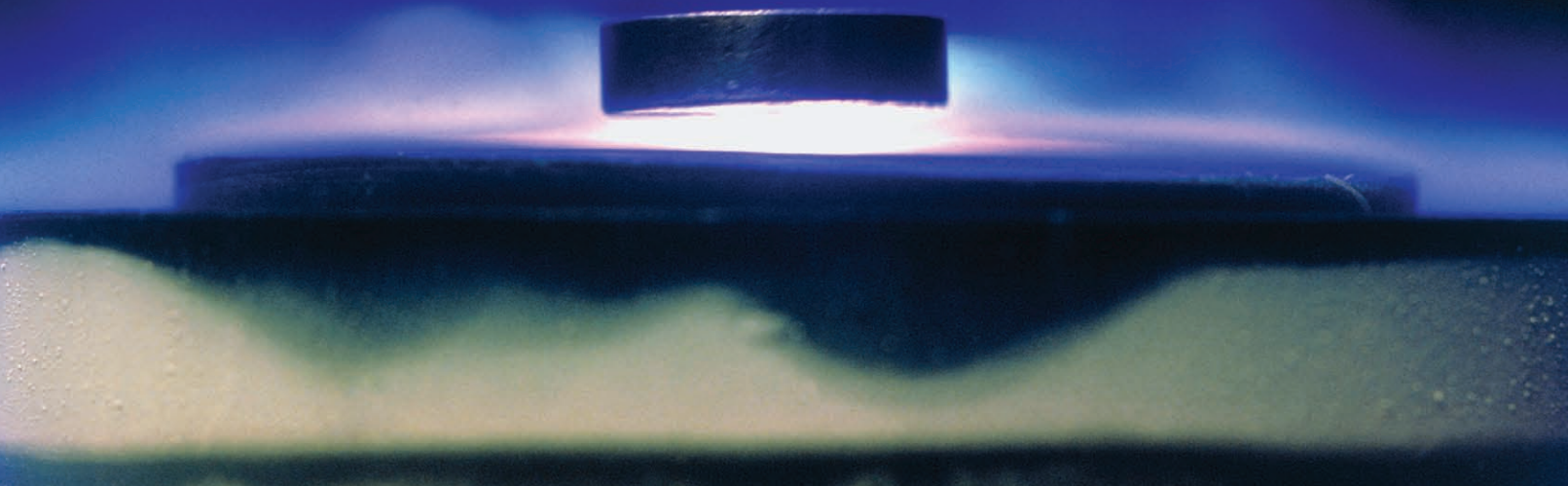


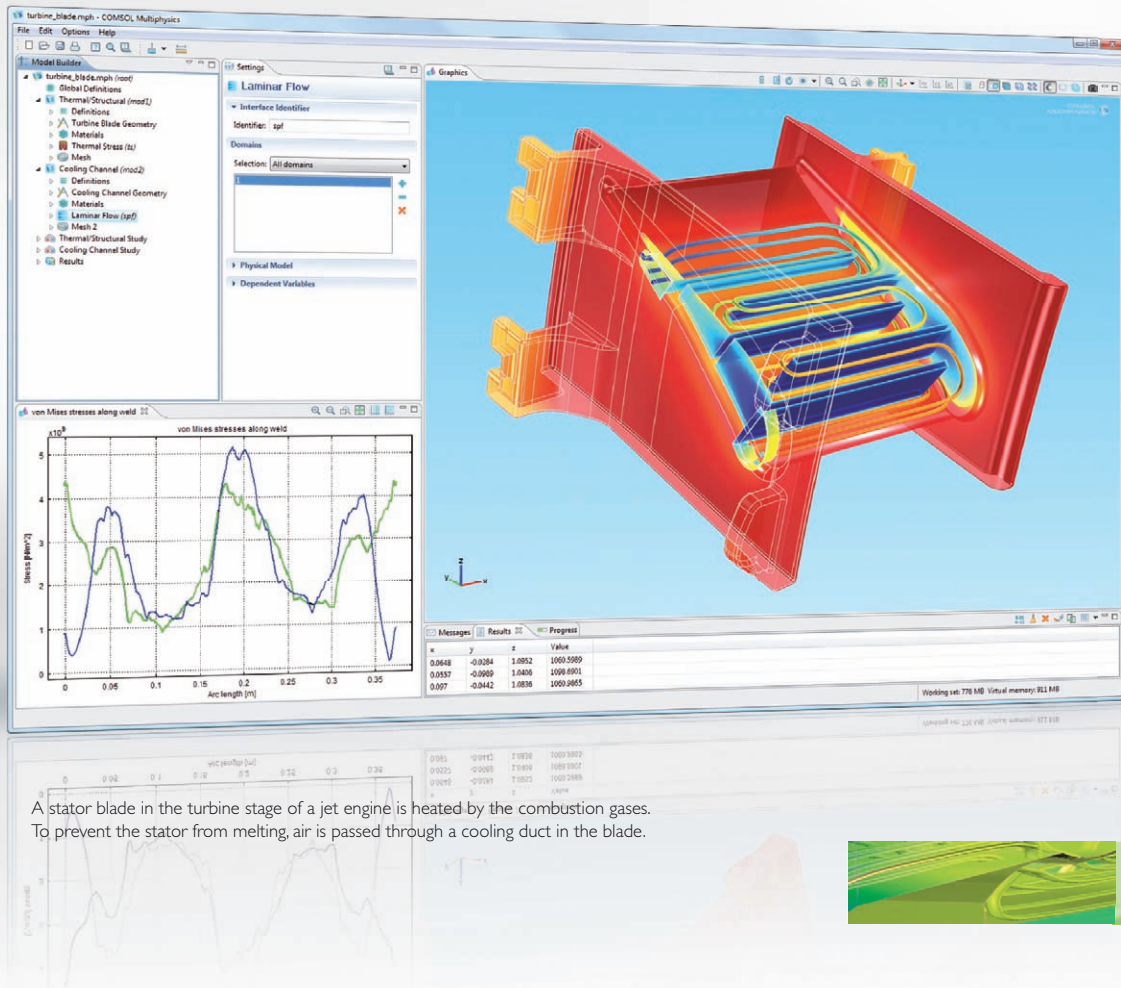
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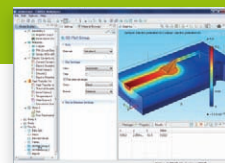


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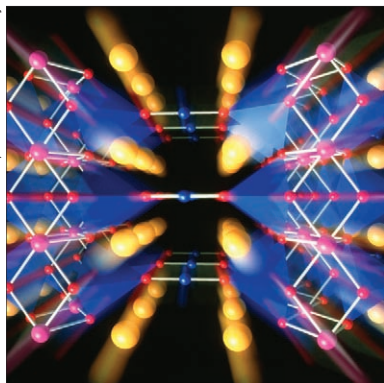
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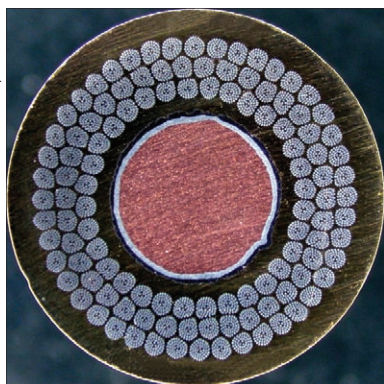
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## For the record

The true scope of the tragedy still remains beyond comprehension and is a shocking reminder of the reality of the nuclear threat

**Mikhail Gorbachev**, former president of the Soviet Union, writing in the *Bulletin of the Atomic Scientists* Marking 25 years since the accident at the Chernobyl nuclear power station, Gorbachev warns of the importance in keeping weapons-grade nuclear material out of the hands of terrorists.

We do have room-temperature superconductivity. It just depends on where you have your room

**Jörg Schmalian**, from Iowa State University, speaking at the 2011 American Association for the Advancement of Science conference in Washington, DC

As materials have been found that superconduct at about 140 K, we do have room-temperature superconductivity – on the Moon that is.

I speak as a citizen not as a scientist, but I think I know a rip-off when I see one

Physicist **Freeman Dyson** quoted in Princeton Magazine

Dyson thinks a lot of people have made a profession out of global warming and decries the “tremendously dogmatic” predictions about worldwide temperature trends.

We are bringing the spirit of science back to a subject that has become too argumentative and too contentious

**Richard Muller** from the University of California, Berkeley, quoted in the *Guardian* Muller is leading the Berkeley Earth project – what claims to be a completely independent assessment of global warming.

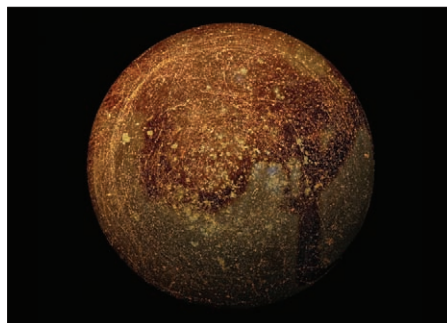
Greenland is destined to be remembered as a classic example of how not to put science on the stage

Physicist and science writer **Graham Farmelo** quoted in the *Times Higher Education* Farmelo was commenting on a play at the National Theatre looking into our society's current position on climate change.

Any woman who collects *Star Wars* toys is fine with me

Physicist **Brian Cox** quoted in the *Daily Mail* Cox, star of BBC TV series *Wonders of the Universe*, explains what made him fall in love with his wife.

## Seen and heard



## No pan intended

Quiz question. What object is shown in the above image? No, it's not Mars or Mercury – or indeed any other planet in our solar system for that matter. The picture is in fact of the underside of that common kitchen utensil – the frying pan. The images were taken by Norwegian-based artist Christopher Jonassen for his new book *Devour*, which showcases the wear and tear of one frying pan after another. Jonassen took the pictures after exposing his collection of worn-out pans to cooking oils, using various lighting techniques to bring out different textures in the images. But Jonassen does not appear to be aware of the pan–planet similarities. “In the beginning, I was mainly interested in the abstract splatter of the cooking oil, but it was really interesting to discover how everyday life was wearing out the surface and metal of the frying pans one tiny scratch at the time,” Jonassen told *Physics World*. “It became a really powerful metaphor for how we are exhausting the planet we inhabit.” Right...

## Place your bids

Got some spare change lying around? Then get down to Sotheby's in New York on 12 April. The auction house is inviting bids for the Soviet Union's legendary Vostok 3KA-2 capsule, which is expected to fetch \$2–10m. The craft, which took off in March 1961, is famous for being the last test flight for the Soviet 3KA-3 capsule that blasted Yuri Gagarin into space 50 years ago on 12 April 1961 and made him the first person to leave the Earth's bounds. But if your piggy bank doesn't quite stretch that far, then you might instead fancy some spacesuits worn by cosmonauts Alexei Leonov and Gennadi Strekalov, which Bonhams are auctioning in New York on 5 May. Estimated to fetch about \$100 000 each, Leonov's suit was worn during the 1975 Apollo–Soyuz mission – the first joint US/Soviet Union spaceflight – while Gennadi's outfit was

worn during a trip to the Mir space station in 1990. Also getting in on the golden jubilee of Gagarin's flight is Australian firm Four Pines Brewing Company, which has developed “Vostok” – the first beer designed to be drunk in space. Vostok is less carbonated than normal beer and has a stronger flavour to counteract the fact that in zero-g the tongue swells and the senses dull. “Wherever humans have journeyed in the last 1000 years, we first worry about water, food, shelter and clothing,” Jaron Mitchell, founder of Four Pines told *news.com.au*. “In many cases, beer is the next consideration.” We'll drink to that.

## Not so elementary

After crushing former *Jeopardy!* TV game-show champions Ken Jennings and Brad Rutter, scientists at IBM must have been pleased with their latest supercomputer “Watson” – until it came up against physicist and US Congressman Rush Holt that is. In *Jeopardy!* contestants are presented with clues in the form of answers, and must phrase their responses in question form. For example, if told “It is the only state lying south of the Tropic of Cancer”, the correct answer would be “What is Hawaii?”. Watson, which was especially designed for *Jeopardy!*, uses a series of algorithms and some heavy-duty processing – including nine servers – to determine the answer with the highest probability of being correct. Watson finally met its match with Holt, former assistant director of the Princeton Plasma Physics Laboratory, who amassed \$8600 to Watson's \$6200. Sadly, the two only came monitor-to-head in a first-round game and never played a full *Jeopardy!* match.



## In it to win it

Speaking of quizzes, what element in the periodic table has the atomic number 36? And which Nobel laureate's real name was Gábor Dénes? These were some of the taxing questions faced by a *Physics World* team at last month's Big Science Pub Quiz held at Imperial College London. A total of 16 teams entered – from the *Guardian* to the BBC – with each group of journalists joining forces with select academics from Imperial. The *Physics World* team, aided by physicist John Tisch and four members of his quantum-optics research group, came a respectable eighth, with 52.5 out of 95. Maybe we could have done with Watson (see above) on our side.

Christopher Jonassen

Caroline Prew

## In brief

**Antarctic meteorite may have seeded life**

Researchers in the US say they have found strong evidence to support the theory that life on Earth was seeded by meteorites from outer space. They studied the CR2 Grave Nunataks (GRA) 95229 meteorite, discovered in Antarctica in 1995, and found that it released abundant amounts of ammonia when treated with water at high temperature (300 °C) and pressure (100 MPa). They speculate that similar meteorites could have provided the Earth's early atmosphere with a supply of nitrogen – a precursor to complex biological molecules such as amino acids and DNA. What is more, many of the nitrogen-based compounds found in the meteorite are water-soluble, which is also essential because biologists agree that life emerged from watery environments (*Proc. Natl Acad. Sci. USA* 10.1073/pnas.1014961108).

**To thicken, just add water**

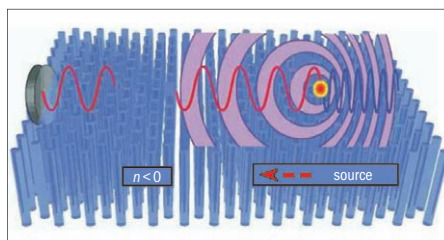
Chefs have known for a long time that melted chocolate can be solidified again with the simple addition of water. Researchers in Germany now say that this counterintuitive transition is a general phenomenon and they have been able to pin down the mechanism responsible. In an experiment, they dispersed water-repelling glass beads into an organic solvent to form a viscous solution. Then, when they stirred water to this mixture, until it made up just 1% of the suspension by mass, the fluid transformed into a gel-like material. The researchers argue that this effect is caused by the fact that the water does not wet as well as the solvent. So instead of coating the particles, the water flows to minimize the total area of contact between the particles and the bulk fluid, thus binding the beads together into a more rigid network (*Science* 331 897).

**Cold atoms coupled with spin**

Spin-orbit coupling has been simulated in ultracold neutral atoms for the first time. Conventionally, this coupling describes the interaction between the intrinsic spin of an electron in a solid and the magnetic field induced by the motion of the electron relative to the surrounding ions. Physicists in the US have now simulated the effect in a Bose-Einstein condensate (BEC) with about 180 000 rubidium atoms at a temperature of less than 100 nK. A laser beam applied to the BEC along the x-direction causes rubidium atoms in a certain spin state to absorb a photon. These atoms can then be stimulated to emit a photon in the y-direction by a second laser beam applied perpendicular to the first. This alters the momentum of the atom, thereby coupling its spin and momentum (*Nature* 471 83).

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## Doppler shift is seen in reverse



**Inverse Doppler effect** Researchers have turned a well-known physics phenomenon on its head.

Doppler shift is a well-known feature of physics, apparent in many processes from the redshifted light emitted by accelerating distant galaxies to the fading pitch of an ambulance siren as it races off into the distance. However, physicists have now seen the more exotic inverse Doppler shift at optical frequencies for the first time. The effect, which was first observed with radio waves, involves the frequency of waves emitted by, or bouncing off, an object increasing (rather than decreasing) as the object moves away from an observer.

The inverse Doppler shift was seen by a group led by Songlin Zhuang of the Shanghai University of Science and Technology in China and Min Gu of the Swinburne University of Technology in Australia. They fired an infrared laser through a photonic crystal comprising a lattice of 2  $\mu\text{m}$  diameter silicon rods attached to a moving platform and then recorded the frequency shift of the light leaving the lattice. As with other photonic crystals,

the lattice has characteristic band gaps that prevent light over a narrow range of wavelengths from passing through it.

By tuning their laser so that its wavelength matched the edge of the band gap, the researchers were able to “negatively” refract the laser light, thus causing the light to be inverse Doppler-shifted. But because the source and detector cannot be positioned inside the crystal, the team devised a clever way of confirming that the effect had indeed occurred. This involved splitting the beam from the laser into two and adjusting the path length of the part not passing through the crystal so that it underwent the same conventional Doppler shift as the light that did go through. The beat frequency when the two beams interfere revealed the frequency shift caused by only the inverse Doppler effect.

According to Gu, the trick is to arrange the silicon rods in such a way as to ensure that the laser beam follows the simplest path through the photonic crystal. Otherwise, he says, it would be too difficult to calculate the expected inverse Doppler shift and impossible to compare theory with experiment. The team also carried out the same experiment using a normal glass prism instead of the photonic crystal, and saw the conventional Doppler shift as expected.

The result is important as it provides further proof of the still-contested phenomenon of negative refraction. It could also lead to practical applications, such as measuring the speed of complicated blood flows.

## Forward to fusion

Physicists at the \$3.5bn National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in California say they have taken an important step in the bid to generate fusion energy using ultra-powerful lasers. Although they have not yet generated enough energy to ensure that the fusion process is self-sustaining, what the NIF researchers have done is to achieve the temperature and compression conditions that would be needed for a fusion reaction to continue without any external energy source. NIF director Ed Moses expects the lab to pass this process of “ignition” next year.

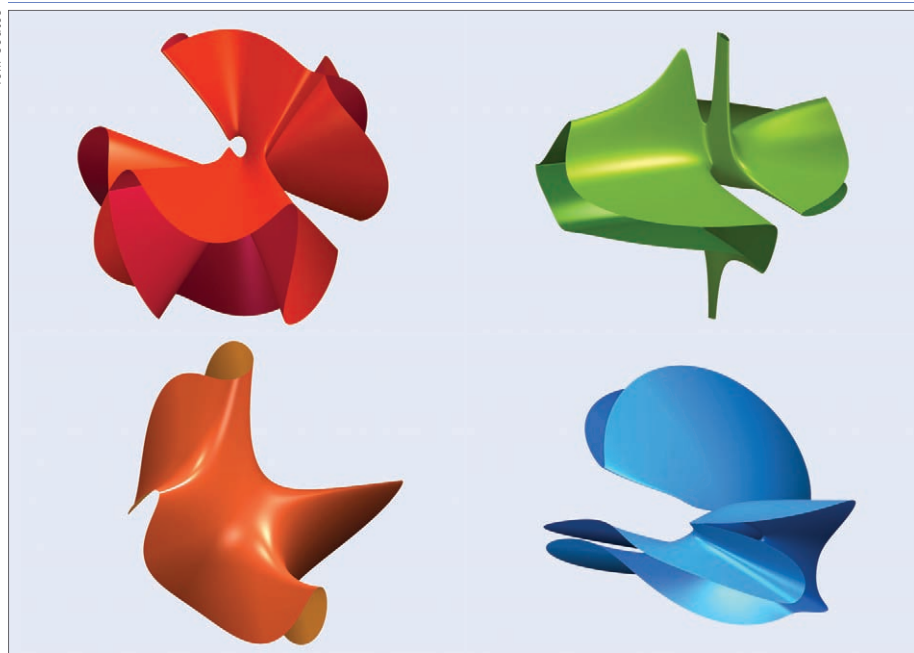
NIF consists of 192 giant lasers focused on a hollow gold cylinder a few centimetres long known as a hohlraum. When fully up and running, this hohlraum will house pepper-corn-sized spheres of beryllium containing deuterium and tritium fuel. Using the lasers, researchers hope to generate enough heat

and X-rays to make the beryllium spheres explode, which will force the deuterium and tritium to rapidly compress. A shockwave from the explosion would then heat the compressed matter enough to let the nuclei overcome their mutual repulsion and fuse. Researchers hope that by burning some 20–30% of the fuel inside each sphere, the reactions will yield between 10 and 20 times as much energy as supplied by the lasers.

In the new experiment, two independent groups at NIF used plastic spheres containing helium, rather than actual fuel pellets, as these are easier to analyse. By combining their experimental measurements with computer simulations, the researchers found that the hohlraum converted nearly 90% of the laser energy into X-rays and that its temperature increased to  $3.6 \times 10^6$  K (*Phys. Rev. Lett.* 106 085004 and *Phys. Rev. Lett.* 106 085003). The next step will be to use beryllium spheres with unequal quantities of deuterium and tritium to study how hydrodynamic stabilities might lead to asymmetrical implosions.



Tom Coates



## Innovation

### Watch this space for quantum-dot TV

TV screens that combine a vast colour range with an incredibly small pixel size could be produced using red, green and blue quantum dots – tiny nanometre-sized regions of compound-semiconductor crystal containing just a few thousand atoms. That is the claim of a group of researchers led by Tae-Ho Kim at the Samsung Advanced Institute of Technology in South Korea along with colleagues in the UK. The quantum dots emit a narrow band of light when electrons inside them recombine with positively charged holes.

Making a colour display with quantum dots involves depositing them onto a substrate in a well-controlled manner, which can be tricky. Monochrome quantum-dot displays have been made before by dropping a dot-containing solution onto a substrate and spinning this around to yield a thin film of the material. But this “spin-coating” approach is not suitable for making a full-colour display because it would cross-contaminate the red, green and blue pixels.

In the new work, Kim’s team overcame this issue by spin-coating red, green and blue dots onto separate “donor” substrates, before transferring them one colour at a time to the display with a patterned rubber stamp. To make a four-inch diameter display with  $320 \times 240$  pixels, a pair of electron-transporting polymers was deposited onto a piece of glass coated in indium tin oxide. Red, green and blue dots were stamped onto this structure, which was then coated with titanium dioxide – a material that transports holes well.

Adding a thin-film transistor array allowed a different voltage to be applied to each of the pixels, which were  $46 \mu\text{m}$  by  $96 \mu\text{m}$  in size. Increasing this voltage makes the pixels shine more brightly because more electrons and holes are driven into the dots, where they recombine to emit light. The researchers say they have also demonstrated an array of narrow quantum-dot stripes  $400 \text{ nm}$  wide, which indicates that it should be possible to do nano-printing of quantum dots with extremely high resolution (*Nature Photonics* 10.1038/nphoton.2011.12). This, the Korean team says, proves that the technology can produce displays with the highest practical resolution for viewing with the naked eye, which can only resolve pixel sizes down to  $40 \mu\text{m}$ .

One downside of the display is that it currently has a relatively low efficiency – just a few lumens per watt, which is about half that of an incandescent bulb. But Byoung Lyong Choi, one of the Samsung researchers, told *Physics World* that far higher efficiencies should be possible by modifying the quantum dots.

## Towards a periodic table for geometry

These colourful figures are part of a new project to create a periodic table of shapes that could do for geometry what Dmitri Mendeleev did for chemistry in the 19th century. The three-year project, led by researchers at Imperial College London, could result in a useful resource for mathematicians and theoretical physicists seeking all the shapes across three, four and five dimensions that cannot be broken down into simpler shapes, of which there are likely to be thousands. They find these basic building blocks of the universe, known as “Fano varieties”, by looking for solutions to string theory, which assumes that in addition to space and time, there are other hidden dimensions. According to the researchers, physicists can study these shapes to visualize features such as space–time or interactions inside subatomic particles. For the shapes to actually represent practical solutions to physical problems, however, physicists will need to look at slices of the Fano varieties known as Calabi–Yau 3-folds, which give possible shapes of the curled-up extra dimensions. The periodic table could also help in the field of robotics, where engineers need to develop algorithms that operate in high dimensions to make movements more lifelike.

## Talking bilingualism

Physicists in Spain are challenging the idea that two languages cannot continue to exist side by side within a society. Jorge Mira Pérez, who led the research, became interested in the issue of language survival because of the situation in his own region of Galicia in north-west Spain, where people speak both Spanish and the local language, Galician. Teaming up with his colleagues at the University of Santiago de Compostela, Mira Pérez built on an earlier mathematical model developed at Cornell University in the US, in which speakers in a society can switch between two distinct language groups.

In the Cornell model, the weaker language always dies out in the end. Mira Pérez’s team realized, however, that the model did not take into account bilingualism and the impact this can have on the stability of each language. The researchers have therefore developed a more advanced model that includes three distinct groups – the two mono-

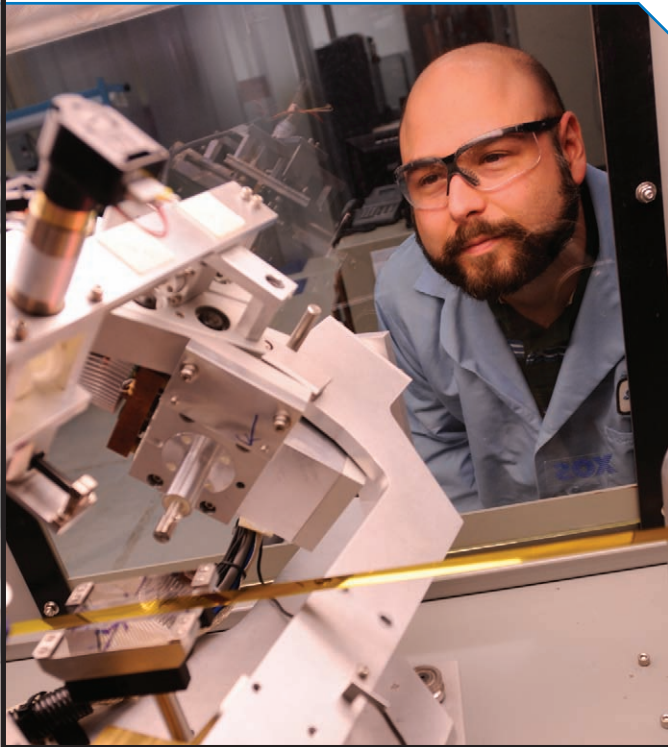
linguists and the bilingual – where people can shift between all three groups.

To test their model against a real-world situation, the researchers compared it with historical data for the preponderance of Spanish and Galician from the 19th century to 1975, and found that the fit was quite good. They find that both languages can co-exist indefinitely as long as each is initially spoken by enough people and both are sufficiently similar. Survival is also related to the “status” of each language, a parameter that takes into account the social and economic advantages of that language (*New J. Phys.* 13 033007).

The findings are good news for languages such as Galician and Catalan, spoken in autonomous communities in Spain, which have relatively steady numbers of speakers and share many similarities with Spanish, the dominant national language. The research could, however, be ominous for more distinctive languages such as Quechua in South America, which is very different from Spanish and is already being marginalized.



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# News & Analysis

## Japan quake triggers nuclear rethink

Governments around the world are planning to review their nuclear programmes following last month's earthquake that badly damaged the Fukushima Daiichi nuclear power plant in Japan. As *Physics World* went to press, officials had raised the security alert level at the plant from four to five on the seven-point International Nuclear and Radiological Event Scale, placing it just two points below 1986's Chernobyl disaster. The rating indicates "an accident with wider consequences" and limited release of radioactive material.

The UK government has already commissioned its chief nuclear inspector, Mike Weightman, to conduct a review into the implications of events at the Japanese nuclear reactors on existing and new plants in the UK. An interim report is expected by mid-May and a final report within six months. "Safety is and will continue to be the number-one priority for existing nuclear sites and for any new power stations," says Chris Huhne, the UK energy secretary. "I want to ensure that any lessons learned from Weightman's report are applied to the UK's new build programme."

Germany has taken its seven oldest reactors offline until at least June and put on hold plans to extend their lives. France, the number-two producer of nuclear power behind the US, has



REUTERS/HO New

meanwhile announced that it will conduct tests on security systems at the country's 58 nuclear reactors. US President Barack Obama has also requested a comprehensive review of American nuclear facilities to be carried out by the US nuclear regulatory commission. India, China and Pakistan are among other nations that will review their nuclear safety too.

Early reports suggest the emergency at Fukushima stemmed from a failure of cooling systems associated with the plant's six reactors. When the earthquake struck, damage to power supplies meant that cooling water could no longer be circulated within the reactor core, causing fuel rods to overheat and their metal casings to

### No smoke without fire

The 9.0 magnitude earthquake and subsequent tsunami that struck Japan last month badly damaged the Fukushima Daiichi nuclear power plant causing explosions and fires.

partially melt. This released chemicals that reacted with water vapour to produce hydrogen, which escaped and exploded, damaging the reactor buildings. As an emergency response, Japanese authorities drenched the reactor compound with seawater late last month, and there have already been signs of elevated levels of radiation in agricultural products such as milk and spinach.

The earthquake and tsunami have also affected some of Japan's major scientific facilities, although the country's strict building codes managed to prevent major damage. A preliminary inspection of the massive new \$1.5bn Japan Proton Accelerator Research Complex (J-PARC), which lies about 200 km south of the region worst hit by the quake, revealed it had come off relatively unscathed, although it is expected to take more than six months for its neutron spallation source to return to normal. Not so fortunate, however, is the Photon Factory, a national synchrotron-radiation facility based at the KEK particle-physics lab in Tsukuba, some 50 km north-east of Tokyo. The lab's director, Soichi Wakisaka, has reported that the facility's linear accelerator has suffered "substantial damage", including the displacement of three radio-frequency modules by about 10 cm.

James Dacey

### Funding

## Physicists face anxious wait for outcome of US budget

Uncertainty is spreading through the US science community as a divided Congress appears unable to agree the details of the country's 2011 budget, which began in October last year. The Republican-led House of Representatives is proposing cuts to discretionary spending, which includes support for science, by a massive \$61bn. Those proposals, which were passed by the House in February, have led to a deadlock in Congress as the Democratic-majority Senate opposes such swingeing cuts.

Since December, Congress has been operating the national budget on a "continuing resolution" bill, which has frozen the 2011 budget at 2010 levels.

**The Task Force on American Innovation has warned that the cuts would have a "devastating impact" on the country's scientific infrastructure**

That resolution was extended to 18 March together with \$4bn in cuts, and just before that deadline, the Senate approved another continuing resolution that would cut another \$6bn and last until 8 April. Although the reductions have so far had little impact on science funding, researchers fear that the House will aim for more reductions in the final 2011 budget, which may not emerge until May.

If the \$61bn cuts pass the Senate, it would mean an 18% reduction in funding for the Office of Science in the Department of Energy (DOE). However, because government departments have been spending at 2010 levels, the actual cut would amount to 31% for the rest of

this financial year. The National Science Foundation (NSF) would lose 8.9% of its funding, while the Environmental Protection Agency would be faced with a massive 30% fall.

The Task Force on American Innovation – representing hi-tech firms, research universities and scientific societies – has warned that the cuts would have a "devastating impact" on the US's scientific infrastructure. It warns that "virtually all DOE national laboratory user facilities...would cease operations...and 10 000 fewer university researchers would receive support [from the NSF]".

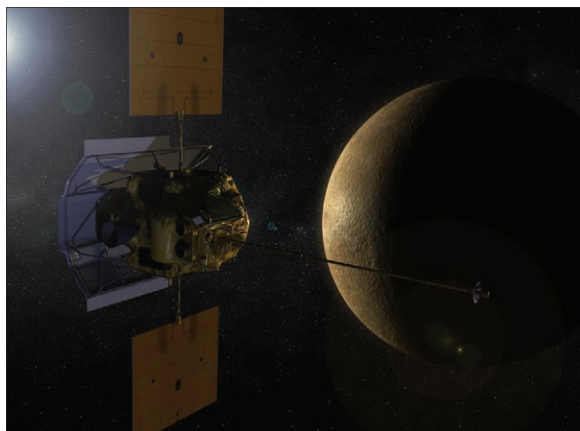
Peter Gwynne  
Boston, MA

## Astronomy

# MESSENGER spacecraft enters orbit around Mercury

The first spacecraft to orbit Mercury began circling the solar system's smallest and least-understood planet last month in what mission scientists hailed as the "historic" conclusion to a six-and-a-half year, 7.9 billion kilometre journey. At 12.45 a.m. GMT on Friday 18 March, the main thrusters on NASA's MESSENGER craft began firing, slowing it down by  $0.862 \text{ km s}^{-1}$  so that it could be "captured" by Mercury, which has an escape velocity of  $4.25 \text{ km s}^{-1}$ . After a 15 min "burn" was completed, staff at Johns Hopkins University's Applied Physics Lab (APL) briefly analysed anticipated radio signals from the craft before announcing success.

"This accomplishment is the fruit of a tremendous amount of labour on the part of the navigation, guidance and control, and mission operations teams, who shepherded the spacecraft through its journey," says the APL's Peter Bedini, MESSENGER's project manager. By 1.45 a.m. GMT the craft had rotated back towards the Earth and started transmitting its first data. Later that morning MESSENGER began its first full orbit around the planet, tracing out an elliptical path that brings it within 200 km of Mercury's scorched and cratered surface before swooping out to 15 193 km,



where the reflected heat from the surface is less intense.

Over the next year, the craft will complete one revolution every 12 Earth-hours, racking up 730 laps before the mission is scheduled to end. During this time, instruments on the half-tonne, \$446m craft will collect unprecedented amounts of data about Mercury's surface features and composition, as well as its magnetic field and tenuous atmosphere, or "exosphere". According to MESSENGER principal investigator Sean Solomon from the Carnegie Institution for Science in Washington, DC, these data will yield new information on some of Mercury's biggest mysteries – inclu-

## Mercury rising

NASA's MESSENGER craft is due to start transmitting its first scientific data on 4 April.

ding the intriguing possibility that it may harbour small amounts of water ice at its poles, even though surface temperatures can exceed 700 K.

MESSENGER is the first spacecraft to visit Mercury since the 1970s, when the Mariner 10 probe flew past three times. Although that mission discovered Mercury's magnetic field and exosphere, it only managed to map 45% of the planet's surface and left many questions unanswered. MESSENGER has already added new insights, having flown past the planet three times in 2008 and 2009, imaging most of what Mariner 10 missed, collecting data on the planet's composition, and sketching out the geometry of its magnetic field.

The craft's orbit around Mercury, however, marks the real start of MESSENGER's mission. One key puzzle is why Mercury has a weak magnetic field, whereas larger planets such as Mars and Venus have no intrinsic dipolar field at all. Another mystery is Mercury's huge density, which at  $5.3 \text{ g cm}^{-3}$  is the biggest of any planet in the solar system, after gravitational compression is factored out.

## Margaret Harris

● Listen to an audio interview with Sean Solomon at [physicsworld.com/cws/article/news/45415](http://physicsworld.com/cws/article/news/45415)

## Space

# Need a lab in space? Yours for just \$200 000 per head

Virgin Galactic has announced the first ever commercial contracts that will enable researchers to carry out experiments in zero-g environments. The deal between Virgin Galactic and the private Southwest Research Institute (SwRI), based in San Antonio, Texas, will pave the way for scientists to perform microgravity, biology, climate and astronomy research on Virgin Galactic's SpaceShipTwo spacecraft. It can travel about 100 000 m above Earth, allowing passengers to experience about 6 min of weightlessness.

The SwRI has made full deposits of about \$400 000 for two researchers to fly on SpaceShipTwo and intends to book six more seats at a total cost of \$1.6m. The SwRI will also aim to help US researchers who do not have direct spaceflight experience to develop



## Flying high

The Southwest Research Institute plans to book seats on Virgin Galactic's SpaceShipTwo craft to carry out research in a microgravity environment.

their payloads on such missions. The experiments will be performed in SpaceShipTwo's cabin, which is about 2.5 m in diameter and 18 m long.

According to SwRI researcher Alan Stern, who will be one of the scientists aboard the spacecraft, all scientists will have to pass pre-flight medical tests. Stern and his co-investigators

Daniel Durda and Cathy Olkin have already been practising with the US's National AeroSpace Training and Research (NASTAR) centrifuges and taking test flights aboard the US Air Force Starfighter F-104 jets to help them get used to the conditions.

One experiment the SwRI researchers will perform will be to measure heart rates and blood pressure of the scientists throughout the flight. SwRI researchers also intend to test the performance of an ultraviolet imager that could be used to study planets at wavelengths that are blocked by Earth's atmosphere. "There are a great deal of risks, but the knowledge to be gained and inspiration to new generations of researchers makes it all well worth it," says Durda.

## Gemma Lavender



## Earth observation

# NASA's Glory mission fails on take-off

NASA has launched an investigation into last month's dramatic failure of the \$424m Glory satellite, although the agency says it has no plans to rebuild the craft. The probe was meant to study how the Sun and aerosols in our atmosphere affect the Earth's climate but it crashed shortly after take-off, landing in the South Pacific. The seven-member investigation panel, led by Bradley Flick, a director at NASA's Dryden Flight Research Center in Edwards, California, is expected to make recommendations to NASA boss Charles Bolden on how to avoid a similar accident happening again. According to NASA spokesperson Stephen Cole, the investigation could take "six months or more" and that "the priority is to do a thorough investigation, not meet a preset deadline".

The 545 kg craft took off on a Taurus rocket early last month from the Vandenberg Air Force Base in California after technical issues delayed the original 23 February launch date. However, six minutes into the mission NASA declared that the Taurus XL rocket had malfunctioned



## Mourning Glory

NASA says it currently has no plans to rebuild the \$424m Glory satellite after it failed just six minutes after take-off last month.

and the "fairing" – the part of the rocket that covers the satellite on top of the rocket – had failed to separate properly so the satellite could not drift away in orbit.

This is not the first time a NASA satellite has failed in this manner. In 2009 NASA's \$270m Orbiting Carbon Observatory (OCO) did not properly

separate from its Taurus XL rocket after launch. The probe later landed in the Pacific Ocean near Antarctica.

Glory was meant to operate at an altitude of 700 km carrying two main instruments: the Aerosol Polarimetry Sensor (APS) and the Total Irradiance Monitor (TIM). The APS, operating from the visible to short-wave infrared, would have studied the distribution of small particles in the atmosphere – including their size, quantity, refractive index and shape – and how they can influence the Earth's climate by reflecting and absorbing solar radiation.

The APS would have been the first space-based instrument to be able to identify different aerosol types, which would have helped researchers to distinguish the effect that natural and man-made aerosols have on the climate. The TIM instrument would have extended the three-decades-long record of the amount of solar energy striking the top of the Earth's atmosphere. The accuracy of Glory's TIM instrument was expected to be better than that of any other solar irradiance instruments currently in space.

Glory was to be the fifth instalment of NASA's "A-Train", which when it is complete will be a set of eight satellites that study changes in Earth's climate system.

Michael Banks

## Astronomy

# US picks Mars sample-return mission as top priority

A sample-return mission to Mars has come top of a wish list drawn up by planetary scientists in the US last month. NASA's \$3.5bn Mars Astrobiology Explorer Cacher (MAX-C) was chosen ahead of missions to Jupiter and Uranus in the survey from the National Research Council (NRC), which picks key missions and challenges in planetary science for the period 2013 to 2022. However, the report, written by a 17-strong panel led by Steven Squyres from the Center for Radiophysics and Space Research at Cornell University, warns that any of the priority missions should be cancelled if costs balloon.

The top pick, MAX-C, is a rover that would collect and store samples from the Martian surface for return to Earth. The second-choice mission is the \$4.7bn Jupiter Europa Orbiter (JEO), which would map the Jovian moon Europa to gain a better understanding of the environment beneath

## First in line

NASA's \$3.5bn Mars Astrobiology Explorer Cacher has been selected as the highest priority planetary mission for launch between 2013 and 2022.



the body's icy surface, where it is thought there is an ocean of water that could harbour life. The third priority is the Uranus Orbiter and Probe mission, which would investigate the planet's interior structure, atmosphere and composition.

However, the report, entitled "Vision and Voyages for Planetary Science in the Decade 2013–2022", says

that NASA should only fund MAX-C if the cost is kept to \$2.5bn. Missions to Jupiter and Uranus are also in the firing line. The authors say that NASA should only build JEO if costs can be reduced, and that if the Uranus probe's budget rises above \$2.7bn, then it should be reduced in scope or even cancelled.

The report does not prioritize "medium-class" missions, which are capped at a cost of about \$500m, but says NASA should select two such missions to fly between 2013 and 2023. "Our recommendations are science driven that have the potential to greatly expand our knowledge of the solar system," says Squyres. "However, in these tough economic times, some difficult choices may have to be made. Our priority missions were carefully selected based on their potential to yield the most scientific benefit per dollar spent."

Michael Banks

## Astronomy

# Dispute arises over antenna giveaway

A decision to give away a prototype US telescope to a consortium of Taiwanese and US astronomers has been put on hold following accusations that the bidding process could have involved “a perception of cronyism”. The National Science Foundation (NSF) announced last year that it would donate the \$6.3m Vertex Prototype Antenna (VPA) – a high precision 12 m diameter millimetre/submillimetre antenna – to any institution or group willing to refurbish the telescope and move it from New Mexico, where it is currently based. But when the NSF announced that the US–Taiwan collaboration had won the bid, a rival complained the choice was based on an old-boy network, rather than scientific merit.

The VPA served as the prototype for the Atacama Large Millimeter Array (ALMA) – a set of 66 antennas located in Chile that will study black holes as well as planetary and star formation when it begins observations later this year. Improvements to the design of the ALMA antennas, based on research performed by the VPA, made the prototype redundant and so the NSF called on US institutions as



Kelly Gatlin/NRAO/AUI

well as countries that “form the North American ALMA region” to submit proposals for hosting the antenna.

In January the NSF announced the VPA would go to a collaboration between the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts, and the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taiwan. The collaboration had indicated that it might relocate the telescope to Greenland. However, Robert Shelton, president of the University of Arizona, expressed his objections in a letter to Edward Seidel, NSF’s assistant director of mathematical and

## Uncertain future

The National Science Foundation is reviewing its decision to let the 12 m diameter Vertex Prototype Antenna be moved to Greenland.

physical sciences. Shelton complained of “a perception of cronyism” from National Radio Astronomy Observatory (NRAO) director Fred Lo, who heads ASIAA’s scientific advisory board, and Vernon Pankonin, the NSF official who made the decision. Shelton asserts the CfA–ASIAA proposal has less scientific merit than that of his university, which planned to place the antenna on nearby Kitt Peak. “The antenna was built with US taxpayers’ money. It cannot be in the national interest to transfer ownership of an asset such as the VPA to a foreign-led group that proposes to locate the antenna in Greenland – yet another foreign country,” he writes.

The NSF has acknowledged Shelton’s letter and plans to review its original decision. The University of Arizona expects a response this month, although the NSF has provided no schedule. Charles Alcock, director of the CfA, says that a CfA–ASIAA collaboration has good experience, having built the world’s only existing submillimetre array, which has operated since 2003 at an altitude of 4 080 m on Mauna Kea in Hawaii. He adds that moving the telescope to Greenland, should that happen, would benefit performing submillimetre observations, as it is substantially dryer than any possible US site.

**Peter Gwynne**  
Boston, MA

## Research misconduct

# China withdraws top science award after fraud claims

The Chinese government has – for the first time – revoked a top national science and technology award because of research fraud. An investigation by China’s National Office for Science and Technology Awards and the country’s science ministry announced in February that Liansheng Li, a mechanical engineer formerly from the Xi’an Jiaotong University (XJTU) in Shan’xi province, was guilty of plagiarism in the work that won him the country’s 2005 Scientific and Technological Progress Award. Li will now be stripped of the award and forced to return the \$15 000 prize money.

A problem first came to light in 2007 when Yongjiang Chen, a retired XJTU mechanical engineer, together with five other XJTU colleagues, found that Li had copied their work for designing reciprocating compressors – a device for compressing air – that are used in air-conditioners and

## Fighting fraud

Daguang Li, from the Chinese Academy of Science’s graduate school in Beijing, was part of a panel that found mechanical engineer Liansheng Li guilty of fraud.



JiFu Du

vacuum pumps. Li claimed to have devised new analytical methods that he then incorporated into a software program used to improve the design of compressors.

However, Chen found that Li had copied both the software and the method from work done by Zhongchang Qu, also from the XJTU. Chen then wrote about the plagiarism in 2009 on *ScienceNet.cn* – a website run by the Chinese Academy of Sciences

(CAS). Li was later fired by the XJTU in March 2010 after an investigative news TV programme in China covered the controversy.

“The fraud is only the tip of the iceberg,” says Daguang Li from the CAS’s graduate school in Beijing, who was a member of the panel that stripped Li of his prize. “I have worked in academic circles for more than 20 years, helplessly watching academic misconduct.”

Others, however, are calling for reforms into how awards and research grants are handed out. “It is essential to have more openness and transparency in handling prizes, awards and grants, to ensure fair competition and selection of the best, and to deter and expose frauds,” says Xuele Chen, a cosmologist at the CAS’s National Astronomical Observatories.

**Jiao Li**  
Beijing



## Funding

# Brazil's researchers dismayed as science budget is cut

Brazil's 2011 science budget will be cut by almost a fifth to help reduce public expenditure and control raging inflation. The budget, which was announced in February by Brazil's recently elected President Dilma Rousseff, will now stand at \$3.84bn – some 18% less than last year. The savage cut was announced after Rousseff vetoed a \$4.4bn package that had already been approved by the country's congress, which would have amounted to a rise of 7%.

The cuts have shocked researchers, who had benefited from the strong support for science from former president Luiz Inácio Lula da Silva. During 2003 and 2010 Lula doubled the country's science budget, the number of student in public universities and the number of grants for researchers. As Rousseff's government was presented during the general-election campaign as a continuation of that of Lula,



## Cutting costs

Brazil's recently elected President Dilma Rousseff has announced an 18% cut to the country's science budget much to the shock of physicists.

scientists trusted she would go on supporting science, especially as she had promised to turn Brazil into a "scientific powerhouse".

It is not clear yet where the cuts will be made but research projects in universities and institutes are likely to be the first to be hit. However, large scientific projects, such as the Brazilian Synchrotron Light Laboratory, are likely to remain unscathed.

Brazilian scientists are hopeful that the cuts will only be temporary. In 2009, for example, an 18% cut in the science budget was reconsidered following protests from the country's scientific community. "Despite previous cuts, Brazil has kept a consistent rhythm of development during the past decade," says Ronald Cintra Shellard, deputy director of the Brazilian Center for Research in Physics (CBPF), in Rio de Janeiro.

**Gabriela Frías Villegas**

## Gravitational waves

# India considers joining Australian bid

Seven Indian institutions have proposed joining the Advanced Laser Interferometer Gravitational Observatory – a US–Australian effort to build an advanced gravitational-wave detector. The Indian scientists would help to commission the facility during 2011–2017 and contribute equipment for LIGO-Australia's sub-systems such as ultrahigh-vacuum components for the detectors. The proposal is currently being evaluated by both the Department of Science and Technology and the Department of Atomic Energy for approval.

Last October the US announced that it would build one of its advanced gravitational-wave detectors at Gingin – about 80 km from Perth – to help determine the origin of such waves, which have never before been detected (see *Physics World* November p10). In early March the LIGO-Australia proposal was submitted to the Australian science minister Kim Carr for a decision. The five-university Australian Consortium for Interferometric Gravitational Astronomy has since been seeking to include other countries, such as India and China, to cover some of the \$140m costs of LIGO-Australia.

"We are certain that Australia would not fund unless there are international partners," says David Blair, director of the

There are so many mutual benefits for India and China to be involved

Australian International Gravitational Research Centre. "There are so many mutual benefits for our major regional partners India and China to be involved that I believe that the proposal is much more compelling with their inclusion."

The seven collaborating institutions in the Indian Initiative in Gravitational-wave Observations (IndIGO) consortium include the Tata Institute of Fundamental Research (TIFR), the Inter-University Centre for Astronomy and Astrophysics in Pune, and the Indian Institute of Science Education and Research in Thiruvananthapuram.

If India joins LIGO-Australia, researchers hope their resulting experience might enable a gravitational-wave detector to be built in India. First mooted in 2007, the TIFR even approved a 3 m interferometer prototype at the institute in 2009 at a cost of \$450 000. The project is part of a roadmap for a 4 km baseline instrument. "LIGO-Australia is the best pathway and opportunity for Indian participation in the global programme of gravitational-wave research and astronomy," says Bala Iyer, a gravitation theorist at the Raman Research Institute in Bangalore and chair of IndIGO's council.

**Ramaseshan Ramachandran**

New Delhi

## Sidebands

## Australia's chief scientist quits

Penny Sackett, Australia's first full-time chief scientist, has resigned only half way through her five-year term, citing both "professional and personal reasons". Sackett took up the post in September 2008 after the Labor government, led by former Prime Minister Kevin Rudd, made the position full-time. Sackett obtained a PhD in theoretical physics at the University of Pittsburgh before switching to astronomy. Since 2002 she has been a professor at the Australian National University, a position that she retained during her time as chief scientist. "She has been a terrific communicator at home and abroad, and has helped convey complicated messages about the issues confronting Australia," science minister Kim Carr said in a statement. The Australian government is now seeking a replacement.

## Carbon-capture plant picks site

The US Department of Energy (DOE) has announced that the \$1.3bn FutureGen carbon-capture demonstration plant, which will involve adapting a 200 MW coal plant that closed last year at Meredosia in Illinois, is to inject its sequestered greenhouse gases into underground rocks at a site some 5 km away in Morgan County. The DOE chose Morgan County as it is relatively close to the Meredosia power plant, thereby simplifying pipeline routing and reducing the project's overall cost. The DOE also highlighted the area's "high-quality geology", which makes it well suited for the long-term storage of carbon dioxide. However, the site still needs an environmental review and permits before carbon can be buried.

## Fear over emissions vote

US climate scientists have raised concerns after the energy and commerce committee of the House of Representatives voted last month to remove the Environmental Protection Agency's regulatory control over greenhouse-gas emissions. Most Republicans on the committee say the agency's control is unnecessary and damages commercial competitiveness. "We can have a good-faith debate about how to deal with the challenges and threats of human-caused climate change, but we cannot have a good-faith debate about its existence," says climate scientist Michael Mann from Pennsylvania State University. "Those who deny the very reality of the problem are poisoning the discourse and potentially causing great harm to us all."

## Obituary

## Simon van der Meer: 1925–2011

Simon van der Meer, who shared the 1984 Nobel Prize for Physics with Carlo Rubbia, died on 4 March at the age of 85. The pair were awarded the prize for their roles in discovering the W and Z bosons – the particles that carry the weak force – at the Super Proton Synchrotron (SPS) at the CERN particle-physics lab near Geneva. Van der Meer pioneered the technique of “stochastic cooling”, which helped to ensure that sufficient antiprotons entered the collider.

Van der Meer was born on 24 November 1925 in the Hague, the Netherlands, before studying technical physics at the University of Technology in Delft. Graduating in 1952, he worked for the Philips Research Laboratory in Eindhoven, developing high-voltage equipment and electronics for electron microscopes. He joined CERN in 1956, where he was to remain until he retired in 1990.

Under the leadership of future CERN boss John Adams, Van der Meer made his name in the early 1960s developing the “neutrino horn” – a device that can increase the intensity of neutrino beams. These devices are still used as they allow focused beams of neutrinos to be sent



through the Earth to huge, ultrasensitive underground detectors. Van der Meer then worked on an experiment at CERN measuring the anomalous magnetic moment of the muon.

It was while developing magnet power supplies for CERN’s accelerators, including the Intersecting Storage Rings (ISR), that Van der Meer devised the idea of stochastic cooling. Although the technique was not used on the ISR, it was trialled on the Initial Cooling Experiment, persuading Rubbia and others in 1976 to deploy it on the SPS. Van der Meer subsequently joined the SPS, helping

**Happy days**

Simon van der Meer (right) with Carlo Rubbia at CERN in October 1984 celebrating the award of that year’s Nobel Prize for Physics.

to lead the Antiproton Accumulator project, which used stochastic cooling to accumulate enough antiprotons for the collider.

The technique uses sensitive electrodes to pick up small “stochastic” electromagnetic signals that register the average condition of a particle beam, such as its density. These stochastic signals – and hence the properties of the beam itself – can then be controlled using a high-frequency “kicker” that sends out rapidly varying electric and magnetic fields. The technique can therefore shrink the size of a beam, thereby boosting its intensity. The beam has been “cooled” because the particles occupy a smaller volume.

Researchers at the SPS eventually discovered the W and Z bosons in experiments between October 1982 and January 1983. Speaking to *Physics World*, Rubbia said Van der Meer was “one of the most extraordinary people” he had ever met. “He was able to make everybody feel at ease by the clarity of his thinking and his enormous kindness,” Rubbia added. “His ideas were extremely original and he was able to make everyone understand them.”

**Matin Durrani**

## Middle East

## Political unrest puts SESAME project in jeopardy

A major scientific project designed to foster collaboration between countries in the Middle East is facing difficulties following growing political unrest in the region. The Synchrotron-light for Experimental Science and Applications in the Middle East (SESAME) is currently being built in Jordan and due to start up in 2015. But the toppling of the Egyptian government – and turmoil elsewhere – is putting a strain on the ability to guarantee the funding needed to complete the facility.

SESAME is designed to produce X-rays to study materials in a range of disciplines from biology to condensed-matter physics. Its members are currently Bahrain, Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority (PA) and Turkey. But the revolution in Egypt and growing anti-government protests in Iran and Bahrain have put the project on an uncertain footing. “In the short term it is

**Troubled times**

A new financial package of \$35m is being negotiated to enable SESAME to open by 2015.

very worrying,” Chris Llewellyn Smith, president of the SESAME council, told *Physics World*.

Although Llewellyn Smith says the unrest has yet to have a direct impact on the project, the former director-general of CERN is working with the SESAME members to put together a financial package that would guarantee the

roughly \$35m that is needed to open the facility by 2015. “[The package] is now in jeopardy as ministers of member countries are changing,” says Llewellyn Smith. “It is a moment of great uncertainty for the project.”

Back in February, Llewellyn Smith had been in discussions with the then Egyptian science minister Hany Helal about SESAME, but days later Helal was removed from office by the military-led government. Egypt had been expected to contribute about \$5m to the \$35m required, but it is not clear what importance any new government will attach to SESAME. Despite the problems, Llewellyn Smith remains “optimistic” about the project, with the new package due to be announced as *Physics World* went to press. “With more democratic governments, maybe we can get renewed and greater support for SESAME,” he says.

**Michael Banks**



## Q&amp;A

# A life in magnets

Industry giant General Electric has a long history of making superconducting magnets for magnetic resonance imaging. Michael Banks talks to

**Kathleen Amm**, GE's head of MRI technology, about the challenges ahead

## How long have you been involved in superconductivity?

For more than 16 years, now. I did my PhD at the National High Magnetic Field Laboratory in Florida, where I worked on the thermal properties of high-temperature superconductors, particularly  $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ , which at 133 K had the highest transition temperature of any other material.

## What attracted you to work for a company attempting to commercialize superconductivity, instead of pursuing an academic career?

My father had a long career as a geophysicist in the oil industry, and I always wanted to go into industry rather than staying in academia. GE was working on products utilizing superconductors – particularly magnets for magnetic resonance imaging (MRI) – and driving new innovations in the area, so it seemed like a good firm to join. When I joined, I was initially working on the properties of superconductors, which was similar to my PhD work.

## How are superconductors used in MRI?

An MRI machine uses a magnet to align the magnetization of particular atoms in the body, which causes the nuclei to produce a rotating magnetic field that is detectable by a scanner. Strong magnetic-field gradients cause nuclei at different locations to rotate at different speeds, so MRI provides good contrast between different tissues of the body, making it especially useful for imaging the brain, muscles, the heart and tumours. Superconducting magnets – made from coils of superconducting wires – can produce greater magnetic fields than standard electromagnets and are also cheaper to operate because no energy is dissipated as heat in the windings.

## What superconducting material does GE use for its MRI magnets and why?

We use niobium titanium ( $\text{NbTi}$ ), as it is a good workhorse material. It has a superconducting transition temperature of about 9.2 K, so it needs to be cooled by liquid helium to around 4.2 K. The advantage of this material



## Looking ahead

Kathleen Amm sees opportunities for superconductors in power generation and renewable energy, but is uncertain where the demand will come from.

is that it has many years of research behind it and it is easy to wind the material for magnets. But we are certainly looking at the potential of using magnesium diboride in our magnets, which is cheaper and has a higher transition temperature of about 40 K.

## What about other materials such as copper oxides or the recently discovered iron-based superconductors. Could they be useful?

We are always looking at other materials and YBCO [yttrium–barium–copper-oxide] is one of them. But the challenge there is building robust structures that can be manufactured into magnets. YBCO is very brittle and although the material has the potential to be cheaper, current manufacturing processes make the conductors expensive at this time. But if the costs come down, then we could see an advantage in using it. As for the iron-based superconductors, we are following the research; it is all very interesting but we will have to see where it leads.

## In the 1970s GE decided not to pursue applications of superconductivity thinking there was not enough demand in the market. In hindsight, was that a good decision?

I wouldn't say that GE dropped the idea of developing applications in superconductivity. GE has a long history in superconductivity and a number of Nobel laureates have worked at GE labs, such as Ivar Giaever, who shared

the 1973 Nobel Prize for Physics with Leo Esaki and Brian Josephson. GE did initially spin-off a company called Intermagnetics General (IG) in 1971, which GE had a vested interest in. The company later became independent and is now part of Philips.

## In 1984, after smelling huge market opportunities in MRI, GE returned to the superconducting market with force, rolling out its first machine that year. Would you say MRI is now the only real market for superconductivity?

Yes. There is no doubt that MRI is the largest opportunity. It is now a \$4bn global market. But there is also a well-established industry for supplying magnets for use in nuclear-magnetic-resonance imaging.

## Can you see any other application of superconductors that may lead to a market as big as that for MRI?

There is potential in power generation and in renewable energy, although I think it is not entirely clear yet where that demand will come from. As it did in the case of MRI, superconductivity must provide a unique value to be successful. For example, the high power density that superconductivity can bring to power generation can lead to applications where weight reduction is critical. For example, GE partnered with the Air Force Research Lab to develop lightweight generators for airborne applications. This aids in developing the power infrastructure needed for the ever increasing electrical demand on aircraft.

## If a room-temperature superconductor was found, how would that change the MRI business?

Well, the dream is to have room-temperature superconductivity. But, of course, whatever material that might be, it would have to be reliable and easily manufactured into wires. If this were the case, then I think you would see it implemented everywhere, as there would be no need for cryogenic equipment.

## What currently excites you about superconductivity?

I can remember back when high-temperature superconductors were first discovered in 1986, and it captured my imagination. There was a lot of excitement in the field and it was something I wanted to be part of. Superconductors also play a critical role in improving healthcare through the use of MRI. It is exciting to be involved in developing a technology that can enhance and save lives.

**Superconductivity must provide a unique value to be successful**

# Wiring the market

Firms have spent the last 25 years trying to create a market for high-temperature superconducting wires, but their widespread application may still be some years away. **Michael Banks** reports

"This will change the world," was the first thought of Gregory Yurek, a metallurgist working at the Massachusetts Institute of Technology (MIT), when he heard about a major discovery in condensed-matter physics. It was 1986 and Georg Bednorz and Alex Müller, both working at the IBM Research Laboratory in Zurich, had just discovered that the electrical resistance of a material made from lanthanum, barium, copper and oxygen (LaBaCuO) fell abruptly to zero when cooled below a temperature of 35 K. The appearance of superconductivity – where a material can conduct electrons with zero resistance below the superconducting transition temperature – was only 12 K higher than the previous record of 23 K in Nb<sub>3</sub>Ge, which was discovered in 1973. However, physicists knew that LaBaCuO was a major breakthrough because different elements in the material could be substituted for others, opening the door to potentially higher superconducting temperatures.

Within a year of Bednorz and Müller's discovery, a new material based on yttrium, barium, copper and oxygen (YBa<sub>2</sub>Cu<sub>3</sub>O, also known as YBCO) became the first material to superconduct above the boiling point of liquid nitrogen at 77 K, with a superconducting transition temperature of 93 K. That was quickly followed in 1988 by a material containing bismuth, strontium, calcium, copper and oxygen (BSCCO) that superconducts at about 105 K. Results and new compounds were appearing thick and fast – there seemed no limit to what transition temperatures might be possible. With the dream of room-temperature superconductors alive, Bednorz and Müller's discovery earned them the 1987 Nobel Prize for Physics.

It was all a revelation to Yurek, who immediately started to work on the chemical and physical properties of these materials. It was not just the understanding of these systems or the hunt for higher superconducting temperatures that fascinated him, but also how society could reap the rewards of the discovery for applications. Indeed, *TIME* magazine ran a whole issue in May 1987 devoted to the breakthrough: "Wiring the future:



**Laying the ground work**  
The Holbrook Superconductor project at a substation in Long Island, New York, has been operating with some 160 km of superconducting cables since 2008.

the superconductivity revolution". The dream then was of maglev "levitating" trains speeding through the countryside with the help of high-temperature superconducting magnets, as well as the promise of power distribution being revolutionized through the lossless transmission of electricity.

Keen to get in on the commercial possibilities, Yurek, together with his wife Carol and fellow MIT researcher John Vander Sande, formed American Superconductor (AMSC) in April 1987. They were buoyed by the fact that a new market for magnets in magnetic resonance imaging (MRI) was then slowly emerging that used superconducting wires from materials with lower transition temperatures, such as niobium tin (Nb<sub>3</sub>Sn), which superconducts at 18.3 K.

Based in Devens, Massachusetts, the company now employs about 900 people. Yet in the 25 years since the discovery of high-temperature superconductors, the widespread application of them has somewhat failed to live up to its promise. Indeed, instead of producing hundreds of kilometres of cable for power grids all over the world as it had envisaged, AMSC has been steadily diversifying its business to other areas such as renewable energy. In the third quarter of 2010 – the latest available figures – barely \$2.1m of AMSC's \$114.2m revenue came from its superconducting-wire business. The rest comes from AMSC's "power systems" division, which provides wind-turbine designs and power electronics for wind turbines and the

power grid.

Yurek is, however, confident that the company's fortunes and demand for superconducting cables is starting to take shape, or as he puts it "superconductors are now coming of age". Indeed, there is some evidence to back up his claims. Last year South Korean power-cable manufacturer LS Cable placed the world's largest order for some three million metres of wire from AMSC. LS Cable plans to use this wire to deploy approximately 25 km of superconductor power cables for the South Korean and global power-grid markets over the next several years.

However, other industry insiders are less sure that the time has come for high-temperature superconducting cables. "Utility companies are still to be convinced," says Pradeep Hal-dar, who co-founded the US-based superconductor-wire manufacturer SuperPower, which was bought up by electronics giant Philips in 2006, and who now works at the University at Albany, State University of New York. "The promise is still there, but it is still a huge challenge to get it widespread in the industry."

## The optical fibre of wire

The first high-temperature superconductor material to be utilized in commercial wires was BSCCO-2223 (Bi<sub>2</sub>Sr<sub>2</sub>Ca<sub>2</sub>Cu<sub>3</sub>O<sub>10+x</sub>) – known as a first-generation (1G) wire – that AMSC brought out in 1995. These superconductor wires are made by packing ceramic powders of BSCCO into silver tubes. The packed powder is extracted and rolled into a flat tape, which is heated to make it suitable for winding cables or coils for transformers, magnets, motors and generators.

Typical BSCCO tapes are 4 mm wide and 0.2 mm thick, and can support a current at 77 K of 200 A, giving a critical current density of about 10<sup>4</sup> A cm<sup>-2</sup>. To make a superconducting cable, the tapes are typically wrapped around a copper core, surrounding which are various levels of electrical shielding. The cables also have thermal insulation for the liquid nitrogen, which is used to cool the tape down to 77 K.

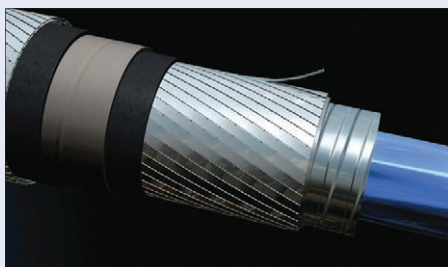
One big success of this 1G wire came in 2008, when it was used in a transmission-voltage superconducting power cable that operated at industry standards for the first time in a grid setting. Funded by the US Department of Energy, the Holbrook Superconductor project involved about 600 m of underground cable containing about 160 km of AMSC's BSCCO



## Superconductors head into the niche

While wire manufacturers wait for utility companies to show more interest in high-temperature superconducting cables, second-generation (2G) wires are finding some applications in generators and motors. A generator's weight can be reduced significantly – by a half or so – with superconductor wires as there is no need for a heavy iron core in the generator. “But when designing a motor or generator with superconducting wires, you have to throw away the book and basically start from scratch,” says Gregory Yurek of American Superconductor (AMSC). “People in the industry say ‘wow that’s fantastic, but I don’t know how to change my business’.”

Yurek says this is why AMSC has decided to start building and selling its own generator and motors that take advantage of superconducting wires. “Sometimes you can’t depend on other companies



and have to take it forward yourself,” he says. One example is in wind turbines, where superconducting cables can be used in the generator to make it more efficient than conventional generators. There is also some interest from the US Navy in using generators made with superconducting wires so that the size and weight of vessels can be reduced. In fact, AMSC

has successfully tested the world’s first 36.5 MW high-temperature superconducting ship-propulsion motor, which has been built at the US Navy’s Integrated Power System Land-Based Test Site in Philadelphia.

Although the industry that AMSC was created to pioneer has yet to fully take off, optimism abounds. “If you look back in history, you would have said that in the 1950s superconductivity looked like a failure, but then magnetic resonance imaging came along and created a billion-dollar industry,” says Pradeep Haldar, who co-founded the US-based superconductor-wire manufacturer SuperPower and now works at the University of Albany, State University of New York. “In my view, we will find a silver-bullet application for high-temperature superconductors, the question we do not know at the moment is what it will be.”

wire, installed at a Long Island substation in New York. The superconducting wire has been successfully operating in the grid since April 2008. Although the demonstration succeeded, the problem with BSCCO wire is that making it requires a lot of silver, which is expensive, and means 1G wires are unlikely to ever be cost-effective when compared with copper.

While other wire manufacturers, such as Japan’s Sumitomo, are still using BSCCO wires, AMSC and SuperPower have already brought out a second-generation (2G) wire, which is based on YBCO. Although YBCO has a lower superconducting transition temperature than BSCCO, it could potentially deliver much higher current densities of about  $10^6 \text{ A cm}^{-2}$  – more than 100 times the current density of copper wires – and outperforms BSCCO in high magnetic fields. “We think that it may be possible for YBCO wires to have a much higher current density, reaching about  $10^7 \text{ A cm}^{-2}$ ,” says Venkat Selvamanickam, SuperPower’s chief technology advisor who is based at the University of Houston, Texas.

Making YBCO involves depositing layers of the superconductor onto a substrate consisting mostly of nickel rather than silver. YBCO wires are about 4–12 mm wide and 0.1 mm thick, and are 1% YBCO with the rest being the nickel, copper and a little silver. Selvamanickam says that SuperPower’s technique can produce wire more than 1 km in length.

As for AMSC’s 2G wire, which goes under the name “Amperium”, it can conduct more than 100 times the electrical current of copper wire of the same dimensions. It now accounts for 85% of all wires sold to industry, and the company has more than 150 pa-

tents on the wire. Yurek calls Amperium the “optical fibre of wire” because just as high-capacity optical fibres have revolutionized the telecoms industry, so superconducting wires, he thinks, will revolutionize the electric power industry.

That may sound optimistic, but wires based on YBCO are starting to be used. AMSC, for example, is involved in the \$1bn Tres Amigas SuperStation, which is located in Clovis, New Mexico, and is expected to be in operation by 2014. The station will connect the US’s three power grids – the Western, Eastern and Texas interconnections – to increase the reliability of the grid and to enable a faster adoption of renewable energy. The grids will be linked together via three superconducting high-voltage direct-current power transmission lines, which allow for much better control of energy and are much more efficient than conventional cables.

There is also a \$39m project called “Hydra”. Initially proposed in 2007, it was put on hold following the global economic downturn, but is now, according to Yurek, “back on the table”. Partially funded by the US Department of Homeland Security, it will deploy 2G wire into the grid in lower Manhattan to protect substations from fault currents – power surges that could damage grid connections. “I think what you are likely to see over the next 10 or 20 years is utilities installing more demonstration cables here and there, but not on a huge scale,” says Haldar.

### A superconductivity revolution?

So why have utility companies around the world not been falling over themselves to install superconducting wires? “The issue with Long Island

and the like is that, although they show that superconducting wires can work, it is not at all a market demonstration,” says Haldar. “Utility companies need something to be tested to work on the scale of many years, maybe up to 30 years, to show that the cables can survive.”

Yurek also blames the “notoriously slow” power industry – sentiments that are reiterated by Trudy Lehner, director of marketing and government affairs at SuperPower. “We have a saying in the industry that the utility companies like to be first to be second,” he says. Another barrier is the price of uprooting parts of a grid to install new cable. Moreover, the current global economic downturn has dissuaded many firms from investing in new infrastructure. “Utility companies have basically told us that they cannot invest at this time, so they have put it back on the shelf,” says Yurek.

Although the cost of YBCO wires is coming down all the time, Selvamanickam says that superconducting cables are still about a “factor of five” times more expensive than standard copper cable, mostly because of the need for coolant systems. However, Haldar thinks that the cost of coolant is a red herring. “In addition to cost, training a whole new set of engineers to work with it, entering an already mature industry and turning it on its head is very hard to do,” he says.

Yet Yurek is expecting a number of “meaningful orders” from China in the coming months and is confident that the US and Europe will eventually begin to catch up with Asia. “As an American who has put a lot of blood, sweat and tears into this, it is a pity [the US is not leading],” says Yurek. “But I am confident that will change at some point.”

**I think what you are likely to see over the next 10 or 20 years is utilities installing more demonstration cables here and there, but not on a huge scale**

# Feedback

Letters to the Editor can be sent to *Physics World*, Dirac House, Temple Back, Bristol BS1 6BE, UK, or to [pwld@iop.org](mailto: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

## Physicists and finance

In his letter (February p20), Jim Grozier surmised that not many readers would agree with using physics PhD studentships to train people for a career in commerce. On the contrary, I think most readers would readily accept that not only do physics PhD studentships offer the ideal environment for commercial training, but that it is right that such studentships should be used for producing well-trained personnel for the banking, finance and services sector.

Far from insisting that those who leave physics for jobs in finance and banking should pay back their studentship money, as Grozier suggests, we should recognize that trained physicists have an immensely positive impact on the economy and that the tax revenues they generate compensate many times over for the costs of their PhDs. Many of these physicists are key people in the financial sector in and around the City of London, which is one of the most successful financial centres in the world. Indeed, the sector contributed £53bn in

taxes to the UK exchequer during the 2009/10 tax year – more than any other area of the economy.

Without such revenues, not only would it be impossible to fund physics PhD places, but also academic positions, such as the one presumably occupied by Grozier, would not be viable. Surely it is clear that we should positively and wholeheartedly encourage physics PhD students to follow their chosen path, especially if they wish to enter the world of commerce and finance, because there they will thrive, and that will be to the benefit of all of us.

**William Quinton**

Reading, UK  
[william.quinton@halarose.co.uk](mailto:william.quinton@halarose.co.uk)

## Still contributing

I much appreciated the article “Retired, but still a physicist” (February pp42–43), which provided both practical advice and a balanced assessment of “career” prospects after retirement. On a personal level, I have been extremely fortunate. Now 76, I have been allowed to retain my office at the university and, as a retired professor, I continue to receive an annual grant for travel and research. I also teach an elective undergraduate course once a year that has been approved for credit (27 students completed the course this year). I attend faculty meetings as an observer and I am occasionally consulted by both faculty and graduate students. I go to the occasional conference, though my presentations tend to focus on “historical” perspectives and assessments, not original work, and I try to

make sure that anything I have to say meets the expectations of the organizers.

There are, of course, problems. My metabolism has slowed and I do not have the concentration to keep up with the literature – a problem exacerbated by failing eyesight. There is no way that I can work in the laboratory or even participate in all the seminars and seminar discussions that I would like to. I have to remind myself that some of my one-time students are now senior staff members with serious responsibilities and at least as much knowledge as I possess, so I try to keep a low profile. I hope that I will retain the good sense to know when I am no longer able to make a contribution.

**David Brandon**

Technion – Israel Institute of Technology  
[brandon@technion.ac.il](mailto:brandon@technion.ac.il)

## Impériale units

I was reminded of the recent *Physics World* discussion about unusual units when, on 16 February, an Ariane 5 rocket blasted off from French Guiana. It was carrying Europe’s second space freighter, the Johannes Kepler, loaded with supplies for the International Space Station. On French television news this payload was described, in French, as being “as big as a London bus”. The French for a double-decker is *l’autobus à impériale*. Thus it would appear that the French, of all people, have invented the ultimate imperial unit!

**Peter Gill**

Riscle, France  
[peter.gill@wanadoo.fr](mailto:peter.gill@wanadoo.fr)

## Comments from *physicsworld.com*

**Zhores Alferov makes an interesting – and controversial – subject for a biography. Renowned in the physics community for his work on heterotransistors, which won him a share of the Nobel prize in 2000, Alferov is also an outspoken communist and a prominent member of Russia’s parliamentary opposition. Which aspect should a biographer emphasize? In his review of *Lenin’s Laureate: Zhores Alferov’s Life in Communist Science* (March pp46–47), Alexei Kojevnikov criticized author Paul R Josephson for softening Alferov’s communist views, arguing that if we want to understand Russia’s current political situation, “we need to start hearing, rather than turning a deaf ear to, the political voices of Alferov and his comrades”. For a few *physicsworld.com* readers, Kojevnikov’s words touched a nerve.**

Why not listen also to other Soviet Nobel winners such as Vitaly Ginzburg, Lev Landau and Andrei Sakharov, who used to be quite pro-Soviet and pro-Communist but came to see how wrong they had been? Landau said in 1957 that “Our regime is

definitely a fascist regime, and it could not change by itself in any simple way. If our regime is unable to collapse in a peaceful way, then a Third World War with all its attendant horrors is inevitable.” And Sakharov, a foremost opponent of the Soviet regime, explained that “Because I had already given so much to the cause and accomplished so much, I was unwittingly creating an illusory world to justify myself.” Why these illusory worlds are so durable is another question.

**gorelik, US**

I think these “illusory worlds” are durable because people need ideals to live and work for – something better than stealing as much as possible from your fellow humans, killing competition as the cheapest way to success, and so on. This is especially true in science. What happens to “science” when it is run as a private business is, in my opinion, nothing good at all. It simply disappears when it is run by “businessmen”, because the *only* purpose of a business is not to make scientific advances (or, for that matter, even to produce anything useful), but simply to make money, as the economist

Milton Friedman said. How [the money is made] is not important – whichever way is cheaper.

**Alex244**

I came from the Soviet Union to the US more than 15 years ago. Although I was very thrilled at first, now I see that both opposites (radical socialism and extreme capitalism) are equally bad, and in some senses are very similar – equally oppressive, but with different tools. Also, people (intellectuals, scientists, writers, etc) who were at the top of the dissident movement in the Soviet Union now are not so excited about what happened in Russia. Most of them have become poor and neglected. Is it possible to combine good characteristics of socialism and capitalism? In Russia they combined negative sides of both systems, as I see it.

**postfuture**

## physicsworld.com

Read these comments in full and add your own at [physicsworld.com](http://physicsworld.com)



# Superconductivity

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## Physics World

Dirac House, Temple Back, Bristol BS1 6BE, UK  
Tel: +44 (0)117 929 7481  
Fax: +44 (0)117 925 1942  
E-mail: [pwld@iop.org](mailto:pwld@iop.org)  
Web: [physicsworld.com](http://physicsworld.com)

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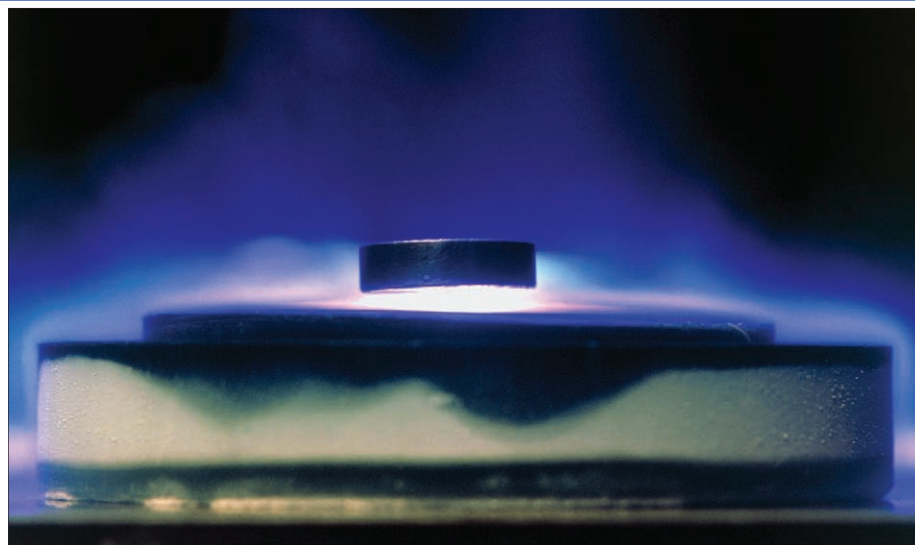
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## The Institute of Physics

76 Portland Place, London W1B 1NT, UK  
Tel: +44 (0)20 7470 4800  
Fax: +44 (0)20 7470 4848  
E-mail: [physics@iop.org](mailto:physics@iop.org)  
Web: [iop.org](http://iop.org)



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# The first 100 years

## *Physics World* celebrates the centenary of the discovery of superconductivity

*Kwik nagenoeg nul*. Scrawled in a lab notebook by the Dutch low-temperature physicist Heike Kamerlingh Onnes on 8 April 1911, these words are what signalled that superconductivity – that mysterious and bizarre phenomenon of condensed-matter physics – had been discovered. Onnes, together with his colleague Gilles Holst, had found that the resistance of mercury, when chilled to a temperature of below 4.2 K, fell to practically zero – the hallmark of superconductivity. Interestingly, it was only last year that the precise date of the discovery and this phrase – which means “Quick[silver] near-enough null” – came to light, thanks to some clever detective work by Peter Kes from Leiden University, who trawled through Onnes’s many notebooks, which had been filled (often illegibly) in pencil (*Physics Today* September 2010 pp36–43).

Researchers soon began to dream of what superconductivity could do (p18), with talk of power cables that could carry current without any losses, and later even levitating trains. Sadly, with a few honourable exceptions such as superconducting magnets (p23), there have been far fewer applications of superconductivity than from that other product of fundamental physics – the laser. Over the years, superconductivity has also baffled theorists: it was not until the mid-1930s that brothers Fritz and Heinz London made a big breakthrough in understanding how these materials work (p26). As for high-temperature superconductors (p33 and p41), theorists are still scratching their heads.

Fortunately, today’s theorists are in good company. A true understanding of superconductivity foxed some of the giants of physics, including Dirac, Feynman and Einstein himself, who in 1922 noted that “with our wide-ranging ignorance of the quantum mechanics of composite systems, we are far from able to compose a theory out of these vague ideas”. Einstein felt that progress in superconductivity could only be made by relying on experiment. A century on from its discovery, those words continue to ring true.

**Matin Durrani**, Editor of *Physics World*

● Check out *physicsworld.com* during April for our series of superconductivity-related videos

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# Down the path of least resistance

Since its discovery 100 years ago, our understanding of superconductivity has developed in a far from smooth fashion. **Paul Michael Grant** explains why this beautiful, elegant and profound phenomenon continues to confound and baffle condensed-matter physicists today

Of all the discoveries in condensed-matter physics during the 20th century, some might call superconductivity the “crown jewel”. Others might say that honour more properly belongs to semiconductors or the elucidation of the structure of DNA, given the benefits that both have brought to humanity. Yet no-one would deny that when a team led by Heike Kamerlingh Onnes stumbled across superconductivity – the absolute absence of electrical resistance – at a laboratory in Leiden, the Netherlands, 100 years ago, the scientific community was caught by complete surprise. Given that electrons usually conduct imperfectly by continually colliding with the atomic lattice through which they pass, the fact that conduction can also be perfect under the right conditions was – and is – surely no less than miraculous.

The discovery of superconductivity was the culmination of a race between Onnes and the British physicist James Dewar as they competed to reach a temperature of absolute zero using ever more complex devices to liquefy gases. Onnes won after he successfully liquefied helium by cooling it to 4.2 K, for which he was awarded the 1913 Nobel Prize for Physics. (The current low-temperature record stands at about  $10^{-15}$  K, although it is of course thermodynamically impossible to ever get to absolute zero.) But researchers did not only want to reach low temperatures just for the sake of it. What also interested them was finding out how the properties of materials, particularly their electrical conductance, change under cryogenic conditions. In 1900 the German physicist Paul Drude – building on the conjectures and experiments of J J Thomson and Lord Kelvin that electricity involves the flow of tiny, discreet, charged particles – had speculated that the resistance of conductors arises from these entities bouncing inelastically off vibrating atoms.

So what would happen to the resistance of a metal immersed in the newly available liquid helium? Physicists had three main suspicions. The first was that the resistance would keep decreasing continuously towards zero. The second was that the conductivity would instead saturate at some given low value because there would always be some impurities off which electrons would scatter. Perhaps the most popular idea, however – predicted by the emerging picture of discrete, lo-

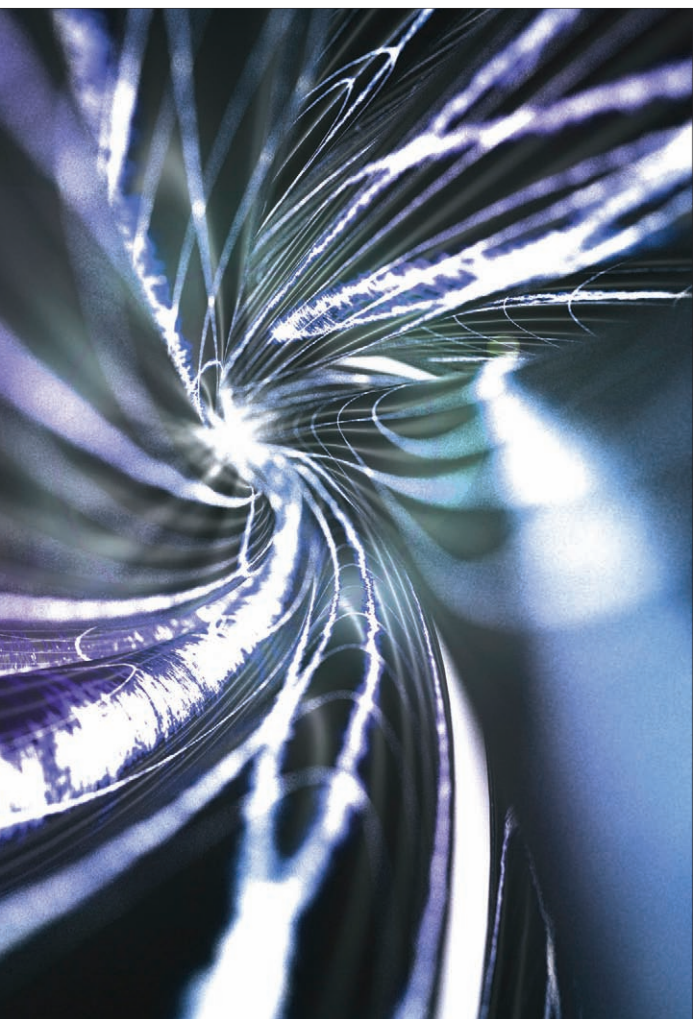
calized atomic orbitals – was that the electrons would eventually be captured, leading to an infinite resistance. But before anyone could find out for sure, researchers needed a very pure metal sample.

Gilles Holst, a research associate in Onnes’s institute at Leiden University, thought it might be possible to obtain such a sample by repeatedly distilling liquid mercury to remove the impurities that were found to dominate scattering below 10 K. The Leiden lab had lots of experience in fabricating mercury resistors for use as thermometers, and Holst suggested enclosing the mercury in a capillary tube to keep it as pure as possible before finally submersing it in a sample of liquid helium. And so it was in April 1911 (the precise date is not known for sure due to Onnes’s unclear and uncertain notebook entries) that Holst and his lab technician Gerrit Flim discovered that the resistance of liquid mercury, when cooled to 4.2 K, reached a value so small that it is impossible to measure. This phenomenon – the complete absence of electrical resistance – is the hallmark of superconductivity. Ironically, had the Leiden team simply wired up a piece of lead or solder lying around the lab – rather than using mercury – their task would have been far easier, because lead becomes superconducting at the much higher temperature of 7.2 K. In fact, three years later, acting on a suggestion by Paul Ehrenfest, researchers at the Leiden lab were able to produce and measure “persistent” currents (which would last a billion years) in a simple lead-ring sample.



**Paul Michael Grant** is at W2AGZ Technologies, San Jose, California, US, e-mail pmpgrant@w2agz.com, Web www.w2agz.com





## For Onnes to publish the discovery without his colleagues as co-authors would be unthinkable today

which they became “normal” conductors dashed early dreams, voiced almost immediately by Onnes and others, that superconductivity could revolutionize the electricity grid by allowing currents to be carried without any loss of power

However, other labs in Europe – and later in North America too – did eventually start to develop their own liquid-helium cryogenic facilities, and as the monopoly held at Leiden slowly broke, interest and progress in superconductivity resumed. In 1933 Walther Meissner and Robert Ochsenfeld observed that any magnetic field near a superconducting material was totally expelled from the sample once it had been cooled below the “transition temperature”,  $T_c$ , at which it loses all resistance. The magnetic field lines, which under normal circumstances would pass straight through the material, now have to flow around the superconductor (figure 1). This finding, which came as a total surprise, was soon followed by the observation by Willem Keesom and J Kok that the derivative of the specific heat of a superconductor jumps suddenly as the material is cooled below  $T_c$ . Nowadays observing both these bizarre effects – “flux expulsion” and the “second-order specific-heat anomaly” – is the gold standard for proving the existence of superconductivity. (Legend has it in fact that the latter measurements were actually performed by Keesom’s wife, who was also a physicist yet did not get any credit at the time.)

History credits – erroneously in my opinion – Onnes as the sole discoverer of what he, writing in English, called “supra-conduction”. (Where the work was first published is hard to decipher, although the first report in English was in the Dutch journal *Communications from the Physical Laboratory at the University of Leiden* (120b 1911).) Clearly, the discovery would not have happened without Onnes, but to publish the work without his colleagues as co-authors would be unthinkable today. At the very least, the announcement should have been made under the names of Onnes and Holst. As it happens, life panned out well for Holst, who became the founding director of the Philips Research Laboratory in Eindhoven and a distinguished professor at Leiden. But that does not mean that he and others should be forgotten as we celebrate the centenary of the discovery of superconductivity.

### Conforming to type

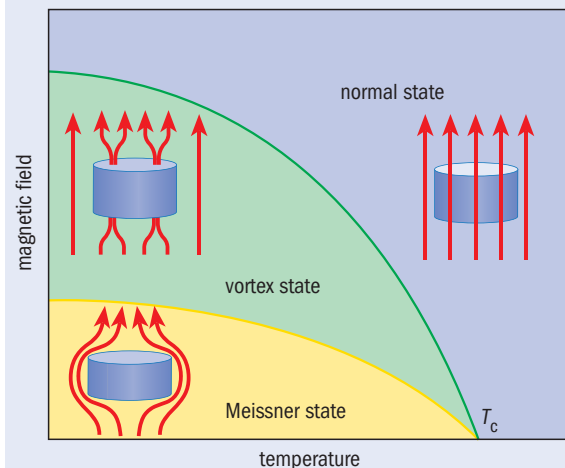
After the 1911 discovery, research into superconductivity languished for several decades, mainly because duplicating the Leiden facility was difficult and expensive. However, research also stalled because the zero-resistance state disappeared so easily when a sample was exposed to even quite modest magnetic fields. The problem was that most early superconductors were simple elemental metals – or “type I” as they are now known – in which the superconducting state exists only within a micron or so of their surface. The ease with

The mid-1930s also saw the discovery by Lev Shubnikov of superconductivity in metallic alloys – materials in which the critical magnetic field (above which superconductivity disappears) is much higher than in simple elemental metals. The experimental and theoretical study of these alloys – dubbed “type II” – quickly dominated research on superconductivity, especially in the Soviet Union under the leadership of Pyotr Kapitsa, Lev Landau and Shubnikov himself. (The latter, who was Jewish, was imprisoned in 1937 by the secret police during the Stalinist purges and later executed, in 1945.) Soviet theoretical efforts on the statistical mechanics of superconductivity – and the related phenomenon of superfluidity – continued throughout the Second World War and the Cold War, led primarily by the late Vitaly Ginzburg, Alexei Abrikosov and Lev Gor’kov. Although much of it was unknown to the West at the time, the Ginzburg–Landau–Abrikosov–Gor’kov, or “GLAG”, model underlies all practical applications of superconductivity. The model is so useful because it is empirical and thermodynamic in nature, and does not therefore depend on the microscopic physics underlying a particular second-order phase transition, be it magnetism, superfluidity or superconductivity.

### Towards BCS theory

Progress in unravelling the fundamental theory underpinning superconductivity advanced more slowly. In 1935 Fritz and Heinz London proposed a phenom-

## 1 Get out, stay out



One of the most unusual properties of superconducting materials is what happens when they are placed near a magnetic field. At high temperatures and field strengths (blue region), the magnetic field lines pass straight through the material as expected. But as Walther Meissner and Robert Ochsenfeld discovered in 1933, when a superconducting material is cooled below the transition temperature,  $T_c$ , at which current can flow without resistance, the field lines are expelled from the material and have to pass around the sample – what is known as the “Meissner effect” (yellow region). Certain superconductors, known as “type II”, can also exist in a “vortex state” (green region), where resistive and superconducting sub-regions co-exist. Practical demonstrations of magnetic levitation always use type II superconductors because the magnetic vortices are pinned in place, making the magnet laterally stable as it hovers.



Yorick van Boheemen

enological “adjustment” to Maxwell’s constituent equations to accommodate the notion of a “penetration depth” of an externally applied magnetic field beyond the surface of a superconductor (see “The forgotten brothers” by Stephen Blundell on page 26). However, it was not until the mid-1950s that the theoretical web surrounding superconductivity was finally unravelled, having frustrated attempts by some of the 20th century’s brightest and best physicists, including Dirac, Einstein, Feynman and Pauli. This feat was eventually accomplished by John Bardeen, Leon Cooper and Robert Schrieffer, leading to what is now called BCS theory, for which the trio shared the 1972 Nobel Prize for Physics (see box on page 35 for more on BCS theory). A key development was the determination by Cooper that a gas of electrons is unstable in the presence of any infinitesimal attractive interaction, leading to pairs of electrons binding together. Bardeen and his student Schrieffer then realized that the resulting quantum state had to be macroscopic and statistical in nature.

But where did the attractive interaction come from? In 1950 Emanuel Maxwell of the US National Bureau of Standards noticed that the transition temperature of mercury shifted depending on which of its isotopes was used in the particular sample, strongly suggesting that somehow lattice vibrations, or “phonons”, are involved in superconductivity. BCS theory proved, given the right conditions, that these vibrations – which are usually the source of a metal’s intrinsic resistance – could yield the attractive interaction that allows a material to conduct *without* resistance.

Quite simply, BCS theory ranks among the most elegant accomplishments of condensed-matter physics. Generally stated, it describes the pairing of two fermions mediated by a boson field: any fermions, by any boson. All known superconductors follow the general recipe dictated by BCS, the basic form of which is an

extraordinarily simple expression:  $T_c \propto \Theta/e^{1/\lambda}$ , where  $T_c$  is the transition, or critical, temperature below which a material superconducts,  $\Theta$  is the characteristic temperature of the boson field (the Debye temperature if it is comprised of phonons), and  $\lambda$  is the coupling constant of that field to fermions (electrons and/or holes in solids). A material with a large value of  $\lambda$  is generally a good candidate for a superconductor even if it is, counterintuitively, a “poor” metal under normal conditions with electrons continually bouncing off the vibrating crystal lattice. This explains why sodium, gold, silver and copper, despite being good metals, are not superconductors, yet lead is (figure 2).

However, BCS is descriptive and qualitative, not quantitative. Unlike Newton’s or Maxwell’s equations or the framework of semiconductor band theory, with which researchers can design bridges, circuits and chips, and be reasonably assured they will work, BCS theory is very poor at pointing out what materials to use or develop to create new superconductors. For all that its discovery was an intellectual *tour de force*, it is the German-born physicist Berndt Matthias who perhaps summed the theory up best when he said (in effect) that “BCS tells us everything but finds us nothing”.

### Later landmarks

Following the development of BCS theory, one of the next landmarks in superconductivity was the prediction in 1962 by Brian Josephson at Cambridge University in the UK that a current could electrically tunnel across two superconductors separated by a thin insulating or normal metal barrier. This phenomenon, now known as the Josephson effect, was first observed the following year by John Rowell and Philip Anderson of Bell Laboratories, and resulted in the development of the superconducting quantum interference device, or SQUID, which can measure minute levels of magnetic field and also provide an easily replicated voltage stan-

Unlike Newton’s or Maxwell’s equations, with which researchers can design bridges, circuits and chips, BCS theory is very poor at pointing out what materials to use or develop



## 2 Spreading its wings

H	superconductors at ambient pressure																He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Rf	Db	Sg	Bh	Hs	Mt									
*		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
**		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Over the last 100 years, an ever bigger range of elements in the periodic table has been found to superconduct. Shown here are those elements that superconduct at ambient pressure, shaded according to when this ability was first unearthed (yellow/orange), and those elements that superconduct only at high pressure (purple). Adapted from *Superconductivity: A Very Short Introduction* by Stephen Blundell (2009, Oxford University Press)

dard for metrology labs worldwide.

For the next landmark in superconductivity, however, we had to wait more than two decades for Georg Bednorz and Alex Müller's serendipitous observation of zero resistance at temperatures above 30 K in layered copper-oxide perovskites. Their discovery of "high-temperature superconductors" at IBM's Zurich lab in 1986 not only led to the pair sharing the 1987 Nobel Prize for Physics but also triggered a boom in research into the field (see "Resistance is futile" by Ted Forgan on page 33). Within a year M K Wu, Paul Chu and their collaborators at the universities of Houston and Alabama had discovered that an yttrium–barium–copper-oxide compound –  $\text{YBa}_2\text{Cu}_3\text{O}_{6.97}$ , also known as YBCO, although the precise stoichiometry was not known at the time – could superconduct at an astounding 93 K. As this is 16 K above the boiling point of liquid nitrogen, the discovery of these materials allowed researchers to explore for the first time applications of superconductivity using a very common and cheap cryogen. The record substantiated transition temperature rests at 138 K in fluorinated  $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{8+d}$  at ambient pressure (or 166 K under a pressure of 23 GPa).

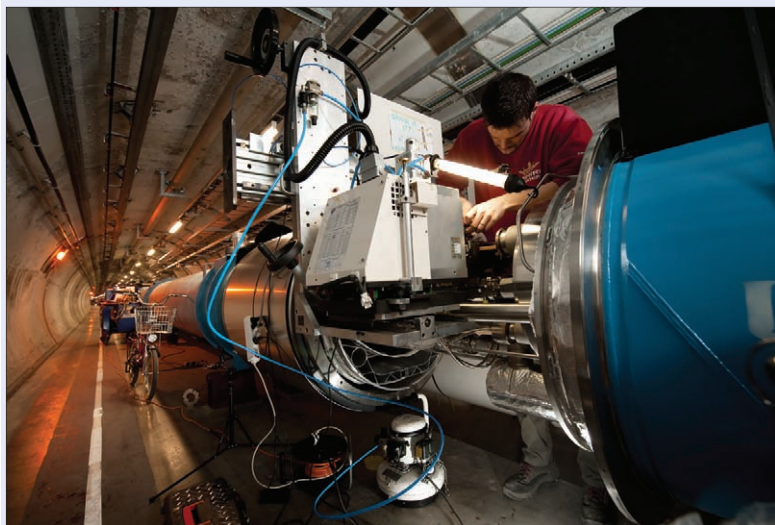
With Bednorz and Müller about to pack their bags for Stockholm as the latest researchers to win a Nobel prize for their work on superconductivity, it was a happy time for those in the field. Literally thousands of papers on superconductivity were published that year, accompanied by a now legendary, all-night celebratory session at the March 1987 meeting of the American Physical Society in New York City now dubbed "the Woodstock of physics" at which those involved, me included, had one hell of a good time.

### Technology ahead of its time

Alongside these advances in the science of superconductivity have been numerous attempts to apply the phenomenon to advance old and create new technologies – ranging from the very small (for ultrafast computers) to the very large (for generating electricity). Indeed, the period from the 1970s to the mid-1980s witnessed a number of technically quite successful demonstrations of applied superconductivity in the US, Europe and Japan. In the energy sector, perhaps the most dramatic was the development between 1975 and 1985 of an AC superconducting electricity cable at the Brookhaven National Laboratory in the US, funded by the Department of Energy and the Philadelphia Electric Company. Motivated by the prospect of large-scale clusters of nuclear power plants requiring massive transmission capacity to deliver their output, the cable attracted a good deal of attention. Although the cable worked, it unfortunately turned out not to be needed as the US continued to burn coal and began to turn to natural gas. Similarly, in Japan, various firms carried out demonstrations of superconducting cables, generators and transformers, all of which proved successful from a technical point of view. These projects were generally supported by the Japanese government, which at the time was anticipating a huge surge in demand for electricity because of the country's growing population. That demand failed to materialize, however, and I know of no major superconductivity demonstration projects in Japan today apart from the Yamanashi magnetic-levitation test track, which opened in the mid-1970s using niobium–titanium superconductors.

In 1996 I published a paper "Superconductivity and

### 3 Round the bend



Superconductors can be found in all sorts of applications, one of the most famous of which is in the dipole magnets at the Large Hadron Collider at CERN. The collider has 1232 such magnets, each 15 m long, consisting of coils of superconducting niobium–titanium wire cooled to 1.9 K using liquid helium. Carrying currents of 13 000 A, the magnets generate extremely high fields of 8.3 T, which help to steer the protons around the 27 km circumference collider.

electric power: promises, promises...past, present and future" (*IEEE Trans. Appl. Supercond.* **7** 1053), in which I foresaw a bright future for high-temperature superconductivity. A large number of successful power-equipment demonstrations once more followed, with various firms developing superconducting cables, generators, conditioners (transformers and fault-current limiters), all of which proved successful. Although few – if any – of these demonstrations have been turned into working products, there is nevertheless a lot of good, advanced superconductor technology now sitting on the shelf for the future, if needed. Unfortunately, it has so far not had much of an impact on the energy industry, which is driven as much by politics and public perception as it is by technological elegance. When it comes to the electronics industry, in contrast, price and performance – say of the latest laptop or smartphone – are everything.

A somewhat similar story accompanies the application of superconductivity to electronics, a prime example being computers based on "Josephson junctions", which promised to bring faster CPU speeds dissipating less heat than the bipolar silicon technology that dominated from the 1960s to the early 1980s. IBM and the Japanese government bet heavily on its succeeding, as it did from a technical point of view, but were blind-sided by the emergence of metal-oxide–silicon field-effect transistors (MOSFETs), which delivered both goals without requiring cryogenic packaging. (Other applications, including my personal top five, are given in "Fantastic five" on page 23.)

#### Cool that sample

In January 2001, exactly a year after the dawn of the new millennium, Jun Akimitsu of Aoyama-Gakuin University in Japan announced at a conference on transition-metal oxides the discovery of superconductivity in magnesium diboride ( $\text{MgB}_2$ ) – a material that

had first been successfully synthesized almost 50 years earlier at the California Institute of Technology. Akimitsu and colleagues had actually been looking for something else – antiferromagnetism – in this material but were surprised to find that  $\text{MgB}_2$ , which has a hexagonal layered structure and can be fabricated with excellent microcrystalline detail, became superconducting at the astonishingly high temperature of 39 K. The discovery prompted many other researchers to study this simple material and, over the past decade, high-performance  $\text{MgB}_2$  wires have been fabricated. Indeed,  $\text{MgB}_2$  has the highest upper critical field (above which type II superconductivity disappears) of any material apart from YBCO, with calculations suggesting that it remains a superconductor at 4.2 K even when subjected to massive fields of 200 T.

However, there is an interesting twist to the story. In 1957 the chemists Robinson Swift and David White at Syracuse University in New York measured the lattice specific heat of  $\text{MgB}_2$  between 18 K and 305 K to see if it depended on the square of temperature, just as other layered structures do. Their results, which showed no  $T^2$  dependence, were published in the *Journal of the American Chemical Society* not as a graph but as a table. When their data were re-analysed after Akimitsu's 2001 announcement and plotted in graphical form, Paul Canfield and Sergei Bud'ko at Iowa State University (as well as the present author, working independently), were surprised to find a small specific-heat anomaly near 38–39 K, indicating the onset of superconductivity.

The question is this: if the Syracuse chemists had plotted their data and shown it to their physicist colleagues, would the history of superconductivity from the mid-20th century have taken a different course? To me it is likely that all the niobium intermetallics, such as the niobium–titanium alloys used in the superconducting magnets in CERN's Large Hadron Collider, would never have been needed, or even fully developed (figure 3). High-field magnets would have been fabricated from  $\text{MgB}_2$  and perhaps even superconducting power cables and rotating machinery made from this ordinary material would be in use today.

The lesson is clear: if you think you have a new (or old) metal with unusual structural or chemical properties, do what Holst, Bednorz and Akimitsu did – cool it down. Indeed, Claude Michel and Bernard Raveau at the University of Caen in France had made 123 stoichiometric copper-oxide perovskites four years before Chu, but having no cryogenic facilities at their lab – and, finding it awkward to obtain access to others elsewhere in the French national research council system – missed making the discovery themselves.

Superconductivity arguably ranks among the ultimate in beauty, elegance and profundity, both experimentally and theoretically, of all the advances in condensed-matter physics during the 20th century, even if it has to date yielded only a few applications that have permeated society. Nonetheless, the BCS framework that underlies superconductivity appears to reach deep into the interior of neutron stars as well, with the pairing of fermionic quarks in a gluon bosonic field experiencing a transition temperature in the range  $10^9$  K. A century after Leiden, in the words of Ella Fitzgerald, "Could you ask for anything more?" ■



# Fantastic five

Superconductivity may be a beautiful phenomenon, but materials that can conduct with zero resistance have not quite transformed the world in the way that many might have imagined. Presented here are the top five applications, ranked in terms of their impact on society today

Perhaps no other potential application of superconductivity has captured the public's imagination more than magnetically levitated (maglev) trains; you can even buy toy models of them. There have also been science-fiction-like maglev concepts that in principle would work, featuring curved tunnels through the Earth's mantle, whereby the train first falls on a levitated track, generating electricity as it does so for the trip back up. Indeed, the first patents on the basic concept date back to 1907 – four years before superconductivity was even discovered.

However, every maglev system ever built, apart from the Yamanashi test line in Japan, has used conventional technology involving ordinary (albeit powerful) iron-

core electromagnets. Moreover, the top speed of the Yamanashi superconducting prototype is  $581 \text{ km h}^{-1}$ , which, despite being a world record for mass surface transportation, is only  $6 \text{ km h}^{-1}$  faster than the ordinary wheel-on-rail French TGV trains. The message is clear: faster surface transportation may be important, but superconductivity has not – and is unlikely to – play much of a role in that quest.

So if not maglev, then what have been the most significant applications of superconductivity in terms of their impact on society? This article lists a top five selected by Paul Michael Grant from W2AGZ Technologies in San Jose, California. Superconducting wires top the list, followed by magnets for medical imaging and for

particle colliders in second and third, respectively, with superconducting motors in fourth and a unique dark-matter experiment in fifth. One other application of superconductors that has not quite made the cut involves using them in electromagnets or flywheels to store energy. Such superconducting magnetic-energy storage devices store energy in the magnetic field created by an electric current flowing in a superconducting coil. As almost all the energy can be recovered instantly, these devices are incredibly efficient and would be ideal for storing electricity in the home should we be forced to rely much more on renewable sources of power that are not always on tap.

But let's start with those wires...

## And the winner is...

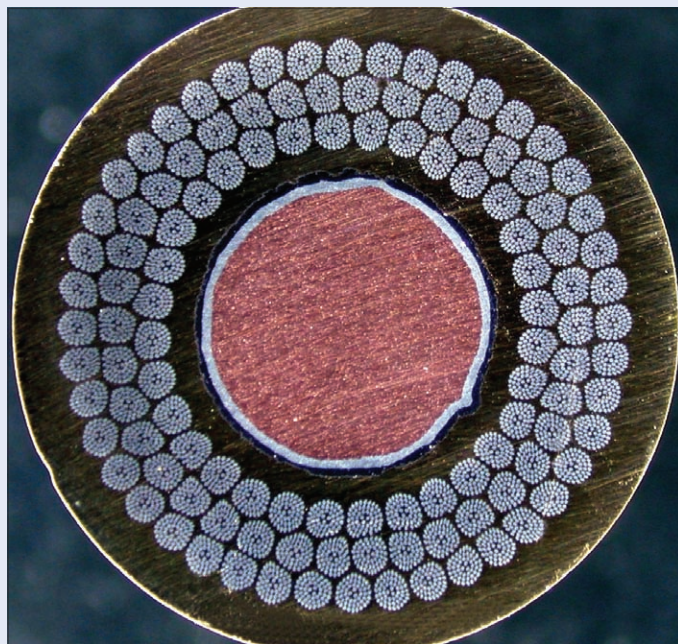
### 1 Wires and films

One thing is for sure: there would be no applications of superconductivity if physicists and materials scientists had not managed to develop – as they did in the 1970s – superconducting wires and films made from niobium–titanium and niobium–tin. These materials can carry high currents, even in the presence of strong magnetic fields, when cooled with liquid helium to a temperature below  $4.2 \text{ K}$ . They are generally packaged as bundles of wires in a matrix, allowing them to be sold both as wire filaments and as solid cores encased in copper. They can carry currents of up to  $50 \text{ A}$  while withstanding magnetic fields of  $10 \text{ T}$ .

Firms such as American Superconductor, SuperPower and Zenergy Power now also make high-temperature superconducting tape from yttrium–barium–copper-oxide (YBCO). It is just as robust as low-temperature niobium alloys and can be used for transmission power cables but using liquid nitrogen – not helium – as the cryogen. What is remarkable is that YBCO is a hard and brittle ceramic (like a teacup), yet it can be made in batches thousands of metres long. This is done by depositing a continuous film of it onto a specially prepared “textured substrate” base – typically a stainless-steel-like alloy coated with another layer of magnesium oxide or yttrium zirconia.

The resulting technology is truly a *tour de force*. Indeed, the “upper critical field” – the maximum field that YBCO tape can be subjected to and still superconduct – is so high at  $4.2 \text{ K}$  that it has never been, and probably cannot be, measured. These materials are ideal for use as superconducting power cables, which could carry electricity without any of the power losses that afflict conventional copper cables. (Note that superconductivity is only “perfect” for direct-current transmission; for alternating current there are always losses.)

The US in particular has ploughed much money into this field, largely through a 20-year research and development effort funded by the Department of Energy that ended in 2010. Its fruits are now on the shelf,



**Slice of magic** Cross-section through a niobium–tin cable.

Supercon Inc.

waiting to be harvested by the utility industry and its suppliers. However, it is likely that upgrading and replacing conventional cables will not happen as fast as was once envisaged. Instead, it is likely to occur gradually through mega-projects, such as the “SuperGrid” concept, which envisages electricity from nuclear power stations carried along superconducting cables cooled by hydrogen that is produced by the power plant and that could also be used as a fuel (*Physics World* October 2009 pp37–39).

## Best of the rest

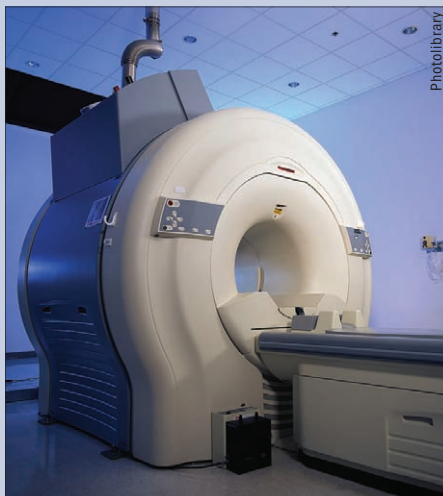
### 2 Medical imaging

A peace-time offshoot of the development of radar in the Second World War was the invention of nuclear magnetic resonance (NMR), which can determine the structure and composition of materials by studying how nuclei, such as hydrogen, with a non-zero spin absorb photons when bathed in a magnetic field. By the late 1960s, with the development of “tomographic” techniques that can build up 3D X-ray images of the human body from a series of individual 2D “slices”, medical physicists realized that NMR could also be used to study the distribution of hydrogen nuclei in living tissue. By the late 1970s the first full-body magnetic resonance imaging (MRI) scanners had been developed, which required a constant and uniform magnetic field surrounding the body of about 1 T – something that is only easily practical using superconducting magnets.

MRI has since become perhaps the most widespread medical diagnostic tool and there is at least one such scanner in every major hospital around the world. An MRI solenoid typically has up to 100 km of niobium–titanium or niobium–tin wire made from individual wires, each several kilometres long, connected by special joints that let the current continue to flow without any losses. Most of these magnets use mechanical cryocoolers in place of liquid helium and thus operate continuously. One variant of MRI that is also becoming popular is “functional MRI” (fMRI) – a technique that needs twice the magnetic field of “standard” MRI machines (sometimes as high as 4 T). It is used to monitor motion in the human body in real time, such as how the flow of blood in the brain changes in response to particular neural activity.

A similar medical scanning technique uses superconducting quantum interference devices, or SQUIDS, held at liquid-helium temperature, to detect the tiny magnetic fields generated by the exceedingly small currents in the heart or brain. Known as magnetocardiography (when studying the heart) or magnetoencephalography (when studying the brain), it is non-invasive and does not require any equipment to be wired directly onto the body. Magnetocardiography, which can detect cardiac anomalies that escape routine electrocardiography, has already undergone numerous successful clinical trials in the US, Europe and China, although it is not yet widely used in hospitals.

We should not forget that MRI-scale superconducting magnets have also had a big impact on condensed-matter physics and materials science. Most universities and industrial laboratories have at least one “physical properties measurement system” that can make a variety of transport, magnetic,



**Take a picture** A magnetic-resonance-imaging scanner uses small superconducting magnet coils to produce detailed images of any part of the body.

optical and microscopy measurements from room temperature to 1.2 K (and below) in fields of up to 16 T.

### 3 High-energy physics

Although it might be considered esoteric and unrelated to general human welfare, it could be argued that no human endeavour surpasses the search for our origins. Every civilization on our planet has devoted a portion of its wealth to that quest – take the pyramids of Giza or Teotihuacan, for example – and today’s large particle-physics labs are continuing that tradition. However, particle colliders would be nothing without the superconducting magnets that bend accelerate particles around in a circle. The Tevatron collider at Fermilab in the US, for example, has huge bending magnets carrying currents of 4000 A that produce magnetic fields of about 4.2 T when cooled with liquid helium, while those at the Large Hadron Collider (LHC) at CERN produce fields of roughly twice that strength at 1.9 K.

The Tevatron, which is due to close later this year, can generate centre-of-mass collision energies of 2 TeV, while the LHC can currently produce 7 TeV collisions, with 14 TeV as a longer-term target. Either facility could, in principle, spot the Higgs boson and thus complete the final piece of the Standard Model of particle physics, although the LHC, operating at higher energy and still so new, is more likely to do so.

But what lies beyond the Standard Model? Many high-energy theorists suspect there may be a large energy gap before something “interesting” appears again, which might require collision energies of 100–200 TeV or more (i.e. 50–100 TeV per beam). Unfortunately, a machine that could generate these energies and that is no bigger than a conventional collider



**Interconnected** A welder works on the junction between two of the Large Hadron Collider's superconducting-magnet systems.

such as the LHC (i.e. with a circumference of about 27 km) would lose most of its beam energy in the form of synchrotron X-rays. (Such X-rays can, though, be extremely useful to characterize materials, which is why there are now 50 or so dedicated synchrotron radiation facilities around the world, most of which have superconducting magnets.)

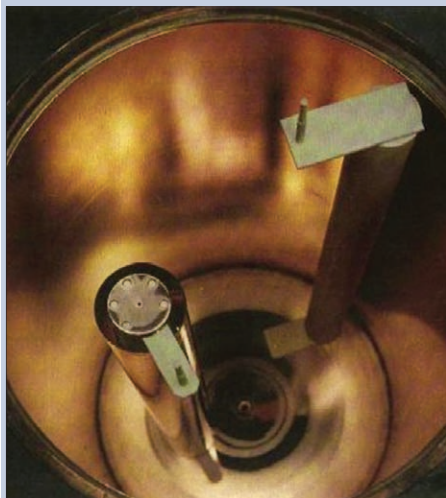
Interestingly, however, Fermilab physicist Bill Foster, now a member of the US House of Representatives, and his colleagues have proposed revisiting an old idea by Robert Wilson, Fermilab's first director. It would involve simply saturating a 2 T iron magnet with a high-temperature superconducting cable cooled with liquid nitrogen and carrying a current of 75 000 A. The snag is that reaching energies of 50 TeV would require a ring with a circumference of about 500 km. Such a large project would be difficult to carry out in areas of significant population, but in principle would be possible to deploy in more remote areas. As ever, all it would take is money.

### 4 Rotating machinery

Superconducting materials have long been touted as having a bright future in motors and generators. The problem is that conventional motors are currently quite good at converting electrical power into rotational power – being up to 95% efficient for large 100 kW–1000 MW industrial devices. Replacing the rotating electromagnet (i.e. the rotor) in a motor with a superconducting material might increase the conversion by 2%, but this will hardly make much difference.

Nevertheless, in 1983 the Electric Power Research Institute (EPRI) in the US, working with Westinghouse Electric Company, successfully demonstrated a 300 MW electric generator using





**A peek inside** The cavity at the centre of the Axion Dark Matter Experiment contains a niobium–titanium superconducting magnet.

niobium–titanium wire kept at 5 K. Similar efforts were carried out at the Massachusetts Institute of Technology, while in 1988 the Japanese government inaugurated the “Super-GM” project, which sought to provide superconducting generators to meet Japan’s growing electricity needs. However, when the country’s power demands failed to materialize, the project, despite having succeeded from a technical point of view, never got off the ground and was never deployed by Japan’s electricity utilities.

The tangible advantage of using superconducting wires – whether of the low- or high-temperature variety – in rotating machines is that they significantly reduce the amount of iron required, which normally forms the core of conventional electromagnets. Removing the iron in this way makes the generator lighter, smaller and so more efficient. These advantages have been fully recognized for many years by the US military, which has a culture in which the effectiveness of a given technology outweighs the cost. However, despite several successful demonstrations of propulsion motors by the US Navy using low-temperature materials, it ultimately did not adopt them.

The winds are now shifting. The US Navy is on the verge of using high-temperature superconducting “degaussing” cables on all of its light, high-speed destroyer-class ships to shield them from being detected by enemy submarines. (These cables are simply loops that create a magnetic field, which cancels that from the iron components of the ship.) Moreover, high-temperature superconducting motors are also likely to be deployed as “outboard” units on US submarines and surface attack resources. If so, we are likely to see such devices “trickle down” to holiday cruise ships and commercial vessels. Finally, superconducting generators are

ADMX Collaboration

also likely to find themselves used in wind turbines, greatly reducing the ecological impact of wind farms. In the far future, we might even see superconducting motors – and possibly magnetohydrodynamic pumps – used to transport water from wet to dry areas to adapt to the effects of global warming.

### 5 Dark matter

As *Physics World* readers will surely know, much of the mass in our galaxy, and others too, is missing, or at least we cannot “see” it. That is, astronomers have observed deviations in the rotational motion of galaxies that cannot be accounted for by ordinary matter that we can observe simply by using electromagnetic radiation. It turns out that about four-fifths of the matter in the universe is invisible “dark matter”. (All matter, dark or otherwise, makes up about 27% of the mass–energy density of the universe, with the other 73% being “dark energy”, but that is another story...) The exact nature of dark matter is, of course, still not clear, which means that finding out is one of the big challenges of physics and indeed a central question underlying our existence.

Dark matter is a field wrought by, or fraught with, considerable confusion and debate. Even the names of the particles that could form dark matter are bizarre – from MACHOs, RAMBOs and WIMPs to chameleons and axions, to name but a few. Where superconductivity fits in is in the search for axions, which are postulated to result from the assumed violation of charge–parity symmetry under strong coupling within the Standard Model. The idea is that when axions of a given mass–energy (in the  $\mu\text{eV}$  to  $\text{meV}$  range) enter a microwave cavity sited in a 5–7 T magnetic field from a liquid-helium-cooled superconducting solenoid, they will interact with the field and decay into photons. These photons can then be amplified and detected using SQUIDS operating at 2 K. The rationale for using SQUIDS is that they lower the noise level, and thus sensitivity, to as close to the ultimate limit set by Planck’s constant as possible.

Such experiments are not science fiction but are already under way as part of the Axion Dark Matter Experiment (ADMX) collaboration, previously located at the Lawrence Livermore National Laboratory and now at the University of Washington in the US. The superconducting magnet at the heart of the device consists of niobium–titanium wire wrapped 37 700 times around the core, which has a bore of 60 cm. Although ADMX has not yet managed to detect any axions, we do know that, if they exist, they cannot have masses in the  $3.3\text{--}3.53 \times 10^{-6} \text{ eV}$  range. Detection of axions at any energy anywhere will surely earn someone a Nobel prize and tickets to Stockholm. Stay tuned.



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# The forgotten brothers

**Stephen Blundell** tells of how Fritz London and his younger brother Heinz cracked the decades-long mystery of superconductivity, but wonders why their achievement is still overlooked today

In 1934 two brothers Fritz and Heinz London, both refugees from Nazi Germany, were working in an upstairs room in a rented house in Oxford. There they solved what was then one of the biggest problems in superconductivity, a phenomenon discovered 23 years earlier. The moment of discovery seems to have been sudden: Fritz shouted down to his wife “Edith, Edith come, we have it! Come up, we have it!” She later recalled, “I left everything, ran up and then the door was opened into my face. On my forehead I had a bruise for a week.” As Edith recovered from her knock, Fritz told her with delight “The equations are established – we have the solution. We can explain it.”

Though the discovery of what are now known as “the London equations” came in a dramatic flash of inspiration, the brothers’ ideas had been gestating for some time and their new intellectual framework would later mature through subsequent work by older brother Fritz. John Bardeen, who won his second Nobel prize in 1972 for co-developing the Bardeen–Cooper–Schrieffer (BCS) theory that provided a coherent framework for understanding superconductivity, regarded the achievement of the London brothers as pivotal. “By far the most important step towards understanding the phenomena”, Bardeen once wrote, “was the recogni-

tion by Fritz London that both superconductors and superfluid helium are macroscopic quantum systems.” Before then, quantum theory had only been thought to account for the properties of atoms and molecules at the microscopic level. As Bardeen explained, “It was Fritz London who first recognized that superconductivity and superfluidity result from manifestations of quantum phenomena on the scale of large objects.”

But despite Fritz’s leading role in the breakthrough that solved one of the knottiest conundrums of the early 20th century, he did not secure a permanent job at the University of Oxford once his temporary contract was up. Only two years later he was forced to up sticks and continue his postdoctoral wanderings. It might seem strange that such a bright spark was not snapped up, but even more surprising, perhaps, is the lack of recognition that the London brothers receive today. Like most institutions, Oxford has a culture of celebrating famous physicists of the past who have worked there, some of whom it has to be admitted have only had a rather tenuous connection with the place. But among the rows of photographs lining the walls of the Clarendon Laboratory, the London brothers are nowhere to be seen. How has this omission of recognition happened?

**Stephen Blundell** is a professor of physics at the University of Oxford and the author of *Superconductivity: A Very Short Introduction*, e-mail [s.blundell@physics.ox.ac.uk](mailto:s.blundell@physics.ox.ac.uk)



### From Breslau to Oxford

Fritz London was born in 1900 in the German city of Breslau (now Wrocław, Poland) and nearly became a philosopher. However, he switched to physics and became immersed in the heady intellectual atmosphere of the 1920s that surrounded the new quantum theory. London's early career saw him travelling around Germany, taking positions with some of the great quantum pioneers of the time: Max Born in Göttingen; Arnold Sommerfeld in Munich; and Paul Ewald in Stuttgart. London worked on matrix mechanics and studied how the newly discovered operators of quantum mechanics behave under certain mathematical transformations, but he really made his name after moving again to Zurich in 1927. The lure of Zurich had been to work with Erwin Schrödinger, but almost immediately Schrödinger moved to Berlin and London teamed up with Walter Heitler instead. Together they produced the Heitler–London theory of molecular hydrogen – a bold and innovative step that essentially founded the discipline of quantum chemistry.

The following year London moved to Berlin, where he worked on intermolecular attraction and originated the concept of what are now known as London dispersion forces. He also succumbed to the interpersonal attraction of Edith Caspary, whom he married in 1929. By now the name “Fritz London” was becoming well known – he was fast gaining a reputation as a creative and productive theorist. However, with Hitler becoming German chancellor in 1933, the Nazis began a process of eliminating the many Jewish intellectuals from the country's academic system, putting both London and his younger brother Heinz at risk. Born in Bonn in 1907, Heinz had followed in his older brother's footsteps, studying physics, but became an experimentalist instead, obtaining his PhD under the famous low-temperature physicist Franz Simon.

A possible way out from the Nazi threat was provided by an unlikely source. Frederick Lindemann, later to become Winston Churchill's wartime chief scientific adviser and to finish his days as Viscount Cherwell, was then the head of the Clarendon Laboratory. Lindemann was half-German and had received his PhD in Berlin, so was well aware of the political situation in Germany. He decided to do what he could to provide a safe haven in Oxford for refugee scientists. His motives were not entirely altruistic, however: Oxford's physics department was then a bit of an intellectual backwater and this strategy would effect an instantaneous invigoration of its academic firepower in both theoretical and experimental terms. Later that year Lindemann persuaded the chemical company ICI to come up with funds to support his endeavour.

Lindemann initially lured both Schrödinger and Albert Einstein to Oxford, although Einstein quickly moved on to Princeton University in the US. Simon also came, bringing with him Heinz London as his assistant as well as Nicholas Kurti (later to be a pioneer of both microkelvin cryogenics and the application of physics to gastronomy). But Lindemann also wanted a theorist and admired Fritz London as a no-nonsense, practical sort of person who was able to work on down-to-earth problems. Thus both London brothers ended up in Oxford, Heinz sharing a rented house with his

### The London legacy begins



**Family affair** Left, Fritz London (1900–1954) and, right, his brother Heinz (1907–1970).

Some 23 years after the discovery of superconductivity, Fritz and Heinz London described how superconductors interact with electromagnetic fields. In doing so they introduced two equations that now bear their name. Their first equation is  $\mathbf{E} \propto d\mathbf{J}/dt$  and relates electric field,  $\mathbf{E}$ , to current density,  $\mathbf{J}$ , where  $t$  is time, and supersedes Ohm's law ( $\mathbf{E} = \rho\mathbf{J}$ , where  $\rho$  is the resistivity). Using Maxwell's equations it can be shown that this leads to  $\nabla^2(d\mathbf{B}/dt) = (d\mathbf{B}/dt)/\lambda^2$ , which predicts blocking out or “screening” of time-varying magnetic fields on a length scale  $\lambda$ . This is enough to explain the Meissner effect, which shows that the magnetic field,  $\mathbf{B}$ , itself is screened.

In 1935 the London brothers argued that a more fundamental relation is given by their second equation,  $\nabla \times \mathbf{J} \propto -\mathbf{B}$ , which, using Maxwell's equations, gives  $\nabla^2\mathbf{B} = \mathbf{B}/\lambda^2$ . This predicts screening of the magnetic field itself, so that an external magnetic field can only penetrate into the surface of a superconductor over a length scale  $\lambda$ , which is now called the London penetration depth. Fritz London later realized that the locking of all carriers into a single momentum state yields the relation  $\mathbf{J} = -(nq^2/m)\mathbf{A}$ , where there are  $n$  carriers per unit volume, each with mass  $m$  and charge  $q$ . This equation linking current density and the magnetic vector potential,  $\mathbf{A}$ , is probably the best summary of the London theory.

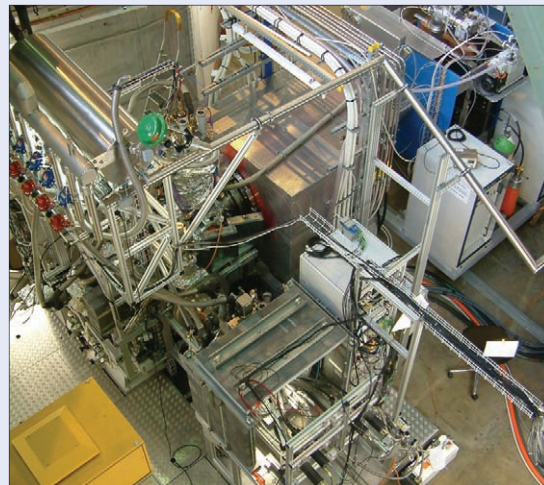
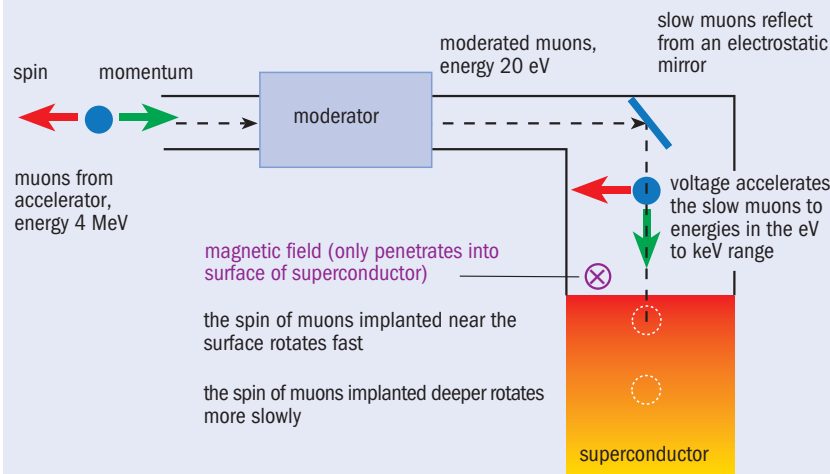
brother and sister-in-law. Fritz was the superior theorist but Heinz had deep insight into, and a great love for, thermodynamics, something that he had picked up from Simon. He frequently quipped “For the second law, I will burn at the stake.” With Simon's arrival in Oxford, and the installation there of the first helium liquefier in Britain, experimental research began on low-temperature physics, leading Fritz London to work on superconductivity.

### The quest to understand superconductivity

The discovery of superconductivity in April 1911 by Heike Kamerlingh Onnes and Gilles Holst was the inevitable consequence of Onnes devoting many years to the development of the cryogenic technology needed to achieve low temperatures. With Onnes's laboratory in Leiden being the first to liquefy helium came the first chance to explore how materials behave in such extreme low-temperature conditions. The disappearance of electrical resistance in a sample of mercury was an unexpected shock, but in retrospect it was an inevitable consequence of having developed a far-reaching new technology that opened up an unexplored world.

But nobody knew how this new effect worked. For decades theorists tried and failed to come up with an

## 1 All in a spin



Elvezio Morenzoni, PSI

The London penetration depth, which is the distance a magnetic field can penetrate into a superconductor, can be inferred using various experimental techniques. Since the 1990s, Elvezio Morenzoni and co-workers at the Paul Scherrer Institute in Switzerland have developed a method of measuring it directly. They use spin-polarized positive muons as a probe. These particles are slowed or “moderated” to a low energy and then reaccelerated into the surface of a superconductor by applying a voltage to it. By varying this voltage, the muons can be implanted at different depths. A magnetic field is then applied and the spin of the muon precesses at a rate that depends on the field it experiences. Measuring this rotational speed of the spin of the muon yields the magnetic field inside the superconductor at different depths, and hence the London penetration depth can be extracted.

explanation. Felix Bloch is remembered for his eponymous theorem about waves in periodic potentials, but his failure to make progress with understanding superconductivity reduced him to formulate a tongue-in-cheek statement that also became known at the time as Bloch’s theorem: “the only theorem about superconductivity that can be proved is that any theory of superconductivity is refutable” or, more succinctly, “superconductivity is impossible”.

The crucial clue came from the famous 1933 experiment of Walther Meissner and Robert Ochsenfeld. They showed that a superconductor cooled to below its transition temperature in an applied magnetic field suddenly expels that magnetic field. In this “Meissner effect”, surface superconducting electrical currents (supercurrents) flow around the superconductor in such a way as to shield the interior from the applied magnetic field. These circulating supercurrents oppose the applied magnetic field, so that deep within the superconductor the magnetic field is close to zero – an effect known as perfect diamagnetism. Fritz London realized that this perfect diamagnetism is even more central to the behaviour of a superconductor than perfect conductivity. Until then perfect conductivity had been thought of as the superconductor’s defining quality – hence the name – but London realized that it is more of a by-product. While others had been trying to figure out how to formulate a new Ohm’s law for a superconductor, in other words to find a relationship between electric current and electric field, London saw that what was needed was a new relation between electric current and magnetic field.

Existing theories had postulated some sort of acceleration equation: an electric field might not drive a current (as it does in a conventional metal) but it might cause one to accelerate. The perfect conductivity in a superconductor meant that there could be no electric field, but this absence of an electric field could be con-

sistent with an already accelerated current of carriers. However, the equations that described this situation only led to a screening of time-varying magnetic fields and not time-independent ones, as evidently screened in the Meissner–Ochsenfeld experiment, and so did not account for the observations.

The London brothers instead insisted that the fundamental principle of superconductivity is the expulsion of magnetic fields. It was their conviction in this line of thought that led to their 1934 eureka moment – the one that caused Edith London’s bruised forehead. They postulated an equation that links the magnetic field to the electric current density and produces the required screening of static magnetic fields and hence the Meissner effect (see box on page 27). This equation and the brothers’ modified version of an acceleration equation became known as the London equations, which they published in 1935 (*Proc. R. Soc. A* **149** 71). Their theory also predicted a length scale over which a magnetic field can penetrate through the surface of a superconductor, which became known as the London penetration depth (figure 1).

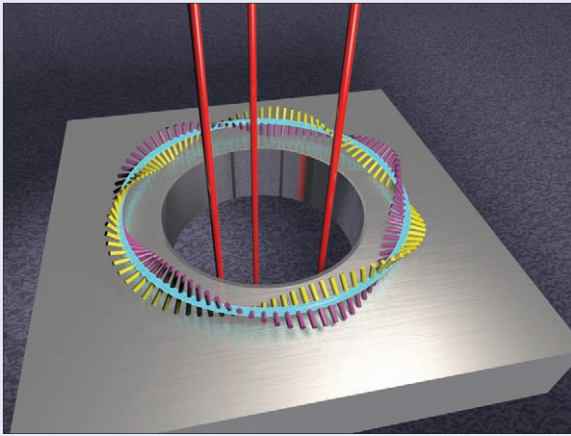
### When the money runs out

In formulating their theory, the London brothers made the most significant progress in our understanding of superconductors in the first half of the 20th century. However, their situation at Oxford was precarious. Their 1935 paper contains a fulsome acknowledgment to “Professor F A Lindemann, FRS, for his kind hospitality at the Clarendon Laboratory” and also to “Imperial Chemical Industries whose generous assistance to one of us has enabled us to undertake this work”. However, the hospitality and generosity were coming to an end.

By 1936 the ICI money that had funded the refugee scientists had dried up and Lindemann could not find funds to offer positions to all of them: he had to make



## 2 Magnetic flux quanta



The magnetic flux through a hole in a superconductor is related to the supercurrent around the inside of the hole. Because the supercurrent (light blue) is phase coherent, the phase of the wavefunction must wind an integer number of times around the loop (shown schematically by yellow and purple rods), which leads to the magnetic flux (red) being quantized. The number of times the wavefunction winds round the loop – here three – is equal to the number of magnetic flux quanta through the loop.

a choice. Heinz was in a junior position without any expectation of remaining at Oxford, and so took an appointment at the University of Bristol, but Fritz entertained hopes of staying on. Schrödinger was a big name and was clearly a high priority for Lindemann to keep, though Schrödinger subsequently left anyway and settled in Dublin. Lindemann also wanted to retain the famous Simon. Fritz London, who had apparently only produced some obscure theoretical work with his brother, which few at Oxford really understood, was told that his contract was at an end.

Fritz therefore accepted an offer of another temporary research position in Paris, where he stayed for three years, eventually leaving for a permanent academic position at Duke University in North Carolina. Fritz and his wife departed from France in September 1939, though because of their German passports they were not permitted to sail on the ship they had planned to board and they were forced to take a later one. This was just as well, as German U-boats torpedoed the earlier ship, with great loss of life.

### Macroscopic quantum coherence

Through work begun in Oxford and furthered in Paris, Fritz London grasped that superconductivity is an example of quantum coherence writ large – not on the scale of a single atom a fraction of a nanometre across, but on the scale of a piece of superconducting wire centimetres across. He coined the phrase *macroscopic quantum phenomenon* to categorize superconductivity: a macroscopic sample of superconductor behaves like a giant atom.

In a normal metal, electrons have the freedom to occupy many different quantum states, but London realized that the carriers in a superconductor are far more constrained. As London put it: “If the various supercurrents really were to correspond to a continuum of different quantum states, it would seem extremely

hard to understand how a supercurrent could resist so many temptations to dissipate into other states.” By locking all the carriers into a single quantum state the supercurrent is fixed to a single value and has no freedom to do anything else. This means that a supercurrent flowing around a loop of wire keeps going on and on, endlessly circulating without dissipation.

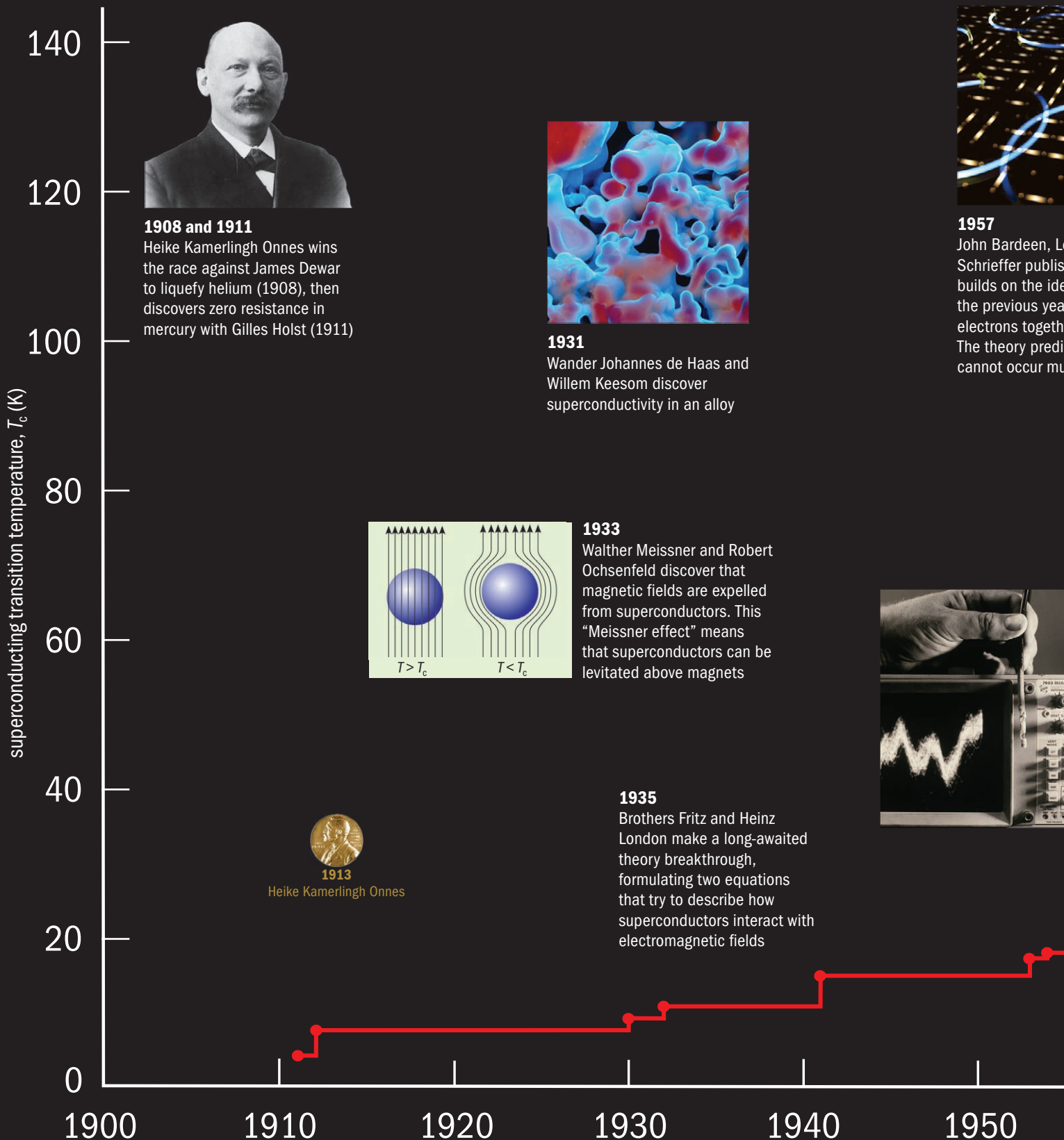
London noticed that this behaviour is reminiscent of the orbits of electrons around an atom: the energy and angular momentum of an electron in an atom are restricted to certain quantized values, because the electronic wavefunction is coherent around the atom. In 1948, still at Duke, he deduced that because the wavefunction in a superconductor is coherent, something similar must occur. If one takes a loop of superconducting wire with a current flowing endlessly round it, London showed that the magnetic flux penetrating the loop should be quantized to certain fixed values (figure 2). A supercurrent travelling in a loop produces a magnetic field that is a precise signature of that supercurrent, and the quantization of magnetic flux is intimately related to the nailing down of that supercurrent to a single quantum state. London calculated that the quantum of magnetic flux would be exceedingly tiny and thus impossible to observe with techniques available at the time. In fact, it was not until 1961, four years after London’s death in 1957, that magnetic flux quantization was experimentally observed by Robert Doll and Martin Näbauer, and, independently, by Bascom S Deaver Jr and William Fairbank.

By that time, the remarkable achievement of Bardeen, Robert Cooper and Leon Schrieffer had provided the world with a wonderfully complete theory of superconductivity that explained most of the properties that had been measured so far. The edifice of BCS theory was built squarely on the foundations provided by Fritz London and his concept of a coherent and rigid wavefunction. London’s vision of macroscopic quantum coherence, where the subtle absurdities of quantum mechanics are writ large, is now a firmly established part of physics, but is no less wonderful or surprising for that.

Bardeen demonstrated his respect for Fritz London’s work by using his cut of the 1972 Nobel prize (he also shared the 1956 prize for discovering the transistor) to fund the Fritz London memorial prize, which recognizes outstanding contributions to low-temperature physics. Duke University has a chair named in his honour, and Fritz London’s life has been recorded in Kostas Gavroglu’s superb 1995 biography. But what is striking is how little known the London brothers are, and in particular the lack of recognition they receive today at the very institution where they came up with those paradigm-changing equations. Perhaps the reason is that Lindemann, who was inordinately proud of his achievement in getting various Jewish scientists out of Germany in the 1930s, did not want to be reminded of the one he was forced to get rid of. In this centenary year of superconductivity I am ensuring that photographs of the London brothers will be hung in the Clarendon Laboratory, and am enthusiastic about publicizing their remarkable contribution to making quantum mechanics move out of the microscopic world of atoms and into our own.

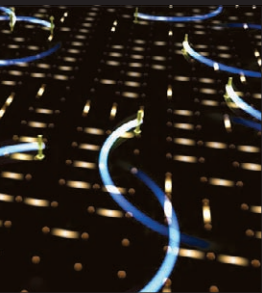
In formulating their theory, the London brothers made the most significant progress in our understanding of superconductors in the first half of the 20th century

# Superconductivity at 100





In the 100 years since the discovery of superconductivity, progress has come in fits and starts. The graphic below shows various types of superconductor sprouting into existence, from the **conventional superconductors** to the rise of the **copper oxides**, as well as the **organics** and the most recently discovered **iron oxides**. Experimental progress has relied on fortuitous guesses, while it was not until 1957 that theorists were finally able to explain how current can flow indefinitely and a magnetic field can be expelled. The idea that the theory was solved was overturned in 1986 with the discovery of materials that superconduct above the perceived theoretical limit, leaving theorists scratching their heads to this day. In this timeline, *Physics World* charts the key events, the rise in record transition temperatures and the **Nobel Prizes for Physics** awarded for progress in superconductivity.



Leon Cooper and Robert  
with their (BCS) theory, which  
idea of Cooper pairs proposed  
r, and describes all the  
er as one wavefunction.  
ects that superconductivity  
uch above 20 K



**1962**  
Lev Landau

**1962**  
Brian Josephson predicts  
that a current will pass  
between two superconductors  
separated by an insulating  
barrier. Two of these  
“Josephson junctions”  
wired in parallel form a  
superconducting quantum  
interference device (SQUID)  
that can measure very weak  
magnetic fields



**1973**  
Brian Josephson



**1972**  
John Bardeen  
Leon Cooper  
Robert Schrieffer



**1986**  
Georg Bednorz (right) and Alexander  
Müller (left) find superconductivity at  
30 K, over the 20 K limit of BCS theory,  
and not in a metal, but a ceramic



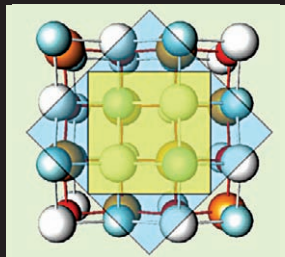
**1987**  
Georg Bednorz  
Alexander Müller

**1987**

Paul Chu and his team break the 77 K liquid-nitrogen barrier and discover superconductivity at 93 K in a compound containing yttrium, barium, copper and oxygen, now known as “YBCO”



**2003**  
Alexei Abrikosov  
Vitaly Ginzburg



**2006**  
Hideo Hosono and colleagues  
discover superconductivity  
in an iron compound. The  
highest  $T_c$  found in these  
materials to date is 55 K

... boiling point of  
liquid nitrogen

**2001**

Jun Akimitsu announces that  
the cheap and simple chemical  
magnesium diboride ( $MgB_2$ )  
superconducts up to 39 K

**1981**

Superconductivity is found by Klaus  
Bechgaard and colleagues in a  
salt – the first organic material to  
superconduct at ambient pressure. To  
date the organic superconductor with  
the highest  $T_c$  is  $Cs_3C_{60}$  at 38 K

1960 1970 1980 1990 2000 2010



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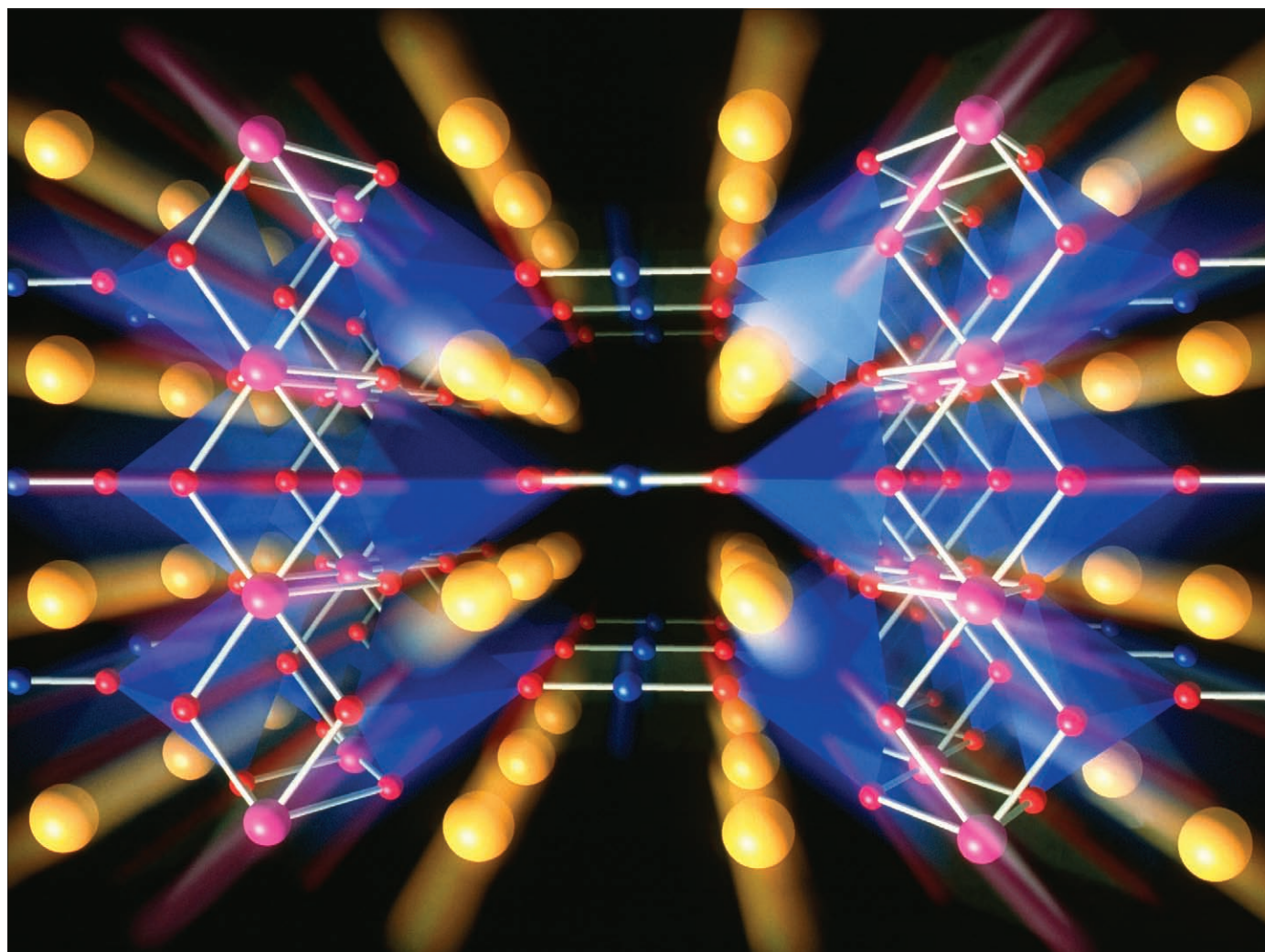
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Pasiela/Science Photo Library

# Resistance is futile

A quarter of a century ago, they were the hottest thing in physics, with a 1987 conference session about them going down in history as “the Woodstock of physics”. So what happened next for high-temperature superconductors? **Ted Forgan** recalls those euphoric early days and assesses the remaining challenges in this still-developing field

My involvement with high-temperature superconductors began in the autumn of 1986, when a student in my final-year course on condensed-matter physics at the University of Birmingham asked me what I thought about press reports concerning a new superconductor. According to the reports, two scientists working in Zurich, Switzerland – J Georg Bednorz and K Alex Müller – had discovered a material with a transition temperature,  $T_c$ , of 35 K – 50% higher than the previous highest value of 23 K, which had been achieved more than a decade earlier in  $\text{Nb}_3\text{Ge}$ .

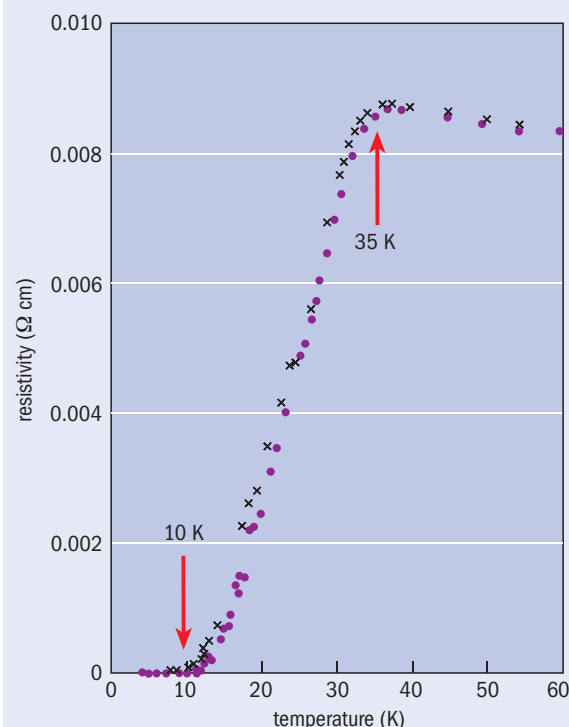
In those days, following this up required a walk to the university library to borrow a paper copy of the appropriate issue of the journal *Zeitschrift für Physik B*. I

reported back to the students that I was not convinced by the data, since the lowest resistivity that Bednorz and Müller (referred to hereafter as “B&M”) had observed might just be comparable with that of copper, rather than zero. In any case, the material only achieved zero resistivity at  $\sim 10$  K, even though the drop *began* at the much higher temperature of 35 K (figure 1).

In addition, the authors had not, at the time they submitted the paper in April 1986, established the composition or crystal structure of the compound they believed to be superconducting. All they knew was that their sample was a mixture of different phases containing barium (Ba), lanthanum (La), copper (Cu) and oxygen (O). They also lacked the equipment to test

**Ted Forgan** is a condensed-matter physicist at the University of Birmingham, UK, e-mail [e.m.forgan@bham.ac.uk](mailto:e.m.forgan@bham.ac.uk)

## 1 The prize-winning plot



Adapted from J Georg Bednorz and K Alex Müller's landmark paper, this graph heralded the beginning of high-temperature superconductivity. It shows that the resistivity of their barium-lanthanum-copper-oxide compound rises as its temperature is reduced, reaching a value about 5000 times that of copper before it begins to fall at ~35 K. Such behaviour is quite different from that of simple metals, for which the resistivity generally falls smoothly as the temperature is reduced, with a sharp drop to zero if they become superconducting. The circles and crosses represent measurements at low and high current densities, respectively.

whether the sample expelled a magnetic field, which is a more fundamental property of superconductors than zero resistance, and is termed the Meissner effect. No wonder B&M had carefully titled their paper "*Possible high  $T_c$  superconductivity in the Ba-La-Cu-O system*" (my italics).

My doubt, and that of many physicists, was caused by two things. One was a prediction made in 1968 by the well-respected theorist Bill McMillan, who proposed that there was a natural upper limit to the possible  $T_c$  for superconductivity – and that we were probably close to it. The other was the publication in 1969 of *Superconductivity*, a two-volume compendium of articles by all the leading experts in the field. As one of them remarked, this book would represent "the last nail in the coffin of superconductivity", and so it seemed: many people left the subject after that, feeling that everything important had already been done in the 58 years since its discovery.

In defying this conventional wisdom, B&M based their approach on the conviction that superconductivity in conducting oxides had been insufficiently exploited. They hypothesized that such materials might harbour a stronger electron-lattice interaction, which would raise the  $T_c$  according to the theory of superconductivity put forward by John Bardeen, Leon Cooper and Robert

Schrieffer (BCS) in 1957 (see box on page 35). For two years B&M worked without success on oxides that contained nickel and other elements. Then they turned to oxides containing copper – cuprates – and the results were as the *Zeitschrift für Physik B* paper indicated: a tantalizing drop in resistivity.

What soon followed was a worldwide rush to build on B&M's discovery. As materials with still higher  $T_c$  were found, people began to feel that the sky was the limit. Physicists found a new respect for oxide chemists as every conceivable technique was used first to measure the properties of these new compounds, and then to seek applications for them. The result was a blizzard of papers. Yet even after an effort measured in many tens of thousands of working years, practical applications remain technically demanding, we still do not properly understand high- $T_c$  materials and the mechanism of their superconductivity remains controversial.

## The ball starts rolling

Although I was initially sceptical, others were more accepting of B&M's results. By late 1986 Paul Chu's group at the University of Houston, US, and Shoji Tanaka's group at Tokyo University in Japan had confirmed high- $T_c$  superconductivity in their own Ba-La-Cu-O samples, and B&M had observed the Meissner effect. Things began to move fast: Chu found that by subjecting samples to about 10 000 atmospheres of pressure, he could boost the  $T_c$  up to ~50 K, so he also tried "chemical pressure" – replacing the La with the smaller ion yttrium (Y). In early 1987 he and his collaborators discovered superconductivity in a mixed-phase Y-Ba-Cu-O sample at an unprecedented 93 K – well above the psychological barrier of 77 K, the boiling point of liquid nitrogen. The publication of this result at the beginning of March 1987 was preceded by press announcements, and suddenly a bandwagon was rolling: no longer did superconductivity need liquid helium at 4.2 K or liquid hydrogen at 20 K, but instead could be achieved with a coolant that costs less than half the price of milk.

Chu's new superconducting compound had a rather different structure and composition than the one that B&M had discovered, and the race was on to understand it. Several laboratories in the US, the Netherlands, China and Japan established almost simultaneously that it had the chemical formula  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$ , where the subscript 7- $d$  indicates a varying content of oxygen. Very soon afterwards, its exact crystal structure was determined, and physicists rapidly learned the word "perovskite" to describe it (see box on page 37). They also adopted two widely used abbreviations, YBCO and 123 (a reference to the ratios of Y, Ba and Cu atoms) for its unwieldy chemical formula.

The competition was intense. When the Dutch researchers learned from a press announcement that Chu's new material was green, they deduced that the new element he had introduced was yttrium, which can give rise to an insulating green impurity with the chemical formula  $\text{Y}_2\text{BaCuO}_5$ . They managed to isolate the pure 123 material, which is black in colour, and the European journal *Physica* got their results into print first. However, a group from Bell Labs was the first to submit a paper, which was published soon afterwards

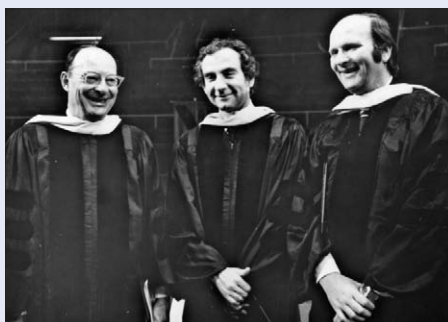
Superconductivity no longer needed liquid helium or liquid hydrogen, but instead could be achieved with a coolant that costs less than half the price of milk



## The BCS theory of superconductivity

Although superconductivity was observed for the first time in 1911, there was no microscopic theory of the phenomenon until 1957, when John Bardeen, Leon Cooper and Robert Schrieffer made a breakthrough. Their “BCS” theory – which describes low-temperature superconductivity, though it requires modification to describe high- $T_c$  – has several components. One is the idea that electrons can be paired up by a weak interaction, a phenomenon now known as Cooper pairing. Another is that the “glue” that holds electron pairs together, despite their Coulomb repulsion, stems from the interaction of electrons with the crystal lattice – as described by Bardeen and another physicist, David Pines, in 1955. A simple way to think of this interaction is that an electron attracts the positively charged lattice and slightly deforms it, thus making a potential well for another electron. This is rather like two sleepers on a soft mattress, who each roll into the depression created by the other. It is this deforming response that caused Bill McMillan to propose in 1968 that there should be a maximum possible  $T_c$ : if the electron–lattice interaction is too strong, the crystal may deform to a new structure instead of becoming superconducting.

The third component of BCS theory is the idea that all the *pairs* of electrons are condensed into the same quantum state as each other – like the



**B, C and S** John Bardeen (left), Leon Cooper (centre) and Robert Schrieffer.

photons in a coherent laser beam, or the atoms in a Bose–Einstein condensate. This is possible even though individual electrons are fermions and cannot exist in the same state as each other, as described by the Pauli exclusion principle. This is because *pairs* of electrons behave somewhat like bosons, to which the exclusion principle does not apply. The wavefunction incorporating this idea was worked out by Schrieffer (then a graduate student) while he was sitting in a New York subway car.

Breaking up one of these electron pairs requires a minimum amount of energy,  $\Delta$ , per electron. At non-zero temperatures, pairs are constantly being broken up by thermal excitations. The pairs then re-form, but when they

do so they can *only* rejoin the state occupied by the unbroken pairs. Unless the temperature is very close to  $T_c$  (or, of course, above it) there is always a macroscopic number of unbroken pairs, and so thermal excitations do not change the quantum state of the condensate. It is this stability that leads to non-decaying supercurrents and to superconductivity. Below  $T_c$ , the chances of all pairs getting broken at the same time are about as low as the chances that a lump of solid will jump in the air because all the atoms inside it are, coincidentally, vibrating in the same direction. In this way, the BCS theory successfully accounted for the behaviour of “conventional” low-temperature superconductors such as mercury and tin.

It was soon realized that BCS theory can be generalized. For instance, the pairs may be held together by a different interaction than that between electrons and a lattice, and two fermions in a pair may have a mutual angular momentum, so that their wavefunction varies with direction – unlike the spherically symmetric, zero-angular-momentum pairs considered by BCS. Materials with such pairings would be described as “unconventional superconductors”. However, there is one aspect of superconductivity theory that has remained unchanged since BCS: we do not know of any fermion superconductor without pairs of some kind.

in the US journal *Physical Review Letters*. This race illustrates an important point: although scientists may high-mindedly and correctly state that their aim and delight is to discover the workings of nature, the desire to be *first* is often a very strong additional motivation. This is not necessarily for self-advancement, but for the buzz of feeling (perhaps incorrectly in this case) “I’m the only person in the world who knows this!”.

### “The Woodstock of physics”

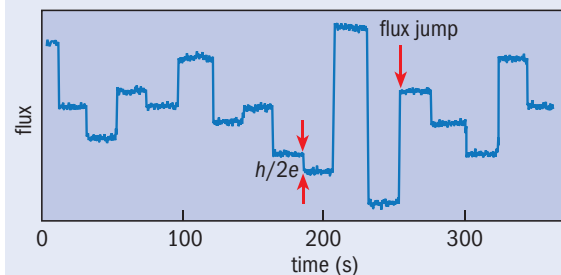
For high- $T_c$  superconductivity, the buzz reached fever pitch at the American Physical Society’s annual “March Meeting”, which in 1987 was held in New York. The week of the March Meeting features about 30 gruelling parallel sessions from dawn till after dusk, where a great many condensed-matter physicists present their latest results, fill postdoc positions, gossip and network. The programme is normally fixed months in advance, but an exception had to be made that year and a “post-deadline” session was rapidly organized for the Wednesday evening in the ballroom of the Hilton Hotel. This space was designed to hold 1100 people, but in the event it was packed with nearly twice that number, and many others observed the proceedings on video monitors outside.

Müller and four other leading researchers gave talks greeted with huge enthusiasm, followed by more than 50 five-minute contributions, going on into the small hours. This meeting gained the full attention of the press and was dubbed “the Woodstock of physics” in

recognition of the euphoria it generated – an echo of the famous rock concert held in upstate New York in 1969. The fact that so many research groups were able to produce results in such a short time indicated that the B&M and Chu discoveries were “democratic”, meaning that anyone with access to a small furnace (or even a pottery kiln) and a reasonable understanding of solid-state chemistry could confirm them.

With so many people contributing, the number of papers on superconductivity shot up to nearly 10 000 in 1987 alone. Much information was transmitted informally: it was not unusual to see a scientific paper with “*New York Times*, 16 February 1987” among the references cited. The B&M paper that began it all has been cited more than 8000 times and is among the top 10 most cited papers of the last 30 years. It is noteworthy that nearly 10% of these citations include misprints, which may be because of the widespread circulation of faxed photocopies of faxes. One particular misprint, an incorrect page number, occurs more than 250 times, continuing to the present century. We can trace this particular “mutant” back to its source: a very early and much-cited paper by a prominent high- $T_c$  theorist. Many authors have clearly copied some of their citations from the list at the end of this paper, rather than going back to the originals. There have also been numerous sightings of “unidentified superconducting objects” (USOs), or claims of extremely high transition temperatures that could not be reproduced. One suspects that some of these may have arisen when a voltage

## 2 In flux



When a ring of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  is subjected to deliberate electromagnetic interference, the magnetic flux jumps in and out of the ring in integer multiples of the flux quantum (top). In accordance with BCS theory, the value of this flux quantum was measured to be  $h/2e$ . The photograph (bottom) shows the apparatus used to measure the flux quantum – complete with Blu-Tack. (Adapted from C E Gough *et al.* 1987 *Nature* **326** 855)

lead became badly connected as a sample was cooled; of course, this would cause the voltage measured across a current-carrying sample to drop to zero.

Meanwhile, back in Birmingham, Chu's paper was enough to persuade us that high- $T_c$  superconductivity was real. Within the next few weeks, we made our own superconducting sample at the second attempt, and then hurried to measure the flux quantum – the basic unit of magnetic field that can thread a superconducting ring. According to the BCS theory of superconductivity, this flux quantum should have the value  $h/2e$ , with the factor 2 representing the pairing of conduction electrons in the superconductor. This was indeed the value we found (figure 2). We were amused that the accompanying picture of our apparatus on the front cover of *Nature* included the piece of Blu-Tack we used to hold parts of it together – and pleased that when B&M were awarded the 1987 Nobel Prize for Physics (the shortest gap ever between discovery and award), our results were reproduced in Müller's Nobel lecture.

## Unfinished business

In retrospect, however, our  $h/2e$  measurement may have made a negative contribution to the subject, since it could be taken to imply that high- $T_c$  superconductivity is “conventional” (i.e. explained by standard BCS theory), which it certainly is not. Although B&M's choice of compounds was influenced by BCS theory, most (but not all) theorists today would say that the interaction that led them to pick La–Ba–Cu–O is *not* the dominant mechanism in high- $T_c$  superconductivity. Some of the evidence supporting this conclusion came from several important experiments performed in around 1993, which together showed that the paired superconducting electrons have  $l = 2$  units of relative angular momentum. The resulting wavefunction has a four-leaf-clover shape, like one of the  $d$ -electron states in an atom, so the pairing is said to be “ $d$ -wave”. In such  $l = 2$  pairs, “centrifugal force” tends to keep the constituent electrons apart, so this state is favoured if there is a short-distance repulsion between them (which is certainly the case in cuprates). This kind of pairing is also favoured by an anisotropic interaction expected at larger distances, which can take advantage of the clover-leaf wavefunction. In contrast, the original “ $s$ -wave” or  $l = 0$  pairing described in BCS theory would be expected if there is a short-range isotropic attraction arising from the electron–lattice interaction.

These considerations strongly indicate that the electron–lattice interaction (which in any case appears to be too weak) is not the cause of the high  $T_c$ . As for the actual cause, opinion tends towards some form of magnetic attraction playing a role, but agreement on the precise mechanism has proved elusive. This is mainly because the drop in electron energy on entering the superconducting state is less than 0.1% of the total energy (which is about 1 eV), making it extremely difficult to isolate this change.

On the experimental side, the maximum  $T_c$  has been obstinately stuck at about halfway to room temperature since the early 1990s. There have, however, been a number of interesting technical developments. One is the discovery of superconductivity at 39 K in magnesium diboride ( $\text{MgB}_2$ ), which was made by Jun Akimitsu in 2001. This compound had been available from chemical suppliers for many years, and it is interesting to speculate how history would have been different if its superconductivity had been discovered earlier. It is now thought that  $\text{MgB}_2$  is the last of the BCS superconductors, and no attempts to modify it to increase the  $T_c$  further have been successful. Despite possible applications of this material, it seems to represent a dead end.

In the same period, other interesting families of superconductors have also been discovered, including the organics and the alkali-metal-doped buckyball series. None, however, have raised as much excitement as the development in 2008 (by Hideo Hosono's group at Tokyo University) of an iron-based superconductor with  $T_c$  above 40 K. Like the cuprate superconductors before them, these materials also have layered structures, typically with iron atoms sandwiched between arsenic layers, and have to be doped to remove anti-ferromagnetism. However, the electrons in these materials are less strongly interacting than they are in the cuprates, and because of this, theorists believe that they

On the experimental side, the maximum  $T_c$  has been obstinately stuck at about halfway to room temperature since the early 1990s

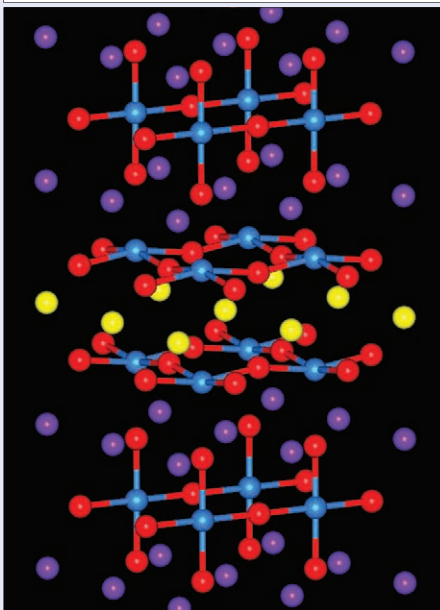
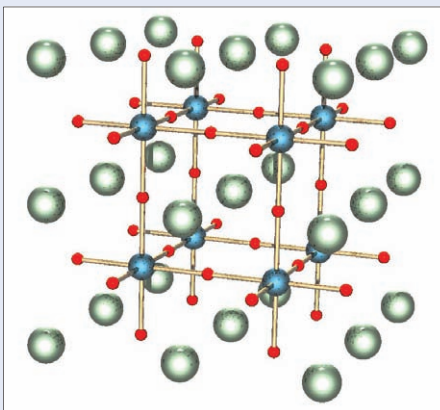


## The amazing perovskite family

Perovskites are crystals that have long been familiar to inorganic chemists and mineralogists in contexts other than superconductivity. Perovskite materials containing titanium and zirconium, for example, are used as ultrasonic transducers, while others containing manganese exhibit very strong magnetic-field effects on their electrical resistance (“colossal magnetoresistance”). One of the simplest perovskites, strontium titanate ( $\text{SrTiO}_3$ ), is shown in the top image. In this material,  $\text{Ti}^{4+}$  ions (blue) are separated by  $\text{O}^{2-}$  ions (red) at the corners of an octahedron, with  $\text{Sr}^{2+}$  ions (green) filling the gaps and balancing the charge.

Bednorz and Müller (B&M) chose to investigate perovskite-type oxides (a few of which are conducting) because of a phenomenon called the Jahn–Teller effect, which they believed might provide an increased interaction between the electrons and the crystal lattice. In 1937 Hermann Arthur Jahn and Edward Teller predicted that if there is a degenerate partially occupied electron state in a symmetrical environment, then the surroundings (in this case the octahedron of oxygen ions around copper) would spontaneously distort to remove the degeneracy and lower the energy. However, most recent work indicates that the electron–lattice interaction is not the main driver of superconductivity in cuprates – in which case the Jahn–Teller theory was only useful because it led B&M towards these materials!

The most important structural feature of the cuprate perovskites, as far as superconductivity is concerned, is the existence of copper-oxide



layers, where copper ions in a square array are separated by oxygen ions. These layers are the location of the superconducting carriers, and they must be created by varying the content of oxygen or one of the other constituents – “doping” the material. We can see how this works most simply in B&M’s original compound, which was  $\text{La}_2\text{CuO}_4$  doped with Ba to give  $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$  ( $x \sim 0.15$  gives the highest  $T_c$ ). In ionic compounds, lanthanum forms  $\text{La}^{3+}$  ions, so in  $\text{La}_2\text{CuO}_4$  the ionic charges all balance if the copper and oxygen ions are in their usual  $\text{Cu}^{2+}$  (as in the familiar copper sulphate,  $\text{CuSO}_4$ ) and  $\text{O}^{2-}$  states.  $\text{La}_2\text{CuO}_4$  is insulating even though each  $\text{Cu}^{2+}$  ion has an unpaired electron, as these electrons do not contribute to electrical conductivity because of their strong mutual repulsion. Instead, they are localized, one to each copper site, and their spins line up antiparallel in an antiferromagnetic state. If barium is incorporated, it forms  $\text{Ba}^{2+}$  ions, so that the copper and oxygen ions can no longer have their usual charges, thus the material becomes “hole-doped”, the antiferromagnetic ordering is destroyed and the material becomes both a conductor and a superconductor.  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  or “YBCO” (bottom) behaves similarly, except that there are two types of copper ions, inside and outside the  $\text{CuO}_2$  planes, and the doping is carried out by varying the oxygen content. This material contains  $\text{Y}^{3+}$  (yellow) and  $\text{Ba}^{2+}$  (purple) ions, copper (blue) and oxygen (red) ions. When  $d \sim 0.03$ , the hole-doping gives a maximum  $T_c$ ; when  $d$  is increased above  $\sim 0.7$ , YBCO becomes insulating and antiferromagnetic.

will be an easier nut to crack. A widely accepted model posits that the electron pairing mainly results from a *repulsive* interaction between two different groups of carriers, rather than attraction between carriers within a group. Even though the  $T_c$  in these “iron pnictide” superconductors has so far only reached about 55 K, the discovery of these materials is a most interesting development because it indicates that we have not yet scraped the bottom of the barrel for new mechanisms and materials for superconductivity, and that research on high- $T_c$  superconductors is still a developing field.

### A frictionless future?

So what are the prospects for room-temperature superconductivity? One important thing to remember is that even supposing we discover a material with  $T_c \sim 300$  K, it would still not be possible to make snooker tables with levitating frictionless balls, never mind the levitating boulders in the film *Avatar*. Probably 500 K would be needed, because we observe and expect that as  $T_c$  gets higher, the electron pairs become smaller. This means that thermal fluctuations become more important, because they occur in a smaller volume and can more easily lead to a loss of the phase coherence essential to superconductivity. This effect, particularly in high mag-

netic fields, is already important in current high- $T_c$  materials and has led to a huge improvement in our understanding of how lines of magnetic flux “freeze” in position or “melt” and move, which they usually do near to  $T_c$ , and give rise to resistive dissipation.

Another limitation, at least for the cuprates, is the difficulty of passing large supercurrents from one crystal to the next in a polycrystalline material. This partly arises from the fact that in such materials, the supercurrents only flow well in the copper-oxide planes. In addition, the coupling between the *d*-wave pairs in two adjacent crystals is very weak unless the crystals are closely aligned so that the lobes of their wavefunctions overlap. Furthermore, the pairs are small, so that even the narrow boundaries between crystal grains present a barrier to their progress. None of these problems arise in low- $T_c$  materials, which have relatively large isotropic pairs.

For high- $T_c$  materials, the solution, developed in recent years, is to form a multilayered flexible tape in which one layer is an essentially continuous single crystal of 123 (figure 3). Such tapes are, however, expensive because of the multiple hi-tech processes involved and because, unsurprisingly, ceramic oxides cannot be wound around sharp corners. It seems that even in

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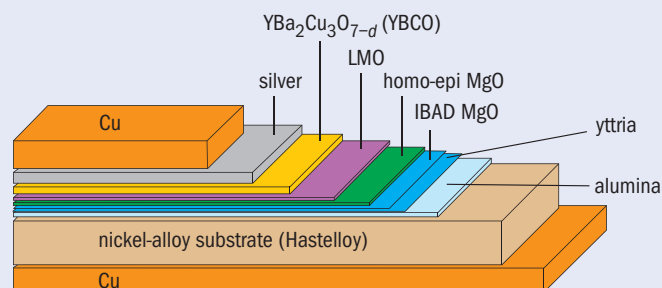
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## 3 Wired for superconductivity



The make up of a second-generation superconducting wire, showing the multiple layers required to achieve good conductivity in the YBCO. Layers of copper (Cu) protect against transient resistive voltages, while layers of lanthanum manganate (LMO) and two types of MgO form substrates for growing single-crystal YBCO films.

existing high- $T_c$  materials, nature gave with one hand, but took away with the other, by making the materials extremely difficult to use in practical applications.

Nevertheless, some high- $T_c$  applications do exist or are close to market. Superconducting power line “demonstrators” are undergoing tests in the US and Russia, and new cables have also been developed that can carry lossless AC currents of 2000 A at 77 K. Such cables also have much higher current densities than conventional materials when they are used at 4.2 K in high-field magnets. Superconducting pick-up coils already improve the performance of MRI scanners, and superconducting filters are finding applications in mobile-phone base stations and radio astronomy.

In addition to the applications, there are several other positive things that have arisen from the discovery of high- $T_c$  superconductivity, including huge developments in techniques for the microscopic investigation of materials. For example, angle-resolved photo-electron spectroscopy (ARPES) has allowed us to “see” the energies of occupied electron states in ever-finer detail, while neutron scattering is the ideal tool with which to reveal the magnetic properties of copper ions. The advent of high- $T_c$  superconductors has also revealed that the theoretical model of weakly interacting electrons, which works so well in simple metals, needs to be extended. In cuprates and many other materials investigated in the last quarter of a century, we have found that the electrons cannot be treated as a gas of almost independent particles.

The result has been new theoretical approaches and also new “emergent” phenomena that cannot be predicted from first principles, with unconventional superconductivity being just one example. Other products of this research programme include the fractional quantum Hall effect, in which entities made of electrons have a fractional charge; “heavy fermion” metals, where the electrons are effectively 100 times heavier than normal; and “non-Fermi” liquids in which electrons do not behave like independent particles. So is superconductivity growing old after 100 years? In a numerical sense, perhaps – but quantum mechanics is even older if we measure from Planck’s first introduction of his famous constant, yet both are continuing to spring new surprises (and are strongly linked together). Long may this continue!



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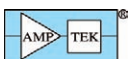
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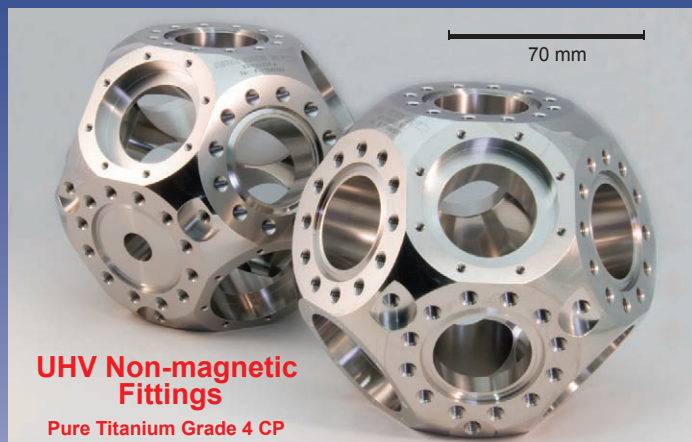
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## On the money

Stock markets that rise unsustainably can end up plummeting back down – but can physics create laws describing how such crashes occur?

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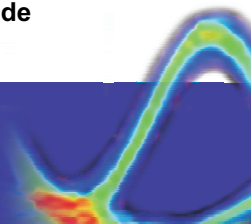
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# Taming serendipity

The discovery of high-temperature iron-based superconductors in 2008 thrilled researchers because it indicated that there could be another – more useful – class of superconductors just waiting to be found.

**Laura H Greene** shares that enthusiasm and calls for global collaboration to reveal these new materials



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A century on from the discovery of superconductivity, we still do not know how to design superconductors that can be really useful in the everyday world. Despite this seemingly downbeat statement, I remain enthusiastic about the search for new superconducting materials. Although my own research in this area has had its share of null results and knock-backs, in that I am in good company with the true leaders in the field. Optimism abounds, and the past couple of years have seen a renewed passion, with researchers worldwide wanting to work together to find a way to design new materials that we know in advance will function as superconductors.

That would be very different from most of the discoveries in superconductivity, which have often been serendipitous. Indeed, the main quest of Heike Kamerlingh Onnes was to liquefy gases, and only after managing to liquefy helium in 1908 did he set his Leiden lab to work on a study of the properties of metals at low temperature. The choice of sample was fortunate – mercury was used because it is a liquid at ambient temperature and so could easily be purified. The discovery of its dramatic drop in resistance when cooled to 4 K, which we now know to be the critical temperature,  $T_c$ , was an unexpected and fortuitous surprise.

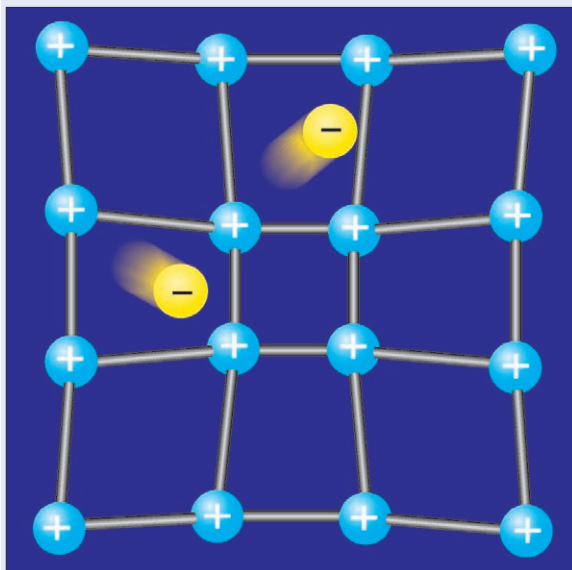
In subsequent years, increasing the critical temperature was achieved by systematic experimental tests of elements, alloys and compounds, predominantly led by

Bernd Matthias from about 1950, who in doing so became the first researcher to discover a new class of superconductors. To begin with, the only known superconductors were elements, but Matthias found superconductivity in various combinations of elements that on their own are non-superconducting. The earliest of these was the ferromagnetic element cobalt combined with the semiconductor silicon to form  $\text{CoSi}_2$ . What changed the game was the discovery by John Hulm and his graduate student George Hardy at the University of Chicago in 1952 of the vanadium–silicon compound  $\text{V}_3\text{Si}$ , the first of the then-called high- $T_c$  superconductors. This was a completely new class of superconductors – known as the A15s (a particular crystal structure of the chemical formula  $\text{A}_3\text{B}$ , where A is a transition metal) – and it enabled Matthias to discover more than 30 compounds of this type, with values of  $T_c$  that ranged up to 18 K in the case of  $\text{Nb}_3\text{Ge}$ .

Increasing the critical superconducting temperature is certainly what most interests the media, but it is not the only property with which to rank new superconductors. The A15s were the first family of superconductors that maintained a high critical current density,  $J_c$ , in the presence of strong magnetic fields, which is crucial for all current-carrying applications. In 1963 Hulm, then with co-workers at the Westinghouse Research Laboratories, developed the first commercial

**Laura H Greene** is a professor of physics at the University of Illinois at Urbana-Champaign, US, e-mail lhgreene@illinois.edu

## 1 When a robust theory breaks down



The electrons in all superconductors form Cooper pairs, which carry the superconducting current. This was accounted for in the Bardeen–Cooper–Schrieffer (BCS) theory, and in conventional metallic superconductors the microscopic mechanism was correctly identified as electron–phonon coupling. Phonons are the quantized normal-mode vibrations of a lattice, and a strong electron–phonon coupling means that the lattice is “squishy” to the electron, like a soft mattress. As shown in this figure, an electron can distort the lattice, which affects the phonon, leaving something like a positive “wake” that later attracts the second member of the Cooper pair. The two negatively charged electrons are not bound in real space but are correlated through the vibrational distortions they leave behind. This brilliant idea showed how Coulomb’s law could be repealed. But in many novel superconducting families, electron–phonon coupling alone cannot account for the pairing, the explanation for which remains an unsolved mystery.

superconducting wires, based on random alloys of niobium–titanium, a material discovered at the Rutherford Appleton Laboratory in the UK. Although niobium–titanium alloys exhibit a lower  $T_c$  and  $J_c$  than the A15s, they were chosen for wires because they are malleable, reliable and can be used in nearly all practical applications, including the medical technique of magnetic resonance imaging (MRI). Despite the importance of a high  $J_c$ , achievements in this area receive little recognition compared with progress in increasing  $T_c$ . But as my former boss, John Rowell, stated at the retirement party of Jack Wernick, who is noted for the discovery of several A15s, “High- $T_c$  wins Nobel prizes; high  $J_c$  saves lives.” So although the search for new families of higher- $T_c$  superconductors is what makes the headlines, what really matters when it comes to applications is a high value of  $J_c$  and mechanical properties that are good for making wires.

In 1979 Frank Steglich and colleagues discovered superconductivity in materials containing rare earths (elements with a 4f electron orbital) or actinides (those with a 5f electron orbital). These compounds are called the “heavy fermions”, because with antiferromagnetic ground states, and at low temperatures, the itinerant electrons behave as if they have masses up to 1000 times larger than the free-electron mass. This discovery was significant because the heavy fermions were the

first truly tunable superconductors, through a competition between superconductivity and magnetic order. But what was even more important was that heavy-fermion superconductors did not follow the rule book: for the first time, the brilliant Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity was shown to break down. BCS theory explains what is happening at the microscopic level – it involves paired electrons known as “Cooper pairs” travelling around the crystal lattice – and this part of the theory remains robust in all the known superconductors. But the microscopic mechanism for superconductivity in all previously found superconductors was attributed in BCS to electron–phonon coupling, which was not sufficient to cause the electron pairing in the new heavy-fermion superconductors (figure 1).

Before the heavy fermions were discovered, it was accepted that any kind of magnetism would harm the superconducting state. But in this new class of superconductor the magnetism appeared integral to the strength of the superconductivity. Another exciting aspect of this class is that higher- $T_c$  heavy-fermion superconductors – in particular the “115” series beginning with the discovery of CeCoIn<sub>5</sub> – were not discovered purely by serendipity, but driven by guidelines learned from many preceding substitution and pressure studies.

## New classes

Enter the high- $T_c$  oxides. First was the sensational revolution of the copper oxides, or “cuprates”: Georg Bednorz and Alex Müller discovered LaBaCuO in 1986 with a  $T_c$  of 40 K, and subsequently Maw-Kuen Wu and Ching-Wu (Paul) Chu discovered YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-d</sub>, or “YBCO”, with a  $T_c$  of more than 90 K. (For more about the high- $T_c$  revolution, see “Resistance is futile” on page 33.) These transformative discoveries again relied on guidelines put together by thoughtful and talented physicists, but serendipity certainly played a factor. Indeed, I believe the only discovery of a high- $T_c$  system that was driven predominantly by theory is Ba<sub>1-x</sub>K<sub>x</sub>BiO<sub>3</sub>, or BKBO (to date at least): Len Mattheiss and Don Hamann at Bell Labs used electronic-structure calculations of an earlier low- $T_c$  system, Ba(Pb,Bi)O<sub>3</sub>, to predict and then make BKBO, for which their colleague Bob Cava drove the  $T_c$  to a respectable 30 K.

But what of materials with even higher transition temperatures? Through a tremendous amount of hard work worldwide by many talented physicists, transition temperatures in the cuprates have been pushed up to 135 K at ambient pressure and above 150 K at high pressure in HgBa<sub>2</sub>Ca<sub>2</sub>Cu<sub>3</sub>O<sub>8+d</sub> (also known as Hg-1223), which was discovered in 1993. We were then left with the idea that perhaps there were no other families of high- $T_c$  superconductors. Could it be that the cuprate were the only high- $T_c$  class we would ever find? The fear was that systematic studies had already found the highest possible  $T_c$ .

But we had guidelines and ideas. Many of these were published in a 2006 report for the US Department of Energy, *Basic Research Needs for Superconductivity*. Particularly of note in that report, which outlined the prospects and potential of superconductivity, was our canonical phase diagram (figure 2), which hinted that we knew where to look: at the boundary between com-

Heavy-fermion superconductors did not follow the rule book: for the first time, the brilliant BCS theory was shown to break down



peting phases. This personifies the concept of “quantum criticality”, where a phase transition occurs not because of thermal fluctuations as in a typical thermodynamic phase transition, but because of quantum-mechanical fluctuations at zero temperature. The phase diagram shows an antiferromagnetic insulator on the left and a normal metal on the right. Where they meet at the centre is the quantum critical point, and as that point is approached, the quantum fluctuations of the competing phases get stronger and a strange “emergent” state of matter appears – in this case, high-temperature superconductivity. The general rule was: the stronger the competing phases, the stronger the emergent phase. Those ideas remain, but where were these new families of superconductors? Had we hit a dead end?

Finally, in 2008, a second class of high- $T_c$  superconductor was discovered. Hideo Hosono at the Tokyo Institute of Technology had discovered iron-based superconductors two years earlier, and in January 2008 his first “high- $T_c$ ” paper on these materials was published, which precipitated a renewed excitement and a frenzy of activity. Within four months, Zhongxian Zhao’s group at the Institute of Physics in Beijing created related materials that hold the record with a  $T_c$  of 58 K. Many of us were awestruck – here finally was a new class of high-temperature superconductors that broke the 22-year tyranny of cuprates, and in materials that no-one had predicted and were contrary to our basic notions of how superconductivity works. How could iron – the strongest ferromagnetic element in the periodic table – be a basis for superconductivity at all, let alone high-temperature superconductivity? There now exist whole arrays of iron-based superconductors – pnictides and chalcogenides – all found by clever, hard work, but originally discovered by serendipity.

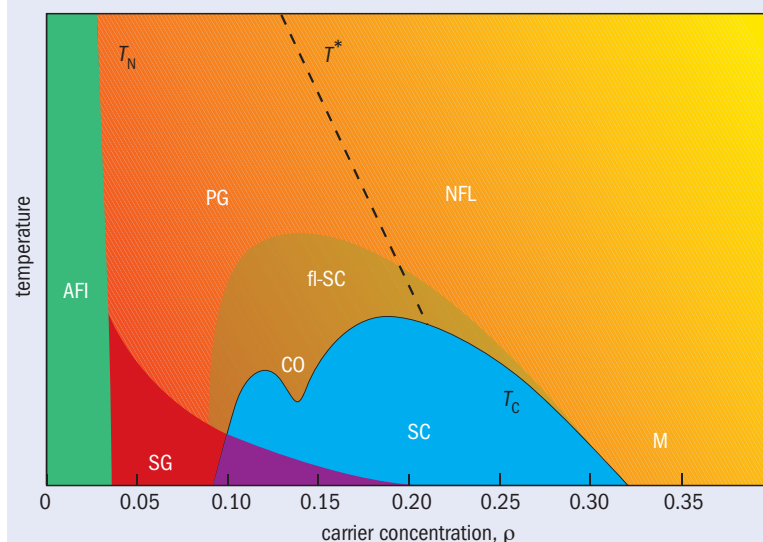
### Laying down the gauntlet

All of these families of superconductors have a great deal in common, yet also have unique properties. The physics seems to be growing more complex with time, and we continue to build more guidelines and structure into our search for new superconducting materials. Although the discovery of iron-based superconductors gave us a lot of research fodder, they will not necessarily tell us all we need to know about how to find new classes of superconductors. But one thing is for sure: the cuprates are not unique and as there is a second class of high- $T_c$  superconductors, I believe there must be a third.

The discovery of iron-based superconductors – the first new class of high- $T_c$  superconductors after more than two decades of only incremental progress – injected a new-found positivity into the field, rivalled only by the discovery of superconductivity in the cuprates. The resulting surge of global research, however, has a very different feel from that in 1986. In the early days of high-temperature superconductivity the competition was fierce – there was a real race to obtain higher transition temperatures. But now that zealous sense of urgency has been replaced by a more paced and considered approach.

Many scientists have been working on understanding novel superconductors for decades, often in productive collaborations. Recently, our research funding and support have been revitalized on a worldwide scale,

## 2 Competing phases



This figure maps out a general phase diagram of the high-temperature cuprate superconductors. The horizontal axis is nominally the carrier concentration,  $\rho$ , which can be tuned by pressure or atomic substitution (doping). The vertical axis is temperature. The antiferromagnetic insulating (AFI) state on the left occurs below the Néel temperature,  $T_N$ , and the normal metal (M) state occurs at high  $\rho$ . The superconducting (SC) state is bounded by the critical temperature,  $T_c$ , and emerges between competing AFI and M phases as discussed in the text. The origin of the intriguing pseudogap (PG) state, which appears below the dashed line,  $T^*$ , and of the other labelled phases – spin-glass (SG), charge-ordered (CO), fluctuating superconductivity (fl-SC) and non-Fermi liquid (NFL) – remains elusive.

in part because of the need to address the global energy crisis by significantly increasing the efficiency of power transmission. After 25 years of intense and fruitful work, the cuprates remain promising, but for various reasons may still not be the materials of choice to impact our power grid. The newly discovered iron-based high-temperature superconductors exhibit many positive aspects, but are likewise not yet in a position to impact power transmission. Another class of superconductors is needed.

For any one of us, putting all of our efforts towards attacking this problem of discovering a new superconductor is highly risky. If we want to find such a thing but do not manage this after three to five years – the typical length of most research grants – we seriously risk losing our funding. As a result, we focus most of our efforts on understanding the existing novel superconductors. So, I and my colleague Rick Greene (no relation) of the University of Maryland, aided by the Institute for Complex Adaptive Matter, have made a call to arms to the international community, which we are spreading via working groups at conferences and workshops: “It is time for us to join our expertise and resources together, on a worldwide scale, to search for that new class of superconductors.”

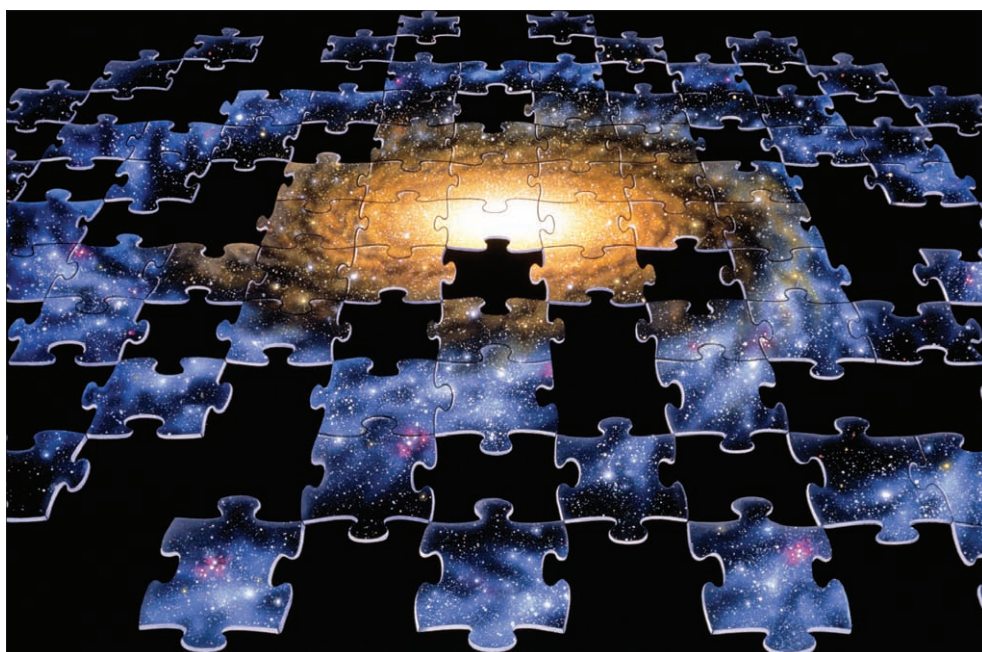
The gauntlet is being taken up with enthusiasm. With communication now flowing between different groups, and across funding and geographical barriers, we hope to soon reveal at last a clarified vision of high-temperature and novel superconductivity that will set us in the best possible stead in the quest for a new class.

It is gratifying to see superconductivity, at 100, finally growing up.

# Reviews

Robert P Crease

## The dark-energy game



Lynette Cook/Science Photo Library

**Puzzling behaviour**  
Finding the missing pieces of the universe.

**The 4% Universe: Dark Matter, Dark Energy, and the Race to Discover the Rest of Reality**  
*Richard Panek*  
2011 One World/  
Houghton Mifflin  
Harcourt £12.99pb/  
\$26.00hb 320pp

The universe is not like a clock, where well-understood parts tick in predictable ways, nor like a balloon expanding or contracting. It is in fact pushing itself apart with a strange kind of energy, and 96% of it is made of an unknown kind of matter. How we discovered this is the subject of *The 4% Universe*, which condenses the complex, messy and startling tale – people, science, instruments, events – into an easily digestible, fast-paced 243 pages. That is a startling achievement in itself. To the connoisseur of popular science, indeed, the way author Richard Panek tells the tale is as interesting as the events: half drama, half detective story.

The prologue begins with a one-page “wow!” moment. On 5 November 2009 scientists at 16 institutions around the world dropped their collective jaws as they seemed to catch a first-ever glimpse of an entirely new structure of the universe. Two pages follow explaining its significance. Referring to the year when Galileo first used the telescope to reveal entire new worlds previously unknown to humankind, Panek writes “It’s 1610 all over again.”

What follows in Act One is the

story of how cosmology went from speculation to science: how astronomers discovered that the furniture of the universe was more than planets and stars, and was on the move to boot. The universe “had a story to tell”, Panek writes. “Instead of a still life, it was a movie,” he says. We learn how scientists uncovered this movie’s plot by peering over the shoulders of Act One’s two main characters: theoretical physicist Jim Peebles, author of the classic textbook *Physical Cosmology* on the physics of the early universe; and astronomer Vera Rubin, whose work on the galaxy-rotation problem pointed the way to the idea that the universe contains some amount of “dark” matter, invisible to present-day instruments.

Act Two introduces more characters and “the game”, in which two different teams of scientists vie to unravel the plot by finding distant “Type 1a” supernovae. The game is played with telescopes equipped with charge-coupled devices, which revolutionized astronomical photography, and with the Hubble Space Telescope, which peered into hitherto invisible corners of the universe, among other equipment. The first team, the Super-

nova Cosmology Project (SCP), was led by Saul Perlmutter and Carl Pennypacker, particle physicists at the Lawrence Berkeley National Laboratory who applied the tools of their trade to astronomy. In doing so, Panek observes, “[T]hey weren’t drifting towards a new discipline. The discipline was drifting towards them.”

The second team was known as High-Z, where Z is a term for redshift. Highly redshifted objects are among the oldest and most distant in the universe, meaning that they would bear the clearest traces of any expansion or contraction. High-Z’s main members were Adam Reiss and Brian Schmidt, who hailed from Harvard University and viewed supernovae as their area of expertise. They saw the Berkeley group as being out to “beat them at their own game”. While SCP had a six-year head start, High-Z recruited the “old-boy network” to, in effect, beat the Berkeley group at beating them at their own game.

In 1997 the two teams converged – simultaneously, yet reluctantly – on two wild, tooth-fairy-like ideas: that the universe contained “dark matter they couldn’t see and [a] new force they couldn’t imagine”. In Act Three, all the main characters introduced so far in the drama gather at a meeting where the SCP’s results (picked up by discerning newspaper reporters) suggest that “SCP was beating [High-Z] at beating the SCP at beating [High-Z] at their own game”. Then High-Z outdid that by securing full credit in the media. The discovery of this new force – soon dubbed “dark energy” – became *Science* magazine’s “breakthrough of the year” in 1998.

The new idea – that the universe’s expansion is accelerating – both simplifies things, by explaining a lot of puzzling data, and makes them more complex, by raising a lot of questions.

In Act Four, SCP and High-Z make plans to hunt for answers to one question – dark matter – while struggling over credit for the other, dark energy. The existing picture of the universe turns “preposterous”. But as Perlmutter remarks on the final page of the book, what usually attracts physicists to their field is “not the desire to understand what we already know but the desire to catch the universe in the act of doing really bizarre things”. And so, at the book’s conclusion, while one chapter in astronomy ends, another begins.



Panek tells the story briskly yet warmly, capturing personalities and not overlooking controversies. He chooses characters carefully. Through Rubin, for instance, we not only learn about dark matter, but also what it is like to be a woman in science, literally balancing child and career: textbook in one hand, pram in the other. Panek also has a knack for summarizing developments concisely and efficiently, such as in the following passage about how astronomy became more specialized over time.

You couldn't just study the heavens anymore; you studied planets, or stars, or galaxies, or the Sun. But you didn't study just stars anymore, either; you studied only the stars that explode. And you didn't study just supernovae; you studied only one type. And you didn't study just Type 1a; you specialized in the mechanism leading to the thermonuclear explosion, or you specialized in what metals the explosion creates, or you specialized in how to use the light

## The book conveys a good picture of scientists catching the universe doing bizarre things

from the explosion to measure the deceleration of the expansion of the universe – how to perform the photometry or do the spectroscopy or write the code.

Inevitably, Panek makes some compromises, and the seams of his crisp storytelling occasionally show. Galileo is mentioned once too often, and Panek's apothegmatic style can ring precious, as in this remark about the signal from a radio antenna: "[T]his time the source wasn't a radio broadcast from the West Coast. It was the birth of the universe." The reader

sometimes feels manipulated, too. That "wow!" moment that kicks things off so dramatically in the prologue? You don't find out until page 197 that it was phoney – not a discovery after all.

Another author might have explored why it initially seemed to be a discovery, why its announcement was hyped even after problems were uncovered, and what this says about science and scientists. But by this time, you are so absorbed in the story that you do not care that much. And the book *does* convey a good picture of scientists in the act of catching the universe doing really bizarre things – while also showing that this is why they took the job. Give this book to your non-scientist friends to show them what it is all about – and to fellow scientists as a model of how to write popular science.

**Robert P Crease** is chairman of the Department of Philosophy, Stony Brook University, and historian at the Brookhaven National Laboratory, US, e-mail rcrease@notes.cc.sunysb.edu

## Web life: STAR-LITE



URL: [www.starlite.nih.gov](http://www.starlite.nih.gov)

### So what is the site about?

STAR-LITE is a game designed to teach basic laboratory safety to researchers at the start of their careers; the name is an acronym of Safe Techniques Advance Research – Laboratory Interactive Training Environment (whew!). To play, you must guide an on-screen avatar through 15 safety-related "quests", helped (and sometimes hindered) by your computer-controlled lab mates. The game is free to download and is available for PCs and Macs.

### What are some of the quests?

After you have designed your avatar (warning: if you try to wear dangly jewellery or flip-flops, you'll get told off), you begin the real game with a tour of the virtual laboratory environment. This includes an

equipment storage room and a tissue-culture area, as well as a large multipurpose lab, library and staff room. Once you complete this orientation, your avatar's next task is a "scavenger hunt", where you must find and identify pieces of lab kit such as fume hoods and centrifuges, as well as warning signs for biohazards, flammable materials and the like. As the game progresses, you come across problems such as broken equipment and chemical spills that you have to deal with safely. One helpful feature is that before you can begin a particular task, your avatar needs to be wearing the correct protective gear. For example, if you try to handle liquid nitrogen with latex gloves instead of insulated ones, your lab mates get annoyed and you lose "health points".

### Who is behind it?

The game was developed by the Division of Occupation Health and Safety within the US National Institutes of Health (NIH) to make safety training fun and engaging. The idea is that by playing an interactive video game, trainees will retain more information than they would if they just listened to a safety officer drone on about improperly stored gas cylinders for an hour and a half. (Not that we speak from personal experience.)

### Who is it aimed at?

High-school students and undergraduates are the

game's main audience, but some quests could also be part of a refresher course for postgraduates or other new lab users. Annoyingly, there are no menus within the game that would allow you to choose which quests to complete, so you cannot skip irrelevant or too-simple ones once you have started playing. However, it is possible to tinker with the game files to delete quests before you begin; see the site's FAQs page for details.

### How useful is it for physicists?

Moderately. As you would expect from an NIH initiative, the game is primarily designed with microbiologists and biochemists in mind. Consequently, a few of the quests – such as operating a centrifuge and disposing of Petri dishes – will probably only interest the biophysicists in *Physics World's* readership. The game environment does include a laser room and a radiation lab, but unfortunately both are "dummy" areas that your avatar is not trained to access. This is a pity, because both the idea and the execution of STAR-LITE are excellent, and if these specialized rooms were made "live" (perhaps as an advanced game level), then it would be a great improvement. That said, the game's designers have obviously tried to be as inclusive as possible, and quests such as storing chemicals, looking up information in material safety data sheets and identifying trip hazards are pretty much universal.

John W Moffat

# Taking the multiverse on faith



PhotoLibrary

**Dial M for multiverse**  
Dreaming of a single theory of everything.

**The Grand Design**  
Stephen Hawking and  
Leonard Mlodinow  
2010 Bantam Press  
£18.99hb 208pp

*The Grand Design* begins with a series of questions: “How can we understand the world in which we find ourselves?”, “How does the universe behave?”, “What is the nature of reality?”, “Where did all this come from?” and “Did the universe need a creator?”. As the book’s authors, Stephen Hawking and Leonard Mlodinow, point out, “almost all of us worry about [these questions] some of the time”, and over the millennia, philosophers have worried about them a great deal. Yet after opening their book with an entertaining history of philosophers’ takes on these fundamental questions, Hawking and Mlodinow go on to state provocatively that philosophy is dead: since philosophers have not kept up with the advances of modern science, it is now scientists who must address these large questions.

Much of the rest of the book is therefore devoted to a description of the authors’ own philosophy, an interpretation of the world that they call “model-dependent realism”. They argue that different models of the universe can be constructed using mathematics and tested experimentally, but that no one model can be claimed as a true description of reality. This idea is not new; indeed, the Irish philosopher and bishop George Berkeley

hinted at it in the 18th century. However, Hawking and Mlodinow take Berkeley’s idea to extremes by claiming that since many models of nature can exist that describe the experimental data equally well, such models are therefore equally valid.

It is important to the argument of the book – which leads eventually to more exotic models such as M-theory and the multiverse – that readers accept the premise of model-dependent realism. However, the history of science shows that the premise of one model being as good and useful as another is not always correct. Paradigms shift because a new model not only fits the current observational data as well as (or better than) an older model, but also makes predictions that fit new data that cannot be explained by the older model. Hawking and Mlodinow’s assertion that “there is no picture- or theory-independent concept of reality” thus flies in the face of one of the basic tenets of the scientific method.

Consider the Ptolemaic model of the solar system, in which the planets move in circular orbits around the Earth, and the heliocentric model put forward by Copernicus. The authors suggest that the two models can be made to fit the astronomical data equally well, but that the heliocentric model is a simpler and more convenient one to use. Yet this does not make them equivalent. New data differentiated them: Galileo’s observation of the phases of Venus, through his telescope, cannot easily be explained in Ptolemy’s Earth-centred system. Similarly, Einstein’s theory of gravity superseded Newton’s laws of gravitation when its equations correctly described Mercury’s anomalous orbit. One theory, one perception of reality, is not just as good as another, and this can be shown empirically: Einstein’s gravity is even used to make corrections to Newton’s in the Global Positioning System.

It is true, however, that the situation in quantum mechanics has not yet been resolved. Several different models, such as the “many worlds” interpretation of Hugh Everett III, the Copenhagen interpretation and certain Bohmian hidden-variable models, all agree with quantum-mechanical experiments, and as yet none of

the interpretations has produced a prediction that would experimentally differentiate them. Based on the history of science, however, we have no reason to assume that in the future there will not be a decisive experiment that will support one model over the others.

A second premise that the reader is expected to accept as *The Grand Design* moves along is that we can, and should, apply quantum physics to the macroscopic world. To support this premise, Hawking and Mlodinow cite Feynman’s probabilistic interpretation of quantum mechanics, which is based on his “sum over histories” of particles. Basic to this interpretation is the idea that a particle can take every possible path connecting two points. Extrapolating hugely, the authors then apply Feynman’s formulation of quantum mechanics to the whole universe: they announce that the universe does not have a single history, but every possible history, each one with its own probability.

This statement effectively wipes out the widely accepted classical model of the large-scale structure of the universe, beginning with the Big Bang. It also leads to the idea that there are many possible, causally disconnected universes, each with its own different physical laws, and we occupy a special one that is compatible with our existence and our ability to observe it. Thus, in one fell swoop the authors embrace both the “multiverse” and the “anthropic principle” – two controversial notions that are more philosophic than scientific, and likely can never be verified or falsified.

Another key component of *The Grand Design* is the quest for the so-called theory of everything. When Hawking became Lucasian Professor of Mathematics at Cambridge University – the chair held by, among others, Newton and Paul Dirac – he gave an inaugural speech claiming that we were close to “the end of physics”. Within 20 years, he said, physicists would succeed in unifying the forces of nature, and unifying general relativity with quantum mechanics. He proposed that this would be achieved through supergravity and its relation, string theory. Only technical problems, he stated, meant that we were not yet able to prove that supergravity



solved the problem of how to make quantum-gravity calculations finite.

But that was in 1979, and Hawking's vision of that theory of everything is still in limbo. Underlying his favoured "supergravity" model is the postulate that, in addition to the known observable elementary particles in particle physics, there exist superpartners, which differ from the known particles by a one-half unit of quantum spin. None of these particles has been detected to date in high-energy accelerator experiments, including those recently carried out at the Large Hadron Collider at CERN. Yet despite this, Hawking has not given up on a theory of everything – or has he?

After an entertaining description of the Standard Model of particle physics and various attempts at unification, Hawking and his co-author conclude that there is indeed a true theory of everything, and its name is "M-theory". Of course, no-one knows what the "M" in M-theory stands for, although "master", "miracle" and "mystery" have been suggested. Nor can anyone convincingly describe M-theory, except that it supposedly exists in 11 dimensions and contains string theory in 10 dimensions. A problem from the outset with this incomplete theory is that one must hide, or compactify, the extra seven dimensions in order to yield the three spatial dimensions and one time dimension that we inhabit. There is a possibly infinite number of ways to perform this technical feat. As a result of this, there is a "landscape" of possible solutions to M-theory,  $10^{500}$  by one count, which for all practical purposes also approaches infinity.

## A key component of the book is the quest for a theory of everything

That near-infinity of solutions might be seen by some as a flaw in M-theory, but Hawking and Mlodinow seize upon this controversial aspect of it to claim that "the physicist's traditional expectation of a single theory of nature is untenable, and there exists no single formulation". Even more dramatically, they state that "the original hope of physicists to produce a single theory explaining the apparent laws of our universe as the unique possible consequence of a few simple assumptions has to be abandoned". Still, the old dream persists, albeit in a modified form. The difference, as Hawking and Mlodinow assert pointedly, is that M-theory is not one theory, but a *network* of many theories.

Apparently unconcerned that theorists have not yet succeeded in explaining M-theory, and that it has not been possible to test it, the authors conclude by declaring that they have formulated a cosmology based on it and on Hawking's idea that the early universe is a 4D sphere without a beginning or an end (the "no-boundary theory"). This cosmology is the "grand design" of the title, and one of its predictions is that gravity causes the universe to create itself spontaneously from nothing. This somehow

explains why we exist. At this point, Hawking and Mlodinow venture into religious controversy, proclaiming that "it is not necessary to invoke God to light the blue touch paper and set the universe going".

Near the end of the book, the authors claim that for a theory of quantum gravity to predict finite quantities, it must possess supersymmetry between the forces and matter. They go on to say that since M-theory is the most general supersymmetric theory of gravity, it is the *only* candidate for a complete theory of the universe. Since there is no other consistent model, then we must be part of the universe described by M-theory. Early in the book, the authors state that an acceptable model of nature must agree with experimental data and make predictions that can be tested. However, none of the claims about their "grand design" – or M-theory or the multiverse – fulfils these demands. This makes the final claim of the book – "If the theory is confirmed by observation, it will be the successful conclusion of a search going back 3000 years" – mere hyperbole. With *The Grand Design*, Hawking has again, as in his inaugural Lucasian Professor speech, made excessive claims for the future of physics, which as before remain to be substantiated.

**John W Moffat** is a member of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, and professor emeritus at the University of Toronto. He is the author of, most recently, *Einstein Wrote Back: My Life in Physics* (2010, Thomas Allen & Son), e-mail john.moffat@utoronto.ca

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## Between the lines

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### Precious

Keeping the Earth safe involves learning from past disasters.

### Apocalypse eventually

The list of disasters that threaten life on Earth is long and varied. The list of books that have been written about such disasters, however, is even longer. With what is, in retrospect, spectacularly bad timing, we picked this month to review a trio of recent books that explores the science of disasters. Of the three, *Armageddon Science: The Science of Mass Destruction* is the most conventional. In it, the science writer Brian Clegg presents a tour of the science and history behind numerous possible doomsday scenarios, ranging from the unlikely (antimatter bombs and planet-eating black holes) to the all too real (climate change). Not all of them are covered in the same depth. For example, tsunamis, earthquakes, asteroid impacts, supervolcano eruptions, alien invasions and irradiation by interstellar gamma-ray bursts are all crammed into a mere 26 pages. In contrast, the chapter on nuclear weapons takes up almost a quarter of the book, and sections on nanotechnology and climate change are also relatively meaty. One reason for this emphasis may be the author's own background: Clegg is a physicist by training, and he seems more at home with physics-related disasters than he does with geological ones. However, as the book's thoughtful introduction and conclusion make clear, Clegg is also primarily interested in disasters that are in some sense *caused* by science, not merely explained by it. Noting that Marie Curie died of radiation-induced leukaemia, he observes that "scientists don't always have a great track record in keeping themselves and others safe". Apparently callous attitudes such as these – which Clegg links, tenuously, to the fact that many scientists exhibit mild symptoms of autism – have a detrimental effect on the way outsiders perceive the scientific community.

● 2010 St Martins Press  
£18.99/\$25.99hb 304pp

### A scientific conspiracy?

Large-scale US government support of scientific research was born in the Second World War. To keep federal dollars flowing in peacetime, scientists have repeatedly spread alarms about natural disasters such as asteroid impacts and climate change – the solutions to which, inevitably, involve more government-funded research. This, at least, is the argument put forward by James Bennett in *The Doomsday Lobby: Hype and Panic from Sputniks, Martians, and Marauding Meteors*. As this synopsis indicates, Bennett, a political scientist at George Mason University in Virginia, is actively hostile to government support of scientific research – or, as he terms it, "the federal appropriation dole". However, readers who are thick-skinned enough to withstand repeated insults will find a few atoms of truth inside Bennett's layers of anti-government ideology. As he points out, state-funded science is not always a benign matter: it has also meant despoiling large swathes of the American West with dams, subsidized mining and weapons testing. Moreover, it is true that in former times, science functioned tolerably well without state support. As Bennett describes in the book's opening chapters, the rise of US astronomy in the early 20th century was funded almost entirely by philanthropists. Yet his privately funded scientific utopia has a fundamental flaw. One of the anecdotes he uses to describe it concerns a 19th-century "Society for the Diffusion of Useful Knowledge", which built itself an observatory after selling more than 300 memberships at \$25 each. That may sound commendably egalitarian, but it is worth noting (as Bennett does not) that when the observatory opened in 1845, \$25 was worth as much to the average person as \$12 300 is today, as measured by per capita GDP. The fact is that before

the late 19th century, scientists were, overwhelmingly, either aristocrats or people who could persuade aristocrats to back them financially. Is that really a better system?

● 2010 Springer £22.99/\$24.95pb 200pp

### Things fall apart

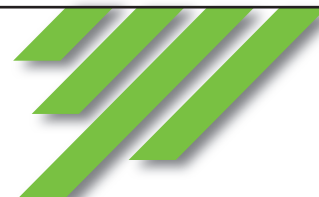
What do the Tay Bridge disaster, a tense family game of Monopoly and the loss of vegetation in the Sahara have in common? According to Bristol University physicist Len Fisher, who uses each of them as examples in his book *Crashes, Crises and Calamities*, they all have something to tell us about "critical transitions", which occur when a system "abruptly, without apparent warning...jump[s] to a very different state". Sometimes, such transitions are obvious, as in the 1879 collapse of the rail bridge across Scotland's Tay estuary, or a player overturning a Monopoly board in frustration. Others, such as desertification, are more subtle, and are preceded by characteristic signs that can – if properly interpreted – alert observers to impending change. The key point, Fisher writes, is that "to anticipate and deal with such disasters, we need to be able to predict the changeover point". His book outlines three overlapping approaches for doing this. One of them, catastrophe theory, classifies transition-prone systems into distinct mathematical types – including one, the "cusp catastrophe", that has variously been used to explain love-hate relationships and the behaviour of cornered dogs. The second approach, computer modelling, is useful for predicting the outcome of complex situations, while the third focuses on early-warning signs such as fluctuations in the population of an animal species. It is all fascinating stuff, even if the threads that bind Fisher's examples together sometimes seem weak.

● 2011 Basic Books £13.99/\$23.95hb 256pp



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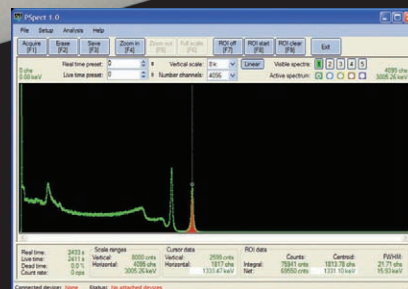
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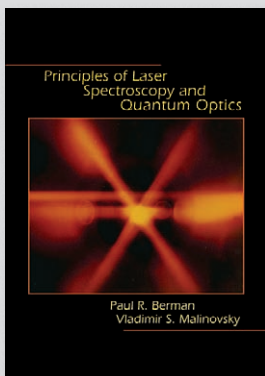


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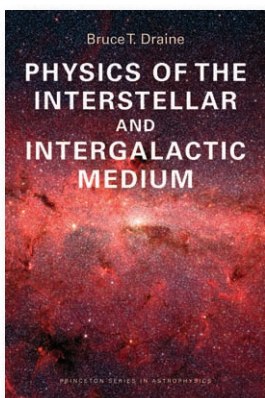


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# Careers

## A super(conducting) career

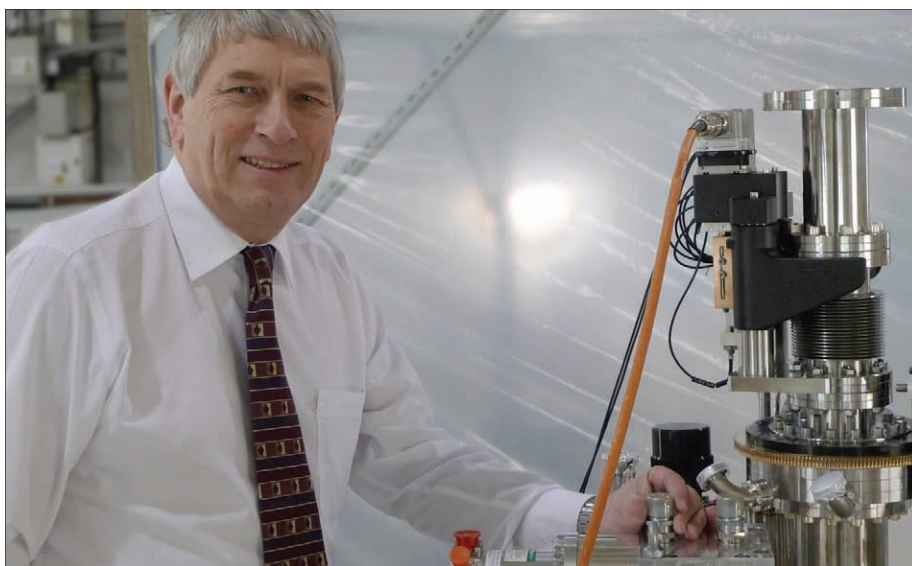
**Joe Brown** explains why he is still enthusiastic about designing and manufacturing superconducting magnets after nearly 40 years in the industry

Shortly after the discovery of superconductivity in 1911, many scientists believed that it would soon be possible to construct electromagnets that could generate high fields without the high power requirements of conventional resistive windings. Those hopes were, however, quickly dashed when it was discovered that the presence of magnetic fields of  $\sim 30$  mT destroyed a material's ability to carry current without resistance. It would be another 25 years before researchers found materials such as  $\text{PbTi}_2$  that retained some ability to carry current without resistance in the presence of a magnetic field, and it was not until the late 1950s and early 1960s that materials such as  $\text{Nb}_3\text{Sn}$  and  $\text{NbTi}$  were developed into forms that would allow superconducting magnets to be manufactured commercially.

One of the first firms to take advantage of these developments was Oxford Instruments, which was formed in 1959 as the first spin-out company from the University of Oxford. Today, superconducting magnets have applications that range from the "big physics" of the Large Hadron Collider through to magnetic resonance imaging (MRI) machines used in medical diagnosis, and producing or maintaining them is still very much a part of Oxford Instruments' activities. As a consultant magnet engineer in the firm's nanoscience division, I am involved at every step of the process, from understanding customers' requirements, through design and manufacture, to delivery, installation and technical support.

### From welder to magnet engineer

My involvement with superconductivity began almost by accident when, in 1972, I applied for a job as a welder at a company in Oxfordshire. I had done my apprenticeship as a fitter/welder at the UK Atomic Energy Research facility in nearby Harwell, and then spent five years developing advanced welding technologies related to nuclear-fuel and medical-isotope containment. During those years, I had also studied applied physics part-time at what was then Oxford Polytechnic (now Oxford Brookes University).



**Magnetic attraction** Joe Brown could not resist the pull of a career in superconductivity.

Perhaps because of this experience, instead of offering me a position as a welder, the company, Thor Cryogenics, asked if I was interested in a role as a superconducting magnet technician – someone responsible for winding and assembling superconducting magnets. I had always been interested in science, and the opportunity to work in a company using superconductivity was very attractive to me, so I said yes.

My role as a magnet technician developed, and by the time I joined Oxford Instruments in 1986 I had moved into project engineering, where I mixed technical activities such as designing magnets and cryogenic systems with project-management work like ensuring equipment was built on time and within commercial constraints. In 1999 I progressed to my current role, which is biased towards the technical aspects of magnet design. However, most magnet engineers do have some project-management responsibilities, and I am also involved in mentoring and training junior colleagues, visiting customer laboratories and speaking at conferences.

My career path has not been a typical one: most of my colleagues who have joined Oxford Instruments in recent years have taken the more academic route of full-time university education to first degree or even PhD level. However, there is little formal training on the specifics of magnet design available, so much of the required knowledge has to be gained "on the job". This means that a good general education to degree level in physics or engineering is adequate as a

foundation because it gives you the information you need to understand the concepts and processes involved in magnet design and construction.

The design process for a superconducting magnet is a marriage of mathematical modelling and engineering. Today, much of the modelling is done via computer programs, most of which have been developed to provide the specific information needed by the magnet designer. There is, however, a large part of magnet design that is based on empirical data that have built up over the years, related to the processes used to build a working magnet. This is where the engineering comes into play, with the need to understand how to work with the materials and structures used in magnet construction.

A good example of the type of magnet I am currently working on is one designed for use in neutron-scattering experiments. This magnet has two windings separated by a gap through which researchers can fire a neutron beam at the sample being studied and observe the resultant scattered neutrons. This type of magnet is known as a "split pair" and several factors make it particularly challenging to design. One is the huge attractive forces between the two halves when the magnet is energized, which can be as high as a few hundred tonnes. Such forces present challenges for the mechanical structure and the interfaces between coils and supporting structure; if the magnet is not designed and manufactured correctly, its performance can degrade over time. The



usual solution is to separate the two halves of the magnet with a series of aluminium alloy rings, which, while sufficiently transparent to neutrons, are strong enough to support the attractive force.

Another design challenge with this type of magnet is that there are trade-offs between the particular geometry of the coils that would minimize the superconductor volume (and hence cost), and geometries that produce the required uniformity of magnetic field over the sample volume. Resolving this problem normally comes down to a compromise depending on the individual circumstances: financial versus technical.

A third consideration is the need for sufficient operating margins in terms of flux density, current density and temperature for the superconducting wires used within the magnet coils. There are also design considerations related to dimensional constraints such as the size of the samples and the neutron-scattering angles. The magnet's overall size, both mechanically and in terms of "magnetic footprint" (stray flux density), can be a prob-

lem in many applications because of restricted access or proximity to other equipment.

When we design magnet structures we do so with the aid of finite-element modelling, where the magnet assembly is computer modelled under its loaded condition to determine stress and strain magnitudes and distributions. This is an iterative process in which the structural components are optimized to provide the required structural integrity. After a magnet has been designed, the next steps are to manufacture and test it. Here, engineers like me are involved at every stage, from defining manufacturing processes and testing strategies to analysing test results and presenting them in the form of operating instructions and manuals.

### Seeing results

With my roots firmly in the practical side, I find my role very satisfying because it means that I get to be involved with the complete process – from the customer's first ideas of what they require to a piece of hardware that allows the experiment to be performed. I also

get a great sense of pride when I read an article or paper detailing the experimental results obtained using a magnet I have designed and helped to manufacture. Most of the magnets we manufacture at Oxford Instruments are for laboratory-based research and tend to be "one-offs" specially designed to suit a particular set of experimental requirements.

When it comes to job satisfaction, I think the fact that I have been in the business for almost 40 years says it all. It has not always been easy because, even after 50 years of superconducting-magnet manufacture, there are still times when a new behaviour of a magnet will catch you out, leading to sleepless nights when you are trying to work out what is going on. However, it is very rewarding, and for anyone looking for a challenging role in a hi-tech industry that is still developing, I cannot think of a better place to be.

**Joe Brown** is a consultant magnet engineer at Oxford Instruments NanoScience, UK, e-mail [joe.brown@oxinst.com](mailto:joe.brown@oxinst.com)

## Once a physicist: Rob Cook



**Rob Cook** is vice-president of advanced technology at Pixar Animation Studios. In 2001 he won an Oscar for "significant advancements to the field of motion-picture rendering" for co-creating the RenderMan animation software

### Why did you decide to study physics?

I became interested in it in high school when I read a book on relativity. I thought it was the most fascinating thing around, and I was hooked.

### How did you get into computer graphics?

After I graduated from Duke University in 1973, I was not sure what I wanted to do. However, I had learned to program computers as part of a lab course, so I found a job at the Digital Equipment Corporation in Massachusetts. There was one person there who was doing computer graphics, but he was actually more interested in medical databases, so I said I would do graphics instead. After I got into it, I thought "This is great, this is what I want to do", so I went to Cornell University to get a Master's in computer graphics.

### How did you get involved in film?

At that time, images that were made using computer graphics looked really artificial, like plastic, and nobody knew why. It turned out that the model they were using for light reflecting off surfaces was just something someone had made up – it was not based on physics at all. So for my thesis, I used a different model that included the

physics of how light reflects off surfaces. The results looked really good: I was able to simulate particular types of materials and really get control over the appearance of the surface. That caught the attention of Lucasfilm, which was just setting up a computer-graphics division, and it hired me.

### What inspired you to develop RenderMan?

When you look around, you notice that most things are not just made of one material such as bronze or ivory. They are more complex than that: they have multiple materials, they are beaten up, they have scratches. We needed to give artists control over those surface appearances, so I worked on something called programmable shading that uses equations to describe how a surface looks, but also builds a framework over them to allow artists to make really complex, rich surfaces. That is at the heart of what we do with RenderMan, and over the last 16 years, every film nominated for visual effects at the Academy Awards has used it.

### How has your training in physics helped you?

Aside from my thesis work, it also helped when we were developing RenderMan. In computer graphics, you have a virtual camera looking at a virtual world, and for special effects you want to match this with live-action footage. But for it to look convincingly real, you have to get the characteristics of your virtual camera to match those of the physical camera. That turns out to be hard for a number of reasons. One is something called "motion blur": when a physical camera takes a picture, it opens the shutter and a certain amount of time goes by before it closes. During that time, things move, and

this causes the image to blur. This blur turns out to be really important for making the motion look smooth, so you have to simulate it in the renderer.

Another thing you have to simulate is the aperture of the lens – the light is not entering the camera in one spot, but all over the lens, and that gives you depth of field. You need to simulate both blur and lens effects, but that means that not only are you integrating the scene around each pixel, you also have to integrate that pixel over time and over the lens and over other things. You end up with this incredibly complex integral, and it turns out that there is a technique in physics called Monte Carlo integration that is perfectly suited to dealing with it.

However, none of this stuff was in the undergraduate curriculum – I had to learn it on my own later. What physics really taught me was how to think about things in a creative and rigorous way. It taught me how to think about hard problems.

### Any advice for today's physics students?

I always advise people to do something they really love because you are likely to be better at it and you are going to spend a lot of time doing it, so it should be something you genuinely enjoy. I think it is a mistake to decide "I'm going to go into this even though I don't really like it that much because I think it's going to be a good career". It is your life, and you want to spend it doing something you love.

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## Careers and people



### Spotlight on: Asoke Nandi

The subject of this month's spotlight is Asoke Nandi, a physicist and engineer at the University of Liverpool, UK, who has recently been awarded a Finland Distinguished Professorship (FiDiPro). Such grants are awarded by the Finnish government to researchers who want to collaborate with colleagues in Finland on specific projects.

Nandi's project will combine theoretical studies of machine learning with experimental research on how written English is pronounced and how the human brain responds to music. The connection between these seemingly unrelated topics, he explains, lies in the ability of computational-intelligence algorithms to discover or "learn" the relationships between a set of parameters. "Let's say you were looking at a series of pictures of human faces and sorting them into faces you like or don't like," Nandi explains. "You might not know why you put a face into a particular group, but a computational-intelligence algorithm can analyse many different parameters and uncover the

underlying relationship between them."

For example, the algorithm might be able to discover that less-preferred faces exhibit subtle asymmetries that humans do not perceive consciously.

The technology needed to support such research has only become available in the past 10–15 years, and Nandi now wants to develop new algorithms that will help computers to uncover pronunciation rules for spoken English, and others that will "teach" computers how to select and classify patterns in brain scans taken while a subject listens to different types of music.

Music is closely linked to human emotion and this link may date back to an early period of evolution, since it seems to cross cultures. Figure out a link between music and brain patterns, Nandi argues, and it might one day be possible to recreate the experience of listening to a symphony by stimulating the appropriate areas of the brain, leaving out the ear entirely.

As for the language-learning side of his project, Nandi believes that a list of English pronunciation rules might help students – particularly those with learning difficulties – to master a language. Part of the reason he was drawn to work in Finland, he says, is

that the country's education system is "very advanced" in the way that it includes students with such difficulties in the classroom, and how it uses the latest research to help teach them.

During his four-year stint as a FiDiPro, Nandi plans to spend his summers in Finland, working with researchers in the departments of information technology, music and psychology at the University of Jyväskylä in central Finland, and with brain-imaging scientists at Aalto University in Helsinki.

### Movers and shakers

Particle physicists **Douglas Bryman** of the University of British Columbia, Canada, **Laurence Littenberg** of the Brookhaven National Laboratory, US, and **AJ Stewart Smith** of Princeton University, US, have won the American Physical Society's W K H Panofsky Prize for their role in the 1997 discovery of a rare form of kaon decay. The trio will share a \$10 000 prize.

Three physicists are among 11 winners of the US Presidential Awards for Excellence in Science, Mathematics and Engineering Mentoring. **Richard Cardenas** of St Mary's University, Texas, **Isaac Crumblly** of Fort Valley State University, Georgia, and **Douglass Henderson** of the University of Wisconsin-Madison each receive \$10 000 to advance their mentoring programmes.

The Royal Astronomical Society has awarded its 2011 Gold Medal for Astronomy to **Richard Ellis** of the California Institute of Technology for his work on cosmology and astronomical instrumentation. **Eberhard Grun** of the University of Colorado received the society's 2011 Gold Medal for Geophysics for research on dust in the solar system.

The American Astronomical Society has awarded its annual Henry Norris Russell Lectureship to **Sandra Faber** of the University of California, Santa Cruz, in recognition of "a lifetime of seminal contributions" to our understanding of galaxy evolution and the distribution of dark matter in the universe.

**Mogens Høgh Jensen** of the Niels Bohr Institute in Copenhagen, Denmark, has won the Gunnar Randers Research Prize from the Norwegian Institute for Energy Technology. Jensen, a biophysicist, received the DKK 100 000 (£11 000) award for his work on complex systems.

Astrophysicist **Saul Perlmutter** of the University of California, Berkeley, and astronomer **Adam Riess** of Johns Hopkins University in Maryland, US, will share the Albert Einstein Society's 2011 Einstein Medal for leading the teams that discovered that the expansion rate of the universe is accelerating.

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### Detector Physicist



UCL invites applications for an immediate opening for a detector physicist funded as a core-physicist on the UCL STFC rolling grant who will have responsibility for the development and construction of detectors for the HEP group. The successful candidate will have in-depth knowledge in detector physics and hands-on experience in developing, building and commissioning modern as well as traditional detector systems used in particle physics (scintillator and gaseous detectors, semi-conductor detectors, cryogenic equipment etc.). Familiarity with detector readout technologies is also expected. Apart from his/her own research work the appointee will liaise closely and manage a team of engineers and technicians involved in detector projects.

Salary will be in the range from £31,905 to £38,594 per annum inclusive of London Allowance.

The closing date for applications is 15 April 2011.

Further details about the position and the application procedure can be found at

[http://www.hep.ucl.ac.uk/positions/detector\\_physicist\\_Mar2011.shtml](http://www.hep.ucl.ac.uk/positions/detector_physicist_Mar2011.shtml).

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As part of this important, internationally-leading activity at The Cockcroft Institute, candidates will also have the opportunity to take advantage of the unique research centres provided at the University of Manchester, including the Dalton Nuclear Institute, Photon Science Institute and the Jodrell Bank Centre for Astrophysics. Applications are invited from Physical and Applied Scientists and Engineers with a PhD degree at the top of their profession seeking an academic career specialising in Particle Accelerator Science and Engineering with a focus on applications to any of the disciplines of

Physics, Energy, Optoelectronics, Photonics, Material, Quantum Electronics, Quantum Optics and various electrical engineering disciplines of sensors, instrumentation and ultrafast signal processing, and electromagnetic modelling. Significant start-up laboratory equipment and infrastructure is expected to be made available to the appointed faculty from the Cockcroft and Photon Science Institutes. The successful candidate will be expected to work synergistically with existing Cockcroft faculty at the University of Manchester.

Candidates are sought with interest in areas such as conception and design of particle colliders, novel light sources and free electron lasers, for fundamental research as well as for developing cost- and energy-efficient photo-voltaic nano-structures towards solar energy, conception and design of high current proton accelerators for fundamental research and towards accelerator-driven subcritical reactors and various applications of proton and photon beams for health, medicine and security. These represent exciting and challenging opportunities for someone wishing to excel and lead a significant contribution to world-wide development of tomorrow's particle accelerator systems for science and society.

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The successful candidate will already have an extensive track record in internationally-leading research in any of the areas of theoretical, computational or experimental particle accelerator, laser and photon beam physics in

any of the following areas: linear and nonlinear charged particle dynamics; collective dynamics of beam and plasma instabilities; microwave, radio-frequency, terahertz and optical sciences and engineering; power engineering; materials science including nanostructures and photo-voltaics; charged particle and optical beam diagnostics and digital electronics, optronics, photonics, sensors and instrumentation. S/he will have a high-impact publication record commensurate with such experience. S/he will also demonstrate proven ability to lecture at postgraduate and undergraduate level at the highest levels of quality and support / encourage taught course and research students. An understanding of current global priorities for particle accelerator science and related applications will be important, together with the ability to contribute to and develop existing taught provision in related areas of curricula with an international dimension.

Active involvement and collaboration with the existing Cockcroft faculty and specialist research areas within the University of Manchester, along with relevant activities particularly with the other partners in the Cockcroft Institute will be encouraged.

**Application forms and further particulars are available from our website**  
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**The closing date for applications is: Tuesday 17 May 2011**

**For further information about the Cockcroft Institute, visit <http://www.cockcroft.ac.uk> or contact Prof. Swapan Chattopadhyay ([swapan@cockcroft.ac.uk](mailto:swapan@cockcroft.ac.uk))**



Mathematical, Physical and Life Sciences Division

Department of Physics

## University Lectureship in Accelerator Science

University of Oxford & STFC Rutherford Appleton  
Laboratory in association with Wolfson College Oxford  
and a

## Departmental Lectureship in Accelerator Science

University of Oxford

The John Adams Institute for Accelerator Science (JAI) in Oxford wants to appoint a University Lecturer in Accelerator Science (permanent academic post) on a joint appointment with STFC's Rutherford Appleton Laboratory, and a Departmental Lecturer in Accelerator Science (a 5-year fixed term appointment). Current projects include novel compact light sources and FELs based on laser-plasma acceleration, linear collider, neutrino factory, the Muon Ionisation Cooling Experiment (MICE), non-scaling Fixed-Field Alternating Gradient accelerators and plasma accelerator diagnostics. Applications are welcome in any area of accelerator science, especially those aligned with the strategic interests of the JAI, for example the development of compact light sources, areas of synergy between laser and plasma physics and accelerator physics, and areas where accelerator science may prove beneficial in technology, energy and medicine. This work involves close international collaboration. Details about the JAI can be found at <http://www.adams-institute.ac.uk>.

## University Lectureship in Accelerator Science, jointly with the STFC Rutherford Appleton Laboratory

**Salary on the scale £42,733 - £57,431**

The appointee will undertake lecturing, research and administration within the JAI and the Department of Physics in Oxford, and will undertake research at the Rutherford Appleton Laboratory. The successful candidate will be offered a supernumerary Fellowship at Wolfson College Oxford; upon completion of a satisfactory review after an initial period of employment (normally five years), a University Lecturer is eligible for reappointment until retiring age.

## Departmental Lectureship in Accelerator Science

**Salary on the scale £29,099 - £39,107**

This is a 5-year fixed-term appointment. The Appointee will undertake lecturing, research and administration within the JAI and the Department of Physics in Oxford.

Informal enquiries about either post may be made to Professor Andrei Seryi, email: [Andrei.Seryi@adams-institute.ac.uk](mailto:Andrei.Seryi@adams-institute.ac.uk), and further particulars are available at <http://www.physics.ox.ac.uk/pp/jobs/JAI-UL-DL-fp.htm>. The deadline for applications is 1st June 2011. Interviews will be held in mid June to early July; candidates should consult the web-site for the exact date and keep this date free in case they are called for interview.

Applicants should submit before the deadline a letter of application setting out how they meet the criteria set out in the further particulars, supported by a curriculum vitae, list of publications, a statement of research interests to Mrs. Sue Geddes, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK, email: [s.geddes@physics.ox.ac.uk](mailto:s.geddes@physics.ox.ac.uk), FAX 0044-1865-273417. In addition, candidates should arrange for the three letters of reference to be sent to Mrs. Sue Geddes by the closing date. Applicants should state whether they wish to be considered for the University Lectureship, Departmental Lectureship or both.

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Appointments will be made at senior academic grades, with the possibility of professorial positions for suitably qualified applicants.

If you are looking to accelerate your research career and think you have what it takes, please make your formal application to the relevant academic unit:

- Electronics and Computer Science:  
Professor Darren Bagnall, email: [dmb@ecs.soton.ac.uk](mailto:dmb@ecs.soton.ac.uk)
- Physics and Astronomy:  
Professor Anne Tropper, email: [act@soton.ac.uk](mailto:act@soton.ac.uk)
- The Optoelectronics Research Centre:  
Professor David Payne, email: [hos@orc.soton.ac.uk](mailto:hos@orc.soton.ac.uk)

Your application must include a full academic CV (including publication record) and a statement outlining the research you envisage doing in the next 10 years, together with your vision of how this area at the University of Southampton will grow under your research leadership.

For more information on the Faculty of Physical and Applied Sciences please visit [www.soton.ac.uk/about/faculties/faculty\\_physical\\_applied\\_sciences.html](http://www.soton.ac.uk/about/faculties/faculty_physical_applied_sciences.html)

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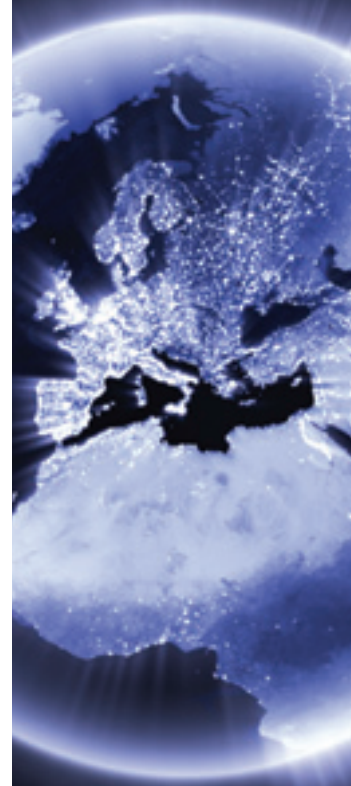
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The lectureship will be based in the Department of Physics as part of the High Energy Physics group in the Cavendish Laboratory. The appointment will consolidate the recent expansion of the group, and is intended to strengthen the group's existing international reputation in particle physics phenomenology (<http://www.hep.phy.cam.ac.uk/theory/>). The successful candidate will have a world-class research record in phenomenology and will be expected to work closely with the Cavendish Laboratory's experimental High Energy Physics group, currently involved in the ATLAS, LHCb and MINOS experiments. The post is part of the Extreme Universe strategic theme of the School of the Physical Sciences, building on existing strengths and collaboration between the Department of Physics, the Institute of Astronomy and DAMTP. The successful candidate will be expected to contribute to teaching and other academic activities in the Cavendish.

Informal enquiries about the post may be addressed to Professor James Stirling ([wjs2@cam.ac.uk](mailto:wjs2@cam.ac.uk)) and further information about the Department may be found at <http://www.phy.cam.ac.uk>.

Further details are available from Ms Leona Hope-Coles ([lh294@cam.ac.uk](mailto:lh294@cam.ac.uk)) to whom applications should be sent by email consisting of a full curriculum vitae, list of publications, a statement (up to 6 pages) of research interests and future plans, and the names and contact details of three academic referees. Applications should be accompanied by a completed CHRIS/6 cover sheet, Parts 1 and 3 only, (see: <http://www.admin.cam.ac.uk/offices/hr/forms/chris6/>) and should be received no later than 20 April 2011.

Please quote reference: KA07953. Closing date: 20 April 2011.

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**If you are an ambitious scientist with an international reputation for excellence in research, please contact Professor Peter Ratoff, Head of Department, on tel: +44 1524 593639 or email: [p.ratoff@lancaster.ac.uk](mailto:p.ratoff@lancaster.ac.uk) or Professor Colin Lambert, Director of the Quantum Technology Centre, on tel: +44 1524 593059 or email [c.lambert@lancaster.ac.uk](mailto:c.lambert@lancaster.ac.uk) for an informal discussion.**

Closing date: 23rd May 2011.

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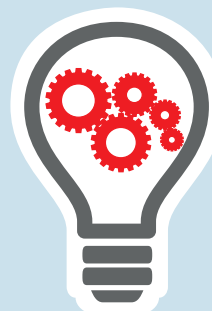
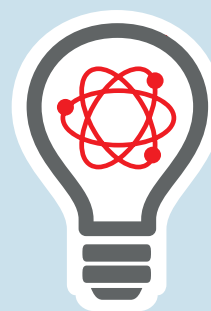
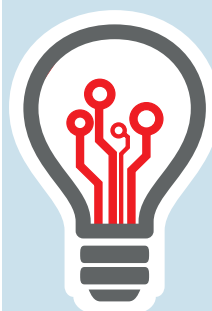
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## Consortium for Construction, Equipment and Exploitation of the Synchrotron Light Laboratory Director position at the ALBA light source

The Consortium CELLS - jointly owned by the Spanish and Catalan Administrations – is responsible for the operation and future development of ALBA, a 3 GeV third generation synchrotron light facility. At present, the construction is finished and the accelerator complex is being commissioned. Seven state of the art beamlines covering a variety of research fields are already installed and expected to be commissioned with photons by mid 2011 and fully open to external users in 2012. Details may be found at [www.cells.es](http://www.cells.es).

ALBA is located in Cerdanyola del Vallès, at some 20 km from Barcelona, in a metropolitan region of about 4.5 million people, a zone of improving scientific and technological level, with several international schools, universities and scientific and technological parks and with very good international communications.

The Consortium is looking for a new Director of the facility. The Director is responsible for the scientific and technical exploitation of ALBA, for the definition of short and long term development strategies and must report to the Governing Bodies of the Consortium (an Executive Commission and a Rector Council whose delegates are appointed by the Owner Administrations).

Candidates must have experience in research institutes or similar facilities, a solid experience with synchrotron light research and have qualifications for Directorship. The working language at Alba is English. Knowledge of Spanish and or Catalan is an asset.

The Director will be offered a full time contract according to the Spanish law. Employment conditions and salaries can take into account the needs of professionals and their families. The incorporation date to the position is expected in January 2012.

Applications should be sent to the Chairman of the Executive Commission of ALBA; Carretera BP 1413 de Cerdanyola a Sant Cugat, km 3.3; E 08290 Cerdanyola del Vallès; Spain. Candidates should send a letter of motivation and their CV to the Chairman of the Executive Commission of ALBA Prof. Ramon Pascual ([pascual@cells.es](mailto:pascual@cells.es)).

Deadline for receiving applications: 15th May 2011.

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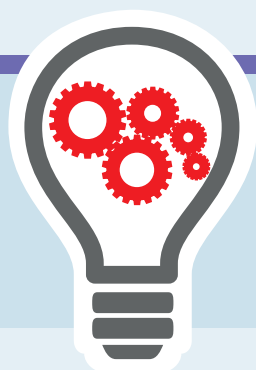
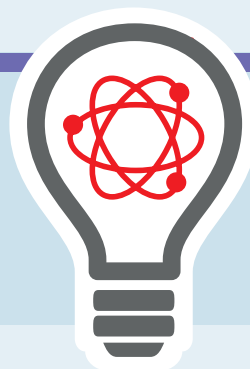


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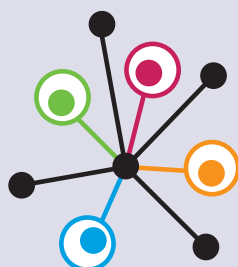
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# Superconductor memories

I can still remember the first time I heard the word superconductor. (A great moniker, by the way, catchy and accurate). We were told in school that some chap Onnes discovered that the electrical resistance of mercury disappeared when cooled to 4.2 K (of course, *why* anyone would be conducting experiments at this sort of temperature was not explained, but he got a Nobel prize for this sort of thing). The news puzzled me greatly: what about Ohm’s law? Didn’t  $I = V/R$  imply that an infinitely large current could arise under such circumstances? Wasn’t that dangerous? From that point on, I thought of Ohm’s law as Ohm’s relation-that-is true-for-some-materials-at-some-temperatures. This was an early lesson in the approximate nature of some physical laws.

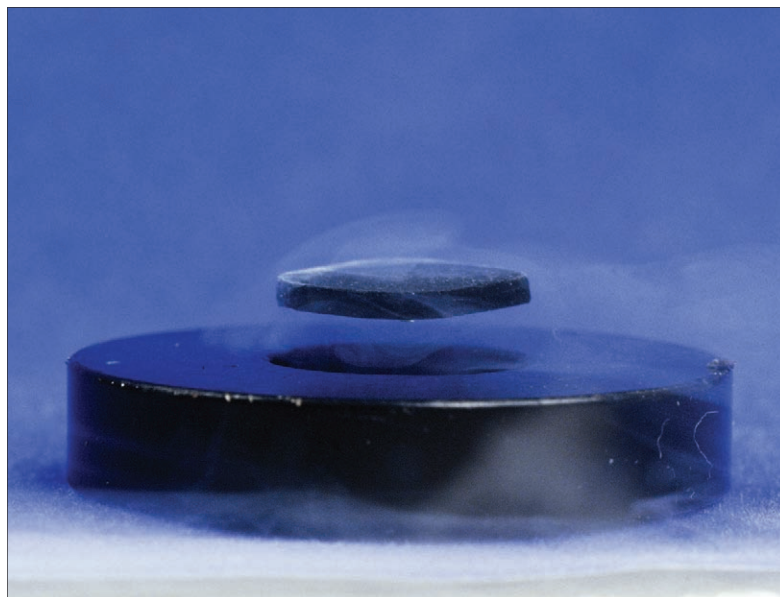
Superconductivity showed up again in my first year at university. This time around, it was even more mysterious. Apparently, a material in superconducting state could repel an external magnetic field, and even levitate a small magnet (another Nobel prize). Clearly, there was something special about these materials; superconductors were not merely super conductors! However, it was not until I was immersed in the horrors of third-year quantum physics that some sort of explanation was forthcoming.

Ah, yes, that business of energy gaps and Cooper pairs; according to the theory of Bardeen, Cooper and Schrieffer (BCS), electrons could get together in pairs and act in concert. Another Nobel prize, but I must confess I didn’t really understand the theory at the time. (It was years later that I realized that the point was that electrons in a superconducting phase can form a condensate not unlike a Bose–Einstein condensate.)

Anyway, the boffins must have got something right; there were plenty of successful applications of superconductor technology already in existence when I was a student in the mid-1980s, from memory devices based on Josephson junctions to sensitive magnetometers utilizing the splendidly named SQUIDs (superconducting quantum interference devices, if you must). Of course, the killer application was the superconducting magnet, a technology ideal for the intense magnetic fields required by high-energy particle accelerators to bend particles into a circular path. And how could anyone forget the Superconducting Super Collider (SSC)? I was still an undergraduate when the SSC was approved; sadly, it was destined never to be built.

Around this same time, along came superconductivity mark 2. I had just started a PhD in semiconductor physics at Trinity College Dublin when suddenly everyone was talking about a brand new phenomenon – the discovery of high-temperature superconductors by Müller and Bednorz (yet another Nobel prize). However, it soon transpired that the correct expression should have been *higher-temperature* superconductors; the new materials had critical temperatures of 30 K, which still called for very specialized experimentation. Another snag was that these materials were not simple compounds but complex ceramics with names such as lanthanum–barium–copper-oxide. (Ceramics? I thought ceramics were insulators.) Such materials necessitated skilled chemists and materials scientists on the team, so my supervisor and I decided to stick with semiconductors.

Still, it was a very exciting time in physics, with research



Takeshi Takahara/Science Photo Library

Superconductors were not merely super conductors

teams around the world cooking up ceramics of every combination and reporting superconductors with ever higher critical temperatures. By 1987 materials with critical temperatures above 77 K had been discovered. Suddenly, superconductivity research was no longer the preserve of the world’s richest labs; experiments could be done using liquid nitrogen as a refrigerant. I remember colleagues in the research group of Mike Coey, an experimentalist at Trinity, making several significant advances.

Intriguingly, it emerged at around this time that good old BCS theory could not account for the new class of superconductors. Indeed, there seemed to be no sign of an underlying explanation. I have a vivid memory of Coey remarking acidly at a public seminar that there seemed to be as many theories as there were theorists. In the absence of a successful theory, brute empirical work forged ahead in a manner the philosopher Ernst Mach would surely have admired.

All in all, it seemed at the time that materials science was truly at the cutting edge of physics. Anything was possible. It was straight into this atmosphere that Pons and Fleischmann dropped their announcement of cold fusion. The story of the cold-fusion controversy has been told many times, but superconductivity is rarely mentioned. Yet I’m convinced it played a role. Physicists had just been shown how little we knew of the solid lattice and nothing was off the table. Indeed, quite a few of my contemporaries were diverted into cold-fusion research for some months.

What is the state of play with superconductivity now? Progress with novel superconducting materials has continued, but the holy grail of this field – a material that exhibits superconductivity at room temperature – remains as elusive as ever. There is also still no sign of a successful theory for the effect, so there is another superconducting Nobel out there for someone...



**Cormac O’Raifeartaigh** lectures in physics at Waterford Institute of Technology in Ireland and is currently a research fellow with the Science, Technology and Society Group at the Kennedy School of Government of Harvard University, US, e-mail coraifeartaigh@wit.ie



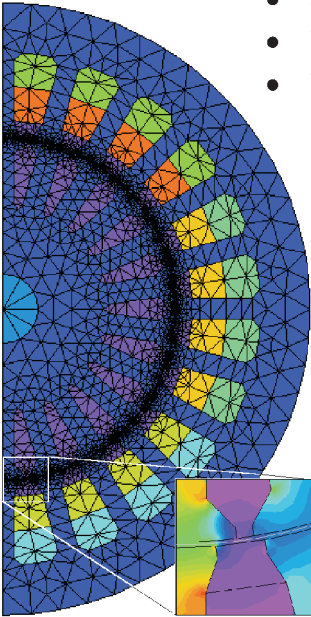


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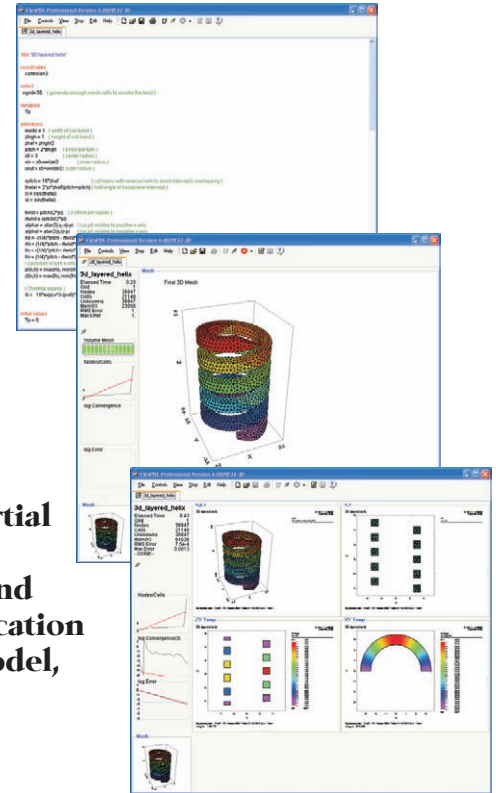
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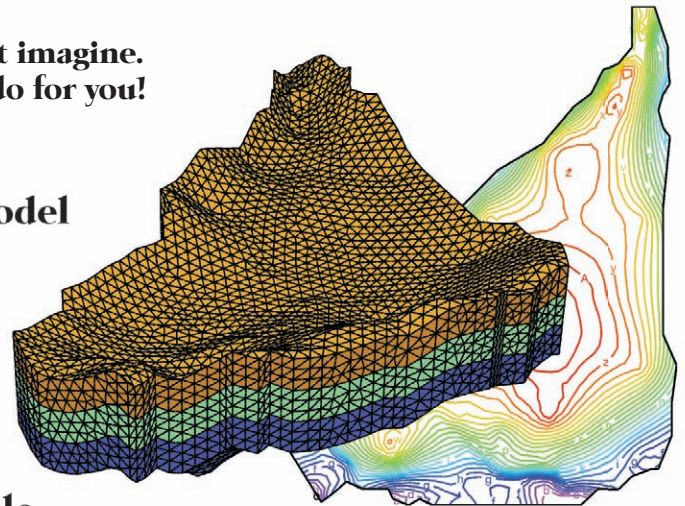
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