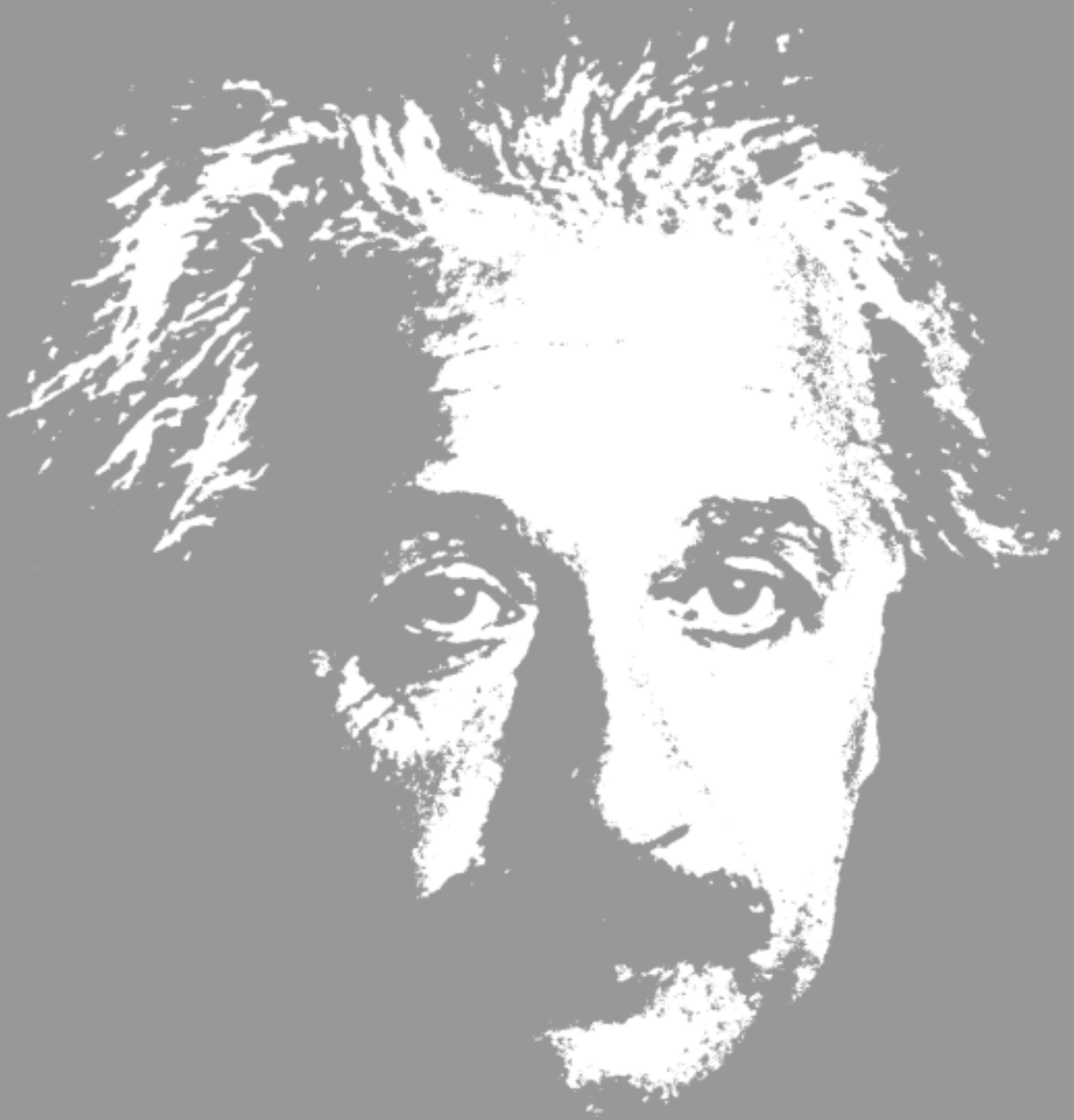


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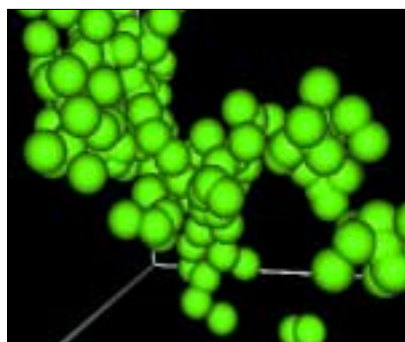
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Physics World is published monthly as twelve issues per annual volume by Institute of Physics Publishing Ltd, Dirac House, Temple Back, Bristol BS1 6BE, UK

United States Postal Identification Statement

Physics World (ISSN 0953-8585) is published monthly for \$400 per year within the United States.

Periodicals postage paid at Melville, NY, and additional mailing offices.

POSTMASTER: Send address changes to *Physics World*, American Institute of Physics, Suite 1N01, 2 Huntington Quadrangle, Melville, NY 11747-4502.

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Microscopic ‘pen’ rewrites the rules

Scientists in the Netherlands have modified an atomic force microscope so that it can write and etch sub-micron patterns on a surface with molecular “ink”. Atomic force microscopes (AFMs) were originally designed to study surfaces by monitoring the interaction between an extremely sharp “tip” and the test material, but they can be used for surface modification as well. In the new device the ink flows from a reservoir through a microfluidic channel in the cantilever that holds the tip and then on to the tip itself (S Deladi *et al.* 2004 *Appl. Phys. Lett.* **85** 5361).

Using 1-octodecanethiol as the ink, Miko Elwenspoek and colleagues at the University of Twente drew lines just 0.5 μm wide on a gold substrate. The ink reacted with the gold to produce a stable monolayer structure on the substrate. In separate experiments with a commercial etchant, the tip was able to etch trenches just 0.3 μm wide

and 14 nm deep in a chromium surface.

The team used the technique to draw and etch straight lines, but any pattern could, in principle, be created. It might also be possible to reduce the width of the lines and the trenches further by sharpening the tip of the AFM.

Elwenspoek and co-workers say their device is an improvement on existing AFM-based surface-modification techniques, like “dip-pen lithography”, because it can hold more ink and the flow of the ink can be controlled more precisely. Moreover, by creating a local environment around the tip, the operation of the device is not affected by humidity in the atmosphere.

The pen could be used in new nanofabrication techniques to create 3D nanostructures, and the Twente team now plans to do further work on the device itself and also on the ink, including improvements to its viscosity and wetting properties.

Physicist solves desert mystery



Singing dunes – in order to study the sounds of desert sand dunes, Bruno Andreotti first had to trigger avalanches by sliding down the dune face.

From Marco Polo onwards explorers have told stories about strange sounds they have heard in the desert. It is known that sounds are produced by sand dunes when they avalanche, but the exact mechanism behind the phenomenon has remained a mystery. Now Bruno Andreotti of the University of Paris 7 has proposed that the sounds come from vibrations in the sand bed that have been excited by collisions between sand grains (B Andreotti 2004 *Phys. Rev. Lett.* **93** 238001).

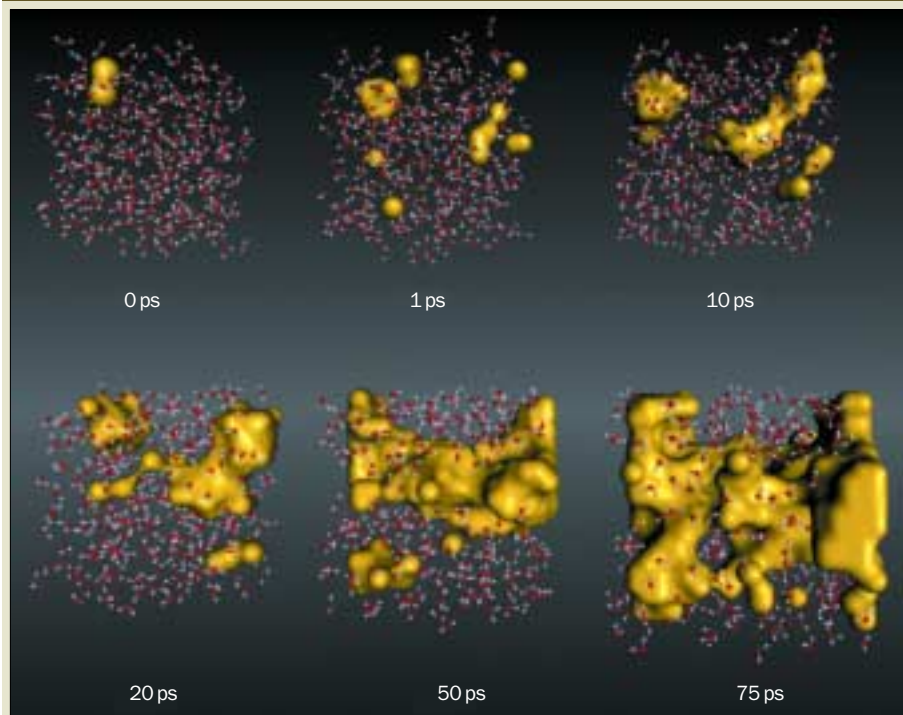
“Singing dunes are one of the most puzzling and impressive natural phenomena I have ever encountered,” says Andreotti. “The sounds can be heard up to 10 km away and resemble the beating of a drum or the noise of a low-flying jet.” The dunes produce sounds that are as loud as 105 dB – roughly equivalent to a car horn – and have frequencies between about 95–105 Hz.

The French physicist took his equipment – including a microphone, digital audio tape and accelerometer – from Paris to the Atlantic Sahara in Morocco, which contains more than 10 000 crescent-shaped dunes known as barchans. The wind in the desert can erode the back of these dunes, causing sand to build up at the top. When too much sand has accumulated, an avalanche occurs and the dunes start to “sing”.

Andreotti simultaneously measured vibrations in the sand bed and acoustic emissions in the air, and was then able to extract information about the frequency, amplitude and the phase of these signals. He found that the vibrations in the sand behaved like slow-moving elastic sound waves that were localized at the surface of the dune and had an amplitude that was about a quarter of the diameter of an individual grain of sand.

“The sounds are produced when grains drum against one another, exciting elastic waves on the dune surface, with the vibration of the sand bed tending to synchronize the collisions,” says Andreotti. “In many ways the surface of the sand bed acts like the membrane in a loudspeaker.”

Boiling water inside a computer



Although the boiling of water is one of the best-known examples of a phase transition, what happens at the level of molecules during this apparently simple phenomenon is not so well understood. In particular, little is known about the start of the process when regions of gas vapour begin to form in the liquid. Now Dirk Zahn of the Max Planck Institute for Chemical Physics of Solids in Dresden has taken a major step forward in the study of evaporation by simulating the behaviour of 256 water molecules at a temperature of 100 °C (D Zahn 2004 *Phys. Rev. Lett.* **93** 227801). Even though this represents a volume of water of just $2.1 \times 2.1 \times 2.1 \text{ nm}$, the computational demands of the simulation meant that the trajectories of the molecules could only be followed for a fraction of a microsecond. However, this was long enough to reveal the beginning of the phase transition, when vacuum cavities (yellow regions in the image above) spontaneously form in the liquid phase of water as a result of the breaking of hydrogen bonds. Nearby cavities then begin to merge into larger vacuum domains, while others quickly disappear, and the water molecules at the liquid–vapour interfaces tend to leave the liquid surface. Eventually these evaporation events outnumber the competing process whereby the molecules return to the liquid phase. Zahn is now applying the technique, developed by David Chandler and co-workers of the University of California at Berkeley, to other phase transitions such as the evaporation of alcohol during the distillation process.

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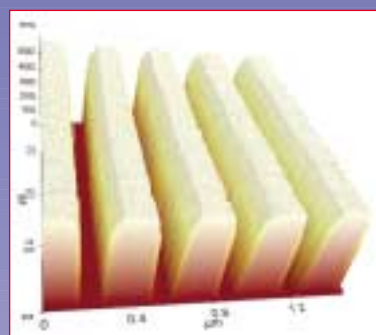
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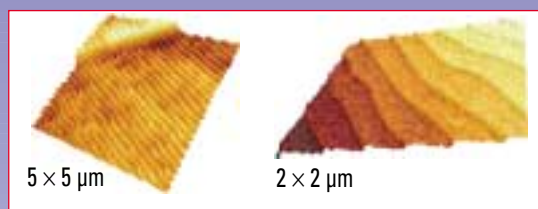
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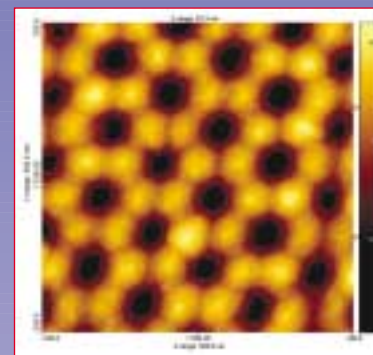
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NC-AFM image of 0.16 μm wide, 0.55 μm deep trenches shown in 1:1 aspect ratio 3D rendering (1.5 \times 1.5 μm).



SrTiO₃ films with mono atomic steps (0.18 nm step height) imaged in water.



Non-contact AFM image of nano structures patterned on aluminium surface (0.5 \times 0.5 μm). The fine details on this image demonstrate about 2 nm lateral resolution.

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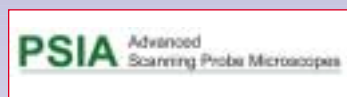


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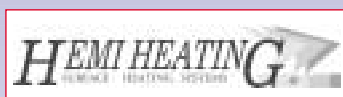


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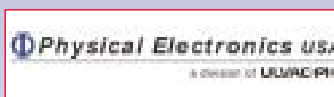
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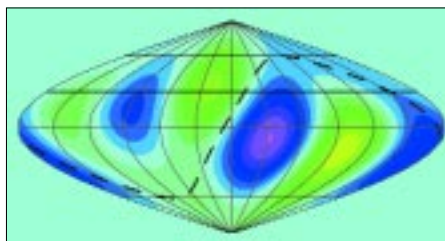
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Doubts cast over map of cosmos

The cosmic microwave background is often called the echo of the Big Bang, but recent research suggests that some of its features might have their origins much closer to home. Although most cosmologists think that the tiny variations in the temperature of the background are related to quantum fluctuations in the early universe, Glenn Starkman and colleagues at CERN and Case Western Reserve University in the US have now found evidence that some of these variations might have their roots in processes occurring in the solar system. If correct, the new work would require major revisions to the standard model of cosmology.

The cosmic microwave background was formed about 380 000 years after the Big Bang, when the expanding universe had cooled enough for electrons and protons to form hydrogen atoms. In the early universe these electrons scattered the radiation created in the Big Bang, but when this scattering stopped, the density distribution of the universe at the time became imprinted as tiny fluctuations in the temperature of the microwave background. These variations in density eventually became the large-scale structure of galaxies and clusters of galaxies that we see in the universe today.

The detection of fluctuations in the cosmic background by the COBE satellite in 1992 was a milestone in the history of cosmology, and subsequent experiments – notably the Wilkinson Microwave Anisotropy Probe (WMAP), which was launched in 2001 – have measured the background in more and more detail. Cosmologists plot the magnitude of these fluctuations as a function of the angle they subtend across the sky, with different angular scales like musical harmonics, each with a different frequency. The lowest harmonic is almost entirely due to the Doppler-shifted motion of the solar system through the universe: the microwave



Local effect? – astrophysicists have found that the plane of the solar system (dashed line) threads itself through hot and cold spots (circles) in the cosmic microwave background, suggesting that some of the variations in the latter are not caused by events that took place in the early universe.

radiation is very slightly hotter in the direction in which the solar system is moving and cooler in the reverse direction. This “dipole” harmonic has a hot spot at one end of the sky and a cold spot at the opposite end.

In analysing their data, physicists working on the WMAP mission have to subtract this radiation from the rest of the signal so that they are left only with the temperature fluctuations created at the time of the Big Bang. But Starkman and colleagues have found strong evidence that the second harmonic, the “quadrupole” (two hot spots and two cold spots), and the third, the “octopole” (three hot and cold spots) also have their origins in the solar system. When they combined the fluctuations from the quadrupole and the octopole on the map of the sky, they found that the plane of the solar system threads itself through the resulting hot and cold spots (see image), suggesting a link between the orientation of the solar system and the formation of these temperature fluctuations (2004 *Phys. Rev. Lett.* **93** 221301).

Other results appear to support this suggestion. For example, the relative magnitude of temperature differences in opposite halves of the sky is greatest when the sky is divided up along the plane of the solar sys-

tem. Starkman estimates that the odds of all of these different pieces of evidence being a fluke are anything up to a million to one.

“Each of these correlations could just be an accident,” says Starkman. “But we are piling up accident on accident. Maybe it is not an accident and, in fact, there is some new physics going on.”

What might this new physics be, assuming there is not some subtle misunderstanding of the WMAP instrument? The first possibility, according to Starkman, is that the solar system has some previously unknown property, or contains additional matter that can emit or absorb microwaves. Second, he says, cosmologists might have to revise the generally accepted idea that the very early universe underwent a period of extremely rapid expansion, known as inflation, just after the Big Bang. The inflationary model predicts fluctuations in the microwave background of about the size found by WMAP (in fact, slightly larger), so subtracting the foreground contribution from the solar system would leave this model wanting.

Charles Bennett of NASA’s Goddard Space Flight Center, who is WMAP’s principal investigator, is cautious about their conclusions. “While the *a priori* probability of the alignments [between solar system and temperature fluctuations] is low, the alignments are seen as a result of an *a posteriori* selection,” he says. “So their significance is uncertain.”

But Pedro Ferreira, an astrophysicist at Oxford University, says he would be surprised if there were no local contributions to the microwave background. “The data we have on our galaxy are not as precise as those produced by WMAP,” he says. “Which means that we cannot really take the WMAP data, use another accurate map to remove the effect of the galaxy and see what is left. To some extent we have to guess.”

Edwin Cartlidge

AWARDS

Quantum-cryptography research scoops Descartes prize

A collaboration of physicists from six European countries and the US has been awarded part of the European Union’s Descartes research prize for work on quantum cryptography. The IST-QuComm collaboration consists of research groups in Sweden, Germany, France, Switzerland, Austria and the UK, plus a team from the Los Alamos National Laboratory in the US. They share the €1m prize with life scientists studying mitochondrial DNA.

Quantum cryptography allows two parties to share a secret “key” – encoded with

single photons – so that they can communicate much more securely than is possible with existing cryptographic techniques. Any attempts by a third party to eavesdrop on the communications can be readily detected. Quantum cryptography could have applications in everything from electronic communications to e-banking and e-voting. The IST-QuComm consortium last year performed the first ever quantum cryptographic bank transfer over a 6 km fibre-optic link in Vienna.

Meanwhile, Wolfgang Heckl, who is

director general of the Deutsches Museum in Munich, has been awarded the first ever Descartes prize for professional scientists involved in science communication. He was given the €50 000 prize for his ability to explain complex scientific topics in a simple manner. Heckl, who appears regularly in the German media, was previously a physicist at the Ludwig Maximilians University in Munich, where he ran a centre for nanobiotechnology. He joined the museum last October (see page 60).

Belle Dumé and Matin Durrani

SIDEBANDS

Oxford tops scientific table

Cambridge University is the best in the world at science, according to a survey carried out by the *Times Higher Education Supplement*. The survey ranked universities' performance in science based partly on a survey of 1300 academics in 88 countries and partly on quantitative measures, such as the number of citations that each faculty member receives. Each university's score was normalized to that of Cambridge, which received 200 points. Oxford was second with 169.8 points, followed by Harvard (159.8), Caltech (159.0) and the Massachusetts Institute of Technology (135.1). However, if the universities are ranked only in terms of citations, then the US scoops the first 16 positions, with Harvard in the top spot. The highest ranked university outside the US is the ETH Zurich in Switzerland in 17th place, followed by Durham (18th) and Cambridge (19th).

Magnetic effects seen in water

Physicists in Japan have discovered that the melting point of water increases slightly in a strong magnetic field. Hideaki Inaba and colleagues at Chiba University found that it increases by 5.6 mK for ordinary water in a field of 6 T, and by 21.8 mK for heavy water (2004 *J. Appl. Phys.* **96** 6127). Inaba's group found that the changes in the melting points were proportional to the square of the magnetic field. "We believe that the thermal motion of the partially charged atoms in the water gives rise to a Lorentz force when a magnetic field is applied," says Inaba. "By suppressing the thermal motion, the Lorentz force makes the hydrogen bonds stronger, which could account for the rise in the melting points."

US airports look to terahertz screening

The US government is giving \$0.5m to terahertz pioneers TeraView to develop a device that can detect explosives in airline baggage. The UK-based company will be working with US X-ray inspection and trace detection experts Smiths Detection. Together they will explore how terahertz imaging could enhance the screening of explosives in hold luggage. Researchers have 12 months to develop a next-generation security system that impresses officials from the US Department of Homeland Security. If successful, the technology could be fitted in every US airport by 2010. In a separate project, TeraView has received funding from the UK government to develop a hand-held wand for screening airline passengers for traces of explosives at check-in.

PUBLISHING

Google adds scholarly search engine

Can't find that reference to a key paper on quantum cryptography, or want to locate a reference text on spintronics? The Internet search engine Google now has a tool to help researchers seek out scholarly literature that is stored or cited online. Google Scholar works in a similar way to the generic Google search facility. The main difference is that it focuses its search on peer-reviewed papers, theses, books, preprints, abstracts and technical reports, rather than trawling through each and every document on the Internet.

Results to queries are ranked using a proprietary algorithm that takes into account the full text content, the publication in which it appeared, and its citation record. This should mean that seminal papers in respected journals are ranked higher than, say, Web blogs on identical topics. The search tool also lists works that are not available on the Internet but are still cited by other researchers.

Google Scholar is currently available for free as a "beta" – or test – version while the

company evaluates its good and bad points. Researchers are also being encouraged to test the relevance of scholarly searches for themselves. However, physicists can already find most papers they need on the arXiv.org and Spires databases, and will find Google Scholar most useful for retrieving references to historic papers and books.

Yet unless publishers or libraries actually put the text of historical works online, Google Scholar will not help physicists to access older materials either. "Our library has its historical papers in a cellar, where one has to climb down ladders to consult them," says Gerard 't Hooft, the Nobel-prize-winning theorist from the University of Utrecht. "Google Scholar appears to provide access to some of these, but not all."

Google is planning to collaborate with several US research libraries and Oxford University to digitize their collections, but how much will be put online is not known.

Paula Gould

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IRELAND

Astronomers oppose move to Dublin

Irish astronomers want the government to help reverse a decision to end research at the Dunsink Observatory, the oldest scientific institution in Ireland. Four academic staff plus a number of support staff and three PhD students are currently involved in research at Dunsink, but they are all employed by the Dublin Institute of Advanced Studies (DIAS), which has decided to move them to its headquarters in the centre of Dublin at the end of this month. Over 150 astronomers have signed a letter to the minister for education and science, Mary Hanafin, asking her to intervene.

Founded in 1783 on a hill about 8 km from Dublin, research at Dunsink is focused mainly on active galactic nuclei, galaxies with starbursts and clusters of galaxies. DIAS decided to move its staff from the observatory after an international panel of researchers, chaired by Alan Green of ETH Zurich, reviewed its activities at Dunsink. "The panel's recommendations are based on review of the academic work, the staffing levels and its physical location," says Cecil Keavney, the institute's registrar. "We are integrating the research staff at Dunsink under one roof toward the greater efficiency for Irish research astronomy."

However, many Irish astronomers disagree. "We believe that aborting its research now sends the wrong message about the current state of Irish astronomy," they write in



Under threat – the Dunsink Observatory.

their letter to Hanafin. They are worried that "closure in the short term leaves the observatory very much at direct physical risk". They also point out that Ireland is about to celebrate the 200th anniversary of the birth of Dunsink's most famous director, the mathematical physicist William Rowan Hamilton.

"Why don't they just do a proper study of the alternatives and not act precipitously like this," says Brian McBreen, the astronomer at University College Dublin who organized the letter to the government. "The observatory lies on 14 acres of land so why not avail of that and expand its educational and outreach activities, perhaps with a planetarium or something similar."

John Moore

Cork, Ireland

NEUTRINO ASTRONOMY

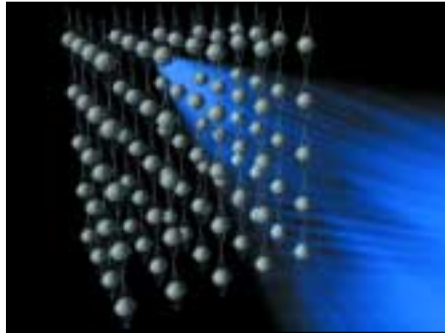
Antarctic ice set to probe the universe

Later this month scientists and engineers working at the south pole will lower a string of light sensors down a hole in the ice more than 2 km deep. Over the next five years they will lower about 80 such strings, creating a network of light sensors embedded in the ice to form a telescope known as IceCube. Their aim is to detect cosmic neutrinos – chargeless, almost massless particles that are generated by extreme astrophysical phenomena such as exploding stars. As well as providing a new view of such phenomena, these neutrinos could help us find dark matter and reveal the origin of cosmic rays.

Neutrinos are useful as astronomical messengers because they hardly interact with other matter. This means that they can pass through regions in space that absorb electromagnetic radiation, such as gas clouds or the all pervasive cosmic microwave background. But the neutrinos' virtue is also their vice: their weak interaction means they are extremely difficult to detect. Doing so requires building extremely large detectors, so that if there are enough atoms in the target a neutrino will interact with one of them sooner or later.

An astrophysicist in the US even thinks that a neutrino detector could be developed using one of Jupiter's moons (see box). But for the time being, researchers are sticking to detectors on Earth. IceCube, which will cost \$270m, is being developed by researchers in the US, Germany, Sweden, Belgium and Japan, and will occupy a volume of 1 km^3 , with the strings (electrical cables) distributed over an area of 1 km^2 . Each string will contain 60 sensors – photomultiplier tubes housed in protective glass spheres – distributed evenly along the lowest 1 km of cable. Neutrinos reaching the Earth's northern hemisphere will pass through the planet and occasionally interact with a proton or a neutron in an atomic nucleus to create another subatomic particle called a muon. Any muons generated in or just below IceCube can be detected by the Cerenkov radiation they give off as they travel at high speed through the ice. This radiation will allow physicists to determine the flux and trajectory of the incoming neutrinos. The detector will be deep enough to screen out cosmic rays – the stream of charged particles that constantly bombards the Earth – generated in the southern hemisphere and dark enough to avoid interference from natural light.

A prototype of IceCube has already been operating at the south pole since 2000. Known as AMANDA, this experiment has proved the feasibility of observing neutrinos in the ice, having so far detected about 4000 neutrinos, with energies up to about



Cool stuff – the IceCube detector at the south pole will be used to detect cosmic neutrinos.

Neutrino detectors in space

Peter Gorham of the University of Hawaii believes that to observe highly energetic cosmic neutrinos (with energies of about 10^{20} eV) physicists should consider making a detector out of Europa, the ice-covered moon that orbits Jupiter ([arXiv.org/abs/astro-ph/0411510](http://arxiv.org/abs/astro-ph/0411510)).

When neutrinos with energies of 10^{20} eV interact with ice, they produce Cerenkov radiation at radio wavelengths (as well as at visible wavelengths), which can be detected hundreds of miles away from the ice. This mechanism is currently being exploited by a NASA-sponsored mission called ANITA, which will use a high-altitude balloon to monitor the radio pulses from about one million cubic kilometres of Antarctic ice. However, ANITA will be limited by the thermal noise and lack of transparency of the ice, which has a temperature of 240 K.

According to Gorham, the best way to overcome this problem is to use large bodies of ice in the solar system, such as Europa, as detectors. About the size of the Moon, Europa is thought to be covered by a thick layer of ice that has a temperature of about 90 K and penetrates to a depth of tens of kilometres or more. Gorham believes that a satellite, or satellites, orbiting Europa could detect extremely high-energy cosmic neutrinos by picking up neutrino-induced radio emissions from a much deeper volume of much colder ice than is available on Earth.

IceCube principal investigator Francis Halzen disagrees, however. "To calculate how difficult it will be to develop such a telescope you just have to extrapolate the effort and cost needed to build IceCube. I do not think it is something for my lifetime," he says. But Halzen is careful not to rule out the concept altogether. "Most people said we that we could never build IceCube. But we are."

10^{15} eV , generated by cosmic rays passing through the Earth's atmosphere near the north pole. But AMANDA has only 1.5% of the volume of IceCube and has been unable to detect any higher-energy cosmic neutrinos, which are much rarer than their atmospheric counterparts.

That will not be the case with IceCube, which is predicted to detect neutrinos from a number of astrophysical sources with energies up to 10^{18} eV . These include the mysterious sources of cosmic rays. Astrophysicists have some evidence that cosmic rays are accelerated near black holes – possibly those associated with active galaxies or gamma-ray bursts – but detecting neutrinos from these objects would prove this, according to IceCube's principal investigator Francis Halzen of the University of Wisconsin-Madison in the US. This is because neutrinos are generated by the decay of particles known as pions and kaons, which themselves result from the decay of protons (cosmic rays).

IceCube will also search for "weakly interacting massive particles" (WIMPs), which some cosmologists think could be a source of dark matter. It will do so by looking out for the neutrinos given off in the annihilation of very massive WIMPs in the centres of the Sun and Earth.

Halzen says that IceCube should find its first cosmic neutrino well before it is finished in 2010, and that the completed instrument is expected to detect hundreds of events per year. But he adds that it would be disappointing if the experiment only found what was expected to exist. "I would not be doing this if there were not opportunities for discovering new things," he says.

Also following in AMANDA's footsteps are two experiments being constructed in the Mediterranean Sea. ANTARES will use photomultiplier tubes on strings attached to the sea bed off the south coast of France, while NESTOR will involve a rigid tower of sensors fixed to the sea bed off the Greek island of Pylos. Due to be completed within the next couple of years, these experiments are about the same size as AMANDA and follow on from a smaller experiment located in Lake Baikal in Siberia.

But physicists working on the projects hope that they can eventually use the expertise that they have gained developing these experiments to build an underwater detector with a volume of 1 km^3 , sometime after 2012. "Neutrino astronomy is not going to take off unless we build a 1 km^3 detector in the northern hemisphere as well," says Halzen.

Edwin Cartlidge

SIDEBANDS

NASA seeks new boss...

NASA was awaiting a new administrator as *Physics World* went to press following the resignation of Sean O'Keefe, who is a candidate to become the new president of Louisiana State University. O'Keefe, who spent just three years at the helm of NASA, would earn over \$500 000 as president of the university, compared with just \$158 000 as boss of the US space agency. He leaves several challenges for his successor. The Space Shuttle remains grounded following the *Columbia* disaster, the International Space Station faces delays, and the Bush administration's plans to send astronauts to the Moon and Mars have been severely criticized. Most importantly, the new administrator must continue O'Keefe's efforts to change a lackadaisical NASA culture that led to the loss of *Columbia*.

...and urged to send shuttle to Hubble

Astronauts should be sent on the Space Shuttle to service the Hubble Space Telescope, according to a panel set up by the National Research Council (NRC). Led by Louis Lanzerotti – a physicist from the New Jersey Institute of Technology – the panel says that NASA should organize a mission to fly to Hubble as soon as the shuttle is cleared for flight. This would be needed, the panel says, to prevent the deterioration of components that could make the telescope both unusable and impossible to de-orbit safely. Given the quality of science that the telescope can continue to produce 14 years after it was first launched, a shuttle mission “is worth the risk”, according to Lanzerotti. Outgoing NASA boss Sean O'Keefe had said the telescope should be repaired robotically because it would be too dangerous to let astronauts do the job. He had previously argued it should not be serviced at all, but was forced to change his mind following an outcry from astronomers.

Caltech astronomers given new home

The California Institute of Technology is to build a \$50m facility that will bring together observational astronomers, theorists and instrument-makers under the same roof. Caltech astronomers currently occupy four different buildings, which “from the intellectual point of view leaves a lot to be desired”, says Tom Tombrello, chair of physics, mathematics and astronomy. The Cahill Center for Astronomy and Astrophysics, which is mainly funded by the philanthropist Charles Cahill, will be complete by this spring and will house about 100 staff.

ENERGY

Cold fusion gets luke-warm backing

Cold fusion remains unproven but should not be written off, according to a review of the disputed energy source carried out by the US Department of Energy (DOE). The review concludes that although there is no firm experimental evidence to support cold fusion – the generation of controlled nuclear fusion using just table-top devices – funding agencies should still consider supporting individual experiments in the field.

The report, issued last month, revives the controversy begun in 1987, when electrochemists Martin Fleischmann of the University of Southampton in the UK and Stanley Pons of the University of Utah in the US reported that they had produced deuterium–deuterium fusion by using a battery connected to palladium electrodes in heavy water. Their subsequent announcement of the research at a press conference in March 1989 grabbed the world's attention. The excess heat that they claimed to have generated in the experiment suggested a new type of energy source – one that would not require the million-degree temperatures needed in conventional fusion. But the failure of other scientists to replicate the results and a negative review of the technique carried out by the DOE discredited the work.

Despite this, a few scientists and engineers have continued to investigate cold fusion, and in late 2003 a group of researchers per-

sueded the DOE to take another look at the issue. The DOE sent a paper prepared by four members of the group to nine reviewers with backgrounds in experimental and theoretical nuclear physics, materials science, and electrochemistry. Those reviewers and nine others, all of whom remain anonymous, then spent a day questioning the four authors and other scientists involved in research on cold fusion.

The reviewers say they remain unconvinced about the reality of cold fusion, and believe that the field has been hampered by poorly designed experiments and badly documented results. But their verdict is not entirely negative: they think that the calorimeters used by cold-fusion researchers have become significantly more sophisticated than they were in 1989. Indeed, a third of the reviewers believe that the phenomenon could potentially create excess power.

“Before the review the ratio of negative to positive feelings about cold fusion was 100 or more to one,” says David Nagel, an engineer at George Washington University in Washington DC, and one of the group who submitted the paper to the DOE. “But among the reviewers, the ratio was more like two to one. So I cannot see anything but positives in that.”

Peter Gwynne
Boston, MA

US FUNDING

Congress destroys budget goal

In late November last year, almost two months after the start of the US financial year, Congress finally agreed on a budget for 2005. The budget was not good news for the National Science Foundation (NSF), which funds researchers at most US universities. It ended up with \$5.47bn, some 1.9% less than it received in 2004. According to Kei Koizumi, a budget analyst at the American Association for the Advancement of Science, the reduction destroys any chance of achieving the goal, agreed by both parties in Congress, of doubling NSF's budget between 2002 and 2007.

In general, physics projects supported by the NSF suffer uniform losses at about the 1.9% level. But one significant new undertaking, the Rare Symmetry Violating Processes (RSVP) project, which will explore matter–antimatter asymmetry in the universe, loses half of its proposed funding. The project, construction on which was due to start later this year at the Brookhaven National Laboratory, will

receive \$15m rather than the requested \$30m. According to Koizumi, the reduction will almost certainly delay the scheduled completion of the facility beyond 2007.

Other physics-related projects fare better in the budget, however. Research on inertial-confinement fusion supported by the Department of Energy receives \$50m more than requested by the Administration. NASA, meanwhile, wins an increase of 4.5% over its 2004 budget of \$15.38bn, although the American Physical Society has expressed concern that NASA's scientific activities might be reduced in order to support the agency's proposed missions to the Moon and Mars.

Peter Gwynne
Boston, MA

● **President Bush has nominated chemical engineer Samuel Bodman as Energy Secretary, replacing Spencer Abraham who resigned in November shortly after the election. Bodman, 66, has spent the past four years as a deputy secretary in the US Commerce and Treasury departments.**

UK UNIVERSITIES

Scottish physicists form a superteam...

Physicists from six Scottish universities are to join forces to create the largest physics department in the UK. They will form a single entity known as the Scottish Universities Physics Alliance (SUPA) that will carry out joint research projects and run a single graduate school. With over 200 full-time researchers and initial funding of over £14m for the next four years, SUPA aims to make Scottish physics more competitive on the international stage. However, there was bad news in England last month: Newcastle University is to stop teaching pure physics degrees – ending a 130-year tradition – while Keele University is to axe all physics research apart from astrophysics (see below).

SUPA will bring together physicists from Edinburgh, Glasgow, Heriot Watt, Paisley, St Andrews and Strathclyde universities. It will receive £6.9m from the Scottish Higher Education Funding Council, £5.9m from the six universities, as well as £1.3m from the Office of Science and Technology for new equipment. SUPA aims to make physicists in Scotland play to their strengths, rather than compete with one another for



Critical mass – physicists at Glasgow (above) and the rest of Scotland will work together.

funds. It was also set up to encourage the Scottish Executive to invest more in Scottish universities, which do not – unlike their counterparts in England – charge students tuition fees.

Physics research will initially focus on five key areas – astronomy and astrophysics, condensed matter and materials physics, nuclear and plasma physics, particle physics, and photonics. There are plans to recruit

four new chairs as well as 16 lecturers, who will be the “rising stars” of the future. A further 14 advanced fellowships will be given to promising young researchers. Although all staff will be employed by the university at which they are based, they will be recruited centrally. Eight PhD prize studentships will also be offered every year.

“We have worked for about 18 months on this plan and I am delighted to see it come to fruition,” says Alan Miller, vice principal for research at St Andrews. “SUPA sends a message that Scotland has a strong science base and a faith in the importance of physics. Planning the alliance has developed a very positive synergy between the universities.”

John Chapman, head of physics and astronomy at Glasgow, adds that most physicists support the plan. “The staff are keen and I think SUPA will succeed,” he says. “We will also look to move into new research areas as time goes by as we do not simply want to freeze in whatever pattern was right in 2004.”

Matin Durrani

● www.supa.ac.uk

...while Newcastle axes pure physics

Physics has been placed on a list of subjects of “national strategic importance” by the outgoing education secretary Charles Clarke. He drew up the list shortly after Exeter University announced that it will close its chemistry department due to a lack of money and just as Newcastle University revealed that it will no longer offer degrees in pure physics. Clarke has asked the Higher Education Funding Council for England for advice on how to protect subjects on the list, which also includes other sciences, engineering and languages.

Newcastle’s decision was made after the university carried out a review to “build on its strengths” in physics. Although all existing physics students will be allowed to complete their degrees at Newcastle, no new students will be admitted from next autumn. The university currently has 35 first-year physics undergraduates, the last of whom is due to graduate in 2008.

The university will, however, launch a new master’s degree in computational physics later this year as well as an interdisciplinary “natural sciences” degree in 2006. It is also considering strengthening nanotechnology and materials science, which, it says, “are more attractive to students and have greater potential for generating research income”.

Malcolm Young, pro vice-chancellor for

science at Newcastle, claims to be “delighted at the progress” the university is making. “It is essential that we move with the times in the sciences,” he says. “I believe we will emerge with a much stronger portfolio of physics and chemistry teaching and research programmes that will be more relevant to the world we live in today.”

However, Albert Crowe, head of physics at Newcastle, calls the decision “unfortunate” and says that the university had filled its places in physics relatively easily. He was, however, relieved that none of the department’s seven staff will lose their jobs. Ironically, the news emerged a day after Newcastle was awarded “science city” status by the Chancellor Gordon Brown. It will share £100m with Manchester and York to boost science research in the three cities.

According to Crowe, the decision to stop teaching physics is linked to the fact that Newcastle only got a grade 4 for its physics research in the 2001 Research Assessment Exercise (RAE). Since then the government has cut funding for 4-rated departments, and focused it on those rated 5 or 5*.

“The vice chancellor [Christopher Edwards] feels that we will not be able to improve any further unless the university makes a major investment in physics, which it is not prepared to do,” says Crowe. “He

thinks the only way we will do any better – without investing in new staff – is if we do not have to teach a full physics degree.” A plan to move Newcastle’s physicists to Durham fell through last year.

The theoretical physicist and best-selling author Paul Davies says he is “saddened but not shocked” at Newcastle’s decision to drop its undergraduate physics degree. Davies left Newcastle in 1990 for a research position in Australia after becoming disillusioned with physics in Britain. Ironically, before he left, Davies had led negotiations to merge the physics departments at Newcastle and Durham. “In the end the plan was vetoed,” he says. “There is a lesson for all physics departments: it really is a case of ‘divided we fall’.”

Matin Durrani

● Keele University is to wind down all physics research, apart from astrophysics. The physics department, which received a grade 3a in the last RAE, currently has 14.5 full-time staff, nine of whom work on nuclear physics, polymers, lasers and theory, and the rest in astrophysics. Although Keele has no plans to sack any staff, a senior physicist at the university says staff are “very worried” about their futures. And although Keele’s dual-honours degrees in physics or astrophysics with a second subject have been saved, they will be now taught by fewer staff.

Los Alamos looks to uncertain future

The contract to run Los Alamos, the home of the atomic bomb, is up for grabs. Improving security will be a major challenge for the lab's new managers, as **Peter Gwynne** reports

Ever since it was established in 1943, the Los Alamos National Laboratory in New Mexico has been managed by the University of California. Initially home to the Manhattan atomic-bomb project, the lab is now responsible for ensuring the safety and reliability of America's stockpile of nuclear weapons, as well as carrying out a wide range of research in physics and related disciplines. With some 13 600 employees and an annual budget of \$2.1bn, it is a prestigious and lucrative asset to the university.

But from October this year the lab may be in new hands. An embarrassing series of security and safety lapses has hit Los Alamos in the past five years, leading to shutdowns, firings and other interruptions. These lapses persuaded officials at the Department of Energy, which funds the national-laboratory system, to put the contract to manage Los Alamos out to tender. Although the University of California can still bid for this contract, other universities and industrial companies are keen to take over.

Troubled times

The recent controversies at Los Alamos started in 1999, when a physicist at the lab, Taiwan-born Wen Ho Lee, was accused by the US government of leaking secret information on nuclear weapons and radar technology to China. This accusation quickly proved to be an embarrassing overreaction; Lee eventually pleaded guilty to a single charge of downloading classified material onto a non-secure computer. But other incidents soon followed. In 2000 two hard drives from the lab containing highly classified information were lost for four days before being found in an area that had been previously searched. And in late 2002 allegations of fraud, theft and the mismanagement of supplies led to several employees being dismissed and the lab's top two security officials being reassigned to other duties within the lab. More importantly, the incidents resulted in the lab's director, John Browne, resigning and being replaced by Peter Nanos, a retired admiral with a PhD in physics and extensive experience in managing military laboratories.

But the security problems continued, culminating in a series of incidents last July. In one, a lawyer at Los Alamos sent a classified e-mail message from his unclassified home computer. In another, an accident in a laser experiment burned a 0.5 mm hole in the retina of an undergraduate intern, damaging her vision. A subsequent investigation determined that the student and her supervisor,



Is the writing on the wall for the University of California's management of Los Alamos?

David Cremers, were not wearing protective goggles and had ignored other safety rules. In response, Nanos fired Cremers and tried to persuade other scientists involved with the laser programme to resign. Cremers has since appealed against his dismissal.

The incident that really created a stir, however, involved the apparent loss of two storage drives containing classified information on an experiment in weapons physics. In an effort to renew confidence in the institution and to "exercise control over our own destiny", Nanos sacked four employees, suspended 19 others, put a temporary halt to all classified work at the lab, and then suspended almost all the lab's activities so that staff could review their security procedures. He reportedly described employees at the lab as being in "suicidal denial" and as propagating a "culture of arrogance". Commenting soon after the incident in July, Joe Barton, Republican Congressman for Texas, said he thought that there is "probably better security at the public library over CDs and videos".

Further investigation provided strong evidence that the missing drives had never in fact existed, and that their apparent disappearance was due to a book-keeping error. Nevertheless, Nanos continued to shake up the lab's management, splitting its operations directorate in two in order to put more emphasis on security. He also appointed Don Cobb, associate director for threat reduction at Los Alamos, as acting deputy laboratory director.

Most of the lab's activities have returned to normal, although 10 of the 19 highest security projects at the lab – most of them in the dynamic-experimentation division, which deals with the simulation of nuclear-weapons testing – remain in limbo. A lab spokesperson indicates that even those projects should be running again "fairly soon".

Putting the house in order

It now remains for the University of California to show that it can clear up these problems for good. Until now, the university had received virtually automatic renewals of its contract every five years. But last month the National Nuclear Security Agency (NNSA), a semi-autonomous agency within the Department of Energy responsible for the nuclear stockpile, issued a preliminary request for proposals to manage the lab.

This document asks candidate organizations to prove they can manage the lab's research activities to a high standard. In addition to "stockpile stewardship" these activities range from particle and nuclear physics to superconductors, quantum information, energy, the environment and medicine. Candidates will also need to demonstrate their ability to manage the lab's wider business operations. The winner of the bidding process will retain the lab's current staff, apart from the director and the most senior managers, and, as an incentive, could have its contract extended incrementally for up to 15 years beyond the original five-year term. The NNSA expects to pick a winner before the end of the summer.

No bidders have yet been confirmed, but several organizations have shown an interest. These include the University of Texas, which is spending \$500 000 to prepare its bid, and Texas A&M University. Other possible candidates include aerospace giants Lockheed Martin and Northrop Grumman, engineering and services firm Fluor Corporation, consulting firm CSC, and the Washington Group of BWX Technologies, which specializes in managing nuclear operations.

After much soul-searching, it seems likely that the University of California will try to retain its contract, possibly in collaboration with an industrial partner. New Mexico governor Bill Richardson, who oversaw Los Alamos as President Clinton's energy secretary, recently recommended that the university should apply to run the scientific side of the contract, with a partner such as Lockheed Martin, Northrop or the Washington Group handling safety and security. "In my experience, University of California management is critical to the success of the lab," said Richardson at a meeting of university chiefs in December last year.

Whether the University of California can retain the contract remains to be seen, of course. But no matter who wins the contract, they will face a major challenge in making sure that Los Alamos puts its security problems behind it.

MEDICAL PHYSICS

New boosts for US neutron therapy

Cancer patients should soon benefit from an improved type of neutron therapy, thanks to a new agreement between US company Isotron and the Oak Ridge National Laboratory in Tennessee. Oak Ridge has licensed "neutron brachytherapy" to Isotron, a technique that could help combat certain types of prostate cancer, locally advanced breast cancer, cervical cancer, melanomas and brain cancer. "Until now there has been no therapy for brain cancer," says Manfred Sandler, president of Isotron. "Our therapy will give patients with brain cancer a little longer to live with a decent quality of life."

Neutron therapy is better at treating certain cancers than the more widely used X-ray or proton therapy because neutrons can deposit a greater fraction of their energy in the tumour, making it tougher for damaged cancer cells to repair themselves. Brachytherapy involves placing a source of radiation inside or near the tumour to target the cancer cells directly. In neutron brachytherapy a source of californium-252, which emits neutrons when it undergoes spontaneous fission, is put through a hollow tube.



Spot on – neutrons target cancer.

This technique has been available for a little over 10 years, having been experimented with in the 1960s and 1970s.

Until now, however, the large wire-like sources used in neutron brachytherapy have not only killed the cancerous cells but also the surrounding healthy cells. Researchers at Isotron and Oak Ridge have combated this by reducing the diameter of the tube

from 2.8 mm to a little over a millimetre. So even though the new source is over 10 times stronger than its predecessor, it is also safer. The neutron-therapy machine has also been made safer for people operating it.

Assuming that Isotron gets the go-ahead from the US Food and Drugs Administration to start clinical trials, Sandler hopes to start licensing the company's improved instrument out to treatment facilities from 2007 onwards.

Meanwhile, the Fermi National Accelerator Laboratory near Chicago has restarted a neutron-therapy programme that had run for 27 years and treated more than 3000 cancer patients. The programme shut in 2003 when a local hospital ended its involvement. Fermilab is now collaborating with Northern Illinois University to form a new Institute for Neutron Therapy that has secured \$2.7m from the US government. The institute – only the third site in the US to offer the treatment for cancer patients – could open later this month.

Querida Anderson
New York

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69 Tm	70 Yb
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73 Ta	74 W
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79 Au	80 Hg
81 Tl	82 Pb
83 Bi	84 Po
85 At	86 Rn
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Subscription information 2005 volume

For all countries except the UK and Ireland, the subscription rates are: institutions €320/\$400 per annum, individuals €73/\$95 per annum. Single issues £16.50/€24/\$30. Orders to: IOP Circulation Centre, WDIS Ltd, Units 12 & 13 Cranleigh Gardens Industrial Estate, Southall, Middlesex UB1 2DB, UK (tel: +44 (0)20 8606 7518; fax: +44 (0)20 8606 7303).

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Bibliographic codes ISSN: 0953-8585 CODEN: PHWOEW

Printed in the UK by Warners (Midlands) plc, The Maltings, West Street, Bourne, Lincolnshire PE10 9PH

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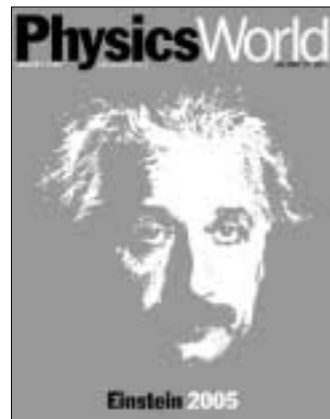
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Physics World has an ABC audited circulation for 2003 of 36 206

Ahead of his time

What would Albert Einstein think if he were alive today? As someone who disliked the limelight, he would probably be embarrassed by the celebrations that are planned as part of the International Year of Physics to mark the centenary of his remarkable achievements in 1905. As a theorist who was interested in experiments, in his early career at least, he would be pleased to know that a small band of 21st-century physicists are still trying to find flaws in the special theory of relativity, while others are busy checking out the predictions of the general theory. And having spent the final years of his life trying to unify general relativity with electromagnetism, without success, he could be forgiven for thinking that criticisms of his relative non-productivity in those years were somewhat unfair. No-one else has succeeded where he failed.



It is impossible to overstate the importance of what Einstein did in 1905. His work on Brownian motion provided the theoretical framework for experiments to prove that atoms were real. Hard as it might be to believe now, at the time the majority of physicists did not believe in atoms. The special theory of relativity completely changed our notions of space and time, while $E = mc^2$ led to the remarkable conclusion that mass and energy are one and the same. And his work on the photoelectric effect was the start of a love-hate relationship with quantum mechanics that still fascinates physicists today.

And 1905 was just the beginning. The general theory of relativity – his truly outstanding achievement – followed 10 years later, with its predictions for the bending of light by mass being confirmed a few years after that during the solar eclipse of 1919. But even then Einstein did not abandon his interest in atoms, photons and quantum mechanics. The Einstein *A* and *B* coefficients for spontaneous and stimulated emission – without which we would not have lasers – made their debut in 1916, and the prediction of Bose-Einstein condensation – one of the hottest topics in experimental physics for the past decade – followed in the 1920s.

This special issue of *Physics World* covers all this and more. On page 19 Mark Haw describes Einstein's theory of Brownian motion as a "slower, subtler revolution" than his work on relativity or quantum mechanics, but just as influential nonetheless. On page 27 Clifford M Will provides an update on the renaissance in experimental gravitational physics and reports how the general theory has so far survived all scrutiny, although it has not yet been tested in the strong-field limit. Most exciting, however, is the fact that theories that seek to unify gravity with the three other fundamental forces of nature predict departures from general relativity that will soon be within experimental reach.

Of course, the outstanding prediction of general relativity that has yet to be confirmed is the existence of gravitational waves: on page 37 Jim Hough and Sheila Rowan describe the almost superhuman efforts that are being made to find out if Einstein was right on this occasion. And as if to show that the great physicist could also be wrong, on page 47 Harald Weinfurter reports on the state of the art in quantum entanglement – the phenomenon that Einstein once dismissed as "spooky action at a distance". Other topics covered range from Einstein's love of music to the way his image is protected by the Hebrew University of Jerusalem and a Hollywood agent.

These articles are obviously preaching to the physics converted, but the organizers of the International Year of Physics – also known as World Year of Physics and Einstein Year – have much loftier ambitions. Through a world-wide programme of events, demonstrations and other activities they hope to inspire the next generation of physics students. Einstein would have approved.

Peter Rodgers

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A brief history of Albert Einstein

Born in Germany in 1879, Einstein became the most famous physicist the world has ever seen

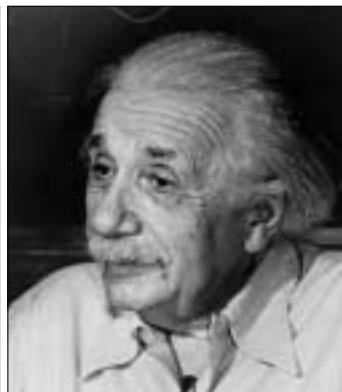
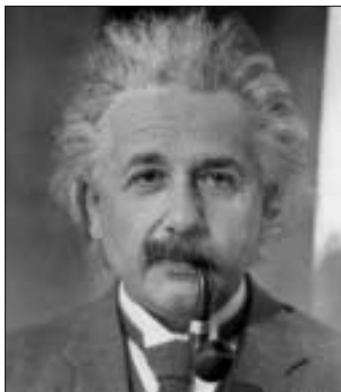


IMAGE ARCHIVE ETH-BIBLIOTHEK, ZÜRICH; AIP, EMILIO SEGRE VISUAL ARCHIVES

The early years

1879 Born 14 March at Bahnhofstraße 135, Ulm, Germany

1880 Einstein's family moves to Munich, where his father founds a firm manufacturing electrical equipment

1888 Enters Luitpold Gymnasium in Munich

1894 Family moves to Italy; Albert stays in Munich, but gets depressed without his family and does not complete his schooling

1895 Albert joins family in Italy; fails entrance exam for the ETH Zurich; moves to Aarau, Switzerland

1896 Obtains diploma from cantonal school in Aarau, which allows him to enrol for the ETH Zurich; relinquishes German citizenship

1900 Receives diploma from Zurich, scoring 5 (out of a possible 6) for theoretical physics, experimental physics and astronomy, and 5.5 for theory of functions

Life after college

1901 Becomes a Swiss citizen, but declared unfit for military service due to flat feet and varicose veins; gets a few temporary school-teaching jobs

1902 Appointed technical expert (third class) at the patent office in Bern with a salary of SwFr 3500; fiancée Mileva Marić – a fellow student from Zurich – gives birth to illegitimate daughter Lieserl

1903 Marries Mileva on 6 January

1904 First son, Hans Albert, born 14 May

1905 Einstein's *annus mirabilis*: submits PhD thesis on molecular dimensions to University of Zurich, as well as two papers on special relativity, one on quantum theory and another on Brownian motion to *Annalen der Physik*

1906 Promoted to technical expert (second class), salary raised to SwFr 4500

1907 Einstein has "the happiest thought of my life" – that a gravitational field is equivalent to acceleration

Turning professional

1909 Resigns from patent office and starts work as associate professor at University of Zurich on 15 October

1910 Second son, Eduard, born 28 July

1911 Appointed full professor at the German University of Prague, where he works out that the bending of light should be detectable during a solar eclipse; attends first Solvay Congress in Brussels

1912 Returns to Switzerland as professor at the ETH Zurich

1914 Becomes professor at the University of Berlin; moves into a bachelor apartment after separating from Mileva, who returns with sons to Zurich

1915 Completes theory of general relativity; co-signs an anti-war manifesto urging people to join a "League of Europeans"

1916 Writes 10 papers, including first paper on gravitational waves,

and one on the spontaneous and stimulated emission of light; publishes *The Origins of the General Theory of Relativity*; succeeds Max Planck as president of the German Physical Society

1917 Becomes founding director of Kaiser-Wilhelm Institut, Berlin; writes paper on the twin paradox; introduces the cosmological constant; overwork triggers liver problem, stomach ulcer and jaundice that together confine him to bed for several months – looked after by his cousin Elsa Einstein Löwenthal

Public fame

1919 Marries Elsa on 2 June; divorce settlement with Mileva stipulates that she would receive any Nobel-prize money from Einstein; eclipse watchers confirm his prediction that the Sun bends distant starlight, leading to headlines around the world

1920 Toys with leaving Germany after attacks on relativity by anti-semites

1921 Visits the US for first time

1922 Awarded 1921 Nobel Prize for Physics for his "services to theoretical physics and in particular for his discovery of the law of the photoelectric effect" – prize money of about \$32 000 given to Mileva; completes first paper on unified field theory

1924 Einstein Institute founded in Potsdam; predicts Bose–Einstein condensation

1927 Attends fifth Solvay Congress in Brussels and starts debate on quantum theory with Niels Bohr

Life in the US

1933 Leaves Germany after Nazis take power and joins the Institute for Advanced Study in Princeton – a "quaint and ceremonious village of demigods on stilts"; rejects cosmological constant

1935 Publishes strident attack on quantum theory with Boris Podolsky and Nathan Rosen

1936 Elsa dies

1939 Signs letter to President Roosevelt warning of dangers of atomic bomb

1940 Becomes US citizen, while retaining Swiss citizenship

1944 Retires from Princeton, aged 65; writes out by hand his original 1905 paper on special relativity for auction, raising \$6m for US war effort

1946 Becomes chairman of the Emergency Committee of Atomic Scientists; calls for world government to be formed

1952 Turns down an offer to be President of Israel

1955 Signs "Russell–Einstein manifesto" on 11 April urging nations to renounce nuclear weapons; dies in Princeton at 1.10 a.m. on 18 April from ruptured abdominal aorta; brain removed by pathologist Thomas Harvey; body cremated at the Ewing Crematorium

Matin Durrani

Einstein resources and events

Online information

Albert Einstein Archives

jnul.huji.ac.il/einstein

Albert Einstein: Image and Impact
(online exhibit)

www.aip.org/history/einstein

Einstein Papers Project

www.einstein.caltech.edu

Einstein Year: A Year Celebrating Physics
(UK and Ireland)

www.einsteinyear.org

Einstein@HOME

www.physics2005.org/events/einsteinathome/index.html

Einstein's FBI file

www.theeinsteinfile.com

World Year of Physics

www.wyp2005.org

World Year of Physics (US site)

www.physics2005.org

Diary dates

13–15 January

Physics for Tomorrow: Launch Conference
of the International Year of Physics
UNESCO, Paris

www.wyp2005.org/unesco

17–21 February

AAAS Annual Meeting: World Year of Physics
Washington, DC

www.aaas.org/meetings/Annual_Meeting/02_PE/PE_07_SemD.shtml

4–9 March

Physik seit Einstein
Berlin

www.dpg-physik.de/wyp2005

10–14 April

Physics, a century after Einstein
Warwick, UK

www.physics2005.iop.org

11–15 July

Beyond Einstein: Physics for the 21st Century
Bern, Switzerland

www.eps13.org

11–15 July

Le Siècle d'Albert Einstein (for the public)

Paris
einstein2005.obspm.fr/indexr.html

18–22 July

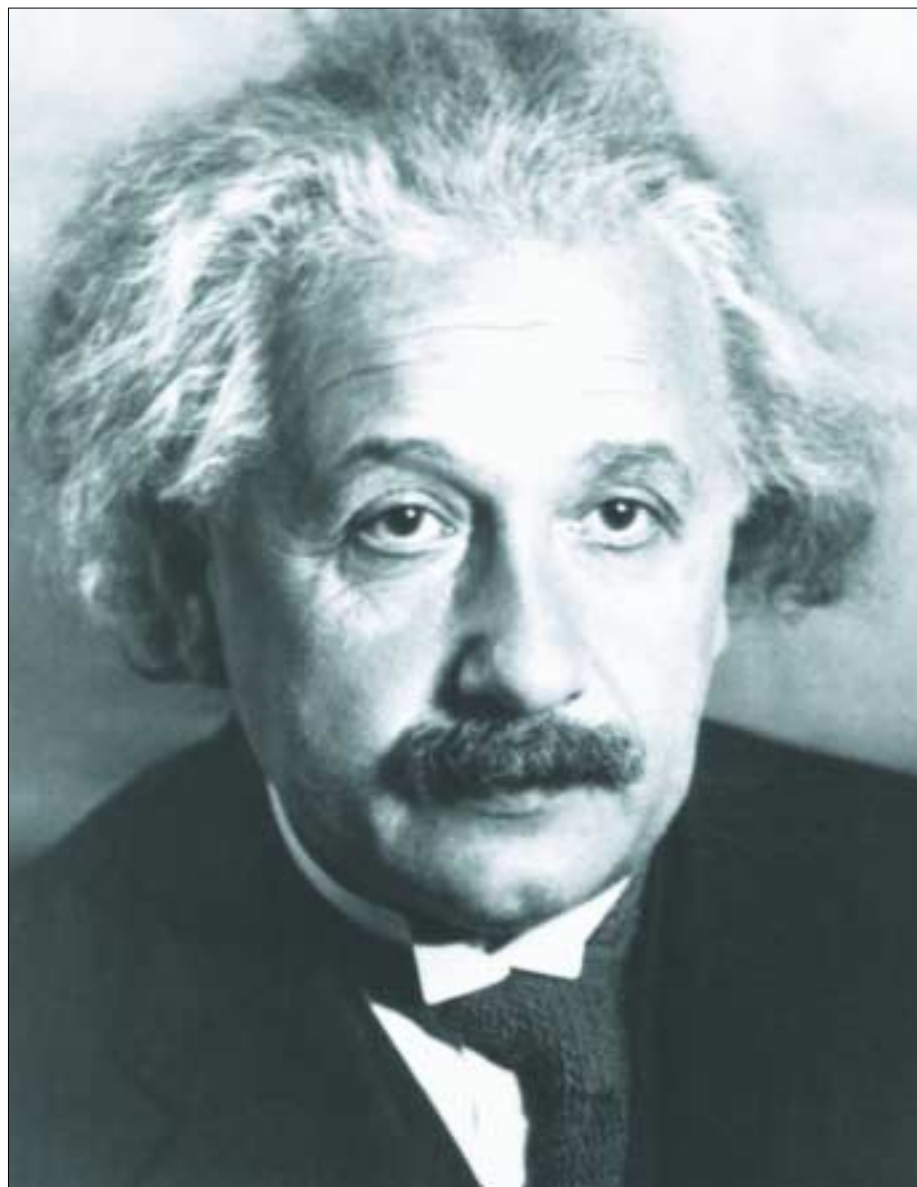
Albert Einstein Century International
Conference

Paris
einstein2005.obspm.fr/indexr.html

31 October–2 November

World Conference on Physics and
Sustainable Development

Durban, South Africa
www.saip.org.za/physics2005/WCPD2005.html



AIP Emilio Segre Visual Archives

Master of the universe. Albert Einstein is probably the most famous person in history, and almost certainly the smartest. Many of the world's greatest thinkers sought Einstein out during his lifetime – the photograph above was taken during a meeting with the Nobel-prize-winning Indian poet Rabindranth Tagore in 1930 – and today, 50 years after his death, the father of relativity still captures the imagination of the world at large. Walk into a shop selling toys for children and you will find “Baby Einstein” CDs and books. Ask for help in Microsoft Word and a cartoon Einstein will do his best to solve your problem. To physicists and non-physicists alike, Einstein has become a byword for genius. This year the physics community will celebrate the centenary of 1905 – the year that Einstein kick-started modern physics with his work on special relativity, Brownian motion and quantum mechanics – with a worldwide programme of events. Every month during 2005 *Physics World* will publish news of these events (see panel on left), together with photographs and quotations from the original master of the universe.

In his own words

The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction.

The Expanded Quotable Einstein (Princeton University Press)



Five papers that shook the world

In 1905 an anonymous patent clerk in Bern rewrote the laws of physics in his spare time.

Matthew Chalmers describes Einstein's miraculous year

Most physicists would be happy to make one discovery that is important enough to be taught to future generations of physics students. Only a very small number manage this in their lifetime, and even fewer make two appearances in the textbooks. But Einstein was different. In little more than eight months in 1905 he completed five papers that would change the world for ever. Spanning three quite distinct topics – relativity, the photoelectric effect and Brownian motion – Einstein overturned our view of space and time, showed that it is insufficient to describe light purely as a wave, and laid the foundations for the discovery of atoms.

Perhaps even more remarkably, Einstein's 1905 papers were based neither on hard experimental evidence nor sophisticated mathematics. Instead, he presented elegant arguments and conclusions based on physical intuition. "Einstein's work stands out not because it was difficult but because nobody at that time had been thinking the way he did," says Gerard 't Hooft of the University of Utrecht, who shared the 1999 Nobel Prize for Physics for his work in quantum theory. "Dirac, Fermi, Feynman and others also made multiple contributions to physics, but Einstein made the world realize, for the first time, that pure thought can change our understanding of nature."

And just in case the enormity of Einstein's achievement is in any doubt, we have to remember that he did all of this in his "spare time".

Statistical revelations

In 1905 Einstein was married with a one-year-old son and working as a patent examiner in Bern in Switzerland. His passion was physics, but he had been unable to find an academic position after graduating from the ETH in Zurich in 1900. Nevertheless, he had managed to publish five papers in the leading German journal *Annalen der Physik* between 1900 and 1904, and had also submitted an unsolicited thesis on molecular forces to the University of Zurich, which was rejected.

Most of these early papers were concerned with the reality of atoms and molecules, something that was far from certain at the time. But on 17 March in 1905 – three days after his 26th birthday – Einstein submitted a paper titled "A heuristic point of view concerning the production and transformation of light" to *Annalen der Physik*.

Einstein suggested that, from a thermodynamic perspective, light can be described as if it consists of independent quanta of



Genius at work – Einstein was just 26 when he made three ground-breaking contributions to physics in a single year. Here he is pictured at the Swiss patent office in early 1906.

energy (*Ann. Phys.*, *Lpz* **17** 132–148). This hypothesis, which had been tentatively proposed by Max Planck a few years earlier, directly challenged the deeply ingrained wave picture of light. However, Einstein was able to use the idea to explain certain puzzles

“The arguments Einstein used were staggering in their boldness and beauty.”

about the way that light or other electromagnetic radiation ejected electrons from a metal via the photoelectric effect.

Maxwell's electrodynamics could not, for example, explain why the energy of the ejected photoelectrons depended only on the frequency of the incident light and not on the intensity. However, this phenomenon was easy to understand if light of a certain frequency actually consisted of discrete packets or photons all with the same energy. Einstein would go on to receive the 1921 Nobel Prize for Physics for this work, although the official citation stated that the prize was also awarded "for his services to theoretical physics".

"The arguments Einstein used in the photoelectric and subsequent radiation theory

are staggering in their boldness and beauty," says Frank Wilczek, a theorist at the Massachusetts Institute of Technology who shared the 2004 Nobel Prize for Physics. "He put forward revolutionary ideas that both inspired decisive experimental work and helped launch quantum theory." Although not fully appreciated at the time, Einstein's work on the quantum nature of light was the first step towards establishing the wave-particle duality of quantum particles.

On 30 April, one month before his paper on the photoelectric effect appeared in print, Einstein completed his second 1905 paper, in which he showed how to calculate Avogadro's number and the size of molecules by studying their motion in a solution. This article was accepted as a doctoral thesis by the University of Zurich in July, and published in a slightly altered form in *Annalen der Physik* in January 1906. Despite often being obscured by the fame of his papers on special relativity and the photoelectric effect, Einstein's thesis on molecular dimensions became one of his most quoted works. Indeed, it was his preoccupation with statistical mechanics that formed the basis of several of his breakthroughs, including the idea that light was quantized.

After finishing a doctoral thesis, most physicists would be either celebrating or sleeping. But just 11 days later Einstein sent

another paper to *Annalen der Physik*, this time on the subject of Brownian motion. In this paper, "On the movement of small particles suspended in stationary liquids required by the molecular-kinetic theory of heat", Einstein combined kinetic theory and classical hydrodynamics to derive an equation that showed that the displacement of Brownian particles varies as the square root of time (*Ann. Phys.*, *Lpz* **17** 549–560).

This was confirmed experimentally by Jean Perrin three years later, proving once and for all that atoms do exist (see "Einstein's random walk" on page 19). In fact, Einstein extended his theory of Brownian motion in an additional paper that he sent to the journal on 19 December, although this was not published until February 1906.

A special discovery

Shortly after finishing his paper on Brownian motion Einstein had an idea about synchronizing clocks that were spatially separated. This led him to write a paper that landed on the desks of *Annalen der Physik* on 30 June, and would go on to completely overhaul our understanding of space and time. Some 30 pages long and containing no references, his fourth 1905 paper was titled “On the electrodynamics of moving bodies” (*Ann. Phys., Lpz* **17** 891–921).

In the 200 or so years before 1905, physics had been built on Newton’s laws of motion, which were known to hold equally well in stationary reference frames and in frames moving at a constant velocity in a straight line. Provided the correct “Galilean” rules were applied, one could therefore transform the laws of physics so that they did not depend on the frame of reference. However, the theory of electrodynamics developed by Maxwell in the late 19th century posed a fundamental problem to this “principle of relativity” because it suggested that electromagnetic waves always travel at the same speed.

Either electrodynamics was wrong or there had to be some kind of stationary “ether” through which the waves could propagate. Alternatively, Newton was wrong. True to style, Einstein swept away the concept of the ether (which, in any case, had not been detected experimentally) in one audacious step. He postulated that no matter how fast you are moving, light will always appear to travel at the same velocity: the speed of light is a fundamental constant of nature that cannot be exceeded.

Combined with the requirement that the laws of physics are the identical in all “inertial” (i.e. non-accelerating) frames, Einstein built a completely new theory of motion that revealed Newtonian mechanics to be an approximation that only holds at low, everyday speeds. The theory later became known as the special theory of relativity – special because it applies only to non-accelerating frames – and led to the realization that space and time are intimately linked to one another.

In order that the two postulates of special relativity are respected, strange things have to happen to space and time, which, unbeknown to Einstein, had been predicted by Lorentz and others the previous year. For instance, the length of an object becomes shorter when it travels at a constant velocity, and a moving clock runs slower than a stationary clock. Effects like these have been verified in countless experiments over the last 100 years, but in 1905 the most famous prediction of Einstein’s theory was still to come.

After a short family holiday in Serbia, Einstein submitted his fifth and final paper of 1905 on 27 September. Just three pages long and titled “Does the inertia of a body depend on its energy content?”, this paper presented

Elsewhere in 1905



Einstein’s *annus mirabilis* tends to overshadow other scientific developments that took place in 1905. So what else was going on in the year that cellophane was invented, the neon sign made its debut, and people were getting to grips with tea bags for the first time? In terms of the number of citations in physics and physical-chemistry journals since 1945, three of Einstein’s 1905 papers feature in the top five, according to Werner Marx and Manuel Cardona of the Max Planck Institute for Solid State Research in Stuttgart. Indeed, his papers on Brownian motion and special relativity take first and second place, respectively, with 1467 and 642 citations (his papers on the photoelectric effect and $E = mc^2$ are fifth and 11th). The fourth most-cited paper of 1905 was by Paul Langevin, who derived a fundamental formula in kinetic theory – clearly a popular subject at the time – while Lawrence Bragg published a paper about the energy loss of alpha particles in different media, which became the sixth most-cited paper of the year.

Hendrik Antoon Lorentz, who was influential in the development of special relativity, was elected as a fellow of the Royal Society in 1905 and published several papers, including one on the motion of electrons in metallic bodies. Nuclear physics was also a subject of intense interest at the time, with Ernest Rutherford and Frederick Soddy publishing their theory of nuclear transmutation and Bertram Boltwood demonstrating that lead is the final product of uranium decay. Further afield, Victor Goldschmidt introduced a method to reduce metallic oxides to metals, while Haldane and Priestley demonstrated the role of carbon dioxide in the regulation of breathing.

Outside the world of science, an unsuccessful revolution was beginning in Russia, Antonio Gaudi began two of his famous buildings in Barcelona, and H G Wells had written *Kipps*. Meanwhile, Jean-Paul Sartre and Henry Fonda were born, as was the Nobel-prize-winning physicist Emilio Segrè, who 40 years later would witness the application of $E = mc^2$ with the detonation of the first atomic bomb. **MC**

an “afterthought” on the consequences of special relativity, which culminated in a simple equation that is now known as $E = mc^2$ (*Ann. Phys., Lpz* **18** 639–641). This equation, which was to become the most famous in all of science, was the icing on the cake.

“The special theory of relativity, culminating in the prediction that mass and energy can be converted into one another, is one of the greatest achievements in physics – or anything else for that matter,” says Wilczek. “Einstein’s work on Brownian motion would have merited a sound Nobel prize, the photoelectric effect a strong Nobel prize, but special relativity and $E = mc^2$ were worth a super-strong Nobel prize.”

However, while not doubting the scale of Einstein’s achievements, many physicists also think that his 1905 discoveries would have eventually been made by others. “If Einstein had not lived, people would have stumbled on for a number of years, maybe a decade or so, before getting a clear conception of special relativity,” says Ed Witten of the Institute for Advanced Study in Princeton.

’t Hooft agrees. “The more natural course of events would have been that Einstein’s 1905 discoveries were made by different people, not by one and the same person,” he says. However, most think that it would have taken much longer – perhaps a few decades – for Einstein’s general theory of relativity to emerge. Indeed, Wilczek points out that one consequence of general relativity being so far ahead of its time was that the subject languished for many years afterwards.

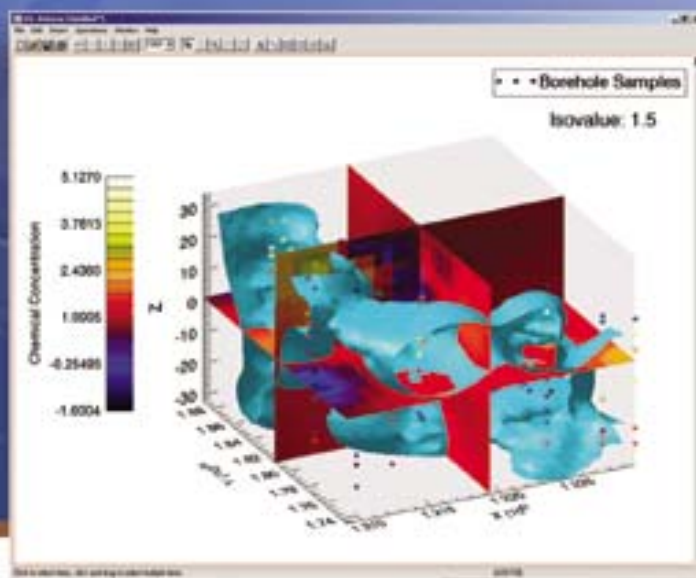
The aftermath

By the end of 1905 Einstein was starting to make a name for himself in the physics community, with Planck and Philipp Lenard – who won the Nobel prize that year – among his most famous supporters. Indeed, Planck was a member of the editorial board of *Annalen der Physik* at the time.

Einstein was finally given the title of Herr Doktor from the University of Zurich in January 1906, but he remained at the patent office for a further two and a half years before taking up his first academic position at Zurich. By this time his statistical interpretation of Brownian motion and his bold postulates of special relativity were becoming part of the fabric of physics, although it would take several more years for his paper on light quanta to gain wide acceptance.

1905 was undoubtedly a great year for physics, and for Einstein. “You have to go back to quasi-mythical figures like Galileo or especially Newton to find good analogues,” says Wilczek. “The closest in modern times might be Dirac, who, if magnetic monopoles had been discovered, would have given Einstein some real competition!” But we should not forget that 1905 was just the beginning of Einstein’s legacy. His crowning achievement – the general theory of relativity – was still to come.

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The story of Brownian motion began with experimental confusion and philosophical debate, before Einstein, in one of his least well-known contributions to physics, laid the theoretical groundwork for precision measurements to reveal the reality of atoms

Einstein's random walk

Mark Haw

MOST OF US probably remember hearing about Brownian motion in high school, when we are taught that pollen grains jiggle around randomly in water due the impacts of millions of invisible molecules. But how many people know about Einstein's work on Brownian motion, which allowed Jean Perrin and others to prove the physical reality of molecules and atoms?

Einstein's analysis was presented in a series of publications, including his doctoral thesis, that started in 1905 with a paper in the journal *Annalen der Physik*. Einstein's theory demonstrated how Brownian motion offered experimentalists the possibility to prove that molecules existed, despite the fact that molecules themselves were too small to be seen directly.

Brownian motion was one of three fundamental advances that Einstein made in 1905, the others being special relativity and the idea of light quanta (see "Five papers that shook the world" on page 16). Of these three great works, Einstein's analysis of Brownian motion remains the least well known. But this part of Einstein's scientific legacy was the key to a revolution that is at least as important as relativity or quantum physics. One century later, Brownian motion continues to be of immeasurable importance in modern science, from physics through biology to the latest wonders of nanotechnology. Indeed, this is reflected in citation statistics, which show that Einstein's papers on Brownian motion have been cited many more times than his publications on special relativity or the photoelectric effect.

The story of Brownian motion spans almost two centuries, its unlikely roots lying in a scientific craze that swept western Europe at the beginning of the 1800s. And it starts, surprisingly enough, not with a physicist but with a botanist.

Brown's botany

In the early 19th-century Europeans became fascinated by botany. In Britain this interest was fuelled by explorations to the corners of the growing empire, particularly Australia or "New Holland" as it was known at that time. One of the first

people to get their botanical teeth into New Holland was Robert Brown, who had grown up botanizing in the Scottish hills.

After completing a medical degree at Edinburgh University and a brief period in the army, during which he spent most of his time specimen-hunting around Ireland, Brown secured a place as ship's botanist on a surveying mission to Australia in 1801. Risking attack from Napoleon's fleets, Brown spent four years exploring the Australian and Tasmanian coasts before returning to London laden with thousands of specimens of new species, his reputation as one of Europe's leading botanists already secure.

But Brown was interested in more than collecting and cataloguing different species – he was also a pioneer of botany as a scientific investigation. Indeed, he is credited with the first clear description of the cell nucleus, and it was Brown that Charles Darwin came to for advice before setting out in the *Beagle* in 1831. In fact, the botanical craze in which Brown had played a major part laid the vital groundwork for Darwin's theory of evolution.

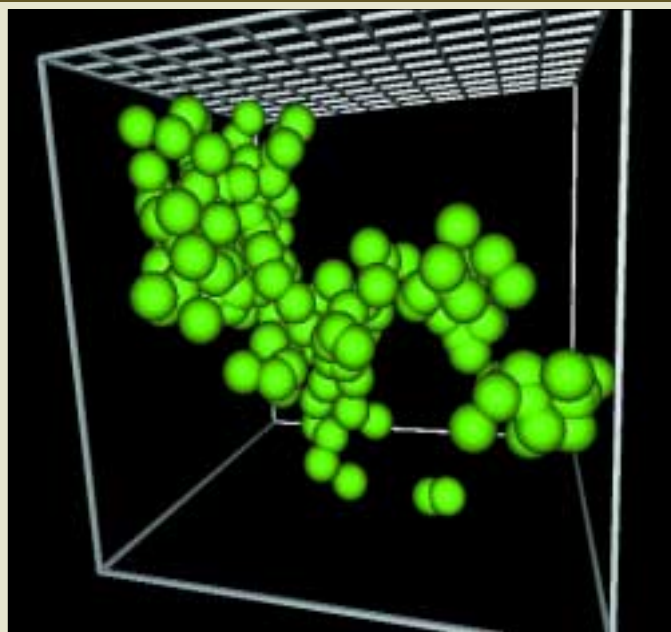
Brown is, of course, better known among physicists for the phenomenon of Brownian motion. In the summer of 1827



Physics in motion – Einstein's theory of Brownian motion allowed Jean Baptiste Perrin to demonstrate the existence of atoms in 1908. Perrin, who won the 1926 Nobel Prize for Physics for this work, is sitting sixth from the left, leaning forward, while Einstein is standing second from the right. This picture was taken at the first Solvay Congress in Brussels in 1911.

BOUAMIN COURTEL - INSTITUT INTERNATIONAL DE PHYSIQUE SOLVAY/ANP ENILIO SERRÉ VISUAL ARCHIVES

1 Random walks



In 1827 Robert Brown noticed that pollen grains suspended in water perform a chaotic and endless dance, but it took many years before it was realized that Brownian motion could reconcile an apparent paradox between thermodynamics and Newtonian mechanics. Einstein played a key role in understanding Brownian motion by predicting that the root mean square displacement of such a particle (green) with respect to its starting point (the centre of the box) increases with the square root of time. Before Einstein came along, experimentalists had assumed that this displacement varied linearly and had therefore been measuring the wrong quantity.

he began to make microscopic observations of suspensions of grains released from pollen sacks taken from a type of evening primrose called *Clarkia pulchella*. What Brown saw surprised him: the tiny grains, which were suspended in water, appeared to be in constant motion, carrying out a tireless and chaotic dance. This motion never appeared to slow or stop. Moreover, as Brown verified, it was not caused by external influences such as light or temperature. He also quickly ruled out his first idea – that the grains were somehow alive – by examining grains from inorganic minerals. So, Brown had shown that whatever it was, this incessant dance was not biology after all: it was physics.

Curiosity and paradox: Brownian motion and kinetic theory

For decades the significance of Brown's observations went almost entirely unappreciated. A few scientists returned now and then to the phenomenon, but it was seen as little more than a curiosity. In hindsight this is rather unfortunate, since Brownian motion provided a way to reconcile the paradox between two of the greatest contributions to physics at that time: thermodynamics and the kinetic theory of gases.

The laws of thermodynamics were one of the crowning achievements of physics by the middle of the 19th century. Through them a vast range of material behaviour could be understood, irrespective of particular theories of matter, simply in terms of the concepts of energy and entropy. But many scientists were not satisfied with this simple picture, and sought not just a statement but an explanation of the laws.

Chief among these were James Clerk Maxwell and Ludwig Boltzmann, who built on the 18th-century idea that matter, such as a volume of gas, is composed of many tiny particles.

They showed that many of the experimental results of thermodynamics could be explained by calculating the average or statistical behaviour of such a collection of particles, in what became known as kinetic theory.

But Maxwell and Boltzmann's theory only brought into sharper focus the paradox between thermodynamics and Newtonian mechanics. Key to kinetic theory was the idea that the motion of individual particles obeyed perfectly reversible Newtonian mechanics. In other words there was no preferred direction of time. But the second law of thermodynamics expressly demanded that many processes be irreversible. Or, as Tom Stoppard puts it in his 1993 play *Arcadia*, you cannot “unstir” the jam from your rice pudding simply by stirring it in the opposite direction. So, if matter was made up of particles obeying perfectly reversible Newtonian equations, where did the irreversibility come from?

This violation of the second law on the scale of single particles in kinetic theory was perfectly apparent to Maxwell, but he missed the subtle link to Brownian motion that might have immediately allowed the paradox to be investigated experimentally. One clue lay in the fact that Brownian motion also apparently violated the second law, since the dance of a Brownian particle seemed to continue forever, never slowing down and never tiring. It therefore ought to be possible to extract endless work from such a particle. But such perfect conversion of heat into work was forbidden by the second law, which states that some energy must always be irreversibly lost as heat whenever work is done. And if some energy is always irretrievably lost, how can the Brownian motion continue forever?

It was not until near the end of the 19th century that scientists such as Louis Georges Gouy suggested that Brownian motion might offer a “natural laboratory” in which to directly examine how kinetic theory and thermodynamics could be reconciled. In other words they decided to turn the problem around and use Brownian motion to throw light on the great paradox of the second law.

There was, however, one problem with this natural laboratory: it was not clear which quantities needed to be measured. This was where, a few years into the 20th century, a young patent clerk called Albert Einstein came to the fore.

Atoms: philosophy, analogy or reality?

Einstein was not the kind of scientist to simply pick a problem and solve it out of idle curiosity, and this is as true of Brownian motion as it is of relativity. He had another motive for wanting to find a theory of Brownian motion, but to understand what this was we first have to consider another controversy that stemmed from kinetic theory.

Ludwig Boltzmann had championed a way out of the reversibility paradox via the statistical interpretation. He suggested that any single molecule would behave entirely in accord with reversible mechanics, but that when you put a large collection of particles together, the statistics implied irreversibility and led unavoidably to the second law. Despite its mathematical success, Boltzmann's “statistical mechanics” met with criticism. Why swap the solid ground of the laws of thermodynamics – the product of a century of careful experimental verification – for the ephemeral world of statistics and chance?

It seemed like a return to the chaos of the middle ages, before the time of Galileo and Newton, and it would take com-

elling evidence to convince people to throw this hard-won determinism away. In fact, it would take direct evidence that Boltzmann was counting something physical and real: a proof that the particles of kinetic theory really existed.

Today we take atoms for granted, but even as recently as the turn of the 20th century not everyone accepted this “discontinuous” description of matter. Even Boltzmann and Maxwell tended to sit on the fence. Boltzmann described kinetic theory as a mechanical analogy, and Maxwell never expected that his illustrative mechanisms – the pictures that helped him build mathematical theories – would be taken literally.

The so-called energeticists, such as Ernst Mach and Wilhelm Ostwald, went even further. They insisted that kinetic theory was no more than a convenient picture that should not be taken literally – certainly not, the latter argued, until you had direct evidence for the existence of atoms. Ostwald’s caution was partly justified. It could be dangerous for the credibility of science to base a complete theory of matter on some hypothetical object that had never been seen – especially at a time when science was under strident philosophical attack from intellectuals, who despaired at its apparently inhumane reductionism.

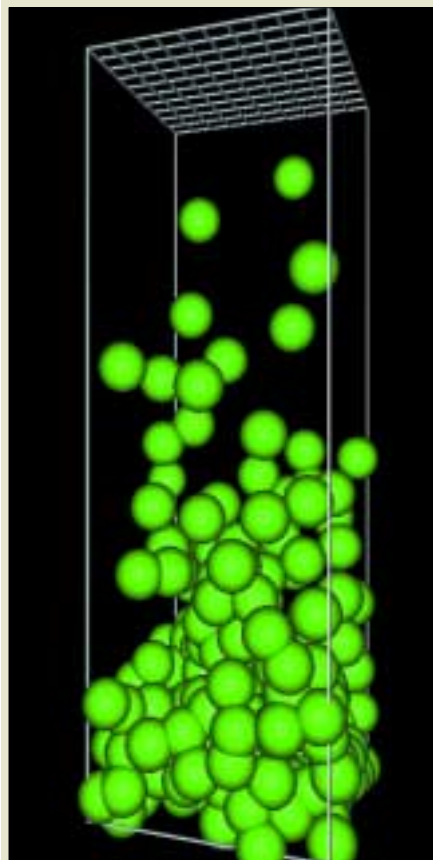
But Einstein took a different view. He was one of a new generation of physicists who had grown up on a diet of Maxwell and kinetic theory, and therefore saw little reason to doubt the physical reality of atoms. Indeed, by analysing Brownian motion, Einstein set out to obtain a quantitative measure of the size of the atom so that even the most cautious sceptics would be convinced of its existence.

As the great year 1905 dawned, Einstein was still an unknown physicist working in obscurity at the Bern patent office. But that year he would take the decisive theoretical step towards proving that liquids really are made of atoms. He joined the thermodynamics of liquids with statistical mechanics to obtain the first testable theory of Brownian motion, and the first chance of a direct glimpse inside the atomic world.

Quantitative predictions: Einstein and Brownian motion

In his quest for the literal truth of atoms Einstein had to accept that individual atoms could not be seen. By anyone’s estimate they were simply too small and too fast. But Einstein recognized that if the predictions of statistical mechanics were correct, then *any* particle immersed in a “bath” of atoms must basically behave like a very large atom because it would be in thermodynamic equilibrium with the atoms in the bath. Furthermore, the equipartition of energy theorem predicted exactly how the particle’s kinetic energy would depend on temperature: for each degree of freedom the aver-

2 The reality of atoms



This simulation shows an “atmosphere” of Brownian particles suspended in a liquid and falling under gravity. The concentration of particles decreases exponentially as the height increases, which Jean Perrin measured directly to demonstrate that Brownian particles obey Boltzmann’s equipartition of energy theorem – just like they would if they were very large molecules. Perrin then went on to confirm Einstein’s “square root law” and ultimately proved that atoms were not just convenient theoretical abstractions.

age kinetic energy is $k_B T/2$, where k_B is Boltzmann’s constant and T is the temperature of the bath.

Einstein realized that a particle with a diameter of, say, $1\ \mu\text{m}$ – large enough, in other words, to be visible using a microscope – would provide a “magnifying glass” into the world of the atom. It would be like an atom you could see, and the behaviour of which you could compare directly against kinetic theory to decide once and for all whether Boltzmann’s ideas agreed with reality.

Einstein predicted that, just like a molecule in solution, such a Brownian particle would diffuse according to a simple equation: $D = \sqrt{[(k_B T/6\pi\eta R)t]}$, where D is the displacement (technically the root mean square displacement) of the particle, T is the temperature, η is the viscosity of the liquid, R is the size of the particle and t is time. This equation implied that large particles would diffuse more gradually than molecules, making them even easier to measure. Moreover, unlike a ballistic particle such as a billiard ball, the displacement of a Brownian particle would not increase linearly with time but with the square root of time (figure 1).

Attempts had already been made to measure the velocity of Brownian particles, but they gave a nonsensical result: the shorter the measurement time, the higher the apparent velocity. This suggested that if you could measure the velocity in an extremely short (infinitesimal) instant, you would obtain a velocity approaching infinity. But if Einstein’s derivations were correct, the mystery was explained because you cannot measure

the velocity of a Brownian particle simply by dividing a distance by a time. The experimenters had been measuring the wrong quantity! Thanks to Einstein’s pioneering analysis, the mathematical stage was now set, and it was time for someone to get down to some serious experimenting.

The man who proved atoms are real

Jean Perrin, a physical chemist working at the Sorbonne in Paris, belonged to the same atom-believing tradition as Einstein. And it was Perrin’s microscope studies of Brownian particles that confirmed Einstein’s theory and sealed the reality of the discontinuous, atomic nature of matter.

These studies began in 1908, when Perrin and his team of research students embarked on an exhaustive set of experiments. Tragically, many of Perrin’s team would lose their lives only a few years later in the First World War.

Their first task was to obtain a suspension of Brownian particles that were each as close as possible to being the same size, since the rate of diffusion depended on particle size, and whose size was precisely measurable. This was no mean feat for particles with a diameter of a thousandth of a millimetre.

3 Brownian motion in action



Einstein is best known for his theories of relativity, but his work on Brownian motion in 1905 kick-started a revolution in statistical physics that is still going on today. Examples include the stock market, where Brownian-motion theory has been used to model the fluctuation of share prices, traffic flow and molecular motors, in which Brownian motion plays an important role in chemical transport in cells.

Starting with kilograms of suspended “gamboge” – a gum extract that forms spherical particles when it is dissolved in water – Perrin’s team eventually managed to produce just a few grams of usable particles.

Using a microscope, Perrin showed that when these particles were dispersed in water, they formed a kind of atmosphere under gravity, since the concentration of particles decreased exponentially with height in the same way that the density of gas molecules in the Earth’s atmosphere decreases. This meant that, as Einstein had predicted, the Brownian particles obeyed Boltzmann’s equipartition of energy theorem just like gas molecules did (figure 2).

Perrin’s group went on to measure the diffusion of the particles, confirming the square root of time law and validating Einstein’s kinetic-theory approach. In further experiments over the following five years, Perrin produced a wealth of measurements that could not be contested. Soon enough even Ostwald – the arch sceptic – conceded that Einstein’s theory, combined with Perrin’s experiments, proved the case. It was official: atoms were real.

A fluctuating future

Science developed fast in those first decades of the 20th century. Armed with Perrin’s experimental validation of statistical mechanics, there was little to stop the statistical revolution spreading into every field. Moreover, Einstein and Perrin had unknowingly paved the way for the acceptance of the inherently probabilistic quantum mechanics.

Ironically, Einstein himself never accepted the statistical interpretation of quantum mechanics. Statistics in a liquid of atoms was fine because you knew that you were counting real, physical atoms. But what did it mean to speak of the statistics of a single electron? What was “hidden” behind the electron that caused it to behave statistically? This was a question that Niels Bohr’s “complementarity” simply barred you from asking, and Einstein was never satisfied with that (see “The power of entanglement” on page 47).

The quantum revolution gained so much attention through the first half of the 20th century that it obscured the success of

classical statistical mechanics. Only in recent decades has the importance of Einstein and Perrin’s classical work become clearer. As physics increasingly overlaps with biology, nanotechnology and the statistics of complex phenomena, we can begin to see how understanding Brownian fluctuations is vital to everything from cell function to traffic flow, and from models of ecologies to game theory and the stock market (figure 3).

Einstein did not live long enough to appreciate the true significance of Brownian motion. In his later years, immersed in the search for a “theory of everything” through his general theory of relativity, Einstein himself dismissed his work on Brownian motion as unimportant. He was a philosopher as much as a physicist, and to him the philosophical implications of Brownian motion seemed minimal compared with those of relativity.

But if he were alive today, then perhaps he would change his mind. Since Robert Brown’s first observations of *Clarkia pulchella* 180 years ago, scientists across many disciplines are realizing that random fluctuations are fundamentally important in many, if not most, of the phenomena around us. Without them, there would be no phase behaviour, no protein folding, no cell-membrane function and no evolution of species. And we are only beginning to realize an even deeper subtlety from the latest work on complex systems, such as molecular motors and cell membranes.

These functional biosystems must satisfy almost contradictory requirements: they must be robust to a complicated and ever-fluctuating environment, yet at the same time they must also be able to exploit the fluctuations to carry out complicated biological functions, such as the transport of vital molecules in and out of cells. Almost two centuries after Brown, this trade-off at the heart of nature is gradually becoming clearer: there is an extraordinary balance between function and fluctuation, between hard physical rules and the subtle effects of randomness.

Einstein’s role in demystifying Brownian motion was pivotal in this ongoing revolution. In developing the first testable theory that linked statistical mechanics – with its invisible “atoms” and mechanical analogies – to observable reality, Einstein acted as a gateway. Through this gateway, years of confused observations could be turned into the solid results of Perrin, and from these could grow a new, proven world view with statistics at its heart.

From our more distant perspective, it is clear that the Brownian-motion papers of 1905 had just as much influence on science as did relativity or light quanta. Brownian motion was just a slower, subtler revolution: not a headlong charge, but more of a random walk into a vast and unsuspected future.

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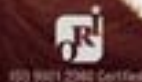
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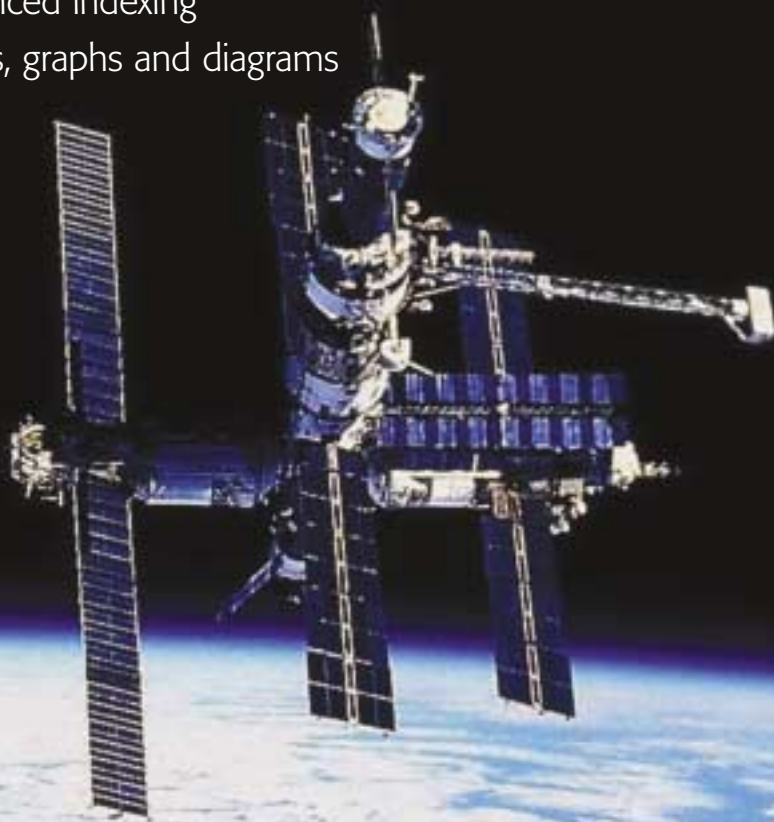


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The 1919 eclipse: a celebrity is born

Einstein shot to fame in 1919 when a team of astronomers led by Arthur Eddington found that the light from a distant star can be bent by the Sun, as predicted by relativity. But as **Matthew Stanley** explains, Eddington's expedition was partly motivated by a desire to heal the wounds between Britain and Germany after the First World War

In the spring of 1919, while Europe was just beginning to recover from the effects of the First World War, teams of British astronomers thousands of miles from home laboured to measure a tiny effect predicted by an obscure German scientist. This scientist was Albert Einstein, and when those astronomers presented their results he would move from little-known physicist to global celebrity. How did this dramatic turn of events come to be?

It was in 1907 that Einstein first began systematic work to include gravity and acceleration in his earlier special theory of relativity. One of his first insights toward this new "general" theory was the equivalence principle, which postulated that there can be no observable difference between a gravitational field and uniform acceleration (at least as measured over the distance scales typical of laboratories). An immediate consequence of this was a thought experiment in which it seemed that a beam of light would be bent slightly in a gravitational field. Early attempts to observe this effect were uniformly unsuccessful, which turned out to be fortunate for Einstein: he later changed the quantitative value of his prediction using a more refined version of his theory.

When Einstein presented his full field equations for general relativity in 1915, there were tremendous obstacles preventing the dissemination of his ideas to the world scientific community. Einstein was working in Berlin, and Germany had been isolated from the basic channels of scientific communication soon after the beginning of the First World War. Einstein's technical achievement went almost completely unnoticed on the other side of the trenches. The astronomer Willem de Sitter, working from the neutral Netherlands, sent his own presentation of general relativity to Britain, where he hoped to find someone receptive to Einstein's ideas. In a fortunate turn of history, de Sitter's papers landed on the desk of Arthur Eddington, head of the Cambridge Observatory and an officer of the Royal Astronomical Society.

Not only was Eddington one of just a handful of British scientists who were familiar enough with tensors and differential geometry to understand Einstein's theory, he was also one of an even smaller group of British scientists that was willing to pay at-



Peacemaker – Arthur Eddington (bottom left) used the 1919 eclipse to show that Einstein's general relativity, which Willem de Sitter (top right) had promoted during the war, was correct. Also shown here are Einstein, Paul Ehrenfest (back row, centre) and Hendrik Lorentz (bottom right).

tention to German science at all. Soon after the beginning of the war the British scientific community became outraged at the apparent complicity of German intellectuals with the Kaiser's treaty-breaking army. (In addition to waging what was seen as an aggressive and atrocity-laden conflict, the Germans had flagrantly broken their commitment to respect the neutrality of Belgium.)

The lack of trustworthiness this implied led to calls for Germany to be exiled from international science. Just as the German violation of neutral Belgium had made the claims of its politicians unreliable, it was felt that its scientists' reports were now worthless. Scientific journals from allied countries would no longer be sent to Germany or Austria, and foreign members from those countries were expelled from the Royal Society and other organizations.

Quaker, pacifist and adventurer

Eddington was one of the few voices that continued to argue for scientific internationalism. As a Quaker, he was a pacifist and believed strongly that international co-operation was critical to good science, partic-

ularly astronomy. He worked furiously and unsuccessfully to push back the emerging jingoism of British science, and he seized on relativity as a tool to break down wartime barriers. This was groundbreaking science coming from a peaceful German, and Eddington set out to both gain support for Einstein and to use that support to help heal the wounds of war.

The debate over relativity developed quickly, with Eddington becoming known as the theory's primary defender: he was Einstein's bulldog. However, nationalistic considerations, in addition to the technical difficulty and metaphysical strangeness of general relativity, limited the number of Einstein's supporters in Britain. This was despite the fact that in 1915, when first presenting the theory, Einstein used it to explain the long-known anomalies in the orbit of Mercury. People were impressed, but wanted further proof. Much of the discussion therefore turned to the possibility of tests of the theory: a predicted redshift in the solar spectrum appeared to be too difficult to observe, which left only a phenomenon known as gravitational deflection.

The curvature of space-time near massive bodies described by Einstein, if correct, would result in an apparent shift in position of stars near the Sun's edge. This shift would be minuscule and could only be observed during a solar eclipse, when stars could be seen during the day. Frank Dyson, Britain's Astronomer Royal, pointed out that there would be a solar eclipse on 29 May 1919 directly in front of the Hyades, a dense field of stars perfect for trying to detect the Einstein deflection. Unfortunately for the British scientists, the path of the eclipse was across difficult-to-reach parts of the southern hemisphere.

On the trail of the eclipse

Two teams were organized – Eddington and colleagues went to the island of Principe, which lies off the west African coast, while Andrew (A C D) Crommelin led a team to Sobral, Brazil. Both used techniques that were very similar to those used for standard eclipse observations of the day: a telescope was laid horizontally and a clockwork-driven mirror placed at the front to track the Sun's motion across the sky, with large glass photographic plates placed at the back of the telescope to capture images of the solar



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corona and nearby stars.

The plan was to compare photographs of the gravitationally deflected stellar images surrounding the eclipsed Sun with “check plates” of the same star fields taken when the Sun was absent. Einstein predicted that stars at the edge of the Sun would appear to be only 1.75 arcseconds from their normal position in the sky – a small difference that was equivalent to about one-sixtieth of a millimetre on the photographic plates. Many physicists were sceptical of making such a small measurement, but, in reality, contemporary astronomers were quite comfortable detecting such changes thanks to their long experience performing conventional stellar-parallax measurements.

Eddington’s observations in Principe were nearly ruined by the weather, but he managed to bring back several good photographs with an average deflection of 1.61 ± 0.3 arcseconds. The observations in Brazil were somewhat more complicated. The team there had two telescopes, one of which performed splendidly and returned results of 1.98 ± 0.12 arcseconds. The second telescope, however, suffered an optical defect (astigmatism) that corrupted the photographs. Crommelin, who was the chief observer in Brazil, declared on the scene that the results should not be trusted. For the sake of completeness, however, the plates were still measured, and a deflection of 0.93 arcseconds (or 1.52 arcseconds if the astigmatism was accounted for) was derived.

A legend is born

Back in London, at a joint meeting of the Royal Society and the Royal Astronomical Society, Eddington presented the results on 6 November 1919 with all the skill of a practised showman. He dramatically portrayed the expedition as a crucial test between two master scientists – Newton and Einstein. Repeatedly emphasizing the international character of the theory and its test, he announced that Einstein’s esoteric prediction had been confirmed by the expedition’s photographs, and that space was in fact warped and that light had weight.

The mass media, with significant encouragement from Eddington, picked up the story and ran with it. The appeal of a German theory being proved by British scientists so soon after the war captured the imagination, and Einstein was catapulted from an obscure physicist to worldwide celebrity literally overnight. His mythical reputation as an inscrutable sage was born instantly when the *New York Times* declared that no more than “12 wise men” in all the world could understand relativity. In the resulting demand for information about relativity and Einstein, Eddington led the popularization of the theory and the man, using the opportunity to show that science could rise above wartime hatreds. Einstein, as the Newton-supplanting genius trapped behind national-



Solar power – measurements that were made during the 1919 eclipse agreed with the predictions of general relativity.

istic barriers, was presented as a powerful argument for international science.

It is sometimes suggested that Eddington’s internationalism led him to “fudge” the data from the expedition to ensure a positive result for Einstein. There is no reason to think this was the case. Usually those proposing this myth claim that Eddington threw out results that were unfavourable (meaning the second telescope from Brazil). In fact, those results were declared unusable by observers in the field who did *not* include Eddington.

Furthermore, copies of the photographic plates from all three telescopes were distributed to astronomers around the world for them to make their own measurements and analysis. No contemporary accused Eddington of altering the results – this is purely a modern myth based on poor understanding of the optical techniques in use at the time. The influence of Eddington’s pacifism is to be found in his championing of the expedition as a scientific goal and his popularization of Einstein as a major scientific figure, not in manipulated data.

Einstein was pleased with Eddington’s efforts on his behalf, although he was not too concerned as he always said he knew what the result of the eclipse expedition was going to be. The pair later met on a couple of occasions and appeared to get on well together: Einstein said that he wanted to learn English so that he could talk to Eddington about relativity. But as both were in the main solitary investigators, they never collaborated formally.

Thanks to Eddington, the expedition has entered our collective memory as a great victory for scientific internationalism, and its triumphant and dramatic confirmation of general relativity launched Einstein to worldwide fame. Our image of Einstein as the scientific rebel who overthrew Newton was thus a result of surprising contingencies of war, peace and nationalism.

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Gravitational physics has become a truly experimental science
as tests of the special and general theories of relativity reach new levels of precision

Relativity at the centenary

Clifford M Will

WHEN I was a first-term graduate student in the late 1960s, it was said that the field of general relativity was “a theorist’s paradise and an experimentalist’s purgatory”. There were some experiments – Irwin Shapiro, for instance, had just measured the effects of general relativity on radio waves as they passed the Sun – but the field was dominated by theory and by theorists. This seemed to reflect Einstein’s own attitudes: although he had a keen insight into the workings of the physical world, he felt that the bottom line was the theory. As he once famously said, when asked how he would have reacted if an experiment had contradicted the theory, “I would have felt sorry for the dear Lord. The theory is correct”.

Since that time the field has been completely transformed. Today, at the centenary of Einstein’s *annus mirabilis*, experiment has become a central component of gravitational physics. I know of no better way to illustrate this than to cite a paper by the LIGO Scientific Collaboration that was published in *Physical Review D* last year (see Abbott *et al.* in further reading). This was one of the papers reporting results from the first science run of the Laser Interferometer Gravitational-wave Observatory (LIGO), but with 374 authors from 41 institutions in 8 countries it is reminiscent of particle physics, not general relativity.

The breadth of current experiments – ranging from tests of classic general relativity such as the Shapiro delay and the bending of light, through space-based measurements of “frame-dragging” to searches for gravitational waves or violations of the inverse-square law – attests to the ongoing vigour of experimental gravitation. With all this data, can we still be sure that Einstein was right?

Testing the foundations

At the heart of the general theory of relativity is the equivalence principle – an idea that came to Einstein two years after he developed special relativity and led him to the dramatic conclusion that mass and gravity are intimately linked



Right on time – an artist’s impression of the Cassini spacecraft flying between Jupiter and Saturn, and transmitting radio waves past the Sun and towards the Earth. The radio waves are delayed by their passage through the curved space-time near the Sun, an effect called the Shapiro time delay. Bruno Bertotti of the University of Pavia in Italy and colleagues have analysed these waves, and their value for the Shapiro time delay agrees with the predictions of general relativity to 1 part in 10^5 .

to the curvature of space-time (see figure 1 and box on page 28).

Put in simple terms, the equivalence principle states that gravity and acceleration are equivalent. Embellished over the years, this idea is now called the Einstein equivalence principle and encompasses three separate principles: the weak equivalence principle, and the principles of local Lorentz and local position invariance.

The weak equivalence principle states that test bodies fall with the same acceleration independent of their internal structure or composition: in other words *gravitational mass* (the m in $F = GMm/r^2$, where F is the gravitational attraction between two masses a distance r apart and G is the Newtonian gravitational constant) and *inertial mass* (the m in $F = ma$, where a is the acceleration caused by any force F) are the same. There is also a strong version of the equivalence principle that goes beyond the weak version by stating that *gravitational energy* will fall with the same acceleration as ordinary matter and other types of energy in a gravitational field (see box on page 30).

The principle of local Lorentz invariance states that the outcome of any local

non-gravitational experiment carried out in a freely falling reference frame is independent of the velocity of that frame, while the principle of local position invariance holds that the outcome of any local non-gravitational experiment is also independent of where and when in the universe it is performed. In this context “local” means confined to a suitably small region of space and time, while “freely falling” means falling freely under gravity with no other forces acting.

Although Einstein used it to derive general relativity, his equivalence principle implies only that gravitation must be described by a “metric theory” – a theory in which matter responds to the geometry of space-time and nothing else. However, general relativity is not the only metric theory of gravity, and other examples include the “scalar-tensor” theory developed by Carl Brans and Robert Dicke at Princeton University in 1961, building on earlier work by Markus Fierz and Pascual Jordan.

Special and general relativity

When Einstein introduced the concept of “relativity” in 1905 – the notion that there is no absolute motion in the universe, only relative motion – he overthrew ideas that had been in place since the time of Newton some 200 years before. In addition to $E = mc^2$, special relativity predicted various novel effects that occurred when bodies moved at close to the speed of light: time slowed down (an effect known as time-dilation) and lengths became shorter (Fitzgerald contraction). With the general theory Einstein then went on to show that we do not reside in the flat (Euclidean) space and uniform time of everyday experience, but in curved space–time instead.

Special relativity helped us to understand the microworld of elementary particles and interactions, while general relativity revolutionized our view of the universe by predicting astrophysical phenomena as bizarre as the Big Bang, neutron stars, black holes and gravitational waves.

The theory of relativity is a single, all-encompassing theory of space–time, gravity and mechanics, although special relativity and general relativity are often viewed as being independent. Special relativity is actually an approximation to curved space–time that is valid in sufficiently small regions called “local freely falling frames”, much as small regions on the surface of an apple are approximately flat, even though the overall surface is curved.

Einstein’s great insight was to realize that gravity and acceleration are equivalent in free fall, and he then went on to show that the laws of physics, such as the equations of electromagnetism, should have built-in local Lorentz and local position invariance.

In special relativity the “distance” between two points in space–time is given by the line element, ds , which is defined as $ds^2 = -c^2 dt^2 + dx^2 + dy^2 + dz^2$, where t is time and c is the speed of light in a vacuum. In the curved space–time of general relativity ds is defined as $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$, where x^1, x^2 and x^3 are the three spatial dimensions, $x^0 = ct$, and $g_{\mu\nu}$, which is called the metric, is a function in space–time. The right-hand side of the equation must be



Big success – the centre of the Milky Way is home to a supermassive black hole.

summed over all values of μ and ν between 0 and 3.

General relativity provides a set of field equations that allow us to calculate the space–time metric (i.e. the amount of curvature) from a given distribution of matter – something that is not defined by the equivalence principle. Einstein’s aim was to find the simplest field equations that made this possible. The result was a set of 10 equations, symbolized by the seductively simple equation $G_{\mu\nu} = 8\pi G T_{\mu\nu} / c^4$, where $G_{\mu\nu}$ is Einstein’s curvature tensor, which can be obtained directly from $g_{\mu\nu}$ and its derivatives, and $T_{\mu\nu}$ is the stress-energy tensor of normal matter. Sweating the details hidden in this equation has kept generations of relativists occupied.

In the past it was customary to speak of the three classical tests proposed by Einstein: the deflection of light by a massive body; the advance of the perihelion of Mercury; and the gravitational redshift of light (although this is actually a test of the Einstein equivalence principle rather than general relativity itself). Many new tests have been developed since Einstein’s time: in 1964 Irwin Shapiro, then at the Massachusetts Institute of Technology, predicted a delay in the propagation of light past a massive body; and in 1968 Kenneth Nordtved Jr of Montana State University showed that theories other than general relativity do not necessarily obey the equivalence principle in certain situations. One of the most striking predictions of general relativity is the black hole: when a massive star collapses under its own gravity it can warp space–time to such an extent that nothing, not even light, can escape. There is now convincing observational evidence for these objects.

One of the outstanding problems in physics is to unify general relativity, which is our best theory of gravity, with the quantum field theories that describe the three other fundamental forces. Although this challenge defeated Einstein, it should not surprise us that all the leading candidates for a unified theory – string theory, branes and loop quantum gravity – are all fundamentally geometrical.

When it comes to testing metric theories of gravity, we need to distinguish between the weak-field limit, which is valid in the solar system (see figure 2 and box on page 32), and the strong-field regime that is needed to describe regions where gravity is extremely strong, such as in the vicinity of a black hole or a neutron star. If we are being really ambitious, we might also try to describe situations where gravity is strong and quantum effects are important, such as during the Big Bang, but that is a separate story (see “Welcome to quantum gravity” *Physics World* November 2003 pp27–47).

In non-metric theories matter can respond to something other than the geometry of space–time, and this can lead to violations of one or more pieces of the Einstein equivalence principle. For instance, in the string theories that seek to unify gravity with the other three forces of nature, the equivalence principle is violated because matter can respond to additional long-range fields. Searching for violations of the Einstein equivalence principle is therefore a good way to search for new physics beyond the standard metric theories of gravity.

In the balance

To test the weak equivalence principle one compares the accelerations of two bodies with different compositions in an external gravitational field. Such experiments are often called Eötvös experiments after Baron von Eötvös, the Hungarian physicist whose pioneering experiments with torsion balances provided a foundation for Einstein’s ideas on general relativity.

In a torsion balance two bodies made of different materials are suspended at the ends of a rod that is supported by a fine wire or fibre. We then look for a difference in the horizontal accelerations of the two bodies as revealed by a slight rotation of the rod. The source of the horizontal gravitational force could be the Sun, a large mass in the laboratory, a nearby hill, or, as Eötvös recognized, the Earth itself.

The best test of the weak equivalence principle to date has been performed by Eric Adelberger and the Eöt-Wash collaboration at the University of Washington in Seattle, who have used an advanced torsion balance to compare the accelerations of various pairs of materials toward the Earth, the

Sun and the Milky Way.

A completely different test of the weak equivalence principle involves bouncing laser pulses off mirrors on the lunar surface to check if the Earth and the Moon are accelerating toward the Sun at the same rate. Lunar laser-ranging measurements actually test the strong equivalence principle because they are sensitive to both the mass and the gravitational self-energy of the Earth and the Moon. The bottom line of these experiments is that bodies fall with the same acceleration to a few parts in 10^{13} (see figure 1).

In the future, the Apache Point Observatory for Lunar Laser-ranging Operation (APOLLO) project, a joint effort by researchers from the University of Washington in Seattle and the University of California at San Diego, will use enhanced laser and telescope technology, together with a good, high-altitude site in New Mexico, to improve the lunar laser-ranging test by as much as a factor of 10 (see Williams *et al.* in further reading and *Physics World* June 2004 p9).

The next major advance may occur in space, if two satellite missions are successful. MICROSCOPE, which could be launched in 2008, aims to test the weak equivalence principle to 1 part in 10^{15} , while a later mission called the Satellite Test of the Equivalence Principle (STEP) could improve on this by a factor of 1000. These experiments will compare the acceleration of different materials moving in free-fall orbits around the Earth inside a drag-compensated spacecraft. Doing experiments in space means that the bodies are in perpetual fall, whereas Earth-based experiments at “drop towers” are over in seconds, which leads to much larger measurement errors.

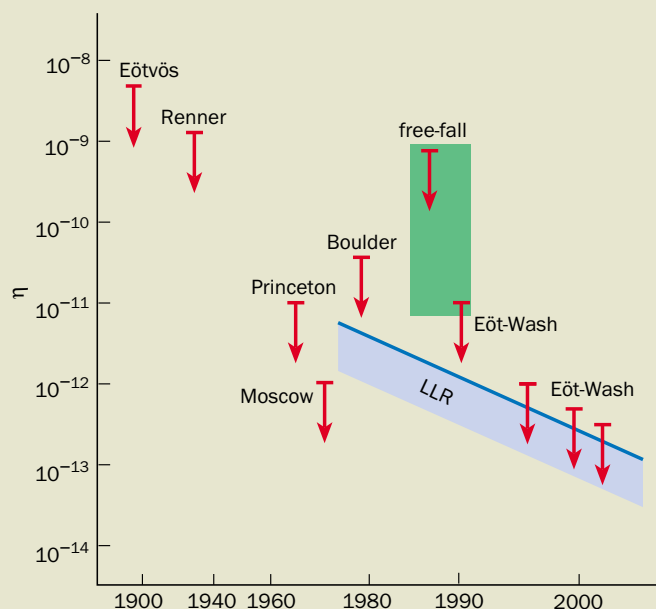
Many of the techniques developed to test the weak equivalence principle have been adapted to search for possible violations of the inverse-square law of gravity at distances below 1 mm. Such violations could signal the presence of additional interactions between matter or “large” extra dimensions of space. No deviations from the inverse-square law have been found at distances between $100\text{ }\mu\text{m}$ and 10 mm, but there are enough well-motivated theoretical predictions for new effects at these distances to push experimentalists towards better sensitivities and shorter distances.

Tests with atomic clocks

The predictions of general relativity can also be tested with atomic clocks. Local position invariance requires that the internal binding energies of all atoms, and thus the time given by atomic clocks, must be independent of their location in both time and space when measured in a local freely falling frame. However, if two identical atomic clocks are placed in different gravitational potentials, they will be in different local frames and, according to the Einstein equivalence principle, they will give slightly different times.

In 1976 Robert Vessot, Martine Levine and co-workers at the Harvard Smithsonian Astrophysical Observatory and the Marshall Space Flight Center compared a hydrogen maser clock on a Scout rocket at an altitude of 10 000 km with one on the ground, and verified Einstein’s 1907 prediction for this “gravitational redshift” to a few parts in 10^4 . This redshift actually has an impact on our daily lives because it must be taken into account (along with the time dilation associated with special relativity) to ensure that navigational devices that rely on the Global Positioning System (GPS) remain accurate. Relativistic effects mean that there is a 39 ms per day differ-

1 Tests of the weak equivalence principle



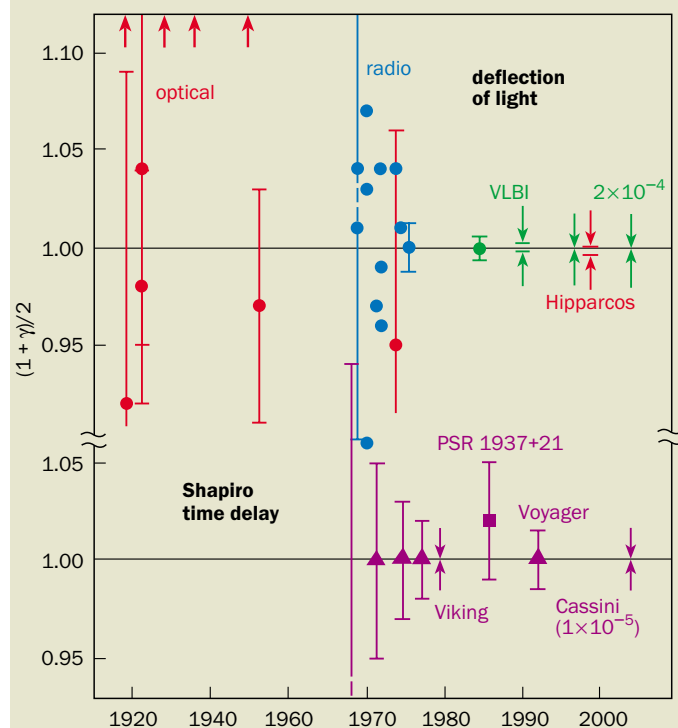
In 1907 Einstein realized that gravity and acceleration are equivalent, thus starting him on the path that led to the general theory of relativity. The weak equivalence principle – which states that test bodies fall with the same acceleration independent of their internal structure or composition – can be tested by measuring the accelerations, a_1 and a_2 , of two bodies made of different materials in the same gravitational field. It is customary to plot $\eta = (a_1 - a_2) / 2(a_1 + a_2)$, and this figure shows how the upper limit on η has decreased over time since the first experiments by Baron von Eötvös. Most of the tests have been performed with torsion balances (red arrows), apart from free-fall experiments in which the bodies are dropped in a tower (green region), and lunar laser-ranging experiments (LLR; blue region) that measure the accelerations of the Earth and the Moon in the gravitational field of the Sun. The green region indicates a period when many experiments were performed in search of a “fifth force”.

ence between ground-based atomic clocks and those on the GPS satellites.

Recent clock-comparison tests of local position invariance undertaken at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, and the Observatory of Paris have shown that the fine-structure constant – which determines how fast the atomic clocks “tick” – is constant to 1 part in 10^{15} per year. The NIST team compared laser-cooled mercury ions with neutral caesium atoms over a two-year period, while the Paris team compared laser-cooled caesium and rubidium atomic fountains over five years. Plans are being developed to perform such clock comparisons in space, possibly on the International Space Station.

Atomic clocks can also be used to test the two pillars of special relativity – Lorentz symmetry and position invariance. At the centenary of special relativity, it is useful to recall that acceptance of this theory was slow in coming – Einstein’s 1921 Nobel Prize was for the photoelectric effect, another of his 1905 triumphs, not for relativity. However, special relativity is now such a foundation for modern physics that it is almost blasphemy to question it, although that has not stopped a growing number of theoretical and experimental physicists searching for violations of Lorentz and/or position invariance (see “A very special centenary” on page 43). In earlier times, such thinking would have been called “crackpot”, but these new ideas are well rooted in attempts to find a quantum theory of gravity and, ultimately, a unified theory

2 Tests of general relativity



Einstein became a public celebrity when Arthur Eddington and colleagues measured the deflection of light by the Sun during the solar eclipse of 1919 and found that their results agreed with the predictions of general relativity. Measurements of the deflection (top) – plotted as $(1 + \gamma)/2$, where γ is related to the amount of spatial curvature generated by mass – have become more accurate since 1919 and have converged on the prediction of general relativity: $(1 + \gamma)/2 = 1$. The same is true for measurements of the Shapiro time delay (bottom). “Optical” denotes measurements made during solar eclipses (shown in red), with the arrows pointing to values well off the chart; “radio” denotes interferometric measurements of radio-wave deflection (blue); while Hipparcos was an optical-astrometry satellite. The left-most data point is the measurement made by Eddington in 1919, while the arrow just above it refers to the value obtained by his compatriot Andrew Crommelin (see “The 1919 eclipse: a celebrity is born” on page 25). The best deflection measurements (green) are accurate to 2 parts in 10^4 and were obtained with Very Long Baseline Radio Interferometry (VLBI; see Shapiro *et al.* in further reading). A recent measurement of the Shapiro time delay by the Cassini spacecraft, which was on its way to Saturn, was accurate to 1 part in 10^5 (see Bertotti *et al.* in further reading).

of the four fundamental forces of nature.

Various string theories, for instance, allow for the possibility of long-range fields that are linked to the average matter distribution of the universe. If these fields couple weakly to local matter, they could lead to effects that can be observed in experiments. In particular, we know from observations that the Earth moves through the cosmic background radiation at a speed of 350 km s^{-1} . With the right kind of long-range field, this motion could produce an effective interaction that has a preferred direction associated with it. If this long-range field were then to couple weakly to, say, electromagnetism, then the electromagnetic fields in atoms could be changed by an amount that depends on the orientation of the atom relative to our direction of motion through the universe.

During the late 1980s researchers at Seattle, Harvard and NIST looked for these effects by checking if atomic transition frequencies change over the course of a year as their orientation changes relative to our cosmic velocity. Exploiting the then newly developed techniques of atom trapping and cooling, the

Self-energy and the strong equivalence principle

Special relativity and $E = mc^2$ tell us that energy and mass are essentially the same. The mass of a proton and an electron is greater than that of a hydrogen atom because energy must be supplied to break the electromagnetic bond in the atom. The weak equivalence principle asserts that this difference will change both the gravitational mass and the inertial mass by the same amount. This means that all forms of energy at microscopic scales – electromagnetic, strong and weak – respond to gravity in the same way. But what about large bodies like the Earth and Sun, or even extreme gravitational bodies like black holes, which also have measurable gravitational binding energy? The strong equivalence principle goes beyond the weak version by stating that gravitational energy falls with the same acceleration as ordinary matter and other forms of energy in a gravitational field. Although the gravitational self-energy contained in the gravitational forces that hold the Earth together only changes its total mass energy by less than 1 part in a billion, lunar laser-ranging experiments (see main text) can achieve a precision of 1 part in 10^{13} and can therefore test the strong equivalence principle. General relativity obeys the strong equivalence principle, whereas the Brans–Dicke theory and many other alternative theories do not.

researchers found no effects down to a few parts per 10^{26} .

These “clock anisotropy” experiments are latter-day versions of the classic Michelson–Morley experiments of 1887. In the Michelson–Morley experiment the “clocks” being compared were defined by the propagation of light along each of the two perpendicular arms of an interferometer. Einstein took the null result of these experiments for granted in his 1905 paper on special relativity, although he never referred to them by name.

Looking to the future, the discreteness of space–time at the Planck scale that is found in some quantum theories of gravity could also lead to effective violations of Lorentz invariance. However, a wide range of experiments, including tests of CPT (charge–parity–time) symmetry in particle-physics experiments and careful observations of gamma rays and synchrotron radiation from astrophysical sources, have ruled these out to a high-level of precision.

Does space–time do the twist?

A central prediction of general relativity is that moving matter generates a gravitational field that is analogous to the magnetic field generated by a moving charge. Thus, a rotating body produces a “gravitomagnetic” field that drags space–time around with it, and this “frame-dragging” may play an important role in the dynamics of matter spiralling into supermassive black holes in quasars and other active galaxies. Frame-dragging might also be partly responsible for the collimated relativistic jets seen in such systems.

The Gravity Probe B satellite is currently measuring this effect near the Earth. Launched on 20 April 2004, its goal is to measure the precessions of four gyroscopes relative to a telescope trained on a nearby guide star called IM Pegasi over the course of a year (until the liquid helium that is used to cool the experiment runs out). The gyroscopes are spheres that are perfect to a few parts in 10 million and are coated with a thin layer of superconducting niobium. When the spheres rotate, the superconducting films develop magnetic moments that

3 Gravity Probe B



The Gravity Probe B (GP-B) satellite (left) is currently measuring two predictions of general relativity: frame-dragging and geodetic precession. The experiment involves detecting tiny changes in the motion of four gyroscopes that contain extremely smooth spheres made of fused quartz (right). The satellite, which is currently in a polar orbit at an altitude of 640 km, is a collaboration between Stanford University, Lockheed-Martin and NASA. The first results from GP-B are expected next year.

are precisely parallel to their spin axes. This means that any precession of the spins can be measured by monitoring changes in the magnetic flux through superconducting current loops fixed in the spacecraft.

General relativity predicts that frame-dragging will lead to a precession of 41 milliarcseconds per year, and the Gravity Probe B team hopes to measure this with an accuracy of 1%. The experiment will also measure the “geodetic” precession caused by the ordinary curvature of space around the Earth. General relativity predicts a value of 6.6 arcseconds per year for this effect. Gravity Probe B has been designed so that these precessions are perpendicular to one another, and the first results from the mission are expected in early 2006 (see figure 3).

Meanwhile, last October Ignazio Ciufolini of the University of Lecce in Italy and Erricos Pavlis of the University of Maryland used techniques in which laser beams were reflected from satellites to make a measurement of frame-dragging on the orbit of a satellite. Their result agreed with general relativity, with errors at the level of 10% (see *Physics World* November 2004 p7).

The binary pulsar

In 1974 Russell Hulse and Joseph Taylor, then at the University of Massachusetts, discovered a binary pulsar called PSR 1913+16 that was to play a crucial role in tests of general relativity. Pulsars emit pulses of radio waves at very regular intervals and are thought to be rotating neutron stars. PSR 1913+16 was special because it was a pulsar that was in

orbit around another compact object.

By carefully measuring small changes in the rate of the pulsar “clock”, Hulse and Taylor were able to determine both non-relativistic and relativistic orbital parameters with extraordinary precision. In particular they were able to measure three relativistic effects: the rate of advance of the periastron (the analogue of the perihelion in a binary system); the combined effects of time-dilation and gravitational redshift on the observed rate of the pulsar; and the rate of decrease of the orbital period.

If we assume that general relativity is correct and make the reasonable assumption that both objects are neutron stars, then all three relativistic effects depend on the two unknown stellar masses. Since we have, in effect, three simultaneous equations and just two unknowns, we can determine the mass of both objects with an uncertainty of less than 0.05%, and *also* test the predictions of general relativity. If we as-

sume that the orbital period of the system is decreasing due to the emission of gravitational waves, then theory and experiment agree to within 0.2%. Hulse and Taylor shared the 1993 Nobel Prize for Physics for this work.

Binary pulsars can also be used to distinguish between different theories of gravity because they have very strong internal gravity (see *Stairs* in further reading). Indeed, several tenths of the rest-mass energy of a neutron star is contained in the gravitational forces that hold the star together, while the orbital energy only accounts for 10^{-6} of the total mass energy of the system. In the Brans–Dicke theory this internal self-gravity leads to the prediction that binary pulsars should emit both dipole and quadrupole gravitational radiation, whereas general relativity strictly forbids the dipole contribution. The emission of dipole radiation would have a characteristic effect on the orbital period of the system, but such an effect has not been seen. Several recently discovered binary-pulsar systems may allow new tests of general relativity.

Gravitational waves

One of the outstanding challenges in physics today is to detect gravitational waves, and new gravitational-wave observatories in the US, Europe and Japan hope to achieve this, possibly before the end of the decade. In addition to exploring various astrophysical phenomena, these observatories might also be able to carry out new tests of fundamental gravitational physics (see “The search for gravitational waves” on page 37).



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General relativity makes three predictions about gravitational radiation that can be tested: gravitational waves have only two polarization states, whereas other theories can predict as many as six; gravitational waves travel at the speed of light, while other theories may predict different speeds; and the emission of gravitational waves acts back on the source that is emitting them in a characteristic manner.

For example, as is described above, scalar–tensor theories and general relativity make different predictions for the nature of the gravitational waves emitted by binary pulsars, and it may be possible to detect these differences. Moreover, if gravitational waves with long wavelengths travel more slowly than those with shorter wavelengths, then it might be possible to observe this behaviour – which is generally associated with massive (as opposed to massless) elementary particles – in the gravitational radiation from binary systems.

Although the collision of two compact objects to form a black hole is too complex to allow precision tests of general relativity, analysis of the gravitational waves produced in the collision will reveal information about the masses and spins of the compact objects themselves, and also about the mass and angular momentum of the final black hole. Such observations will therefore reflect dynamical, strong-field general relativity in its full glory.

Making firm predictions for this situation involves solving Einstein's equations in a regime where weak-field methods fail, and therefore requires large-scale numerical computations. This challenging task has been taken up by many “numerical relativity” groups around the world. The discovery and study of the formation of a black hole through gravitational waves would provide a stunning test of general relativity.

Relativity and beyond

Einstein's special and general theories of relativity altered the course of science. They were triumphs of the imagination and of theory, with experiment playing a secondary role. In the past four decades we have witnessed a second triumph for Einstein, with general relativity passing increasingly precise experimental tests with flying colours. But the work is not done. Tests of strong-field gravity in the vicinity of black holes and neutron stars need to be carried out. Gamma-ray, X-ray and gravitational-wave astronomy will all play a critical role in probing this largely unexplored aspect of the theory.

General relativity is now the “standard model” of gravity. But as in particle physics, there may be a world beyond the standard model. Quantum gravity, strings and branes may lead to testable effects beyond general relativity. Experimentalists will continue to search for such effects using laboratory

Testing metric theories in the solar system

General relativity is one of several “metric” theories in which gravity arises from the geometry of space–time and nothing else. If we want to distinguish between different metric theories in the weak-field limit, it is customary to use a formalism that dates back to Arthur Eddington's 1922 textbook on general relativity and was later extended by Kenneth Nordtvedt Jr and the present author. This parametrized post-Newtonian (PPN) formalism contains 10 parameters that characterize how the predictions of the different metric theories differ from those of Newtonian gravity, and therefore from each other, for various phenomena that can be measured in the solar system.

Six of these parameters are shown in the table below. For instance, γ is related to the amount of spatial curvature generated by mass and determines the size of classic relativistic effects such as the deflection of light by mass, while β is related to the degree of nonlinearity in the gravitational field. Another four parameters – ξ , α_1 , α_2 and α_3 – determine if gravity itself violates a form of local position invariance or local Lorentz invariance (such as G depending on our velocity through the universe).

In the PPN formalism the deflection of light and the Shapiro time delay are both proportional to $(1 + \gamma)/2$. The “1/2” corresponds to the so-called Newtonian deflection (i.e. the deflection that a body moving at the speed of light would experience according to Newtonian gravity). This result was derived over two centuries ago by Henry Cavendish, who never published it, and then discovered again by Johann von Soldner in 1803, who did publish it. The “ $\gamma/2$ ” comes directly from the warping of space near the massive body.

The PPN parameters can have different values in the different metric theories of gravity. In general relativity, for instance, γ and β are exactly equal to one and the other eight parameters all vanish. Four decades of experiments have placed bounds on the PPN parameters that are consistent with general relativity (see figure 2).

Parameter	Effect	Bound (GR = 0)	Remarks
$\gamma - 1$	Shapiro delay	2.3×10^{-5}	Cassini tracking
	light deflection	4×10^{-4}	VLBI on 541 radio sources
$\beta - 1$	perihelion shift	3×10^{-3}	solar oblateness 2×10^{-7}
	Nordtvedt effect	5×10^{-4}	lunar laser ranging plus bounds on other parameters
ξ	anisotropy in Newton's G	10^{-3}	gravimeter bounds on anomalous Earth tides
α_1	orbit polarization for moving systems	10^{-4}	lunar laser ranging
α_2	anomalous spin precession for moving bodies	4×10^{-7}	alignment of solar axis relative to ecliptic
α_3	anomalous self-acceleration of spinning, moving bodies	2×10^{-20}	pulsar spin-down timing data

experiments, particle accelerators, instruments in space and cosmological observations. At the centenary of relativity it could well be said that experimentalists have joined the theorists in relativistic paradise.

Further reading

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Einstein and his love of music

As a keen and talented violinist, music was one of Einstein's life-long passions. His musical tastes, however, were distinctly conservative, as **Brian Foster** explains

As we celebrate the centenary of his seminal 1905 papers, it is humbling to note that Einstein was not only the outstanding scientist of the 20th century, but also a gifted and enthusiastic musician. He once said that had he not been a scientist, he would have been a musician. "Life without playing music is inconceivable for me," he declared. "I live my daydreams in music. I see my life in terms of music... I get most joy in life out of music."

Einstein's mother, Pauline, was a talented pianist who brought music to life in the family home. Albert began to learn the violin at the age of six, while his family was still living in Munich. However, he toiled under unimaginative tuition until discovering the joys of Mozart's sonatas at the age of 13. From that point on, although he had no further lessons, his violin was to remain his constant companion.

When Einstein moved to Aarau in Switzerland in 1895 to complete his schooling, he seems to have devoted a good deal of his time to music. It is recorded that he worked hard on the Brahms G-major violin sonata in order to get the full benefit from a visit to Aarau of the great violinist Joseph Joachim, on whose programme it appeared.

Just before his 17th birthday Albert played at a music examination in the cantonal school. The inspector reported that "a student called Einstein shone in a deeply felt performance of an adagio from one of the Beethoven sonatas". In addition to his prowess on the violin, he also played the piano and, in particular, loved to improvise.

For fun and physics

Music was not only a relaxation to Einstein, it also helped him in his work. His second wife, Elsa, gives a rare glimpse of their home life in Berlin. "As a little girl, I fell in love with Albert because he played Mozart so beautifully on the violin," she once wrote. "He also plays the piano. Music helps him when he is thinking about his theories. He goes to his study, comes back, strikes a few chords on the piano, jots something down, returns to his study."

In later life, his fame as a physicist often led to invitations to perform at benefit concerts, which he generally accepted eagerly. At one such event, a critic – unaware of Einstein's real claim to fame as a physicist – wrote, "Einstein plays excellently. However, his worldwide fame is undeserved. There are many violinists who are just as good".

One wag, on leaving another concert in which Einstein had played, commented, "I suppose now [Austrian violinist] Fritz Kreis-



Gifted amateur – Einstein once said that the violin had given him the "most joy" in his life.

Listen and learn

Einstein Year will encompass many celebrations of his science, personality, interest in peace and engagement with the state of Israel. Few of these events would have been closer to his heart than the world tour of concerts being undertaken by one of the most brilliant of young UK violinists, Jack Liebeck, to celebrate the International Year of Physics. This series will include a gala concert in London organized by the Institute of Physics on 14 March – Einstein's birthday.

Liebeck and I will also be touring with a lecture that mixes physics with specially commissioned music from two outstanding young UK composers, Emily Hall and Anna Meredith. Partly funded by the UK research councils and the University of Oxford, the performances will mostly be in schools and concert halls in the UK, but also in venues stretching from the US to Korea. The lecture will look at how our understanding of the universe has developed through modern ideas of particle physics and cosmology up to the concept of superstrings.

Liebeck uses his great Guaragnini violin, the "ex-Wilhelmj", made in 1785 to demonstrate some of the concepts in the lecture by analogy. For example, the sequence of harmonics on one violin string represents the mass spectrum of some families of particles in superstring space. I hope that this lecture will not only introduce those interested in physics to music played by a superb violinist, but also that lovers of music will gain an appreciation of the excitement of physics.

- www.jackliebeck.com
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ler is going to start giving physics lectures".

There are nevertheless conflicting accounts of his musical abilities. Probably the least generous come from great artists, of whom Einstein counted many as personal friends as well as chamber-music partners. These included the pianist Artur Schnabel, the cellist Gregor Piatigorski, and Bronislaw Huberman, one of the most remarkable and idiosyncratic violin virtuosos of the 20th century. Huberman visited Einstein in Princeton to discuss his plans to found the orchestra that eventually became the Israel Philharmonic, of which Einstein was a prominent supporter.

Probably the summary of Einstein the violinist that comes nearest to the mark comes from his friend Janos Plesch, who wrote, "There are many musicians with much better technique, but none, I believe, who ever played with more sincerity or deeper feeling".

Bach yes, Wagner no

The physics revolutionary who overturned the classical universe of Newton was nonetheless deeply conservative in his musical tastes. He adored Mozart and worshipped Bach, of whom he wrote in response to an editor, "I have this to say about Bach's works: listen, play, love, revere – and keep your trap shut". Beethoven he admired but did not love, while Schubert, Schumann and Brahms gained only guarded and partial approval.

Indeed, the more contemporary the composer, the less enthusiastic Einstein became. Of Wagner he said, "I admire Wagner's inventiveness, but I see his lack of architectural structure as decadence. Moreover, to me his musical personality is indescribably offensive so that for the most part I can listen to him only with disgust".

Despite having been offered the chance to own a Guarneri, Einstein preferred to play a much less distinguished violin, leaving the great instruments to those whom he felt really needed their power and complexity. Towards the end of his life, as he felt facility leaving his left hand, he laid down his violin and never picked it up again. However, Einstein never lost his love for the instrument. As he once said, "I know that the most joy in my life has come to me from my violin".

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Looking after the image of a legend

The use of Albert Einstein's name and image are tightly controlled. **Peter Gwynne** explores who owns the rights to the Einstein brand and how it is protected

The name of Albert Einstein and the image of a moustached old man with wild hair are recognized the world over. Such is the universal appeal of the quintessential scientific genius that Einstein's image is used to sell almost anything, from T-shirts and coffee mugs to postcards and physics magazines. This will certainly be the case in 2005, as the physics community celebrates the 100th anniversary of Einstein's *annus mirabilis*, the year in which he published his groundbreaking papers on special relativity, Brownian motion and the photoelectric effect.

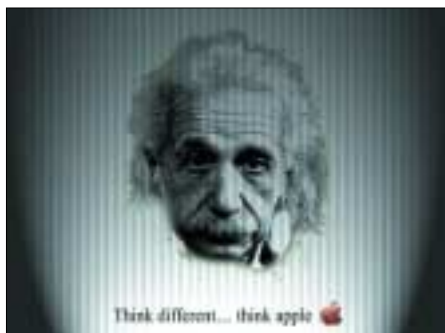
However, all such Einstein-related activity will be carefully monitored. For the past 22 years the Hebrew University of Jerusalem (HJU) has owned the rights to most of Einstein's words, images and personal papers. And since 1985 a US firm, the Roger Richman Agency, has acted as the exclusive licensing agent for the university. Based in Beverly Hills, and also managing the estates of several Hollywood film legends – from W C Fields to Steve McQueen – the agency represents, protects and licenses the use of the Einstein “brand” on behalf of the HJU.

“We are the worldwide exclusive enforcement and licensing agent of the Hebrew University of Jerusalem,” says Richman, whose father was a rabbi who helped Einstein to escape Nazi Germany. “If anyone anywhere in the world wants to use any part of the Einstein brand, then they have to go through the Roger Richman Agency.”

HJU owns the copyright for all Einstein's quotations and scientific formulae, and some of the images of him (the rest of the photographs are owned by the people who took them or by photographic agencies). Although scholars at Boston University, Princeton University and the California Institute of Technology have participated in the production of an anthology called *The Collected Papers of Albert Einstein*, the universities themselves have no licensing rights to the Einstein material.

Humble beginnings

Einstein himself made no systematic effort to preserve his scientific papers during his early career. But in 1919, when the initial proof of his general theory of relativity confirmed his scientific stature and greatly increased his correspondence, he engaged a secretarial assistant – his step-daughter Ilse Löwenthal – to file his papers. Nine years later a new secretary, Helen Dukas, started to conserve his work in a more systematic way. And in 1933, after the Nazis took power in Germany, Einstein's son-in-law



Mass appeal – Einstein's image has been used by many companies, including Apple.

Rudolf Kayser helped to take his papers from Berlin to his new home in Princeton.

Einstein appointed Dukas and Otto Nathan, an associate of his from Germany, as the trustees of his estate. For a quarter of a century after Einstein's death in 1955 they organized and expanded the archive, helped in large measure by Harvard physicist and science historian Gerald Holton. Then in 1982, in a desire to consolidate the archive and satisfy the demands for the materials to be housed in Israel, the Einstein estate transferred the papers to the HJU.

Since then the archive has continued to grow. For example, Holton recently made a donation to the HJU of more than 3000 books, among them several works on Einstein and relativity, from his own private collection. “I do not retain any particular permission for them except for my own use,” Holton says.

Getting permission

So how do you obtain a licence to use copyrighted Einstein material? These days the process starts with a visit to the Richman agency's website (www.albert-einstein.net), where applicants fill in a form. The agency then responds with a suggested price. Educational and promotional use of the Einstein material typically requires no fee, but, says Richman, “everything is subject to our client's [the HJU's] approval”.

Over the last three years the agency has approved 400 licences. Microsoft, for instance, needed a licence to create the animated Einstein character for its Word program, as did Apple for its “Think different” advertising campaign (see above) and the Walt Disney Company for a range of educational toys that it produces under the “Baby Einstein” brand. But, unsurprisingly, requests for permission to use the Einstein brand have increased with the approach of the International Year of Physics, the

worldwide series of activities taking place throughout 2005 to celebrate the *annus mirabilis*. Currently there are about five requests per day.

In the UK, the Institute of Physics obtained permission to use the name “Einstein Year” for its contribution to the International Year of Physics. This licence took a fair amount of negotiation, and does not include permission to use any of the agency's images or to produce Einstein-related merchandise, although the Institute has used a copyright-free image of Einstein from the agency for its promotional literature. “The licence really just allows us to use the name,” says Caitlin Watson, Einstein Year project manager at the Institute.

Typically, the agency turns down about a quarter of the requests it receives, and there are some areas that are completely out of bounds. “We have an absolute prohibition on alcohol and tobacco,” Richman says. “We also turn down charities that say, for example, Einstein died of an aneurysm. We do not license diseases.”

If the agency does learn of an unlicensed use it first warns the offending party, then issues a “cease and desist” letter, and, if that has no effect, may then take the user to court. But occasionally the agency takes immediate action. A few years ago, for example, Spencer Gibbs, a retail chain owned by Universal Studios, produced a T-shirt carrying Einstein's name and the phrase “eat shit”. Using his Hollywood connections, Richman made what he calls “an irate phone call” to Lew Wasserman, the chairman of Universal Studios. “The T-shirts were gone almost immediately,” he recalls. Currently, the agency is in negotiations regarding a video game in which Einstein, Hitler and other characters can kill one another.

So how much does it cost to get a licence? Neither the HJU nor the Richman agency are prepared to say, but *Science* magazine says that it paid \$1700 for permission to use a cartoon of Einstein on its cover in 1998. And how much money do the licences generate? More than \$1m per year, according to Richman. The money goes into the university's general fund, where, among other things, it helps to support the 70% of its 24 000 students who receive scholarships. That, at least, would please Einstein.

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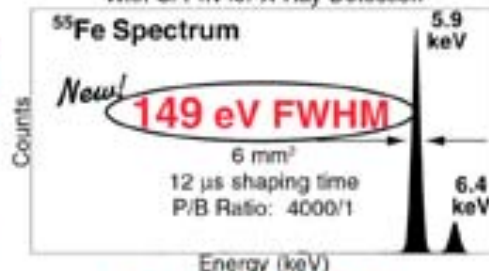
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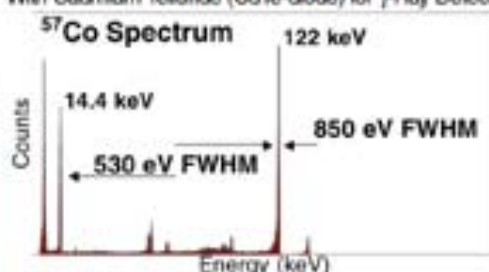
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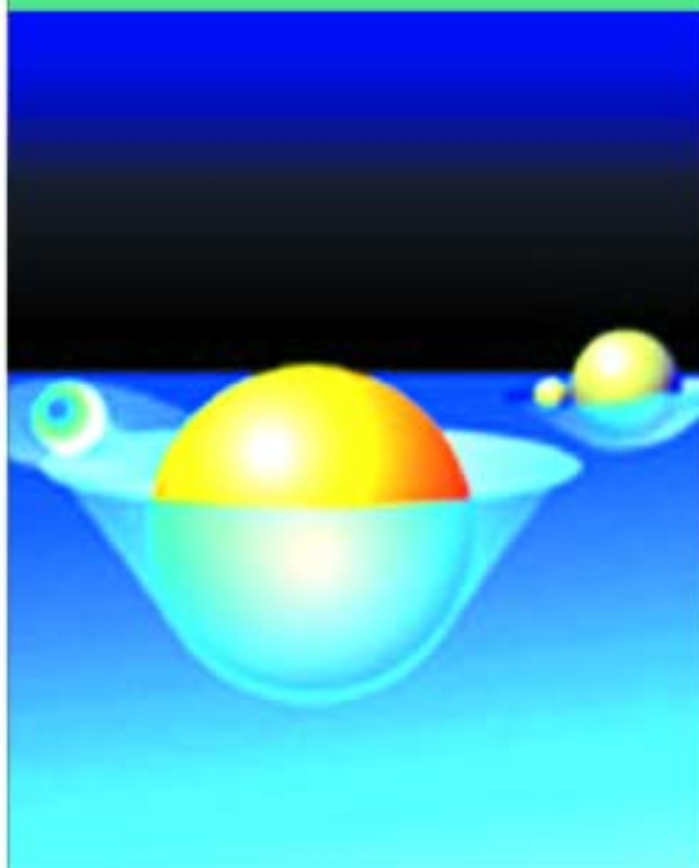
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General relativity predicts that ripples are produced in the fabric of space–time when mass is accelerated. Detecting this phenomenon is one of the outstanding challenges in physics

The search for gravitational waves

Jim Hough and Sheila Rowan

LAST AUGUST the bookmaker Ladbrokes offered the public a chance to bet on science. When the betting opened, Ladbrokes was offering odds of 500/1 that gravitational waves – a so far unconfirmed prediction of Einstein’s general theory of relativity – would be detected by a laser-based experiment called LIGO before 2010. To those of us working on gravitational waves this was an opportunity not to be missed, and we quickly staked the maximum amount allowed by the bookmakers. Others did the same, and when the betting closed a few weeks later the odds had shortened to 2/1.

It would appear, therefore, that gravitational-wave physicists have more confidence in their experiments than Ladbrokes, but they have not always been so confident. Dismissed by Arthur Eddington as being “transformable away at the speed of thought”, and even rejected by Einstein at one stage, gravitational waves are so weak that they have escaped the best efforts of physicists to detect them over the last 40 years. In 1974 Russell Hulse and Joseph Taylor found indirect evidence for gravitational waves in observations of a binary pulsar – a feat that was recognized with a Nobel prize in 1993 – but experiments designed to detect the waves directly have so far drawn a blank.

That looks set to change with the start up of LIGO in the US and a number of other similar experiments around the world: VIRGO, GEO 600 and TAMA. Success with these experiments would be a huge breakthrough. In addition to providing the best evidence to date that general relativity really is the correct theory of gravity, it would also open up a new window on the universe. Because gravitational waves are so weak, only astrophysical phenomena involving extremely massive objects such as black holes can generate waves strong enough to be detectable. But the very weakness of these waves means that they can pass through regions in space that absorb electromagnetic radiation. As a result, they carry information about their source that cannot be obtained using conventional telescopes.



Reaching out – the LIGO facility in the US consists of a pair of laser interferometers that search for tiny changes in the separations of test masses caused by the passage of gravitational waves. Each interferometer – one at Hanford in Washington state (above), the other near Livingston in Louisiana – has arms that are 4 km long.

Making waves

In the general theory of relativity Einstein showed that mass and gravity are generated by the curvature of space–time. If we restrict ourselves to one dimension of space and one of time, we can picture space–time as an infinite 2D surface that is curved by the presence of mass. Gravitational waves are generated on this surface whenever a mass accelerates, just as radio waves are generated whenever an electric charge is accelerated.

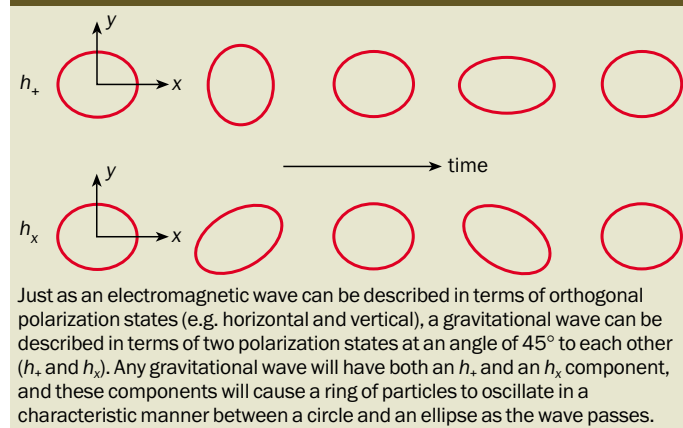
However, electrical charge can be positive or negative, whereas mass has only one sign, and this leads to important differences between electromagnetic and gravitational waves. For instance, whenever a mass is accelerated, the conserva-

tion of momentum dictates that another mass must recoil, and this leads to the gravitational radiation from the two masses tending to cancel out. This means that gravitational waves are not dipole in nature.

A system will therefore only generate a net flux of gravitational radiation if it changes shape as well as accelerates. Such changes of shape can be seen in a binary-star system or the asymmetric collapse of a massive star to form a black hole. Gravitational waves emitted by these systems will travel across the universe by continually squeezing and expanding space–time along their path. They travel at the speed of light and, like electromagnetic waves, can be characterized by their frequency and polarization (see figure 1).

Gravitational waves can be emitted either continuously or in bursts. The former are produced by stable phenomena such as binary stars or pulsars, while the latter – which last for just a few cycles – are generated by short-lived events such as supernova explosions or the formation of black holes. A third type of gravitational signal – the “chirp” – is thought to be produced by the merging of compact binary stars. This chirp, which starts at low frequencies and rises in pitch over time, has a lifetime somewhere between that of a burst and a continuous wave.

1 How a gravitational wave behaves



To detect gravitational waves we need to measure the changes that they make to the shape of space–time. The trouble is that the very weak nature of gravity and the non-existence of dipole radiation mean that only a tiny fraction of the mechanical energy in the source is converted into gravitational radiation. Even the strongest astrophysical gravitational waves are predicted to produce strains – fractional changes in the dimensions of space–time – that are less than about 1 part in 10^{22} . This is equivalent to the distance between the Earth and the Moon changing by little more than the diameter of an atomic nucleus.

Early claims

The first attempt to detect gravitational waves was made by Joseph Weber of the University of Maryland in the 1960s. Weber suspended a 1 tonne aluminium bar in a vacuum tank and bonded a ring of piezoelectric transducers around its centre. The idea was that a passing gravitational wave would cause the bar to expand and compress very slightly, making it resonate if the frequency of the wave roughly matched the fundamental resonant frequency of the aluminium bar. The instrument had to be heavy because the amplitude of the thermal oscillations in the bar is inversely proportional to the square root of its mass, and this thermal “noise” has to be kept to a minimum so as not to swamp any signal from a passing gravitational wave.

Between 1969 and 1970 Weber operated bar experiments at the University of Maryland and the Argonne National Laboratory in Illinois, and observed coincident excitations of the bars about once a day. He claimed that these events were gravitational-wave signals. However, similar experiments at Moscow State University, IBM’s TJ Watson Research Center in New York, Bell Labs in New Jersey, the Max Planck Institute for Physics in Munich, and Glasgow University were unable to detect such signals. Several years of lively debate ensued, resulting in a somewhat predictable stand-off between Weber and the rest of the community. Indeed, David Blair, in his book *Ripples on a Cosmic Sea*, recalls that a fist fight almost broke out at a meeting on gravitational waves at the Massachusetts Institute of Technology in 1972.

A number of independent analyses suggested that Weber’s bars were sensitive to strains of about 1 part in 10^{16} for millisecond pulses of gravitational waves. But this sensitivity seemed to be at odds with Weber’s claim to be detecting one gravitational wave per day from the centre of the Milky Way.

Martin Rees of Cambridge University and a number of other astrophysicists worked out that for both statements to be true the galaxy would have been losing mass so quickly that it should have been possible to observe the stars at the edge of the galaxy moving outwards. Some astronomers suggested that the gravitational-wave energy was emitted in a narrow beam, which would significantly reduce the overall energy loss, but this idea was not widely accepted.

The best way to break the impasse was to improve the sensitivity of the detectors. Weber and groups at Stanford University, Louisiana State University, the University of Rome, the University of Western Australia and, more recently, the universities of Trento and Padua in Italy, did this by cooling the bars to reduce thermal oscillations. Initially cooled to liquid-helium temperatures (4.2 K), but nowadays reduced to a few millikelvin, these bars have been operated for the last 25 years, sometimes in pairs or larger groups.

Although none of these detectors has found definitive evidence for the existence of gravitational waves, a few coincident events have been observed. In 2003, for instance, it was reported that the Nautilus detector in Rome and the Explorer detector at CERN in Geneva had recorded 31 coincident events over a 90-day period in 2001 (see figure 2). Sam Finn of Pennsylvania State University and colleagues have questioned the statistical significance of these events, although the Rome group, led by Eugenio Coccia, also of the Gran Sasso National Laboratory, has been careful not to claim it has discovered gravitational waves. Coccia says that if the signals are from gravitational waves, they are unlikely to be from standard sources such as stellar collapses but from exotic sources such as X-ray bursters in the Milky Way. The Rome group is about to release new results based on the analysis of another year’s worth of data.

Modern bar detectors are currently about 1000 times more sensitive than Weber’s original design and are likely to become even more sensitive in the future with the development of advanced low-temperature amplifiers. In addition, some groups are building spherical resonant-mass detectors because spheres can be heavier than bars for the same resonant frequency and can be excited by gravitational waves in more than one direction at the same time. They should therefore produce a larger signal-to-noise ratio than bars. One such detector, the MiniGRAIL experiment at Leiden University in the Netherlands, started taking data at the end of last November.

There has also been a substantial improvement in the bandwidth of bar detectors – the range of frequencies over which they are sensitive – and this has allowed them to detect a greater number of different sources. Until about two years ago most bars had a bandwidth of about 1 Hz but this figure has now increased to several tens of hertz, with the AURIGA detector near Padua in Italy reaching 80 Hz (see figure 2).

Bandwidths could increase still further if a new “nested” detector design – which contains two masses with different resonant frequencies – being developed by Massimo Cerdonio and colleagues in Padua and Trento proves successful. If a passing gravitational wave has a frequency between the resonant frequencies of the two masses it will cause the mass with lower frequency to move in phase with the wave and the other mass to move in antiphase. The two masses oscillating out of phase with one another will in effect double the signal, which leads to a greater sensitivity than would be

2 Low-temperature bar detectors



For the last 40 years physicists have been attempting to detect gravitational waves using large metal bars. The idea is that the bar will resonate if its fundamental vibrational frequency matches the frequency of the wave. No bar has definitively detected a gravitational wave, but physicists at the University of Rome say they have seen interesting coincident signals in the Explorer bar at CERN (left) and the Nautilus bar in Rome. While no such claim has been made by researchers working on the AURIGA detector near Padua in Italy (right), this bar has demonstrated the feasibility of carrying out searches for gravitational waves over relatively large bandwidths.

possible with one mass. More importantly, the system can operate across a range of frequencies bounded by the resonant frequencies of the two masses.

The interferometers

Despite improvements in the performance of bar detectors, most researchers believe that the best way to detect gravitational waves is to use laser interferometers, because these have a higher sensitivity and bandwidth than bars. First proposed by Mikhail Gertsenshtein and Vladislav Pustovoit of Moscow University in 1962, interferometer detectors work by splitting a laser beam into two components that then travel at right angles to one another down separate “arms”. The beams bounce off polished “test masses” at the end of each arm and return to their starting point, where they interfere with one another (figure 3). The interferometer is set up so that in its default mode the beams interfere destructively and there is no output. However, a passing gravitational wave would make one arm slightly longer and the other slightly shorter, which would lead to some positive interference and a tiny amount of light at the output.

Robert Forward of the Hughes Aircraft Corporation built the first gravitational-wave interferometer, with arms just 2 m long, in the late 1960s. But with a sensitivity of about 1 part in 10^{13} – some eight to nine orders of magnitude too small – it was a long way from being a working observatory. Since then, however, technological advances have brought interferometers to the brink of detecting a gravitational wave. These advances include high-powered lasers (which increase the output signal in the interferometer), the use of kilometre-scale arms, and techniques for further increasing the path-length of the laser beams, usually by reflecting the beams many times within the arms before they are made to interfere. This increased pathlength will result in a larger output, since gravitational waves increase or decrease distances by a given fraction.

Prototype interferometers were constructed during the 1970s and early 1980s by a number of physicists around the

world, including Rai Weiss and colleagues at MIT; Ron Drever, Jim Hough and colleagues at Glasgow University, and subsequently Ron Drever at the California Institute of Technology; Albrecht Ruediger, Roland Schilling, Walter Winkler and colleagues at the Max Planck Institute for Quantum Optics in Garching; and Nobuki Kawashima and colleagues in Japan. By the mid to late 1980s the gravitational-wave community considered interferometer technology sufficiently mature to make a strong case for building much larger detectors, despite the scepticism of many scientists outside their community. As a result a new network of large-scale interferometers came into being.

The largest of these is the Laser Interferometer Gravitational-wave Observatory (LIGO) in the US. There are actually two LIGO interferometers – one situated at Hanford in Washington state, the other near Livingston in Louisiana – and both have arms that are 4 km long. A separate 2 km interferometer has also been built inside the arms of the detector at Hanford. Other large-scale interferometers include the French–Italian VIRGO detector near Pisa (3 km long), the British–German GEO 600 device near Hanover in Germany (600 m), and the TAMA interferometer near Tokyo (300 m). In general these detectors will work together to discriminate against local events that could mimic the passage of a wave – such as earth tremors, aircraft or thunderstorms – and also to pinpoint the source of the waves by comparing the arrival time at the different detectors.

In designing these interferometers it has been necessary to minimize three main sources of noise: seismic noise, thermal noise and “shot” noise. Seismic vibrations can be reduced by suspending the test masses and optics from wires. Thermal noise is a problem in the test masses and suspensions, which is why components with very low mechanical loss factors are used, while the shot noise caused by statistical fluctuations in the photodiode that detects the interference pattern can be reduced by using more powerful lasers. It is also necessary to keep the vacuum pressure in the arms as low as possible, typically less than 10^{-8} millibars, because any gas molecules pre-

sent will affect the laser beams.

Progress in combating these various sources of noise has brought the interferometers to within touching distance of their design sensitivities. The LIGO detector in Hanford, for instance, is now within a factor of two of its design sensitivity of 1 part in 10^{21} for pulses of gravitational waves lasting several milliseconds. VIRGO is close to completion and should reach its design sensitivity within about a year, while TAMA is also now operational.

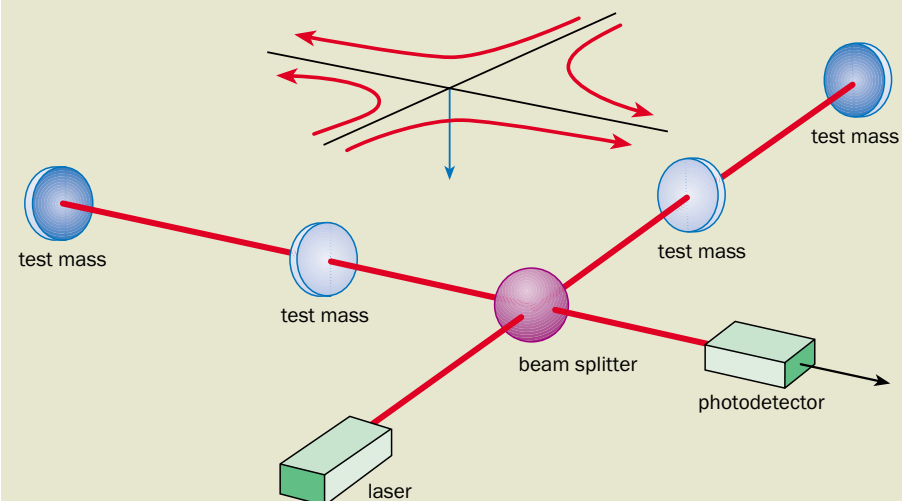
GEO 600, meanwhile, has pioneered a number of technological innovations to improve sensitivity. These include suspending the test masses with fused silica, in which thermal vibrations are prominent over a far narrower range of frequencies than in the stainless-steel wire used in the other interferometers. Construction of GEO 600 has now been completed and the interferometer's sensitivity is expected to approach that initially obtained in VIRGO and LIGO at frequencies above a few hundred hertz.

These detectors are now beginning to produce their first results. LIGO has so far carried out three experimental runs, each lasting a few weeks, with GEO 600 and TAMA taking part in two of the runs and the Allegro bar detector in Louisiana taking part in one. These runs have not produced any evidence for gravitational waves, but they have placed upper limits on the strength of signals from potential sources such as pulsars, coalescing compact binary stars and short bursts of gravitational radiation that could come from a number of sources (see Abbott *et al.* in further reading). Results from the second run are about to be published, and those from the third run are being analysed.

During the next few years we can expect to see sensitivities approach about 10^{-21} for signals from compact binary coalescences, and close to 10^{-26} for pulsars. The chances of detecting gravitational waves with the currently available detectors over the next five years lie somewhere between 2:1 and 5:1. Sensitivity needs to improve by about a factor of 10 if we are to be relatively certain of observing waves from the most predictable sources – coalescing compact binary stars.

This should occur with the advent of Advanced LIGO, an upgrade to LIGO that has been provisionally approved by the US National Science Board. Advanced LIGO would use test masses made from huge sapphires or lumps of silica and suspended by fused silica. Seismic isolation would also be improved, laser power would be increased and the laser beams would be “recycled” more effectively. The upgrade should start in 2009 and be completed by 2011 or 2012, which would allow Advanced LIGO to start detecting gravitational waves by about 2013. It should observe somewhere between 10 and 500 mergers of binary neutron stars per year. GEO 600 will also be upgraded after 2008 and should be sensitive enough to see gravitational waves from neutron “starquakes”.

3 Interferometer detectors



Physicists have built a number of huge interferometers to detect gravitational waves. These devices split a laser beam into two components at 90° to one another, sending each component down a separate “arm” that is hundreds or thousands of metres long. The beams bounce off a polished “test mass” at the end of each arm and then recombine at a photodetector. A gravitational wave passing through the device will stretch one of the arms and compress the other, and therefore change the interference pattern observed at the photodetector. However, the change to the length of the arms will be tiny – about one-hundred-thousandth of the diameter of an atomic nucleus – and the associated change in the interference pattern will therefore also be tiny. This change can be increased by bouncing the laser beams repeatedly between the test masses (dark blue) at the ends of the arms and those test masses (lighter blue) placed near the beam splitter, but the resulting change in the interference pattern is still tiny – about 10^{-12} – 10^{-13} of a fringe in LIGO. The effect of the gravitational waves on the interferometer arms is shown by the red arrows. At a particular instance, space is stretched in the left–right direction and compressed in the back and forth direction, assuming that the gravitational wave propagates perpendicular to the plane of the interferometer (blue arrow). Half a wavelength later the directions of stretching and compression will be reversed.

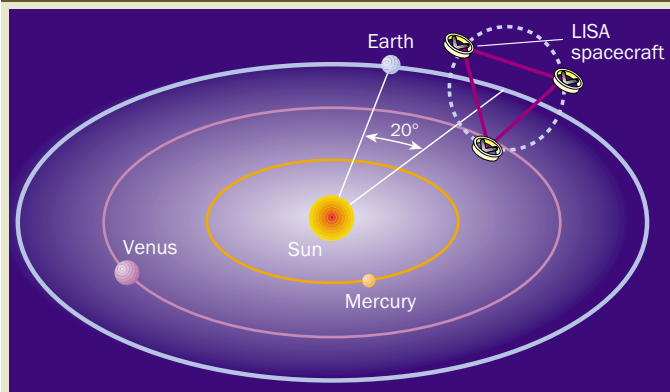
Looking up and beyond

Despite their scope for increased sensitivity, the current generation of interferometers all have one significant drawback: they cannot detect gravitational waves at frequencies below about 10 Hz. This is because a huge number of everyday events cause disturbances that occur on timescales of a tenth of a second or more. For example, a fox running past the end of an interferometer arm could cause a noticeable change in the local gravitational potential purely by virtue of its own body mass. Japanese physicists are hoping to reduce some of these sources of noise, such as seismic vibrations, by building a 3 km interferometer in the Kamioka mine 1000 m below ground. They hope to start operating the device in 2009, with the aim of detecting a gravitational wave at about the same time as Advanced LIGO.

However, the only way to completely avoid such disturbances is to go into space. A group of scientists at NASA and the European Space Agency is developing a mission called the Laser Interferometer Space Antenna (LISA), which will be sensitive to gravitational waves from about 0.1 Hz down to about 0.1 mHz. Working at such frequencies will allow LISA to observe the formation and coalescence of black holes with masses some 10^3 – 10^6 times greater than that of the Sun. This would be a significant achievement in astrophysics, and the ultra-high gravitational fields involved would provide a valuable testing ground for general relativity.

LISA will consist of three spacecraft positioned five million kilometres apart in the shape of an equilateral triangle (see figure 4). Laser beams bounced between test masses on board each spacecraft would create three separate interferometers,

4 Space-based detection



NASA and the European Space Agency are developing a mission known as LISA to detect gravitational waves in space. LISA will consist of three spacecraft positioned about 5 million kilometres apart and flying in a triangular formation around the Sun, with the centre of mass of the triangle trailing about 20° behind the Earth. Laser beams bounced between the spacecraft will form three separate interferometers.

and the arm length of five million kilometres would provide much larger signals than those from ground-based devices. LISA would therefore require far less-sensitive optical-sensing techniques to detect a gravitational wave. Assuming that funding is approved as expected, it will be launched in about 2013 and should be producing data for about 10 years after that.

Even further into the future, physicists hope to launch a successor to LISA that would study what is believed to be a cosmic background of gravitational waves. These waves, which are thought to permeate the entire universe, would have been produced just 10^{-35} s after the Big Bang, far earlier than the oldest electromagnetic radiation we can detect. So as well as allowing us to study the structure of space-time and a number of exotic astrophysical objects, gravitational waves could also help us to shed new light on the origins of the universe. But before we do that we need to make sure that gravitational waves actually exist. That, in itself, will be a remarkable achievement.

Further reading

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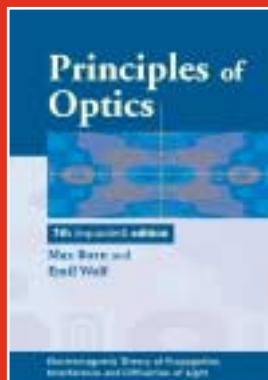
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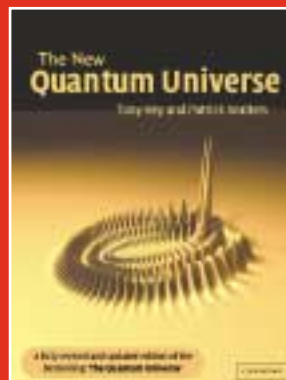


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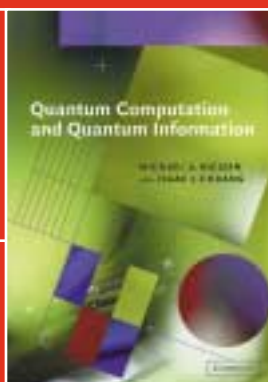
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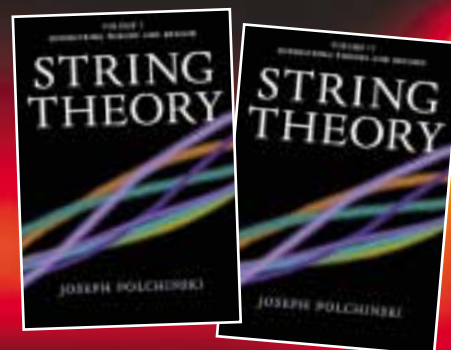
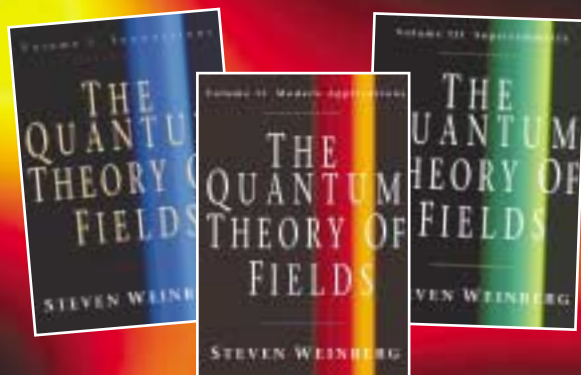
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A very special centenary

Einstein's theory of special relativity has been a cornerstone of modern physics for decades, but, as **Robert Bluhm** describes, physicists are still putting it to the test

Every physics teacher recognizes the look of astonishment that appears on a student's face when they are taught special relativity. The first tenet on which the theory is built goes along with common sense: the laws of physics are the same in all inertial or non-accelerating frames. Billiards, for example, can be played on a steady cruise ship just as well as it can be played on solid land.

It is the second tenet – that the speed of light in a vacuum is the same in all inertial frames – that causes jaws to drop. It is a bit like saying that two police officers, one standing still and the other in a fast-moving car, will both clock the same speed for a passing motorist. Clearly, this defies all common sense. It took the genius of Einstein to suspend his disbelief and explore the consequences of these two requirements.

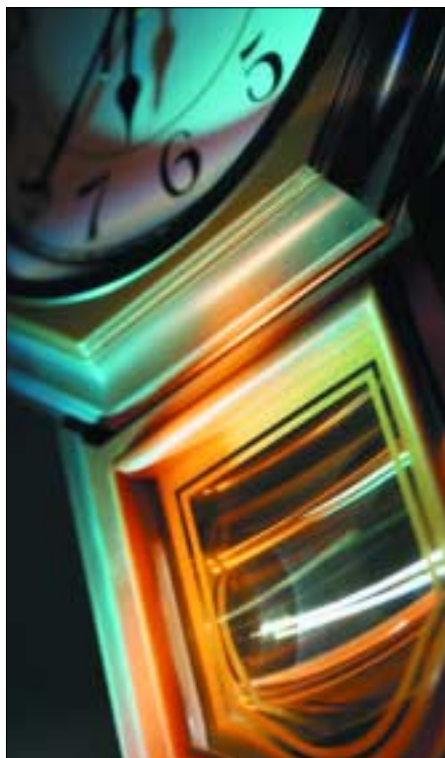
A special theory

Special relativity revolutionized our understanding of space and time by predicting that clocks slow down and lengths get shorter when moving at close to the speed of light. In a follow-up paper published later in 1905, Einstein derived the famous relation between energy and mass, $E=mc^2$, which brought with it the dawning of the nuclear age.

The predictions of special relativity have been observed in countless experiments, beginning with those of Michelson and Morley in 1887 (i.e. before Einstein's work) that proved that the speed of light is independent of the Earth's motion. More recently, atomic clocks placed on aircraft have verified time dilation, while common electronic devices on the Global Positioning System satellites have to take special relativity into account in order to function properly.

As strange it seems at first, special relativity has a particular appeal because it is based on an elegant principle of symmetry: just as a sphere looks the same no matter how you rotate it, the laws of physics remain the same under a set of transformations between inertial frames called Lorentz transformations.

However, as Einstein quickly discovered, special relativity is really an approximate theory that only holds in the absence of gravitational fields. His general theory of relativity, which he published a decade later, shows that gravity is caused by the curvature of space-time. This curvature also breaks the Lorentz symmetry of special relativity, and the laws of special relativity are only recovered in local "freely falling" frames, such as the weightless environment of a spacecraft.



Revolutionary – special relativity overturned the Newtonian view of space and time.

In many situations, however, the effects of general relativity are extremely small and so special relativity can be tested directly. For example, the energy levels of an atom are virtually unaffected by gravity, so the special-relativistic corrections can be measured and calculated to high precision. To date, the experiments and Einstein's theory agree completely (see "Relativity at the centenary" on page 27).

Relativity violations

Despite the success of relativity, some physicists have been working hard to find violations of the theory. Their motivation stems from efforts to unify quantum theory and general relativity into a single framework. At ultrahigh energies known as the Planck scale, we know that these two pillars of modern physics must meet up.

The quantum world is "fuzzy" or granular because the position and velocity of a particle can never be precisely measured at the same time. It follows that the smooth space-time of relativity should have an underlying quantum granularity at the Planck scale.

One effect of unifying quantum physics and gravity might be that the laws of relativ-

ity do not hold at the Planck scale. Indeed, some 15 years ago Alan Kostelecky of Indiana University and co-workers started looking for violations of relativity as a signature of new physics at the Planck scale. In particular, they found that string theory – a promising candidate for a unified theory in which particles are described as 1D strings – can lead to violations of Lorentz symmetry (see *Physics World* March 2004 pp41–46).

In another approach developed by Giovanni Amelino-Camila of the University of Rome and Lee Smolin of the Perimeter Institute, among others, special relativity is altered by treating the Planck scale as a second invariant quantity (along with the speed of light). Just as no velocity can exceed the speed of light in Einstein's 1905 theory, no energy can exceed the Planck scale in these "doubly special" relativity theories.

Standard Model extension

Regardless of what might cause violations of relativity, these violations must ultimately be revealed through their interactions with known particles. For example, the energy or momentum of a certain particle might depend on its motion or orientation, and therefore violate Lorentz symmetry. To study these violations, Kostelecky and co-workers have extended the Standard Model of particle physics so that it can accommodate Lorentz violation, and this model has now become the standard framework used by experimentalists searching for small violations of relativity.

A number of recent experiments have reached extraordinary levels of precision, including sensitivity to effects that could arise at the Planck scale. For example, Ronald Walsworth and co-workers at the Harvard-Smithsonian Center for Astrophysics have looked for small variations in the hyperfine structure of atomic energy levels in hydrogen masers as the Earth rotates. These experiments show that special relativity is correct to about 1 part in 10^{27} , and provide the sharpest bounds on violations of relativity involving the proton. Additional experiments with other particles have also been performed, and more stringent tests are likely in the coming years.

Whatever the future holds for special relativity, it remains one of the most elegant and at the same time mind-boggling theories of all time. It is simple enough to be taught to undergraduates, yet it is full of puzzles and paradoxes that can still confound most teachers. Whether the core ideas of relativity are exact or not, only time will tell. But there is no question that the theory has abolished our notions of absolute time and space, and altered our view of the universe forever.

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Strange ways of light and atoms

Two of Einstein's less well-known discoveries – Bose–Einstein condensation and stimulated emission – have had a huge impact on the modern world, explains **Charles W Clark**

Einstein is best known for relativity and his other 1905 breakthroughs – explaining the photoelectric effect and his work on Brownian motion – but his ideas also underpinned the development of the laser and the creation of a new state of matter called the Bose–Einstein condensate. These discoveries, which were made in 1916 and 1924, respectively, were based on Einstein's investigations into “bosonic” particles such as photons. Moreover, Bose–Einstein condensation was predicted to occur in one of the simplest physical systems: the ideal gas.

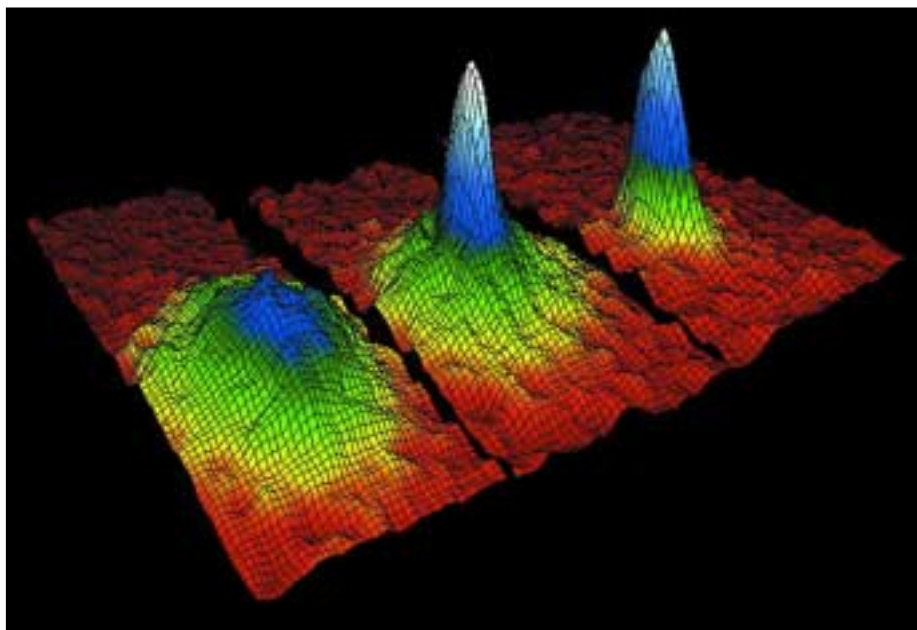
An ideal gas is a system of non-interacting particles that are in thermal equilibrium – hardly a promising vehicle for surprising discoveries. Indeed, it is the epitome of disorder, with atoms and molecules flying about randomly. But Einstein showed that for any temperature there is a density above which the particles in an ideal gas do not participate in the thermal agitation.

In other words, if we take an ideal gas and compress it at a constant temperature by, say, squeezing the walls of its container, then the gas will eventually separate into two components. One component remains engaged in the familiar wild party of thermal motion, while the other is quiescent, effectively at zero temperature, even though it is surrounded by a mob of hot atoms. As the density is increased, more atoms fall into the zero-temperature component, which eventually dominates the gas. In practice, researchers cool a gas with a given density until atoms start to enter this zero-temperature component.

Bose–Einstein condensates

This phase transition, which cannot be understood in classical physics, is called Bose–Einstein condensation and is one of the most active areas of research in physics today (see *Physics World* September 2003 pp37–40). But, as the name suggests, it was not all down to Einstein: the existence of this new state of matter was predicted when Einstein applied to material particles ideas about the statistical mechanics of photons that had been proposed by the Indian physicist Satyendra Nath Bose.

In 1923 Bose sent Einstein a paper that described a new way to derive Planck's radiation law by treating photons as indistinguishable particles. At the time, Bose was a little-known lecturer in physics at Dacca University (now in Bangladesh), and his paper had been rejected by *The Philosophical Magazine*. Einstein, on the other hand, was the most famous physicist in the world, and



Quantum insight – Einstein predicted that a gas of bosons will collapse into a single quantum state called a condensate, which was created for the first time in 1995. These images show how such a state emerges in a gas of rubidium atoms that has been cooled from its classical state (left) to close to absolute zero (right). The appearance of a second, asymmetric profile in the middle figure is the “smoking gun” of Bose–Einstein condensation.

was sufficiently impressed by Bose's paper to translate it from English into German and submit it to the *Zeitschrift für Physik*, where it was published under Bose's name.

Bose considered a system of photons, and proposed that any number of photons could occupy a given quantum state. This led to a system that was in thermal equilibrium in accordance with Planck's law of black-body radiation. Einstein's contribution was to extend Bose's idea to material particles, postulating that phase space could be divided into elementary cells of volume h^3 , where h is Planck's constant, and that any number of particles could occupy a given cell. An alternative prescription was proposed by Enrico Fermi in 1926, in which no more than one particle can occupy an elementary cell. Today, we recognize that all the elementary particles in nature are either bosons or fermions, and are described either by Bose–Einstein or Fermi–Dirac statistics.

The quantum viewpoint

From the standpoint of quantum mechanics, the transition from a gas of bosons to a condensate is straightforward. In a classical ideal gas, which is described entirely by its temperature and density, there is only one characteristic length scale of microscopic origin: the mean distance between the atoms or molecules. For example, in an

ideal gas at room temperature and atmospheric pressure this distance is about 3 nm. Quantum mechanics, however, introduces another microscopic length scale: the de Broglie wavelength, $\lambda = h/p$, where p is the momentum of the particle. Bose–Einstein condensation occurs when the de Broglie wavelength becomes comparable to the average separation between particles.

For the nitrogen molecules in the atmosphere at room temperature, the de Broglie wavelength is about 0.02 nm, which is much smaller than the classical molecular separation. We might therefore think that we could create a condensate by compressing ordinary air by a factor of about a million. However, this will not work because the mean distance between the air molecules would become about 10 times less than the length of a normal molecular bond, and so we would be left with a solid with an incredibly high density, rather than an ideal gas.

Indeed, no familiar substance can approach the conditions required for Bose–Einstein condensation, which led many to regard the phenomenon as nothing more than a mathematical curiosity. In 1938, however, superfluidity was discovered in liquid helium, and Fritz London noted that the conditions for the onset of superfluidity were remarkably similar to those for Bose–Einstein condensation. London re-

cognized that the helium-4 atoms – which, like photons, are bosons – in these conditions could hardly be considered an ideal gas because the interactions between the atoms were so strong. However, he felt that some relic effect of condensation might drive a quantum phase transition in such a strongly interacting system.

Laser cooling

The concept of Bose–Einstein condensation as the iconic quantum phase transition, combined with its possible links to superfluidity, made it a “holy grail” for experimentalists. But it took almost 70 years to realize. In 1995 Eric Cornell, Carl Wieman and co-workers at the JILA laboratory in Boulder, Colorado, created the first condensate in a gas of laser-cooled rubidium atoms. This work, which has since been followed by demonstrations in some 40 laboratories worldwide, has placed Bose–Einstein condensates – and their fermionic counterparts – at the forefront of modern research. In 2001 Cornell, Wieman and Wolfgang Ketterle of the Massachusetts Institute of Technology shared the Nobel prize for their work on Bose–Einstein condensation.

The creation of the first condensates relied on the use of lasers to trap and cool atoms – work that was recognized with the award of the 1997 Nobel prize to Steven Chu, Claude Cohen-Tannoudji and Bill Phillips. Remarkably, the development of the laser can also be traced to the work of Einstein. In 1916 Einstein found that quantum mechanics meant that atoms were more likely to emit photons into electromagnetic modes that already contained photons than into modes that did not – a process called stimulated emission. In other words, a photon with a particular energy, and therefore frequency, can cause an atom to emit a photon with the exact same frequency. Einstein related the probability of stimulated emission to that of *spontaneous* emission using two expressions that are now called the Einstein *A* and *B* coefficients.

At the time this discovery did not have immediate practical consequences because the stimulated light – which is said to be coherent because it consists of photons with a single frequency – had to be amplified in some way. This was first achieved by Charles Townes and Arthur Schawlow in the microwave region with the development of the “maser” in 1954, and implemented in the optical regime by Theodore Maiman in 1960. Einstein’s work on stimulated emission thus presaged a device that is now found in households around the world, and which is an essential accessory in virtually every field of science and engineering.

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Do you play dice?



AIP/EMILIO SEGRE VISUAL ARCHIVES

Test your knowledge of the world’s greatest physicist with this special Einstein quiz. There is a prize of £50 for the reader who gets the most questions right.

Facts and figures

All the answers to the following questions appear somewhere in this issue.

1. From which university did Einstein receive his PhD?
2. How many children did Einstein have with his first wife Elsa?
3. Which two musical instruments did Einstein enjoy playing?
4. How many references did Einstein include in his first 1905 paper on special relativity?
5. What part of Einstein’s body was not cremated after he died?
6. Which university currently owns Einstein’s papers?

Who said that?

7. Who told Einstein to “stop telling God what to do”? (A. Niels Bohr B. Paul Dirac C. Werner Heisenberg)
8. When asked if it was true that only three people in the world understood Einstein’s theory of relativity, who is reported to have said, “I’m just trying to think of who the third person might be”. (A. Arthur Eddington B. Edwin Hubble C. Max Planck)
9. Who declared during a colloquium by Einstein, “You know, what Mr Einstein said is not so stupid!”. (A. Paul Ehrenfest B. Wolfgang Pauli C. Erwin Schrödinger)
10. Shortly after Einstein first became known in the physics community, who said, “I only hope and wish that fame does not exert a detrimental influence on his human side”. (A. His friend Michele Besso B. His sister Maja C. His first wife Mileva Marić)
11. Who declared in 1966 that Einstein “was almost wholly without sophistication and wholly without worldliness”? (A. Robert Oppenheimer B. I I Rabi C. Victor Weisskopf)
12. Who said that Einstein’s work on general relativity was “one of the greatest – perhaps the greatest – achievements in the history of human thought”? (A. W H Bragg B. Ernest Rutherford C. J J Thomson)

Mix and match

About whom did Einstein say the following? Match the six quotes to the six people.

13. “He was one of the finest people I have ever known...but he really did not understand physics.”
 14. “[He] was as good a scholar of mechanics as he was a deplorable philosopher.”
 15. “She has a sparkling intelligence, but despite her passionate nature she is not attractive enough to present a danger to anyone.”
 16. “He is truly a man of genius...I have full confidence in his way of thinking.”
 17. “She is an unfriendly, humourless creature who gets nothing out of life.”
 18. “He was one of my dearest acquaintances, a true saint, and talented besides.”
- A. Niels Bohr
B. Marie Curie
C. Paul Langevin
D. Ernst Mach
E. Mileva Marić
F. Max Planck

True or false?

19. The FBI kept a file on Einstein.
20. Einstein was left-handed.
21. Einstein was a vegetarian.
22. Einstein approved the patent for the Toblerone chocolate bar while working in the Swiss patent office.
23. Einstein won the Nobel prize for his work on special relativity.
24. Einstein worked on the Manhattan nuclear-bomb project for the Allies.

● Send your entries to *Physics World* Einstein Quiz, Dirac House, Temple Back, Bristol BS1 6BE, UK (fax +44 (0)117 925 1942; e-mail pwld@iop.org). The closing date for entries is Monday 7 February 2005. The winner will be the person with the most correct answers. In the event of a tie, a winner will be picked at random.

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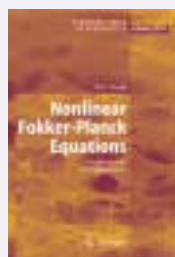


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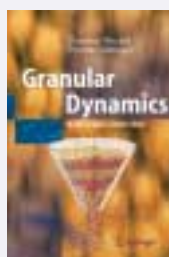


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Hating the inherent randomness of quantum mechanics, Einstein tried to show that the theory was incomplete by drawing attention to a phenomenon that we now call entanglement.

As it turns out, entangled particles are the key to quantum computing

The power of entanglement

Harald Weinfurter

EINSTEIN is rightly famed for his revolutionary work on relativity. But he was also one of the founders of quantum physics and in 1905 became the first physicist to apply Max Planck's quantum hypothesis to light. Einstein realized that the quantum picture can be used to describe the photoelectric effect – that only light above a certain frequency can eject electrons from the surface of a metal. Indeed, it was mainly for deriving the law of the photoelectric effect that he was awarded the 1921 Nobel Prize for Physics.

Despite the undeniable success of quantum theory, Einstein never liked all of its implications. In particular, he simply could not accept the idea that randomness should be an inherent principle of nature. He felt that the theory did not – and could not – explain why quantum effects should appear random to us. Einstein's hope was that quantum mechanics could be completed by adding various as-yet-undiscovered variables. These “hidden” variables, he thought, would let us regain a deterministic description of nature. He expressed his discomfort in his celebrated saying, “[God] does not play dice”.

Einstein spent many years debating the pros and cons of quantum theory with the leading physicists of his day, particularly the Danish theorist Niels Bohr. This culminated in a final attack in 1935 when Einstein, Boris Podolsky and Nathan Rosen (together known as EPR) published a famous paper in which they outlined their objections to quantum mechanics. The title alone – “Can quantum-mechanical description of physical reality be considered complete?” – hinted at their concerns.

In their paper, EPR argued that any description of nature should obey the following two properties. First, anything that happens here and now can influence the result of a measurement elsewhere, but only if enough time has elapsed for a signal to get there without travelling faster than the speed of light. Second, the result of any measurement is predetermined, particularly if one can predict it with complete certainty; in other words a result is fixed even if we do not carry out the measurement itself.

Einstein, Podolsky and Rosen then examined what impact these two conditions would have on observations of quan-



Does God play dice? – Einstein thought not.

tum particles that had previously interacted with one another. They concluded that such particles would have very peculiar properties. In particular, the particles would exhibit correlations that lead to contradictions with Heisenberg's uncertainty principle. Quantum mechanics, it seemed, was incomplete.

Later in 1935 Erwin Schrödinger published a response to the EPR paper, in which he introduced the notion of “entanglement” to describe such quantum correlations. He said that entanglement was the essence of quantum mechanics and that it illustrated the difference between the quantum and classical worlds in the most pronounced way. Schrödinger realized that two entangled particles have to be seen as a whole, rather

than as two separate entities.

If, say, the polarization of two photons is entangled, we will find that the polarization of each photon, when measured separately, appears to be random. However, if we find that one photon is circularly polarized in a right-handed sense, then we know immediately that the other photon is polarized in a left-handed sense – even if we do not actually measure the second photon.

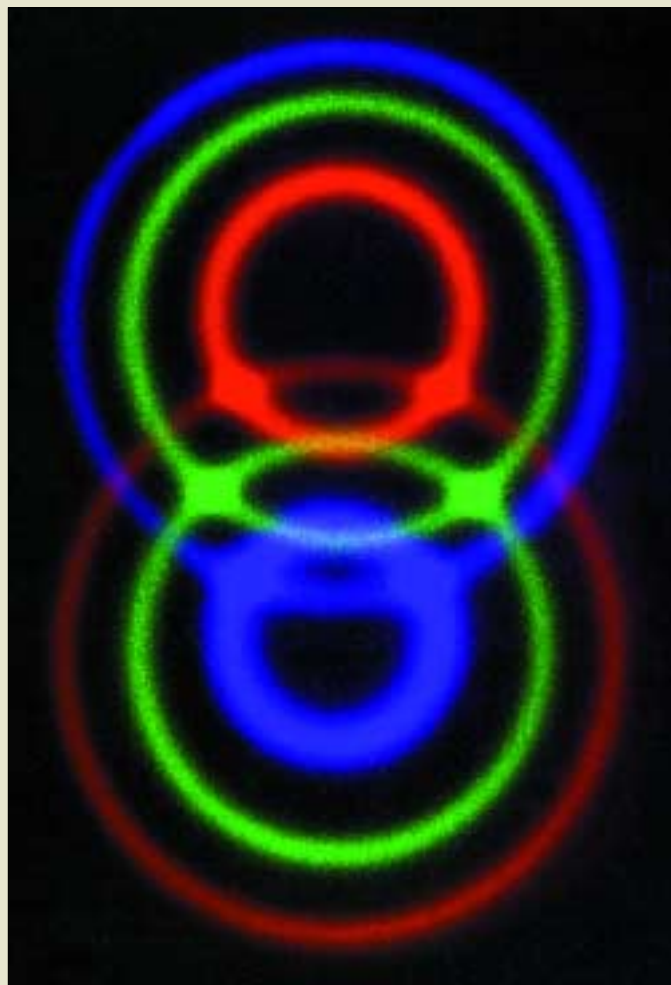
Entanglement is not so spooky

The problem, as far as Einstein was concerned, was that measuring the spin of one photon should have an instantaneous effect on the other photon, even though the two photons might be physically far apart. Einstein did not like this “non-localism” – or what he later called “spooky action at a distance” – because nothing should be able to travel faster than the speed of light. He wanted nature to be local and deterministic.

For the next 50 years entanglement was seen as a somewhat weird effect that was essential only for answering the rather philosophical questions that EPR had raised about nature itself. Only recently, however, have physicists begun to realize that entanglement is not just an abstract concept. It is also important for understanding a variety of effects, such as “decoherence” – the process by which quantum effects die away and the classical world takes over.

Moreover, entanglement has real practical consequences and lies at the heart of the emerging field of quantum in-

1 Entangled photons



The best way of entangling two photons is to use the technique of parametric down conversion. This image, obtained by Paul Kwiat and Michael Reck at the University of Innsbruck in 1995, illustrates two entangled infrared photons. The photons were created by shining ultraviolet light with a wavelength of 351 nm onto a crystal of beta barium borate. About 1 in 10 billion of the photons were down-converted into two photons with a wavelength of 702 nm that were emitted along separate cones (green). The photons on one cone were vertically polarized, while those on the other were horizontally polarized. Entanglement was observed where the green cones overlap. Photons emitted at other wavelengths (blue: 681 nm and red: 725 nm) were not entangled. (See “Iconic images” *Physics World* November 2002 page 37)

formation, which includes quantum computing, quantum cryptography and quantum teleportation (see *Physics World* March 1998 pp33–57). In the case of quantum computing, entanglement enables certain computational tasks to be performed much faster than is possible using classical physics. A quantum computer could be built from any system that can store information in a two-level quantum state, such as an atomic nucleus with a spin that can point either up or down. Unlike the bits in a classical computer, which can only be “0” or “1”, these quantum states, known as “qubits”, can be in a superposition of both states and hold any value between 0 and 1. Moreover, a quantum computer with N qubits can exist in 2^N different states. Each of these states can be processed at the same time. This “quantum parallelism” might lead to an entangled quantum state allowing a quantum computer to, for example, factorize large numbers exponentially faster than a conventional computer.

En route to entanglement

But how can we generate and observe entanglement between particles in the first place? There are basically two options. One method is to let a particle emit (or decay into) other particles. Conservation rules dictate that the properties of these daughter particles will be strongly correlated and possibly entangled. The other option is to “engineer” entanglement by allowing two particles to interact for a fixed length of time. If the interaction depends on the states of the two systems, they can become entangled once the period of interaction is over.

Of course, all particles interact with each other in one way or another, which means that entanglement is not such a special feature of nature at all. In fact, the challenge for experimental physicists who want to observe entangled particles is to isolate them completely from anything else. If the particles do interact with any further particles, the initial entanglement between them is easily lost. But thanks to huge progress in laser physics, atom optics and superconducting technology, physicists can now generate and observe entanglement in quantum systems using any of these techniques.

Although photons do not interact strongly enough to be entangled directly, they can be entangled through various emission processes, many of which are well known. Indeed, correlations between photons that are stronger than those allowed by classical physics were first observed by Chien-Shiung Wu and Irving Shakhnov at Columbia University in New York back in 1950. They carried out experiments in which an electron collides with a positron to create positronium – a short-lived state in which the electron and positron are bound together. This state then rapidly decays to produce entangled gamma-ray photons. The two photons have spins pointing in opposite directions, so that if one photon is found to be spin-up, then the other will have to be spin-down.

Two photons can also be entangled when they are emitted in quick succession from an excited atom. The only proviso is that the photons are emitted when an electron falls in two steps to lower energy levels, such that the initial and the final state both have zero orbital angular momentum. If the first photon is, say, left circularly polarized and has a quantum state $|L\rangle_1$, then the second photon has to be right circularly polarized and will have a quantum state $|R\rangle_2$. Similarly, if the first photon is right circularly polarized ($|R\rangle_1$) then the second photon will be left circularly polarized ($|L\rangle_2$). Provided that the final state of the atoms is the same in both cases, a “coherent” superposition of the two decay options is obtained and the overall wavefunction for the two entangled photons is $|\Psi\rangle = (|R\rangle_1|L\rangle_2 - |L\rangle_1|R\rangle_2)/\sqrt{2}$, with the minus sign reflecting the fact that the final state has zero spin. The wavefunction is no longer the product of the quantum states of the two photons separately and their quantum states are intimately interlinked.

Atomic-cascade experiments, which were pioneered in the 1970s and 1980s, are not easy. They require lots of equipment, including a vacuum vessel for the atomic beam, strong lasers that are exactly tuned to excite the atoms, and large lenses to collect enough photons, which are emitted in all directions. Currently the best way of creating pairs of entangled photons is to use a technique called parametric down conversion, which involves shining blue or ultraviolet laser light onto a crystal with nonlinear optical properties (figure 1).

The crystals are special in that they distort an incoming electromagnetic wave in such a way that, for example, its frequency is exactly doubled. Very occasionally this process is

reversed and a blue photon is converted into two new photons that have exactly half the energy (and frequency) of the original photon. The directions in which the photons are emitted depends on the polarization and direction of the incoming beam, as well as on the orientation of the crystal axis.

Using this technique we can arrange for the two photons to be either vertically or horizontally polarized and to be emitted in two different directions. Provided that these two options are in a coherent superposition the two photons are entangled. Depending on the type of light used and the nature and orientation of the crystal it is also possible to entangle other properties of the photons, such as their frequency or direction. Entangled photons that can be sent down two separate fibre-optic cables can also be created.

Inspired by Einstein

All of these experimental advances were largely inspired by the questions that Einstein originally raised. In the early 1960s, for example, the Irish physicist John Bell tried to find a way of showing that the notion of hidden variables could remove the randomness of quantum mechanics. These hidden variables might, for example, provide values for all components of the polarization of a photon at all times and dictate whether it is left or right circularly polarized.

In 1964 Bell therefore proposed a famous experiment that would give one result if quantum mechanics is correct and another result if hidden variables are needed. As it turned out, hidden variables were pretty much ruled out first by experiments carried out by Stuart Freedman and John Clauser in 1972 at the University of California at Berkeley and later by a comprehensive series of high-precision tests using atomic-cascade emission by Alain Aspect and co-workers at Orsay near Paris in the early 1980s.

Thanks to the high quality of the crystals used for parametric down conversion it is now possible to observe entangled particles that are separated by a distance of almost 10 km. None of these experiments supports the need for hidden variables, although we cannot be totally sure because they do not detect a big enough fraction of the total flux of photons. The ultimate experimental test would not only involve detecting a high proportion of entangled particles but also performing measurements so fast that any mutual faster-than-light influence can be ruled out.

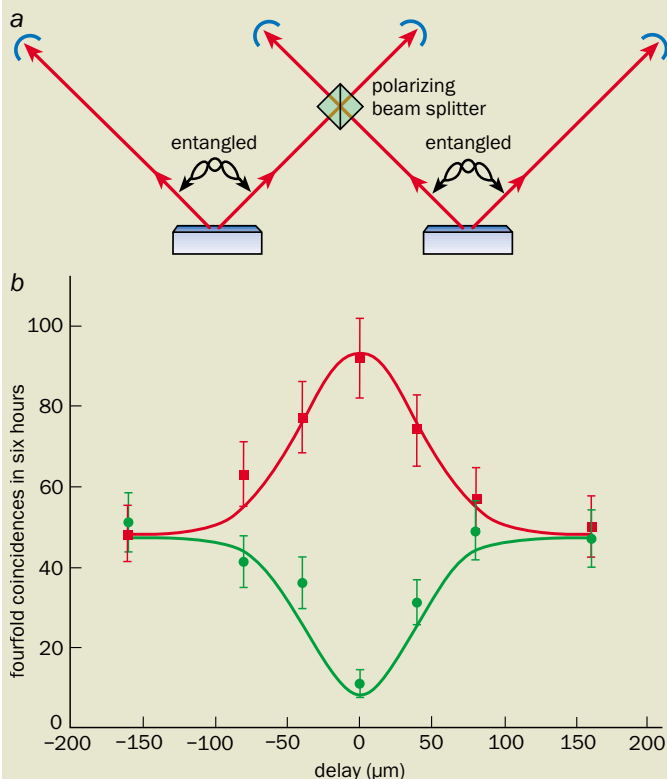
If and when this test is carried out, we will be able to say once and for all that nature is deterministic and local as Einstein believed – or whether he was wrong.

Entangling more particles

In recent years physicists have sought to entangle more and more particles at the same time. One reason for this interest is that multiparticle entangled states will be useful for quantum information. Such states can also refute EPR's arguments more directly – a fact that was first pointed out by Daniel Greenberger, Michael Horne and Anton Zeilinger in 1989.

In practical terms, complex, multiphoton entangled states can be created by firing high-power pump lasers at several parametric-down-conversion crystals, which simultaneously emit several pairs of photons. These photons can then be brought together using specially arranged semi-transparent mirrors and other optical devices. For example, Anton Zeilinger at the University of Vienna and colleagues have used this technique to entangle three, and later four, infrared pho-

2 Four-photon entanglement



This experiment shows how four photons can be entangled and measured. (a) The set-up consists of two crystals, each of which emits a pair of entangled photons. The two photons from each crystal are entangled – in other words they are in a superposition of being both horizontally polarized or both vertically polarized. Two of the photons – one from each pair – travel towards a polarizing beam splitter that is designed to transmit horizontally polarized photons but reflect vertically polarized photons. If these two photons reach the beam splitter at the same time – i.e. with zero delay – and if they leave the beam splitter in different directions, then all four detectors register a photon and observe a four-photon entangled state. (b) The graph shows the number of these “four-photon coincidences” over a six-hour measurement period for different relative distances between the two crystals and the beam splitter. Maximum interference occurs when both photons are overlapped at the beam splitter with exactly zero delay. To confirm that the photons are entangled a polarization filter is placed in front of each detector that can be at either +45° or –45°. The difference between the data when all filters are at +45° (red) and when one filter is at –45° (green) is proof of four-photon entanglement. The curves are a guide to the eye.

tons (figure 2). And last year Jian-Wei Pan and colleagues at the University of Science and Technology of China in Hefei even managed to observe non-classical correlations from five photons.

In addition, several groups of researchers are trying to increase the yield by entangling photons emitted by “quantum dots”. These are nanometre-sized islands of conducting material that confine electrons in three dimensions and therefore exhibit discrete energy levels, very much like atoms. Although no-one has yet succeeded, mainly because of inhomogeneities and distortions in the dots, I fully expect this to change soon.

The problem with these methods is that the probability of generating – and then observing – entangled photon pairs is very low. Indeed, the more photons you try to entangle, the less chance you have of creating them. However, novel crystals, better laser systems and improved optical resonators to tailor the emission will boost the number of entangled photons further and allow such systems be used for multiparty communication.

3 Entangling ions



Ions can be entangled using a linear chain of them that have been trapped in the electric field between a pair of elongated electrodes. This photo shows the experimental set-up used to trap calcium ions at the University of Innsbruck.

FERDINAND SCHMIDT-KALER AND RAINER BLATT, INSTITUTE FOR EXPERIMENTAL PHYSICS, UNIVERSITY OF INNSBRUCK

at the University of Innsbruck in Austria. Currently the most advanced way of entangling quantum particles is to use a linear chain of ions that have been trapped in the electric field between a pair of elongated electrodes. At room temperature the ions oscillate vigorously back and forth along the chain. However, using the technique of “laser cooling” it is possible to slow down the ions so that they end up near to absolute zero. Lasers can then be used to excite the atoms so that they move in tandem. This collective centre-of-mass oscillation has the energy of a single quantum of motion, known as a phonon.

The key points about this experiment are that it is then possible to excite the phonon by letting any ion in the chain interact with a laser beam and that subsequent interactions depend on whether the phonon has been excited. The quantum state of an ion can therefore be transferred to the quantum state of motion. Since its excitation is simultaneously shared with all the other ions, another laser beam can then be used to entangle a second ion with the motional state of the chain. Finally, that state can be transferred back to the first ion, which leaves the two ions entangled. Manipulating the quantum states in this way can be viewed as the application of a quantum logic gate, which is the basic component of a quantum computer.

In 2003 Ferdinand Schmidt-Kaler, Rainer Blatt and co-workers in Innsbruck entangled up to three ions by carrying out the controlled-NOT (CNOT) operation, which corresponds to the XOR gate operation of a classical computer. The Innsbruck team trapped calcium ions (figure 3) and used focused laser beams to manipulate two particularly long-lived electronic states of each ion. These two states – and any superposition of them – carry the quantum information of the ions. The advantage of the technique is that it could, in principle, be modified to include many more ions, provided that the total time to engineer the states is less than the decoherence time. This time is a measure of how fast entanglement is lost, which occurs, for example, when the ions scatter off any residual atoms in the ultra-high vacuum of the trap.

Last year a group led by David Wineland at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, used a slightly different approach to entanglement that does not require ground-state cooling and is less sensitive to experimental imperfections. In this experiment a pair of beryllium ions is exposed to two laser beams simultaneously. The beams apply an oscillating force to the ions – but only if they are in specific internal electronic states. This “state-dependent” coupling is what is needed to achieve entanglement. The NIST group is now trying to use this approach to entangle more ions by developing a “multitrap” architecture where ions are physically moved between memory and processing segments of a large trap.

Entanglement on a grand scale

But if you want a truly large number of entangled atoms, a group led by Immanuel Bloch at the University of Munich (now at the University of Mainz) has found the way forward. In an experiment reported last year, Bloch and co-workers began by creating a dense, ultra-cold gas of rubidium atoms in which all of the atoms were in the same quantum state – a Bose–Einstein condensate. They then transferred about 10 000 of these atoms to an “optical lattice” – a periodic 2D intensity pattern that is formed where two standing waves

Engineered entanglement

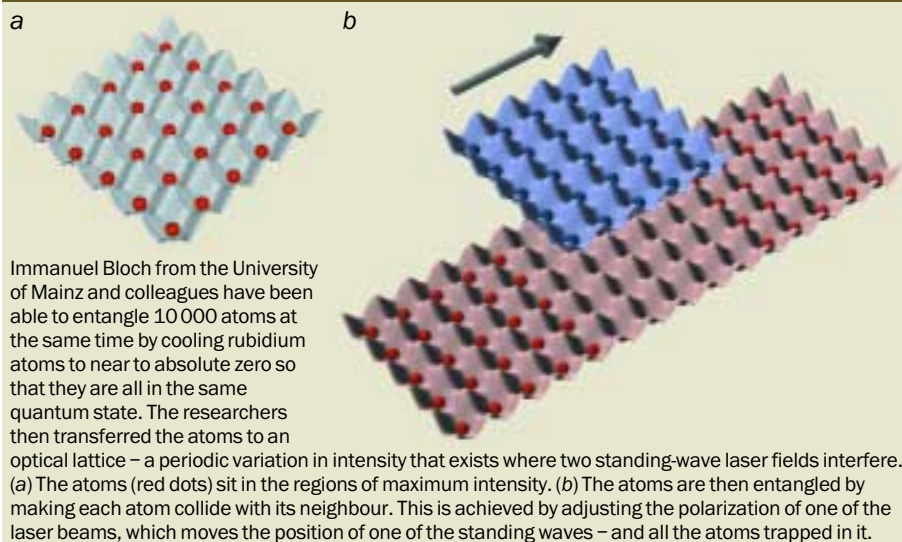
The experiments described so far generate entanglement using photons originating from an emission process. But we cannot deliberately engineer entanglement between photons because they interact so weakly. However, this process is possible with atoms – very much in the spirit of EPR’s proposal.

The first experiment to entangle three atoms was carried out in 2000 by Serge Haroche, Jean Michel Raymond, Michel Brune and colleagues at the Ecole Normale Supérieure in Paris. They used the electromagnetic field of a microwave resonator to mediate the interaction between three highly excited rubidium atoms. As an atom passes through the resonator there is a 50% chance of it dropping to a lower energy state and depositing a photon in the resonator. The resonator then contains either no photons or one photon, with the atom either in the excited or the lower state. This means that the atom is entangled with the field of the resonator.

The resonator is then detuned so that the next atom that passes through it only undergoes a phase shift if there is a photon already present. What this means is that if the second atom is prepared in a superposition of the two states, it is entangled both with the state of the resonator and with the first atom. The resonator is then tuned back to resonance so that when a third atom passes through it all three atoms are entangled with each other – but not with the resonator. The problem with this method is that the atoms come randomly out of an oven, which means that the chance of detecting a certain number of entangled atoms within a given time again falls rapidly with number.

The solution to this problem is to first capture a controlled number of atoms and only then let them interact with each other. Ideas for performing such experiments have been developed over the last 10 years, mainly by Ignacio Cirac and colleagues at the Max Planck Institute for Quantum Optics in Garching, Germany, and by Peter Zoller and co-workers

4 Atomic entanglement spreads its wings



at 90° to each other interfere (figure 4). The atoms sit in a regular array at every position of maximum brightness, a bit like eggs in an egg-box.

Since each atom can be put in two alternative quantum states, Bloch and colleagues therefore set up two different standing waves along one axis of the lattice. One wave trapped atoms that were in one quantum state, while the other trapped atoms that were in the other quantum state. The team then tweaked the polarization of one of the laser beams, which moved the position of one of the standing waves – and all the atoms trapped in it. Pairs of neighbouring atoms then approach each other and collide, but only if they are in one of the four possible distinguishable states. However, by preparing the atoms in a superposition of their two quantum states, Bloch's team ensured that all the atoms collided and became entangled in a common quantum state.

The main experimental difficulty is to measure the properties of each of the atoms separately. Bloch's team used light with a wavelength of 780 nm, which led to a lattice spacing of only 390 nm – too close to resolve each of the atoms. But by exciting all the atoms simultaneously and then observing their fluorescence, it was shown that many of them had formed one huge entangled state – ideal for quantum computation (see Bloch in further reading).

What's next?

A long time has passed since Einstein, Podolsky and Rosen's seminal work of 1935. But in recent times – and the last 15 years in particular – physicists have made significant headway in understanding the fascinating non-classical features of entangled states and in creating entangled quantum systems experimentally. Physicists have learned about the variety and power of entangled states, and found ways of engineering these states very much in the spirit of EPR's original prescription. The work opens the door to new methods of quantum communication and quantum information processing, and to improved high-precision measurements.

New ways of entangling particles are being reported almost every month. Entanglement has, for example, been observed between macroscopic systems, such as clouds of atoms or bright pulses of light. In the case of a cloud of atoms, the col-

lective spin of the atoms become entangled with the spin of atoms in another cloud in a separate glass cell (see Polzik in further reading).

Entanglement has also been observed in solid-state systems. In 2003, for example, Yuri Pashkin and co-workers at NEC and the RIKEN research lab in Japan entangled two micrometer-size superconducting qubits (see Wendin in further reading). Each qubit is based on a superconducting loop with a transistor formed from a single "Cooper pair" of electrons. This results in charge qubits in which the two states (0 and 1) are defined by a lack or excess of these pairs. Although Pashkin's team only indirectly observed the effects of two-qubit entanglement, the work moves us a step closer to solid-state quantum information processing (see Mooij in further reading).

It is even possible to entangle two different types of particle, such as an atom and a photon. To pull off this trick you need an excited atom that can decay to two alternative ground states. Chris Monroe and colleagues at the University of Michigan in the US demonstrated this effect in 2004 by analysing the correlation between the polarization of a photon and a trapped cadmium ion. This research could lead to quantum processors that are connected to each other, just as conventional PCs are linked over the Internet. Another possibility is for the processors to be used as basic repeater stations or error-correction units for communicating quantum information over long distances.

Although Einstein's objections to quantum mechanics were never confirmed during his lifetime, physicists are now reasonably sure that what he stood for – determinism and locality – are not properties of nature. But until we have definite experimental proof, it is too early to say that he was wrong. Still, it is ironic that entanglement, which Einstein first highlighted in *objection* to quantum theory, is a real phenomenon that researchers can not only understand but also put to practical use.

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The other side of Albert Einstein

Einstein has attained iconic status as a scientist and humanist, but, as **Tim Chapman** discusses, he has also been labelled a plagiarist, a philanderer and an absent father

Einstein's standing as a scientific genius and cultural icon is second to none. His contributions to physics and his wider intellectual concerns have led to countless accolades: for example he was named "Person of the century" by *Time* magazine, and the greatest physicist of all time by *Physics World* at the turn of the millennium. But Einstein has also received his fair share of bad press in recent years.

The most widely publicized allegations have concerned Mileva Marić, his first wife. Marić, who was three years older than Einstein, was also a physics student, and rumours have spread since the early 1990s that she was the real brains of the partnership. The story reached its widest audience via a television documentary that was aired on public-broadcasting television stations across the US in 2003 called *Einstein's Wife* (see *Physics World* April 2004 p14).

Marić had come to general attention with the publication of love letters between her and Einstein as part of *Collected Papers of Albert Einstein* (Princeton University Press). The letters show that the two students discussed their work and planned to carry out research together, and that Marić supported her lover while he looked for work before they married in early 1903.

But did Marić collaborate on Einstein's groundbreaking papers of 1905, or even, as some critics claim, do the bulk of the work? John Stachel, director of the Center for Einstein Studies at Boston University and editor of the *Collected Papers* does not think so. "The fact there was nothing by Marić in her own name or co-signed with Einstein, either before she met him, while they were living together, or in the 30 years after they separated, I take as strong evidence that she never played a major creative role in his thinking," he says.

Marić did act as Einstein's assistant, checking his calculations and looking up data, but while he continued to discuss his work in his letters to her, she often did not reply in kind. "We have one of his most important letters about the electrodynamics of moving bodies (i.e. special relativity), and her response where she discusses everything else in his letter but that," Stachel adds. "There is no evidence she acted as anything more than a sounding board for his ideas."

Einstein's women

Einstein may not have cheated Marić of her place in physics history, but he was still far from the ideal husband. A year before they married Marić gave birth to a daughter,



Troubled relationship – Einstein was unfaithful to his first wife Mileva, but did he steal her ideas?

Lieserl, while Einstein was away. The child's fate is unknown, but it is presumed that she was given up for adoption, perhaps under pressure from Einstein, who is thought to have never seen her. After getting married, Mileva bore two sons, but the family did not stay together. Einstein began an affair with his cousin Elsa Löwenthal while on a trip to Berlin in 1912, leaving Mileva and his children two years later. Albert and Mileva finally divorced in 1919. After the divorce, Einstein saw little of his sons. The younger, Eduard, was diagnosed with schizophrenia and died in an asylum.

Einstein married Elsa soon after the divorce, but a few years later began an affair with Betty Neumann, the niece of a friend. By one account, Elsa allowed Einstein to carry on with this affair so that he could at least be open in what he was doing. That affair ended in 1924, but Einstein continued to have liaisons with other women until well after Elsa's death in 1936. He did not remarry.

Einstein enjoyed female company, and his intellectual celebrity would certainly have appealed to women in Berlin and, later, the US. The relationships rarely lasted, however. Usually once they were established Einstein cooled off and began to look elsewhere. Avoiding deep emotional ties in this way may have given him the solitude he needed to pursue his work, even if it meant him disregarding the feelings of the women in question.

Questions of precedence

In addition to allegations that he plagiarized the work of Marić, Einstein has also been accused of stealing ideas from Hendrik Lorentz and Henri Poincaré. Elements of Einstein's 1905 paper on special relativity paralleled parts of a 1904 paper by Lorentz and a contemporary paper by Poincaré.

Although Einstein read earlier papers by the two, he claimed not to have seen these later works before writing his first paper on special relativity.

A frequent criticism of Einstein is that this paper did not contain any references, which might suggest that he was consciously hiding his tracks. But Stachel is doubtful. "At the time, I do not think it was that unusual," he says. "There is no evidence that he ever consciously took from some source and neglected to mention it in order to get the credit himself."

Equally, there are questions over general relativity. One frequent accusation is that David Hilbert completed the general theory of relativity at least five days before Einstein submitted his conclusive paper in November 1915. There are marked similarities between the two men's work, and they did squabble for some time over primacy. But Stachel says that he and co-workers have found evidence that the first proofs for Hilbert's paper did not include the crucial field equations for general relativity. He says that these proofs were also based on Einstein's earlier rejection of the principle of general covariance, a central tenet of general relativity that shows that the laws of relativity hold for any inertial frame. Einstein's 1915 paper, in contrast, showed that relativity could be made generally covariant by adopting a new geometric model of space-time.

The man they love to hate

So why has Einstein attracted so much criticism? Stachel has identified three general reasons, the first being anti-semitism. Many of Einstein's early critics in Germany were allied with the then-dominant Nazi party, including Nobel-prize winner Johannes Stark, and many of these allegations continue to be recycled.

Stachel also points out that in recent decades some feminist critics have picked on Einstein in an attempt to show that women are under-represented in the history of science. "On the human aspect there is much criticism to be made of Einstein's attitude to a number of women in his life, and Mileva Marić in particular, but that does not mean the ideas came from her or she was a great scientist," Stachel says.

Finally, according to Stachel, there is simple iconoclasm. The physics community, in promoting Einstein as a kind of secular saint, has to take some of the blame. "Too much of an idol was made of Einstein," Stachel says. "He is not an idol – he is a human, and that is much more interesting."



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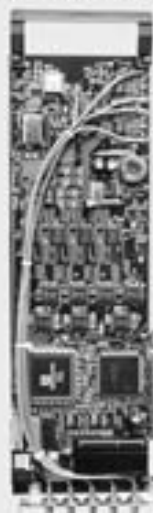
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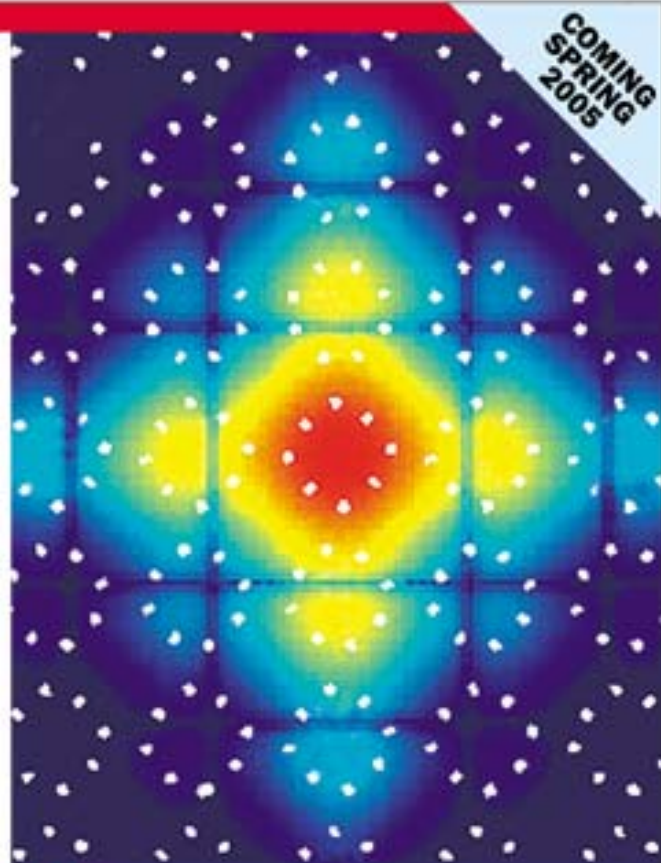
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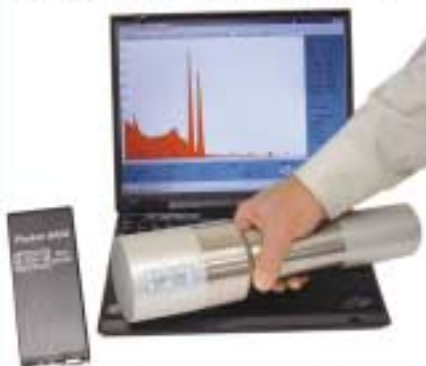
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Collaborating for the future



The king is dead. Long live the king!

There is the Einstein who grew up, worked and died, but there is also the Einstein who became the public face of science. **Robert P Crease** explains the difference

In his classic work *The King's Two Bodies: A Study in Medieval Political Theology* the historian Ernst Kantorowicz examined the development of the political doctrine that distinguished between a monarch's natural body and his or her political body. Whereas the monarch's natural body is mortal – it lives, breathes, becomes ill and dies – the political body, which is the embodiment and representative of the state, is immortal. Yet somehow the two bodies comprise a single unit in making appointments, conducting wars and signing treaties. The paradox is encapsulated in the expression, “The king is dead. Long live the king!”

Einstein has such a great and enduring cultural visibility that it is tempting to try to understand him in similar terms. He had a natural body that emerged into the world one day in March 1879, matured, and passed out of the world in April 1955, his ashes dispersed by the currents of the Delaware river. But Einstein also has another kind of body – it is too dynamic and influential to be called an icon – that is as alive as ever half a century after his death. It features in magazines, movies, novels, the arts, advertisements, commercials, cartoons, and in just about every niche of popular culture, including “Baby Einstein” toys. It also features prominently in the minds of professional physicists.

The king's political body – symbol and agent of the realm – was officially defined, generally sought-after, and often a struggle to maintain. Einstein's political body was thrust upon him, and he was ambivalent about it. As he once wrote to a friend, “Take pleasure that only a few care about you and, believe me, it has a good side. Better an understanding spectator than an electrically illuminating actor”.

Einstein's political body continues to represent science itself. Like that of the king, it is linked in some way with his private body.

Uniting the bodies

Scientists generally prefer to separate Einstein's two bodies; after all, his scientific work is what is important. Indeed, anyone who tries to tether a scientist's work and personality can get their fingers burned, as Robert Oppenheimer once found to his cost. Having previously worked with Einstein at the Institute for Advanced Study in Princeton, Oppenheimer was invited to give a talk at a UNESCO conference that was held in Paris in December 1965 to mark the 10th anniversary of Einstein's death.

The occasion called for polite words about Einstein's political body. But Oppenheimer



More than a physicist – this statue of Einstein sits at the National Academy of Sciences in Washington, DC.

chose instead to speak about Einstein's background and its limitations, pointing out that in his later years Einstein worked all by himself on what many considered to be a fruitless quest – a unified field theory. Although this was something that many scientists had said privately for years, they had never openly admitted it at a public event. Some colleagues were furious. Wounded, Oppenheimer declined an invitation to speak about Einstein a few weeks later.

The public, however, is not content to separate the two bodies, and is endlessly fascinated by information about Einstein's private body and its relation to his political one. Where did Einstein get his ideas? How did he treat women? Was he a good parent? What were his views on the Jewish people? Vegetarianism? World peace?

The craving for answers to such questions can elicit what may seem to be excessive responses from those able to satisfy it. Consider, for instance, the tone of *The Private Albert Einstein*, a book written by Peter Bucky, the son of one of Einstein's close friends. In the opening chapter Bucky claims to have known Einstein probably “as intimately as did any other man on Earth”. He goes on to provide us with reminiscences of Einstein's early-morning “jolly whistling...echoing in the bathroom”, of the smells of “the not unpleasant aroma of his pipe tobacco”, of Einstein's clothes, eating habits, picnics and other things that make for irresistible reading but seem to shed little light on his science.

Scientist or symbol?

But is Einstein's political body really a scientist, or is it a mere symbol of science, like the flag of a country? Does it not clean up

and oversimplify the complex and messy process of real science? As the French intellectual Roland Barthes once pointed out, photographs of Einstein – i.e. of his private body – generally show him next to a blackboard covered with equations, while popular images generally depict him next to a clean blackboard with only one equation, $E=mc^2$, as if giving birth to it were that simple. This might be fine for science museums and children's textbooks, but is it at the cost of abandoning real science?

This distance between Einstein's political body and Einstein the working scientist is cleverly parodied in a new musical called *Einstein's Dreams: A Musical Romance*, a version of which will be performed at the Prince Music Theater in Philadelphia next month. Based on the best-selling novel by the physicist Alan Lightman, the musical includes a scene in which Einstein, the private body, explains $E=mc^2$ to his friend Michele Besso, who was an engineer, and a later scene in which Einstein the political body appears at a news conference. Forced to speak about the equation, he stammers and cannot do it. “*E equals...E equals something, I'm fairly sure,*” Einstein blurts out, “and whatever it equals I'm sure it's important.”

It is therefore tempting to dismiss the significance of Einstein's public body as having nothing to do with science. But that would be a mistake. For it plays an important role in the interaction between scientific and popular culture.

When two cultures interact, they never engage each other simultaneously at all levels. Rather, they meet through what ethnographers call “congeners” – little lenses through which one culture looks at, tries to understand, and responds to the other, accompanied by deepening curiosity and interest. A congener is thus more than something that symbolizes or denotes another culture; it crystallizes an interaction with it.

Einstein serves, in effect, as a congener. He is the means through which many non-scientists acquire more than a superficial understanding of science; he is the conduit through which they become acquainted with key theories, individuals and events in science history. The frontier between science and the public needs more such congeners.

Albert Einstein is dead. Long live Einstein!

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Einstein's quest for unification

The last 30 years of his life were spent on a fruitless search for a unified field theory, but as **John Ellis** explains, Einstein put this “holy grail” of modern physics on the theoretical map

The definitive scientific biography of Einstein, *Subtle is the Lord...*, which was written by Abraham Pais in 1982, delivered an unequivocal verdict on Einstein's quest for a unified field theory. Pais wrote that the time for unification had not come, and that Einstein's work “led to no results of physical interest”. But a lot of water has flowed under the bridge of unification since then, allowing us to look back with perhaps more indulgence as we celebrate the centenary of Einstein's 1905 papers.

Let us briefly recall the relevant physics that was known in the 1920s, when Einstein embarked on his quest. The only known subatomic particles were the proton and the electron: the neutron and the neutrino, for example, were not predicted or discovered until the 1930s. Most “fundamental” physicists were striving to understand quantum physics – an endeavour from which Einstein stood apart. The structure of the nucleus was regarded as an interesting but secondary problem, and the unification of forces was considered, in the words of Pais, a minor issue.

For Einstein and his few unification-minded colleagues the big issue was to unify general relativity – a theory of gravity – with Maxwell's electrodynamics. Theodor Kaluza and Oskar Klein proposed starting from a 5D theory, which contained an extra



Ahead of his time – Einstein's last blackboard in Princeton.

that his unification papers were not always ground breaking. For example, after some initial confusion he recognized that the two papers he wrote in 1927 were equivalent to the work of Klein. But he might have been happy to know that some of today's particle physicists will search for Kaluza–Klein excitations using the Large Hadron Collider

all the components of the electric and magnetic fields. Indeed, none of Einstein's unification attempts ever reproduced the free-field Maxwell equations. In Einstein's defence, it should be mentioned that we now recognize that other types of antisymmetric tensor fields emerge naturally from string theory. However, this type of theory had not been invented in Einstein's day.

A more basic problem with many of Einstein's proposals was that they did not include the general theory of relativity itself. However, in his final years following 1945 he returned to a theory with a fundamental tensor that was not symmetric and would include both the metric and the electromagnetic tensor, which avoided some of these problems.

“Einstein's true dream of unification still eludes us.”

“compactified” spatial dimension in addition to the three spatial and one temporal dimensions of everyday experience. Electromagnetism then emerged naturally from this extra dimension.

Perhaps more so than Pais, we now recognize these early theories as breakthroughs in unification because of their many echoes in the supergravity and string theories of the past 20 years. Einstein was an early enthusiast; as he wrote to Kaluza in April 1919, “The idea of achieving unification by means of a five-dimensional cylinder world would never have dawned on me... At first glance I like your idea enormously”. Kaluza published his idea in 1921, which Einstein pursued in his first unification paper with Jacob Grommer the following year. Indeed Einstein was to return to 5D theories every few years for the rest of his life.

However, even Einstein had to admit

at CERN. Einstein had hoped to identify quantum fields with such higher components that only arose in the 5D theories.

Generalization

Another recurring theme in Einstein's quest for unification was to generalize the “metric” of relativity – the symmetric tensor that describes the curvature of space–time – so that it could also describe the electromagnetic field. He pursued many apparently blind alleys, such as asymmetric generalizations of the metric, and even postulated that there might be no tensor at all. As Einstein himself said in a letter to Klein in 1917, “this process of deepening the theory has no limits”.

Unfortunately, these ideas were unsuccessful. For example, in his first unification paper in 1925 the antisymmetric part of his tensor field was not suitable for describing

No stone left unturned

It is difficult to accuse Einstein of leaving stones unturned – no matter how unpromising they might appear. For example, in the early 1940s he even toyed with the idea that nature might not be described by partial differential equations. Modern theorists can hardly be accused of excessive conservatism, but even they have not revived this startling speculation!

What is most impressive about Einstein's quest for unification was his persistent indefatigability. He tried many different ideas, and often returned to earlier theoretical haunts, such as Kaluza–Klein theories, with something new to say. However, the truth is that he was adrift from many of the most

important developments in physics at the time. For instance, he was famously sceptical – if not downright hostile – towards quantum physics, and he does not seem to have followed closely the discoveries of new particles and interactions. More surprisingly, perhaps, he seems to have missed out on some of the most far-reaching new theoretical ideas of that period, which now play key roles in modern approaches to unification.

For example, Einstein recognized Hermann Weyl's seminal 1918 work on scale transformations in four dimensions, even paying it the backhanded compliment that “apart from the agreement with reality, it is at any rate a grandiose achievement of the mind”. Weyl's ideas led to the discovery in the late 1920s of local phase transformations, which laid the foundations for the gauge theories of the weak and electromagnetic interactions in the 1950s and beyond. However, Einstein was never involved personally in these far-reaching developments.

He also seems to have been affected by frequent mood swings during his quest for unification. On several occasions he switched rapidly from unwarranted optimism about the prospects of a new idea to complete rejection. More alarmingly, his mood often swung in the full glare of publicity. For many years a new scientific paper by Einstein was a major public event, with hun-

dreds of journalists hanging on the utterances of the great man. The closest present-day parallel would be Stephen Hawking and his recent comments on black holes and quantum mechanics.

Einstein's legacy

Why were Einstein's papers on unification not more successful? It is surely insufficient simply to say that only young theorists have brilliant new ideas. The many distractions of fame in his later years should also not get all the blame. Einstein himself wrote in his early years that “formal points of view...fail almost always as heuristic aids”. But later he seems to have abandoned this insight in his quest for unification, and instead was seduced more by mathematical novelty than by physical intuition.

It could be, however, that Einstein was simply ahead of his time, since even if he had been following contemporary physics more closely, the information available before his death was probably insufficient to make significant progress in unification. For example, the unification of the weak and electromagnetic interactions in the 1960s required many unforeseen experimental discoveries as well as new theoretical ideas. Even now, the unification of gravity with the other interactions – which was Einstein's true dream – still eludes us.

Following Einstein, most theoretical physicists assign a central role to geometrical ideas. Most of the particle-physics community believes, for example, that string theory provides the appropriate framework for realizing Einstein's dream. Here, fascinating generalizations of Kaluza and Klein's hidden dimensions, such as “Calabi–Yau manifolds”, are able to dispose of the several extra dimensions required by the theory. However, not all general relativists are convinced, and there is absolutely no experimental evidence for string theory. Are we also in danger of being seduced by formal beauty?

Although some of the unification ideas pursued by Einstein are now recognizable in developments such as string theory, this is not to say that Einstein's work actually inspired these modern unification attempts. It seems to me that the real significance of Einstein's quest for unification lies in its quixotic ambition. Einstein, more than any of his contemporaries, put unification on the theoretical map and established it as a respectable intellectual objective. Even if we do not have all the necessary theoretical tools or experimental information, unification is the “holy grail” towards which our efforts should be directed.

John Ellis is in the Theory Division at CERN, Geneva, Switzerland, e-mail john.ellis@cern.ch

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How to be a patent attorney

Einstein may have spent his days at the patent office in Bern thinking about relativity, but what is life really like in the patent world today? **Simon Mounteney** reveals all

A few years ago I visited a client in Yorkshire with a freshly qualified barrister, who was shadowing me in order to learn more about the patent system. Over lunch, my client referred to me as a “patent lawyer” and our learned friend simply could not resist interjecting. Putting on her most earnest face, she sagely informed my client that “whilst Simon *does* know a lot about patent law, he is *not* a patent lawyer”.

My client, whom I had been advising on patent law for over 12 years, did a fairly good job of keeping a straight face. I could have said something, but I resisted. Even allowing for the fact that “lawyer” is a colloquial term, she was basically correct. A patent attorney is not a lawyer – or a scientist, or an engineer, or a business person, or a teacher, or a manager, or a linguist, or a negotiator, or a mediator. Most of us are a mixture of all of these things and need all the associated skills. It is this combination that gives many patent attorneys a buzz and makes our lives a real challenge.

Career options

I must confess that I did not know all this when choosing my career. Like many others, I came to the patent profession by accident. Back in 1988, during the final year of my physics degree at the University of Reading, I knew only that I wanted to broaden my horizons yet still use my degree in my work. I had not even heard of the patent profession when I started looking for jobs, although this is nothing to be ashamed of because there are only about 1500 patent attorneys in the UK. However, as soon as I had opened the file in the careers library labelled “patents”, I knew that I was on to something.

I quickly learned that a patent is essentially a bargain in which a government grants a monopoly on an invention, provided that the owner of the invention discloses it in such a way that it can be used after the patent expires. I realized for the first time that an “invention” is not just a gadget, but anything that is new and solves a problem in a technical way. I also learned that many patents involve complex physics.

The file explained that this meant that scientific knowledge is often required to understand and analyse these inventions and that physicists could therefore become patent attorneys (representing the applicants) or patent-office examiners (representing the government). The file also mentioned that science graduates could find careers as barristers and solicitors specializing in intellec-



Rewarding life – become a partner in a firm of patent attorneys and you could earn a six-figure salary.

tual-property law. However, I realized that I wanted to become a patent attorney, which would provide me with much more day-to-day contact with inventors.

After a bit more research, I discovered that some patent attorneys work for industrial companies that wish to secure patents on their technology. Others prefer to join patent agencies, where they are hired by others to act on their behalf. Private practice appealed to me because I liked the idea of acting for and advising clients. So after writing to about a dozen firms, I landed a position with Marks and Clerk. It is the largest firm of patent attorneys in the UK, employing over 500 staff at 12 offices around the country and six overseas. I have been working there ever since.

Learning the ropes

As is commonly the case, I started my career under the wing of one of the partners and received a rigorous training not only in law, but also in drafting and interpreting patent specifications, advising clients and developing the business itself. The training, which lasted a total of five years, was very much on the job, although I also attended the occasional study course and regularly had my nose in books during the evening.

Some would argue that communication – and particularly the ability to write good English – is the most important part of the job. Whether or not this is correct, it is certainly very high up the list, because the

strength and scope of a patent are determined entirely by the way its specification is written. Getting that right requires a profound understanding of the inventor's objectives, which can only be understood by building a good relationship with them. My supervising partner said that I had to learn to be a “surgeon with words”, and my experience suggests that he was spot on.

My training also exposed me to a variety of inventors. Some were private clients beavering away in garden sheds and garages, but the vast majority were highly able scientists and engineers operating at the forefront of their fields. I therefore had to acquire a lot of new science and engineering knowledge, and rapidly get to grips with a range of new technologies. I also had to become familiar with other types of intellectual property law, including trademarks, designs, copyright and unfair competition.

In particular I learned a lot from pitting my wits against examiners at the UK Patent Office. They are a supremely capable and knowledgeable group of people – do not forget that Einstein spent seven years as a patent examiner in Switzerland. While we patent attorneys want to secure a patent with the widest possible commercial scope for our clients, examiners want to ensure the patent does not extend any further than is legally appropriate. Much of my time is therefore spent submitting arguments outlining why I think the examiners are wrong or filing amendments to their objections.

Being examined

One of the downsides to becoming a patent attorney is the exams. They are far from easy and few people sail through them, despite the fact that a very high proportion of patent attorneys have a degree from one of the leading universities and/or a PhD. I had to take "foundation" exams after a year, UK qualifying exams to become a chartered patent attorney after three years, and European exams to qualify as a European patent attorney a year after that. The last qualification gave me the right to act before the European Patent Office.

The UK exams test your legal knowledge in situations involving new technology, as well as your ability to write patent specifications and interpret the language used in specifications in order to determine the scope of the monopoly that they afford the patent. You also get tested on your ability to decide whether – and to what extent – a patent is valid and whether anything infringes it. The European exams are similar, but one of the papers also requires an ability to read technical documents in French or German. Luckily I had O-levels in both languages, although I also took three years of German lessons that my firm provides for its employees. Reading is, of course, a lot easier than speaking, and you are allowed to take a dictionary into the exams.

After qualifying, I spent several years building relationships with clients and developing the skills that I had learned during my training. I handled a wide variety of technologies, including radio communications, cryptography, gas turbines, optoelectronics and semiconductor devices. About eight years after joining the firm I became a partner and was appointed an "equity partner" (i.e. owner) of the firm a few years later.

Partnership brought many new challenges and experiences. I was suddenly involved in running a business, albeit in a slightly peripheral role at first. I started travelling overseas on a regular basis, mainly to Asia, to manage relationships with some larger clients, which included Samsung Electronics and Alstom Power. I started handling cases that were more complex and commercially important. I also began training other people.

I am now head of the "electronic arts" team in the London office, which covers any technologies based on physics, electronics or computer science. It also handles most of the patent work relating to the protection of business methods. There are 30 people in the team, many of whom are physicists. My job involves managing staff on a day-to-day basis and developing a business unit that turns over more money than quite a few companies. I have also recently been appointed to the firm's board of management.

This is a whole new challenge in itself – particularly since my main remit is marketing and business development.

Financial risks and rewards

Patent attorneys are well rewarded financially. Trainees earn about £25 000–30 000, while most partners earn six-figure salaries at an early stage, with substantial increases thereafter. But there are risks associated with those rewards: partners will have invested a lot of their own capital and could literally lose everything they own if a negligence action goes against them. They are therefore likely to have very keen business minds.

Despite the time that I now have to devoted to other aspects of the firm, I still spend most of my day working on professional matters. That means helping clients to protect and exploit their inventions, which in turn means understanding, analysing and applying physics. I am still very much a physicist – I just happen to have a career that requires me to turn my hand to a lot of other things. If you want to use your physics degree yet move off the more commonly beaten track, I cannot recommend life as a patent attorney highly enough.

Simon Mounteney is a patent attorney and partner at Marks and Clerk, London, e-mail smounteney@marks-clerk.com



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Once a physicist...



This month we feature **Wolfgang Heckl**, who is the new director-general of the Deutsches Museum in Munich, Germany. He was previously a physicist at the Ludwig Maximilian University of Munich, where he led an interdisciplinary research team in nanotechnology. Last month he won a 2004 Descartes prize for science communication (see page 5).

Why did you originally choose to study physics?

Because my high-school physics and maths teachers were outstanding. Good guys must do good things, I thought. And having been brought up in the Bavarian countryside, I was fascinated by the natural world. It therefore seemed logical to me to study all aspects of the natural sciences – biology, chemistry and so on – that I was most interested in. I also had a boyhood fascination for electronics and astronomy – I even used to build my own equipment. I loved watching Carl Sagan on TV.

How much did you enjoy your research?

What I liked was playing around and solving riddles, rather than carrying out long data-mining procedures. However, I did enjoy my research a lot and will continue to do a small amount of it at the Deutsches Museum on scanning-probe microscopy. Indeed, since the museum was founded in 1903 its staff have had a duty to not only collect and display artefacts but also to carry out research. I will therefore bring my students to the museum to collect original data, the idea

being to display the results of this research and – most importantly – discuss the process of research itself. This new Deutsches Museum project is called “Open Science”.

What made you decide to join the Deutsches Museum?

The decision was easy. The Deutsches Museum is the world's most renowned museum devoted to science and technology. So to become director-general is a dream job. It also lets me expand on my vision of becoming a “Renaissance man” – someone who can understand not only one single subject, but also get an integrated view of the whole of nature. Can you think of a better place to do that than the Deutsches Museum? Moreover, I have a collector's gene in my blood, having collected radios, natural objects, minerals and old scientific books since I was a boy. I also have in my two homes a private museum of “techniquities” – the literal translation of a word I created in German to describe technological antiques.

How will the museum be celebrating the work of Einstein this year?

From 5 May until the end of the year we will be hosting a major exhibition called “The Adventure of Discovery: Albert Einstein and 20th Century Physics”. Through exhibits, hands-on experiments and computer simulations, visitors will be able to explore how Einstein developed relativity and quantum theory, and show how he was inspired by his work on technical problems at the Swiss patent office. It will also tell the story of Einstein's life and put his scientific work in its political, cultural and historical context.

● www.deutsches-museum.de

Movers & shakers

Stephen James, Geoff Ashwell and Ralph Tatam from the Centre for Photonics and Optical Engineering at Cranfield University are among the winners of this year's National Measurement Awards from the UK Department of Trade and Industry. They won the “frontier science and measurement” prize for developing a method of covering optical fibres with single layers of organic molecules. Such fibres could be used as sensors.

Other winners of the awards include materials scientists at Oxford University led by **George Smith**, along with researchers at Oxford nanoScience, who scooped the “innovative measurement” award for building a “3D atom probe”. The device consists of a field-ion microscope to visualize individual atoms on the surface of a solid, a mass spectrometer to chemically identify individual atoms, and a position-sensitive detection system to locate atoms with sub-nanometre precision.

Four physicists have each scooped €1.2m to set up new research groups in Germany. They were among 11 winners of the Alexander von Humboldt Foundation's Sofja Kovalevskaja prizes. The money, which comes from the German government, is designed to let scientists who are based abroad to spend up to four years in Germany. The winners include astrophysicist **Yanbei Chen**, who will move to the Max Planck Institute for Gravitational Physics in Potsdam, **Michal Czakon** (theoretical particle physics, Würzburg University), **Jian-Wei Pan** (atomic physics, Heidelberg University) and **Eckhard von Törne** (experimental particle physics, Bonn University).

The 2004 Mullard award of the Royal Society has been given to **Jeremy Baumberg** of the University of Southampton for his work in nanoscience and nanotechnology, and for helping to set up the firm Mesophotonics, which uses photonic crystals to make new optical devices. The £2000 award is given each year to a scientist with an outstanding academic record whose work could contribute to the UK economy. An article detailing how Mesophotonics was founded appeared in *Physics World* last year (June pp39–40).

Michael Foale, the British-born astronaut who studied physics at Cambridge University, has been appointed NASA's deputy associate administrator for exploration operations. He will advise the agency on various near-term aspects of its “vision for space exploration”, which aims to send humans to the Moon by 2015 and to Mars by 2030.

Adrian Sutton from Oxford University has been appointed head of condensed-matter theory and professor of nanotechnology in the Department of Physics at Imperial College, London.

Careers update

Fame beckons for scientists

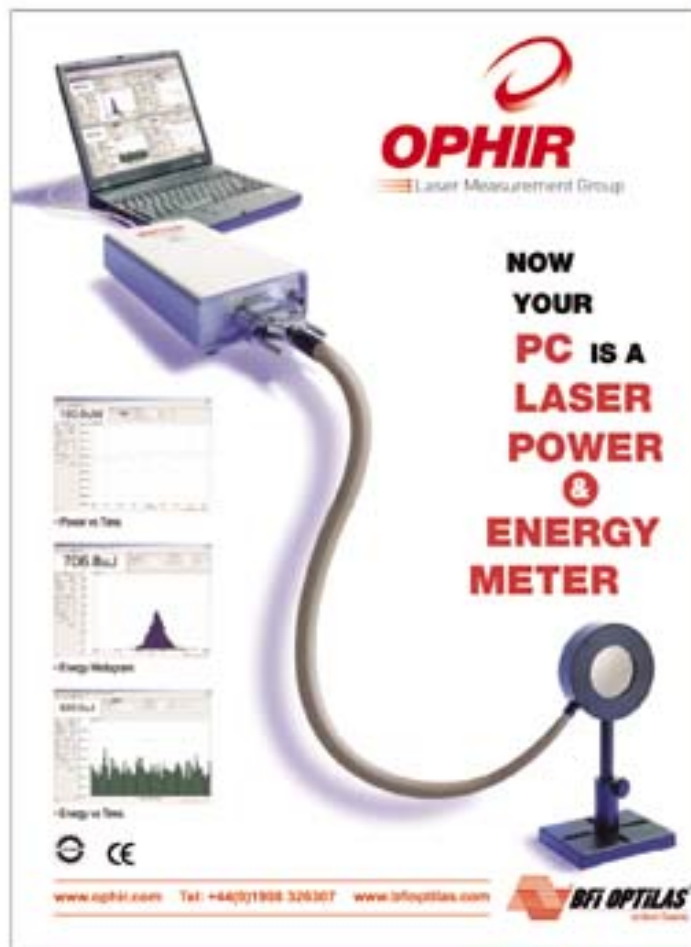
So you think you have what it takes to get people excited about science? Then why not take part in FameLab – a new competition to find the UK's best new science communicators? Simply turn up at one of six regional heats and give an “entertaining, original and exciting” talk – lasting no longer than five minutes – on any aspect of science. Heats will take place in Manchester (12 March), Bristol (19 March), Cardiff (2 April), Glasgow (9 April), London (14 April) and Belfast (16 April). The 12 winners will progress to a final at next year's Cheltenham Festival of Science, which runs from 8–12 June. The overall winner will receive a cash prize of £2000, appear on Channel 4 and go on a tour of public events. Two runners-up will each get £750 and two speaking engagements.

● www.famelab.org

Students show less desire for US

The number of overseas students studying at universities in the US has fallen for the first time in over 30 years. According to the *Open Doors 2004* report from the Institute of International Education in New York, the total number of international students fell by 2.4% to 573 000 in 2003/04. Most of the decrease was at undergraduate level, where numbers fell by a total of 9%. Graduate enrolment, however, rose slightly by 2.5% across all subjects and by 3.3% in the physical sciences. The institute attributed the overall decline to real and perceived difficulties in obtaining student visas, rising US tuition costs, vigorous recruitment activities by other English-speaking nations, and perceptions that international students are not welcome in the US. Despite this year's fall, the total number of international students in the US is still far higher than the last decline in 1971/2, when numbers dropped by 3% to 140 000.

● opendoors.iienetwork.org



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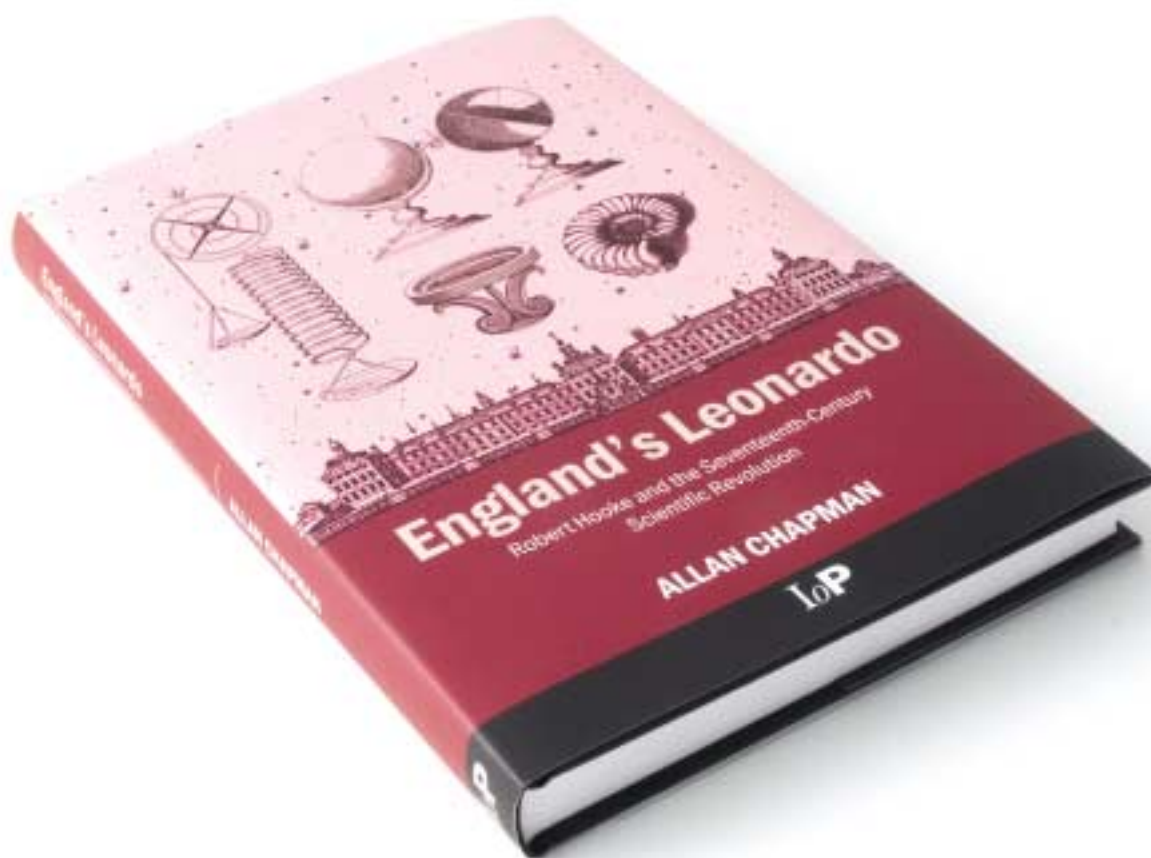
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Further information about Swansea and our research can be found at <http://www.swansea.ac.uk/physics> or by contacting Professor Simon Hands (s.hands@swan.ac.uk)



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PROFESSORSHIP OF APPLIED PHYSICS

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- Atmospheric, Environmental and Aerosol Physics
- Applied Optics, Photonics and Lasers
- Astronomy & Astronomical Instrumentation

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Information on the Department of Experimental Physics is available at: <http://www.physics.nuigalway.ie>

For informal discussion, please contact: Dr. G.P. Morgan, Dean of the Science Faculty; Tel: +353-91-750370 or Email: dean.science@nuigalway.ie

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National University of Ireland, Galway,
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Postdoctoral Research Associate

Ref: PHY/CV/196

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Ref: PHY/CV/204

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Informal enquiries may be made to Dr Apostolos Pilaftsis, tel: +44(0)161 275 4216, e-mail: pilaftsi@theory.ph.man.ac.uk.

Applications for the above, marked 'Confidential - Staff Application', including a full curriculum vitae, a list of publications, a brief description of research interests and the names of three referees should be addressed to Dr Apostolos Pilaftsis, School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester M13 9PL or by fax to +44 (0)161 275 4218. The closing date for applications is 10 January 2005. Please quote reference number above.

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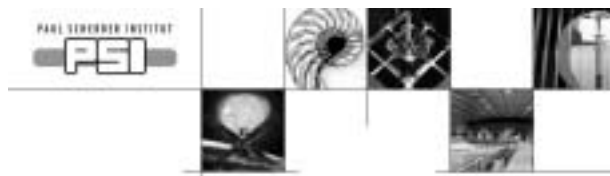
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RGA-6



2 March 2005

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Institute of Physics

Research Assistant

Ref: 04/W232A

School of Mathematics and Physics

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Closing date: 4.00pm, Friday 17 December 2004

Please visit our website to download the application pack - www.qub.ac.uk/jobs or alternatively contact the Personnel Department, Queen's University Belfast, BT7 1NN. Telephone (028) 90973044 or (028) 90973854 (answering machine). FAX: (028) 90971040 or e-mail on personnel@qub.ac.uk

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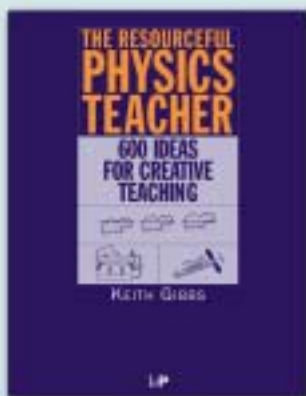
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The Centre is supported by a wide range of UK Photonics companies, including BAE Systems, NPL, Renishaw, AWE, OptoSci, Unipath, and Qinetiq.

For further information and an application form, contact
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Please submit your application, Curriculum vitae, and brief description of research interest to Prof. Alexei Kamshilin, Department of Applied Physics, University of Kuopio, Savilahdentie 9, 70211 Kuopio, Finland, phone +358-17-162-561, fax: +358-17-162-585, E-mail: Alexei.Kamchiline@uku.fi.

Deadline for applications is January 20, 2005.



School of Physics & Astronomy

Lecturers in Theoretical Particle Physics (Two posts)

As part of a new initiative and commitment to excellent research in particle physics, applications are invited for the above posts in the School of Physics and Astronomy.

The particle theory group being established at Nottingham, under the leadership of Professor E Copeland, will focus primarily on "The Physics of the Early Universe" and ways of constraining models with current observational data. For example, the exciting areas of Dark Energy, particle cosmology and M-theory cosmology will be part of the group's research profile. The group will develop close links with both the Astronomy Group, whose research programme is focussed on extragalactic astronomy and cosmology, and with the Mathematical Physics Group in the School of Mathematical Sciences, whose research is in the area of Quantum Gravity. Two lecturers are required whose research interests lie in the general area of Early Universe Cosmology; applications are particularly encouraged from candidates with an interest in the overlap areas of particle physics and cosmological observations, as well as the overlap between string theory and cosmology.

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Candidates must have a PhD in physics or a related subject.

Salary will be within the range £23,643 - £35,883 pa, depending on qualifications and experience. These posts are available from 1 July 2005.

Informal enquiries may be addressed to Professor E Copeland, Email: Ed.Copeland@Nottingham.ac.uk or Professor P Coles, tel: 0115 951 5132, Email: Peter.Coles@Nottingham.ac.uk. Information about the School is available at: <http://www.nottingham.ac.uk/physics>.

Further details and application forms are available on the WWW at: <http://www.nottingham.ac.uk/hr/vacancies/academic.html> or from the Human Resources Department, Highfield House, The University of Nottingham, University Park, Nottingham NG7 2RD. Tel: 0115 951 3262. Fax: 0115 951 5205. Please quote ref. RUB/6685. Closing date: 25 February 2005.

DEPARTMENT OF PHYSICS

To continue the expansion of the Nuclear Physics Group we are looking to appoint two enthusiastic persons who hold, or will soon gain, a PhD in experimental nuclear physics to join research programmes investigating nuclear astrophysics and the structure of exotic proton-rich nuclei.

Research Associate

Ref: AR04518

The nuclear astrophysics programme, led by Dr Alison Laird, is aimed at the investigation of key reactions in nova explosions. The experimental programme will mainly utilise radioactive beams from ISOL facilities such as those at TRIUMF (Canada). In addition, you would be expected to assist in the development of a new ion chamber for nuclear astrophysics.

Research Associate

Ref: AR04519

The second programme, led by Professor Bob Wadsworth, will involve the study of $N \leq Z$ nuclei using the technique of gamma-ray spectroscopy. This programme will mainly utilise stable beams from facilities such as those at GANIL (France), Argonne National Laboratory (USA) and Jyväskylä (Finland). The focus of the work will be the study of shape coexistence and neutron-proton pairing effects in $N \sim Z$ nuclei and the development of the beta-gamma tagging technique for studies of odd-odd and odd N ($< Z$) nuclei using the GREAT spectrometer.

You would be expected to assist in the development of one of the above programmes and also to initiate new activities in the chosen area, which you would lead.

Informal enquiries for both posts Professor Bob Wadsworth, tel: +44(0)1904 432242, email: rw10@york.ac.uk or Dr Alison Laird, tel: +44(0)1904 432240, email: al34@york.ac.uk

Both posts are available from April 2005 and are for a fixed-term of two years, with a possibility of an extension of up to 15 months for post AR04519.

Starting salary will be within the range £19,460 - £21,640 p.a.

For further particulars and details of how to apply, please see our website at: <http://www.york.ac.uk/admin/persnl/jobs/> or write to the Personnel & Staff Development Office, University of York, Heslington, York YO10 5DD, quoting the appropriate reference number. Applications are welcome for one or both of the positions.

Closing date: 28 February 2005.

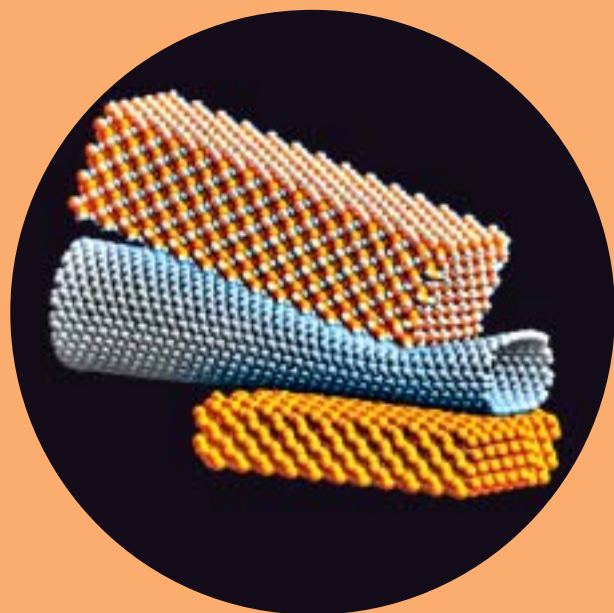
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Image: Partial view of the model of a nanomechanical fluid control valve
S D Solares et al *Nanotechnology* 2004 **15** 1405–1415



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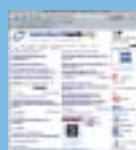


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An evening with the Einsteins

The following article was discovered by Rosemary Prichard – the grandmother of mathematical physicist Andy Hone from the University of Kent. It was written by Prichard's mother Lady Neysa Perks (pictured below), who was born Neysa Cheney in New Rochelle, New England, in 1896.

At the age of 17, Perks went to Munich to study opera singing and to learn German. A year later she moved to Milan, where she acted in silent films to make enough money to pay for her singing lessons. In later life she wrote poems, historical novels and stories for children. A keen observer of human nature, she also kept a diary of everything that she experienced. She was married to the British architect Malcolm Perks, who became a knight of the realm.

After her mother died in 1991, Prichard found among her papers the following account of an evening that Perks spent with Albert Einstein and his second wife Elsa in pre-war Berlin. Prichard believes that it was written for an interview with BBC Radio Kent that was never broadcast.



Einstein and his second wife Elsa in Berlin, where they had an elegant villa in the suburbs.

It so happened that in 1930 I was very ill in a private clinic in Berlin. My husband had stayed with me until I was out of danger but then he had to hurry back to London, so I was feeling rather lonely.

My surgeon's wife called to see me and said, "Do you know that Professor Einstein's little daughter is ill in the next room to yours? Her mother comes to see her every day. If you like, I will ask her to visit you. She is a great friend of mine." Then she said, in a confidential tone, "Einstein plays the violin you know".

I didn't know and looked surprised. "My husband plays the violin too," she continued, "and they get together for musical evenings with two other doctors. One plays the cello and one the piano – Mozart and Beethoven. Do you like music?"

I told her it was my greatest pleasure. "Well then, when Mrs Einstein visits you, tell her you love music and she will invite you to come with us to our next musical".

The next day there was a tap on my door, and in came a plump, motherly figure, badly dressed. She sat down by my bed and talked in German. I enquired for her daughter and she stayed chatting for quite a while. Then I told her I loved music, and her face lit up and she said, "You must come and hear my Albert play".

She came to see me every day and brought me a bunch of violets. We became very friendly and she told me some amusing things about her husband. Apparently he had very thick grey hair that she cut at home with scissors. "I also cut my own," she said proudly. "What is the use of paying a barber when you have a pair of scissors yourself?" (Her hair was cut off in an uneven bob all around and looked terrible!)

She warned me never to ask her husband about his "theory". "He hates people to ask him," she said. "He also hates having his picture taken, or posing for artists, and they are always worrying him. I will tell you a funny story about Albert. He was sitting in a train and a strange man stared and stared at him, and then asked him what

Einstein had thick grey hair that Elsa cut at home with scissors



was his profession. 'I am an artist's model,' my husband said crossly. He also hates giving autographs and he now charges a fee for each one and gives the money to charity."

"Do you understand the theory of relativity yourself?" I asked her. She roared with laughter.

"Of course not, and I sometimes think Albert does not entirely understand it himself. I wish I had married a normal man. He dreams and dreams, and will not eat with the family. I have to carry his trays into this study and dare not speak to him. He lets his food get cold and calls me to heat it up again." She gave a big sigh.

"That must be very hard for you," I said in sympathy.

"Oh, but it is worth it. Albert is so kind and a very simple man. You will see, he is 'down to earth' when he is not dreaming."

The great evening arrived, and my surgeon and his wife collected me and drove me to an elegant villa in the suburbs of Berlin near a lake. A German maid let us in and Mrs Einstein greeted us. She was wearing a most extraordinary gown of black

satin that had obviously grown too tight, so she had slashed it open from top to bottom, inserted what looked like a gathered lace curtain that was pinned into the gap and tied around the middle with a black velvet ribbon. Around her neck she was wearing a curious gold chain with what looked like ivory scarabs hanging from it.

"Egyptian?" I asked her.

"Ach, no – my children's teeth! I have had each one set in gold. They are as precious to me as pearls."

Then Einstein came in and was presented. He had sad brown eyes like a blood hound, a droopy moustache, a small cleft chin and a shock of untidy hair. He was then about 51, but looked older. For a moment I was a little nervous at meeting such a great man and spoke to him in English.

He replied in German: "The only word I know in English is water closet".

I was startled, but realized he was trying to shock me – so I replied in German, "I am sure that is a most useful word to know". He laughed, the ice broke, and he took me in to dinner.

After dinner we went into the music room and the doctors got together to tune their instruments while we all had coffee. They decided on a Beethoven quartet.

To my surprise, plates of grapes were brought in by the maid, who passed each of the ladies a bunch of grapes. I will never forget Mrs Einstein sitting there, audibly sucking grapes and spitting out the seeds during the music.

Confusion followed. Einstein played well and his fat white fingers (like rather grubby little sausages) flew over the strings, but he got ahead of the others. The pianist stopped and said, "Where are you Herr Professor?"

"On page two, bottom line," said Einstein.

"Oh well," said the cellist. "I am on page two at the top!"

"I am still on page one at the end," said my surgeon.

After this tangle got sorted out, they all went back to square one, and Mrs Einstein went on calmly eating grapes.

It was a memorable evening.



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