you find your heart is racing while you speak, just pause for a moment and take a deep breath while you look at a slide or take a sip of water."

Another way to build confidence and effectiveness, Keegan believes, is to make sure you get a good start by summarizing your presentation in a couple of sentences at the beginning. "Make it so clear you could 'sell it' to someone you meet in an elevator," he urges. The rest of the talk's structure is also important. Collins suggests removing any topics that are so complex you will not have time to explain them properly, and making sure the information flows in a logical fashion.

Ed Copeland, a University of Nottingham physicist who regularly gives outreach talks in schools and to the general public, agrees that delivering "a take-home message" is important. Sheridan, however, found that while this advice greatly improved an outreach talk he gave for school pupils, it did not work so well in a research presentation. "Colleagues want an argument built up block by block with rigour," he explains.

However well you mentally and physically prepare, no presentation ever goes perfectly. So Collins emphasizes the importance of making notes on what went well, and what aspects you can learn from and work on for next time. And for anyone who feels they are just no good at public speaking, Smith has one final piece of advice: persevere. "Practising in front of smaller audiences, and imagery, will help you improve your ability to give presentations," he says.

Accepting that you may get nervous can help you deliver a good presentation

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EPSRC Wind Energy Systems Doctoral Training Centre

University of Strathclyde Glasgow

Wind Energy Systems Research Studentships

EPSRC Engineering and Physical Sciences Research Council

Study for a PhD with the UK's leading University Wind Energy Research Centre and become qualified to contribute to this dynamic and fast growing sector.

The UK Wind Energy Research Centre at the University of Strathclyde is pleased to offer **10 prestigious 4 year EPSRC research studentships** for talented engineering or physical science graduates to undertake a PhD in wind energy research.

Successful students will join the recently established EPSRC Centre for Doctoral Training in Wind Energy Systems, which is part of this national centre of excellence at the University. Accreditation of the Wind CDT by the IET and IMechE enables students to develop professionally throughout the course and gain all the competencies required for Chartership.

Course Details
Our CDT offers a unique programme, combining training and research which will aid graduates in transitioning into careers in the wind energy sector. With proven and rapidly growing international demand for highly qualified engineers and researchers, this course offers high level training which is attractive to industries. To prepare for this exciting future, graduates will work closely with manufacturers, developers and researchers. This multidisciplinary programme brings together graduates from various science and technology disciplines to create a unique community of researchers. Training covers all aspects of wind energy systems including the wider socio-economic context.

The PhD programme covers a number of disciplines that include:

- Postgraduate-level training in all aspects of wind energy systems
- Professional development enabled through course accreditation by the IET and IMechE
- Research and industrial engagement

Entry Requirements
Studentships are available to UK and eligible EU citizens with (or about to obtain) a minimum of a 2.1 or a Masters degree in Physical Science or Engineering. These competitive Studentships will commence each year in October and will cover University fees and provide a highly competitive stipend.

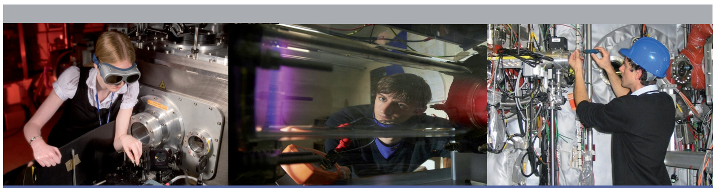
Applicants must be able to demonstrate enthusiasm, creativity, resourcefulness and a mature approach to learning.

Applying
To apply now for October 2013 intake, please follow the application link: https://ben.mis.strath.ac.uk/pguserprofile/control/enterDetailsPage

For further details on our Centre please visit:
http://www.strath.ac.uk/windenergy/

For further enquiries contact Drew Smith, CDT Administrator:
Tel: 0141 548 2880

Email: drew.smith@strath.ac.uk



PhD studentships

Fusion Energy: Materials and Plasma Scientists

The Universities of Durham, Liverpool, Manchester, Oxford and York, with Culham Centre for Fusion Energy, the Central Laser Facility and AWE have formed the Fusion Doctoral Training Network: an EPSRC Centre for Doctoral Training.

With ITER under construction and the operation of NIF in the US, fusion energy is entering an exciting new era. We work with world-leading facilities, including JET, MAST and the Central Laser Facility, while our Low Temperature Plasma research is linked with major international companies in areas such as semiconductor processing.

Our PhD programme offers:

- fully funded 3 and 4-year research studentships
- a training programme in fusion energy, covering materials and plasma science
- exciting research projects, linked to world-leading fusion facilities
- materials and plasma research projects for fusion energy
- plasma projects in high energy density physics and laboratory astrophysics
- opportunities for international collaboration and travel

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ACRITAS

ACRITAS (Actuation and Characterisation at the Single Bond Limit) is a Marie Curie Initial Training Network whose primary focus is advanced training and research in scanning probe-based nanoscience at the single bond limit. **ACRITAS** runs for four years from Oct. 2012, involves eleven core partners and thirteen associate partners spanning academia, industry, professional bodies, and NGOs.

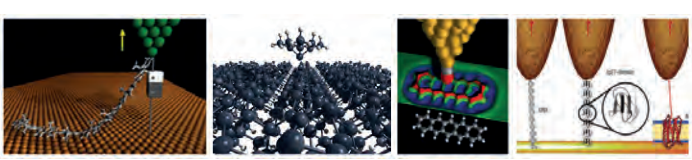
Research Fields

Physics - Surface physics
Chemistry - Physical chemistry

Eligibility criteria

Candidates must be in the first 4 years of their research careers and have not been awarded a doctorate degree. Preference will be given to candidates with a first degree in Physics or Chemistry. (If the degree is in Chemistry there should be a strong background in physical chemistry). As part of our commitment to promoting diversity we encourage applications from women. All studentships are subject to the Marie Curie mobility and eligibility criteria described at **http://ec.europa.eu/research/mariecurieactions/** .

The fellowship will entail secondments to at least one core and one associate network partner. See **http://www.acritas.eu** for a list of all **ACRITAS** partners.



Vacancies

Eight early stage researcher positions are now available within the **ACRITAS** network and we invite suitably qualified candidates to apply. Note that all appointees will be expected to register for a PhD, must hold a primary degree of an appropriate standard in a relevant subject (e.g. Physics, Chemistry, Materials Science – please contact the lead partner for the PhD project in which you're interested for advice), and must meet the Marie Curie mobility regulations.

Funding organisation / Contacts

University of Nottingham Physics & Astronomy

Academic
School of Physics and Astronomy,
University of Nottingham,
University Park,
Nottingham NG7 2RD,
United Kingdom
http://www.nottingham.ac.uk/physics/research/nano

E-mails **philip.moriarty@nottingham.ac.uk**

11 PhD & 4 Post-Doctoral Researcher Positions

SpinIcur

EC Funded project on Spin Currents
A Marie Curie Initial Training Network

The network brings together 10 international partners and offers a total of 11 Early Stage Research (ESR) PhD positions for 36 months and 4 Experienced Researcher (ER) post-doctoral positions for 24 months.

Spintronics offers the potential for logic operations that are faster and consume much lower power when compared to conventional semiconductors. Passive spintronic devices are already the basis for a multi-billion dollar data-storage industry. The scientific goal of SpinIcur is to understand the fundamental physics of pure spin currents – where electrical charge and spin are separate, their generation and propagation through effects such as the spin Hall effect, spin pumping and the spin Seebeck effect. The culmination of the research will be in exploring the fundamentals of spin amplification in designs such as the spin-torque transistor for a new generation of spintronics devices.

Positions available at

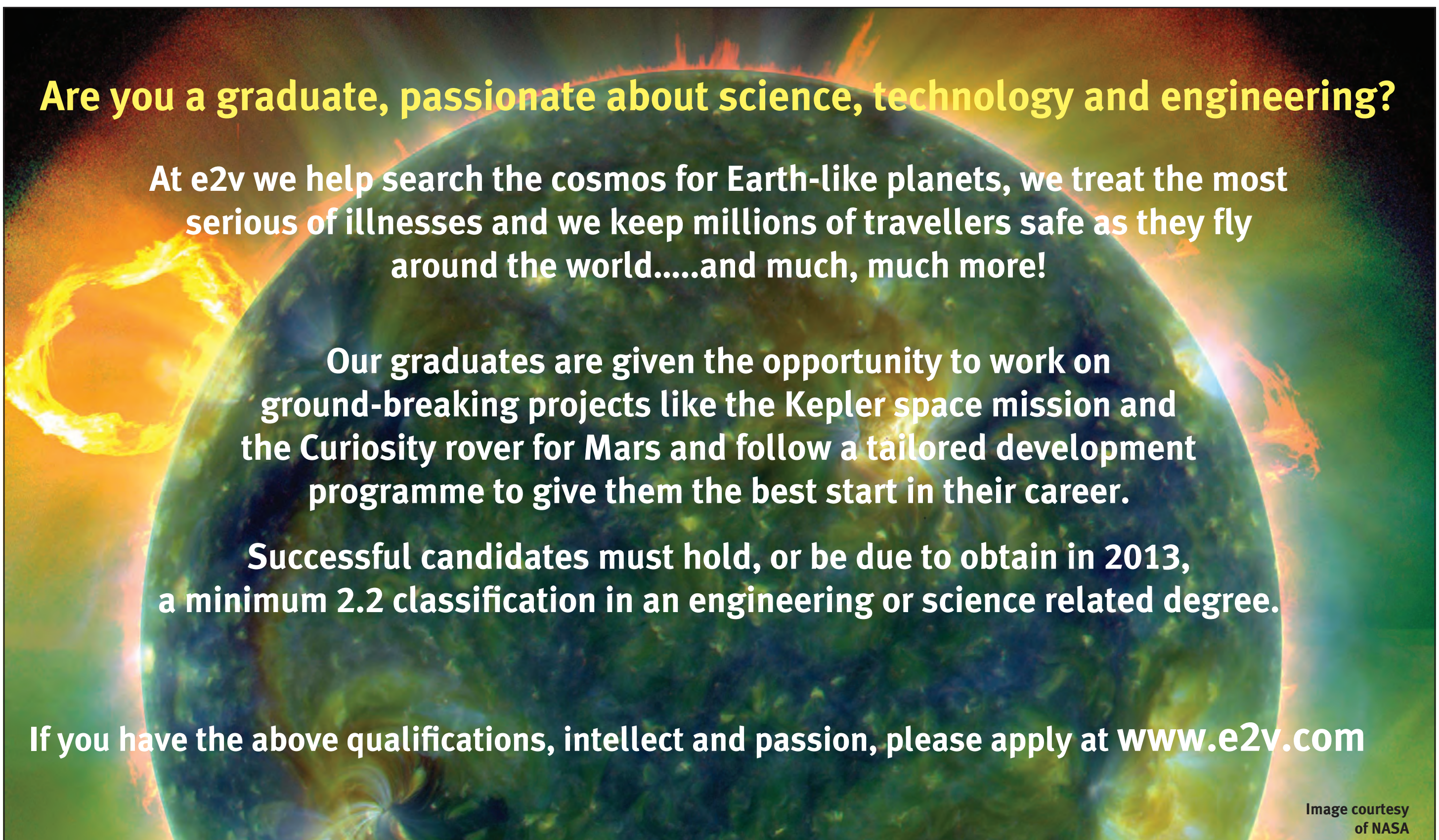
- University of Leeds UK
- INESC-MN Portugal
- IBM Research Zurich Switzerland
- International Iberian Nanotechnology Laboratory Portugal
- University of Cambridge UK
- Hitachi Cambridge Laboratory UK
- University Regensburg Germany
- Delft University of Technology Netherlands
- Norwegian University of Science and Technology Norway

Key benefits

- Generous salary and additional allowances to cover living costs and travel, including a contribution to some family related expenses and the cost of annual travel back to home country.
- Opportunities for international collaboration and travel to world class academic and industrial partners.
- Training in a range of state-of-the-art scientific skills, intellectual property and project management skills.
- Secondment placements within the network's industrial partners.
- Funds to support their participation in the SpinIcur ITN European wide research and training events.

How to apply

Shortlisting and interviews from April 2013 and posts available to commence soon after, so early applications are encouraged.
Further information concerning the positions and projects, together with the full application procedure, is available at:
www.spinicur.org



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THE UNIVERSITY *of York*

DEPARTMENT OF PHYSICS

Chair in Experimental Tokamak Physics

The University of York is one of Britain's leading universities, placed in the top ten UK universities by the 2008 Research Assessment Exercise (RAE) and regularly ranks amongst the top 100 universities worldwide. The University and the Engineering and Physical Sciences Research Council have invested over £4m creating the York Plasma Institute in the Department of Physics, formally opened in October 2012 by Professor Sir John Beddington, the UK Government Chief Scientific Advisor.

We are seeking an individual with an international reputation in Experimental Tokamak Physics to join the research team at the York Plasma Institute. You will have an outstanding track record in plasma science, amongst the World's leaders in the field. You will ideally have expertise in tokamak exhaust physics, but very strong applicants with an internationally leading reputation in other areas of tokamak physics will also be considered. You will be expected to provide research leadership and compete for research funding. Strong collaboration with Culham Centre for Fusion Energy, including participation in the MAST and/or JET tokamak programmes is expected.

Informal enquiries may be made to Prof Howard Wilson, Director of the York Plasma Institute, email: howard.wilson@york.ac.uk

For further information and to apply on-line, please visit our website: http://www.york.ac.uk/jobs/

Closing date: 13 March 2013.

The University of York is committed to promoting equality and diversity.

www.york.ac.uk

Universidad de los Andes Colombia

FACULTY POSITION IN THEORETICAL PHYSICS

UNIVERSIDAD DE LOS ANDES – BOGOTA, COLOMBIA

The Physics Department at Universidad de los Andes, Colombia, is seeking to fill a position in theoretical physics for a faculty member. We are looking for applicants with a strong theoretical background and with a wide range of research interests in the areas of Statistical Physics, Many-Body Physics, Quantum Field Theory, and Quantum Information Theory.

A Ph.D. degree and commitment to excellence in independent research and teaching is required. Postdoctoral experience is preferred. Interested applicants should send a curriculum vitae, a description of research and teaching interests, and arrange to have three recommendation letters sent to:

Carlos Ávila, e-mail: director-fisica@uniandes.edu.co
Chairman, Physics Department, Universidad de los Andes
A.A. 4976, Bogotá, Colombia.
Phone (57-1)-332-4500, Fax (57-1)-332-4516.

First review date: March 30th, 2013. Position will remain open until filled.
Position starting date: August 2013 or January 2014

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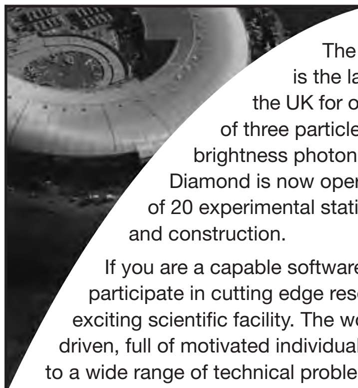

The Diamond synchrotron light source is the largest scientific facility to be built in the UK for over thirty years. The facility consists of three particle accelerators which provide high brightness photon beams to experimental stations. Diamond is now operational with an initial complement of 20 experimental stations and a further 12 in design and construction.

If you are a capable software engineer this is an opportunity to participate in cutting edge research, developing software in an exciting scientific facility. The working environment is technically driven, full of motivated individuals applying software technology to a wide range of technical problems.

Software Engineer — Ref: DIA0808/SB

Salary: Competitive

In this role, you will work closely with a team of scientists and engineers, to develop software to control the Diamond accelerators. This will involve software design, development and support of a suite a client side tools realised in C++, Python and Java. Candidates must have a good honours degree in physics, mathematics or computer science; experience of software engineering, and excellent programming skills in object orientated languages; and a good understanding of mathematics and physics.

Software Systems Engineer — Ref: DIA0800/SB

Salary: Competitive

In this role, you will work closely with a team of scientists and engineers, to develop control systems on the Diamond photon beamlines, and experiment stations. This will involve system design, software development and hands on commissioning of state of the art experimental facilities. Candidates must have a good honours degree in physics, electronic engineering or computer science; experience of software engineering applied to real-time applications and excellent programming skills in C and or object orientated languages.

Diamond is committed to equality of opportunities for all, and offer a competitive salary (dependent upon skills, qualifications and experience), comprehensive benefits, an index-linked pension scheme and flexible working hours.

For an application form and further information including work permit and visa requirements for non-EU nationals please visit our website at www.diamond.ac.uk telephone our recruitment line on 01235 778218 or write to us at the address below, quoting the appropriate reference number.

For further information about this role please visit: www.diamond.ac.uk

Closing date: 17th March 2013.

www.diamond.ac.uk

diamond

Diamond Light Source Ltd, Diamond House, Harwell Science and Innovation Campus, Didcot, Oxfordshire OX11 0DE

Postdoc and PhD Positions in Statistical Physics/ Quantitative Biology

The University of Cologne offers a Postdoc and a PhD position in the research groups of Prof. Michael Lässig and Prof. Johannes Berg within the framework of the Collaborative Research Centre SFB 680 “Molecular Basis of Evolutionary Innovations”.

We are looking for highly motivated individuals who enjoy working in an international team at the interface between statistical physics and quantitative biology. Current research topics include gene expression, molecular evolution, and genomics. Projects involve concepts and methods from equilibrium and non-equilibrium physics and build on experimental collaborations. For more details, see **www.thp.uni-koeln.de/~lassig/** and **www.thp.uni-koeln.de/~berg**.

Applicants should have a strong background in statistical physics and a genuine interest in biology. The appointment will start in autumn 2013 or earlier. Applications including a CV, publication list, research statement, and two letters of recommendation (one for the PhD position) mailed independently should be sent to **SFB 680, c/o Christa Stitz, Institute for Theoretical Physics, University of Cologne, Zülpicher Straße 77, D-50937 Köln, Germany**. Applications can also be sent by email in a single PDF-file to **cstitz@uni-koeln.de**. Pre-application enquiries are welcome.

Cologne University is an equal opportunity employer, the positions are open to Eu and non-Eu members. For further information see **http://www.sfb680.uni-koeln.de/openpositions.html**.

LANCASTER UNIVERSITY DEPARTMENT OF PHYSICS

Chair/Reader in Experimental Neutrino Physics

Reference: A649 Professorial (minimum £59,669)/ Reader £47,314 - £53,233

Lecturer in Experimental Neutrino Physics **Reference: A650 £32,267 - £36,298**

We wish to appoint two outstanding experimental particle physicists at the level of Chair/Reader (equivalent to a Full Professor/Associate Professor respectively) and Lecturer (equivalent to an Assistant Professor) to lead/support an expansion of our experimental neutrino physics programme at current and future long baseline facilities.

You will be expected to develop a world-class research activity in this field and will be able to join an existing group working with the T2K collaboration at JPARC (one professor, one lecturer, two researchers and several PhD students) as well as build up a Lancaster contribution to one of the future long baseline neutrino oscillation projects.

Our department was ranked first and equal-first respectively in the 2008 and 2001 UK Research Assessment Exercises (RAE) and is seeking to further enhance its scientific standing.

The posts are permanent and tenable from 1 October 2013. In addition to your research activities, you will also be involved with undergraduate and postgraduate teaching.

Please contact Professor Peter Ratoff (Head of Department) if you wish to have an informal discussion about this opportunity: Email: p.ratoff@lancaster.ac.uk Tel: +44 1524 593639.

We are strongly committed to fostering diversity within our community as a source of excellence, cultural enrichment, and social strength. We welcome those who would contribute to the further diversification of our department.

Closing date: 21 March.

www.lancaster.ac.uk/jobs

The incomprehensibility principle

Educators and psychologists invented the term "attention span" to describe the length of time anyone can concentrate on a particular task before becoming distracted. It is a useful term but span, or duration, is only one aspect of attention. Attention must also have an intensity – and the two variables are independent of each other. Perhaps one can postulate an analogue of the Heisenberg uncertainty principle, in which the intensity of attention multiplied by its span cannot exceed some fixed value. I call this the "incomprehensibility principle" and I have had plenty of opportunities to observe its consequences.

In the hands of skilled presenters, information can be carefully packaged as entertainment so that the attention needed to digest it is minimal. The trick is to mask the effort with compelling emotional appeal and a floppy boy-band haircut. However, the need to pay attention is still there; in fact, absorbing even the most trivial information demands a modicum of attention. How many of us, when leaving a cinema, have had the nagging feeling that although the film made for great entertainment, some details of the plot remained less than crystal clear?

iStockphoto/Francisco Romero

The existence of a minimum level of attention suggests that it is, in some sense, a quantum substance

The existence of a minimum level of attention suggests that it is, in some sense, a quantum substance. This means that under close examination, any apparently continuous or sustained effort at paying attention will be revealed as a series of discrete micro-efforts. However, while attention can be chopped up and interleaved with other activities, even tiny pulses of attention demand full concentration, to the exclusion of all other voluntary activities. Any attempt at multitasking, such as using a mobile phone while driving a car, is counterproductive.

The incomprehensibility principle plays a major role in education, where it is closely linked to the learning process. Because of the subject matter and/or the teacher, some school lessons require more time to assimilate than others. This trend accelerates in higher education. In my case, a hint of what was to come appeared during my third year of undergraduate physics, when I attended additional lectures on quantum mechanics in the mathematics department at Imperial College London.

My teacher was Abdus Salam, who went on to share the Nobel Prize for Physics in 1979. Salam's lectures were exquisitely incomprehensible; as I look back, I realize he was probably echoing his own experiences at Cambridge some 15 years earlier at the hands of Paul Dirac. He referred us to Dirac's book *The Principles of Quantum Mechanics*. At a first and even a second glance this book shone no light at all, but after intense study, a rewarding glimmer of illumination appeared out of the darkness.

Motivated by Salam's unintelligibility, I began postgraduate studies in physics only to find that my previous exposure to incomprehensibility had been merely an introduction. By then, there were no longer any textbooks to fall back on and journal papers were impressively baffling. With time, though, I realized that – like Dirac's book – they could be painfully decrypted at "leisure", line by line, with help from enlightened colleagues.

The real problem with the incomprehensibility principle came when I had to absorb information in real time, during seminars and talks. The most impenetrable of these talks always came from American speakers because they were, at the time, wielding the heavy cutting tools at the face of physics research. Consequently, I developed an association between incomprehensibility and accent. This reached a climax when I visited the US, where I always had the feeling that dubious characters hanging out at bus stations and rest stops must somehow be experts in S-matrix theory and the like, travelling from one seminar to the next. Several years later, when I was at CERN, seminars were instead delivered in thick European accents and concepts such as "muon punch-through" became more of an obstacle when pointed out in a heavy German accent.

Nevertheless, I persevered and slowly developed new skills. The incomprehensibility principle cannot be bypassed but even taking into account added difficulties such as the speaker's accent or speed of delivery – not to mention bad acoustics or poor visual "aids" – it is still possible to optimize one's absorption of information.

One way of doing this is to monitor difficult presentations in "background mode", paying just enough attention to follow the gist of the argument until a key point is about to be reached. At that moment, a concerted effort can be made to grab a vital piece of information as it whistles past, before it disappears into the obscurity of the intellectual stratosphere. The trick is to do this at just the right time, so that each concentrated effort is not fruitless. "Only cross your bridges when you come to them," as the old adage goes.

By adopting this technique, I was able to cover frontier meetings on subjects of which I was supremely ignorant, including microprocessors, cosmology and medical imaging, among others. Journalists who find themselves baffled at scientific press conferences would do well to follow my example, for the truth is that there will always be a fresh supply of incomprehensibility in physics. Don't be disappointed!

Gordon Fraser, a former editor of *CERN Courier* magazine, died in January before this article could be revised. It was completed by staff at *Physics World* and is published both here and in *CERN Courier* this month as a tribute.

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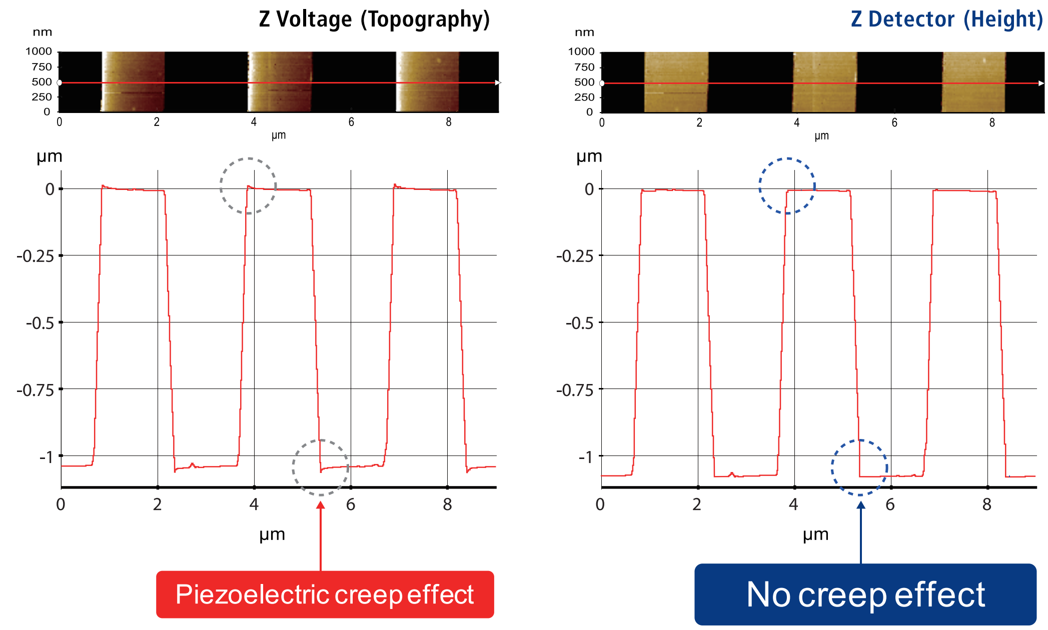

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