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Volume 22 No 7 July 2009

# How physics is changing biology

# XRF Solutions

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## Silicon Drift Detectors
## Si-PIN Detectors
## CdTe-diode Detectors

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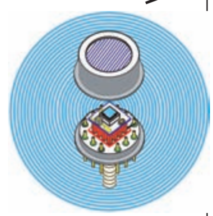

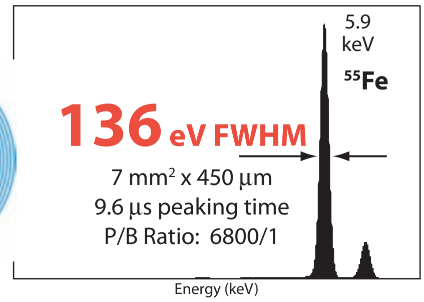


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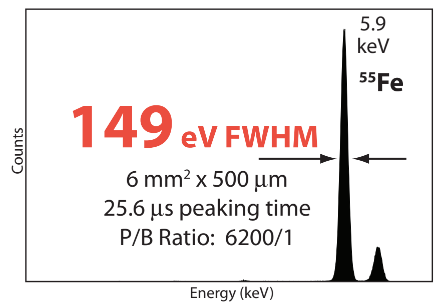
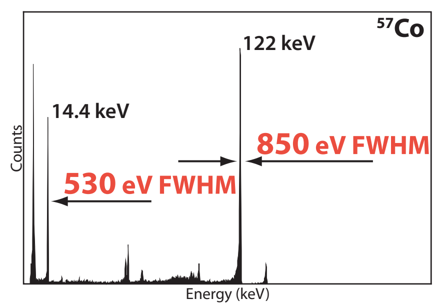



CdTe →

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### APPLICATIONS

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physicsworld

Bill Sanderson/Science Photo Library

Darwin's domain – quantum effects in biology; physics of the cell; brain architecture; new standards for cosmology 22–45



**On the cover**
How physics is changing biology (*Science Photo Library/Photolibrary*) 22–45

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# Quanta

## For the record

**Energy efficiency is not just low-hanging fruit; it is fruit that is lying on the ground**

*US energy secretary* **Steven Chu** *quoted in* The Times

Visiting the UK last month, Chu said that the quickest and easiest way of reducing the world's carbon footprint is through energy efficiency.

**Running the institute is like herding cats. He didn't do it terribly well, but then nobody would**

*Physicist* **Freeman Dyson** *speaking at the Bristol Festival of Ideas*

Dyson was talking about Robert Oppenheimer, who after finishing work on the Manhattan Project was director of the Institute for Advanced Study at Princeton. Oppenheimer brought many of the world's top physicists to the institute, including Dyson.

**I see scientific enlargement mainly in the direction of particle astrophysics**

*CERN director-general* **Rolf-Dieter Heuer** *quoted in* Symmetry

Heuer was commenting on ways of extending the research carried out at CERN.

**The Church never fears the truth of science, because we are convinced that all truth comes from God**

*Vatican City's governor* **Cardinal Giovanni Lajolo** *quoted in* USA Today

A Vatican delegation visited the CERN particle-physics lab last month where it welcomed any breakthroughs physicists would make there.

**I think there was an element of teenage-boy bravado in choosing what was clearly a ridiculously difficult degree**

*Comedian* **Dara O'Briain** *quoted in* New Scientist

O'Briain, who has a degree in mathematical physics from University College Dublin, says that the rush he got from standing in front of an audience and making them laugh made him give up pursuing a physics career and go into comedy.

**When it hit me, it knocked me flying**

*Student* **Gerrit Blank** *quoted in the* Daily Telegraph

Blank was walking to school in Essen, Germany, when a pea-sized meteorite allegedly hit his hand before bouncing off and creating a foot-wide crater in the ground.

## Seen and heard

Louis Vuitton/Annie Leibovitz

### The handbag has landed

Astronauts probably wouldn't use one as their toolbag when in space, but the fashion house Louis Vuitton is running an advertisement campaign for its famous hand and travel bags featuring former astronauts Buzz Aldrin, Jim Lovell and Sally Ride. The advert, which will appear in magazines this month, is being launched to coincide with the 40th anniversary of Neil Armstrong becoming the first man to walk on the Moon on 20 July 1969. The images of the astronauts were taken in the Californian desert and show them sitting on and standing next to an old pick-up truck while looking at the stars with a $1500 Louis Vuitton "Icare" travel bag on the bonnet. Physicists will probably just have to stick with their somewhat cheaper shoulder bag from their last conference.

### Physics has talent

Over 19 million people in the UK watched the final of the TV show *Britain's Got Talent* in late May, but not many of them would have guessed that one of the winners was a physics student. An 11-strong dance group called Diversity stormed to the final and beat the favourite, Scottish singer Susan Boyle. However, the group's leader and choreographer is Ashley Banjo, a second-year physics undergraduate at Queen Mary, University of London. He formed the all-boy troupe group at his mother's street-dance studio in Dagenham in Essex. Even with the chance to perform in front of the Queen at the Royal Variety Performance in November and bagging the £100 000 top prize, Banjo still insists that he will not quit his physics degree. "My parents drummed into me the importance of doing well at school," Banjo told the *Daily Mail* newspaper. "I am not going to be spinning on my head when I'm 50, but as a qualified scientist I can always earn a living."

### Calling the space 'tweedia'

NASA is proving to be surprisingly good at entering the social-networking world. When the Phoenix Mars lander launched in August 2007 it had its own *Facebook* page and its astronauts have recently been posting updates of other missions on the Web. Now, for the launch of the Space Shuttle *Discovery* at the Kennedy Space Centre in Florida next month, NASA will be inviting only those journalists who will use *Twitter* – the website where users can post an answer to the question "What are you doing?" in under 140 characters. These so-called tweedia will consist of about 150 bloggers and journalists who will be at Kennedy's media site and must follow the launch by posting tweets on *Twitter*. NASA is still deciding who to invite and whether it should restrict access only to US citizens. At a conference in Orlando last month, NASA advisor George Whitesides noted that more people follow CNN's tweets than watch the channel during prime-time hours. A sobering thought indeed.


### Who needs the lunar breakdown services?

If your car has ever broken down late at night, then the first port of call is, of course, the breakdown services. Failing that, you can always get your hands dirty and turn to your trusted Haynes manual for help. Haynes publishes owners' manuals for seemingly every make and model of cars, motorcycles and trucks, but to mark the 40th anniversary of the first Moon landing, the company has brought out an owners' manual for the Apollo 11 mission. The manual contains technical illustrations and photographs of the 1969 model, including descriptions of the Saturn V booster rockets as well as the CM-107 command module, the SM-107 service module and the LM-5 lunar module, which took the astronauts to the surface of the Moon and back. The manual also contains "how it works" and "how you fly it" guides that give insights into launch procedures, flying and landing the lunar module and even a guide to walking on the Moon. So if one of the landing legs is a bit stuck, the lunar-module hatch is jammed or the carbon-dioxide filter gets clogged, then who needs the 400 000 people who helped build Apollo 11? Just get your hands on the Haynes manual for only £17.99.

# Frontiers

## In brief

### Data storage enters the fifth dimension

Researchers in Australia have proposed a "5D" data-storage technique that they say could lead to the first terabyte DVDs within five years. Optical discs, such as CDs and DVDs, store data as a spiral track of microscopic pits etched onto their surface. The new disc expands this 3D storage by incorporating gold nanorods, which a laser "reads" as different colours and polarizations depending on their apparent size and orientation. The researchers have created a prototype and achieved a data-storage density of 1.1 terabits per cubic centimetre (*Nature* **459** 410–413).

### Laser boosts light-bulb efficiency

Researchers in the US have discovered that firing a laser at a light-bulb filament provides a novel way of boosting the bulb's efficiency. It involves exposing part of a tungsten filament to a number of 65 femtosecond laser pulses at a wavelength of 800 nm to blacken its surface. This improved efficiency by 25% at 400 nm and 55% at 800 nm (*Phys. Rev. Lett.* **102** 234301).

### MRI guides radiotherapy beam

Researchers in the Netherlands have shown that a radiotherapy photon beam can be guided to a cancer tumour using magnetic resonance imaging (MRI). Using medical imaging in radiotherapy could improve the accuracy of targeting tumours, reduce the irradiation of neighbouring tissue and lessen side effects. The researchers used a prototype device comprising a 6 MV linear accelerator positioned laterally to a 1.5 T MRI system to produce diagnostic-quality images of prostate, brain and kidney tumours. They hope to begin full clinical trials within a year (*Phys. Med. Biol.* **54** N229–N237).

### Flaw revealed in theory of transistor noise

Transistors play an essential role in electronics but these devices can have defects that cause them to fluctuate between their "on" and "off" states. For decades engineers have known that this "random telegraph noise" becomes more pronounced as the size of the transistor decreases. Now, however, physicists in the US and Taiwan have observed this effect in an ultrathin transistor (0.085 × 0.055 μm) and found that at this scale its amplitude becomes significantly greater than standard theory predicts. Unless our understanding of transistor noise is reviewed, then the development of low-power laptops and mobile phones that rely on nanoscale transistors could be hampered, warned the researchers when presenting their findings at a recent industry conference in Texas.

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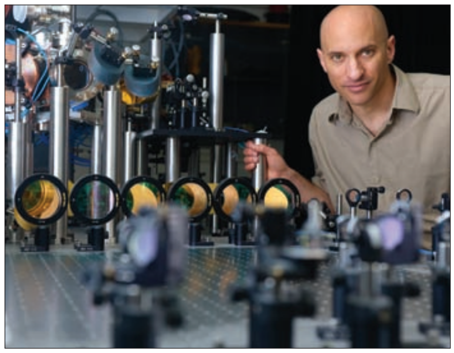
## Black-hole analogue traps sound



Technion – Israel Institute of Technology

**Event horizon** Jeff Steinhauer hopes to detect Hawking radiation in the lab.

Physicists in Israel have created a black-hole analogue that can trap sound in the same way that an astrophysical black hole can trap light. The system, which comprises a "density-inverted Bose–Einstein condensate", may offer one of the best ways yet of detecting elusive Hawking radiation.

In an astrophysical sense, a black hole is a region of space so dense that the gravity at its centre approaches infinity. Surrounding this region is the so-called event horizon, beyond which nothing – not even light – can escape. Although physicists initially believed that black holes could not be detected directly, in the early 1970s Stephen Hawking from Cambridge University suggested that this need not be the case.

Hawking calculated that if a particle–antiparticle pair came into existence straddling the event horizon, then the particle closer to the black hole would fall inwards while the other would escape as Hawking radiation. The problem is that these particles would have less than one-billionth of the energy of the universe's background radiation, and therefore would be very difficult to detect.

Now, Jeff Steinhauer and colleagues at the Technion – Israel Institute of Technology in Haifa have approached the problem in a different way by creating an analogue of a black hole for sound. Using a laser, they set up a Gaussian potential in a bunch of ultracold atoms and then shifted this potential rapidly from side to side so that atoms fell in and climbed out of the potential at a speed faster than sound in the medium, or about 1 $\text{mm s}^{-1}$.

If a sound wave approaches the atoms in the opposite direction to their movement, it will enter a sonic "black hole". Conversely, if the sound wave approaches in the same direction, it will never reach the atoms, in which case the atoms will act as a sonic "white hole". If the temperature of the system can be raised by an order of magnitude, then Hawking radiation may reveal itself as phonons, or packets of sound energy, say the researchers (arXiv:0906.1337).

## New light on axions

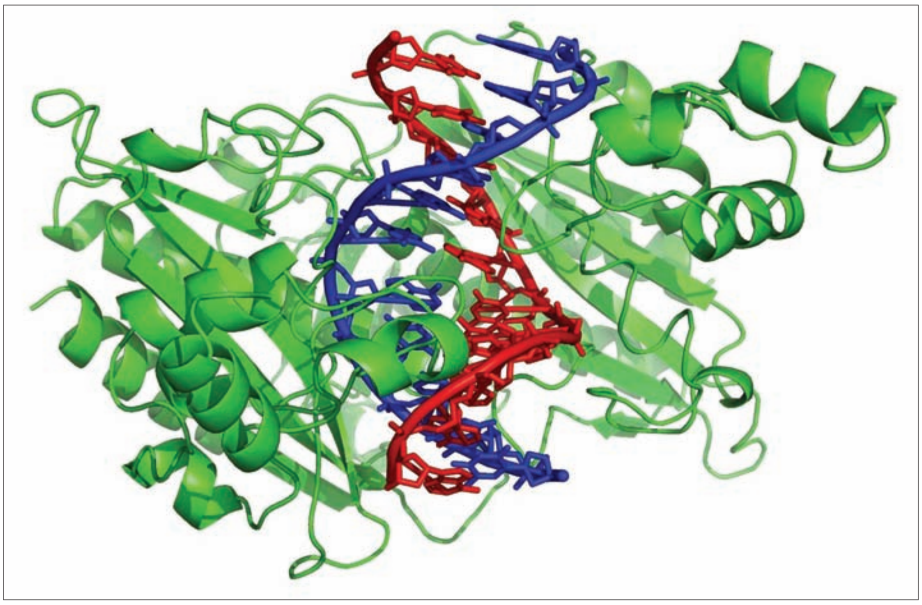
If you think that the weather on Earth is unpredictable, on the Sun it is far more puzzling. For decades scientists have wondered how the Sun's corona – or outer atmosphere – can be so much hotter than its surface. Then there is the question of what powers solar flares, which can shower satellites and astronauts with lethal radiation. Now, a group of physicists at CERN thinks the answer to these puzzles may lie with the "axion", a hypothetical particle first proposed in the late 1970s.

Although axions have never been detected, some physicists think that small electric fields inside the Sun's hot core would convert thermal X-ray photons into these particles, which would then travel outwards. At some point near the Sun's surface, magnetic fields would convert the axions back into X-ray photons, thereby transferring heat from the core to corona, with the most energetic triggering solar flares. However, the Sun is observed to emit X-rays at all angles, whereas they would only be emitted radially if the axions follow a straight path.

Now, Konstantin Zioutas and colleagues at CERN have carried out Monte Carlo computer simulations that suggest that axions could account for these observations after all. The work is based on the idea that some of the X-rays beneath the Sun's surface ionize surrounding matter, before the liberated electrons scatter secondary X-rays in all directions as they lose energy (arXiv:0903.1807). One drawback is that this mechanism could only be satisfied by an axion with a mass in the region of 0.02 eV, which is too light to be detected with current experiments. Zioutas's group has now submitted a proposal for a more sensitive version of CAST – an experiment at CERN that searches for axions leaving the Sun by trying to convert them back into photons in a magnetic field.

The idea, however, has already faced some criticism. "The multiple scattering needed to randomize the directions of the axion-induced X–ray flux destroys the coherence of the process converting axions to X-rays in the first place," says Aaron Chou, a physicist at Fermilab in the US.

Richard Wheeler, Oxford University



## Double helix is an 'electric slide' for proteins

DNA may contain the blueprint for life but for organisms to be built it takes proteins to read it. The image shows a bunch of "DNA-binding proteins" swarming around the iconic double helix because of electric attraction – proteins have a net positive charge and DNA has a net negative charge. Miraculously, these proteins can then bind to exactly the right section of the long, coiling DNA so that they can then carry out vital functions such as copying genetic information and translating genes into templates for protein production. Vincent Dahirel of the Pierre and Marie Curie University in Paris and colleagues have now proposed a physical model for this process using Monte Carlo simulations. The DNA was modelled as a long cylinder and the protein as one of four solids: a sphere, a cylinder, or a cube or cylinder with a groove carved in one side. The researchers find that as the first three protein-shapes approach the DNA, the electric attraction continues unabated. However, in the case of grooved cylinders, the proteins start to be repelled once they get to within 0.1–0.75 nm of the DNA. Dahirel and his team attribute this force to the solution in which these biological molecules are bathed. As the protein approaches the DNA, positively charged ions in the solution become trapped in the gap, thus driving more water into the region as a result of osmosis. If the inward electric attraction is balanced by the outward water pressure, then a protein can slide along the helix until it reaches its target. At this point the hydrogen-bond attraction between DNA and protein overpowers the osmotic barrier and the two bind together (*Phys. Rev. Lett.* **102** 228101).

# Hot dating for old pots

Researchers in the UK have developed a new artefact-dating technique that involves refiring ancient pots and inferring their ages from the amount of steam given off. The researchers, led by Moira Wilson at the University of Manchester, say that the technique could become as important a tool for dating ceramics as carbon dating is for organic materials.

The new method relies on the fact that fired-clay ceramics – like bricks, tiles and pottery – start to combine chemically with water as soon as they are exposed to the atmosphere. This process of "rehydroxylation" is different from absorption, and the researchers calculate that its rate has obeyed a $(\text{time})^{1/4}$ power law throughout history, independent of environmental conditions except ambient temperatures.

The dating procedure involves first measuring the mass of a ceramic then heating it to about 500 °C in a furnace to remove the water. The refired ceramic is then repeatedly weighed using a highly sensitive microbalance in order to determine precisely the rate of water recombination. Once the rate is known, the age of the artefact can be calculated based on the amount of water removed during the heating stage (*Proc. R. Soc. A* 10.1098/rspa.2009.0117).

The researchers used the technique to date a Roman brick, known from historical records to be 2001 years old, to within a year of the correct date. Intriguingly, repeated testing of a medieval brick from Canterbury gave its age as 66 years because the heat generated by incendiary devices and fires during a Second World War blitz had refired the brick and effectively reset its clock.

Wilson told *Physics World* that she and her colleagues are now exploring ways of establishing an international research centre in the UK for rehydroxylation dating.

## Innovation

# Diamond targets *E. coli*

A firm in the US is drawing up plans for a badge-sized, wearable sensor that can detect in real time the presence of *E. coli*, anthrax, salmonella and other biological threats. The sensor, which contains tiny diamond cantilevers, is being developed by Advanced Diamond Technologies (ADT) in Illinois. The company is currently six months into a three-year research programme and hopes to have prototype devices available by the end of 2011, *writes Matin Durrani*.

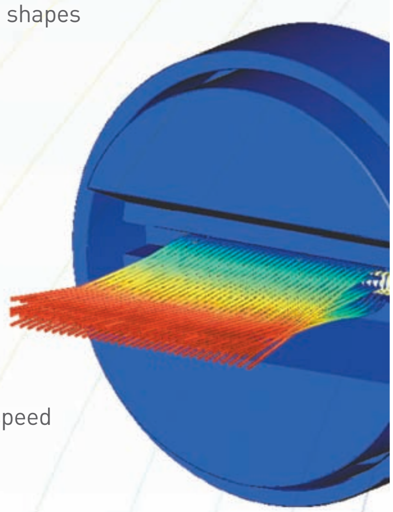
Diamond is well known for being exceptionally hard and a good conductor of heat. But it also has other properties that make it useful as a biosensor. In particular, the surface of diamond is covered with strong hydrogen–carbon bonds, which means that it is stable in water, unlike other sensor materials like silicon. Moreover, the hydrogen atoms can be stripped off and replaced with antibody molecules that can bond, like a lock and key, with a target biomolecule like *E. coli*.

The new device consists of diving-board-shaped cantilevers, each about 100 μm long, mounted on a semiconductor chip. Each diamond cantilever is highly uniform and consists of nanocrystalline grains, each about 2–5 nm in diameter, deposited using chemical-vapour deposition. Any biomolecule landing on the surface of the cantilever changes the device's vibrational frequency, which can be converted into an electrical signal through the piezoelectric response of the cantilever.

To ensure that the signal is strong enough, ADT is planning to incorporate as many as 50 individual cantilevers in each sensor. One challenge will be to concentrate the pathogenic agents so that even tiny amounts can be detected – the initial target is to detect 100 cells in 100 μl of fluid. The sensor could even be used to detect a range of different target molecules by simply attaching different antibodies to each cantilever.

"We want to miniaturize the sensor so that it can be worn as a badge or around the neck," says lead investigator John Carlisle. The final device will also have to communicate its signal wirelessly so that, say, a firefighter wearing the sensor is aware of potentially hazardous conditions in a building and also that information is sent to a centralized response team.

Although the project is being fully funded by a $4.8m contract from the US Defense Threat Reduction Agency, the firm says the sensor could have non-military applications such as determining whether, say, water is safe to drink. Carlisle even wants to adapt the sensor so that it can detect not just water-based biomolecules but those that are air-borne too. "There are very sizeable opportunities," he says.







NIRQUEST
NEAR-INFRARED SPECTROMETER

# News & Analysis

## China opens giant celestial scanner

A telescope that will survey the universe in the finest detail yet was officially opened last month in China and has now begun a 12-month commissioning period. The $34m Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) is the biggest survey telescope of its kind in the world and will study the formation and evolution of galaxies and test fundamental cosmological models.

The optical telescope is located in Hebei province, north east of Beijing, at the Xinglong Station of the National Astronomical Observatories of the Chinese Academy of Sciences. LAMOST has an aperture of 4.3 m and will be able to detect galaxies up to two orders of magnitude fainter than the 2.5 m aperture Sloan Digital Sky Survey (SDSS) in New Mexico.

LAMOST will also be able to obtain the spectra of up to 4000 celestial objects at the same time. The SDSS, in contrast, can obtain just 600 spectra simultaneously. "This is the highest spectrum acquiring rate in the world," says Yaoquan Chu from the University of Science and Technology of China and project scientist of LAMOST.

**Portal to the universe**
The LAMOST facility will obtain the spectra of up to 4000 celestial objects at a time.

Scientists at LAMOST will carry out two major surveys over the next five years and hope to obtain the spectra of over two million stars, two million galaxies and one million quasars. The data, which Chu says will be available to astronomers from around the world, will be used to search for evidence of dark energy and dark matter.

"Among the tens of billions of various celestial objects recorded by imaging surveys, only about tens of thousands of these have been observed using spectroscopic methods," says Chu. "LAMOST will break through this 'bottleneck' of spectroscopic observation in astronomy."

Richard Ellis, an astronomer at the California Institute of Technology who took part in a recent evaluation of the telescope's scientific plans, says that it is a major undertaking for Chinese astronomers. He is impressed by several of the telescope's innovative design elements, such as its ability to change the shape of its mirror automatically, which can, for example, eliminate spherical aberration.

Ellis adds that data from LAMOST will also help the European Space Agency's Gaia space telescope, which will be launched in 2011. Gaia will chart a 3D map of our galaxy, including the position and velocity of over a million stars. "LAMOST will be a very good companion for Gaia as they will both be taking data at around the same time," says Ellis.

**Michael Banks**

**Fusion**

## Cautious ITER chiefs opt for 2026 target

**The redesign and recosting of the ITER fusion project took a step closer to completion last month when the project's council approved a step-by-step approach to construction designed to reduce the risk of something going wrong. Under the new plan, only a stripped-down reactor will be ready in 2018 to produce a plasma of normal hydrogen. Researchers will not attempt to achieve a burning plasma, which requires a fuel of deuterium and tritium, until late 2026 – up to two years later than planned – after further components have been added.**

**"It's a low-risk approach. We're proposing just building the core of the machine to reach first plasma," says David Campbell, ITER's deputy head of fusion science and technology. ITER aims to show that nuclear fusion, which powers the Sun and stars, could be a controllable commercial source of electricity. Researchers spent about 15 years working out a first design for ITER, completed in 2001, before the project's members – China, the European Union, Japan, South Korea, Russia and the US – decided in 2005 to build it in Cadarache in France. The ITER organization was officially created in October 2007, with India on board as the seventh member.**

ITER

**Waiting game**
An artist's impression of the ITER fusion project in Cadarache, France, which will now not try to make a burning plasma until 2026.

**Since then, researchers have been working to update the 2001 design to incorporate recent advances in plasma science and to revise the cost estimate. During the negotiations, the nominal cost of constructing ITER, based on the 2001 design, was €5bn, with a further €5bn needed for 20 years' operation. But the rising cost of building materials such as copper and steel, plus extra components that researchers say are needed to ensure success, are driving up the cost. Nothing has been said officially, but sources suggest it may be anything from a 30% increase to a doubling of the construction cost. ITER staff are working to present details of the redesign, a revised schedule and a new cost estimate to the council when it next meets in November.**

**The reactor produced in 2018 will essentially just comprise the vacuum vessel, the superconducting magnets to hold the plasma in place and the cryogenic system to cool the coils of the magnet. With such a simple machine, it should be easier for researchers to find and fix any problems that may arise. "We want to test everything out at each stage of construction," says Steven Cowley, director of Culham Science Centre, home to the Joint European Torus.**

**Once the basic reactor is working, ITER engineers will add diagnostic instruments, microwave and particle heating systems to bring the plasma up to $1.5 \times 10^8$ K, a metal blanket lining the inner wall of the vessel to absorb neutrons and the diverter to extract helium, the waste fuel from fusion.**

**Daniel Clery**

Medical physics

# Isotope shortage triggers delays for patients

An unplanned shutdown of a nuclear reactor in Canada is disrupting the supply of medical isotopes across North America and forcing some hospitals to cancel or postpone patients' tests. The closure of the National Research Universal (NRU) reactor in Chalk River, Ontario, has also embarrassed Canadian officials, including a senior government minister who was forced to apologize after calling the isotope shortage a "sexy" career challenge.

The NRU reactor normally produces around one-third of the global supply of molybdenum-99, the parent isotope of technetium-99m, which is used extensively for medical imaging. But a leak of heavy water discovered in January forced the reactor's owners, Atomic Energy of Canada Limited (AECL), to close the 51-year-old facility on 14 May, and it is not expected to reopen before mid-August at the earliest. The short half lives of $^{99}$Mo and $^{99m}$Tc – 66 hours and six hours, respectively – mean that neither can be stockpiled.

Hospitals and clinics in Canada quickly felt the consequences of the shortage of $^{99m}$Tc, finding it difficult to schedule scans with isotope supplies in flux, according to Christopher O'Brien, director of nuclear medicine at Brantford General Hospital in Ontario. Since then, the problem has spread beyond Canada: a survey conducted by the US-based Society of Nuclear Medicine in mid-June found that 60% of its members had dealt with the shortage by delaying tests, while 31% had cancelled procedures.


AECL

**Down and out** The National Research Universal nuclear reactor at the Chalk River laboratories has been closed since May.

The other main global producer of $^{99}$Mo – the High Flux Reactor (HFR) in Petten in the Netherlands – has now increased its medical-isotope production by 50% to help ease the supply crisis. However, the HFR will close from mid-July until mid-August for routine maintenance and inspection.

Sites in Belgium, France and South Africa are expected to boost $^{99}$Mo production over the summer, but this is unlikely to plug the shortfall. "We are very concerned still about the situation," says O'Brien.

This is the second time in 18 months that the NRU has been taken offline unexpectedly (see *Physics World* January 2008 p8). Canada had attempted to secure the isotope supply by building two new reactors, MAPLE 1 and 2, at Chalk River to replace the aging NRU, but technical issues led AECL to abandon the project. However, the government has so far rejected calls to re-open the MAPLE reactors, and the long-term future of the country's medical-isotope production appears uncertain after prime minister Stephen Harper announced in mid-June that the government would soon be "out of the business" of making the isotopes.

Harper's comments came a day after national resources minister Lisa Raitt formally apologized for tape-recorded comments in which she expressed doubts about a colleague's ability to handle the shortage, and also called radioactive leaks and cancer a "sexy" issue.

**Paula Gould**

Nuclear power

# Sweden picks site for waste repository

Nuclear power-plant operators in Sweden have selected a site where they can permanently store the country's spent nuclear fuel. The repository would be located 500 m below ground at Forsmark, roughly 200 km north of Stockholm, which is already home to a nuclear power plant. The decision was taken after two decades of study by the Swedish Nuclear Fuel and Waste Management Company (SKB), which is owned by the country's nuclear firms.

SKB will now have to convince regulators, politicians and the public to accept the disposal plan, which would initially involve burying up to 6000 copper containers filled with nuclear waste in crystalline bedrock. Each canister could hold two tonnes of fuel and would be embedded in bentonite clay, which would swell around the canisters to form a waterproof barrier. After disposal, the tunnels and rock caverns would be sealed.

SKB chose Forsmark over a rival site at Oskarsham, where waste is currently held on a temporary basis, because Forsmark "offers rock at the repository level that is dry and has few fractures". The firm intends to submit a detailed construction application by mid-2010 to the Swedish Radiation Safety Authority and the Environmental Court. If approved, construction could begin by 2015 with the repository opening in about 2023. The repository is expected to cost some SwKr 20–25bn (€1.8–2.3bn).

News of the permanent-disposal plans came just months after conservative Prime Minister Fredrik Reinfeldt and his centre-right coalition partners sought to end a nearly 30-year-old ban on construction of new nuclear power plants (*Physics World* March p9). Saida Laârouchi Engström, a SKB spokesperson, told *Physics World* that government officials appear to be supportive of the permanent-disposal plan. "They are happy we have selected a site, happy for progress," she says.

> While the plan is reasonable, the target date of 2023 might be optimistic

Mats Jonsson, a nuclear chemist at the KTH Royal Institute of Technology in Stockholm, thinks that while the SKB plan is reasonable, the target date of 2023 might be optimistic. "My guess is that some additional studies on the barrier integrity will be required before the plan can be approved," he says.

However, Johan Swahn, head of the non-governmental Office for Nuclear Waste Review, opposes the SKB plan, citing a 2007 study indicating that copper could corrode and that the bentonite clay might not be an effective barrier between the nuclear waste and the environment. He believes deep-borehole disposal at depths of 2–5 km could be a better method and that SKB may eventually have to go back to the drawing board.

**Ned Stafford**

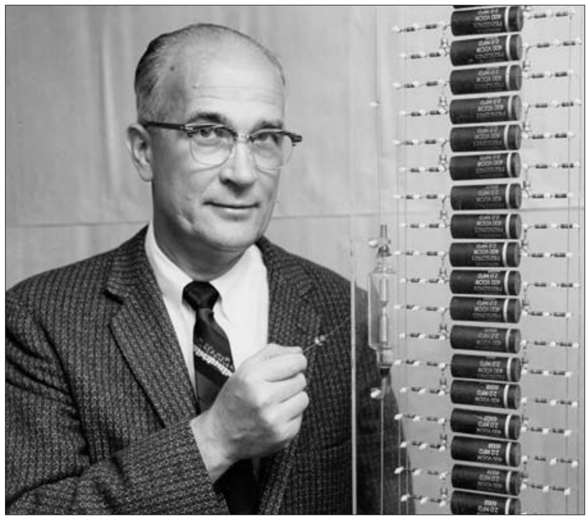
People

# ‘Shockley park’ stirs racism row

A local authority in Northern California has encountered unexpected resistance to its decision to name a park after the Nobel-prize-winning physicist William Shockley, with a coalition of churches and civic groups preparing to petition against the name at a meeting scheduled for 23 July.

The Auburn Recreation District was offered 28 acres of parkland about a year ago from the Shockley estate, on the condition that it named the land “Nobel Laureate William B Shockley and his wife Emmy Shockley Memorial Park”. In March of this year, the district’s board voted three to two to accept the land, which Shockley’s father had originally owned, along with $50 000 to maintain it. The two dissenters were opposed on financial grounds, fearing that upkeep of the park would cost at least $20 000 annually and would require extra staff time.

However, another concern arose soon after the decision. While Shockley shared the 1956 Nobel prize for inventing the transistor, he spent his later scientific life analysing the genetics of intelligence. He advocated eugenics, calling for the voluntary sterilization of people with IQs below 100 and arguing that black populations were inherently less intelligent than white ones. “I think he was a racist in part because of the time he grew up in and in part because he had no contact whatsoever with African-Americans,” says Shockley’s biographer, science writer Joel Shurkin.


Fred English Photographs/AIP Emilio Segrè Visual Archive

**Still controversial** William Shockley.

Shortly after the March vote, some Auburn residents brought that history to the attention of the district’s board. “I didn’t even know about Shockley’s racial views,” recalls board member Scott Holbrook. “I had to reacquaint myself with what eugenics truly meant.” The issue also came to the attention of the Sacramento County chapter of the American Civil Liberties Union (ACLU), which saw it as a matter for action. “Shockley could say anything he wanted to when he was alive – we would defend it,” chapter chair Jim Updegraff told *Physics World*. “Here, it’s a little different. The land is a public area. We’re opposed to a government body accepting a park named after an individual who’s an affront to African-Americans.”

The ACLU chapter sent a letter to the board stating its position. It also joined with the National Association for the Advancement of Colored People and local churches to persuade the board to change its mind. Holbrook, however, is adamant that “we’re not going to do anything” to reverse the March decision.

**Peter Gwynne**
Boston, MA

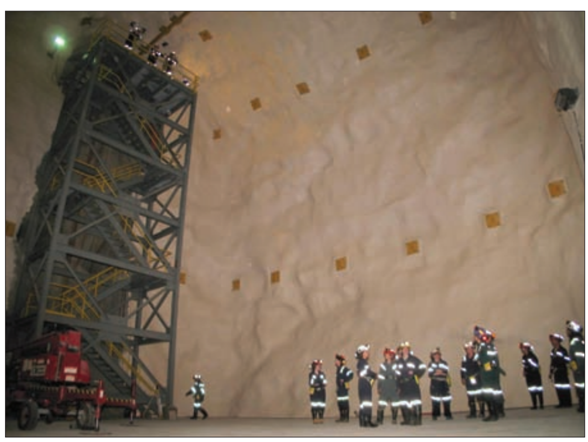
Facilities

# Canadian neutrino lab branches out

**A decade after it opened, the Sudbury Neutrino Observatory Laboratory (SNOLAB) in Ontario, Canada, is undergoing a C$65m facelift, adding two underground chambers that will house four new experiments, including two designed to study dark matter.**

**Excavation for the new chambers – which are located more than 2 km underground and occupy 6300 m$^3$ in total – finished earlier this year. In late June the facility was awarded a C$10.6m grant from the Canada Foundation for Innovation, which will now allow it to activate the already built experiments, worth C$10–15m (£5.5–8.1m) each. Data collection is scheduled to commence by late summer, at the earliest.**

**The laboratory’s expansion will allow researchers to run experiments simultaneously, which was not possible in the old configuration due to a lack of space. The new facilities will include the Polaris Underground Project at SNOLAB (PUPS), which will map out earthquakes in three dimensions; and an experimental neutrino detector, dubbed Mini-CLEAN, which will test the feasibility of using liquid neon to study neutrinos.**


SNOLAB

**Deep underground** The Sudbury Neutrino Observatory Laboratory in Ontario is undergoing a C$65m upgrade.

**The two new dark-matter experiments will employ technology developed in SNOLAB’s existing DEAP-1 experiment, which uses a 1 kg liquid-argon detector to look for weakly interacting massive particles, or WIMPS. These hypothetical particles interact only via the weak nuclear force and gravity, and are a prominent dark-matter candidate. Scientists hope to probe the nature of these WIMPs using the new DEAP-3600’s 3.6 tonne liquid-argon detector to track the rate of radioactive beta decay.**

**The second dark-matter experiment, PICASSO, will use fluorine in its hunt for dark-matter particles. Should one of these elusive particles hit the experiment, it will form a small bubble and an acoustic pulse that will be picked up by electric sensors surrounding the experiment.**

**The challenge for both dark-matter searches will be the relative paucity of results compared with detecting neutrinos, SNOLAB director Tony Noble told *Physics World*. “Typically you expect to see ballpark figures of perhaps as few as one interaction per year in a tonne of material,” he says.**

**During construction, the existing SNO experiment – the source of a major neutrino-physics breakthrough in 2001, when data from its underground detectors confirmed that neutrinos have mass – will continue to operate. Its ongoing mission is to pin down the precise composition of neutrinos that stream towards the Earth from the Sun. The existing experiment will be refurbished. The next-generation project, dubbed SNO+, will study the properties of neutrinos in more detail as well as search for neutrinos from supernovas.**

**Elizabeth Howell**
Ottawa

## Sidebands

**Telescope rises to the Sun**
An observatory to measure the Sun's magnetic field was launched last month at the ESRANGE space centre in Kiruna, Sweden. Built by the Max Planck Institute for Solar System Research in Katlenburg-Lindau, Germany, Sunrise will map the Sun's magnetic fields with a resolution of 35 km. It was taken skywards using a balloon filled with one million cubic metres of helium gas, which will carry it over the northern Atlantic Ocean following the polar winds. Sunrise has on board a 1 m aperture telescope, a polarimeter for high-resolution spectral-line measurements, a visible and ultraviolet camera, and a "magnetograph", which will provide maps of the Sun's magnetic field.

**Sweden bags neutron source**
Sweden will host Europe's next-generation neutron facility that, once built, will be the most powerful source of neutrons in the world. The €1.48bn European Spallation Source (ESS) will cater for thousands of researchers every year in fields ranging from condensed-matter physics to biology. At a meeting of research ministers in Brussels last month to decide the site for the ESS, nine countries including France, Germany and Italy supported Sweden's bid of Lund, while one country, Portugal, supported Spain's bid. Spain will now contribute to the ESS in Lund with a site in Bilbao for testing and manufacturing accelerator components.

**Boost for carbon-capture facility**
US energy secretary Steven Chu has announced plans to revive the $1.3bn FutureGen carbon-capture demonstration plant to be built in Mattoon, Illinois. The Department of Energy (DOE) will provide the facility with $1bn of funding from the recovery and reinvestment bill. Under George W Bush's administration, the DOE pulled the plug on the facility in the 2008 budget, when the costs appeared to have ballooned from $1bn to $1.8bn. That, however, turned out to be a $500m accounting error and it was actually only $300m over budget.

Careers

# Women beat men to faculty positions

**Women have a better chance of being interviewed and hired for faculty positions at US universities than their male colleagues, according to a new report from the National Academy of Sciences. The report, which looks at gender differences in the careers of American scientists, engineers and mathematicians, still finds, however, that far fewer women than men apply for professorships in the US.**

**The report is based on the findings of two surveys sent to 89 US institutions in 2004 and 2005. One survey asked almost 500 departments in six disciplines, including physics, chemistry and engineering, about hiring, tenure and promotion processes, while the other examined the careers of over 1800 faculty members in US universities.**

**The report finds that between 1999 and 2003, on average, just 14% of PhD graduates in physics were women. But despite their low numbers, women have a greater chance of getting permanent tenured positions. The report found that, on average, although women make up only 12% of applicants for tenure-track positions in physics, a fifth of them go on to get offers.**

We have a fundamental problem with our profession in the increasingly long time to tenure

**The report states that even though the number of women in faculty positions is increasing, women are "still underrepresented in many of the disciplines". The report also finds that female full professors are paid on average 8% less than their male counterparts. There was no salary difference at associate- and assistant-professor levels.**

**The report offers no recommendations to further increase the proportion of female professors, but it does say that having a majority of female members on the search committee encourages more women to apply.**

**"Our study suggests that we have a fundamental problem with our profession, namely the increasingly long time to tenure, that is discouraging both men and women from entering academia – it just happens to be worse for women," says Claude Canizares, a physicist at the Massachusetts Institute of Technology, who co-authored the report. "Fixing that will take a lot of work and some time."**

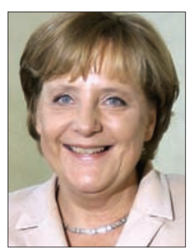
**Michael Banks**

Funding

# Germany unveils €18bn research plan

The German government has unveiled an ambitious plan to inject a total of €18bn into teaching and research over the next decade. The German chancellor Angela Merkel, who has a degree in physics, announced that she was releasing the funds despite concerns from her social-democrat coalition partners that financing the package could be difficult in the economic downturn.

Some €2.7bn of the cash will go towards extending until 2017 the government's "excellence initiative", which began in 2006 to boost research standards at German universities. The initiative, which has so far received €1.9bn, has resulted in nine universities, including those in Heidelberg, Karslruhe and Munich, receiving extra cash. It has also led to the setting up of 40 graduate schools, the creation of 30 "clusters of excellence" that connect research institutes with industry, and the recruitment of an additional 4300 scientists, a quarter of whom are from overseas.



**Bold vision**
Angela Merkel.

A further €7.9bn of the new money will support a second phase of the "higher-education pact" that the German government launched in 2007 to help universities and technical schools recruit more students. The initial plan was to raise numbers by 100 000 between 2005 and 2010, but the new cash will allow a further 150 000 extra students to be taken on by 2019.

The rest of the money – some €7.5bn – will go to Germany's four national scientific institutions: the Fraunhofer Society, the Helmholtz Association, the Leibniz Association and the Max Planck Society. These institutions will receive the money between 2011 and 2015, raising their budgets by 5% each year over that period. "The government has sent a strong signal for education and research in Germany," says the country's science minister Annette Schavan. "We are decisively strengthening the ability of German science to compete on the international stage."

**Michael Banks**

# Deflecting another Tunguska

**Mark Williamson** reports from a recent international conference in Spain that looked at ways to track the paths of asteroids and protect the Earth from these dangerous objects

In October 2008 astronomers in the US discovered an asteroid measuring a few metres across that appeared to be on a collision course for Earth. The astronomers, based at the Catalina Sky Survey near Tucson, Arizona, calculated that it would impact the atmosphere in just 19 hours. Sure enough, the asteroid – named 2008 TC3 – hit the atmosphere over northern Sudan early the next morning, producing what NASA called "a brilliant fireball", with an estimated energy equivalent to a kilotonne of TNT.

The event might sound like a plot for a Hollywood disaster movie, but it was not the first time that the Earth has found itself in the crosshairs of a cosmic shooting gallery. The evidence ranges from the 1200 m diameter Meteor Crater in Arizona and the Tunguska airburst of 1908 that flattened 2000 km$^2$ of Siberian forest to the "K–T extinction event" of some 65 million years ago that is thought to have killed off the dinosaurs.

Such events – and the desire to protect the Earth from their disastrous consequences – have in recent years encouraged scientists to work together to design a system to detect another "killer asteroid", known more formally as a near-Earth object (NEO). Indeed, the biggest complaint of the over 100 scientists and engineers attending the first planetary-defence conference of the International Academy of Astronautics in Granada, Spain, in April was the lack of a functional early-warning system.

Don Davis/NASA

**Deep impact**
Scientists have called for new telescopes to be built that could identify and track the next killer asteroid.

### Detect and destroy

Thankfully there has been progress in detecting NEOs. In 1998 NASA began the Spaceguard Survey, which aimed to find over 90% of NEOs (asteroids and comets) greater than 1 km in diameter. According to Lindley Johnson of NASA's NEO Program Office at the Jet Propulsion Laboratory in California, the survey has already found 856 NEOs, while the count of all near-Earth asteroids has "reached more than 6000". Although it will be difficult to know when the target of 90% of all objects has been reached, Johnson is optimistic. "Five teams with nine telescopes were originally making seven or eight discoveries a month, but now the rate has dropped to two per month," he says. "We believe we have found the better part of the population."

In 2005 NASA upped the ante by starting a programme to detect, track, catalogue and characterize the physical characteristics of NEOs equal to or larger than 140 m in diameter that come to within 195 million kilometres of the Sun. A key objective of the survey is to reach the 90% detection point by 2020, and scientists at the Granada meeting called for investment in new observing facilities to meet this aim.

The two leading contenders for such facilities are the Panoramic Survey Telescope and Rapid Response System (PanSTARRS 4), which comprises four 1.8 m telescopes, and the 8.4 m Large Synoptic Survey Telescope (LSST). According to Don Yeomans, manager of NASA's NEO Office, PanSTARRS 4 is expected to discover at least 600 NEOs larger than 300 m per year. However, the project has yet to be funded, and although the LSST has received some cash from private donors it is not, says Yeomans, nearly enough to bring the system online.

### Size is everything

Detection is only part of the problem, because in this field, size definitely matters. NEO size estimates are based on albedo – the extent to which an object diffusely reflects light from the Sun. According to Marco Delbo from the Côte d'Azur Observatory of the French national research council (CNRS), this can vary by a factor of four, which results in a factor-of-two uncertainty in size and a factor-of-eight uncertainty in the impact energy. That could mean the difference between wiping out a city and wiping out the planet. As conference co-chair Richard Tremayne-Smith, a former head of space environment at the British National Space Centre, puts it, "the error bars on size determination are too large".

Once it is clear that an asteroid is on collision course, deflecting or destroying the object is the next problem

Another key uncertainty is the NEO's trajectory, which governs whether or not it will hit the Earth. This is characterized by the concept of the "keyhole" – a region of space that, as a result of the Earth's gravitational field, changes the course of any asteroid passing through it such that it could then crash into the Earth on its next orbital path. Unfortunately, at least three detections at different times are needed to fix an asteroid's trajectory with any degree of accuracy.

Of the 900 or so NEOs designated "potentially hazardous objects", the best known is Apophis, a 270 m diameter asteroid discovered in 2004. Current predictions show that Apophis will pass below the geostationary orbit (where most communications satellites operate) in April 2029. It will then return in 2036 when the probability of an impact is estimated at 1 in 45 000 (see "The threat from above" *Physics World* March 2006 pp27–29). Not worth losing sleep over, perhaps, but in the words of former Apollo astronaut Rusty Schweikart, who heads the B612 Foundation calling for asteroid-deflection techniques by 2015, "for every Apophis, there are more than 50 Tunguskas!".

Once it is clear that an asteroid is on collision course, deflecting or destroying the object is the next problem. A range of different deflection mechanisms have been proposed, from attaching a "low-thrust" craft to the NEO that nudges it away slowly from its trajectory to detonating a nuclear bomb – known euphemistically as a "physics package" – some way from the asteroid, which would either deflect or destroy the body depending on its composition.

Then there are sensitive political questions, such as which way to deflect the asteroid. While it might make sense to save, say, New York by moving it eastwards away from the Earth, what happens if the deflection system falls short and retargets the body towards China, Russia or Iran? With all these uncertainties, it is obvious why an accurate tracking system is so essential.

# Intel turns to photonics to extend Moore's law

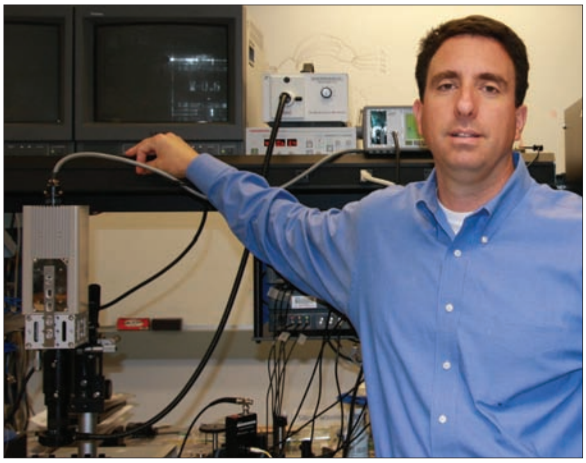
Intel's photonics lab is showing how optics may one day preserve the pace of computer-chip speeds by avoiding the fundamental limitations of electronics. **Breck Hitz** talks to lab director Mario Paniccia

Mario Paniccia settles into his chair with an air of confidence that comes from having been right all along. "We have done all the things that sceptics said we could not," he says. Paniccia, who is director of Intel's Photonics Technology Laboratory in Santa Clara, California, ticks off his group's accomplishments: silicon lasers; high-speed silicon modulators; fast, sensitive silicon photodetectors in the infrared. "We have got beyond the proof-of-principle stage," he says. "Now we're putting it all together so that Moore's law can extend for decades into the future."

Moore's law is the prediction made in 1965 by Intel's co-founder Gordon Moore that the number of transistors in an integrated circuit would double approximately every two years. That prediction has proven breathtakingly accurate during the past four decades. However, as circuits get smaller, scientists and engineers are beginning to see difficulties, such as heat dissipation and current leakage, which affect the ability of electronic circuits to carry information from one place to another fast enough to keep pace with Moore's law. Substituting photons for electrons, however, is one promising way around these limitations.

But not everything is plain sailing. The electronics industry uses mainly silicon, which is not the material found in photonic devices. To combine photonics efficiently with electronics, photonics somehow has to be made to work with silicon. The problem is that silicon is a poor candidate for photonic applications as its electronic structure has an "indirect band gap" making it an extremely poor light emitter. This means that when an electron and hole combine in silicon, the resulting energy released is much more likely to be emitted as vibrational energy, or phonons, rather than a photon.

Less than a decade ago, Paniccia and his group set out to overcome such drawbacks. They identified a number of technologies that must first be developed and put together before so-called silicon photonics can become practical and take Moore's law beyond just the realm of electronics. Paniccia identified three main components that would make up a silicon photonic chip.



Intel

**Focused mind** Mario Paniccia aims to turn silicon photonics into a practical reality.

First, a silicon-based laser would be needed to produce light at a determined wavelength. The light would then be encoded into a "0" or "1" with a silicon modulator and then, at the other end of the link, the state of the light would need to be read-out with a silicon-based detector.

### Photonic building blocks

In the quest for a silicon laser, researchers have tried to overcome silicon's band-gap disadvantage by putting impurities such as neodymium into the silicon lattice that could function as a laser. Those attempts ultimately proved unsuccessful. But in 2004 Bahram Jalali and colleagues at University of California, Los Angeles (UCLA) demonstrated the world's first successful silicon laser without the need for doping.

Jalali's device was a Raman laser, which has the advantage that it has nothing to do with a semiconductor's band gap, but instead is based on phonon scattering in a material. An incoming light beam is scattered from the silicon lattice so that part of the photon's energy is absorbed by the lattice and the scattered photon is shifted down in frequency. If the effect is sufficiently intense, the emitted beam has all the characteristics – spatial and temporal coherence, and monochromaticity – of stimulated emission.

All the parts have been proven to work. Now it's just a matter of putting them all together

However, to avoid significant losses, the laser developed by Jalali had to operate in a relatively slow pulsed mode. To transmit data at the gigahertz rates desired, it is necessary to start with a continuous-wave laser and modulate the photons externally. A few months after Jalali created his laser, Paniccia's group announced the first continuous-wave Raman-based silicon laser. The problem was that this laser still needed another laser to provide the incoming photons.

In 2006, however, Paniccia's group announced it had built a laser that required no optical input. This so-called hybrid silicon laser was built by fabricating an indium-phosphide junction directly on top of a silicon waveguide, so that photons generated in the junction were coupled into the waveguide. Gratings etched onto this waveguide then determined the precise wavelength emitted by the laser. "This was what everyone had been seeking," Paniccia says. "It was an electrically pumped laser that could be directly assembled into a silicon chip, and that could be produced cheaply in large quantities."

### Full-speed ahead

Silicon modulators pose another perplexing problem. For decades, the electro-optic effect – a change in a material's refractive index in response to an applied electric field – has been the keystone of optical-modulation techniques. Here, the applied field alters the material's birefringence so that it rotates the polarization of light passing through it, and a polarizer downstream converts the polarization rotation into amplitude modulation.

But silicon has virtually no electro-optic effect, so Paniccia's group had to devise another solution. The researchers got around this by fabricating a silicon junction across both arms of a "Mach–Zehnder" interferometer. When a voltage is applied to the junction, electrons and holes are created in the junction, which changes the silicon's refractive index. The intensity of the light transmitted through the interferometer is then modulated by changing the phase difference between the interferometer's two arms. In 2007 Paniccia's group achieved amplitude modulation at speeds up to 40 Gbps – similar to that in non-silicon-based modulators.

The final difficulty in creating an all-silicon photonic circuit is getting the silicon to act as a detector that can convert the optical signal into an electrical one. Paniccia and his group solved this problem by growing a thin layer of germanium onto the silicon so that when the photons travel down the silicon waveguide, a part of the signal would "evanescently" couple into the germanium. This creates an electron–hole pair in the germanium and thus an electrical current.

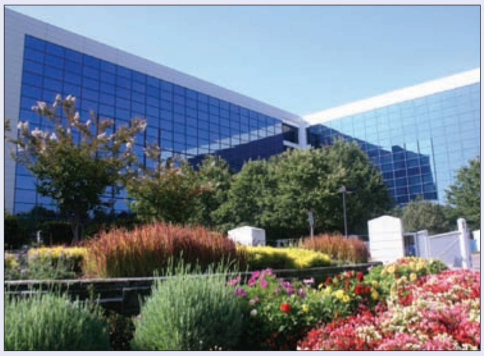
Several months ago Paniccia's group made an even better detector, which produced a stronger electrical signal (*Nature Photonics* **3** 59). This so-called silicon-based avalanche photodetector (APD) uses photons to create electron–hole pairs in a thin germanium layer. The electrons then hit other electrons that are free in a silicon "amplification region", thus triggering a chain reaction that frees ever more electrons. Eventually, this process can increase the number of carriers by a factor of 10 to 100. "This increase in detector sensitivity translates to a reduced need for transmitter power, or greater transmission distances, or other significant system advantages," Paniccia says.

The final challenge is packaging all these components together into a photonic-based circuit. Today's photonic devices, such as CD players, DVDs and fibre-optic telecommunication, must be manually assembled and aligned, which account for more than a third of the cost of photonic equipment . For photonic chips to be economically viable, the assembly and alignment must be automatic. Paniccia and his colleagues are currently developing automatic alignment methods by machining tiny bumps and grooves into the silicon.

With all the basic technologies that Paniccia defined years ago now under control, his group is moving away from demonstrating components towards putting them together into a single chip capable of transmitting a terabit ($10^{12}$ bits) of information per second. "There is nothing sacred about a terabit," Paniccia says. "It is just a stake we have put into the ground for the time being." Intel's scientists may even have higher data rates in the backs of their minds.

So what might a terabit photonic chip look like? Paniccia envisions 25 of his hybrid silicon lasers on a single chip, each at a slightly different wavelength and each modulated at 40 Gbps. A silicon multiplexer would then combine all 25 signals into a single optical fibre. At the other end of the fibre, another chip would have 25 detectors to convert the optical signal back to an electronic one. "All the parts have been proven to work," Paniccia says. "Now it's just a matter of putting them all together."

## Leading light



Intel

Mario Paniccia is based at Intel's Santa Clara Research Center in California. Founded in 1990, it now has over 200 researchers who work on wireless technology, computer architectures and photonic technology. Paniccia, 42, is director of the centre's photonics technology laboratory, which was set up in 2000 and employs about 20 scientists. The lab's main focus is to show that photonics could one day be used in today's standard electronic devises while offering greatly enhanced computer-chip speeds. Paniccia's group is not only interested in building silicon lasers, modulators and detectors (see main text), but is also developing manufacturing techniques for silicon photonics, creating silicon waveguides and integrating electronics and photonics architectures. *Scientific American* named Paniccia one of 2004's top 50 researchers for his work in the area of silicon photonics and in October 2008 he was named by *R&D Magazine* as "Scientist of the Year". He earned a BSc in physics in 1988 from the State University of New York at Binghamton before receiving a PhD in solid-state physics from Purdue University in 1994. He joined Intel the following year as a lead researcher developing optical-testing technology for probing transistor timings in microprocessors, which has led to technology that is now the industry standard. While at Intel, Paniccia has secured over 67 patents that have been issued or are currently pending.
**Michael Banks**

## Game simulates destruction according to the laws of physics

Volition

Video-game enthusiasts who are usually disappointed by unrealistic physical effects should be delighted with a new game that claims to take into account the actual mass and density of buildings for the first time. In *Red Faction: Guerrilla*, released last month, players take control of miner Alec Mason, who belongs to a guerrilla movement trying to take back Mars from the occupying "Earth Defence Force", the members of which want to use the red planet's resources all for themselves. The game has been developed by the US-based firm Volition, which claims to have built "the most realistic physics-based engine" for the game's more destructive elements. So when players start damaging walls, supports and other parts of a building, they see and hear the structure failing exactly as it would in real life. "The destruction in the game cannot be described as 'game like'," says Dave Baranec, the games-systems architect at Volition. "It is more like virtual reality because of the degree to which we are modelling the real physics."
**Michael Banks**

# Comment

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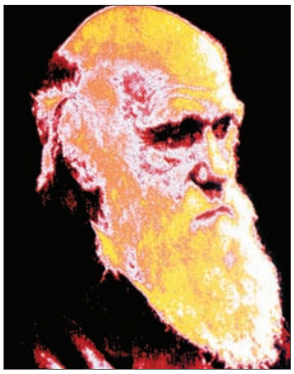
# In praise of Darwin

**Darwin was no physicist, but his approach to science will be familiar to us**

Charles Darwin, who was born 200 years ago, is rightly being celebrated as the founding father of modern biology with a series of events around the world this year. Just as Einstein revolutionized physics, so Darwin changed our understanding of life. He came to realize that "natural selection" could account for the huge diversity of life, with more-efficient groups – arising from random variation – always replacing less-efficient groups in a particular environment as a result of competition. After publishing his seminal book *On the Origin of Species* in 1859 – exactly 150 years ago – Darwin, like Einstein, became the most noted scientist of his time.



Pasieka/Science Photo Library

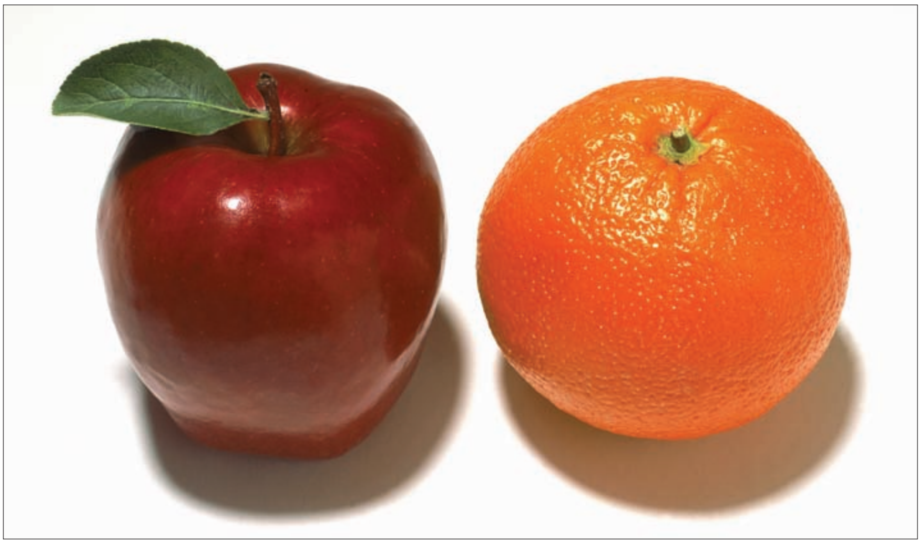
But Darwin was no physicist and *Physics World* is not the place for an in-depth analysis of his achievements. Indeed, he had no particular interest in physics – or astronomy for that matter. Darwin did, however, approach science in a way that will be familiar to many physicists. As a result of spending five years on board the HMS *Beagle* from 1831 to 1836, he painstakingly obtained a welter of information about animals – notably different finches – on the Galápagos Islands off the coast of Ecuador. Darwin's resulting theory of evolution, although not in any way mathematical, was based squarely on firm scientific evidence and careful thought. And like any good physicist, Darwin acknowledged the theory's limitations – he could not, for example, explain exactly why natural selection came about – and was in no doubt that future observations could overturn it. As it turns out, evolution has stood the test of time and is today a thriving field of study in biology.

But while Darwin himself had no formal links with physics, there have been many fruitful collaborations between physicists and biologists over the years – most famously in elucidating the structure of DNA and in developing techniques for medical imaging. Less successful has been physicists' long-cherished hope that quantum mechanics could offer a new framework for understanding living systems. As Paul Davies reminds us in opening this special issue, Erwin Schrödinger published his famous book *What is Life?* as far back as 1944. But although no clear "quantum life principle" has yet emerged, there is, Davies argues, clear and accumulating evidence that quantum mechanics plays a key role in biology (p24). Elsewhere in this issue, Jochen Guck shows how physics is needed to explain, for example, how light passes through the "glial" cells on the way to the retina (p31), while Sam Wang looks at how physicists are helping to understand how the brain is wired and processes information (p37).

Ironically for someone with little interest in physics, Darwin's ideas of reproduction and natural selection actually crop up in some areas of modern physics. In particular, the theorist Lee Smolin has suggested that a collapsing black hole can give birth to another universe with slightly different fundamental constants, with the universe geared so that the production of black holes is maximized. Whether those Darwinian ideas play a role in cosmology or not, Darwin's greatest legacy for physics is that in rejecting the need for a supernatural explanation for life and the universe, he – as Leonard Susskind concludes this issue (p42) – set the standard for what any explanation of nature should be like.

# How physics can inspire biology

**Alexei Kornyshev** thinks that physicists and biologists are now working more closely together than ever before, but that barriers to closer collaboration still exist



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**The same but different** Physicists and biologists need to learn to better understand one another.

In July 1997 Adrian Parsegian, a biophysicist at the National Institutes of Health in the US and a former president of the Biophysical Society, published an article in *Physics Today* in which he outlined his thoughts about the main obstacles to a happy marriage between physics and biology. Parsegian started his article with a joke about a physicist talking to his biology-trained friend.

Physicist: "I want to study the brain. Tell me something helpful."
Biologist: "Well, first of all, the brain has two sides."
Physicist: "Stop! You've told me too much!"

Parsegian went on to list a few areas in biology where input from physicists is particularly welcome. But his main conclusion was that physicists must really learn biology before trying to contribute to the field. He also warned that it may not even be enough for a physicist to have a biologist friend to act as an "interpreter" to translate a problem into the language of physics.

Despite being gentle and elegantly written, the article provoked a stormy reaction from Robert Austin, a physicist at Princeton University, who accused Parsegian of forbidding physicists from tackling the big questions in biology. My view lies somewhere between those of Parsegian and Austin, and, in my opinion, the relationship between physicists and biologists has improved on some fronts in the 12 years since Parsegian's article first appeared. However, I believe that those relationships are still being poisoned by a number of misguided beliefs that are preventing physicists and biologists from working closer together.

### More than beliefs?

Back in the early 1970s, when I was a first-year PhD student at the Frumkin Institute in Moscow, I used to attend theoretical seminars chaired by Benjamin Levich – a former pupil of Lev Landau – who was widely regarded as the founding father of physical-chemical hydrodynamics. Whenever an overly enthusiastic speaker would tell us with 100% confidence how, say, electrons and atoms behave in a solvent near an electrode, Levich would spice up the seminar by joking "How do you know? Have you been there?"

Almost four decades on, physicists now have plenty of experimental tools to "go there". For example, modern X-ray synchrotron sources allow researchers to look at how crystals form, to discover how biological samples mutate and even to pinpoint where ions adsorb on DNA; while techniques such as the fluorescence imaging with nanometre accuracy (FIONA) allow the motion of proteins such as myosin or actin to be traced in real time. But although these techniques often produce fascinating results, they may not be enough without a deep theoretical analysis of what one is actually "seeing". So, the first of these misconceptions is that "seeing is believing". A pretty picture may have a beguiling charm, but on its own it is not enough.

The second belief hampering collaboration is that the formalism of a biological theory must be simple – it should not contain more than exponential functions and logarithms (no Bessel functions, please!). Otherwise, the job should be left for computers to do. This point of view was advocated by Rob Philips of the California Institute of Technology, who came to his new love – biology – from solid-state theory. I strongly disagree with that view, however, and I used to argue with him about it when we were both on sabbatical at the Kavli Institute for Theoretical Physics in Santa Barbara. As I used to point out, James Watson and Francis Crick could never have deciphered the structure of DNA from the X-ray scattering patterns obtained by Rosalind Franklin and Maurice Wilkins had they not had the mathematical tools developed by Crick, William Cochran and Vladimir Vand a year earlier (1952 *Acta. Crystollograph.* **5** 581). Indeed, Bessel functions were at the heart of that analysis.

The third belief is that biologists will never read scientific papers containing mathematical formulas. As Don Roy Forsdyke, a biochemist at Queen's University in Ontario, Canada, once told to me, "The biological literature is vast. Biologists have too many papers to read and too many experiments to make. They will leave aside any reading that looks difficult." If this is true, and I think it is, physicists are in big trouble.

This brings us neatly to the next belief, which is that it is impossible for physicists to publish a serious theoretical paper in a biological journal. Theorists need mathematical derivations to validate their findings, but any paper containing derivations will be rejected. If you then publish the article in a physics journal, it will not be read by those to whom it is addressed. Actually, good papers of that kind are still sometimes published and read, but this remains a difficult issue.

### DNA revolution

Physicists want to simplify and unify things, as much as possible, whereas biologists resist the reductionist approach and are happy with diversification and complexity. So, the biologists' fifth belief is that physicists are too ignorant about diversity to offer them anything useful. Biologists admit that physicists can provide, say, a new spectroscopic technique or apparatus for measuring forces, but that is about it. In their view, biology should be left to the professionals.

The final belief is that biologists think physicists made one big breakthrough – elucidating the structure and function of DNA – but that a similar revolution is unlikely to ever happen again. However, the key to that discovery was the "chemistry" between Watson (a biologist) and Crick (a physicist), which helped them to find a common language and gave rise to the idea of DNA replication and the subsequent principles of molecular biology.

I believe that we can expect other breakthroughs of this sort because physics and mathematics have a long history of revolutionizing not only science but our lives too.

### Meaningful collaborations

In spite of all this, my feeling is that physicists and biologists are getting on better. For example, last month, together with Parsegian and Wilma Olson of Rutgers University, who is another former president of the Biophysical Society, I organized a conference entitled "From DNA-Inspired Physics to Physics-Inspired Biology". Attended by some 140 researchers, the meeting was held at the International Centre for Theoretical Physics (ICTP), in Trieste, Italy, and sponsored by the ICTP and co-sponsored by the Wellcome Trust. But the conference was not just for physicists interested in biology. It was also aimed at biologists who were interested in learning what new physical methods and existing knowledge could offer them, as well as pinpointing for physicists the subjects that

**Physicists want to simplify and unify things, whereas biologists are happy with diversification and complexity**

biologists think could benefit from input from physics.

The conference included over 60 talks – demonstrating the interplay between physics and biology – on everything from DNA mechanics, structure, interactions and aggregation to DNA compaction in viruses, DNA-protein interaction and recognition, DNA in confinement (pores and vesicles) and smart DNA (robotics, nano-architectures, switches, sensors and DNA electronics). More details are available online.

Taking Rutherford's famous saying that there is physics and everything else in science is stamp collecting, Paul Selvin, a physicist at the University of Illinois, recently said that if Rutherford were alive today, he would have said that "all science is either biology or tool-making for biology or not fundable". Today, in general, the arrogance is rarely on the side of physicists. But to overcome the barrier of scepticism, physicists need to demonstrate (or, even better, inspire biologists to show) that insights from physics do not just apply in model systems in the lab but work equally well inside the real world of the cell.

Crick not only had a great mind and was very serious about biology but he was also lucky to meet the right collaborator in Watson. Many of us seeking to do important work in biology will not be able to do so alone unless we too find the right match. The future is far from hopeless – and meetings such as the one held in Trieste last month may well make the difference. As the Cambridge physicist Stephen Hawking once said, "The greatest discoveries of the 21st century will take place where we do not expect them." Likewise, I am convinced that great surprises and discoveries in biology will come from physics.

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# Critical Point The call of the wild

**Robert P Crease** talks to a former string theorist who found what he wanted in science when he applied the tools of physics to fundamental questions in biology

Paul Wiggins yanks the mouse cord from his computer and stretches it between his fingers. "Here's your chromosome, which is about 2 m long." He twists the cord and squeezes it into a ball. "How", he questions, "does it get inside a nucleus that's 10–50 $\mu$m long?"

The animated, 32-year-old researcher at the Whitehead Institute of Biomedical Research in Cambridge, Massachusetts, confesses that we do not know the answer. "But we do know its genetic loci don't end up randomly shuffled. Each ends up at a *particular* spot. Why?"

Wiggins thinks that tools used in physics can help answer these questions – but that to do so involves researchers jumping in at an uncharted interdisciplinary middle, to measure something that can be linked both to the molecular scale and to the cellular scale, or midway between physics and biology.

## Beyond strings

As an undergraduate at Cornell University, Wiggins was entranced by astrophysics and cosmological theories – the grander and more abstract the better. In 2000 he moved to the California Institute of Technology as a graduate student and joined the collective of string-theory pioneer John Swartz, whose work seemed glamorous. "We felt that we were on the threshold of a revolution," Wiggins recalls. But after 18 months the glamour wore off. "The research felt less like a revolution and more like a small perturbation. There were no predictions."

Caltech requires first-year students to attend weekly lectures given by outsiders on their research, and Wiggins found the biophysics talks exciting. "Biophysics involved lots of experiments on incredibly interesting phenomena, and nobody had models," he says. "That appealed to my theoretical instincts." It also activated previously unsuspected experimental desires. Wiggins switched fields, and in 2005 finished a thesis on the statistical mechanics of biomolecules.

His research was so promising that he was named one of five fellows at Whitehead – a prestigious independent research institute that employs about a dozen permanent faculty members affiliated with the Massachusetts Institute of Technology. The institute's fellows programme fast-tracks promising young researchers, putting them in charge of their own labs and bypassing the postdoc phase in which they would have had to labour in someone else's group.

**Island-hop** Paul Wiggins switched from strings to cells.

## Island-hopping

At Whitehead, Wiggins was free to pursue what my Stony Brook colleague Fred Goldhaber calls "island-hopping" research. The analogy comes from the Second World War, when the Allies swept across the Pacific towards Japan. They advanced more rapidly not by conquering islands in sequence, but by skipping over several at a time, leaving them to be liberated afterwards. In a similar fashion, effective research programmes often do not proceed outward in safe steps from thoroughly understood terrain, but in ambitious leaps that skip terrain for other researchers to explore later.

Wiggins' island-hopping has involved taking biological information about cellular structures and applying methods of physics to explore the mechanisms giving rise to these structures. He and some Caltech colleagues, for instance, did experiments to see if physics could shed light on the intricate shapes of the membranes surrounding the cellular subunits known as organelles. The team used optical tweezers to tweak such membranes in various ways, measuring the forces it took to drag membranes into different shapes (2008 *Proc. Natl Acad. Sci.* **105** 19257). Wiggins admits that the researchers have so far made only limited progress. "But," he says, "we have shown that, in a controlled environment at least, we can quantitatively compute the forces involved based on mechanics and structure."

Wiggins' latest research – which he was using his mouse cord to explain – involves studying the chromosomes of the bacterium *E. coli*. These chromosomes are circular, but two key sites are the "origin", where replication begins, and the "terminus", or the opposite point, where replication ends. To explain why *E. coli* always manages to locate genetic sequences in the right place, a physicist naturally thinks of two possible explanations, involving external and internal interactions. The genetic material may be bonding to some external scaffolding, or its position may be determined by internal interactions between the DNA strands themselves.

What Wiggins is doing is using conventional fluorescence-microscopic techniques to determine the precision by which the different sequences end up in their particular places. The width of this distribution – the precision – measures the strength of the coupling between sequence and location, which provides clues to the mechanism tethering it in place. Wiggins' preliminary measurements suggest that external interactions prevail at the terminus, but that internal interactions prevail throughout the remainder of the chromosome. "We seem to know where the biological action is," he says.

## The critical point

Island-hopping faces well-known obstacles. As Wiggins points out, everyone likes the idea of interdisciplinary research, but it requires effort to make it work. "You spend a lot of time being an ambassador," he says, "explaining to colleagues and potential collaborators why your problems are relevant and interesting, which takes you away from the lab bench." Indeed, cultural differences are an obstacle even after a collaboration is formed. As Wiggins puts it, "Physicists always tend to think that they know how to do other people's problems better, while biologists often place little value in mathematical models." In his eyes, both physicists and biologists think that they know how to ask the interesting questions, and tend to treat members of the other culture as mere technicians.

Wiggins has largely been shielded from these problems at the small and biomedically oriented Whitehead Institute, but his five-year stint is drawing to a close. "Next year I have to look for a real job," he says. And although Wiggins does not think that he can sell himself as a biologist yet, for him the move into biology has been worth the risk. "String theory lost its glamour for me when it didn't have achievable targets. What turned me on to biophysics were the interesting measurements and predictions you can make, and the urgent need for models. It is a field that is wide open."

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# Feedback

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

## Reflections on the Schön affair

In her feature article on the fraud perpetrated by Jan Hendrik Schön (May pp24–29), Eugenie Samuel Reich concludes that the fake data Schön generated at Bell Labs were designed primarily to meet the expectations of his peers. She is probably right, but the Schön case was by no means the first of its kind. A century ago the Piltdown fraud, in which medieval cranial fragments were matched with part of an orang-utan jaw bone, convinced British archaeologists and palaeontologists that early hominids developed on the South Downs. The scientific evidence was never fully accepted outside the British Empire, but it still took the UK's Natural History Museum 50 years to recognize the hoax. "Piltdown man" was created to meet the expectations of the British archaeological community, and hence the fraud succeeded.

Moreover, in 1953 the Nobel-prize-winning chemist Irving Langmuir gave a much-reproduced lecture at the Schenectady Laboratories of General Electric, in which he provided many examples of what he termed "pathological science" and noted several characteristics of "breakthroughs": the effects reported are often close to the limit of detection; there are claims that the measurements are of great accuracy; criticisms of both the data and the theory are met by ad hoc excuses; and the ratio of supporters to critics rises dramatically before falling just as fast. Several of these criteria could be applied to much of Schön's data.

In many of the documented cases of bad science, self-deception rather than fraud is the primary factor. Unfortunately, *false* accusations of science fraud are also not uncommon. In the Baltimore case of the late 1980s and early 1990s, Thereza Imanisha-Kari, an internationally recognized serologist at the Massachusetts Institute of Technology and a colleague of the Nobel laureate David Baltimore, was accused by a disgruntled postdoctoral employee of falsifying data in the testing of genetically modified mice. She was suspended without any opportunity to defend herself, barred from her lab and had her lab records confiscated. A US congressional committee called in the Federal Bureau of Investigation, and its agents produced the required "evidence". After the story was leaked to the press, both Imanisha-Kari and Baltimore (who defended her) were subjected to a media witch hunt. It was only after 10 years that the case was reviewed and Imanisha-Kari exonerated. Her only "fault" had been to mislabel one mouse and, sometimes, fail to keep her lab records up to date.

The damage done to progress in molecular electronics by Schön's behaviour is immense, but it is nothing compared with the damage to British palaeontology caused by "Piltdown" or the 10 years in the wilderness suffered by Imanisha-Kari.

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Your article on the Schön case revealed many interesting details of the events, but the article says little about his co-authors, who apparently escaped serious repercussions. In my view, there are two key questions related to co-authorship that should be considered whenever misconduct and ethical issues are discussed. First, how can we evaluate someone's scientific contribution to a paper? And second, can we distinguish the co-authors according to the roles they play?

I have two phenomenological suggestions: a time-based estimate of individual contribution and a classification of co-authors. A "substantial scientific contribution" is surely a basic requirement for co-authorship – indeed, since earlier this year *Nature* has required researchers to declare who contributed what to any paper submitted (**458** 1078). But as this contribution cannot be measured exactly, it seems logical to me to use the time spent on the paper to estimate contribution. In my view, a few hours' effort is not enough to warrant co-authorship. After a few days, co-authorship becomes possible; after a few weeks, it is expected. Although the timescale varies with experience and knowledge, there is always some time-threshold required for co-authorship.

As for classifying the co-authors, I suggest four phenomenological types: writer, worker, provider and leader. The "writer" is the person who composes the manuscript. While others may discuss and suggest changes, the final version is written by the writer, and his or her name is generally first on the list of authors. The "workers" are those who performed any experimental and/or theoretical work. Usually, they are students or junior colleagues of the writer. The "provider" contributes something – for example physical samples or supplementary results. If this was a significant contribution, providers should be recognized as co-authors no matter how much time they actually spent on the work. The final and perhaps the most controversial category is the "leader" – someone of higher rank or position.

Within this category I propose several sub-types: a "mentor" is an almost ubiquitous co-author; a "boss" is an appointed leader, director or similar; and a "project leader" organizes the work and acquires the necessary funding. The evaluation of a leader's contribution is difficult if they appear to have spent little time on the project, and co-authorship based solely on supervision or management has been questioned, notably by the International Committee of Medical Journal Editors.

My choice of names is tentative, and some types can overlap; for example, the writer can also be the leader. However, a more widespread adoption of such a classification might help the community avoid some of the pitfalls of the Schön case.

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## Snowed under: 50 years of the 'two cultures'

With regard to Robert Crease's column on the 50th anniversary of C P Snow's "two cultures" lecture (May p19), I too read Snow's book about the rift between the humanities and the sciences and wondered to what degree this rift really existed and what the reasons were for it. Later, in my professional life, I had the opportunity to work in Canada, France, Germany and the US, as well as in the UK. My impressions were that the rift existed in all of these countries, but not to the same degree: it was widest in the UK and narrowest in France. I concluded that the main reason for the disparity was the difference between the educational systems of these two countries in the years preceding and during the Second World War.

Like many children of middle-class parents in the UK at the time, I was sent to a public school – in my case, Rugby. There, when students reached the age of 15, the student body was split into three streams or "blocks": classical languages, modern languages and natural sciences. These three blocks could have been referred to as "classics", "moderns" and "sciences", but for greater succinctness they were designated A, B, and C, respectively. That set the tone of the place.

## Comments from *physicsworld.com*

**As we reported on our blog last month (12 June), Sigurd Hofmann and colleagues at the GSI heavy-ion lab in Darmstadt, Germany are racking their brains to find a name for element 112. Hofmann created the first atom of the element – temporarily dubbed ununbium, after "*ununbi*", Latin for "one one two" – back in 1996. Scientists at the RIKEN lab in Japan verified its existence in 2004, and now – five years and several squabbles later – the International Union of Pure and Applied Chemistry has credited Hofmann with the discovery and let him submit a new name for the element. Our call for readers' suggestions produced some great responses.**

How about Planckium? Or unobtanium?
**D D Tannenbaum**

Stabilium.
**Captain Physics**

Empedocleum. Empedocles originally suggested that matter is composed of fundamental elements (earth, wind, fire and water), 2500 years ago – his contribution should be acknowledged.
**MacH**

Planckium is not bad. I prefer earthium, though.
**Isaac Abdullah**

My suggestion is gravidium. Let's collect these and forward them to Mr Hofmann – anyone know the e-mail address? :)
**T Mucsi**

Element 112...Fibonaccium! Do they have to end in "-ium"? I like old-fashioned names myself, in the vein of tungsten.
**Schrodingerskitten**

I would call it collossium, bulkium or densium.
**Pedro Lobo**

physicsworld.com

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

The headmaster was a classicist, and from him down it was axiomatic that the block system mirrored the structure of contemporary British society. The pupils of classics were upper class, the modern-language pupils were middle class, while the science pupils were definitely lower class. The natural sciences were taught – and well, I am pleased to say – but only as a grudging concession to the materialism of the age. One often heard the catch phrase "scientists should be on tap, but not on top". The building that housed the science classrooms and labs was known as the "stinks schools", while the pupils who studied there were "C-block squits". No such epithets were used in connection with the other two student blocks.

The rationale that teachers and students of the classics had for their attitude to science was that science teaching narrowed the mind and prepared students only for specialized activities. In an essay by a classics student that I was given to read, he described scientific research as "just adding more facts to the millions already known". Another such student said to me that "In a few years from now, we'll be running the country, while you'll be the little man in a white coat who analyses our urine samples." Classical teaching, in contrast, was considered to broaden the mind, thus preparing its students for whatever life might bring.

I used to wonder what these classics students were being prepared for, and a few years later, at a gathering of former Rugby students at university, I found out. The conversation got onto what we planned to do when we left college, and I was surprised to learn that I, the only scientist present, was also the only one who was not being launched into a profession by his father. One student was set to become assistant manager of his father's boot factory. Another, who was studying law, would in due course be articled to his father, and so on. Thus, what knowledge these students had acquired at the public school did not matter very much: their futures were assured anyway.

Needless to say, these reminiscences of my school days are anecdotal. Perhaps conditions were not the same at other public schools, but I doubt that they were much different. When I was raising my family in France, in contrast, I found that nothing was said or done to prejudice children against science. No preference was given to the classics; the emphasis, if any, was on mathematics.

I consider the rift between the two cultures to be an artefact of the educational system, particularly in the UK. And if C P Snow was sensitive to it, this was because he had witnessed the effects of this system and saw the rift as a fact of life, yet he was sufficiently a scientist to pose the question of whether it needed to be so.

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I read Snow's book when it first came out, with relish. Since then, I have been attempting in my own way to address the problem in Ireland, where the cultural split is not two-way but four-way – between scientists, engineers, the literati and the economists. I consider this to be at the root of the "core-fringe" problem, as experienced by small nations at the European periphery, and even more so in the global postcolonial scene. One prominent aspect of this problem is the process by which countries lose much of their native scientific talent thanks to unfavourable economic conditions at home. This "brain drain" phenomenon was first identified and named in the 1950s by the pioneer of X-ray crystallography John Desmond Bernal, a native of Nenagh, Ireland, and himself an émigré scientist.

The science–engineering dichotomy takes the form of the engineers nearly always looking abroad for innovative technological solutions, and being unaware of potentially useful local scientific expertise. The science–economics dichotomy takes the form of a lack of awareness of the utility of cost–benefit analysis among those attempting to promote science, and an equal lack on the part of development economists of the existence of scientific and engineering knowledge relevant to specific local resources available.

The case needs to be made for an interdisciplinary approach between science, engineering and development economics in addressing the problems of small nations emerging on the fringe of disintegrating imperial systems, and in this context, the literati need to be enlisted to support the associated development of an all-round national culture, inclusive of all subcultures. Is there any relevant international network looking at the above problems? If so, can we be made aware of what is being done?

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I presume that Snow was unaware of the song by Michael Flanders and Donald Swann on the second law of thermodynamics, else he might have had second thoughts about his "two cultures" theme. I do not know if Flanders and Swann would be classed as "literary intellectuals", but I am pretty sure that few in the audiences attending their "Drop of the Hat" stage shows in the 1960s were physicists. My memory is that the laughter at the punch line "That's entropy man!" was loud and spontaneous. Crease is, though, correct about flaws in all stereotyping. Literary intellectuals' awareness of any of the laws of thermodynamics is no different from experts in any field having knowledge of another (medicine and statistics come to mind) – or is it?

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## Italian magic

In your news article "Telescope hunts for cosmic explosions" (May p7) about the MAGIC-II telescope that will study gamma rays produced by distant celestial objects, Italy is not mentioned among the project's major participants. However, Italy is actually the second most important contributor, following Germany, and it participates in MAGIC through the collaboration of several institutions – particularly the Italian National Institute for Nuclear Physics (INFN), the Italian National Institute for Astrophysics (INAF), and the universities of Padova, Siena and Udine. Both the INFN and the INAF are also involved in the Fermi space-telescope mission mentioned in the article.

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## Observing the economy

In "The (unfortunate) complexity of the economy" (April pp28–32) Jean-Philippe Bouchaud presents clear evidence that traditional assumptions of rational markets have to be abandoned. The old investor slogan "buy on promise, sell on rumour" quickly magnifies a downturn into a crisis, which triggers two questions. If physics-based models are applied (beyond understanding and prediction) to actual market decisions, does this make the economy more or less stable? And, is this cause for stronger regulation?

Unlike in a quantum system, the economy can be observed without altering it, but only if the researcher does not apply the results, and keeps them secret.

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## Twinkle, twinkle

Stars twinkle, or scintillate, because of fluctuating atmospheric refraction. But refraction is a dispersive process, so different colours twinkle at different times. Some people claim to see rapid colour flashes in the twinkling of Sirius, the brightest star and therefore the most suitable subject. Anyone can see the colours with binoculars – simply focus on Sirius and then jiggle the binoculars gently so that the image is drawn in a streak, when brilliant colours appear along it. But the effect changes rapidly and a photograph is needed to appreciate the full beauty of the phenomenon.

This image above was obtained with a Nikon P80 digital camera with the vibration reduction (image stabilizer) switched off, the focus set to infinity, the exposure compensation (sensitivity) set to maximum and the optical zoom set to ×18 (equivalent to 486 mm focal length in 35 mm format).

**David Pye and Ray Crundwell**
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**Editor's note**
What do you think of David and Ray's picture? Do you think you could do better? Just for a bit of fun in what is, after all, the International Year of Astronomy, we are looking for the best astronomy photographs taken by *Physics World* readers. E-mail your pictures to pwld@iop.org or post them to the address on page 19. There are no prizes, but we will print a selection of the best later in the year. The deadline is 3 September 2009.

## Sprechen Sie Physik?

Ben Stein's article about the use of the German language in physics (April pp16–17) reminds me that when I started an honours physics degree at Manchester University in 1949, a qualification in German was a requirement for the course. At that time *Zeitschrift für Physik* was a notable journal that had to be read in the original German.

So on Wednesday and Saturday mornings we were lectured for an hour by an elderly German lady (aged at least 40). At the end of the first year there was an examination, in which, with the aid of a dictionary, we had to produce an English translation of a German set piece. At that time this was a real requirement, and on an honours course there were no re-takes – if you failed, you were off the course.

The German requirement, I suspect, was used as a tool to weed out marginal students; some 84 undergraduates started the course, but only 62 took finals. A friend who had failed German and who was appealing against the decision prolonged his stay at Manchester by a serendipitous motorcycle accident on Oxford Road. He found a friendly doctor who decided that the shock rendered him unfit to sit part one of the degree. But he eventually left without taking it, or passing the German requirement!

German is a beautiful language. But I wonder, given the international shifts of power, whether Mandarin might be a better bet for today's students.

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**Correction**
Bremsstrahlung radiation is emitted when electrons or protons are slowed, not photons as stated in the above article (April pp16–17).

## Unusual units

Ken Maxted, who wrote to complain about the use of football pitches as a unit of area (May p23), may be interested in a volume unit popular in Australia – the Sydney Harbour. Few people could put a number to it, but it is "pretty damn big", hence appropriate enough when referring to water storage. In addition, F A Rocke's *Handbook of Units and Quantities* (published by the Australian Atomic Energy Commission in 1984) listed three different pints, of which my favourite is the "dry pint", which is presumably available at The Pub With No Beer, of Australian bush-ballad fame.

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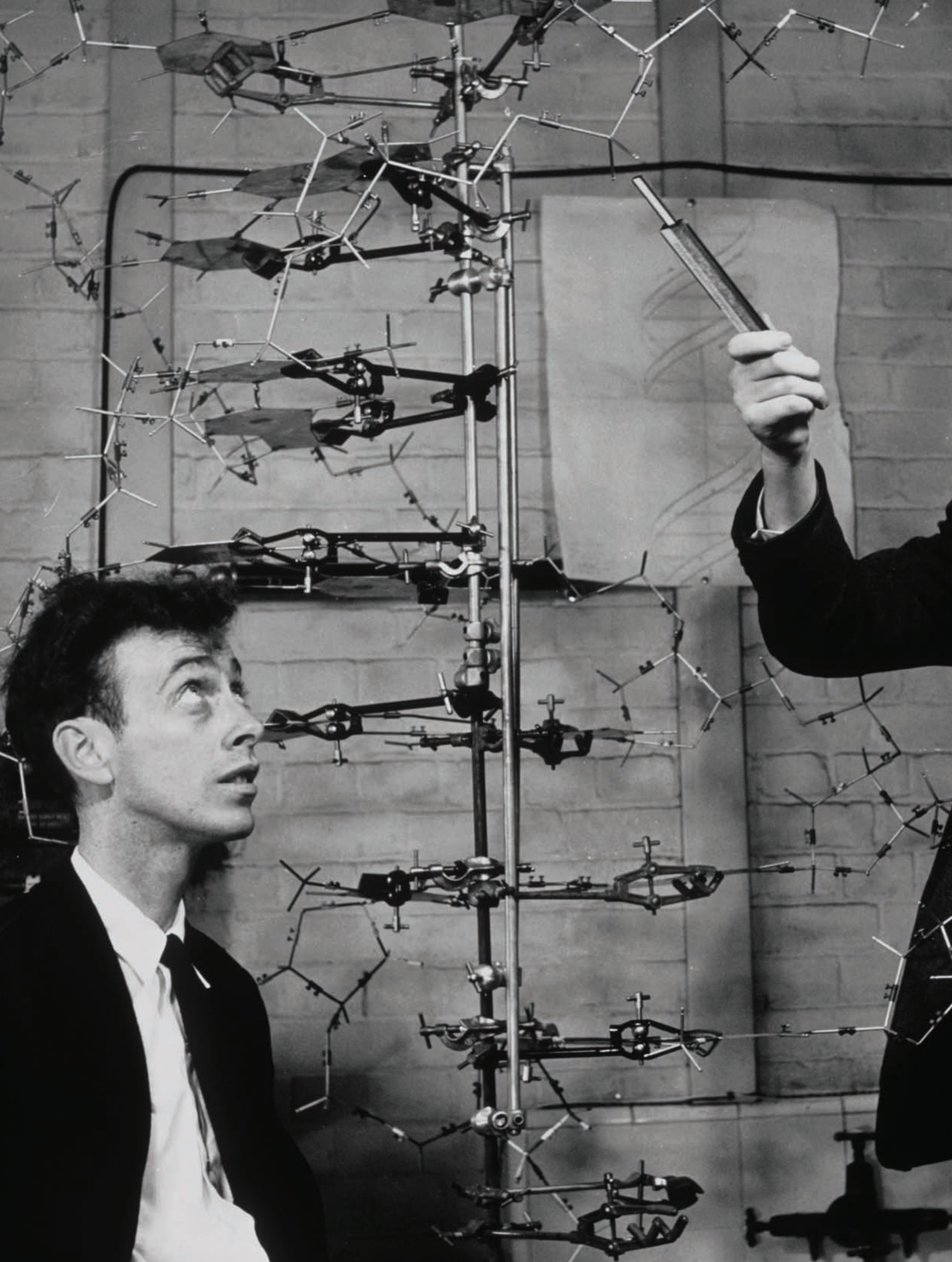

# Changing times

Welcome to this special issue of *Physics World* marking the bicentenary of the birth of Charles Darwin and the 150th anniversary of his seminal work *On the Origin of Species*. Focusing throughout on how physics is changing biology, **Paul Davies** looks at the importance of quantum mechanics to life, while **Jochen Guck** examines the physics of cells and **Sam Wang** describes how physicists are helping to understand the brain. And although Darwin may not have had a special interest in physics or astronomy, **Leonard Susskind** celebrates the scientific approach of the great naturalist, arguing that Darwin "set the standard" for what any explanation of nature should be like. Finally, four full-page illustrations, the first shown here, mark the four Nobel prizes in physiology or medicine won or shared by physicists

Antony Barrington Brown/Science Photo Library

## The secret of life

This photograph of Francis Crick (right) and James Watson (left) explaining their double-helix model of deoxyribonucleic acid (DNA) is one of the most famous images in biology. It was taken in May 1953, a few months after the pair had deciphered the molecule's structure at the Cavendish Laboratory in Cambridge, opening the door to the modern era of molecular biology. Their discovery was without doubt one of the most significant individual partnerships between a physicist (Crick) and a biologist (Watson). The picture itself was taken by Antony Barrington Brown, who graduated from Cambridge in 1951 with a degree in chemistry but changed tack to become a freelance photographer for, among others, the BBC and the UK press. Barrington Brown took the picture to go with a story that a journalist friend wanted to offer to *Time* magazine about Crick and Watson's discovery. Writing in *Chem@Cam* magazine in 2005, Barrington Brown recalled how he had asked the two scientists to "look portentous", which the pair "manifestly failed to do, treating my efforts as a bit of a joke". Although the picture – one of several Barrington Brown took during the 1953 photo-shoot – is iconic, neither it, nor the accompanying article, were actually published in *Time*. In fact, the picture only became famous some 15 years later when it appeared in Watson's 1968 autobiography *A Double Helix*. Its over use is unfair on the physicist Maurice Wilkins, who shared the 1963 Nobel Prize in Physiology or Medicine with Crick and Watson "for their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material". The image also effectively airbrushes out the role of the physicist Rosalind Franklin, whose images of DNA obtained using X-ray crystallography provided crucial clues to the molecule's structure and whose death in 1958 prevented her from being considered for a Nobel prize. But the impact of the discovery itself continues to reverberate, given that efforts like the Human Genome Project and the ongoing search for effective treatments for genetic diseases are direct descendents of the 1953 breakthrough. This image has since become a shorthand for the not just the collaborations between physics and biology, but also for our scientific understanding of life itself.

# The quantum life

The idea that quantum mechanics can explain many fundamental aspects of life is resurging, as **Paul Davies** reveals

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To a physicist, life seems little short of miraculous – all those stupid atoms getting together to perform such clever tricks! For centuries, living organisms were regarded as some sort of magic matter. Today, we know that no special "life force" is at work in biology; there is just ordinary matter doing extraordinary things, all the while obeying the familiar laws of physics. What, then, is the secret of life's remarkable properties?

In the late 1940s and 1950s it was fashionable to suppose that quantum mechanics – or perhaps some soon-to-be-formulated "post-quantum mechanics" – held the key to the mystery of life. Flushed with their success in explaining the properties of non-living matter, the founders of quantum mechanics hoped their theory was both weird enough and powerful enough to explain the peculiar living state of matter too. Niels Bohr, Werner Heisenberg and Eugene Wigner all offered speculations, while Erwin Schrödinger's famous book *What is Life?*, published in 1944, paved the way for the birth of molecular biology in the 1950s.

Half a century later, the dream that quantum mechanics would somehow explain life "at a stroke" – as it had explained other states of matter so distinctively and comprehensively – has not been fulfilled. Undoubtedly, quantum mechanics is needed to explain the sizes and shapes of molecules and the details of their chemical bonding, but no clear-cut "life principle" has emerged from the quantum realm that would single out the living state as in any way special. Furthermore, classical ball-and-stick models seem adequate for most explanations in molecular biology.

In spite of this, there have been persistent claims that quantum mechanics can play a fundamental role in biology, for example through coherent superpositions and entanglement. These claims range from plausible ideas, like quantum-assisted protein folding, to more speculative suggestions, such as the one proposed by Roger Penrose of the University of Oxford and Stuart Hameroff of the University of Arizona that quantum mechanics explains consciousness by operating in the brain over macroscopic dimensions. Unfortunately, biological systems are so complex that it is hard to separate "pure" quantum effects from the shifting melee of essentially classical processes that are also present. There is thus plenty of scope for disagreement about the extent to which life utilizes non-trivial quantum processes.

Life has had three and a half billion years to solve problems and optimize efficiency. If quantum mechanics can enhance its performance, or open up new possibilities, it is likely that life will have discovered the fact

But why should quantum mechanics be relevant to life, beyond explaining the basic structure and interaction of molecules? One general argument is that quantum effects can serve to facilitate processes that are either slow or impossible according to classical physics. Physicists are familiar with the fact that discreteness, quantum tunnelling, superposition and entanglement produce novel and unexpected phenomena. Life has had three and a half billion years to solve problems and optimize efficiency. If quantum mechanics can enhance its performance, or open up new possibilities, it is likely that life will have discovered the fact and exploited the opportunities. Given that the basic processes of biology take place at a molecular level, harnessing quantum effects does not seem *a priori* implausible.

Even if life does not actively exploit "quantum trickery", we cannot ignore the impact of quantum mechanics on biology. Quantum uncertainty sets a fundamental bound on the fidelity of all molecular processes. A distinctive feature of biology is the exquisite choreography involved in its highly complex molecular self-organization and self-assembly. For the cell to perform properly, it is crucial that the right parts are in the right place at the right time. Quantum mechanics sets fundamental limits to the accuracy with which molecules can cooperate in a collective and organized way. We might expect some of life's processes to evolve at least as far as the "quantum edge", where a compromise is struck between speed and accuracy.

The 19th-century view of life as "magic matter", exemplified by the use of the term "organic chemistry", has been replaced by a model of the cell as a complex system of linked nanomachines operating under the control of digital software encoded in DNA. These Lilliputian components, made mostly from proteins, include pumps, rotors, ratchets, cables, levers, sensors and other mechanisms familiar to the physicist and engineer. Their exquisite design, honed by eons of evolution, exhibits extraordinary efficiency and versatility, and is an inspiration to nanotechnologists. Intuition gained from macroscopic and mesoscopic mechanisms can be misleading on a nano-scale, where quantum phenomena such as the Casimir effect could come into play and dramatically change the nature of the forces involved.

## Early speculations

An early idea about quantum effects in biology was proposed by Herbert Fröhlich of the University of Liverpool, who in 1968 suggested that the modes of vibration

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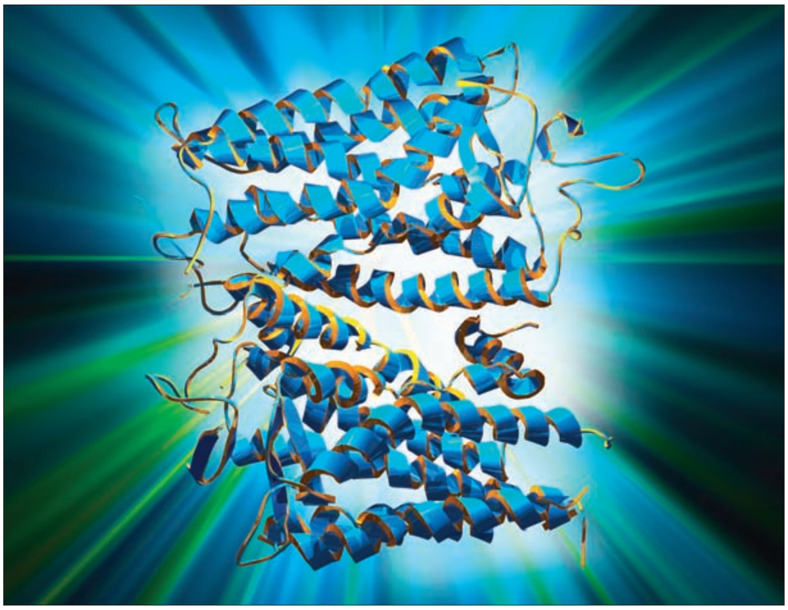
**Quantum of life**
Quantum physics might be responsible for photosynthesis.




**Protein trickery** Protein chemistry involves a complicated protein choreography in a complex energy landscape. Physicists have found strong evidence that quantum tunnelling is fundamental to the efficiency of these processes.

of some membranes in the cell might exhibit the phenomenon of a Bose–Einstein condensate, in which many quanta settle into a single quantum state with long-range coherence. Bose–Einstein condensates are normally associated with very low temperatures, but Fröhlich proposed that non-linear coupling between a collection of dipole oscillators driven by a thermal environment could quite generally channel energy into a single coherent oscillator even at biological temperatures. Quite what advantage an organism would gain from this mode of energy storage is unclear, although it could perhaps be used for controlled chemical reactions.

Another early and recurring speculation is that some biological mutations come about as a result of quantum tunnelling. The genetic basis of life is written in the four-letter alphabet of the nucleotides A, G, C and T that pair up to make the rungs of the twisted-ladder structure of DNA. The normal assignment is that T pairs with A and that G pairs with C, with the pairs being held together by two or three hydrogen bonds, respectively. However, the nucleotide bases can also exist in alternative, chemically related forms, known as tautomers, according to the position of a proton. Quantum mechanics predicts that a proton can tunnel with a finite probability through the potential barrier separating these two states, leading to mispairing, for example, of T with G instead of A. Mutations are the driver of evolution, so in this limited sense, quantum mechanics is certainly a contributory factor to evolutionary change. The physicist Johnjoe McFadden of the University of Surrey has built on this process to suggest a quantum model of adaptive change, in which environmentally stressed bacteria seem able to select favourable mutations that boost their survivability.

Another example of quantum tunnelling with biological relevance concerns the chemistry of proteins – large molecules that fold into complex 3D shapes. Some proteins contain active sites that bond to hydrogen, and to reach the sites, the hydrogen atom has to negotiate an elaborate and shifting potential-energy landscape. Quantum tunnelling can speed up this process. Studying just how important tunnelling might be is highly challenging, because many complicated interactions occur as the protein molecule jiggles around and changes shape as a result of thermal agitation. One approach taken by the chemist Judith Klinman of the University of California, Berkeley, is to work with deuterium instead of hydrogen. As the deuteron is roughly twice as heavy as the proton, using it makes a big difference to the tunnelling rate. Comparing the relative reaction rates of hydrogen and deuterium over a wide temperature range has therefore allowed experimentalists to separate out the relative importance of quantum effects. The results seem to confirm that quantum tunnelling is indeed significant, which raises the fascinating question of whether some proteins have actually evolved to take advantage of this, making them in effect "tunnelling enhancers". In evolution, even a small advantage in speed or accuracy can bootstrap into overwhelming success, because natural selection exponentiates the relative proportion of the winners over many generations.

### Photosynthesis and ornithology

Although the previous examples have been in the literature for many years, they have not led to a widespread acceptance that quantum physics is important for biology. However, the subject matter is sufficiently rich that I held an entire workshop on quantum biology at the BEYOND Center for Fundamental Concepts in Science at Arizona State University in December 2007, which was followed by another organized by physicists Vlatko Vedral and Elisabeth Rieper at the National University of Singapore in January 2009. This flurry of activity was spurred by two new and rather dramatic experimental developments.

The first involves a study of photosynthesis by Berkeley chemist Graham Fleming and his group. Photosynthesis is a highly complicated and sophisticated mechanism that harvests light energy to split water by using individual photons to create a cascade of reactions. The process is extraordinarily efficient, and represents a classic example of how evolution has fine-tuned the design of a physical system to attain near-optimal performance.

The primary receptor of the light energy is a complex of pigment molecules known as chromophores. These can become excited and pass on the energy of excitation in a multistage process to the final reaction centre where charge separation occurs. Because the wavelength of the photon is much larger than the molecular assemblage, a superposition state of many excited pigment molecules is initially created, and this proceeds to evolve over a timescale of some hundreds of femtoseconds. Fleming and his group used laser excitation and probe pulses to study the relaxation pathways of these light-harvesting complexes, and observed a type of "quantum beating" effect in which the maximum amplitude of the excitation visits and revisits different molecules in the system coherently. Fleming claims that, with appropriate timing, the system can "grab" the coherent excitation (which persists for a few hundred femtoseconds) with greater probability than if it was merely distributed according to classical statistical mechanics. He believes this could lead to a many-fold increase in the speed of the energy transfer.

The results have recently been complemented by the work of Elisabetta Collini and Gregory Scholes at the University of Toronto, who demonstrated room-temperature coherence in electron-excitation transfer along polymer chains. An important feature of photosynthesis is that the molecular architecture involved is structured in a highly unusual and compact manner, which suggests that it has been "customized" to exploit long-range quantum effects. It could be that the particular configuration is efficient at preserving coherence for surprisingly long durations, thereby enabling the system to "explore" many pathways simultaneously and thus speed up a "solution" (i.e. delivering energy to the reaction centre).

The second recent development that suggests that quantum physics is relevant to biology concerns bird navigation. It is well known that some birds perform amazing feats of navigation using a variety of cues that including the local direction of the Earth's magnetic field. The nature of this magnetic sensor has, however, remained something of a mystery and the problem is particularly acute because the magnetic field penetrates the entire organism. How, for example, is the angle of the field relative to the bird translated into neural information? A study by Thorsten Ritz at the University of California, Irvine, Christine Timmel's group at Oxford University and Elisabeth Rieper at the National University of Singapore has made a plausible case, at least for the European robin, that the key lies with a class of proteins found in the bird's retinas.

The mechanism currently under investigation appeals to the photo-activation above the thermal background of a 2D array of aligned proteins, producing radical ion pairs involving singlet two-electron states. The spins of these entangled electrons are linked, and in the presence of a uniform magnetic field they would precess in synchrony, maintaining the singlet configuration. However, if the ejected electron moves away somewhat, the two electrons may experience different magnetic environments. Although both electrons will be subjected to the same ambient field of the Earth, the electron tied to the ion in the protein will also be affected by the ion's nuclear magnetic field, which produces hyperfine splitting. This difference in magnetic fields experienced by the entangled electrons causes the singlet state to oscillate with a triplet state, with a periodicity depending in part on the strength and orientation of the Earth's field relative to the array of proteins. The system may then de-excite in stages and initiate a reaction that in effect acts as a chemical compass, because the relative proportion of the reaction products can depend on the singlet–triplet oscillation frequency.

There remain considerable uncertainties both about the mechanism and the precise identities of the molecules involved. Nevertheless, general evidence in favour of a quantum model of some sort comes from experiments conducted by Wolfgang and Roswitha Wiltschko of the University of Frankfurt, who studied the behaviour of robins in the presence of a small, oscillating magnetic field. They found that for frequencies near 1.315 MHz, the birds' vaunted navigational prowess is seriously compromised. A possible interpretation of the experiments is that the perturbing field produces a "resonance" causing singlet–triplet transitions, thereby upsetting the chemical compass.

Anthony Cooper/Science Photo Library

**Flight path** Recent studies indicate that the European robin uses an array of aligned proteins in its retina as a magnetic-field sensor that helps it to navigate.

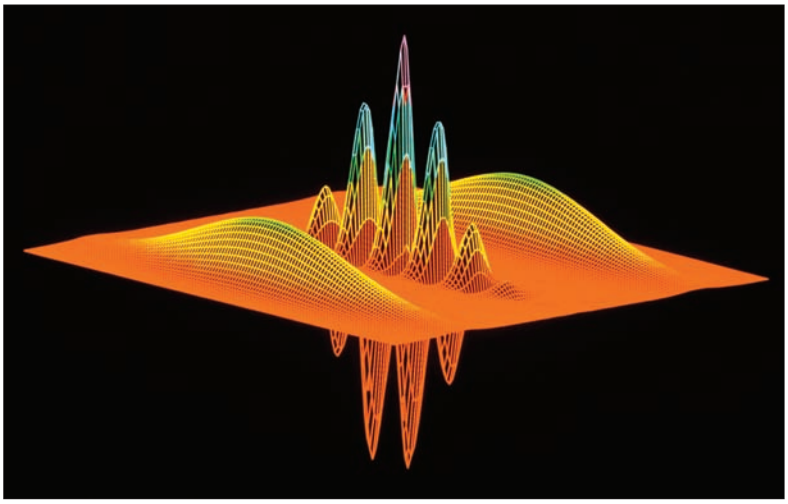
### How to avoid decoherence

Although at least some of these examples add up to a *prima facie* case for quantum mechanics playing a role in biology, they all confront a serious and fundamental problem. Effects like coherence, entanglement and superposition can be maintained only if the quantum system avoids decoherence caused by interactions with its environment. In the presence of environmental noise, the delicate phase relationships that characterize quantum effects get scrambled, turning pure quantum states into mixtures and in effect marking a transition from quantum to classical behaviour. Only so long as decoherence can be kept at bay will explicitly quantum effects persist. The claims of quantum biology therefore stand or fall on the precise decoherence timescale. If a system decoheres too fast, then it will classicalize before anything of biochemical or biological interest happens.

In recent years, much attention has been given to decoherence, and its avoidance, by physicists working in the burgeoning field of quantum computation and quantum-information science. A quantum computer is a way to process information more efficiently than classical physics would allow by using quantum states that are allowed to perform logical operations through the coherent evolution of quantum superpositions. Decoherence represents a source of computational error, so physicists have been busy designing environments that are theoretically free of decoherence, or that minimize its impact. A key parameter is temperature: the higher it is, the stronger the decoherence. For this reason, most attempts at quantum computation employ ultra-low-temperature environments such as superconductors or cold-atom traps.

At first sight, the warm and wet interior of a living cell

There is accumulating and tantalizing evidence that quantum mechanics plays a key role here and there in biology



Isaac Chuang/IBM Almaden Research Center/Science Photo Library

**Keeping it coherent** Quantum biology is only possible if decoherence is avoided, which might seem implausible in the warm environment of the living cell. However, results in quantum computation indicate that biological systems might be less susceptible to decoherence than simple models predict.

seems a very unpromising environment for low decoherence. Back-of-the-envelope calculations suggest decoherence times of less than $10^{-13}$ s for most biochemical processes at blood temperature. However, there are reasons why real biological systems might be less susceptible to decoherence than simplistic models predict. One is that biological organisms are highly non-linear, open, driven systems that operate away from thermodynamic equilibrium. The physics of such systems is not well understood and could conceal novel quantum properties that life has discovered before we have. Indeed, sophisticated calculations indicate that simple models generally greatly overestimate decoherence rates. For example, Jianming Cai Hans Briegel of the University of Innsbruck and Sandu Popescu of the University of Bristol have found that a two-spin quantum system dynamically driven away from equilibrium can exhibit ongoing coherence even when coupled to a hot and noisy environment that would rapidly decohere a static system. A calculation based on the so-called spin-boson model by Anthony Leggett of the University of Illinois at Urbana-Champaign also suggests dramatically extended decoherence times for low-frequency phonons. Leggett also points out that because the dominant mode of decoherence is via phonon coupling to the environment, an acoustical mismatch between the immediate and wider environment of the quantum system could prolong coherence at low frequencies. Furthermore, it is not necessary for all degrees of freedom to enjoy subdued decoherence: significant quantum biological effects might require only a small subset to be protected.

### The origin of life

A century and a half after Charles Darwin published *On The Origin of Species*, the origin of life itself remains a stubborn mystery, and is deeply problematic. The simplest known living organism is already stupendously complex, and it is inconceivable that such an entity would arise spontaneously by chance self-assembly. Most researchers suppose that life began either with a set of self-replicating, digital-information-carrying molecules much simpler than DNA, or with a self-catalyzing chemical cycle that stored no precise genetic information but was capable of producing additional quantities of the same chemical mixture. Both these approaches focus on the reproduction of material substances, which is only natural because, after all, known life reproduces by copying genetic material. However, the key properties of life – replication with variation, and natural selection – does not logically require material structures themselves to be replicated. It is sufficient that *information* is replicated. This opens up the possibility that life may have started with some form of quantum replicator: Q-life, if you like.

It is well known that wavefunctions as such cannot be cloned, but discrete quantum information, for example spin direction or energy-well occupation, can be copied. The advantage of simply copying information at the quantum level, over building duplicate molecular structures, is speed. A copying event might proceed on a chemical or tunnelling timescale of femtoseconds. This should be compared with the 10 ms that it takes to replicate a DNA base pair. Q-life can therefore evolve many orders of magnitude faster than chemical life. Moreover, quantum fluctuations provide a natural mechanism for variation, while coherent superpositions enable Q-life to evolve rapidly by exploring an entire landscape of adaptive possibilities simultaneously. Of course, the environment of this hypothetical Q-life is unknown, but the surface of an interstellar grain or the interior of a comet in the Oort cloud offer low-temperature environments with rich physical and chemical potential.

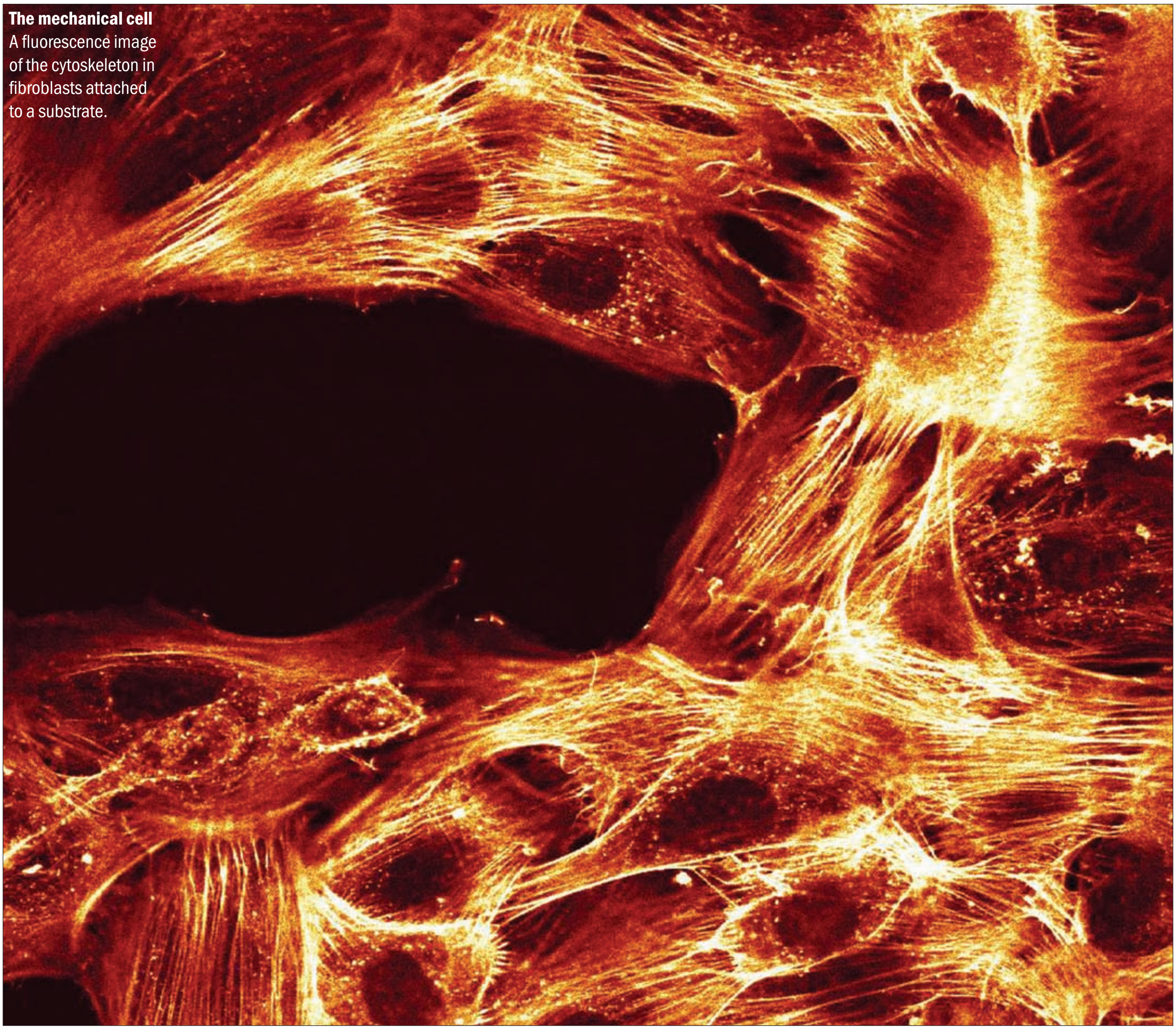
How would Q-life evolve into familiar chemical life? A possible scenario is that organic molecules were commandeered by Q-life as more robust back-up information storage. A good analogy is a computer. The processor is incredibly small and fast, but delicate: switch off the computer and the data are lost. Hence computers use hard disks to back up and store the digital information. Hard disks are relatively enormous and extremely slow, but they are robust and reliable, and they retain their information under a wide range of environmental insults. Organic life could have started as the slow-but-reliable "hard-disk" of Q-life. Because of its greater versatility and toughness, it was eventually able to literally "take on a life of its own", disconnect from its Q-life progenitor and spread to less-specialized and restrictive environments – such as Earth. Our planet accretes a continual rain of interstellar grains and cometary dust, so delivery is no problem. As to the fate of Q-life, it would unfortunately be completely destroyed by entry into the Earth's atmosphere.

There is accumulating and tantalizing evidence that quantum mechanics plays a key role here and there in biology. What is lacking is any clear case for a general "quantum life principle" that might offer a new conceptual framework in which the remarkable properties of living systems can be understood, as Schrödinger and others hoped. However, the physics of complex far-from-equilibrium quantum systems with non-linear couplings is in its infancy, and further surprises undoubtedly lie in store. Meanwhile, researchers in quantum-information science intent on reducing decoherence might find the study of biological nanomachines surprisingly rewarding. ■

# Viral link

Bacteriophages like the one shown here are viruses that attack bacteria – *E. coli* bacteria in this case. For the interdisciplinary team of physicist Max Delbrück, geneticist Alfred Hershey and microbiologist Salvador Luria, who shared the 1969 Nobel Prize in Physiology or Medicine , these "phages" became a remarkable tool for studying the complex processes by which viruses infect bacteria, exchange genetic information and replicate themselves with the help of their hosts. Their work provided important insights into the way bacteria develop resistance to attacking agents such as antibiotic drugs, and established the simple, quick-replicating phage as a workhorse of microbiology research. Delbrück's Nobel prize, lying as it does well outside the traditional confines of physics, is a testament to the value of physicists whose ideas stretch beyond disciplinary boundaries.

Lee D Simon/Science Photo Library



**The mechanical cell**
A fluorescence image of the cytoskeleton in fibroblasts attached to a substrate.

# Do cells care about physics?

Startling new discoveries show that there is more to the cell than just genetics and biochemistry, explains **Jochen Guck**

Ever since James Watson and Francis Crick cracked the code of life and laid the foundations for molecular biology, biologists have almost exclusively focused on the molecular aspects of biological systems. This cumulated in the mapping of the entire human genome a few years ago – the entire blueprint of every cell. So, does that mean we can stop? Is everything known that we can possibly know about cells? Far from it.

The situation is similar to knowing all the elements in the periodic table, which is just the basic information you can have on one particular level of structural organization. But the combinations of these elements are many. The situation is even worse with genes and proteins because there are many more of them, and so many ways in which they can interact and influence each other to come to some ultimate outcome, not to mention the redundancy in the system. One just needs to look at the extensive interaction cascades of proteins, so-called signalling pathways, being diligently constructed by countless molecular biology labs using gene- and protein-expression screens to feel queasy.

Bioinformatics might seem like an appropriate way to deal with this wealth of information. Just let a computer grind through the data to find some pattern or

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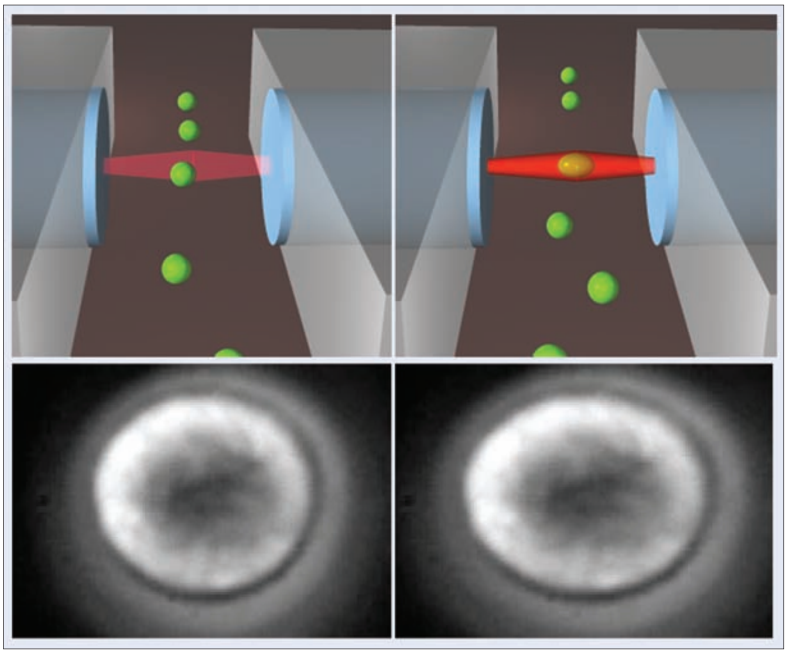


**Stretching it** Cells flowing along a microfluidic channel are trapped (top left) and consecutively stretched (top right) by two counter-propagating laser beams. This can be used to serially test the deformability of cancer cells. An image of a suspended cell trapped (bottom left) and deformed (bottom right) in an optical stretcher. The amount of deformation is directly related to the mechanical properties of the cell.

some statistically significant change in a subset of proteins. But does that help? How can this contribute to any sort of conceptual understanding of the system? Could there be other aspects of cells that might be more informative for understanding cellular behaviour? The situation has been likened to trying all the switches in the cockpit of a plane in mid-air in order to find out how to fly it. Surely there is some chance that this might ultimately be successful – given enough tries. But then again, this does not answer the key question: why would it work? The conceptual level of understanding that involves the connection between speed, wing shape and the resulting lift is not accessible in this way. The essence of why planes fly is lost. Well, maybe it is also time to take a few steps back and to take a fresh look at the situation with living cells.

Could the global elastic properties of cells in concert with that of their surrounding tissue be important in understanding what cells can and cannot do?

### A physicist's view

Physicists are used to jumping between length scales as appropriate to solve a particular problem. Nobody would try to describe the motion of a rubber ball bouncing up and down by solving Schrödinger's equation for all the constitutive atoms. Instead, the emergent resulting effect of the many interactions between all the atoms is captured in a single number, the elastic modulus, that is sufficient to describe the motion of the ball. So, could the global elastic properties of cells in concert with that of their surrounding tissue also be important in understanding what cells can and cannot do?

The mechanical properties of cells are largely determined by their cytoskeleton, a hybrid polymer gel consisting of several kinds of different filaments that are transiently connected (or "cross-linked") by specific proteins and pushed along each other by motor proteins. Soft-condensed-matter physics, and specifically polymer physics, has helped to shed some light on this structure and the emergence of its mechanical properties.

But the cytoskeleton is not just some boring packaging material. It is kept far from equilibrium by the coupling of its polymerization to the hydrolysis of adenosine triphosphate, or ATP, the molecule that supplies energy to living organisms. In some cells a significant fraction of their available energy is actually expanded in the constant turnover of the cytoskeleton even when resting. It is conceivable that the cell is doing this for a purpose: to keep it ready to spring into action when needed. Indeed, the cytoskeleton is involved in such vital cell functions as motility (towards food or invading pathogens), phagocytosis (the engulfing of such pathogens) and in the separation of chromosomes just before and during the actual pinching off of the two respective daughter cells throughout cell division. To make the connection back to molecular biology, all these processes are of course controlled by signalling pathways, often involving important molecules that also control the status of the cytoskeleton. But can the connection between cell function and cell mechanics also be used directly? Can we learn something about what cells are doing by measuring their mechanical properties? Recent research is increasingly pointing in this direction.

### Does soft matter?

One of the most fundamental functional changes that can happen is when a normal, mature cell, with a cytoskeleton specific for its task, turns into a cancer cell that stops doing what it is supposed to be doing and starts growing uncontrollably, often to the detriment of the entire organism. It has been known for quite some time that this malignant transformation goes hand in hand with a drastic restructuring of the cytoskeleton, which is key and even diagnostic for the progression of the disease. Therefore, it is not surprising that cancer cells also display different mechanical properties – they generally become more compliant. And there is some indication that they become increasingly more compliant the further the cancer progresses, which makes it more likely that they will spread and form metastatic settlements elsewhere in the body.

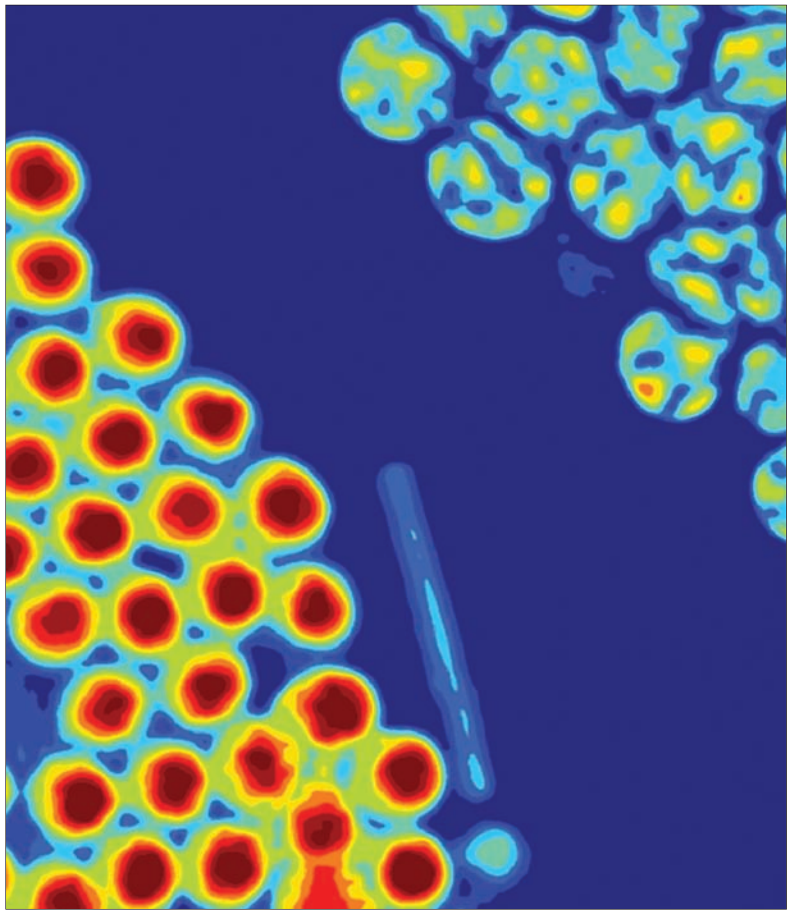
An anthropomorphic explanation for this tendency is that cells need to be soft in order to squeeze through the surrounding tissue, to get into and circulate through the blood or lymph system, and to eventually leave it again. A rigid cell would not be able to do this and would be stuck in its original position.

So, rather than *looking* for suspect cells, it seems sensible to start *feeling* for them. This insight can be exploited in diagnosis, for example, using a "microfluidic optical stretcher" – an optical trap where two non-focused and counter-propagating laser beams trap and localize cells from a flowing suspension and subsequently deform them using purely optical forces. This optical stretcher can be combined with microfluidic delivery of cells and automated control of the measurement process for high throughput. Such a microfluidic optical stretcher lets researchers analyse many individual cells in suspension, which can be obtained non-invasively from a patient by needle-aspiration biopsy from internal tumours or by brushing suspect lesions. As few as a hundred cells are sufficient to get statistically significant data. Such a mechanical analysis could help identify primary tumours that are likely to spread, with a potentially large impact on any therapy.

Identifying cells of interest by their mechanical fingerprint also allows them to be sorted and subsequently cultured for further detailed investigation. In turn, measuring the mechanical properties of cells under the influence of drugs might help identify treatments that can stiffen up potentially dangerous cells to prevent them from infiltrating other tissues. Of course, using mechanical measurements for characterizing and sorting cells is not limited to pathological changes, it can also be done for any functional changes in the cell that influence the cytoskeleton, such as cell division or differentiation.

The importance of mechanical properties goes beyond the borders of an individual cell. It has been known for some time that some cells are sensitive to mechanical stimuli from their environment. One just needs to think of the bone loss experienced by astronauts after they have been deprived of the Earth's normal gravitational pull. It is also conceivable that the cells lining the blood vessels, throat or lungs respond to the mechanical stimulus provided by blood pulsation, the passage of food or breathing, respectively. This mechano-sensitivity – the ability of cells to measure and respond to the mechanical properties of their environment – has increasingly been the focus of much biophysics research in recent years. For example, we now know that many cells migrate up stiffness gradients – a phenomenon aptly termed durotaxis – or change their morphology, appearance, proliferation or growth depending on the stiffness of the substrate that they are sitting on. In fact, Dennis Discher's group at the University of Pennsylvania has shown that stem cells spontaneously differentiate into cell types that would be found in tissues with the mechanical properties of the substrate they were cultured on. When the researchers grew mesenchymal stem cells, which can differentiate into a variety of cell types, on soft substrates that mimicked the softness of the brain, these cells turned into neurons. When the same cells, in the same medium, were grown on substrates with intermediate stiffness (similar to heart tissue), they became muscle cells. And on very stiff substrates, comparable to bone, the cells differentiated into bone cells. Moreover, once these cells had committed to becoming a particular cell type, the standard biochemical method used to induce differentiation was unable to transform them into other cell types. In this case, mechanical cues can obviously supersede even biochemical ones.

This finding also suggests an interesting explanation of why a layer of "feeder cells" – those that are required in order to grow the cells of interest – is required to keep stem cells from differentiating in the culture. The soft feeder cells mechanically shield the sensitive stem cells from the hard culture surface underneath and prevent the differentiation being triggered mechanically. How cells are able to convert these mechanical cues into some signal compatible with the known internal biochemical pathways is currently still an open question and a very hot topic in this field. Still, given that cells are generally cultured on hard plastic dishes and imaged on even harder glass slides (which are many orders of magnitude stiffer than anything found in the body – even bone), one cannot help wondering whether what seems to be known in cell biology might ultimately turn out to be artefacts of these unphysiological conditions.



**Lenses in the cell** Maps of the quantitative phase profiles of conventional (upper-right corner) and inverted (bottom-left corner) photoreceptor nuclei. The dark red colour in the inverted nuclei indicates high refractive index, which turns the nuclei into microlenses.

### Beginning to see the light

In addition to mechanics, there are further examples where cells seem to care more about physics than about gene regulation. For instance, the optical properties of cells found in the retina of vertebrates, including humans, seem to be optimized for the transmission of light. The retina is a layer of tissue covering the back of the eye where light is converted into electrical signals, processed and sent on to the brain. The retina has a striking anatomical peculiarity: it is inverted. The light-sensing photoreceptor cells are located on the wrong side – turned away from the eye lens. This means that any image projected onto the front of the retina has to travel through hundreds of microns of tissue before it is received. Even if the tissue is transparent and does not absorb the light, it still consists of many individual cell bodies and internal organelles with varying refractive indices that should lead to scattering and distortion of any image projected through it. The situation is similar to placing a thin diffusing screen in front of the CCD chip of a camera, which seems absurd. This strange arrangement has puzzled scientists for a long time.

But two recent extraordinary findings by an interdisciplinary group of neurobiologists at the University

**Night light**
An illustration of the light-path through the retina. The two bright structures running vertically are Müller glial cells that act like optical fibres and transmit light incident on the retina from the top towards the photoreceptors at the bottom, bypassing all other potentially scattering cells. In the last third of the retina of nocturnal mammals, the inverted photoreceptor nuclei (spherical objects) act as microlenses and further transport the light to the photoreceptor segments (cylinders) at the bottom.

Jens Grosche, Leipzig University

of Leipzig and the Max Planck Institute for Brain Research in Frankfurt, geneticists at the Ludwigs Maximilian University in Munich and physicists at the Cavendish Laboratory in Cambridge have revealed how nature optimized this unfortunate situation: by tweaking the arrangement and refractive indices of the cells and organelles in the retina. The first discovery involves glial cells, which are specialized cells that make up 90% of the cells in the central nervous system (the other 10% are neurons). The long cylindrical glial cells of the retina, so-called Müller cells, span two-thirds of the thickness of the retina. These cells have a higher refractive index than the surrounding tissue and serve as optical fibres to guide the light through the retina. To reduce potential scattering by these cells, their cytoskeletons are densely packed, arranged along the direction of the light, and otherwise contain very few internal organelles such as mitochondria. Even the nucleus is located outside the cell waveguide and clings to it like a backpack. The dense parallel array of all these Müller cells is reminiscent of artificial fibre-optic plates that are used to relay images over distances with low loss and distortion, which suggests a similar function in the retina.

If this is already a surprising adaptation, then the second discovery is nothing short of stunning. Below the layers bridged by the Müller-cell array is the outer nuclear layer of the retina that the light still has to traverse. It turns out that, in nocturnal animals, the nuclei in these layers have an arrangement of chromatin – the material that forms chromosomes – that is unlike the one found in nuclei of any other cell type in the body or even in the same cells in diurnal animals. The DNA contained in a single nucleus is about 2 m long when stretched out. To fit into a 10 $\mu$m nucleus it is tightly wrapped around proteins and coiled up into chromatin. The chromatin with the genes not currently needed, called heterochromatin, is especially densely packed and stowed away at the nuclear periphery; while euchromatin, containing often-used genes, is more accessible and found at the centre. This arrangement of chromatin is so universal that it can be called "conventional". However, in the outer nuclear layer in nocturnal animals, the heterochromatin is at the centre and the euchromatin is on the outside. Given that denser heterochromatin has a higher refractive index, this unique inversion turns the nuclei from scattering obstacles into little microlenses that focus the light through the outer nuclear layer without much scattering while maintaining a high signal-to-noise ratio. The improved transmission leads to an optical advantage for seeing at low light levels, which has apparently caused this massive rearrangement to occur during evolution. The complete restructuring is even more surprising given that the relative position of the genes with respect to the location of hetero- and euchromatin is heavily implicated in the way that the cell regulates gene expression. This means that these nuclei have thrown the entire conventional nuclear machinery (tried and tested for hundreds of millions of years and conserved in all other cells) overboard in order to optimize their optical properties. There is no light-guiding gene in cells. The refractive index is a collective property emerging at a different conceptual level – physics – and we are increasingly finding that the same applies to many other case studies of the cell.

It should not be surprising that relevant contributions to biology are not only coming from the crowded and very competitive mainstream area of this discipline, but also from its fringes. As Thomas Kuhn argued in his book *The Structure of Scientific Revolutions*, science does not progress linearly within certain paradigms but by changing paradigms. Physicists have always played an important role in opening up the view to new possibilities and new angles of investigation. Maybe it is not a coincidence that contemporary biology, originally conceived in the Cavendish Laboratory, will require physical approaches and considerations to take the next conceptual steps in advancing our understanding of biological systems. Physics may well be the new way to think about biology.

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# Medical lifeline

This image of a child's face was taken using computer-assisted tomography – popularly known as a CAT scan. This non-invasive method of obtaining 3D X-ray images inside the human body has become a ubiquitous tool for radiologists, who use it to detect tumours and diagnose brain injuries. Physicist Allan Cormack, who was the first researcher to tackle the problems of 3D radiography, and Godfrey Hounsfield, who developed the first practical scanner, shared the 1979 Nobel Prize in Physiology or Medicine for their efforts.



# Postcards from the brain

**Sam Wang** describes some of the physics of our most complex organ

Mike Agliolo/Science Photo Library

Brains have long been compared to the most advanced existing technology – including, at one point, telephone switchboards. Today, people often talk about brains as if they were a sort of biological computer, with pink mushy "hardware" and "software" generated by life experiences.

However, any comparison with computers misses a messy truth. Because the brain arose through natural selection, it contains layers of systems that arose for one function and then were adopted for another (even though they do not work perfectly). An engineer with time to get it right would have started from scratch each time, but it is easier for evolution to adapt an old system to a new purpose than to come up with an entirely new structure. Neuroscientist David Linden at Johns Hopkins University has compared the evolutionary history of the brain to the task of building a modern car by adding parts to a 1925 Ford Model T that never stops running.

This complex organ, which is responsible for our thoughts, feelings and awareness, has lured many physicists into applying their own bags of tricks to questions in neuroscience. Some ideas, such as the speculation put forward by Roger Penrose of Oxford University in the UK and Stuart Hameroff of the University of Arizona in the US that brain function is influenced by quantum phenomena, are not taken seriously by neuroscientists. But there are still many respectable roles to be filled by expatriated physicists.

One challenge of neuroscience is to probe brain microstructure and dynamics, which experimentalists can address by designing new techniques. Examples include new methods in optical microscopy and magnetic resonance imaging. Another challenge comes from the very large data sets generated by modern experimental methods, which demand new approaches to analysis. Finally, theoretical principles are waiting to be identified and developed to the point of yielding testable predictions.

### Compact dim bulbs

One striking feature of brain tissue is its compactness. In the brain's wiring, space is at a premium, and it is more tightly packed than even the most condensed computer architecture. One cubic centimetre of human brain tissue, which would fill a thimble, contains 50 million neurons; several hundred kilometres of axons, the wiring over which neurons send signals; and close to a trillion synapses, the connections between neurons.

The memory capacity in this small volume of tissue is potentially immense. Electrical impulses that arrive at a synapse give the recipient neuron a small chemical kick that can vary in size. This variation in synaptic strength is thought to be a means of memory formation. Work at my lab at Princeton University and others has shown that on timescales of less than an hour, synaptic strength flips between extreme high and low states, a flip that is reminiscent of a computer storing a "one" or

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Geoff Tompkinson/Science Photo Library

**Cleverly done** A close-up of the cerebral folds on the surface of a human brain. Folding may reflect optimization to minimize the "wire" length of internal connections.

a "zero" – a single bit of information. These transitions are often triggered by biochemical signals that are generated when the sending and receiving neuron fire in close succession, and jumps in strength may increase the likelihood of the re-occurrence of a particular activity sequence, a repetition that may underpin the first stages of how we store memories and recall past events.

With compactness also comes tremendous efficiency. Your brain uses about 12 W of power, an amount that supports not only memory but all your thought processes. This is less than the energy consumed by a typical refrigerator light, and half the typical needs of a laptop computer. In this sense, we are all dim bulbs.

However, efficiency comes at a cost. Synaptic strength may change in an all-or-nothing fashion, but that is only true for measurements of strength averaged over dozens of signalling events. At any given moment, a single synapse can be remarkably flaky. Even under normal, healthy conditions, synapses release neurotransmitter only a small fraction of the time when their parent neuron fires an electrical impulse. This unreliability may arise because individual synapses are so small that they contain barely enough machinery to function. This may be a trade-off that allows the most function to be stuffed into the smallest possible space, with the idea that a sufficiently large number of synapses can overcome this unreliability. Currently, it is not known whether synaptic unreliability is reflected at the level of behaviour.

Your brain uses about 12 W of power, this is less than the energy consumed by a typical refrigerator light, and half the typical needs of a laptop computer

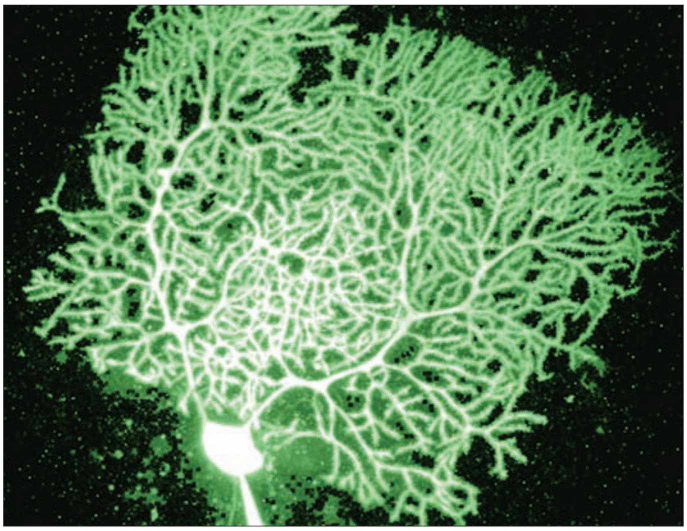
Another consequence of the ruthless efficiency required by natural selection is that the amount of wiring used by brains appears to be minimized. Theorists have investigated the total length of input (dendrite) and output (axon) wiring used in brain circuits from animals as diverse as worms and mammals. Wiring typically fills about one-third of mammalian brain tissue's "grey matter", where the neurons and synapses are found, and nearly all of its "white matter", which is made of axons and gets its colour from the insulating fatty sheath that surrounds each axon. This wiring tends to assume a configuration that has close to the least possible total length. For example, in the cerebral cortex, where nearly all of the connections run from one place to another within the cortex, the grey matter forms a rind that surrounds the white matter. When you look more closely, any given bit of grey matter in the cerebral cortex is layered like a cake, with connections passing from layer to layer. The layers are arranged such that a hypothetical shuffling of the order of the layers would increase the total amount of wiring used, sometimes considerably.

It is not yet known how this wiring is minimized. It is likely that some minimization is predetermined by developmental steps in the form of genetically determined programmes acting through cell biological mechanisms. In addition to pre-programmed steps, the wires themselves may play a self-optimizing role as they grow. Axons growing on a stationary surface have been shown to exert a small amount of force along their length. Such forces can minimize length, in analogy to the way that surface tension acts to minimize the area of soap-film patterns. It has also been suggested that the location of the convolutions on the surface of the brain is determined by such force-generating mechanisms. Just as a sheet with springs here and there would tend to scrunch up, a slab of brain tissue joined at various points by long-distance axons might start to fold.

Other evolutionary constraints may determine the amount of folding, as well as other features of how brain size scales. The mammalian neocortex (also known as cerebral cortex) shows regularities that suggest that brain structure may be subject to universal design constraints. From shrews to whales, mammalian brains vary over 100 000-fold in volume. Over this range, large brains are more folded than small brains: the surface area of the cerebral cortex follows a power law relative to cortical volume that is greater than simple geometry would predict. Using electron microscopy, my group has found that, on average, neocortical axons are wider in large brains than in small brains. The space demanded by these axons is sufficient to account for the increased folding seen in large brains, as well as disproportionate increases in white-matter volume. But why do axons become wider? The conduction velocity of a nerve impulse is known to scale with the thickness of the axon. It may be that widening of axons is driven by an evolutionary need to preserve the time it takes for a nerve impulse to cross the brain.

### Watching the brain in action

Another area where physical scientists can make a contribution is in probing how brain tissue processes information. Addressing this issue requires the monitoring of activity in the intact brain and the reconstruction of whole neural-circuit connectivity – two daunting tasks. Physical scientists have entered the fray by inventing a variety of instruments. One breakthrough technology has been multiphoton microscopy, which uses infrared emission from ultrafast lasers. This light does little damage to living tissue and is capable of excellent optical penetration, thus allowing observations in brain tissue, a highly scattering medium. Fluorescent probes, both synthetic dyes and genetically encodable molecules based on green fluorescent protein, have been developed to label neuronal structure. Some probes have been designed to change conformation, and therefore their fluorescent properties, when they bind to calcium ions, which enter neurons when they



**Action-packed** A mammalian neuron filled with fluorescent dye and visualized using the physics-based technique of two-photon microscopy.

are active. Indeed, neural activity can now even be imaged in live rodents running on a foam ball floating on jets of air! Other probes allow neurons to be activated or deactivated by light. Taken together, these technologies open the possibility of spying on perturbing neural circuitry in action – an exciting frontier in modern neuroscience.

An outstanding challenge is the full mapping of circuit structure along with the neurochemical identity of the circuit's cellular components, and many researchers are working hard to develop tools to trace these connections in unprecedented detail. One such instrument performs scanning electron microscopy on the face of a block of preserved tissue as it is shaved off layer by layer, thereby generating thousands of images that together contain microstructural information from whole volumes of circuitry. Reconstructing a circuit diagram from the resulting terabytes of data is a daunting task requiring advances in image analysis as well as innovative molecular-biological approaches to identifying specific types of cells. The ultimate goal is the full reconstruction – and eventual understanding – of brain circuits and the processing they perform.

### A deeper question

Like many physical scientists, I was drawn to neuroscience by the mysteries of consciousness and thought, and by the promise of a field where the most exciting discoveries lie in the future. I regard neuroscience as a younger cousin to traditional "deep questions" in physics about how the world works, from particle physics (what everything is made of) to cosmology (where it all came from). Neuroscience addresses the issue of how it is that human beings are able to ask any of these questions in the first place.

Today, neuroscience has found its own *raison d'être*. It exists as an area of research that is unusual for the degree to which it draws upon other disciplines, including physics. In 2008 membership of the main US brain-science organization, the Society for Neuroscience, hit an all-time record of nearly 39 000 individuals, close to the American Physical Society's tally of 46 000. Now is the best time ever to have a foot in both camps.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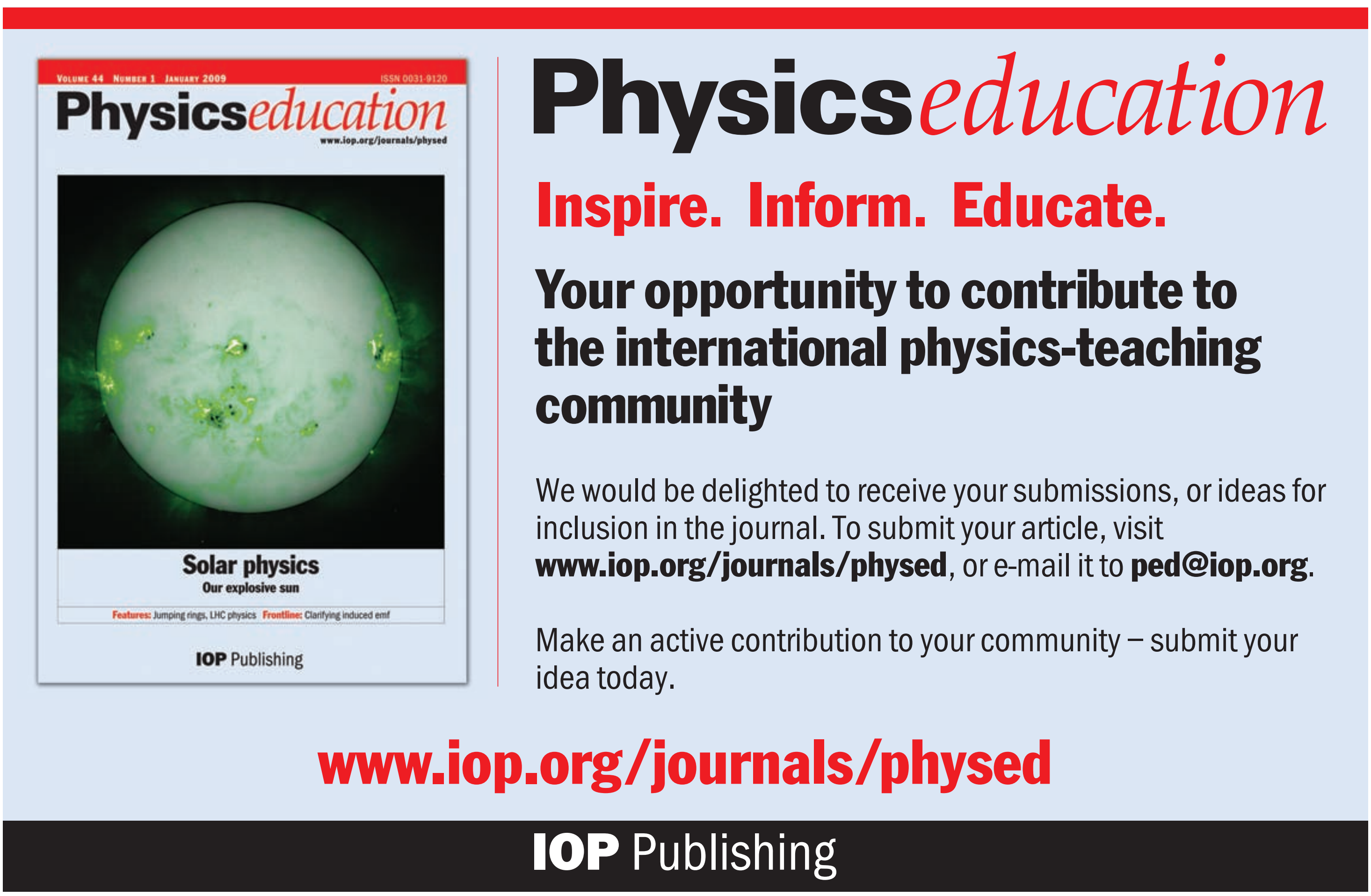
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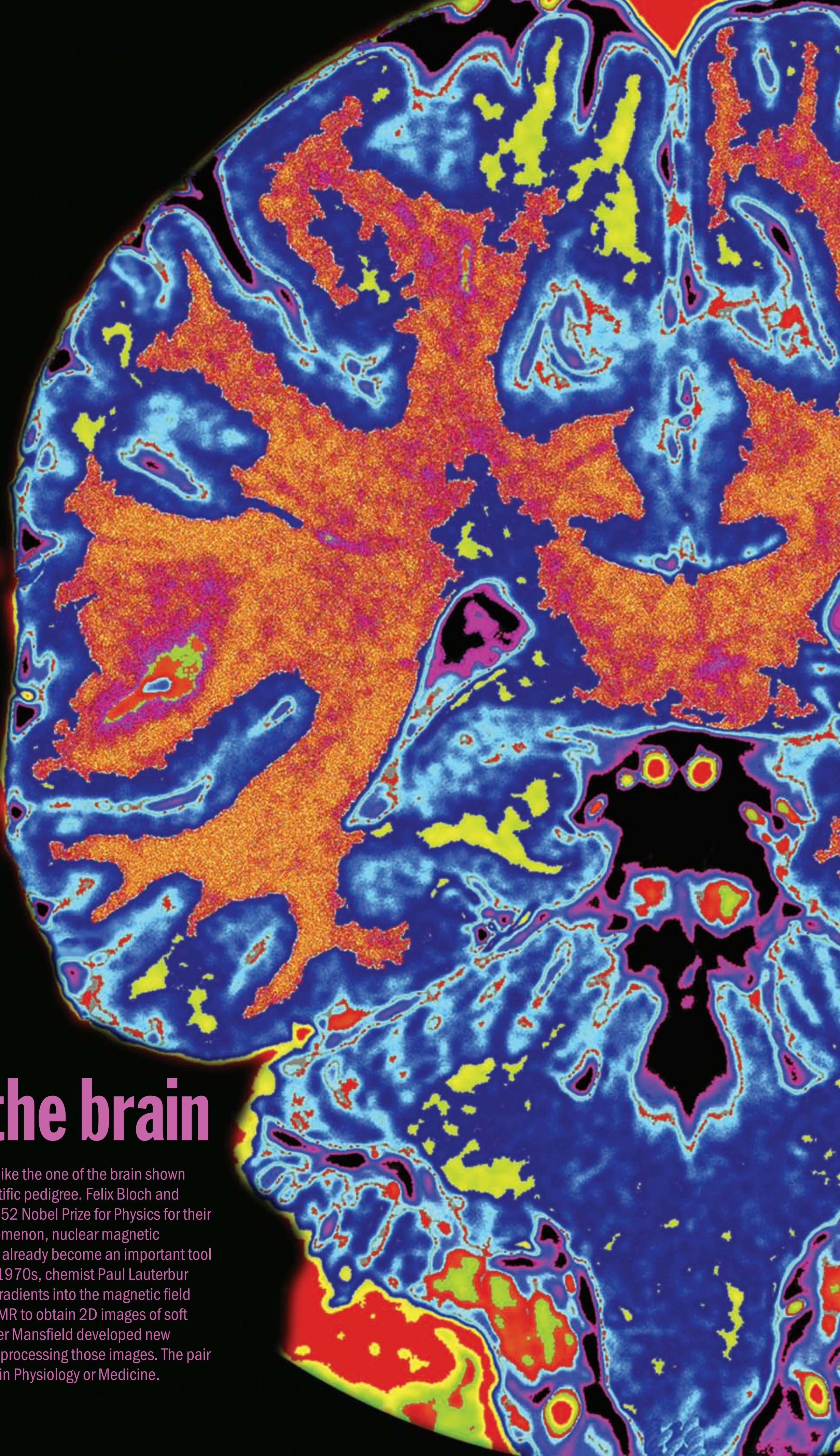

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# Inside the brain

Magnetic-resonance images like the one of the brain shown here have an illustrious scientific pedigree. Felix Bloch and Edward Purcell shared the 1952 Nobel Prize for Physics for their work on the underlying phenomenon, nuclear magnetic resonance (NMR), which had already become an important tool for spectroscopy. During the 1970s, chemist Paul Lauterbur discovered that introducing gradients into the magnetic field allowed researchers to use NMR to obtain 2D images of soft tissue, while physicist Sir Peter Mansfield developed new mathematical techniques for processing those images. The pair shared the 2003 Nobel Prize in Physiology or Medicine.

# Darwin's legacy

Born 200 years ago, Charles Darwin is rightly celebrated for his work explaining the origin of species. But in setting a new standard for what an explanation of nature should be like, he also had a huge impact on physics and cosmology, as **Leonard Susskind** explains

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Charles Darwin was no theoretical physicist, and I am no biologist. Yet, as a theoretical physicist, I have found much to think about in Darwin's legacy – and in that of his fellow naturalist Alfred Russell Wallace. Darwin's style of science is not usually thought of as theoretical and certainly not mathematical: he was a careful observer of nature, kept copious notes, contributed to zoological collections; and eventually from his vast repertoire of observation deduced the idea of natural selection as the origin of species. The value of theorizing is often dismissed in the biological sciences as less important than observation; and Darwin was the master observer.

I think that view misses something essential, namely the great formal beauty and almost mathematical inevitability of Darwin's ideas. Like Einstein's greatest ideas, the theory of evolution is based on a simple gedankenexperiment: start with a very simple reproducing organism, add Mendel's laws of heredity and mutability, and follow the system as it inescapably branches out into a tree of life.

Darwin was not particularly interested in astronomy or physics, yet his impact on cosmology was enormous but in a way subconscious. In successfully explaining the origin of species, he eliminated superstition and set a new standard for what an explanation of nature should be like. As I wrote in my book *The Black Hole War* (Little Brown, 2008), Darwin's masterstroke was to have "ejected God from the science of life".

True, Darwin was not the first scientist to cast out supernatural beliefs. Two centuries earlier, Newton – another great Cambridge scientist – had done so more than anyone before his own time. Inertia (mass), acceleration and a universal law of gravitation replaced the hand of God, which was no longer needed to guide the planets. But as historians of 17th-century science never tire of reminding us, Newton was a Christian and a passionate religious believer at that. He spent more time, energy and ink on Christian theology than on physics.

For Newton and his peers, the existence of an intelligent creator must have been an intellectual necessity: how else could you explain the existence of man? Nothing in Newton's vision of the world could explain the creation, from inanimate material, of so complex an object as a sentient human being. Newton had more than enough reason to believe in a divine origin.

But what Newton failed to do, two centuries later the ultimate (and unwilling) subversive Darwin succeeded at. Darwin's idea of natural selection – combined with the subsequent discovery by James Watson and Francis Crick (also at Cambridge) of the double-helix structure of DNA – replaced the magic of creation with the laws of probability and chemistry.

In other words, before Darwin, even the greatest physicists had little alternative to a supernatural explanation of the origin of life, and therefore of nature itself. It was the success of Darwinism that forced the issue and set the standard for future theories of origins, whether it be it of life or of the universe. Explanations must be based on the laws of physics, mathematics and probability – and not on the hand of God.

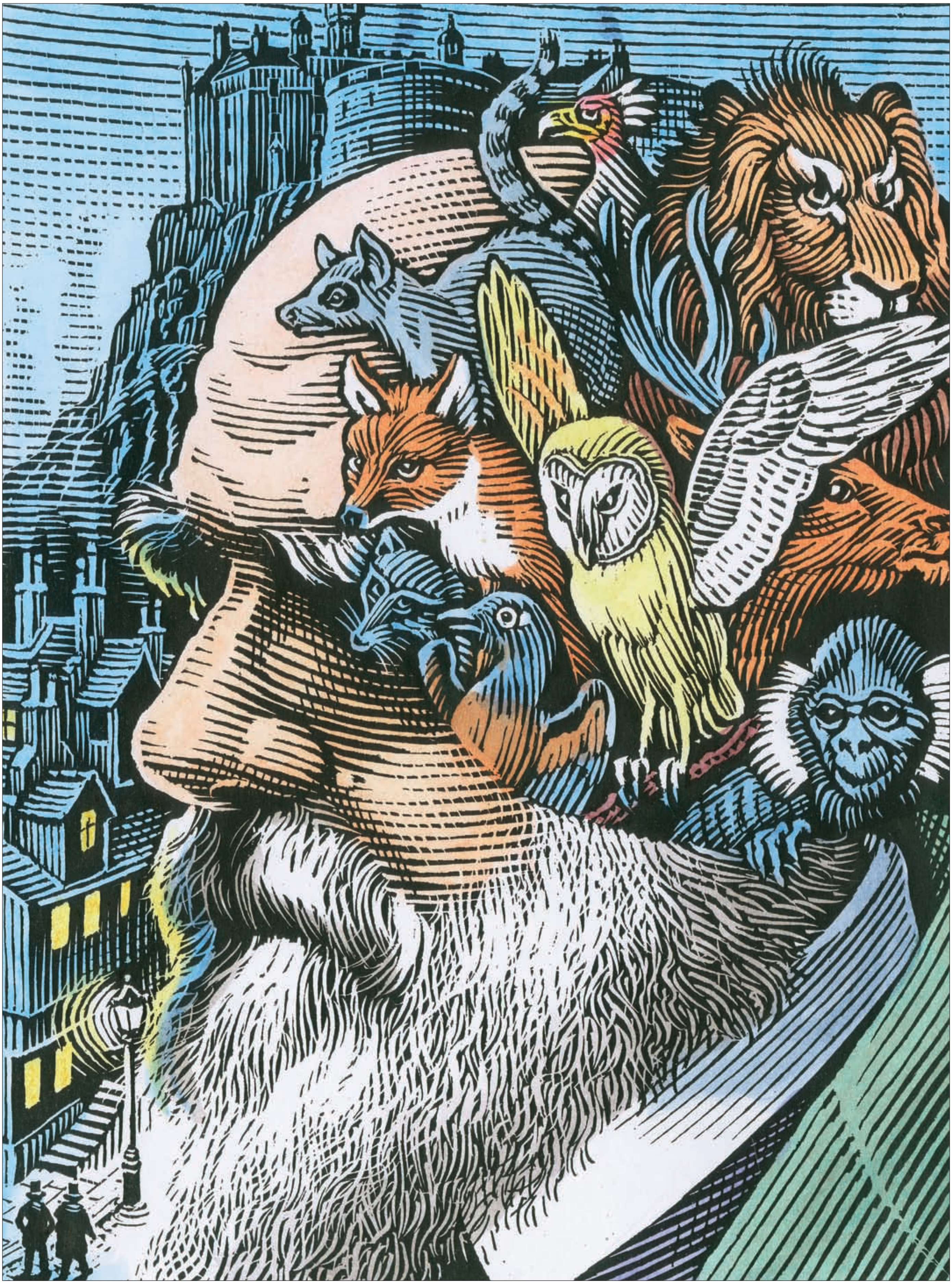
## Rejecting the watchmaker

Early in his life, Darwin was deeply impressed by the arguments of the Reverend William Paley (1743–1805), a cleric who had argued for what we would today call "intelligent design". Paley imagined finding a pocket watch lying on the ground, perhaps while walking in the woods. He might have wondered how such a complex, fine-tuned object came into existence. One possible answer is that it might have been the result of a random accident; a large number of molecules of various types combining by good fortune to form the watch. Paley rightly said that this was too unlikely to be taken seriously. There must be another explanation. The only one that made sense was that the watch had been made for some particular purpose by a skilled craftsperson – the watchmaker.

Paley pursued the thought further. We find in nature certain incredibly complex mechanisms, called human beings, that are capable of far more complex operations than the pocket watch. By analogy Paley argued that accidental creation is too unlikely and that human beings must have been created by an intelligent creator for some purpose.

How and why Darwin came to reject Paley's compelling argument is well known, but what is less noted is that physics and cosmology pose very similar questions,

Explaining the special properties of our universe involves the same two central principles of Darwinian evolution: an enormous landscape of possibilities and random mutation



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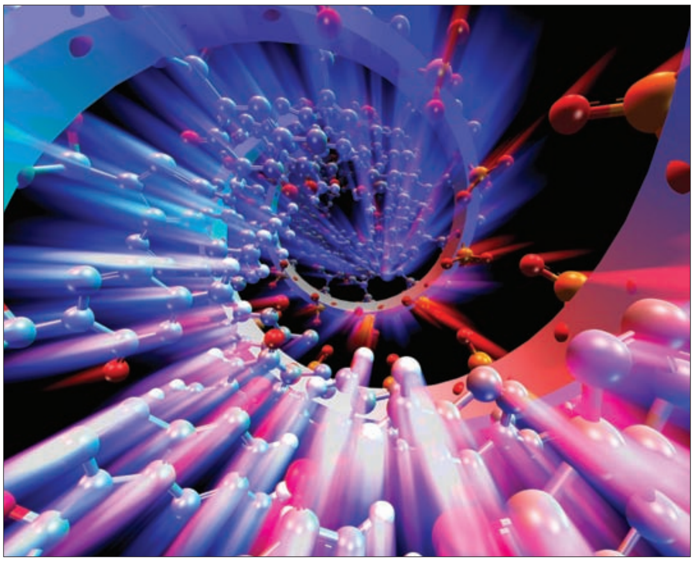

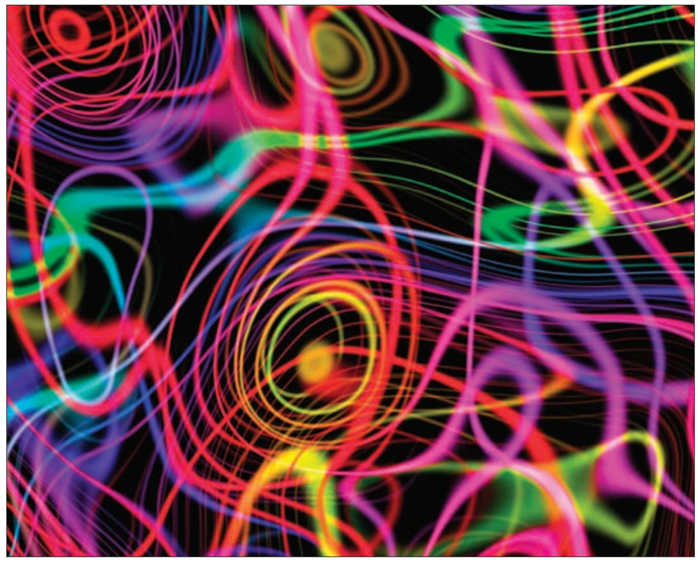

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**Vast possibilities** A DNA molecule (left) with, say, a hundred million different base pairs A, G, C and T can be arranged in $4^{100\,000\,000}$ different ways. For something interesting – life – to emerge from the enormous landscape of possible biological designs, both Darwinian natural selection and the ability of DNA to mutate are needed. Meanwhile, string theory (right) says that the universe consists of fluxes, branes and other elements arranged on a tiny knot of higher-dimensional space. The vast "landscape" of different ways in which these elements can be arranged forms an uncanny parallel with the many different possible arrangements of base pairs on a DNA molecule.

such as why the universe seems so incredibly fine-tuned for the existence of life. The only explanation, if we can call it an explanation, is that if it were less fine-tuned, intelligent observers like ourselves would have been impossible. I am, of course, referring to the cosmological constant, $\Lambda$. Theoretically, one would expect $\Lambda$ to be unity in natural Planck units. But if it were anything bigger now than it is known to be – $10^{-123}$ – it would have prevented the evolution of galaxies, stars and us. Like Paley, we encounter what appears to be an extremely unlikely occurrence.

Most physicists reject a supernatural explanation – a cosmic watchmaker – to account for this fact of fine-tuning. But if not a watchmaker, then what? Until recently, most physicists would have said that it was accidental, a numerical coincidence. The ambition of theoretical physics was to discover a unique mathematical explanation, having nothing to do with our own existence, for all the constants of nature. It would be just a lucky accident that they happened to fall into the narrow range where intelligent life can exist. But as Paley might have complained, accidents involving 123 decimal places are too unlikely.

### Enormity of the landscape

Over the last decade a new view has been taking shape, a view that in certain ways has common features with biological evolution. Darwin and Wallace emphasized mutability and natural selection as the main drivers of evolution, but there is something even more basic. Mutability and natural selection would have been powerless to create a human being if it were not for one central fact: the enormity of the landscape of biological designs.

String theory and eternal inflation provide the only natural explanation of the universe that lives up to the standard set by Darwin

Biological designs are encoded in DNA molecules, which contain two polynucleotide chains twisted around each other to which with four different based pairs (A, G, C and T) are attached. In a complex creature each of these DNA molecules can contain many millions of base pairs. The possible arrangements of those base pairs define the biological landscape, and the number of possibilities is tremendously large. One hundred million base pairs, for example, can be arranged in $4^{100\,000\,000}$ ways.

Suppose for a moment that there were only a thousand possible designs, or even a million. What would be the likelihood that any of them would make an intelligent life-form? Completely negligible. But even if such fortunate designs are extremely rare, given $4^{100\,000\,000}$ combinations there will be a very large number of them. The first principle of biological evolution – even more fundamental than natural selection – is the enormity of the landscape of biological designs.

The second principle is mutability: the fact that while reproducing, the instructions coded in DNA can discretely jump to new configurations. Natural selection is of course important, but without the mutable landscape nothing interesting would come of it.

The emerging paradigm for explaining the special properties of our universe is, in a sense, an attempt to live up to the standard set by Darwinian evolution: to provide a natural (as opposed to supernatural) non-accidental explanation for the apparently very unlikely specialness of the universe and its laws. Surprisingly, it involves the same two central principles: an enormous landscape of possibilities and random mutation. It even involves a mechanism similar to DNA.

### Darwinian standards

Let us begin with the DNA of a universe. What is it and why do we believe such a thing makes sense? String theory is the key. It supposes that at extremely small distances space is a complicated higher-dimensional manifold with many – typically six – tiny "extra" dimensions in addition to the three we see in everyday life. If we could look at the universe through a super-powerful microscope, we would see that it is composed of "Tinkertoy" elements called fluxes, branes, moduli, orientifolds (and more) all arranged on a tiny knot of higher-dimensional space called a Calabi–Yau manifold. The Calabi–Yau manifold is like the basic spine

Detlev van Ravenswaay/Science Photo Library

**Bubble universe** Every so often a new region of space is believed to have been created in the expanding early universe, with different properties and constants. This tiny bubble grew and became a new universe that itself reproduced and mutated – eventually leading to a grand multiverse, rare branches of which allow complex life.

of the DNA molecule, and the other elements can be arranged and rearranged in a huge variety of ways; perhaps as many ways as a real DNA molecule.

Just as the details of DNA determine the biological details of a living organism, so the details of the fluxes, branes and other elements determine the properties of the universe. Again, the numbers are so staggering that even if the world as we know it seems extremely unlikely, there will be many ways of arranging the elements to make the constants of nature consistent with life. In particular, there will be many configurations in which the cosmological constant will be fine-tuned to 123 decimal places.

What about reproduction and mutability? Here is where the inflationary theory of cosmology comes into play. There is much evidence that during the earliest epoch of the universe space itself expanded exponentially. Inflation was a process in which space grew like the surface of an inflating balloon, but instead of thinning out, as the rubber of the balloon would, new bits of space were created to fill the gaps.

For the most part, the new bits of space had the same DNA as the regions surrounding them, but every so often a mutation occurred. A bit of space with new properties, new constants and a new value for the cosmological constant was created. According to standard general relativity, that tiny bubble grew and eventually became a new inflating universe, reproducing and mutating. This whole process is called eternal inflation and it produced a grand multiverse as rich and varied as the tree of life, each with its own laws of physics, constants of nature and elementary particles. Here and there a very rare branch was created that had the special properties that would allow complex life.

Whether string theory with its huge landscape, and eternal inflation with its reproducing pockets of space, will prove to be correct is for the future to decide. What is true is that as of the present time, they provide the only natural explanation of the universe that lives up to the standard set by Darwin. ■

# Reviews

Andrew Steane

# Between chance and necessity

Petra Neumann/Sheelagh Carpendale/Science Photo Library

**Creative complexity** A computer-generated artwork based on the phyllotactic patterns found in nature.

**Reinventing the Sacred**
*Stuart Kauffman*
2008 Basic Books £15.99/$27.00hb 322pp

Stuart Kauffman argues that physics cannot explain biology, and he is right. However, I am willing to grant him this not because his book *Reinventing the Sacred* makes a clear case, but because I already agreed with its central premise, which is that the reductionist approach to science – the idea that physics explains chemistry, chemistry explains biology, and so forth – has its limits. The book nevertheless provides much food for thought; indeed, its chief merit is that it makes the reader ask fruitful questions. However, it falls short of making an argument that might overturn an entrenched position.

In addition to his central theme of reductionism and what might replace it, Kauffman – a complexity theorist and professor of both biology and physics at Calgary University in Canada – has two further aims for his book. One is to present to the non-expert some fascinating areas of science such as chemical-reaction networks, evolution and graph theory. The other is more ambitious: it aims to reassess in a positive way those areas of human life normally called sacred or spiritual, but from a point of view that does not accept supernatural theism.

Kauffman is at his best when writing about what he knows: complexity theory applied to theoretical biology, and some philosophy. Complexity theory deals with systems that typically involve feedback, non-linearity and structure at many scales; such systems turn out to share patterns of behaviour. Physics has made great strides in describing deterministic behaviour on the one hand and randomness on the other, but "critical behaviour" lies right on a fascinating borderline between these two regimes, and it deserves the widespread attention that Kauffman invites.

His introduction to Boolean networks is clear and stimulating, and their application to the cell's genetic control machinery is both beautiful and striking. While reading this chapter, it suddenly became obvious to me why a mere gene count is a completely inadequate measure of the complexity of the associated organism. The fact that the human genome is shorter than some, such as the lungfish, should not have surprised anyone.

Kauffman's treatment of the philosophy of mind is not as careful as a technical treatise would need to be. Still, it is sound and avoids the woefully inadequate statements that have sometimes appeared in connection with neuroscience in otherwise serious scientific journals – particularly claims that demonstrating a correlation between physical brain activity and particular thoughts resolves the mind–body problem or proves the absence or presence of God.

Another strength of the book is that Kauffman maintains reasonably clear lines of demarcation between speculation and knowledge. Within that proper constraint, the text makes some bold and useful speculations, such as the idea that quantum coherence could extend far enough from the surface of protein molecules in the cell to link one protein to another via aligned water molecules. Such speculations are useful because they are both testable and (just) feasible.

Because of these strengths, I would recommend *Reinventing the Sacred* as a healthy read for anyone who thinks that reductionism is the whole story of science. Reductionism is a good slave but a poor master; in other words, it is the right model for almost all the science we have discovered so far, but it is not necessarily the whole story. Cracks in the reductionist edifice include quantum entanglement, emergent phenomena, criticality and the oldest one of all: human free will, without which it is debatable whether any reasoning, and therefore any science, is possible.

On balance, this is a useful book. However, it also contains some glaring errors and omissions. The chapter on the quantum brain, for example, overinterprets the concept of decoherence, misapplies the word "acausal" and misses out entanglement altogether. The book is also repetitive, and sometimes unpersuasive or overblown. Take, for example, Gödel's incompleteness theorem, which states that any large enough, finite system of axioms and rules of deduction must give rise to propositions the truth of which cannot be decided within the system. This theorem is relevant to Kauffman's argument because it shows that not even formal logic can be reduced to a finite number of ideas; mathematics is a rich tapestry of concepts, not a pyramid. Kauffman briefly sketches Gödel's theorem no less than four times, but he never describes it sufficiently well for a reader unfamiliar with it to follow the argument. On the other hand, if readers are already familiar with Gödel, they do not need repeated incomplete sketches.

Moreover, the central argument is unconvincing when the book implies that a case has been proven when it has not. Concerning the animal heart, for example, an early chapter promises "the organisation of the heart arose largely by natural selection, which, as we will see, cannot be reduced to physics", and in due course some relevant evidence is given. However, when later the text says things like "…as we have seen, this cannot be reduced to physics", it leaves the reader feeling that something was missing in the middle. The evidence offered is that the emergent complexity of the biosphere may exceed the capacity of any compact description available beforehand to capture it. This and other arguments provide telling evidence for the case against reductionism, but it is, I think, premature to claim that we can prove the case sufficiently well to make reductionism clearly untenable.

The single greatest problem with this book is not in the science, however, but in the reasoning about the sacred. I am encouraged that Kauffman is willing to address questions of meaning and purpose, and his approach is surely preferable to pseudo-scientific statements along the lines of "the purpose of human life is to replicate genes". His aim is valid and worthy: to draw people together around shared values. With a view to this, the book argues for a kind of pantheism in which the word "god" is applied to the emergent creativity that exists in the universe.

Kauffman is welcome to promote this idea, but he should recognize that this type of thinking has a very long history and its shortcomings have been carefully thought through. For example, it does not adequately address our most basic hunches, such as the value of individual people above grand impersonal systems, and the need for justice or forgiveness. I would encourage him to explore instead those threads of religious thinking that are willing to seek answers beyond physicality, but that take physical evidence seriously.

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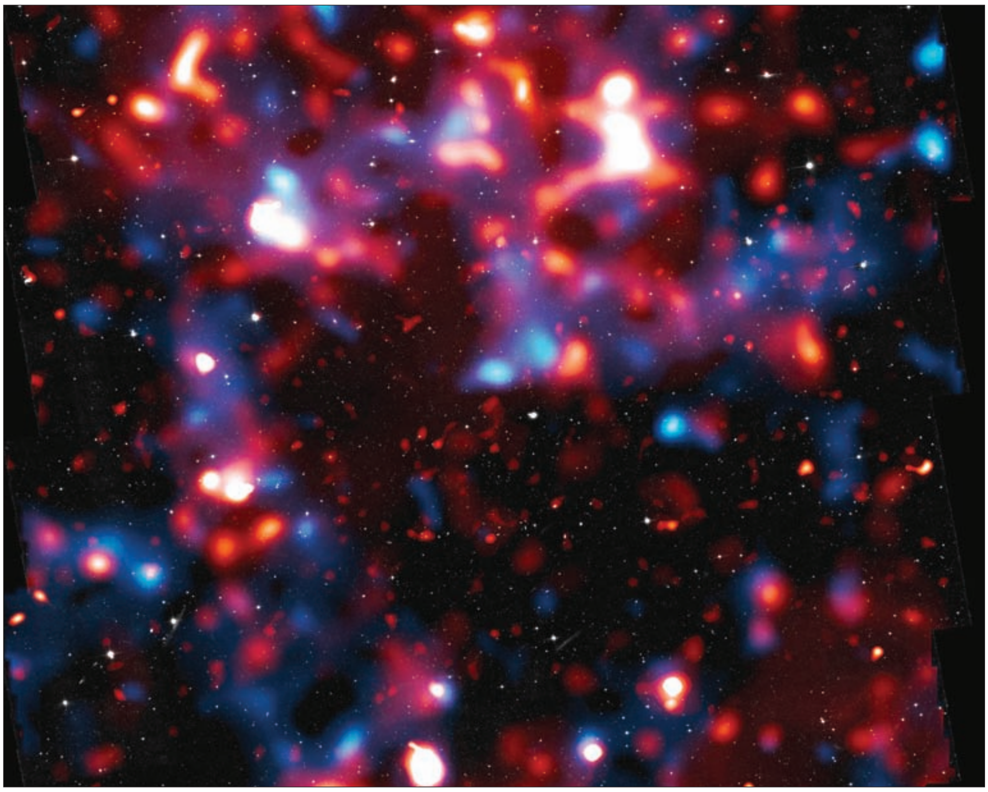
Saturn Stills/Science Photo Library

Giovanni Amelino-Camelia

# Beyond Einstein's gravity



NASA/ESA/R Massey, California Institute of Technology

**The pull of gravity**
A composite image of the cosmos showing normal matter (red), stars and galaxies (grey) and dark matter (blue).

**Reinventing Gravity: A Physicist goes Beyond Einstein**
*John W Moffat*
2009 Collins
£17.99/$27.95hb
288pp

For several years, John Moffat has been developing a new theory of gravitational phenomena as an alternative to Einstein's widely accepted general-relativistic theory. Most physicists would characterize his work as being rather speculative, but would also acknowledge that Moffat, who is now a physicist at the Perimeter Institute for Theoretical Physics in Waterloo, Canada, adopts a very robust methodology. So when I heard that he had written a book, I thought that Moffat would use it as an opportunity to publicize his theory, and that it would be some sort of passionate defence of his work. Such a book would have made sense, since one could legitimately argue that Moffat's work deserves more interest than it has generated in the physics community until now.

However, with *Reinventing Gravity*, Moffat seems to have reached a much more ambitious goal: using his research path as a way to illustrate the dynamics of how science actually achieves progress. The result is a book that I would recommend to several types of readers; in particular, it is a "must read" for those who are thinking of studying physics at university, who will find an exceptionally clear description of the nature of a physicist's work.

The scientific puzzle that takes centre stage is one of the most significant in present-day physics. It concerns certain observations in cosmology that cannot be explained using our current description of the universe's matter content and of gravitational phenomena. The most followed proposal for solving this puzzle advocates the introduction of "dark matter" (and "dark energy", but let me not touch on that even more subtle issue). If we postulate the existence of some forms of matter that are otherwise invisible but carry gravitational charge, then the relevant observations in cosmology can be reconciled with Einstein's theory of gravity.

> The book is a "must read" for those who are thinking of studying physics at university

Of course, a complementary approach is also possible: one can instead stick to the types of matter we know and assume that Einstein's theory must be modified, as is the case in the theory that Moffat has been developing. Moffat's theory is described in the second half of the book in a very pedagogical manner. Although this description is not fully satisfactory for those who, like me, are actually involved in research in related fields (and might therefore benefit from a more technical review), it is admirably accessible to readers with a limited scientific background.

The strength of this approach is that it puts readers – including non-experts – in a position to fully appreciate several aspects of the ongoing scientific debate, especially through Moffat's use of analogies with previous puzzles that have confronted the physics community. Particularly enjoyable is Moffat's description of observations of planetary motion in the years preceding Einstein's proposal of general relativity. In 1859, when astronomers noticed that the precession of the perihelion of Mercury's orbit could not be accurately described in terms of the known planets and Newtonian gravity, it was assumed that the gravitational pull on Mercury by an unknown planet, dubbed "Vulcan", must be responsible for the mismatch. But Vulcan was never found, and the mystery of Mercury was solved only by replacing Newton's gravity with Einstein's theory, which describes the orbits of planets in terms of the curvature of space induced by the Sun's large mass.

This example may appear biased in Moffat's favour, since the analogy suggests that current dark-matter proposals might eventually prove futile, and that a new theory of gravity, like that proposed by Moffat, will emerge. But he does endeavour to provide a balanced perspective by also examining the studies that led to the discovery of Neptune in 1846. Neptune was first contemplated because the orbit of a known planet, Uranus, was found to have features that could not be explained within Newton's gravity without positing the existence of a new planet. Indeed, Neptune was eventually found by deducing its position using Newton's theories.

Through these examples, readers can appreciate how, for the puzzles that physicists study, there is always a sort of war between those who tend to assume the absolute correctness of the laws of physics that are in use, even when this requires imagining previously unseen entities governed by those laws, and those who instead are inclined to imagine that new laws of physics must be discovered. The conservatives are more frequently right, as in the case of Neptune. But the most exciting times for physics are the ones when the "new laws" hypothesis turns out to be correct, as for the orbit of Mercury and the associated discovery of the general-relativistic description of gravitational phenomena.

For readers whose interests are not focused exclusively on science, there are several bits of the book that will prove stimulating. In particular, Moffat devotes several pages to the Aristotelian description of planetary motion, which essentially assumed the existence of rotating crystalline spheres that contained the planets. Revisiting such ancient descriptions, one cannot avoid wondering how naive our current descriptions will appear to anyone who gets a chance to contemplate them in a distant, more advanced future.

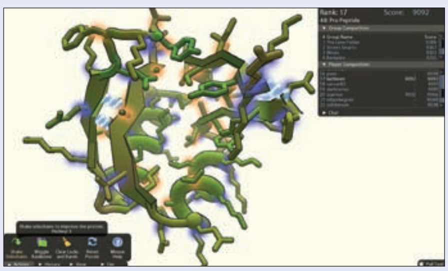
When I was a student, for example, I was quite shocked to learn that until the advent of Fermi's preliminary description of weak interactions, the decays of atoms were rationalized as if their products were pieces of the atom – rather than the result of interactions among subatomic particles, some of which produce additional particles not previously present in the atom. Clearly our intuition of what constituted a decay process did not initially go much further than our experience of mugs falling on the floor and breaking into pieces! The reality of nature often far exceeds the reach of our imagination and intuition.

Einstein's fascinating role in 20th-century physics is also discussed at several points in the book, together with the perennial issue of Einstein's cumbersome legacy. The amount and quality of Einstein's contributions to physics far exceeded those of even his most famous colleagues, so it is not surprising that some physicists seem to be waiting for a "new Einstein" – somebody who has inherited his extraordinary intellectual talents – to show up. But that is too much to ask. Nobody can be that way, not with our modern way of doing research, yet it seems people keep looking.

Moffat claims quite a big slice of Einstein's heritage for himself, by arguing that his research work has been "following in Einstein's footsteps, tracking the course he would have taken if he were alive today". I tend to be sceptical whenever candidates for "new Einsteins" are proposed or pieces of Einstein's legacy claimed. But readers will end up acknowledging that the methodology adopted in Moffat's research and his curiosity-driven way of looking at puzzles in present-day physics do resemble the characteristics that Einstein championed in the last century, and that these qualities were of good service to the production of this enjoyable book.

**Giovanni Amelino-Camelia** is a physicist at the University of Rome La Sapienza, Italy, e-mail giovanni.amelino-camelia@roma1.infn.it

## Web life: *Foldit*



**URL:** fold.it/portal

### So what is the site about?

Like the popular SETI@home program, which uses the downtime of home computers to sift radio-telescope data for evidence of alien life, *Foldit* draws on the idle hours of several thousand data-crunchers for help in solving scientific puzzles. But there is a twist. For a start, *Foldit* is all about biophysics. The project's goal is to understand how proteins – the chains of amino acids that drive processes inside living cells – fold themselves into a myriad of different shapes. But the most striking difference is that *Foldit*'s protein-folding operators are actual human beings, and the datasets they are sifting are disguised as an amazingly addictive computer game.

### Nice touch. What is it like to play?

The simple answer is that *Foldit* is a bit like Tetris, only infinitely more useful and without the annoying background music. On the screen, protein molecules appear as brightly coloured cartoon chains, with hydrophilic (water-loving) and hydrophobic (water-hating) sidechains dangling off them. A variety of tools allows you to poke, squeeze, tug and shake the proteins into more energetically favourable configurations. The more stable the protein becomes, the more your score increases. If your wiggles and tweaks succeed in improving the protein, then the game rewards you with encouraging little messages ("great hydrogen bonding!"); you also get the satisfaction of watching your solution creep up the scoreboard compared with other players' efforts.

### How do I get started?

Once you have downloaded the game from the website (it is free and available in Windows and Mac versions), the next step is to work through a series of tutorials that introduces you to the physics of protein-folding. For example, proteins tend to be surrounded by water, so hiding the hydrophobic sidechains away inside the rest of the molecule will reduce the amount of energy needed to maintain the protein's shape. The tutorials also introduce advanced tools like "shake sidechains" that allow you to move several parts of the molecule simultaneously, and offer a few hints about techniques to try. Once you have solved the introductory puzzles, you can try more advanced ones, form groups to solve puzzles together, chat with other players, challenge them to duels and generally fold away to your heart's content.

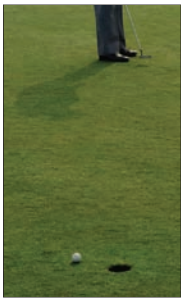
### Are we really doing science here?

Well…sort of. *Foldit* grew out of Rosetta@home, a computerized protein-folding project led by David Baker of the University of Washington. Baker won the Sackler International Prize in Biophysics in November 2008 for his work, but by that time his team had already identified a problem: sometimes, Rosetta@home's computers became bogged down in local minima, ignoring "obvious" lower-energy configurations nearby. Humans, in contrast, are famously good at spotting patterns, and many are inveterate puzzle-solvers. So Baker brought in some computer-scientist colleagues to develop a computer game around protein-folding, effectively outsourcing these puzzles to anyone with a computer and some free time. Eventually, the *Foldit* project members hope to get human players to tackle protein-folding problems that have no known solution. They are not there yet, however, and current research is focused instead on finding out what types of problems *Foldit* players can solve with ease, and which are better left to the machines.

### Any new developments I should look out for?

New protein-folding problems appear on the site every few days, and in late May the *Foldit* team added an important new twist: a series of puzzles that allows players to design their own proteins, not just manipulate existing ones. Protein engineering is relatively uncharted territory for both humans and machines, and the team thinks that in this wide-open field, a casual gamer might be able to make a real contribution – perhaps even design a new protein-based drug. It may seem unlikely, but as an excuse for playing a computer game, finding a cure for HIV is tough to beat.

# Between the lines: summer sports special



**That sinking feeling** The science of golf.

## Bad golfers of the world, unite

According to the author A A Milne, golf is popular "because it is the best game in the world at which to be bad". One reason for this is golf's handicap system, which purports to create a level playing field. Yet as John Wesson explains in *The Science of Golf*, in reality neither the dizzyingly complex UK handicapping system nor the simpler US version does any such thing: a "scratch" player with no handicap will beat a 14-handicap player 58% of the time under American rules and 72% of the time using the British system. Anomalies like these are the book's greatest strength, and it is a pity that Wesson does not make more of them. Instead, the book focuses on comparatively well-worn topics in the "sports science" genre such as the aerodynamics of a ball in flight. There are still some gems here, however: dimples on a golf ball's surface, for example, provide a good excuse for discussing phenomena like critical airspeed; and Wesson's analyses of golfing "sins" like hitting the ball off-centre are particularly insightful. Another highlight – perhaps especially for golfers in search of fresh explanations for putts gone awry – is the section on muddy balls, which describes a series of experiments in which a small weight was attached to one side of the ball, simulating a smudge of dirt. The results showed that just 100 mg of mud can cause a straight 4.5 m putt to miss the hole – although elsewhere Wesson notes wryly that "for most players the inaccuracy of their putts would typically be three or four times larger than the effect of the bias". There goes another excuse.

● 2009 Oxford University Press £16.99/$40.00hb 224pp

## Physics tackles rugby

Picture a rugby prop forward. Huge, mud-spattered and possessing almost no neck, the stereotypical prop bears little resemblance to the popular caricature of a physicist. Yet a prop's role depends critically on understanding the science of forces and motion. The momentum crunch as the two sides engage, the torque as a scrum begins to rotate, the kinematics of tackling a gazelle-like fly half – the success of all these manoeuvres relies as much on Newton as it does on training. In *The Physics of Rugby*, Trevor Davis Lipscombe offers up explanations aimed at props and armchair players alike. In some cases this information is genuinely useful; for example, he describes how as members of an outgunned front row you can "get the Earth, with a mass of more than $10^{24}$ kg, to play for your team" if you dig in and lock your legs, transmitting the opposing pack's force into the ground. Knowing that a zigzagging runner exhibits Brownian motion is of less practical use, and the analogy between interceptions and particle–antiparticle interactions even more esoteric, yet Lipscombe deserves credit for going beyond simple kinematics. Even the physics of sound gets a look-in, as the author invokes the logarithmic nature of the decibel scale to explain why 100 000 Welshmen singing "Land of My Fathers" at 75 dB each does not produce a seismic 7.5 million dB wave. A one-time forward at Oxford whose physics career took off after he broke his neck in a collapsed scrum, Lipscombe presents the science on a basic level, with plenty of references to great rugby players and famous matches along the way. The result is a book that should resonate with rugby-mad schoolchildren – and perhaps even a lumbering prop or two.

● 2009 Nottingham University Press £20.00/$28.95pb 200pp

## Avast ye landlubbers

Many popular-physics books have been written about bosons. Comparatively few, in contrast, have been written about bosuns. Sailing straight into this gap (and trailing a shocking number of bad nautical puns in its, er, wake) is *Float Your Boat! The Evolution and Science of Sailing*, a light-hearted yet informative look at the physics of sailing ships. Written by Mark Denny, a former theoretical physicist, this is actually two books rolled into one. The first book is a short, breezy history of how sailing vessels progressed from Viking longships to the tall ships of the 18th and 19th centuries to the racing yachts of today. The second is a technical, but still accessible, exploration of the physics behind phenomena like torque, hull speed and why Scottish windsurfers prefer the island of Tiree. In the physics sections, Denny bases his discussions on a series of increasingly complex model craft, from a simple, square-sailed brig to a triangle-sailed schooner. Intriguingly, the angle of both crafts' wake will be precisely 38.94°. In fact, ducks, aircraft carriers and a hypothetical craft sailing on a lake of alcohol will all produce the same wake angle, which is known as the Kelvin envelope after the Scottish physicist who studied it. Clearly, the connections between physics and sailing run deep; as Denny points out, even Einstein was an avid weekend sailor.

● 2008 Johns Hopkins £14.00/$26.95hb 280pp

## Into the woods

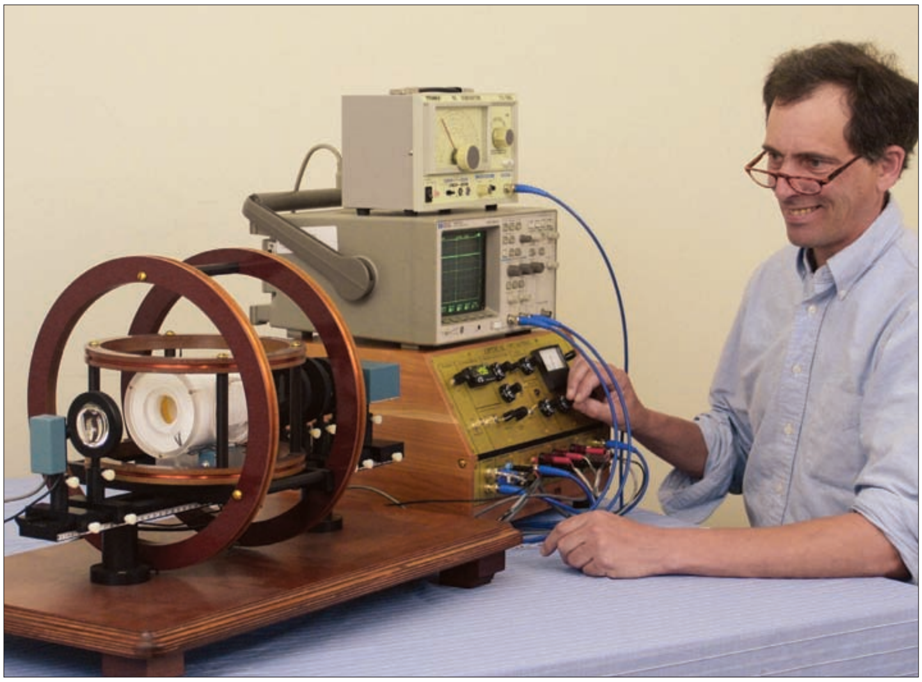
Readers who disdain team sports, suffer from seasickness or share Mark Twain's opinion that golf is "a good walk spoiled" may prefer the gentler sporting pleasures on offer in John A Adam's *A Mathematical Nature Walk*. In this book, Adam, a mathematical physicist at Old Dominion University in the US, has compiled answers to 96 questions about natural phenomena, loosely grouped into categories like sky, water and forest. These sections contain questions on a tremendous variety of topics, ranging from the shape of an egg to the time required to empty Loch Ness and the physics of upside-down "smiley face" rainbows. Unsurprisingly, the book is liberally sprinkled with equations; however, although a few of the problems require calculus, most can be solved using only arithmetic or advanced algebra. Of course, the mathematics of topics like the Fibonacci sequence can be deceptive in their apparent simplicity, and occasionally one gets the impression that Adam is skimming over some rather deep mathematical waters. Mie scattering theory and the method of partial waves, for example, crop up in his answer to the classic question "Why is the sky blue?" and by his own admission "it gets a lot more complicated!". Still, Adam's love of both nature and mathematics is obvious, and his chatty style and sense of humour – look out for the question about spontaneously combusting haystacks – enliven a book that will get readers thinking as well as itching for a pleasant stroll.

● 2009 Princeton University Press £16.95/$27.95hb 280pp

Careers

# Tools for learning

Some instruments in teaching laboratories may look old-fashioned, but those wooden boxes can hold surprisingly advanced equipment. **George Herold** describes his career designing experiments for undergraduate labs



**Design for life** In developing equipment for lab experiments, George Herold requires tenacity and skill.

The old joke is, "If it squirms, it's a biology lab, if it stinks, it's a chemistry lab and if it doesn't work, it's a physics lab". My current job is to make a lie of the latter, by making physics apparatus that works for the students without needing a "resident expert" to maintain or explain it.

I work for TeachSpin, a small company that builds equipment that is used to teach students in advanced undergraduate physics labs. Some of the instruments are capable of making "research grade" measurements, and all are designed for open-ended investigations where the students can go beyond what is outlined in the manual. As TeachSpin's senior scientist, I am in charge of designing new experiments, supervising their construction and testing them before they leave the workshop for new homes in labs around the world. The instruments the firm makes span a range of physics topics, from atomic physics and magnetic resonance to acoustics and optics; they can be as simple as magnetic-force apparatus or as complex as measuring the hyperfine splitting in the excited states of rubidium atoms using Doppler-free spectroscopy.

TeachSpin was founded in 1992 by Jonathan Reichert, who was then a physics professor at the University of Buffalo in the US. He was also my thesis advisor – proving once again that when it comes to careers, it is often who you know rather than what you know that counts. After I completed my PhD in solid-state physics in 1993, I worked at TeachSpin for several months, designing electronics for its first instrument – a pulsed nuclear magnetic resonance spectrometer. A few postdoc positions later, I found myself working as a staff scientist at the W M Keck Free Electron Laser at Vanderbilt University when the facility lost its funding for a year. As a recently married new father, I thought I should start looking for a job that did not depend on the three-year research-funding cycle. By that time, TeachSpin had grown and it was looking to hire a full-time physicist. It was a perfect fit for both of us.

### From "care and feeding" to design

Part of my time is spent on what I call "care and feeding" of existing instruments. This can range from talking to potential customers about the apparatus, to helping existing users get their experiments up and running, and even to coaching students. Every once in a while, I get some good physics questions, but in the main, people want to know about set-up and specifications.

This part of my job also includes production-related work like answering questions from people in the workshop, finding replacement parts for something that is about to become obsolete or helping set up equipment for intermediate-level testing. My favourite part of production work is the final testing of the apparatus. First, I make sure all the mechanical parts and electronics are working. Then, I get to take the first pieces of data from this particular unit. Even though I have seen the same dips, bumps and/or wiggles of data hundreds of times before, it is still a bit of a thrill to see them in their latest incarnation. Once the data are recorded and a copy placed in the user manual, I wheel the instrument out to be packed up for shipping. At these times, I cannot help feeling a little like a proud father sending another of my "babies" out into the world, hoping the new owners will cherish it as much as I do. Note that "father" is a good analogy – it is the production people who do all the finicky assembly.

Most of my time, however, is devoted to designing new instruments. This could be in collaboration with an outside expert – the firm built both its diode-laser spectroscopy unit and its Fabry–Pérot cavity with Ken Libbrecht of the California Institute of Technology, for example – or entirely with in-house staff. My favourite part of the design process is starting on a new project. For example, my latest project is the study of "Johnson" and "shot" noise in electronic circuits; there are some beautiful correlation techniques using two identical amplifiers that can be used to remove the noise, but it looks like I will not be able to do this with a single instrument. As is often the case, I may at this point have to learn some new physics (a great excuse to go and buy some books) and, at this early stage, the sky is the limit. My colleagues and I always like to think about all the possible things the new piece of apparatus might do, and any crazy ideas can be explored.

Soon after this, reality sets in and we have to balance things like the costs and the time involved against the potential for increased sales. With a few more parts, for example, our optical-pumping apparatus could be made into a rubidium magnetometer or an atomic clock, but most students will still be struggling with the basics after several weeks of using the equipment. The challenge is to let the apparatus be used over as wide an experimental range as possible – giving the student lots of different knobs to turn (figuratively and literally) – yet keep the price low enough that physics departments can still afford to buy it. I sometimes feel like I am cheating the student by doing all the design work: I learn a great deal from all the mistakes I make, but the students do not get this opportunity. However, making mistakes takes time, and in undergraduate labs, this is often in short supply.

### Making things work

A career in instrument building can involve knowledge from almost any area of science and technology. A list of what I use daily might start with practical topics like electronics, technical drawing and material properties, and continue on to entire fields like optics, atomic physics, electromagnetism or solid-state physics. One very useful trait for this job – common to many scientists and engineers – is a desire to understand how things work, and perhaps to make them work better or be produced more cheaply. Aside from this, I think one of my greatest assets is having the tenacity to stick with a problem until I understand it. A small glitch or wiggle in an experimental spectrum is not acceptable. Chasing down all the small noise sources that can crop up in a piece of equipment takes time, but the reward is a good instrument.

One of the drawbacks of working for a small firm is that there are few other physicists to help you bounce ideas around. E-mail helps, but it is not the same as standing at a whiteboard, drawing pictures and waving my hands. However, this changes for a few months each year when David Van Baak, a physicist from Calvin College, visits to collaborate on new projects. During this period, we have a marvellous time and the ideas just keep on coming – we brainstorm, argue, refine and continually think of more experiments to do with the apparatus we are designing until we finally have to stop and focus on getting it out the door.

As there is a large practical component to my work, my advice to anyone interested in a similar career is to get to know the technicians in your department or university workshop. If you are a graduate student designing equipment for an experiment, do not just submit a drawing to the technicians – take the time to talk to them about what you are doing. You may have to bribe them with pizza or other offerings, but this will be money and time well spent. You do not have to accept all of their suggestions, but they are bound to have some good ideas about how to make things work.

Obviously, a physics degree can be good preparation for this kind of work, but my first degree was actually in engineering, so I was not exposed to the classic advanced-physics labs. This naivety can be useful. First, I do not have preconceived notions of how the experiments should be done, so I may be able to think of a different way to show the desired effect. For example, you do not necessarily need to be able to sweep the frequency of your Fabry–Pérot cavity if you can tune the wavelength of your diode laser. And perhaps even more importantly, when I start a new project, I am approaching it much like the students: I am doing it for the first time.

**George Herold** is a senior scientist at TeachSpin, Buffalo, US, e-mail gherold@teachspin.com

## Careers and people

### Gran Sasso picks new boss

Lucia Votano will be the new director of the Gran Sasso National Laboratory in Italy, the world's largest underground scientific facility and a major centre for experiments to detect neutrinos and dark matter. Votano, a particle physicist who has collaborated on research projects at CERN and at the DESY laboratory in Hamburg, Germany, had recently served on a pan-European committee on the future of astroparticle-physics research in Europe. She will replace current Gran Sasso chief Eugenio Coccia in September, and will be the first woman to lead one of the four laboratories run by the INFN, the Italian national institute of nuclear physics.

### Atomic physicist wins gold

A physicist has been awarded France's top science prize for his work on atomic physics and quantum optics. Serge Haroche – one of the founding fathers of cavity quantum electrodynamics – was named as this year's "gold medal" winner by the French national research council (CNRS) in June. Haroche currently heads the electrodynamics and simple-systems group at the CNRS's Kastler Brossel lab in Paris. Previous physics recipients of the award include the Nobel-prize winners Albert Fert and Claude Cohen-Tannoudji, who was Haroche's PhD supervisor. The gold medal is awarded annually in recognition of a lifetime's academic achievement.

### Hubble project earns prize

Three astronomers from three different continents have won the Gruber Cosmology Prize for leading a project that pinned down the value of the Hubble constant – a key parameter in determining the age of the universe. Wendy Freedman, director of the Observatories of the Carnegie Institute of Washington in Pasadena, California, US, Robert Kennicutt, director of the Institute of Astronomy at Cambridge University in the UK, and Jeremy Mould, a physicist at the University of Melbourne, Australia, will share the $500 000 prize for their work on the Hubble Space Telescope key project on the extragalactic distance scale. The trio led a multinational team of more than two dozen astronomers in an effort to determine the age of the universe using Cepheid variable stars to estimate distances.

### Movers and shakers

Astronomer **Eileen Friel** has become the 10th director of Lowell Observatory in Flagstaff, Arizona, US, succeeding Bob Millis, who retired in June.

Manchester University physicist **Andre Geim** has been awarded a Royal Society 2010 Anniversary Research Professorship, one of four academics to receive the 10-year post, which forms part of the society's 350th birthday celebrations.

**David Griffiths**, Howard Vollum Chair of Physics at Reed College in Portland, Oregon, is retiring after 31 years at the institution. Griffiths is best known for his widely used introductory texts on electricity and magnetism, quantum mechanics and particle physics.

**Kate Kirby**, a Harvard University astronomer and research physicist at the Smithsonian Astrophysical Observatory in Washington, DC, has been named as the new executive officer of the American Physical Society.

Two **NASA** websites have received Webby Awards for "excellence on the Internet". The main NASA site was named best government website in a contest that drew more than 500 000 votes from members of the public, while the Cassini mission was deemed best science site by judges from the International Academy of Digital Arts and Sciences, which sponsors the Webbys.

**Frank Shu** has won the 2009 Catherine Wolfe Bruce Gold Medal for lifetime achievement in astronomy. Shu, a space scientist at the University of California, San Diego, US, was honoured for his work on spiral structures in galaxies and the theory of star formation.

## Once a physicist: Bruce McWilliams

**Bruce McWilliams** is chairman of the board of directors at Tessera, a semiconductor packaging, imaging and optics company based in San Jose, California, US. Between 1999 and 2008 he also served as Tessera's president and chief executive officer

### Why did you choose to study physics?

When I was about 11, I got some electronics kits; I made radios and circuits, and read about how the transistor works. I wanted to understand why things worked, and I remember being so fascinated by the TV set that I took it apart. My mother didn't like that! As a teenager, I had a very good high-school physics teacher who gave me lots of advanced books to read, including the *Feynman Lectures*. Back then, my favourite part was being able to estimate something or predict it.

### How did you become interested in electronics?

During the summers when I was studying physics at Carnegie Mellon University, I programmed microprocessors with a small start-up company. These were the first microprocessors, back in 1976 or thereabouts, and there were no programmes written for them, so we could sell the software in hobby magazines. We actually made a lot of money, about $40 000, because everybody needed software. But my PhD (also at Carnegie Mellon) was actually on gauge theories of electroweak interactions and how to look for the Higgs particle. Gauge theories were the hot thing in the 1970s, and I was interested in fundamental theories, so that is what I studied.

### What made you decide to switch from research to industry?

While I was doing my PhD, I sometimes picked up 20-year-old journals, and I realized that 99% of the stuff in them was already irrelevant. Another factor was that I finished my PhD at the depth of the great recession of the 1970s, when nobody was being hired. So instead, I went to work at the centre for computer engineering at the Mellon Institute on a salary of $26 000 a year, which seemed like an enormous amount of money to me at the time. Later, I worked for someone who did not like the fact that his firm's competitors were reverse-engineering his products so they could copy them, and he wanted to print his entire product on a custom microchip to prevent them from taking it apart. So I got on a plane for Silicon Valley and started finding out how hard it was to put sensors on custom chips. One thing led to another, and I have been in California ever since.

### How has your physics training affected your approach to business?

Business and physics are very similar in that if you can precisely define the problem, you have done 80% of the work in solving it. I have found that as a chief executive, you basically show up every day and find a new problem waiting for you. It might be an employee threatening to quit or a customer who is upset or a problem in manufacturing, but if you love solving problems, then you will like being a chief executive. Also, physics is the perfect training for working in technology, because the field moves very quickly; if you are grounded in the fundamentals, you can always understand what is going on. What physics does not, however, give you is people skills, so you have to develop those. Business in general is not best learned in the college classroom but by doing it – by being in the foxhole with bullets going over your head.

### What do you think are the biggest challenges facing microelectronics?

Many of the products have become commodities, so the profit margins are not large. It is difficult to keep innovation going; with semiconductors, the capital investments required to move up to the next level are enormous, so that is a huge challenge for the industry. Fundamentally, the problem is that we are where cars were in the 1960s and 1970s. We still have lots of growth, but it is not an easy business; you do not really know where the consumer is going to go. Every decade has a theme; in the 1980s it was personal computers, in the 1990s it was networks and now it is the mobile phone. These things are what drive new innovation.

### Do you still find the time to keep up with any physics?

I try to spend maybe an hour a day reading or thinking about it, and to facilitate that I endowed a centre for cosmology at Carnegie Mellon. I stay involved there, I talk with the physicists, go to some seminars, participate in hiring decisions – giving advice about how we are going to grow and find money for new projects.

### What career advice would you give to physics students today?

Stay open and try to do as many different types of things as you can. Try to find what your passion is, because if you find your passion, you will do well. Also, think ahead – what do you want to be doing 10 years from now? Some people are suited to a research environment, some less so.

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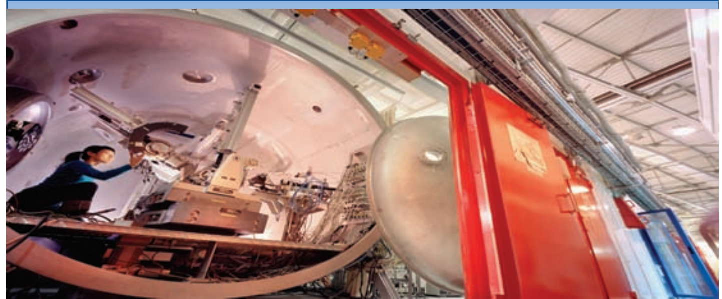

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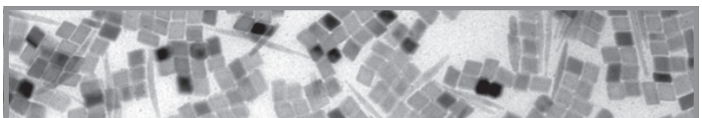

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The candidates will be engaged in a R&D program for the development of PET technologies applied to breast cancer detection **(http://www.lip.pt/experiments/pet/)**. A prototype PET scanner with high-resolution based on scintillating crystals and avalanche photodiodes (ClearPEM) was developed and is presently in clinical evaluation. A scanner combining PET and ultrasound imaging is being developed in collaboration with the European Center for Medical Imaging (CERIMED) and CERN. The PET developments are done by a scientific consortium led by LIP in collaboration with the company PETsys.

Candidates are expected to have a PhD degree in experimental physics. Experienced researchers in medical or particle physics instrumentation are considered. Applications including a CV and motivation letter should be sent to Sandra Dias **(sandra@lip.pt)** before 19 July.

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A tenure track faculty position is available at the Department of Physics and Astronomy of the University of Leuven, Belgium starting October 1, 2010 in the field of experimental physics: nanoscale fluxonics and plasmonics. More information can be found on the web:

**http://www.kuleuven.be/personeel/jobsite/vacatures/science.html**

Closing date: September 30, 2009

The full-time position will be offered for a period of five years at the level of assistant professor. A positive evaluation at the end of the five-year appointment will result in a tenured appointment as associate professor. The K.U.Leuven is an equal opportunity employer. Non-Dutch speaking candidates should be able to teach in Dutch within three years.

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Career Path VII

**Purpose of the job:**

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**Key Activities:**

The Director of Programmes will:

- Be responsible for the setting of programmatic priorities and resource planning;
- Conduct regular Programme reviews;
- Provide regular information and status reports to the Director General;
- Report on ESO Programmes as required by Council and other external committees and to the community at large via conferences and special events;
- Work together with the Director General, the other Directors and the Division Heads to develop and implement ESO-wide policies and strategies;
- Identify opportunities for improvement/development within and across Divisions, and for further development/growth of the organization; and
- Assist the Director General in developing strategic plans for ESO's overall programmes.

The tasks are not limited to the above and a flexible approach and ability to adapt to an evolving situation is required.

**Professional Requirements / Qualifications:**

Basic requirements for the position include a PhD in astronomy, astrophysics, physics or related fields; a proven record of scientific leadership and at least 10 years' experience in international scientific collaborations. Substantial management and leadership experience within a scientific organisation, preferably international, is also required. Excellent communication skills and a very good knowledge of English are essential.

The Director of Programmes is a member of the ESO Astronomy Faculty and is encouraged and expected to conduct active astronomical research.

**Key Competences:**

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**Application:** If you are interested in working in areas of frontline technology and in a stimulating international environment, you are invited to apply online at https://jobs.eso.org/. Applications must be completed in English and should include a motivation letter and CV. The position requires three **letters of reference** to be sent to vacancy@eso.org.

**The review of application will start on 1 September 2009; however applications will be accepted until the position is filled.**

Although recruitment preference will be given to nationals of ESO Member States (members are: Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, Switzerland and United Kingdom) no nationality is in principle excluded.

The post is equally open to suitably qualified female and male applicants.

# On the origin of the Darwin unit

During my PhD studies, I, like many others, supplemented my meagre income by working as a demonstrator in undergraduate physics practicals. Whenever possible, my fellow demonstrators and I emphasized to the students the importance of using SI units. However, in the privacy of the technician's room we often conspired to introduce non-standard units of our own.

The most successful of these non-standard units was one based on the Darwin Awards, which honour "those who improve the species...by accidentally removing themselves from it". The probability that a student would remove either themselves or other students from the gene pool during practicals through incompetence, foolhardiness or an overdeveloped sense of adventure was estimated using a unit known as the darwin. In this year, the 200th anniversary of Charles Darwin's birth, it seems appropriate that we should now attempt to have this non-standard unit more widely recognized.

The darwin (Dw) is a robust unit, defined as the mathematical probability of one undergraduate (or faculty) fatality per practical if the person in question is left to their own devices. The 1 Dw unit was calibrated against a student who was barred from practical classes after an experiment to make a mirror by evaporating aluminium onto glass under vacuum went horribly wrong. Having accidentally rewired the filament circuit so that the entire oil diffusion pump was electrically live, he almost succeeded in electrocuting the supervising lecturer who had the misfortune to touch the pump first. Only the quick thinking of a passing technician, who hit the cut-out switch, prevented the darwin from being renamed posthumously.

Of course, the darwin is a little unwieldy, so smaller units are available too. For example, we judged that one millidarwin (1 mDw) is equivalent to the probability of losing one finger/toe/eye, while one centidarwin is the probability of losing one hand/foot, and one decidarwin represents the probability of losing one major limb. It also scales upwards, with 2 Dw, 5 Dw and 30 Dw representing the loss of a practical pair, group and class, respectively – although in fairness, measurements on these larger scales are more likely to be used in chemistry rather than physics. All students who were identified with darwin values greater than 5 $\mu$Dw (the probability of singed hair) were allocated extra supervision, and I am proud to say that on my watch we never lost a student or witnessed anything greater than a 20 $\mu$Dw event – the probability of the loss of bladder control associated with helium-gas-induced high-pitched-voice experimentation.

An alternate use of the darwin could be to indicate the level of hazard associated with a particular experiment. An obvious example of this would be the famous "lightning kite" experiment supposedly performed by US scientist Benjamin Franklin in 1752 to show that lightning is an electrical discharge. Although Franklin survived the experiment, it would nevertheless have a rating of 2 Dw, since records indicate that at least two people have died trying to reproduce his results.

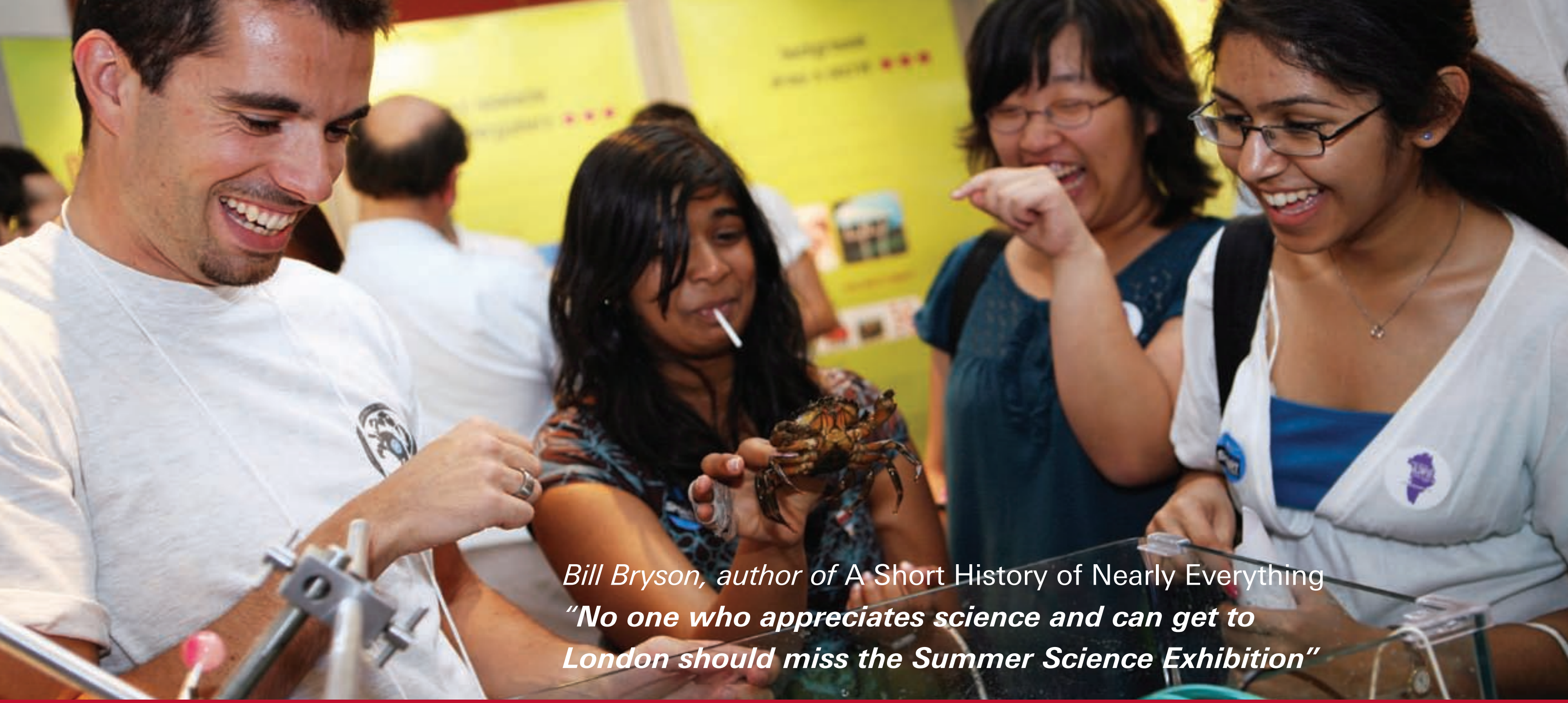
Continuing with the theme of self-experimentation, medicine is littered with 1 Dw events. In 1885 the Peruvian medical student Daniel Carrión-García persuaded his best friend Evaristo Chavez to help him infect himself with fluid from "Peruvian warts" (*verruga peruana*) so that he could demonstrate that this was the less-aggressive stage of the fatal "Oroyo fever". Carrión died within three months. For his part in the experiment Chavez was arrested and tried for his friend's murder – a salutary lesson for all research collaborators and co-authors. Although most medics now call the disease Bartonellosis, in Peru it is still called Carrión's disease. Similarly, in 1900 Jesse Lazear confirmed the origin of yellow fever by allowing himself to be bitten by infected mosquitoes, and subsequently died of the disease aged 34.

I have witnessed many scenarios where the darwin might be applied outside the laboratory

In a lighter vein, back in the 1930s, medical research assistant Werner Forssmann believed that a catheter could be inserted into the heart for applications such as the direct delivery of drugs and dyes, or the measurement of blood pressure. The major concern at the time was that such an intrusion into the heart would be fatal. To prove his theory, Forssmann inserted a catheter into the brachial vein of his own forearm, guided it fluoroscopically into his right atrium and took an X-ray of his chest with it in place. When he showed the X-ray to his supervisor, he was thrown out of the hospital and forced to quit cardiology; he took up urology instead. In 1956 Forssmann shared the Nobel Prize in Physiology or Medicine primarily for his daring self-achievement.

In the 20 years since I finished my PhD studies, I have witnessed many scenarios where the darwin might be applied outside the laboratory. My personal favourite is illustrated in the accompanying photo which I took in December 2008 while working on a solar-disinfection research project in Cambodia, where the standard unit of transport is the moped (Mp) – but that is another article for another time. The image shows a man who passed me on a rural dirt track with at least a dozen 50 l containers of petrol precariously strapped to his moped. While you might think that this would be a 1 Dw event, closer examination reveals a lit cigarette proudly clenched in his teeth. Surely this warrants an upgrade to 30 Dw!

**Kevin McGuigan** is a senior lecturer in medical physics at The Royal College of Surgeons in Dublin, Ireland, e-mail kmcguigan@rcsi.ie

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