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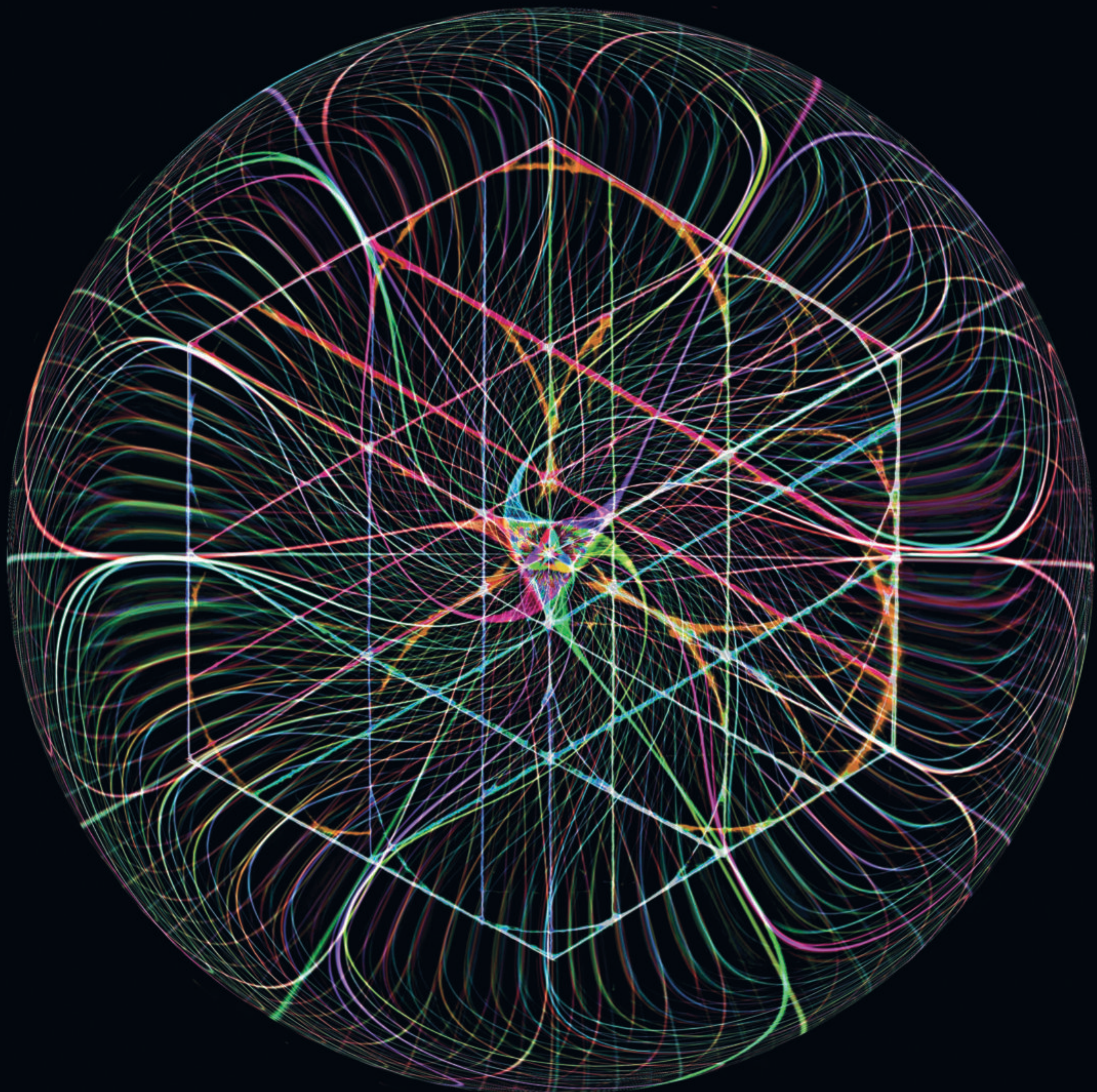
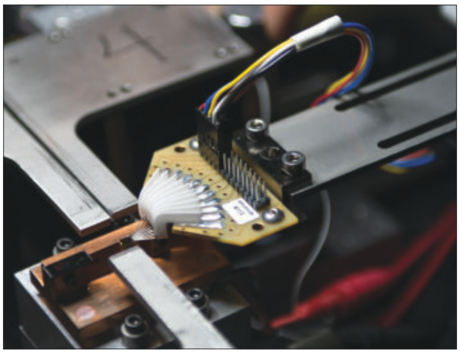
Maxwell's imaginary vortices

How "fictional" models have shaped science



Strange discrepancy Why measurements of *G* vary so wildly
A numbers game Is reality ultimately just about mathematics?
Lighter, lower, longer Towards a more sustainable economy

physicsworld



Features

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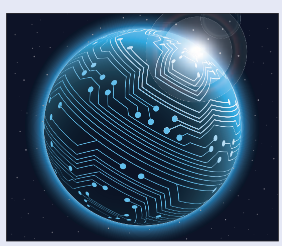


Multimedia

Check out the digital version of *Physics World* this month:
- Hear about quantum computing (p6)
- Listen to a Hardanger fiddle (p46)
- Watch ice spikes form (p52)

Quanta

For the record

I feel an obligation to talk about gender

University of Cambridge physicist **Athene Donald** *writing in the* Daily Telegraph

Donald, who is also the new master of Churchill College, Cambridge, says she gets frustrated when she sees young women facing obstacles, adding that "we need to nurture them to make the most of their potential".

Heavily rewarding failure is not good for science

Columbia University mathematician **Peter Woit** *quoted in the* Guardian

Woit says that the Fundamental Physics Prize, which was jointly awarded late last year to the string theorists Michael Green and John Schwarz, should not be given to work in this area as the theory "isn't working".

We're not sending generic people to Mars

NASA chief scientist **Ellen Stofan** *quoted in* Nature

Stofan, who became the agency's chief scientist last August, defends the need to send astronauts to Mars to fully understand the red planet, given the success in recent years of robotic rovers.

Today I wouldn't get an academic job

Nobel laureate **Peter Higgs** *from the University of Edinburgh quoted in the* Guardian

Higgs says that he wouldn't be regarded as productive enough to get a position at a university today, adding that he became an "embarrassment to the department" when they carried out research assessment exercises for staff members.

If that had failed it would have been curtains

Space X boss **Elon Musk** *in the* Daily Telegraph

Musk says that Space X came very "close to dying" after three launch failures, but that the company was saved following the success of the fourth attempt.

I'm even mistaken for a young scaffolding worker

Neutrino researcher **Sho Tada** *from the KEK particle physics lab in Tsukuba, quoted in the* Japan Times

Tada, who has bleached blond hair and usually wears military camouflage outfits while at work, has recently been giving public talks about physics to raise the subject's profile.

Seen and heard

Alexander Hartmann

Spin glass: the game

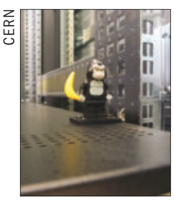
Alexander Hartmann is determined to make condensed-matter physics fun. The University of Oldenburg physicist has created a board game for two players dubbed "Spinglas", in which each player has either white or black counters (representing spin up or down) and then takes turns to place three pieces on the board. The pieces can be either the counters or wooden links representing "interactions" between spins – blue being ferromagnetic and red antiferromagnetic. If a player's move results in the majority of interactions around the spin being "satisfied" – like ferromagnetic bonds between two similar spin orientations – then the energy is negative, but if more are unsatisfied, like an antiferromagnetic interaction between two up spins, then the net energy is positive. A total positive energy near the spin means that a player can also "flip" the spin to result in a lower energy. The winner is whoever has more counters of their colour on the board at the end of the game. "People who played the game say that it is a real challenge," Hartmann told *Physics World*, adding that high schools and universities are using it to teach students. Full instructions on how to make Spinglas are on *arXiv* (1312:1839), but a professionally made version will cost you €14.50. Hartmann now has another idea for a physics-themed board game based on complex networks, which is "pretty far advanced". Hopefully it won't be too complicated, though.

Tracking down time travellers

Astrophysicist Robert Nemiroff together with graduate student Teresa Wilson from Michigan Technological University recently took up an unusual challenge – they took to the Internet for signs of time travellers (arXiv:1312.7128). The duo did this by using search engines and social media to look for signs of knowledge of an event before it had happened, including the election of Jorge Mario Bergoglio as head of the Catholic Church on 13 March 2013. Nemiroff told *Physics World* that the idea came about during a game of poker with his students, and he challenged them to approach the problem scientifically. So did they find any evidence for time travellers? Sadly not. Nemiroff, who actually believes that time travel to the past is impossible, says that the team had "great fun" doing the work and that they even received several collaboration requests, yet they have no plans to continue this line of research. "But then again, I don't know the future," he says.

Lukewarm physics

Gérard Liger-Belair from the University of Reims Champagne-Ardenne and colleagues have been studying the energy needed to launch a cork from a champagne bottle (*Journal of Food Engineering* **116** 78). The intrepid researchers opened bottles of bubbly at different temperatures and used high-speed infrared cameras to study the cloud of carbon dioxide released when the cork pops. They found that the amount of carbon dioxide and the cork's speed both increase with the temperature of the champagne, so that at 18 °C the velocity of the cork was almost 55 km/h – some 15 km/h more than if the tipple was at 4 °C. But who drinks warm champagne?



CERN

LEGO scavenger hunt

You may remember that we recently reported on how you can navigate around CERN using Google Street View (November 2013 p3). Well, what we didn't know then was that Stefan Lüders, CERN's computer security officer, had decided to stash 20 LEGO minifigures around the CERN computing centre before the cameras rolled. Lüders, who is a big LEGO fan, took around an hour placing the minifigures, which were hidden in some not-so-obvious places and in some cases were even camouflaged. CERN then launched a competition, which ended on 31 January, inviting people to identify the locations of the minifigures. "It is absolutely amazing to count the number of replies we received and are still receiving," Lüders told *Physics World*. The lucky winners will get their pick from the CERN holiday gift guide, which unfortunately doesn't include the LEGO model of ATLAS that was created last year.

Frontiers

In brief

Ultracold beams of molecules created
Physicists in Germany have produced the first ever near-continuous beams of molecules slowed and cooled to a temperature of just one degree above absolute zero. Their method, which involves running the molecules through a centrifuge, could help provide new insights into quantum states of matter and even allow physicists to work out if the electron has an electric dipole moment. The researchers have so far created a range of continuous ultracold beams – previous such molecular beams have always been pulsed – including beams from fluoromethane that could prove useful in studying chemical reactions that occur when molecules collide (*Phys. Rev. Lett.* **112** 013001).

Infrared could create hydrogen from water
Infrared light could help split water into hydrogen and oxygen, despite the fact that infrared photons have less energy than is needed to drive the reaction. That is the claim of physicists in China, who have calculated that the reaction could proceed with the help of a bilayer catalyst that has a strong internal electric dipole. The team used advanced computational algorithms based on density functional theory to design the ultrathin catalyst. It consists of a bilayer of boron nitride functionalized with hydrogen atoms on the upper surface and fluorine atoms on the lower one. The researchers are now trying to come up with a more practical alternative to make the catalyst in the lab. If successful, such catalysts would allow a far larger proportion of the solar spectrum to be used to generate hydrogen, making it commercially viable (*Phys. Rev. Lett.*, in press).

First noble-gas molecules found in space
An international team of astronomers has accidentally spotted the first space molecules bearing a noble gas, argon, in the debris of an exploded star. The surprising discovery reveals the element's isotopic composition, confirming long-standing predictions that argon is forged in such stars. The researchers made the discovery using the Herschel Space Observatory to study supernova remnants, including the well-known Crab Nebula, as they searched the far-infrared spectra for lines from molecules such as carbon monoxide. Instead, they saw two mysterious emission lines – one at a wavelength of 243 μm, the other at exactly twice that value, suggesting that it was a simple diatomic molecule. After failing to find a match with common diatomic molecules, they realized that they had spotted the argon hydride molecular ion, ArH^+ (*Science* 10.1126/science.1243582).

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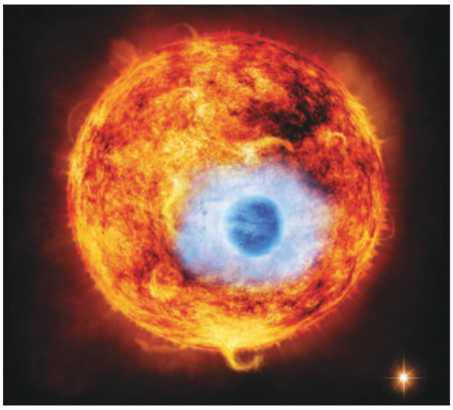
Atmosphere reveals exoplanet mass


NASA/CXC/M Weiss

Crossed paths An artist's illustration of the "hot Jupiter" HD 189733b.

Astronomers in the US have unveiled a new way of measuring the mass of an exoplanet by studying several different parameters of the body's atmosphere. Although the technique has so far only been tested on Jupiter-sized planets, the researchers say that the next generation of telescopes – such as the James Webb Space Telescope, which comes online in 2018 – will allow it to be used on objects that are the size of the Earth.

An exoplanet's chemical composition – which holds important clues about its ability to support life – can be determined by measuring its mass and radius. These values are normally obtained by studying the Doppler shift of the "wobble" of the parent star that is caused by the planet's orbit around it. But while this technique works well with Jupiter-sized planets, it fails for rocky planets in orbits similar to that of the Earth.

The new mass-measurement technique, developed by Julien de Wit and Sara Seager of the Massachusetts Institute of Technology, works on "transiting" exoplanets, which periodically pass in front of their host star. These planets block some of the starlight from reaching the Earth and so by measuring this apparent stellar dimming, the orbital period of the exoplanet and its diameter relative to that of the host star can be determined. Moreover, as the transit occurs, a small amount of the starlight travels through and gets absorbed by the planet's atmosphere, with the resulting absorption spectrum yielding important information about the composition, density and temperature of the atmosphere.

In this latest research, the team extended its study to include the pressure of the atmosphere, and how it changes as a function of the distance from the exoplanet's surface. Calculations reveal that the pressure gradient, density and temperature of the atmosphere are related to the mass of the planet by a relatively simple equation. Also, all three values can all be measured independently from the transit spectrum, thus giving the mass.

The researchers tested their method by calculating the mass of the recently discovered exoplanet HD 189733b, whose mass is already known to within about 5% (about 1.16 times the mass of Jupiter), as it is an ideal candidate for existing telescopes to study. The new technique yielded the same mass within a similar uncertainty range (*Science* **342** 1473).

Pulsar to test relativity

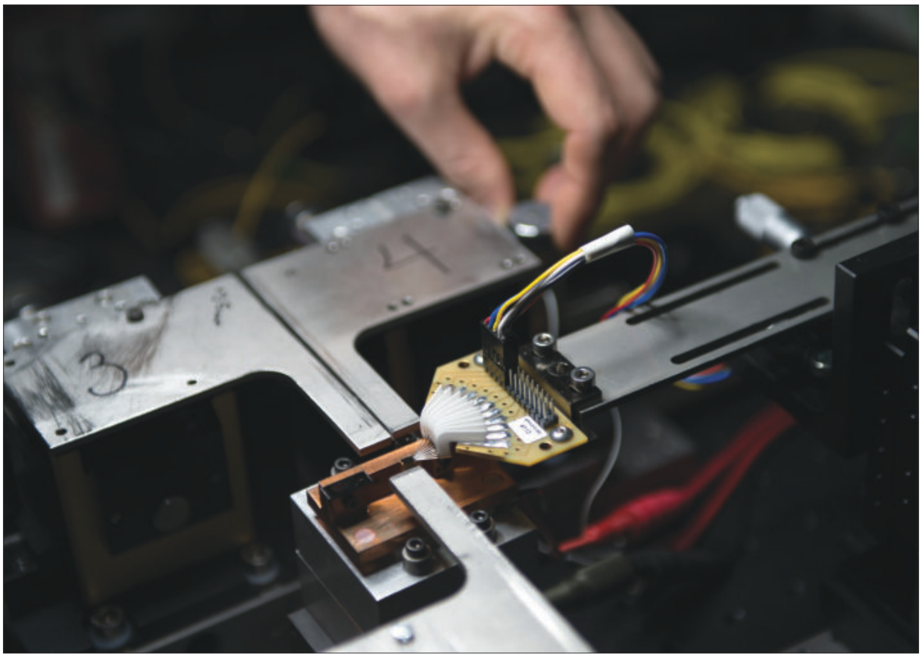
The first ever pulsar with two stars circling it has been observed by an international team of astronomers. By watching the three objects orbit one another, the team will soon be able to perform the best ever test of the "strong equivalence principle" – a key prediction of Einstein's general theory of relativity.

The strong equivalence principle says that gravity should accelerate all objects in the same way, even if the objects hold themselves together with their own gravity. While previous tests of this principle have been carried out in the solar system by tracking the orbits of the Earth and the Moon, none of the objects is strongly self-gravitating.

Now, Scott Ransom of the National Radio Astronomy Observatory in Virginia and colleagues have discovered a millisecond pulsar (PSR J0337+1715) that spins 365.953363096 times each second. By recording when the pulsar's pulses reach Earth, Ransom's team discovered small delays caused by the gravitational tugs of its two companions, both of which are white dwarfs. One star is much closer to the pulsar than Mercury is to the Sun, while the other is about as far out as the Earth is from the Sun.

The pulsar and the inner white dwarf are both falling through the gravitational field of the outer white dwarf. Although the pulsar has much greater self-gravity, general relativity says both it and the inner white dwarf should respond in exactly the same way. Ransom and colleagues are currently tracking the exact positions of all three objects and expect a verdict of their test of the strong equivalence principle within a year (*Nature* 10.1038/nature12917).

M Thompson



Complex quantum processing of the future

Pictured above is the most functionally complex integrated quantum circuit ever built. Fabricated from a single material, it can both generate and entangle photons at the same time and has been developed by a team led by Mark Thompson of the University of Bristol in the UK. The circuit is made up of two photon sources that interfere quantum mechanically on a 2 mm long silicon chip, with optical fibre input and output coupling. Although quantum interference is at the heart of many quantum information processing algorithms and technologies, the effect can only be observed if the photons are indistinguishable (i.e. identical in every way) and are produced from an identical photon source. Thompson's team achieved this by realizing two identical photon sources on a single silicon chip for the first time. The sources show extremely high quantum interference, which implies that they are exceptionally well matched. Such a circuit could also be used to perform more complex on-chip quantum optics experiments than those possible in bulk or fibre optics (*Nat. Photon.* 10.1038/nphoton.2013.339).

Homing in on earthquake lights

Earthquake lights are strange, glowing orbs that are occasionally seen before or during seismic events. Their origin has long intrigued seismologists – in fact their existence was not confirmed until they were first captured on film in the 1960s. But now, Robert Thériault of Quebec's Ministry of Natural Resources and colleagues, who have studied well-documented observations of the phenomena going back to the 1600s, think the lights may be closely associated with a specific type of geological fault.

The survey of 65 events from Europe and America revealed that lights have occurred alongside earthquakes of a variety of magnitudes – from 3.5 on the Richter scale to 9.2. The majority were associated with earthquakes of magnitude greater than 5.0, which corresponds to a medium-sized earthquake. The lights themselves also varied in shape and size, having appeared as stationary or moving globes, atmospheric illuminations or in flame-like configurations issuing from the ground. There have also been variations in the distance from the earthquake epicentre to where the light was seen.

Unexpectedly, the team found that 97% of earthquake lights were associated with "subvertical" faults, which are responsible for barely 5% of the Earth's total seismic activity. Subvertical faults exist where a region of a tectonic plate is stretched, pulling it apart and causing faults in the form of vertical cracks – or rifts – to form in the crust.

Thériault's study also found that the lights seem to occur only before or during an earthquake. If the lights appear beforehand, the team believes they are linked to the rapid build-up of stress deep underground prior to fault rupture. When lights and earthquakes occur at the same time, the phenomenon is thought to be related to changes in stress that occur as transverse shear waves propagate through the crust (*Seismological Research Letters* **85** 159).

Innovation

Novel ultrathin flexible circuits created

A new way of making ultrathin, flexible and transparent electronics has been unveiled by researchers in Switzerland. The technique involves fabricating micron-thick electronic devices on a conventional silicon wafer, which is later detached by soaking it in water. The researchers also showed that the flexible electronics could be stuck to a range of different surfaces, including human skin, a plant leaf and a number of different everyday materials, including textiles and rubber.

The new technique, developed by Giovanni Salvatore and colleagues at ETH Zurich, begins with a conventional silicon wafer that is 2 inches in diameter. It is coated with thin layers of two different water-soluble glues, one of which is polyvinyl acetate – the main component of the white glue used by schoolchildren and carpenters. A layer of parylene just 1 μm thick is then deposited on top.

The team fabricated electronic components on the surface of the parylene by depositing semiconductor, dielectric and conducting materials in appropriate patterns. The resulting circuits are so thin that they lie less than 200 nm above the surface of the parylene. Initially the researchers used metal conductors in some circuits, but these were not completely transparent. To make fully transparent transistors, they turned to indium tin oxide, which is both optically transparent and an electrical conductor.

Once the devices are built, the wafer is simply immersed in a dish of water. After about half an hour, the glue has dissolved and the film floats to the surface where it can be retrieved and cut into individual components.

One device made using the circuit is a differential amplifier with input and output electrodes, as well as an option to connect a power supply. The team operated the amplifier with the film both flat and bent, finding only a small degradation in performance in the latter configuration. Another device comprising one thin-film transistor (TFT) was wrapped around a human hair, bending the TFT into a radius of curvature of just 50 μm. Despite the strain on the TFT, it was able to operate normally.

The team also integrated a strain gauge into one of its devices, which was transferred to the surface of a contact lens. According to Salvatore, such a device could be used to provide real-time information about the pressure in an eyeball. He and his colleagues argue that such a system could therefore help doctors to improve their diagnosis of glaucoma (*Nat. Commun.* **5** 3982).

News & Analysis

NSA keys into quantum computing

Leaked documents suggest that the US National Security Agency is developing quantum computers to crack cryptography codes, but what progress has the agency really made? **Jon Cartwright** investigates

The US National Security Agency (NSA) has a classified programme to build a quantum computer that can break modern Internet security, according to documents leaked by the former NSA contractor Edward Snowden. The documents, which were published last month in redacted form by the *Washington Post*, have surprised few physicists working in the field. However, they have led to speculation about the status of NSA research and a renewed debate on the risks of developing quantum computers.

Quantum computers are devices that rely on quantum phenomena such as superposition, in which a system exists in multiple states at once, and entanglement, in which the states of two systems become inextricably linked. Unlike classical computers, which store bits of information in definite values of 0 or 1, quantum computers store information in quantum bits, or qubits, which are a superposition of both. When qubits are entangled, any change in one immediately effects changes in the others. Qubits can therefore work in unison and solve certain complex problems much faster than their classical counterparts.

Some of these problems are purely scientific in nature, such as simulating molecules inside biological cells, which could allow researchers to develop more effective drugs. But one problem quantum computers are expected to be most proficient at is factorizing large numbers. If successful, this would allow supposedly secure information on the Internet to be deciphered, including banking transactions, private messages and government files. Although in principle classical computers could perform the same deciphering, the process would usually take so long as to be unfeasible.

In 2006 the NSA openly announced the creation of a joint institute with the University of Maryland in College Park and the National Institute of Standards and Technology in Gaithersburg, both in the US, to develop quantum technology, including quantum computing. But the new documents reveal an additional classified effort at Maryland with the express purpose of breaking data encryption. They state that the NSA wants to build "a cryptologically useful quantum computer" as part of a programme titled "Penetrating Hard Targets", which the *Post* claims has a budget of $79.7m (£48m).

NSA

Listening in The US National Security Agency is allegedly developing quantum computers with the aim of breaking quantum cryptography codes.

Many physicists working in the field of quantum information believe quantum computing is exactly the sort of technology one would expect the NSA to develop. "If you put my level of surprise on a scale from zero to 10, where 10 is very, very surprised, my answer would be zero," says Raymond Laflamme, a leading quantum-information theorist who is based at the University of Waterloo in Canada. "If they were not doing it, they would not be doing their job." Even so, the news has confirmed for many others how important it is to find other ways to make digital information secure.

Unbreakable codes?

Encrypted information on the Internet exists on pages whose URL begins with "https://" as opposed to "http://". It is based on public-key cryptography, which allows someone to send information to someone else by encoding it with a publicly available key. Although anyone on the Internet could intercept and read the message in its encrypted form, only the receiver, who holds a special, private key, can decipher it.

The most common type of public-key encryption is RSA, which was invented by the cryptographers Ron Rivest, Adi Shamir and Len Adleman in the late 1970s. In RSA encryption, both the public and private keys are derived from a pair of large prime numbers, the product of which anyone can find out. If you know the formula, you can in theory work backwards, factorizing the product until you discover the primes – but it is only realistically solvable if your computer is powerful enough.

Quantum computers could do that kind of factorization – and as Laflamme points out, it does not matter that they have not been properly realized yet. Information on the Internet can easily be stored, which indeed the NSA – as well as the UK Government Communications Headquarters (GCHQ), other intelligence agencies and private cloud-computing companies – is doing routinely anyway. That means information encrypted today could be deciphered in 10 years' time – or whenever quantum computers are finally in use.

How much of a problem that poses depends on the sort of information you are encrypting, explains Laflamme, who gives the example of someone using a computer to buy something with a credit card. The development of a quantum computer is not a threat because in 10 years you will have changed your credit card, and unless you are buying something illegal, you will not care that the NSA knows. "But what if you're sending the explanation of a new type of classified technology, one you want to keep secret for 20 years?" asks Laflamme. "Well, then it's problematic."

There are methods to future-proof the transfer of secret information.

One is to create a communication network independent of the Internet through which users can share secret keys, which can then be used to encrypt and decipher messages on the Internet. The security of such networks can be improved further with quantum key distribution (QKD), which in theory guarantees the security of the key transfer – although the latest documents also reveal that the NSA is attempting to exploit practical loopholes in this, too, under a programme known as "Owning the Net".

Vadim Makarov, who himself studies flaws in practical QKD systems at the University of Waterloo, says that cryptographers are also looking into classical "quantum-safe" encryption algorithms for use on the Internet. Like quantum computing, however, quantum-safe encryption and foolproof QKD systems, which cannot be cracked at all, are also taking time to develop and implement. "I just hope we won't be too late," he says.

Secret race

The NSA has not publicly responded to the leaks, but another question raised by the NSA documents is whether the agency could be further ahead in the development of quantum computing than major labs. The main reason functional quantum computers are expected to be many years away is that it is still very difficult to control qubits while protecting them from external interference that can all too easily destroy them. Moreover, no-one is yet sure what type of qubits are most likely to be practical, with physicists exploring types made from trapped ions, photons and superconducting circuits, to name but three.

According to the documents, the NSA expected its scientists to have demonstrated "dynamical decoupling and complete quantum control on two semiconductor qubits" by the end of September 2013. Purely on numbers, the agency would appear to be lagging behind major labs such as the Institute for Experimental Physics at the University of Innsbruck in Austria, which demonstrated entanglement of 14 atomic qubits as far back as 2010. On the other hand, control of qubits made of the semiconductor silicon is less advanced, with only single silicon qubits having been openly demonstrated since 2012. If the NSA has already succeeded in achieving control of two silicon qubits, then it may be ahead in that particular race.

The semiconductor mentioned in the documents could also refer to types of semiconductor that turn superconducting in certain regimes. But experimental quantum physicist Jonathan Home of ETH Zurich in Switzerland believes the NSA is indeed pursuing a regular semiconductor such as silicon, because the "dynamical decoupling" also mentioned – a type of noise mitigation – is not usually applied to superconducting qubits. If the agency is pursuing silicon, that might be because it is easy to build large arrays of silicon devices, Home says. But he adds that it is not so easy with silicon to implement the error correction that would make any devices function like proper qubits. "If I were an NSA manager, maybe I know the solid-state can be scaled up, so I pick that. But maybe I haven't thought so hard about actual quantum computing," he says.

If the NSA is developing quantum computers, does that mean that other intelligence agencies such as GCHQ are too? Physicists contacted by *Physics World* were not sure whether an agency outside the US would have the resources. But one point is obvious: over every development in quantum computing in the coming years, the spies will be watching.

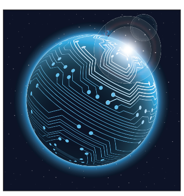
It is still very difficult to control qubits while protecting them from external interference that can all too easily destroy them

Innovation

UK splashes out £270m on quantum technology

Further details have emerged of a new £270m initiative being funded by the UK government to convert quantum-physics research into commercial products. The five-year initiative, which will include the creation of a network of quantum-technology centres, was one of a number of measures revealed by the government in its Autumn Statement in early December 2013 to boost the UK's science base. The chancellor George Osborne said that the money was "additional investment" in research and that science was a "personal priority" of his.

The initiative, which will begin in 2015, will focus on areas such as chip-scale atomic clocks for improved GPS communication, quantum-enabled sensors, quantum communication and quantum computing. Some cash will go to existing university research groups, while about £30m per year will go to the Technology Strategy Board – the UK's national innovation agency – to support immediate commercialization of technology. There will also be money for PhD students and postdocs, while some £4m will go on equipment for the new Advanced Metrology Laboratory being built at the National Physical Laboratory.


iStock/Bellenixe

Quantum commerce The UK has announced it will establish a network of quantum-technology centres to convert quantum-physics research into commercial products.

The quantum-physics initiative, which has involved careful behind-the-scenes negotiations between the UK physics community, government and industry, was formally put to Osborne last year by a group of physicists led by Peter Knight from Imperial College London. Knight, who is the immediate past president of the Institute of Physics, which publishes *Physics World*, says that the prospect of an extra £270m for quantum technology is "highly exciting". However, he adds that he will be "keeping a close eye" to ensure the cash is not simply siphoned off from budgets earmarked for other scientific fields.

The detailed mechanism for distributing the funding among UK researchers is still being discussed, although it is likely to involve the UK's research councils, the Royal Society and the Royal Academy of Engineering. However, Jeremy O'Brien from the University of Bristol, who also helped to get the initiative off the ground, says the UK must properly co-ordinate the new investment. "Fragmentation into small chunks will be the enemy of progress and ultimately could hinder the creation of wealth," he says.

But participants are optimistic about what the initiative can achieve. "There is real potential for long-term transformational change in some information-related technologies, deriving from a complete re-conception of design principles underpinning their operation," says Ian Walmsley from the University of Oxford.

Matin Durrani

Space

Europe's Gaia mission gets ready to map a billion stars

Europe's €450m Gaia spacecraft has taken up its position 1.5 million kilometres from Earth where it is set to begin producing the most accurate 3D map of our galaxy ever. Commissioning and calibration will take several months and, once complete, Gaia will embark on its five-year mission to plot the precise positions, motions, temperatures, luminosities and compositions of a billion stars across the Milky Way.

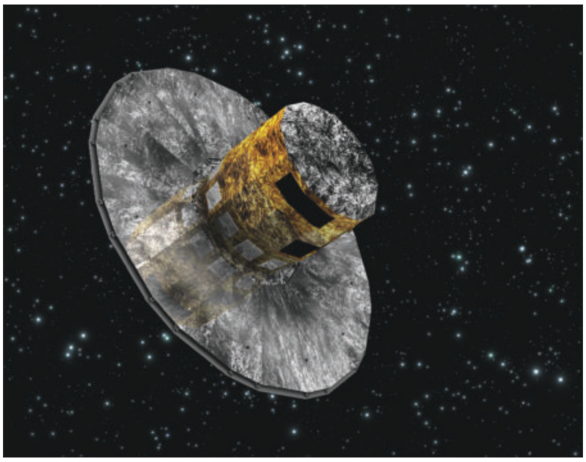
The science of astrometry – measuring the positions of stars – fell out of fashion in the 20th century, in part because of inaccuracies caused by atmospheric distortion. In 1989 the European Space Agency (ESA) showed that it was possible to map stars much more accurately from space with its Hipparcos mission. Despite a launch failure that landed it in an unplanned, highly elliptical orbit, Hipparcos managed to map more than 118 000 stars in our region of the galaxy with an accuracy of 1 milliarcsecond.

Gaia goes significantly further, aiming for an accuracy of 20 microarcseconds in a billion stars, around 1% of the galaxy's total. An Earth-bound telescope with similar accuracy would be able to measure a shirt button on the surface of the Moon. Gaia has two telescopes and the spacecraft rotates once every six hours so that they scan the sky, focusing light onto a huge CCD sensor with nearly a billion pixels – the largest ever flown in space. "Gaia will be a spectacular advance," says Michael Perryman of Princeton University, a former project scientist for Gaia and Hipparcos. "Its scientific grasp will be staggering, plotting nearly every star in the galactic centre."

Gaia plots the positions using parallax: fixing a star's position against the background of stars and then doing the same thing six months later when the spacecraft has travelled round to the far side of the Sun. The amount that the star has moved against the background reveals its distance. Over its five-year mission, Gaia is expected to observe each star around 70 times. The main aim is to understand the formation and evolution of our galaxy under the influence of dark matter as well as reveal how the galaxy has grown over time by cannibalizing other galaxies.

"We'll see streams [of alien material] indicating that part of a dwarf galaxy has been eaten by the Milky Way," says Gaia project scientist Timo Prusti. Gaia will also help to pin down the distances of nearby "standard candles" – stars that are used to measure long distances across the universe – as well as log several hundred thousand asteroids in our solar system and detect extrasolar planets. "It's a discovery machine: it's designed to tell us what we don't know how to ask," adds Gaia's UK principal investigator Gerry Gilmore of the University of Cambridge.

Daniel Clery



ESA

Star of the show The European Space Agency's Gaia craft will accurately maps the positions of millions of stars in our galaxy.

Russia

Putin postpones controversial academy reforms

Russian president Vladimir Putin has delayed plans to reform the Russian Academy of Sciences (RAS) for a year following mass protests. A new round of discussions is now expected to be concluded by November, and could result in changes to the original reform plan. The main sticking point has been the academy losing control of its vast property portfolio, the management of which would have been handed to the newly created Federal Agency of Scientific Organizations (FASO).

Under the reforms, signed into law by Putin on 27 September 2013, the RAS is expected to be merged with two smaller organizations – the Russian Academy of Agricultural Sciences and the Russian Academy of Medical Sciences. While many scientists agree that changes are necessary to make Russian state research more efficient, critics say the move could be used to whittle away the academy's independence, resulting in abuse by corrupt state officials. Opposition to the reform also stems from concerns that the government's only motivation is to profit from the academy's budget of 67.8bn rubles (£1.2bn) and huge property portfolio held by its 500 institutes.

Yet after sustained protests from a majority of Russia's scientists, Putin asked the newly formed FASO to hold back for a year and he imposed a year-long "moratorium" on all property and personnel decisions. After meeting the recently elected RAS president, physicist Vladimir Fortov, and deputy finance minister Mikhail Kotyukov, who is also head of the FASO, Putin noted that there "shouldn't be any decisions made that could lead to irretrievable [property] losses".

There is still, however, uncertainty over the reforms. "No-one likes really quick changes, yet the reform is still happening," says Alexey Akimov, a senior scientific researcher at the Lebedev Physical Institute in Moscow and principal investigator at the Russian Quantum Center. He feels that the reforms could have a positive impact if implemented properly, but that if done the wrong way, they could "kill Russian science". "Only if both sides try to be constructive, is there a chance to succeed," he adds.

Katia Moskvitch

RAS

On the backburner Plans for a new agency to manage the vast property portfolio belonging to the Russian Academy of Sciences have been put on hold for a year.

Italy

Earthquake-stricken L'Aquila opens new study centre

Nearly five years on from the earthquake that killed 309 people, a new graduate school has been inaugurated to spur the rebirth of the L'Aquila region. The Gran Sasso Science Institute (GSSI), which opened late last year, seeks to lure some of the brightest minds in science to the still largely abandoned Italian city. Dreamt up by Eugenio Coccia, former director of the nearby Gran Sasso National Laboratory, the GSSI gained approval from the Italian government in 2012.

Coccia's idea was to use the Gran Sasso lab, renowned the world over for its research on neutrinos and dark matter, as an "attractor" for PhD students in particle physics and related areas. Housed in a building just inside L'Aquila's city walls, the institute offers PhDs in four areas – astroparticle physics, mathematics, computer science and urban studies. The GSSI has initially been provided with €36m to operate for three years – with €6m a year coming from funding to rebuild L'Aquila's economy and another €6m from EU regional development aid.

For the academic year 2013–14, the institute has 36 students (chosen from more than 500 applicants), 14 of whom are from outside Italy, along with more than 30 full- and part-time lecturers. After taking in an expected 40 students a year for the following two years, the institute will then become permanent if it gets the green light from ANVUR – Italy's higher education and research review body – and is able to secure the necessary funding.

Out of the rubble L'Aquila's newly opened Gran Sasso Science Institute offers PhDs in four areas – astroparticle physics, mathematics, computer science and urban studies.

To get this far, however, the institute has already had to overcome heavy criticism by those who feel it will do little to develop the city and surrounding areas. Being run by the National Institute of Nuclear Physics (INFN), the GSSI does not currently have the power to award PhDs on its own and is operating in conjunction with the graduate schools SISSA in Trieste, IMT in Lucca, and Sant'Anna in Pisa.

Guido Visconti, a meteorologist at the University of L'Aquila, says that the GSSI was approved without any proper evaluation, adding that the choice of subject areas largely reflects the personal interests of the five-man panel that drew up the institute's statutes, and that other subjects of greater relevance to L'Aquila, such as seismology, have been ignored. "You use money from an earthquake to parachute in a new institute that deals with particle physics," he says. "If the situation weren't so tragic, it would be hilarious."

INFN president Fernando Ferroni says that the subject areas were chosen deliberately so as not to clash with those offered by the local university, arguing that "in this way you can attract the best without damaging the neighbour". That explanation, however, appears at odds with the rationale offered by Coccia. "We chose those fields for which L'Aquila was already well known," he says, "starting with the physics of the Gran Sasso lab and those of the university's excellent science departments."

Edwin Cartlidge
Rome

Funding

French academy cries out over swingeing cuts

The French Academy of Sciences has issued what it calls a "cry of alarm" denouncing heavy cuts to the 2014 budget for the National Research Agency (ANR), which was set up in 2005 to fund project-based research. The academy warns that the €80m cuts, which amount to 12% of the ANR's budget, would damage fundamental research. The ANR came off particularly badly as the overall government research budget will drop by just 1% to €7.77bn this year.

According to the academy, the cuts could lead to scientists being paid but not having the means to undertake basic research – a "dangerous" scenario that will set French research back many years. The academy also warns that "unfashionable" topics would be particularly vulnerable and that research funding should be protected even in difficult economic times. "Top-level research is our best hope for economic recovery," the academy states.

Budget blow Despite heavy cuts to France's National Research Agency, higher education and research minister Geneviève Fioraso maintains that the government has succeeded in "safeguarding" the budget allocated to research in general.

In December 2013 higher education and research minister Geneviève Fioraso wrote a letter to academy president Philippe Taquet stating that, despite difficult economic times, the government had succeeded in "safeguarding" the budget allocated to research institutes in general. In the letter, seen by *Physics World*, Fioraso stresses that the ANR's budget reductions should not prevent it from funding projects worth a total of around €600m in 2014.

Yet researchers warn that the cuts could result in a brain drain. "Our biggest fear is that the decrease in funding will negatively impact so-called 'non-thematic' research, which will be particularly detrimental for newly recruited and young researchers," says Denis Jérome, a member of the French Academy of Sciences, who is emeritus director of research at the French National Centre for Scientific Research. "These new cuts might further encourage such scientists to go to more attractive countries, like the US, Canada or Switzerland."

Belle Dumé
Paris

Space

India eyes rocket market after cryogenic launch

The Indian Space Research Organization (ISRO) has successfully launched a rocket that is powered by a home-built cryogenic engine rather than imported technology. India's Geo-synchronous Satellite Launch Vehicle (GSLV) took off last month from the Satish Dhawan Space Centre on Sriharikota, an island off the Bay of Bengal, after two previous attempts to launch the rocket failed. India is now the sixth nation after the US, Russia, Japan, China and France to have launched a rocket with an indigenous cryogenic engine.

It has taken India more than 20 years to develop the necessary launch technology for a cryogenic engine – one that cools the propellants (oxygen and hydrogen) down to temperatures of around 120 K so they become liquid. Rather than using solid fuel, liquids have a reasonably high density that allows the volume of the propellant tanks to be relatively low, giving the rocket a better efficiency. In the 1990s India tried to obtain cryogenic know-how from Russia but the US put pressure on the deal, with Russia instead just supplying the parts. India then struggled to learn the art of making this complex technology work, but finally made inroads over the last four years after building new facilities to test the engines and redesigning some components.

The $50m three-stage rocket – dubbed GSLV Mark II – is almost 50 m tall and weighs 415 tonnes. It was used to hoist a sophisticated experimental communications satellite into orbit that will boost television coverage over the subcontinent. Many in India see this success as a way into the huge commercial launcher market, which is worth some $70–80bn per year.


ISRO

Third time lucky After two failures, India's Geo-synchronous Satellite Launch Vehicle successfully took off with a home-built cryogenic engine, opening up the possibility of the country launching bigger cargo into space.

"The successful launch marks a significant step in the nation's space programme," says Michael Blades, a senior industry analyst at the consultancy firm Frost & Sullivan. "The technology is expensive, but if India can keep launch costs in check it could be a viable competitor for future commercial space launches."

Yet even this launch came close to failure. The rocket was initially due to take off on 19 August 2013 but the launch was aborted 74 minutes before lift-off after ISRO scientists found about 750 kg of the fuel, which is highly inflammable and explosive, had leaked. ISRO chairman K Radhakrishnan described it at the time as a "large leak" and said "timely detection and quick action" averted a fire.

Pallava Bagla
Bangalore

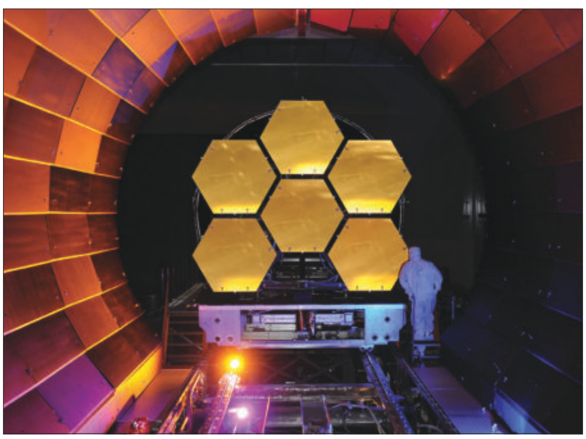
NASA unveils its big astrophysics dreams

A task force appointed by the astrophysicists subcommittee of NASA's advisory council has published a report looking at the technologies needed to answer three big questions: Are we alone? How did we get here? And how does the universe work? The report states that tackling these issues will require the development of large mirrors with high-contrast imaging, new detectors with orders of magnitude improvement, and novel methods of construction in space.

NASA outlines its astrophysics plans for the coming decade every 10 years, but the current report, issued in December 2013, goes far beyond that timescale and has the luxury of ignoring current financial constraints. "We were told to 'dream big'," says task-force chair Chryssa Kouveliotou, a senior technologist in high-energy astrophysics at NASA's Marshall Space Flight Center. "NASA headquarters were very happy with the report."

Activities in the "near-term" – up to about 2025 – will rely mainly on existing or planned missions, such as the James Webb Space Telescope (JWST), due to be launched in 2018, and the planned Wide-Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets (WFIRST-AFTA) mission. Explorations in the "formative era" of the 2030s and the "visionary era" of the 2040s will require notional missions to be designed and built in those decades. "Observatories that seem impossibly daunting today may be feasible a decade or two from now," the report states.

The search for other life forms will focus on planets in other solar systems.


Ball Aerospace

Looking to the future NASA has outlined three big questions for the coming decades, some of which may be answered by the upcoming James Webb Space Telescope.

The report calls for a comprehensive understanding of planetary systems, including characterizing the surfaces and atmospheres of planets around nearby stars via direct imaging and spectroscopy, as well as producing the first resolved images of Earth-like planets. In later decades, space-based interferometry and gravitational-wave studies will refine our understanding of how the universe works via new space missions based on new technologies.

Whether NASA will have the financial resources to afford the recommended missions remains to be seen. Kouveliotou says that while NASA's current budget remains tight, the launch of the JWST will release funds for the astrophysics division. Kouveliotou emphasizes, however, that other organizations such as the European Space Agency could also play a major role in future missions. "About 80% of current astrophysics missions have international partners," she says. "We welcome and encourage international collaboration."

Peter Gwynne
Boston, MA

Astronomy

Project to take first black-hole image

Researchers in the Netherlands, Germany and Italy have won a €14.3m "synergy grant" from the European Research Council to use a network of radio telescopes to take the first direct "image" of a black hole. Led by Radboud University Nijmegen astronomer Heino Falcke, the five-year BlackHoleCam project aims to obtain a "radiopicture" of the massive black hole that is thought to be at the centre of the Milky Way.

The picture will be the result of work carried out at eight observatories distributed around the globe including the ALMA facility in Chile and the South Pole Telescope on Antarctica, together with radio telescopes in Hawaii, California, Arizona, Mexico, Spain and France. All will provide high-resolution observations of Sagittarius A* – a bright and compact radio source that is thought to be the location of the black hole – in the 1 mm wavelength range. The black hole, with an estimated mass of four million times that of the Sun, should appear in radio images as a "punchhole" against the background radiation.

Radboud University Nijmegen

Black hole hunters Astronomer Heino Falcke (left) and colleagues will soon begin studying Sagittarius A* – a bright and compact radio source that is thought to be the location of a black hole in the centre of our galaxy.

The BlackHoleCam project also aims to provide a new rigorous test for Einstein's general theory of relativity from the asymmetries in the light bending patterns surrounding the black disc. Falcke says he would welcome surprises and discrepancies between data and theory, but he has not put any bets on the results yet. "Betting disturbs your scientific views," he says. "And at present getting the project organized is the real challenge."

Martijn van Calmthout
Amsterdam

People

Neutron veteran rejoins ILL as boss

Bill Stirling has taken up the reins as the new head of the Institut Laue-Langevin (ILL) neutron-scattering facility in Grenoble, France. Stirling takes over as ILL boss from Andrew Harrison, who last month started work as head of the Diamond Light Source in Oxfordshire, UK.

The ILL has a nuclear reactor that produces neutrons for 40 instruments that are used each year by about 1200 researchers from more than 40 countries. The UK, France and Germany each provide 25% of the ILL's €107m annual budget, with the remaining money coming from the lab's other 12 members. Stirling, 67, has a long background in neutron science and big science facilities. After studying physics at the University of Edinburgh, he became an instrument scientist at the ILL in 1973, with some of the instruments he designed and built still in operation today. In 1987 Stirling joined Keele University before moving to the University of Liverpool in 1995.

ILL

Back to his roots Bill Stirling has taken over as head of the Institut Laue-Langevin in Grenoble, France.

Stirling also spent seven years as director-general of the European Synchrotron Radiation Facility (ESRF), which is next to the ILL in Grenoble, from 2001 to 2008. He then took up a position as a scientific adviser at the French Atomic Energy Agency (CEA), working on the GIANT Innovation Campus in Grenoble, which includes both the ILL and the ESRF.

"The most important new project for the ILL, one that we hope will be started very soon, is the instrument upgrade programme," says Stirling. "Also, we must continue with modifications to the reactor, buildings and other infrastructure." Stirling adds that he wants to further develop partnerships within GIANT and with other neutron labs across Europe such as ISIS in the UK and the planned European Spallation Source in Lund, Sweden.

Michael Banks

Sidebands

Israel joins CERN

Israel officially became a member of the CERN particle-physics lab in Geneva last month, joining 20 other nations at the facility. Israel's formal association with CERN began in 1991, when the country was granted "observer" status by CERN's council in recognition of the involvement the country already had with the lab. Israel's path to full membership follows CERN's decision in 2010 to enlarge its membership by establishing an "associate membership" category, which all potential full members must first belong to for two years. Israel became CERN's first associate member in 2011. "This is a very special moment for Israeli science and Israel," says Eliezer Rabinovici from the Hebrew University in Jerusalem, who is chair of the Israeli Academy of Science's National Committee for High Energy Physics. "It reflects the decades in which many Israeli scientists, technicians and Israeli industry have contributed significantly to CERN."

IBM leads US patent list

Researchers at IBM were awarded 6809 US patents in 2013, more than any other company. IBM's haul makes it the 21st consecutive year that the company has topped the annual patent list, which is compiled by IFI Claims Patent Services. This year IBM received more patents than Amazon, Google, EMC, HP, Intel, Oracle/SUN and Symantec combined. About 30% of IBM's patents were produced by staff outside the US, up from 22% in 2010. Second on the US patent list was the Korean firm Samsung with 4676 patents. The Japanese companies Canon (3825) and Sony (3098) were third and fourth, respectively, while Microsoft was fifth with 2660 patents.

Let there be light in 2015

The UN has officially declared 2015 the International Year of Light and Light-Based Technologies (IYL). The resolution was adopted in December at the 68th session of the UN General Assembly in Paris. Involving more than 100 partners from 85 countries, the goal of the IYL is to highlight the importance to society of light and optical technologies. A resolution endorsing the IYL was first adopted by the UN Educational, Scientific and Cultural Organization in October 2012 and submitted to the UN in November 2013. The founding scientific sponsors of the IYL include the European Physical Society, the IEEE Photonics Society and the American Physical Society.

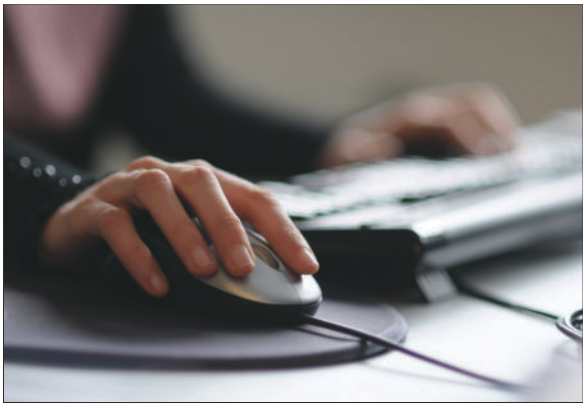
Publishing

Analysis reveals 'half-life' of physics journals

An analysis of journal downloads has found that it can take more than six years for papers in physics to reach one half of the number of downloads they will ever receive. The work, carried out by Phil Davis, an independent researcher and publishing consultant based in Ithaca, New York, looked at the download statistics of 2812 journals run by 13 publishers, including the American Physical Society and Elsevier, in a range of disciplines to calculate a journal's "half-life".

By analysing millions of download events during set sampling periods – ranging from one to 12 months – in 2012 and 2013, Davis looked at the number of the papers downloaded versus the ages of the papers. The median age derived from the resulting age distribution was assumed to be equivalent to the journal's half-life, and was determined for each of 10 subject areas, including physics.

The analysis reveals substantial variations in download behaviour between and within subjects. According to the study, the shortest median half-lives belong to journals covering health and medical science, where, on average, the half-life was between two and three years. Subjects that had the longest half-lives – a median of five to six years – were physics, mathematics and the humanities. Individual physics journal half-lives ranged from nine months to 21 years, although Davis has not revealed the names of the journals in his analysis.


Shutterstock/VojtechVlk

Statistical science An analysis of the download statistics of 2812 journals has shown it can take more than six years for physics papers to reach one half of the number of downloads they will ever receive.

The work could have implications for the implementation of open-access policies. Steven Hall, managing director of IOP Publishing, which publishes *Physics World*, says the study is a valuable contribution in the debate over "green" versus "gold" open access. Green refers to a published paper being initially placed behind a publisher's paywall but where – after a certain embargo period of typically 12 months or more – the researcher is then allowed to place the accepted manuscript in a centralized free-to-access repository, while gold normally involves an author paying an upfront article processing charge (APC) to the publisher, to make the final version of the paper immediately available on an open-access basis.

"If librarians know that most or all of the peer-reviewed articles in a journal will become freely available six months after publication, while 80–90% of usage happens more than six months after publication, then some at least will cancel their subscriptions," says Hall, adding that short embargoes could put publishers out of business. "Rather than take that risk I believe that we should be very cautious on the length of green embargoes while we encourage and support the growth of gold open access."

Astrid Wissenburg, director of research, scholarship and quality at the Open University, agrees that the study aids the economic arguments against short embargo times, but she adds that it does not contribute towards a better appreciation of the scientific value of journal papers. "Financial drivers for publishers should not be the sole driver for setting embargo periods," says Wissenburg. "From a scientific perspective, the use of embargo periods remains second best to immediate open access, facilitated by a gold policy."

Jude Dineley

Physics papers get poor pick-up on social media

Trending topics Only a handful of physics papers make up a list of the most popular scientific papers that were discussed last year on social media.


Shutterstock/Vasya Kobelev

A list of the 100 most popular scientific papers that were discussed on social media in 2013 – those that had the most "likes" on *Facebook*, Tweets or coverage in blogs – is dominated by papers in biology and the social sciences, with physics and mathematics papers only taking up a couple of places on the list.

Produced by Altmetric – a London-based company that analyses and tracks online activity around academic papers – the top 100 is based on how many times a paper was directly linked to on the Web. However, the study does not take into account any discussion of papers on social media that do not link to the paper itself.

Top of the list was a paper about caesium contamination in freshwater fish following the Fukushima nuclear disaster in 2011 in Japan (*Scientific Reports* **3** 2554). This was Tweeted 10 100 times, with 70 posts on *Facebook* about the paper. However, the top physics paper – about creating "molecules of light" (*Nature* **502** 71) – came in at number 24 with just 670 Tweets and 69 mentions on *Facebook*. Another notable physics paper was the Voyager team's results of observations of the interstellar plasma as the spacecraft left the heliosphere (*Science* **341** 1489). This paper came in at number 66 and was Tweeted a paltry 70 times, with only 14 links on *Facebook*.

Many papers on the list, however, were slightly quirky, such as number 74, which was about how dung beetles use the Milky Way to orientate themselves (*Current Biology* **23** 298). Indeed, Altmetric points out that a paper's popularity on *Twitter* does not necessarily imply a high standard of research. Its presence rather depends on the research striking a chord with the public, or the ability to provide striking headlines for news outlets. This finding may disappoint researchers hoping that social media can propagate their results far and wide.

Gemma Lavender

Comment

physicsworld

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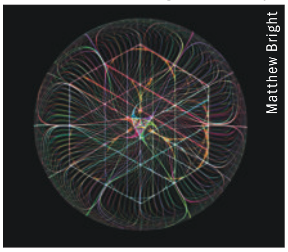
Reality show

"Fictional" models can be surprisingly useful to understand the real world

If you're wondering what the image on the cover of this month's issue is all about, then we can explain. Created by Matthew Bright – a graphic artist based in Australia – the picture seeks to depict "the internal mechanics at the heart of every atom". Bright produced the image, entitled simply *Electromagnetism*, for an online exhibition at a Melbourne gallery in 2011 to "elaborate on the fundamental geometry that has...guided the big thinkers over the past three millennia". It's not a faithful depiction of an atom – what image could be? – but it should nevertheless help us to appreciate the beauty of the subatomic world, even if it is a work of fiction.


Matthew Bright

In a similar vein, there are several instances in physics when "fictional" models of the world can generate real results. One famous example explored by the philosopher Margaret Morrison in this month's issue concerns the model of electromagnetism created in the 1860s by James Clerk Maxwell, which assumed the existence of an aether filled with rotating elastic vortices (represented by large hexagons) surrounded by circular electrical particles that act as "idle wheels" in a system of gears (see pp29–32). Maxwell hoped that his model would show how electromagnetic phenomena could be accounted for in terms of a field, rather than by charged objects acting at a distance.

Of course, no such wheels, vortices or aether actually exist. In fact, Maxwell himself knew his model was entirely imaginary. And yet the model – which also inspired Bright's image above – led Maxwell to derive his famous equations of electromagnetism, which showed that light and electromagnetic waves are one and the same. In other words, as Morrison explains, fictional worlds can give rise to reliable explanations. Maxwell's model proved so useful because it constrained how the physical and mathematical aspects of electromagnetic forces could be described. And without wanting to get too philosophical, what is reality anyway? As Morrison asks: "Are mathematical entities real? Or are they, too, a kind of fiction?" To find some possible answers to that question, you might want to read cosmologist Max Tegmark's feature (pp22–27).

Data deluge

Take part in a survey about how you share and access research information

Physicists today are faced with a huge variety of options when it comes to accessing and sharing scientific information with each other – from giant open data sets to images, software and open-access scientific papers, not forgetting all the new forms of social media. So to find out more about how information practices in the physical sciences are changing, IOP Publishing, which publishes *Physics World*, is working with the Research Information Network (RIN) – a "community-interest" company that carries out research into scholarly communication. You can help shape that understanding by taking a quick survey of your own information habits. And if you need a little sweetener, there's the option of entering a prize draw to win a $500 bursary to attend the academic conference of your choice.

● The survey is open until 10 February at http://ow.ly/sBnbV.

Critical Point The spot in the shadow

Robert P Crease observes a simple demonstration that is at once a compelling educational tool and a dramatic lesson in science history

"It's an extraordinarily simple set-up," says Hal Metcalf as he switches on a small laser pointer, creating a bright green spot about 2 mm in diameter on a wall 10 m away. He then clamps an upright nail to a stand and puts a magnet on its head, before carefully suspending a ball bearing from its tip.

Placing this stand between the laser and the wall, Metcalf adjusts the beam to hit the ball bearing. Its shadow is now surrounded by a glowing green halo, the whole resembling a miniature solar eclipse. Except for one thing: in the dead centre of the shadow is a green spot, glowing as brightly as if the ball were not there. Unbelievable!

A pioneer of laser cooling and a distinguished teaching professor at Stony Brook University, Metcalf gives this demonstration in his third-year optics course and in the university's Laser Teaching Center (LTC). He loves it. "There's no tricks. No lenses, no mirrors, nothing! Just a laser beam and small ball bearing."

It is one of several demonstrations that he and LTC director John Noé use to motivate students. Metcalf and Noé do them without using mathematics, until the students get curious enough about the mysterious happening to ask how to describe it. The ensuing conversations usually go like this:

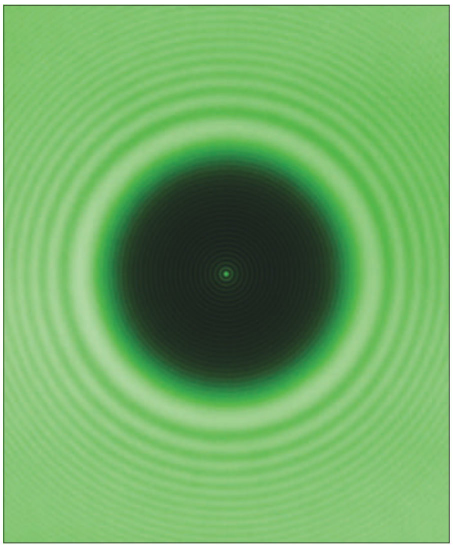
Metcalf: "It's easiest not to use English for the description but mathematics."
Student: "Really? What do I need?"
Metcalf: "Well, differential equations or matrix algebra or calculus…"
Student: "That's *all*?"

"You have to motivate students to want the maths," Metcalf adds. "I hate it when I hear, '*This* happens because it must satisfy *that* equation.' No it doesn't. *This* happens; *that* equation describes it."

But this demonstration – I'm not going to name it, for reasons I'll discuss – is not just a dramatic teaching aid. It is also an instructive episode in the ambiguities of discovery.

Fresnel, Poisson, Arago

At the start of the 19th century, the prevailing theory of light was Newton's "corpuscular" or particle theory, according to which light travels in straight lines. But in about 1807 the British scientist Thomas Young



Claim to fame Who should we credit for discovering the bright spot that lies in the centre of the shadow of an illuminated ball bearing?

demonstrated the wave-like nature of light through its interference effects. Opinion over the true nature of light was divided, not least among members of the French Academy of Sciences, most of whose members championed particles.

At the time, the academy held periodic competitions in a kind of miniature "grand challenge" series whose aim was to clarify controversial matters. And in 1818 it declared that diffraction would be the topic of the competition for the following year.

Enter Augustin-Jean Fresnel. In 1818 Fresnel was supporting himself as an engineer in Rennes, but seized every opportunity to travel to Paris to craft a wave theory of light inspired by Young's observations. He developed a way to calculate the net effect of a set of waves by resolving each wave into two components, adding the components and combining the results. Barely making the deadline, Fresnel entered the academy's competition with an essay proposing a theory that, he claimed, could allow the light intensity at any point behind a diffracting object to be calculated.

The committee charged with judging the competition was, however, dominated by partisans of the particle theory, including Siméon-Denis Poisson, who were sure Fresnel's theory was flawed. In fact, Poisson noticed what seemed to be a showstopper. According to Fresnel's work, if light were shone on a circular obstruction, a bright spot would appear in the centre of the shadow, as bright as if the obstruction were not there at all. Obvious nonsense! Not only that, Fresnel's equations indicated that light shining through a circular hole could produce a dark spot in the middle.

The committee's head was, however, François Arago – one of the few French scientists besides Fresnel acquainted with Young's work, and therefore able to appreciate Fresnel's contributions. Arago carried out the experiment with a flame, filters and a 2 mm metal disc attached to a glass plate with wax. To everyone's surprise, and Poisson's chagrin, Arago observed the spot and Fresnel won the competition.

The episode was deeply satisfying to Fresnel, even if he had little patience with mere praise. "All the compliments that I have received from [committee members] Arago, [Pierre] Laplace and [Jean-Baptiste] Biot," he wrote to Young a few years later, "never gave me so much pleasure as the discovery of a theoretic truth, or the confirmation of a calculation by experiment."

If the demonstration is so simple, I asked Metcalf, why wasn't it discovered earlier in things like eclipses? "The Moon's not nearly round enough," he snorted. "All those mountains! The Sun's not a point source of coherent light. People didn't always have laser pointers."

The critical point

The episode illustrates the ambiguities of discovery. Who's the discoverer? Fresnel, who produced the original framework? Poisson, who showed the spot was a direct consequence but was firmly convinced that it didn't exist? Arago, who did the experiment? Moreover, two other scientists turned out to have noticed the spot a century earlier but did not know what to make of it.

What about the French Academy, whose actions set the discovery in motion? Didn't Young play a role? Even Newton? Moreover, the spot is just an illustration of a more general phenomenon that complementary obstruction patterns produce complementary diffraction results, described by Jacques Babinet's theorem.

To pick out any one person, or combination, may be useful in education, in naming the phenomenon, or in dishing out awards. But philosophically, it's sloppy – like designating the most valuable player in a sports competition as the person who won it. The rigorous answer to the question "Who discovered that spot?" is the entire scientific community.

Robert P Crease is a professor in the Department of Philosophy, Stony Brook University, US, and co-editor-in-chief of *Physics in Perspective*, e-mail robert.crease@stonybrook.edu

Lighter, lower, longer

"Winning the race for growth" is what drives and motivates many politicians, but **Peter Goodhew** argues that physicists can contribute to the debate by arguing that bigger is not always better

Last year I watched a New York Metropolitan Opera House production of Wagner's opera *Parsifal* at a local cinema near my home. It was a great experience but it also allowed me to watch it with a clear conscience. Why? Because I only had to travel a short distance to see it, rather than getting on a plane to fly to New York. Not only that, but I had a very comfortable seat and best of all it cost me much less than going to a live performance. Is this the sustainable future of cultural events?

So how does this experience fit in with the often-repeated mantra of politicians around the world, and especially the UK prime minister David Cameron, of "winning the race for growth"? In the case of watching *Parsifal* at my local cinema, I grew the quality of my cultural life, but I did not help to grow the transport industry or the energy industries. Am I therefore an irresponsible citizen? Of course not.

iStock/KeithBishop

Reassess "Faster, higher, stronger" is a great motto for sports but should it be applied to economics?

I believe we actually need to lose the race for growth so that poorer countries can catch up

Halting efforts

Growth is usually measured (by both governments and the press) in terms of gross domestic product (GDP), which is defined as the monetary value of the goods and services we produce. GDP is used as a proxy for economic health, and ultimately for the health of our whole society. We are assured that – in the short term – GDP growth is the only way (or the least painful way) to recover from the problem of national debt.

Maybe, but what about the longer term?

As scientists we know that we cannot continue to use finite resources – principally energy and materials – at an ever increasing rate. At present the production of "goods" referred to above involves exactly this. The "success" of the UK's economy, for example, currently depends on the depletion of natural resources. Additionally, if we win this race for growth, we will have increased the gap between the rich – who won – and the poor, who lost. I believe we actually need to lose the race for growth so that poorer countries can catch up and we need to concentrate on GDP per capita to take account of changing populations.

I believe that it would actually be responsible of us to attempt to halt the growth of GDP per capita in the UK, and simultaneously try to stabilize or reduce the population. This is not in any way a counsel of doom. Those of you with metallurgical training will recognize the phenomenon of Ostwald ripening, which describes the change of an inhomogeneous structure over time, and also those of nucleation and growth. Within a closed system it is quite possible for individual entities to grow, although others must shrink to provide the resource. Successful companies can grow by innovating, thereby improving our quality of life, while others must shrink to provide the resource.

That is fine – 100 years ago stables shrank and garages grew. More recently, tape-recorder production dropped but hard-drive manufacture increased. When entities get too big (as the banks did a few years ago) we have to intervene to dissolve them, thus providing the resource for nucleation and growth of new entities, but without any need for new material or energy resources. To give another close-to-home example: I am happy to have a safer car with lower fuel consumption (quality improvements), but what we do not need is more cars or cars with a shorter lifetime. I do not think I am being patronizing when I say that the vast majority of voters in the UK do not understand the implications of a continuous positive rate of growth. But physicists do.

Towards a no-grow zone

What then should a physicist do about growth? First, challenge the word whenever you hear it, and ask that it be replaced by the phrase "increase in the quality of life". (If you are feeling particularly brave add "… starting with the poorest".) Second, read *Prosperity Without Growth* by the economist Tim Jackson because it shows that there is a credible alternative economic paradigm. Economists seem to be slow to catch up with real life. Only in 2013 did a movement begin that revised the economics syllabus to account for the fact that the economic theories currently taught failed spectacularly to predict the serious events of the past decade. Physicists are a bit better at revising theories in the light of new experimental data.

A third action is to get out in public more. I signed a petition in November calling for more scientists to be asked to join panel debates, such as those on the primetime UK TV show *Question Time*. Recently comedians have had six times more representation on this programme than scientists!

My fourth suggestion is a bit closer to home: do cheap experiments and stop using grant spending as a proxy for quality. At the risk of sounding like a Luddite, I believe that the most important questions of our age are not being answered – or even addressed – by big physics. At the moment, for instance, harvesting solar energy is more important than, and just as intellectually challenging as, dark matter. Finally, consider putting up a motto over the door of your lab. Not the Olympic Games' "Faster, higher, stronger" but its modern low-growth equivalent "Lighter, lower, longer". Then be prepared to explain to your visitors than you mean lower carbon, lower density, lower growth and longer lasting.

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Feedback

Letters and comments that appear here may have been edited.
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Nine billion or bust?

In reply to a review of Tony Ryan and Steve McKevitt's book *Project Sunshine*, which explores ways in which the Earth could support a future population of nine billion people ("Letting the sunshine in", November 2013 pp50–51, http://ow.ly/r0FTM).

What arrogance and blindness to assert that the planet can sustain nine billion or more humans. What about all the other sentient life forms in the planet? We are exterminating them very rapidly. Is that a planet worth living in? Just us, humans? I think not!

This book shows that the greed gene is a dominant one, along with many other genetic traits that make us very dangerous for any other life forms on our planet and in the galaxy.

There are studies that suggest that the carrying capacity of our planet is one or two billion people, max – let's plan for that goal. But what am I saying? The planet is already on it – at 400 ppm of CO_2 and climbing, the population will be reduced soon enough.

nerd nerd
via *physicsworld.com*

Nerd nerd, people just want to live. Motherhood is not greed. We have to change our attitude and realize again something we have known for the last several million years: that having children is good, that to a large extent having children is what life is about. If you don't have kids, what's the point? Nine billion humans? The number is paltry. A billion billion would still be insignificant in this universe.

Mike Pepperday
via *physicsworld.com*

Working out how to sustain more than nine billion of us? We must be out of our minds. Whatever befalls such an insane human population will be richly deserved. Too bad we'll be taking so much of the vitality and beauty that once graced this tragic planet with us.

a a z Szautner
via *physicsworld.com*

It's possible to sustain nine billion of us, but the problem is that we're throwing out and consuming more than what we are creating. Have a shower once a week if you're that concerned. If you have one every day then you, sir/madam, are a hypocrite.

kinkylampseatingbabies
via *physicsworld.com*

Other neutrino sources

In reply to the *physicsworld.com* news story "Cosmic neutrinos named *Physics World* 2013 Breakthrough of the Year" about the IceCube collaboration and its observation of high-energy cosmic neutrinos (13 December 2013, http://ow.ly/rJjLl; see also January p7).

I want to point out that the first neutrino observation in cosmic rays was done much earlier, in India. A collaboration of particle physicists from the Tata Institute of Fundamental Research (India), Osaka City University (Japan) and Durham University (UK) recorded the first cosmic-ray neutrino interaction in an underground laboratory in India's Kolar Gold Fields in 1965. As far as I know this was, of course, observed in a cosmic-ray shower and not as a direct high-energy neutrino observation.

pbarya
via *physicsworld.com*

IceCube is a breakthrough development for many reasons, but its detection of particles rather than electromagnetic radiation is not unique.

James T Dwyer
via *physicsworld.com*

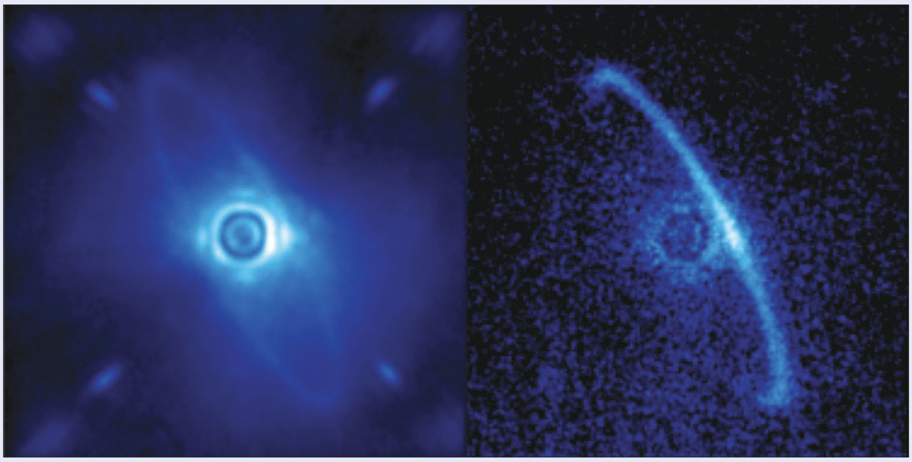
The editor replies:
You are right to point out that neutrinos from beyond the Earth have been seen in the past; the serendipitous detection of neutrinos from the 1987A supernova is another example. And of course, physicists have been studying solar neutrinos for some time now. However, we think it's safe to say that IceCube is the first true neutrino telescope that is designed to look beyond the solar system.

A lucky mistake

In reply to a review of Mario Livio's book *Brilliant Blunders*, which tackles history's greatest scientific mistakes ("Wrong turns and dead ends", December 2013 pp29–30, http://ow.ly/rrDmQ).

I have always considered that the best example of two cancelling blunders that still allowed a major success was the work of Niels Bohr. His theory of atomic structure neglected the zero angular

Young, dusty and beautiful



Gemini Observatory/Lawrence Livermore National Laboratory

This image – showing light scattered by dust orbiting the young star HR4796A – was taken by the Gemini Planet Imager, part of the Gemini South Telescope in Chile, and was chosen as our *Facebook* "Image of the Day" for 8 January.

Wait long enough and you'll see the dust coagulating into planets. (This might take a while.)
Richard Shorter
via *Facebook*

momentum orbital because his was a planetary model, and that orbital is one in which the electron is bouncing off the nucleus – clearly not acceptable in his view of the atom. With this assumption alone, there would have been no agreement with experiment. Fortunately, he made a second error: he assumed that the orbital angular momentum $L = 1, 2, 3, 4$, etc. (multiplied by $\hbar$). We know from quantum mechanics that it is really given by. $L = \sqrt{\ell(\ell+1)} \times \hbar$. Quite remarkably, the two errors cancelled each other, and Bohr was credited with a remarkable theory.
ogryzlo
via *physicsworld.com*

A new use for metamaterials

In reply to the *physicsworld.com* news article "Metamaterials offer route to room-temperature superconductivity" (3 December 2013, http://ow.ly/rpmWj).

In other words, we've hit a brick wall and we're willing to try anything.
Anthony Gianfrancesco
via *Facebook*

This could pave the way for some really cool stuff. Assuming that we do find a material that is superconducting at room temperature, it opens the possibility of usable hover technology through quantum locking. Until then, we are stuck flash-freezing discs to observe the phenomenon.
Joshua Dawes
via *Facebook*

Quantum levitation, however, relies on a magnetic rail and also possibly a current travelling through the material to produce such a magnetic force, thereby making the technology expensive and potentially impractical.
Oliver Rogers
via *Facebook*

True. But it would still make it easier to observe the effect in a lab or classroom environment. That, in turn, could lead to some pretty cool discoveries once the technology is more feasible to obtain in a more everyday situation.
Joshua Dawes
via *Facebook*

One man and the bomb

In reply to a review of Ray Monk's book *Robert Oppenheimer: a Life Inside the Center* ("Making sense of Oppenheimer", December 2013 pp35–36, http://ow.ly/rf0WH).

Oppenheimer would be horrified that anyone might consider him "father" of such a monstrous construction as the atomic bomb, which he actively legislated against for the rest of his haunted life. Only someone of the appalling and twisted ilk of Edward Teller would embrace such a miserable sobriquet – as Teller infamously did with the hydrogen bomb despite the fact that he was wrong in almost every scientific estimate regarding its theory, design, construction and yield.

No-one needs to make "sense" of Oppenheimer. They merely need to appreciate the sense in which his perspective was eminently coherent, if not prescient, for the age in which he lived. Imagine walking, clueless, into the Oval Office and attempting to communicate the horrors of this new weapon to President Harry Truman – a man with an enormous chip on his shoulder because his predecessor (FDR) despised him and kept him in the dark, like a mushroom, until his sudden death – only to be chased out as if he were little more than an errant schoolboy! And then to have the despicable Teller seek revenge on the witness stand for all the imagined abuses he believed Oppenheimer had heaped upon him at Los Alamos, stripping the latter of his security clearance and chairmanship of the Atomic Energy Commission. Why would a man filled with self-loathing and guilt and frustration with the general public's paranoid view of him as a purported communist sympathizer want to leave anything to posterity other than the hard facts of his accomplishments?

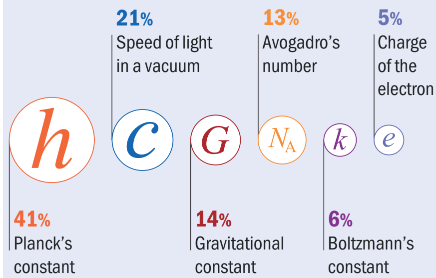
Ultimately, the lessons have not been learned, as we still have talented scientists designing and building some awful weaponry in the name of pure research.

Ckaspereli
via *physicsworld.com*

Oppenheimer was the head of the Manhattan Project, which had the atomic bomb as its intended end product. They succeeded in this task. They knew reasonably well its explosive power. The question is when Oppenheimer started to be horrified by this bomb and why.

M Asghar
via *phyiscsworld.com*

Poll results



What is your favourite physical constant?
This infographic shows the results of one of our *Facebook* polls, and shows a clear preference among our audience for Planck's constant.

Imagination in science

In reply to Robert P Crease's article "Moving the goalposts" (Critical Point, January p18, http://ow.ly/sBhWQ).

I always enjoy Crease's articles and turn to them first in every issue. But in this case, in describing the methodology of science, he misses the essential ingredient: imagination.

Like literature and art, science is created by imagination. From the earliest times, science was driven initially by imagination, then confirmed by reality. Archimedes' eureka moment occurred in the bath. August Kekulé dreamed of the benzene ring. Copernicus and Galileo were men of ideas, while Newton imagined the inverse square law of gravity and then validated it by his calculations. The wave nature of light, Planck's quanta, the nuclear atom and the double helix were all leaps of imagination.

New technology, too, is first imagined, then created. Think of James Watt, Michael Faraday, Thomas Edison, the Wright brothers at Kitty Hawk, Guglielmo Marconi, the Enigma machine, nuclear reactors, the atomic bomb, satellites, the PC and the Internet. Imagination is the key to progress, in science and in engineering.

Francis Farley
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A neutron discrepancy

In reply to a *physicsworld.com* news article on different results for the neutron lifetime obtained using storage-bottle and beam-based experiments ("Mystery of neutrino-lifetime discrepancy deepens", 4 December 2013, http://ow.ly/rrCze).

These time measurements are in the laboratory frame. What is the difference if you compare proper time for the neutrons in the bottle and beam experiments? I think the movements are different for these cases, leading to an observed difference in the lab frame.

Dkostyk
via *physicsworld.com*

I looked up the original paper from 2005, and they say that the beam is a cold neutron beam with an effective temperature of 40 K. This gives a median velocity of about 850 m/s (if my calculations are correct) which is only 0.0002% of the speed of light. This is certainly not enough to account for a ~1% difference in lifetime in the lab frame of reference.

seantellis
via *physicsworld.com*

Correction
In our feature article "The echoes of eternity" (November 2013, pp42–46), the rate of sea-floor spreading was mistakenly given as 1 cm per 1000 years. The correct figure is closer to 1 cm per year.

It's all just mathematics

The world can be described using mathematical equations and numbers, but why does maths do it so well? In his new book *Our Mathematical Universe*, a section of which is abridged and edited here, **Max Tegmark** makes the radical proposal that our reality isn't just described by mathematics – it *is* mathematics

Max Tegmark is a professor of physics, specializing in cosmology, at the Massachusetts Institute of Technology and is scientific director of the Foundational Questions Institute, e-mail ourmathematical universe@gmail.com

Extracted from *Our Mathematical Universe: My Quest for the Ultimate Nature of Reality,* published by Allen Lane at £25.00.

What is the answer to the ultimate question of life, the universe and everything? In Douglas Adams' science-fiction spoof *The Hitchhiker's Guide to the Galaxy*, the answer was found to be 42; the hardest part turned out to be finding the real question.

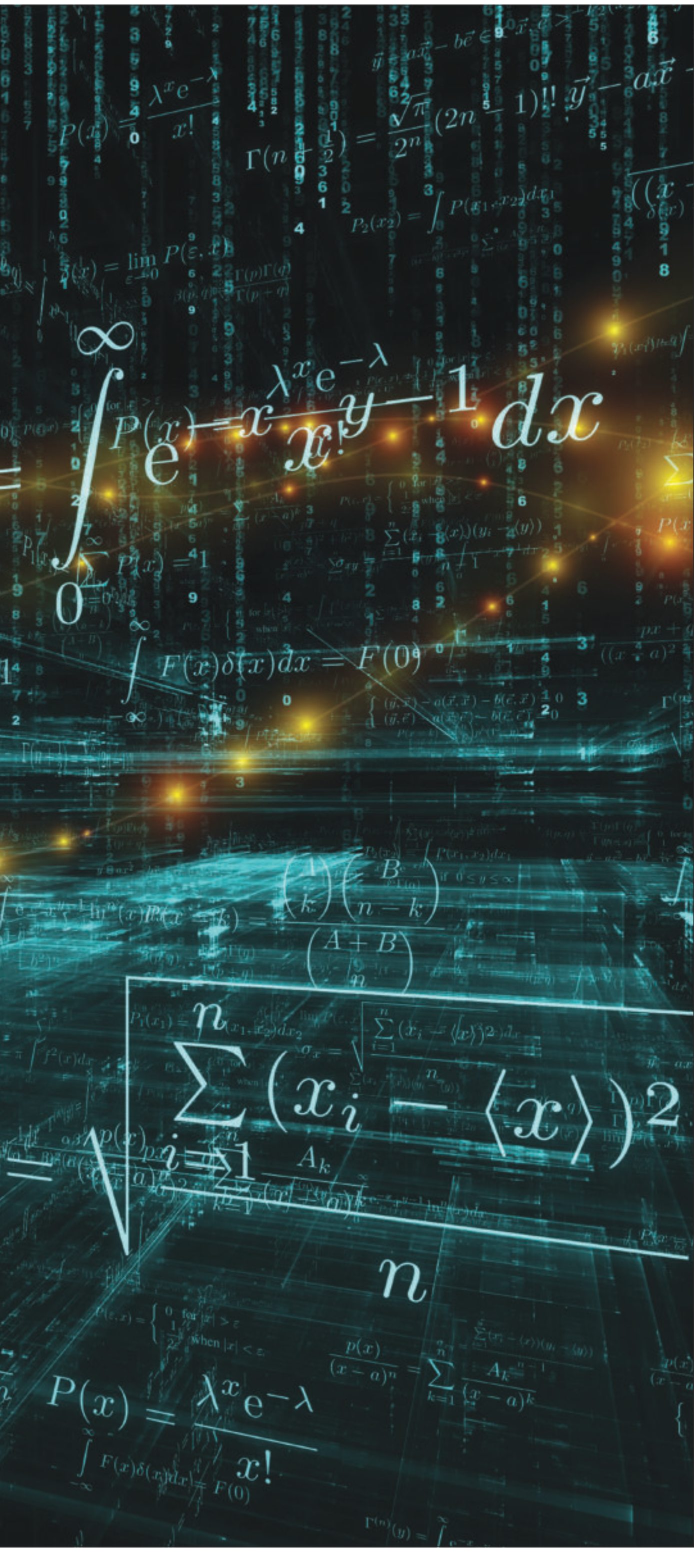
I find it very appropriate that Adams joked about 42, because mathematics has played a striking role in our understanding of the physical world. The idea that our universe is in some sense mathematical goes back at least to the Pythagoreans of ancient Greece, and has spawned centuries of discussion among physicists and philosophers. In the 17th century, Galileo famously stated that our universe is a "grand book" written in the language of mathematics. More recently, the physics Nobel laureate Eugene Wigner argued in the 1960s that "the unreasonable effectiveness of mathematics in the natural sciences" demanded an explanation.

Shapes, equations and numbers

Below we're going to explore a really extreme explanation. However, first I need to clear up what exactly it is that I'm trying to explain. Please stop your reading for a few moments and look around you. Where's all this maths that I'm going on about? Isn't maths all about numbers? You can probably spot a few numbers here and there – for example, the page numbers of this magazine – but these are just symbols invented and printed by people, so they can hardly be said to reflect our universe being mathematical in any deep way.

Because of our education, many people equate mathematics with arithmetic. Yet like physics, mathematics has evolved to ask broader questions. For example, Galileo spoke of geometric figures such as circles and triangles being mathematical, so when you look around you, do you see any geometric patterns or shapes? Here again, human-made designs such as the rectangular shape of this page don't count. But try throwing a pebble and watch the beautiful shape that nature makes for its trajectory. Galileo made a remarkable discovery (illustrated in figure 1*a*): the trajectories of anything you throw have the same shape, called an upside-down parabola. Moreover, the shape of a parabola can be described by a very simple mathematical equation: $y = x^2$, where x is the horizontal position and y is the vertical position (the height). Depending on the initial speed and direction, the shape can be stretched both vertically and horizontally, but it always remains a parabola.

When we observe how things move around in orbits in space, we discover another recurring shape,


Shutterstock/agsandrew

(illustrated in figure 1*b*): the ellipse. The equation $x^2 + y^2 = 1$ describes the points on a circle, and an ellipse is simply a stretched circle. Depending on the initial speed and direction of the orbiting object and the mass of the thing it's orbiting around, the shape of the orbit can be both stretched and tilted, but it always remains an ellipse. Moreover, these two shapes are related: the tip of a very elongated ellipse is shaped almost exactly like a parabola, so in fact, all of these trajectories are simply parts of ellipses.

We humans have gradually discovered many additional recurring shapes and patterns in nature, involving not only motion and gravity, but also areas as disparate as electricity, magnetism, light, heat, chemistry, radioactivity and subatomic particles. These patterns are summarized by what we call our laws of physics. Just like the shape of an ellipse, all these laws can be described using mathematical equations. Why is that?

Equations aren't the only hints of mathematics that are built into nature; there are also numbers. As opposed to human creations such as the page numbers in this magazine, I'm now talking about numbers that are basic properties of our physical reality. For example, how many pencils can you arrange so that they're all perpendicular (at 90°) to each other? The answer is three – for instance, by placing them along the three edges emanating from a corner of your room. Where did that number three come sailing in from? We call this number the dimensionality of our space, but why are there three dimensions rather than four or two or 42? And why are there, as far as we can tell, exactly six kinds of quark in our universe?

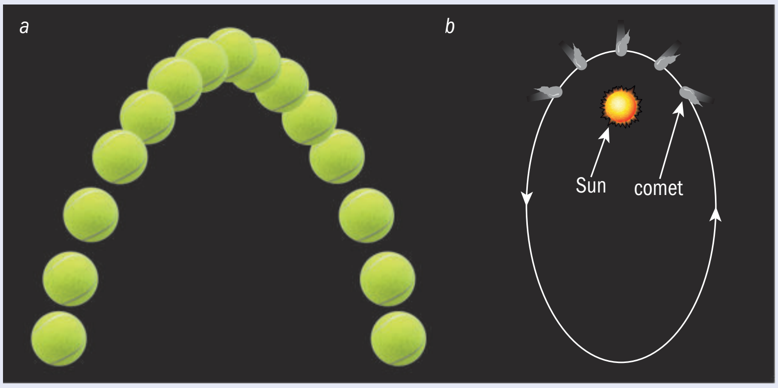
As if that weren't enough mathematical goodies, there are also quantities encoded in nature that aren't whole numbers, but require decimals to write out. Nature encodes 32 such fundamental numbers according to my latest count. Does the number shown when you stand on your bathroom scale count as such a number? No, that number doesn't count, because it's measuring something (your mass) that changes from day to day and therefore isn't a basic property of our universe. What about the mass of a proton, 1.672622×10^{-27} kg, or the mass of an electron, 9.109382×10^{-31} kg, which seem to stay perfectly constant over time? They don't count either, because they're measuring the number of kilograms, and that's just an arbitrary unit of mass that we humans have made up. But if you divide one of these last two numbers by the other, then you get something truly fundamental: the proton is about 1836.15267 times more massive than the electron. 1836.15267 is a pure number, just like π or √2, in the sense that it's a quantity that doesn't involve any human units of measurement such as grams, metres, seconds or volts. Why is it close to 1836? Why not 2014? Why not 42? The short answer is that we don't know, but we think we can in principle calculate this number and every other fundamental constant of nature ever measured from just 32 numbers.

So what do we make of all these hints of mathematics in our physical world? Most of my physics colleagues take them to mean that nature is for some reason described by mathematics, at least approximately, and leave it at that. In his book *Is God a Mathematician?*, the astrophysicist Mario Livio concludes that "scientists have selected what problems to work on based on those problems being amenable to a mathematical treatment". But I'm convinced that there's more to it than that.

First of all, *why* does maths describe nature so well? I agree with Wigner that it demands an explanation. Second, there are many clues suggesting that nature isn't just *described* by mathematics, but that some aspects of it *are* mathematical. Consider the

Why are there three spatial dimensions rather than four or two or 42? And why are there exactly six kinds of quark in our universe?

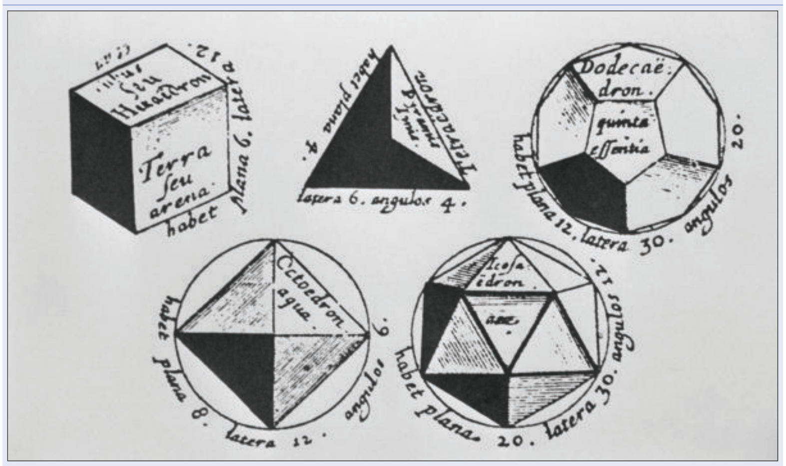
1 Patterns in nature



(*a*) When you throw something up in the air, its trajectory always has the same shape, called an upside-down parabola, if it doesn't collide with anything and air resistance is unimportant. (*b*) When something is orbiting something else due to gravity, its orbit always has the same shape, called an ellipse, which is a circle that is stretched in one direction.

2 A common language

Davisson's *Philosophia Pyrotechnia*/Science Photo Library



The five Platonic solids are the only 3D shapes with flat identical faces. Clockwise from top left, they are the cube, tetrahedron, dodecahedron, icosahedron and octahedron. In any language, be it human, mathematical or alien, only five such shapes exist.

very fabric of our physical world, space itself, which is a purely mathematical object in the sense that its only intrinsic properties are mathematical properties – properties such as dimensionality, curvature and topology. And in our physical world, all the "stuff" is made of elementary particles, which in turn are purely mathematical objects in the sense that their only intrinsic properties are mathematical properties: numbers such as charge, spin and lepton number.

The Mathematical Universe Hypothesis

I was quite fascinated by all these mathematical clues back in grad school. One Berkeley evening in 1990, while my friend Bill Poirier and I were sitting around speculating about the ultimate nature of reality, I suddenly had an idea for what it all meant: that our reality isn't just *described* by mathematics – it *is* mathematics, in a very specific sense that I'll describe below (limited here by space – the full version can be found in my book). Not just aspects of it, but all of it, including you, because if our physical world is mathematical, that makes us self-aware parts of a giant mathematical object. This idea sounds rather crazy and far-fetched, so after telling Bill about it, I mulled it over for many years before writing my first paper about it. Before delving into the details, here's my logical framework for thinking about this business. First, there are two hypotheses, one seemingly innocuous and one seemingly radical:

External Reality Hypothesis: *There exists an external physical reality completely independent of us humans.*

Mathematical Universe Hypothesis: *Our external physical reality is a mathematical structure.*

Second, I have an argument that, with a sufficiently broad definition of mathematical structure, the former implies the latter.

My starting assumption, the External Reality Hypothesis, isn't too controversial. I'd guess that the majority of physicists favour this long-standing idea, though it's still debated. Metaphysical solipsists reject it flat out, and supporters of the Copenhagen interpretation of quantum mechanics may reject it on the grounds that there's no reality without observation. Assuming that an external reality exists, physics theories aim to describe how it works. Our most successful theories, such as general relativity and quantum mechanics, describe only parts of this reality: gravity, for instance, or the behaviour of subatomic particles. In contrast, the Holy Grail of theoretical physics is a Theory of Everything – a complete description of reality.

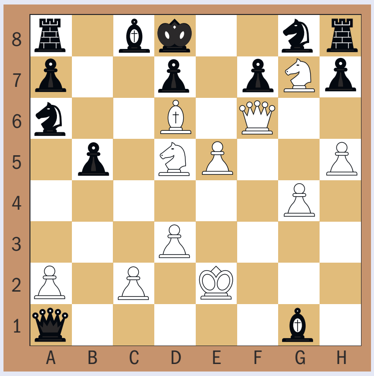
My personal quest for this theory begins with an extreme argument about what it's allowed to look like: if we assume that reality exists independently of humans, then for a description to be complete, it must also be well defined according to non-human entities – aliens or supercomputers, say – that lack any understanding of human concepts. Put differently, such a description must be expressible in a form that's devoid of any human baggage such as "particle", "observation" or other such words.

In contrast, all physics theories that I've been taught have two components: mathematical equations and "baggage" – words that explain how the equations are connected to what we observe and intuitively understand. When we derive the consequences of a theory, we introduce new concepts and words for them, such as protons, atoms, molecules, cells and stars, because they're convenient. It's important to remember, however, that it's we humans who create these concepts; in principle, everything could be calculated without this baggage. A hypothetical ideal supercomputer could calculate how the state of our universe changes over time without interpreting what's happening in human terms, simply by figuring out how all the particles would move or how the wavefunction would change.

But is it actually possible to find a description of the external reality that involves no baggage? If so, such a description of objects in this external reality and the relations between them would have to be completely abstract, forcing any words or symbols to be mere

3 Equivalent descriptions

less abstract, more baggage ⟷ more abstract, less baggage



1.e4 e5 2.f4 exf4 3.Bc4 Qh4+
4.Kf1 b5 5.Bxb5 Nf6 6.Nf3 Qh6
7.d3 Nh5 8.Nh4 Qg5 9.Nf5 c6
10.44 Nf6 11.Rg1 cxb5 12.h4 Qg6
13.h5 Qg5 14.Qf3 Ng8 15.Bxf4 Qf6
16.Nc3 Bc5 17.Nd5 Qxb2
18.Bd6 Bxg1 19.e5 Qxal+
20.Ke2 Na6 21.Nxg7+ Kd8
22.Qf6+ Nxf6 23.Be7

An abstract game of chess is independent of the colours and shapes of the pieces, and of whether its moves are described on a physically existing board, by stylized computer-rendered images or by so-called algebraic chess notation – it's still the same chess game. Analogously, a mathematical structure is independent of the symbols used to describe it.

labels with no preconceived meanings whatsoever. Instead, the only properties of these entities would be those embodied by the relations between them.

Mathematical structures

To answer this question, we need to take a closer look at mathematics. To a modern logician, a mathematical structure is precisely this: a set of abstract entities with relations between them. Take the integers, for instance, or geometric objects such as the dodecahedron, a favourite of the Pythagoreans. This is in stark contrast to the way most of us first perceive mathematics – either as a sadistic form of punishment, or as a bag of tricks for manipulating numbers.

Modern mathematics is the formal study of structures that can be defined in a purely abstract way, without any human baggage. Think of mathematical symbols as mere labels without intrinsic meaning. It doesn't matter whether you write "two plus two equals four", "2 + 2 = 4" or "*dos más dos es igual a cuatro*". The notation used to denote the entities and the relations is irrelevant; the only properties of integers are those embodied by the relations between them. That is, we don't invent mathematical structures – we discover them, and invent only the notation for describing them. If an alien civilization gets interested in 3D shapes with only flat identical faces, they might discover the five that we Earthlings call Platonic solids (figure 2). They might invent their own exotic names for them, but they can't invent a sixth one – it simply doesn't exist.

In summary, there are two key points to take away from our discussion above:

1. The External Reality Hypothesis implies that a Theory of Everything (a complete description of our external physical reality) has no baggage.
2. Something that has a complete baggage-free description is precisely a mathematical structure.

Taken together, this implies the Mathematical Universe Hypothesis – that the external physical reality described by the Theory of Everything is a mathematical structure. So the bottom line is that if you believe in an external reality independent of humans, then you must also believe that our physical reality is a mathematical structure. Nothing else has a baggage-free description. In other words, we all live in a gigantic mathematical object – one that's more elaborate than a dodecahedron, and probably also more complex than objects with intimidating names such as Calabi–Yau manifolds, tensor bundles and Hilbert spaces, which appear in today's most advanced physics theories. Everything in our world is purely mathematical – including you.

The Immortal Game

Earlier, I described how we humans add baggage to our descriptions. Now let's look at the opposite: how mathematical abstraction can remove baggage and strip things down to their bare essence. Consider the particular sequence of chess moves that has become known as the Immortal Game, where white spectacularly sacrifices both rooks, a bishop and the queen to checkmate with the three remaining minor pieces (figure 3). Here on Earth, this game was first played in 1851 by Adolf Anderssen and Lionel Kieseritzky. The same game is replayed annually in the town of Marostica, Italy, with live players dressed as chess pieces, and it's regularly repeated by countless chess enthusiasts around the world. Some players use pieces made of wood, while others use pieces of marble or plastic with different shapes and sizes. Some boards are brown and beige, some are black and white, and some are virtual, being mere 3D or 2D computer graphics. Yet there's a sense in which none of these details matter: when chess aficionados call the Immortal Game beautiful, they're not referring to the attractiveness of the players, the board or the pieces, but to a more abstract entity, which we might call the abstract game, or the sequence of moves.

Let's look in detail at how we humans go about describing such abstract entities. First of all, a description needs to be specific, so we invent objects, words

If you believe in an external reality independent of humans, then you must also believe that our physical reality is a mathematical structure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Playing the same game The chess piece known as the bishop in English has names with very different meanings in different languages. Mathematically, these descriptions are equivalent.

or other symbols to correspond to the abstract ideas: for example, in English, we call the chess piece that can move diagonally a "bishop". Second, it's obvious that this name is arbitrary, and that other names would have worked just as well – indeed, this piece is called a *fou* (fool) in French, *strelec* (shooter) in Slovak, *löpare* (runner) in Swedish and *fil* (elephant) in Persian. However, we can reconcile the uniqueness of the Immortal Game with the multiplicity of possible descriptions of it by introducing the powerful idea of equivalence:

1. We define what we mean by two descriptions being equivalent.
2. We say that if two descriptions are equivalent, then they're describing one and the same thing.

For example, we agree that any two descriptions of a chess position are equivalent if the only difference between them lies in the sizes of the pieces, or in the names that the players give to the pieces in their native language.

Any word, concept or symbol that appears in some but not all of the equivalent descriptions is clearly optional and therefore baggage. So if we want to get down to the bare essence of the Immortal Game, then how much baggage can we strip away? Clearly a lot, since computers are able to play chess without having any notion of human language or human concepts such as the colours, textures, sizes and names of chess pieces. To fully understand how far we can go, we need to make a more rigorous definition of equivalence:

Equivalence: *Two descriptions are equivalent if there's a correspondence between them that preserves all relations.*

Chess involves abstract entities (different chess pieces and different squares on the board) and relations between them. For example, one relation that a piece may have to a square is that the former is standing on the latter. Another relation that a piece may have to a square is that it's allowed to move there. For example, the left and centre panels in figure 3 are equivalent by our definition: there's a correspondence between the 3D and 2D pieces and boards such that whenever a 3D piece stands on a particular square, the corresponding 2D piece stands on the corresponding square. Similarly, a description of a chess position given purely verbally in English is equivalent to a description given purely verbally in Spanish if you can provide a dictionary specifying the correspondence between the English and Spanish words, and if using it to translate the Spanish description produces the English description.

When newspapers and websites print chess games, they customarily use yet another equivalent description: so-called algebraic chess notation (figure 3, right). Here, pieces are represented not by objects or words, but by single letters; "bishop" is equivalent to "B", for example, and squares are represented by a letter specifying the column and a number specifying the row. Since the abstract game description in figure 3 is equivalent to a description in the form of a movie of the game being played on a physical board, everything in the latter description that isn't in the former description is mere baggage – from the physical existence of a board to the shapes, colours and names of the pieces.

Even the specifics of algebraic chess notation are baggage: when computers play chess, they typically use other abstract chess-position descriptions, involving certain patterns of zeros and ones in their memory. So what is it that's left when you strip away all this baggage? What is it that's described by all these equivalent descriptions? The Immortal Game itself, 100% pure, with no additives.

In summary, any particular description of a mathematical structure contains baggage, but the structure itself doesn't. It is important not to confuse the description with that which is described: even the most abstract-looking description of a mathematical structure is still not the structure itself. Rather, the structure corresponds to the class of all equivalent descriptions of it.

Description versus equivalence

There's an important semantic issue that I would like to be very clear about. Whereas most of my physics colleagues would say that our external physical reality is (at least approximately) *described* by mathematics, I'm arguing that it *is* mathematics (more specifically, a mathematical structure). In other words, I'm making a much stronger claim.

Why? Everything I've said so far suggests that our external physical reality can be described by a mathematical structure. If a future physics textbook contains the coveted Theory of Everything, then its equations are a complete description of the mathematical structure that is the external physical reality. I'm writing "is" rather than "corresponds to" here, because if two structures are equivalent, then there's no meaningful sense in which they're not one and the same, as emphasized by the Israeli philosopher Marius Cohen (2003, "On the possibility of reducing actuality to a pure mathematical structure", Master's

If two structures are equivalent, then there's no meaningful sense in which they're not one and the same

thesis, Ben-Gurion University of the Negev, Israel). Recall the powerful mathematical notion of equivalence, as illustrated above in the Immortal Game, which embodies the very essence of mathematical structures: if two complete descriptions are equivalent, then they're describing one and the same thing. This means that if some mathematical equations completely describe both our external physical reality and a mathematical structure, then our external physical reality and the mathematical structure are one and the same, and then the Mathematical Universe Hypothesis is true: our external physical reality is a mathematical structure.

Remember that two mathematical structures are equivalent if you can pair up their entities in a way that preserves all relations. If you can thus pair up every entity in our external physical reality with a corresponding one in a mathematical structure ("This electric-field strength here in physical space corresponds to this number in the mathematical structure," for example), then our external physical reality meets the definition of being a mathematical structure – indeed, that same mathematical structure.

If someone wishes to avoid accepting the Mathematical Universe Hypothesis, they can do so by rejecting the External Reality Hypothesis that there's an external physical reality completely independent of us humans. They could then argue that our universe is somehow made of stuff perfectly described by a mathematical structure, but which also has other properties that aren't described by it, and can't be described in an abstract, human-independent, baggage-free way. However, I think this viewpoint would make the famous science philosopher Karl Popper turn in his grave, since he emphasized that scientific theories must have observable effects. In contrast, since the mathematical description is supposedly perfect, accounting for everything that can be observed, those additional bells and whistles that would make our universe non-mathematical would by definition have no observable effects whatsoever, rendering them 100% unscientific.

The future of physics

If I'm wrong and the Mathematical Universe Hypothesis is false, it means that fundamental physics is doomed to eventually hit a roadblock beyond which we can't understand our physical reality any better, because it lacks a mathematical description. If I'm right, then there's no roadblock and everything is in principle understandable to us. I think that would be wonderful, because then we'll be limited only by our own imagination.

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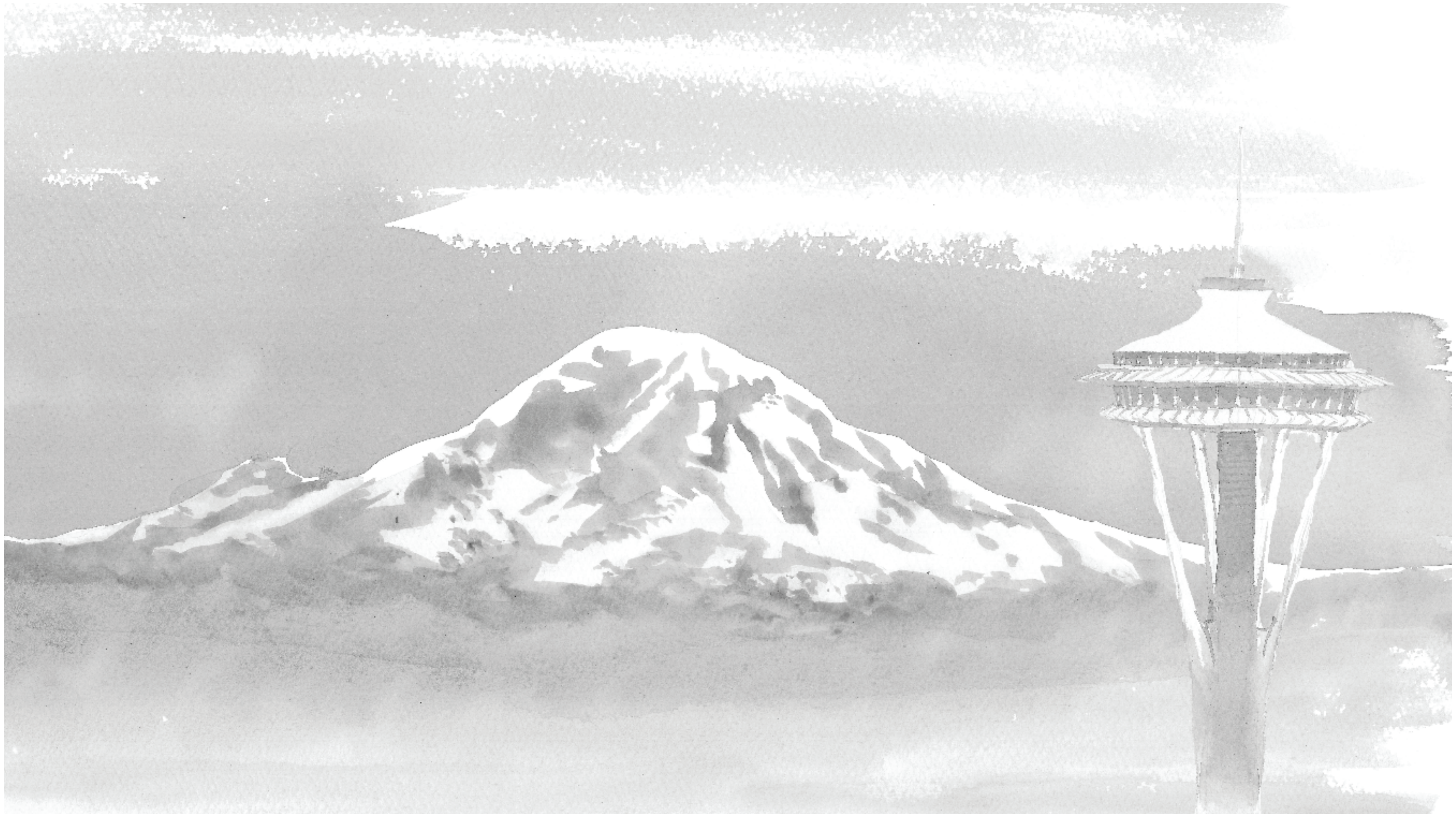

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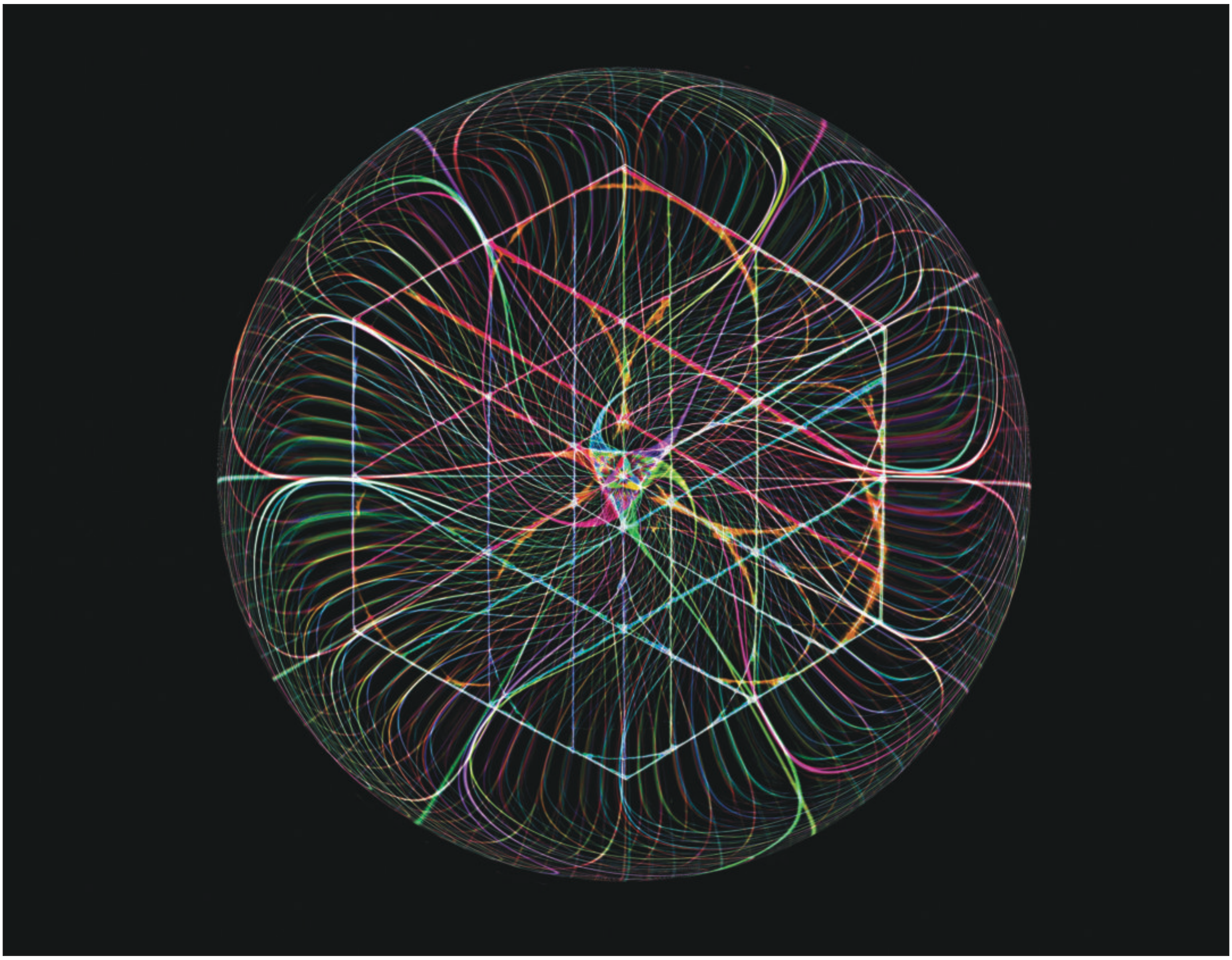

Fictional models in science

When James Clerk Maxwell set out his famous equations 150 years ago, his model of electromagnetism included a piece of pure fiction: an invisible, all-pervasive "aether" made up of elastic vortices separated by electric charges. **Margaret Morrison** explores how this and other "fictional" models shape science

Too often, the word "fiction" is used to describe highly speculative hypotheses put forward by modern science. This is especially true in high-energy physics, cosmology and astrophysics (to name a few). For example, string theory is frequently slapped with the "fiction" label because it fails to make empirically testable predictions, has a tremendously large number of solutions and involves a very large set of possible universes.

But to claim that this type of research is somehow science fiction rather than physics is to misunderstand not only the role that fictional modelling has in science, but also the importance of theoretical speculation. After all, James Clerk Maxwell's prediction of electromagnetic waves that travel at the speed of light was not testable when he made it in 1862; indeed, a quarter-century passed before Heinrich Hertz verified the existence of such waves. Similarly, when the Higgs boson was proposed in 1964 it was not testable either, and finding evidence for its existence took even longer.

Attempts to differentiate fiction from theoretical speculation give rise to an important question: how should we interpret scientific models that incorporate idealized, abstract descriptions that bear little resemblance to the physical and social world we inhabit? The question is important because much of our knowledge of physical phenomena, such as superconductivity and the Higgs boson (not to mention government decisions related to economic pol-

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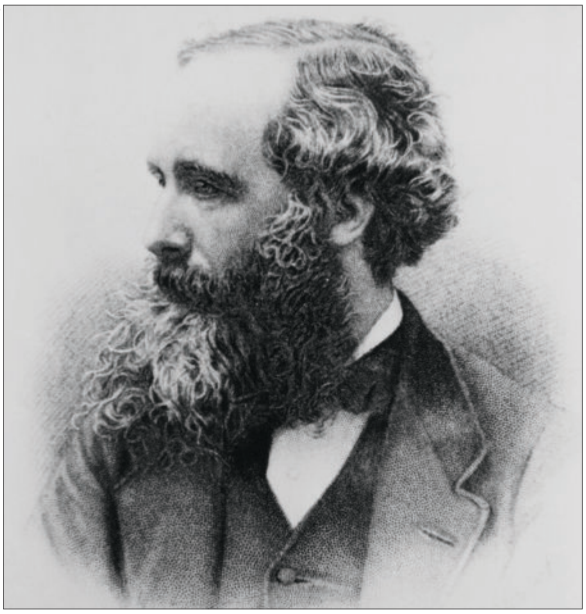


Master modeller James Clerk Maxwell created fictional models to understand reality.

icy and plans for urban development), originates with model-building activities.

From an ideal world...

In some contexts, such as architectural design, models are miniature replicas of what the finished building will look like. But in other fields, models are highly idealized descriptions of phenomena that don't (and won't) exist in nature. For instance, many economic models presuppose that people have perfect information about the economic system they are dealing with, and that all of us make wholly rational decisions on the basis of this information. No real person is capable of such behaviour, yet the idealized human known as "rational economic man" lies at the foundation of many economic models.

Similarly, in modern physics, gases are often modelled as if they were composed of infinitesimally small molecules that have no forces acting between them, when in fact molecules do have a finite size and are subject to intermolecular forces. And in population genetics, many models assume random mating and infinite populations when calculating the effects of natural selection.

These types of modelling share a common feature: although the basis for the model is in some sense a fictional entity (one that doesn't exist in reality), we know how to add corrections to the model to bring it closer to actual situations. We can adjust economic models in ways that incorporate relevant but less than perfect information; we can add mass and forces to gas models to make them more realistic; and we can use approximation techniques to adjust for populations that are very large but not infinite. Hence, although these models are fictional, there are strategies available that enable us to use them to explain and predict features that interest us.

But while I have used the word "fictional" to describe these models, this is somewhat of a misnomer. The model-maker's goal is not to create a fictional representation and see how (or whether) it compares with reality. Rather, the process of creating an ideal, abstract version of a system is often a way of making models more mathematically tractable, or of focusing on properties of interest for the problem at hand. For instance, when we want to model fluid flows, we do not take account of quantum properties; in fact, we sometimes don't even take account of frictional forces. Instead, the fluids are modelled in an "ideal" way. So in some sense, models of this type are not really fictional at all, because their aim is to provide accurate information about real phenomena.

Some models cannot be said to describe real phenomena even in principle, regardless of how many parameters are added

...to an imaginary one

Many models used in physics, economics, biology and other sciences involve descriptions that are fictional in a stronger sense. Models of this type cannot be said to describe real phenomena even in principle, regardless of how many parameters or approximations are added. For example, fictional models frequently occupy centre stage in econophysics, a field that uses physics techniques to study the dynamical behaviour of financial and economic markets. In statistical econophysics, economic agents are treated like microscopic particles in statistical physics: they are modelled as having no intelligence; their behaviour is completely random; and the mathematical outputs of the model are analogous to diffusion reaction models in physics. In this case the fictional, unrealistic aspects of the model(s) are its essential features, and part of its very structure. Moreover, there is no question of adding realistic parameters to it, since the model's fictional status is the reason it functions in the first place. Not only does it enable the user to manipulate large data sets in a relatively simplified way, it also highlights various aspects of financial markets that had not previously been studied in traditional economic analysis. These include phenomena such as the inverse relation between market stability and the range of financial instruments available for facilitating trades.

It is possible, of course, to object to this example on the grounds that the use of some econophysics modelling techniques was partly responsible for the financial crisis in 2008. For example, the famous Black–Scholes model, which describes how the prices of stocks and other financial instruments vary over time, assumes that price changes follow a Gaussian distribution where the probabilities of extreme effects are negligible. Unfortunately for the world's investors, wildly fluctuating markets – like physical systems exhibiting critical behaviour – resist this type of modelling. Instead, they require tools from dynamical systems theory (specifically renormalization group techniques) that allow for "fat-tailed" non-Gaussian distributions of price changes that take account of strongly correlated events. However, it is important to remember that these other tools are also idealized. Hence, it wasn't the *use* of highly idealized models that was the culprit in the financial crisis; rather, it was the use of the *wrong type* of model for the problem at hand.

Another example of the usefulness of fictional modelling can be found further back in the history of physics. To derive his famous field equations for electromagnetism, Maxwell relied on a model of the aether – the supposed carrier of light waves – that consisted of rotating elastic vortex cells separated by electrical particles. We know now that the aether does not exist, and Maxwell himself referred to his model as "imaginary". However, it nevertheless enabled him to formulate the equations governing electromagnetic phenomena, and to show that light and electromagnetic waves are one and the same.

Under these circumstances, it seems natural to ask how a fictional structure can deliver information about real concrete physical systems or financial markets. How do we get from a model that is "false" to information that is true or reliable?

Turning fiction into reality

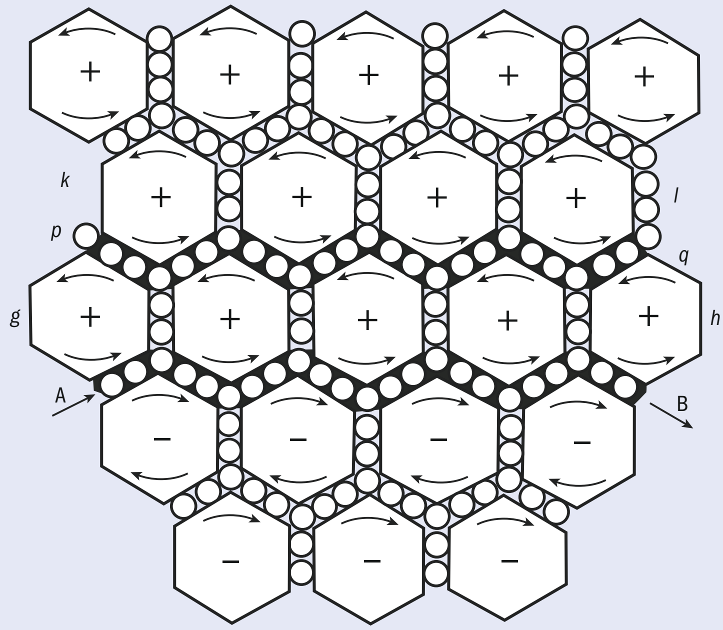
To see how a fictional structure can give rise to reliable explanations, let us look at Maxwell's work in more detail. His four equations – which appeared together for the first time in his 1861–1862 paper "On physical lines of force" (*Philosophical Magazine*, available online at http://ow.ly/scEDk) – describe the electric and magnetic fields arising from varying distributions of electric charges and currents, and how those fields change in time. Before Maxwell, accounts of electromagnetic phenomena had been based on (among other things) Ampère's law, which related the magnetic field to its electric current source. In addition, Michael Faraday had put forward the idea that the seat of electromagnetism was in the spaces surrounding wires and magnets, rather than in the objects themselves. Faraday used iron filings to visualize the patterns of electromagnetic forces in space, referring to their spatial distribution as "lines of force" that constituted a "field".

Maxwell hoped to build on this work by creating a model that showed how electromagnetic phenomena could be accounted for in terms of a field rather than by charged objects (which he interpreted as "centres of force") acting at a distance. He wanted to develop these ideas in a visualizable but mathematically precise way – a process that involved formulating equations that could describe the propagation of electromagnetic waves through space. This was especially challenging because, at the time, light waves were thought to be distinct from electromagnetic phenomena, and while there was supposedly an aether that carried light waves, no such structure existed for electromagnetic waves. So how could a fictional model enable Maxwell to derive field equations that ultimately identified light with electromagnetic waves?

To find the answer, we need to understand how the model first allowed Maxwell to mechanically represent wave propagation in a field, and then enabled him to formulate the proper mathematical equations describing behaviour such as the build-up of charge – all without any appeal to explanations involving charged objects. Maxwell constructed his model by assuming that the aether was composed of elastic "vortex cells", separated by electrical "particles" that acted like idle wheels in a system of gears (figure 1). These particles were assumed to exert tangential forces on the surfaces of the vortices, causing the vortices to deform. The resistance of the vortices to this deformation resulted in an inertial reaction force on the particles, which Maxwell identified as electromotive force.

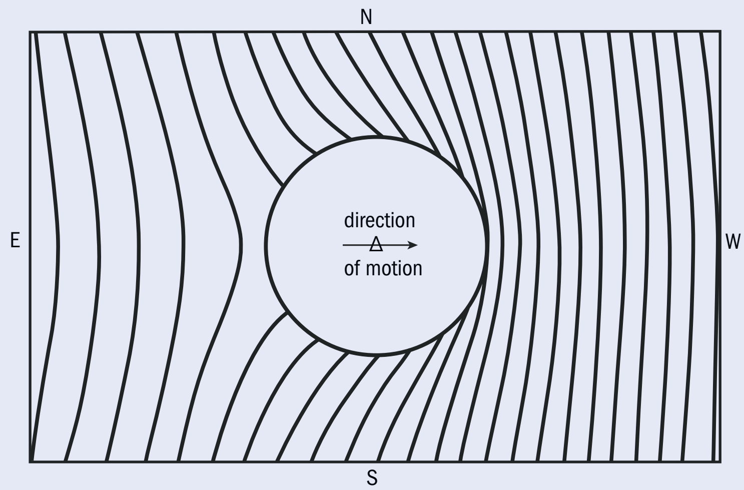
When the vortex cells in Maxwell's model rotated, their rotation set the particles between them in motion. This movement of particles was, naturally, interpreted by Maxwell as an electric current. However, Maxwell also reasoned that the progressive distortion of the vortices would cause the particles to move in the direction of the distortion (figure 2). This motion would produce an elastic restoring force that led to a reverse polarization, and hence a reverse current. Maxwell identified the distortion of the vortex cells as the displacement of electricity, and the current that resulted from it came to be known as the displacement current.

1 Wheels within wheels

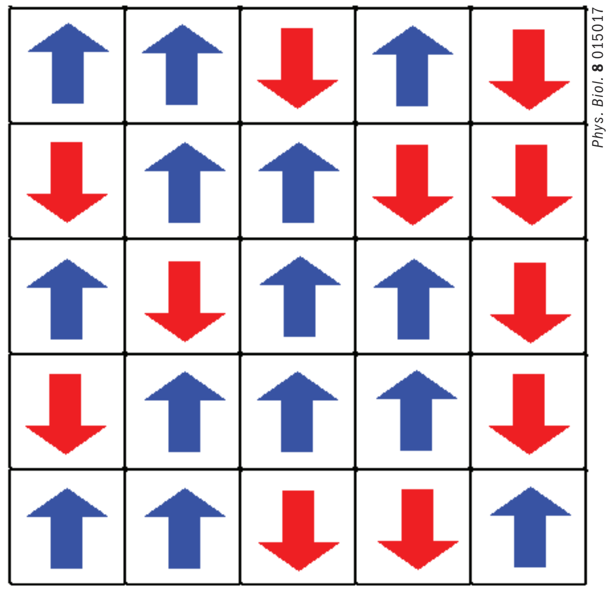


James Clerk Maxwell's schematic diagram of his model of electromagnetism, which hypothesized an aether filled with elastic vortices (represented by large hexagonal spaces) and surrounded by electrical particles (small circles) that acted as idle wheels. In the model, interactions between the vortices and the particles give rise to electromotive force, electric current and displacement current. If a current flows between point A and point B, the row of vortices labelled *g*–*h* will be set in motion in an anticlockwise direction (denoted +). The layer of particles *p*–*q* will be acted on by the *g*–*h* vortices, causing them to move in a clockwise (–) direction from right to left – thereby forming an induced electric current. If this current is checked by the electrical resistance of the aether, the rotating particles will act on the row *k*–*l* of vortices, causing them to also revolve in the (+) direction. This movement continues until the vortices reach a velocity such that the motion of the particles is reduced to simple rotation, resulting in the disappearance of the induced current.

2 A build-up of tension



In James Clerk Maxwell's diagram of his model of electromagnetism, the motion of the particles produces a distortion in the aether.



Ups and downs The Ising model represents atomic spins in one of two states. For instance, here is the plot of an idealized ferromagnet.

We can see how Maxwell's model worked by considering a basic circuit for charging a parallel-plate capacitor. When current flows through the circuit, electric charge will gradually build up on the capacitor plates. Maxwell's model accounts for this behaviour by suggesting that progressive distortion of the vortices in the space between the plates – and the displacement current such distortion produces – causes tension to build up in the aether. Maxwell identified this build-up of tension with electric charge.

The capacitor example is important because it represents a situation not covered by the original formulation of Ampère's law, which involved only closed circuits. But if electromagnetic waves were capable of travelling through space, as they do when current flows through the space between the capacitor's plates, then an additional term – the displacement current – needed to be added to Ampère's law to account for the free transmission of electricity. It was this displacement term that essentially represented the field theoretical features of electromagnetism.

Maxwell used this model of elastic, deformable vortices and the accompanying displacement of electricity as a basis for deriving his electrostatic force law. In doing so, he was able to account for the fact that a changing magnetic field induces an electric field and a changing electric field induces a magnetic field. This, in turn, led to his crowning achievement, which was not just to show that the electromagnetic field was responsible for the propagation of electromagnetic waves, but to calculate that the velocity of such waves coincides with that of light. Ultimately, what the various mechanisms in the model provided was a way of showing how electricity could travel in free space – all on the basis of a fictitious representation.

Seeking generalizations

In Maxwell's case, the route from fictional model to reality came via the fundamental mechanical features of the model, such as the vortices, the electrical particles and the ways they interacted. These features constrained how the physical and mathematical aspects of electromagnetic forces could be described, in much the same way as character development in a novel determines, to some extent, how the story will play out. In other words, the model furnished a "possibility structure" that helped bring into being the mechanical laws and equations representing the behaviour of electromagnetic field phenomena.

Of course, it remained for experiment to decide whether those equations matched reality. But understanding how the fictional model could function in this way requires a careful analysis of the model itself, one that includes both the kind of information the model yields and how that information can be used to develop physical hypotheses and predictions. Although the fictional representation supposedly bears a certain structural similarity to physical reality (for example, both obey mechanical laws) the model functioned as a self-contained entity in Maxwell's investigations. The model, rather than some experimental reality, was the object of inquiry, and predictions were made about the electromagnetic field on the basis of its output.

This example suggests that the answer to our question about how fictional models provide accurate information is that there is no general answer. The process takes place in a way that is specific to the particular model and system under investigation. For example, not all models display the kind of mechanical intricacy that Maxwell's did. A good example is the comparatively simple Ising model, which is used in explaining the behaviour of magnets and other types of phase transitions. It consists of a set of magnetic spins arranged on an abstract mathematical structure called a lattice. How such mathematical structures provide information about physical systems is also an important question for understanding scientific modelling. To answer that question we need to know how mathematics relates to the world. But are mathematical entities real? Or are they, too, a kind of fiction? ■

The lure of G

For over 200 years physicists have tried to pin down the value of the gravitational constant. **Jon Cartwright** finds out what's been taking them so long

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It was back in 1982, during his PhD, when Clive Speake first understood the true nature of gravity. "It was amazing," he recalls fondly. "I remember going out the night I had done the experiment for the first time, and I just looked up at the Moon. It had given me a completely different feel for what the Moon is, you know? Why it's there."

Such epiphanies are not uncommon among those who perform measurements of the gravitational constant. Gravity is the most famous of nature's forces, because it is the one that is most obviously present in our lives. Ever since Isaac Newton was inspired by a falling apple, everyone has known that it is gravity behind the inevitable phrase "what goes up, must come down". Yet despite our familiarity with gravity, few of us have experienced the force other than when it is directed towards the ground beneath our feet.

To see why, you need only look at the numbers. Gravity is the weakest force – 10^{36} times weaker than electromagnetism, the force that governs most other everyday phenomena. The only reason we can feel gravity on Earth is because it scales with mass: our planet's mass of five zetta-tonnes (5×10^{21} tonnes) is enough to bring gravity into the realm of normal human perception. But the force still exists between all other objects, and if you do ever witness it with Earth out of the equation – for example, in the faint shift of two suspended metal weights – it might at first seem like magic. "It's a liberating experience," says Speake, who is now based at the University of Birmingham in the UK.

Liberating – and infuriating. The gravitational constant – "big G", as it is commonly known – is what characterizes the strength of gravity according to Newton's law, and it is fiendishly difficult to measure. Experiments struggle to deliver uncertainties much smaller than one part in ten thousand – compare that, for instance, with the proton–electron mass ratio, which is known to four parts in ten billion.

Low precision alone is enough to keep a metrologist up all night. But in recent years, a much more serious problem has arisen: measurements of big G are in wild disagreement with one another (figure 1). Since the turn of this century, values recorded by some of the best labs in the world have been spread apart by more than 10 times their estimated uncertainties. Something is amiss – yet no-one is quite sure what. "You go over it, and over it, and over it," says Speake. "And there comes a time when you say, I just can't think of anything we've done wrong."

Measurements of big G are in wild disagreement with one another. Something is amiss – yet no-one is quite sure what

A massive task

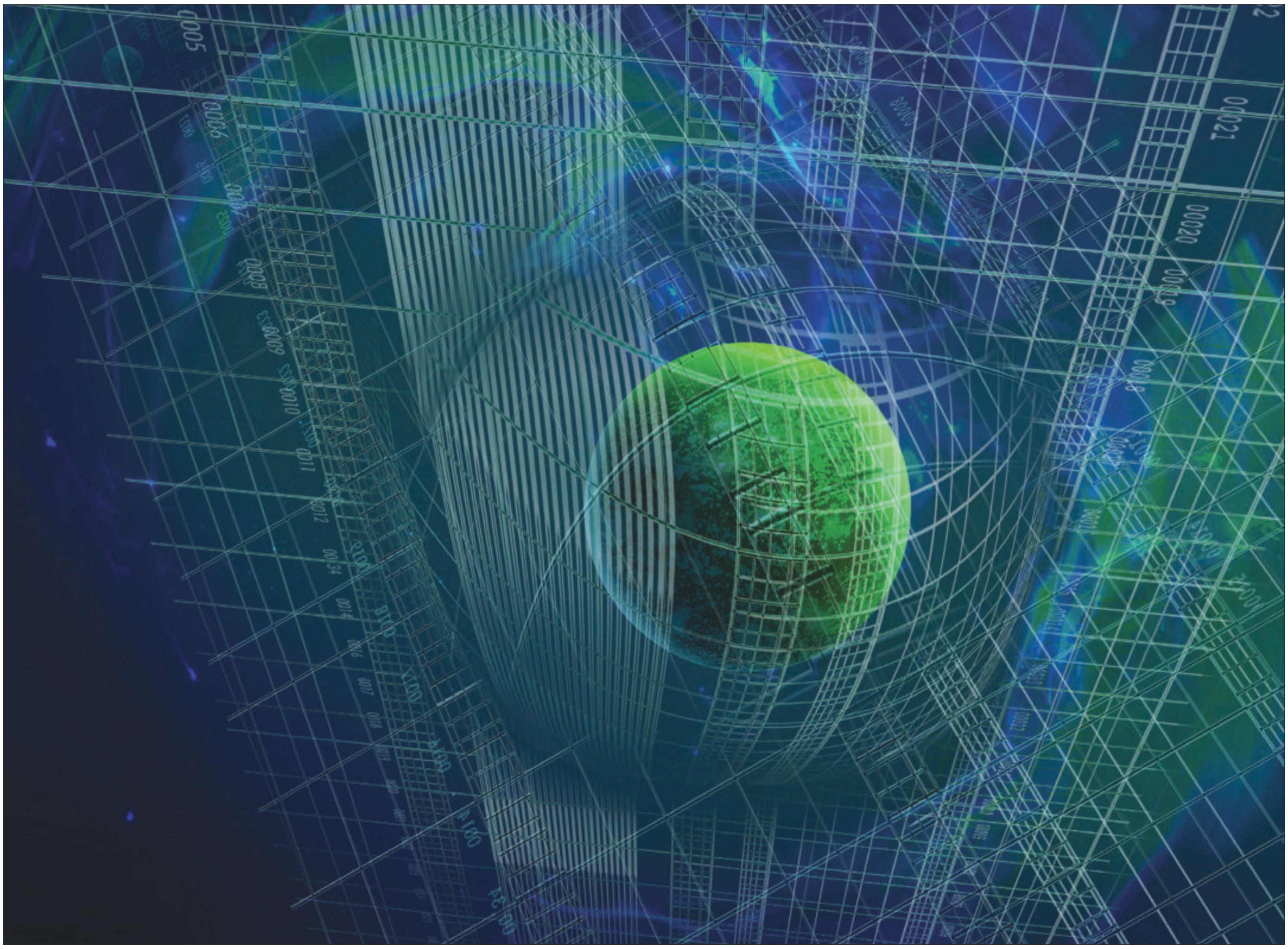
On the face of it, an experimental determination of big G should be straightforward. Newton's law states that the gravitational attraction between two bodies is proportional to the product of their masses, and inversely proportional to the square of the distance between them ($F = Gm_1m_2/d^2$). To generate the biggest force possible, therefore, one needs very big masses, very close together.

Of course, there are various other considerations. The masses ought to be made of homogenous materials, for instance, so that their centres of mass can be accurately located. It is also prudent to keep the apparatus small and seal it in a container, to avoid convection currents generated by temperature changes. But the biggest consideration is so-called "little g": the last headache an experimentalist needs is to measure not only the gravitational force between their test masses, but also the Earth's own gravitational pull.

In 1798 the British scientist Henry Cavendish famously evaded the little-g problem using a torsion balance he had inherited from the geologist John Michell (see photo on p36). A torsion balance consists of a vertical wire attached at its bottom to a horizontal beam, suspended on the ends of which are two known "test" masses. On either side of these a pair of larger, "source" masses is suspended separately. Once rotated a little from their starting position, these source masses cause the test masses to rotate due to gravitational attraction. Crucially, this rotation is perpendicular to – and thus unaffected by – the Earth's own gravitational pull, because the masses all hang vertically.

The rotation of the test masses twists the central wire, which in response exerts a restoring torque; at some angle, this torque matches the masses' gravity. By measuring this angle and knowing the torque generated for a given angle, Cavendish could estimate the gravitational force. Due to older unit conventions, Cavendish did not turn this into a value for big G, but his result is easily expressed in that form.

After Cavendish's experiment, not much changed in 200 years – at least in terms of basic apparatus.



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Hard to pin down
To this day, metrologists cannot agree on the value of the gravitational constant – the number that quantifies gravitational force.

There were modifications, such as the use of vacuum cans to exclude air resistance, and the use of materials with low susceptibilities to avoid magnetic effects. But by the early 1980s, physicists believed they had honed the torsion-balance technique so well as to settle on big G's true value: an experiment performed by Gabriel Luther and William Towler at the US National Bureau of Standards (now known as the National Institute of Standards and Technology, or NIST) in Washington, DC, gave big G as $6.673 \times 10^{-11}\,\mathrm{m^3 s^{-2} kg^{-1}}$ to within 75 parts per million (ppm) – a value that was subsequently adopted by the Committee on Data for Science and Technology (CODATA), which provides the internationally accepted values of the fundamental constants.

A second opinion

For about a decade, all was well. Then in the mid-1990s Winfried Michaelis and others at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, published what they believed to be a more reliable determination of big G. In place of a torsion wire they used a low-friction liquid bearing, the torque of which could be imposed electrically. The researchers calculated a value for big G of $6.715 \times 10^{-11}\,\mathrm{m^3 s^{-2} kg^{-1}}$ – a whopping 50 standard deviations greater than the CODATA value.

Either CODATA or the PTB group was wrong, but which? The problem with absolute measurements is that there is no default answer to fall back on. This is unlike null experiments, in which experimentalists look for a deviation from zero to see whether or not some effect is present – an example being the LIGO team in Washington state and Louisiana, US, which is patiently waiting for the appearance of laser interference that would signal the first direct detection of a ripple in space–time, or gravitational wave. "Most of the very precise experiments are null experiments – or differential measurements, where you're measuring the difference between two things," says Stephen Merkowitz at NASA's Goddard Space Flight Center in Maryland, US. "But absolute measurements are very hard, because of all the calibrations involved."

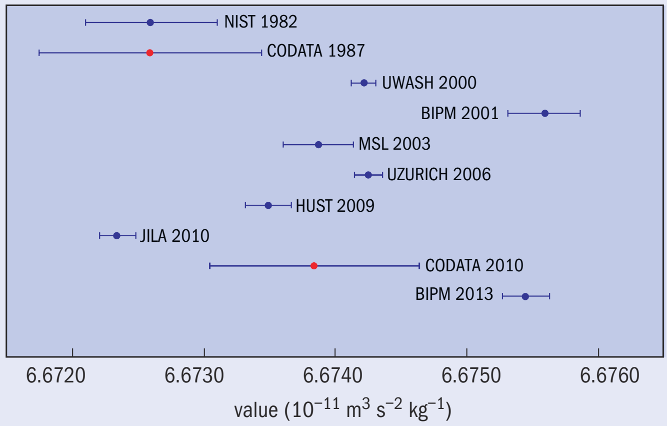
Merkowitz was one of many physicists who, in the wake of the PTB discrepancy, decided to measure big G for themselves. Working then at the University of Washington in Seattle, US, he and his colleague Jens Gundlach came up with an alternative design for a torsion balance in which a torsion pendulum and its associated test masses are rotated continuously on two separate turntables. The acceleration of the inner turntable holding the torsion pendulum could be adjusted to keep the torsion wire itself from twisting. Then, by monitoring the feedback to the inner turntable, the researchers could read off the gravitational force from the circling test masses and thus determine a value for big G.

Part of the appeal of this apparatus was that there

Science Museum/Science & Society Picture Library

The saga begins Henry Cavendish, in 1798, was the first to measure the force of gravity between masses in the laboratory. This scale model shows his torsion balance, which measures the angular torque due to two gravitationally attracting masses.

1 Disagreeing over “big G”



This chart shows wildly differing values of the gravitational constant, *G*, as measured by various high-profile research groups (blue). The values do not agree even within their error bars. Also shown are two values of *G* adopted by the Committee on Data for Science and Technology (CODATA) as international standards (red). The groups are based at the National Institute of Standards and Technology (NIST), the University of Washington (UWASH), the International Bureau of Weights and Measures (BIPM), the Measurement Standards Laboratory of New Zealand (MSL), the University of Zurich (UZURICH), the Huazhong University of Science and Technology (HUST) and the Joint Institute for Astrophysics (JILA).

could be no errors deriving from wire properties – particularly “anelasticity”, in which a wire’s stiffness changes with the frequency of twisting. As a result, Gundlach and Merkowitz could record an uncertainty of just 14 ppm. And yet, prior to their publication in 2000, they still had doubts. “We worried a lot,” says Merkowitz. “Were we forgetting something? And it’s true, we could have.”

Actually, there was good reason to worry. While their value for big G was lower than the PTB group’s, it was still far beyond the error bars of the official CODATA value. And further experiments did not clear up the situation. The next year, a group at the International Bureau of Weights and Measures (BIPM) in Sèvres, France, led by Terry Quinn and including Speake – who had retained a keen interest in precision tests of gravitation since his PhD work – measured big G using two different methods. They performed a torsion-balance experiment using both Cavendish’s technique of measuring the maximum angular deflection, and a new “servo” method in which the masses’ gravitational attraction is balanced by a measured electrostatic torque, such that the torsion balance does not move. Despite the combined result having a small uncertainty of 41 ppm, its value was 200 ppm above Gundlach and Merkowitz’s.

At least half a dozen other experimental groups had a go. In 2006 Stephan Schlamminger and colleagues at the University of Zurich in Switzerland found a similar value to the Washington group. But in 2010 Harold Parks and James Faller at JILA, an institute shared between NIST and the University of Colorado in Boulder, found big G to be 280 ppm below the Washington group’s – though oddly in line with the original CODATA value. The irony was that, by this time, the outlying PTB value that instigated the rush of these new measurements had been written off as a result of some stray capacitance.

Gaining support

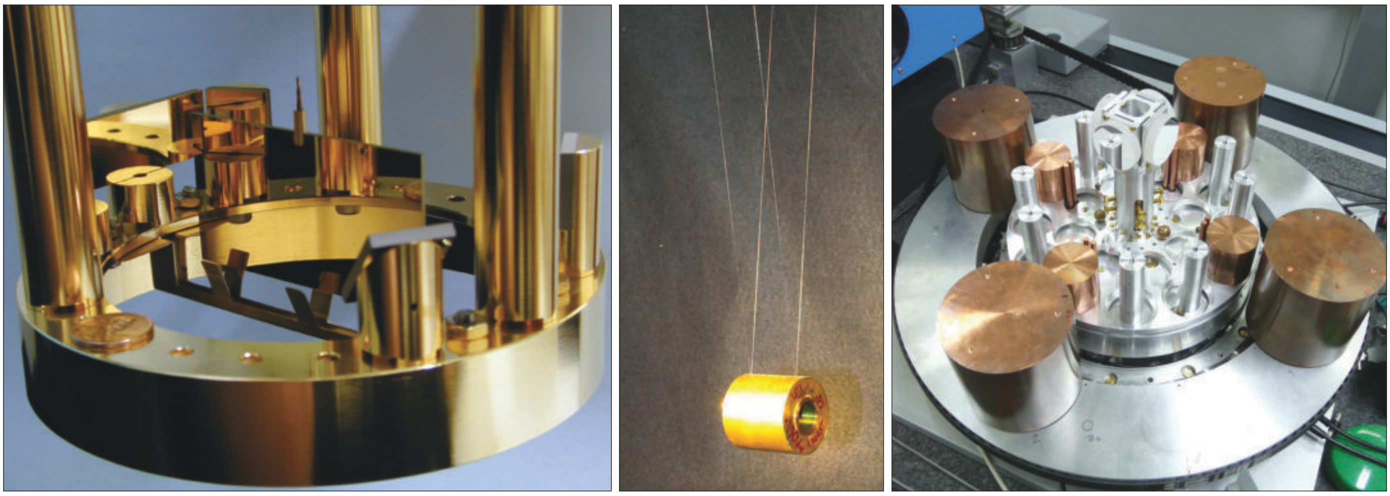
Ask the group members what the true value of big G is, and they all have confidence in their own measurements. But then they all speak highly of the other determinations, too. “It’s always difficult if you ask an experimentalist,” says Schlamminger. “They’ll say, ‘I know the true value of big G because I measured it!’”

Some would argue that the most reliable measurements are those that have been corroborated. Schlamminger and colleagues’ value, which agrees with the Washington group’s, has the distinction that it was based on a very different method, involving a beam balance. Used, for instance, by pharmacists, a beam balance consists of a sealed box containing a mass pan, which can measure weights to very high precision.

Schlamminger and colleagues modified their beam balance so that each of the two test masses could be hung from it: the first two metres below, and the second four metres below. This separation allowed the researchers to place two huge, 500 litre tanks of mercury either between the test masses, or above and below them. By measuring the weight differences between the test masses with the mercury tanks in each position, the researchers could extract a value of big G to within 16 ppm that was consistent with the Washington group’s.

The corroboration was looked upon favourably by CODATA, which in 2010 issued a new official value for big G that was close to the Zurich and Washington groups’ values, although with large error bars. To some in the gravity community, it seemed as though a new consensus was finally taking shape.

It wouldn’t last long. Quinn, who had retired as director of the BIPM in 2003, had already persuaded his old lab to support another big G experiment, to see whether his group’s abnormally high result using two different methods had been a fluke. When they accepted, he didn’t hang around. “I devoted almost



Stephen Merkowitz/University of Washington; James Faller/JILA; Terry Quinn/BIPM

Measuring up
Torsion balances are still used to measure "big G" – and shown here are the University of Washington group's pendulum hanging on a torsion wire (left) and an overall view of the BIPM team's partly dismantled apparatus (right). Meanwhile, the JILA team's experiment (centre) measured the displacement of small hanging pendulum masses as a result of the gravitational field from large, adjacent source masses.

all my time to it," he says. "You just ask my wife; she was not very pleased."

Between 2003 and 2007, Quinn, Speake and colleagues rebuilt almost all their apparatus. They executed an unprecedented number of checks and calibrations, which involved calculating the gravitational influence of every component, down to the last screw. Again, they calculated big G using both the Cavendish and servo method, to exclude a majority of systematic errors. But their result, published last September, was a shock: it was almost exactly as high as before (*Phys. Rev. Lett.* **111** 101102).

The situation now among big G experiments is a spread of values that scarcely overlap. Which raises the question: what will CODATA do when it meets again this August to assess the values of the fundamental constants? "The answer is, I don't know," says Quinn. "I have to say, I am a member of the CODATA panel that evaluates this, but I shall have to leave the room when they talk about it."

Human error

Could some sort of new physics be to blame, in which, for example, the value of big G changes depending on location in space–time? Few researchers think so: the spread of values is too inconsistent to suggest a new force is at work. But some have pointed to a phenomenon that could explain the discrepancy: intellectual phase-locking – or, in simple terms, seeing what you want to see. "People might say, 'Terry, you were an experimentalist in both of these [BIPM experiments],'" says Quinn. "'Did you somehow arrange it that you got the same answer?' Well, maybe I did – but we tried to take steps to avoid that."

Those steps were, essentially, to keep each of the different input parameters under wraps until the last minute, so that it would be impossible for any of the BIPM experimentalists to pre-empt the final value. And Quinn's group was not the only one concerned about such a possibility. "A lot of groups lose sleep in the run up to publishing a value," says Merkowitz. "Even if it agrees with another group's, you think: are we just stopping our analysis now, because it agrees? Or do we need to keep digging, looking for something else? Because you're never sure what the real value is."

Faller believes intellectual phase-locking is impossible to rule out. "Physicists don't like to get the wrong answer," he says. "You look over your shoulder, and you think, 'Oh my God! The last five people who measured it got a number that was higher than my group! What did I do wrong?' That's not the way to do science – but it is the way real people do science."

Even if intellectual phase-locking has biased some values, it has not prevented the overall discrepancy, and it is for this reason that most of those involved assume that the systematic errors have not all been taken into account. Speake quotes the former US defence secretary Donald Rumsfeld, who famously said there are "known unknowns" and "unknown unknowns". Unfortunately, each of the groups is confident its error bars are allowing for these unknowns. "I feel like we've got it right," Speake says. "But I can't point a gun at the other people and say, 'You've got it wrong.' Because I don't know enough about their experiments."

For that, journals could be partly to blame. *Physical Review Letters*, the journal in which most big G results have been published, usually limits papers to four pages; by comparison, Cavendish's original torsion-balance paper is 57 pages long. Many of those in the gravity community believe they have not had the opportunity to properly pick apart one another's techniques.

Fortunately, that opportunity may have finally come. This month, the Royal Society will convene a meeting at Chicheley Hall in Newport Pagnell, UK, of most of those involved in the recent measurements of big G. The hope is that the meeting will allow the metrologists to decide on the most likely sources of systematic error and, ideally, think up an experiment that would avoid them. Many of those contacted by *Physics World* revealed they already have ideas for new experiments – although they were not necessarily keen on performing them themselves. "I say you should never do the same experiment twice," says Schlamminger. "I mean, what would you do if you contradicted yourself?"

Yet like most metrologists who have tried to determine big G, Schlamminger refuses to give up the challenge. "It's difficult to measure it – that's why I want to measure it," he says. "You know, why do people climb Mount Everest? Because it's difficult." ■

Reviews

Patricia Fara

From Euclid to Einstein

Robert Hannah/Royal Institution of Great Britain/Science Photo Library

Heavy thoughts Colin Pask's book is effective as a new translation of Isaac Newton's *Principia* but less so as an introduction to Newton and his work.

Magnificent Principia: Exploring Isaac Newton's Masterpiece
Colin Pask
2013 Prometheus Books $26.00hb 528pp

Colin Pask is a very bossy author. "These chapters…should not be missed!" he instructs his readers. "You must read the final chapter," he orders. Reflecting this self-confident panache, the preface of his *Magnificent Principia: Exploring Isaac Newton's Masterpiece* is called "Why you should read this book". However, the only reason he gives is that Isaac Newton was important for modern science, which is true but unhelpful. I would like to ask Pask a different question: "Who did you write this book for?" Or, to put it more bluntly, "Who is likely to buy it?"

Books about Newton have three main target audiences: the general reader (whoever that might be), historians and scientists. All publishers and many writers have a mass market in sight, and – as James Gleick demonstrated in 2003 with his book *Isaac Newton* – it is certainly possible for a well-informed and detailed account of a scientific icon to be a bestseller. But as Stephen Hawking might or might not have remarked, every equation halves sales, and Pask's version of "Newton made lite" assumes (in an introductory section called "Fundamentals") that all his readers will be familiar with calculus. Although his equations and diagrams are not too off-putting for anybody with university-level mathematics, many potential purchasers will blench on flicking through what resembles an advanced physics primer.

In that sense, the immediate impact of Pask's book is not so very different from that of the original *Principia*. Pask reprimands Newton for using geometry and writing like Euclid, although this had nothing to do with Newton's decision to make the *Principia* difficult: the famously reclusive Lucasian professor wanted to keep out of the limelight and "avoid being baited by little Smatterers in mathematics". For Newton and many of his contemporaries, civilization had gone downhill since the time of the Greeks, and he was determined to recover the lost but pure knowledge of the ancients. Under his influence, British mathematicians spurned algebra until the early 19th century, mocking it as a fancy French practice of juggling with symbols devoid of real-world significance. It was only after a group of Cambridge undergraduates demanded to learn about the latest Laplace transforms and Legendre polynomials being used in Paris that the continental calculus originated by Gottfried Leibniz (or "Leibnitz", as Pask would have it) was imported across the Channel.

So what about historians? Would they buy Pask's book? The equations are not necessarily a deterrent, as a substantial proportion of science's historians (myself included) have first degrees in science. But would they want to brush up their rusty integration techniques? Personally, I abandoned physics not because it was too difficult, but because I found it boring. Other lapsed scientists who share my passion for the past would already be familiar with the content of the introductory historical sections of *Magnificent Principia* and would have little incentive to work their way through 400 pages of technical explanation.

Historians would also be wary of Pask's decision to present the *Principia* as a finished product. Like other historical inaccuracies, this reflects his preference for adulating Newton as a superhuman genius rather than appraising him as an extremely talented but fallible mortal. The *Principia* may well deserve Pask's accolade of magnificence, but it was neither a single-authored book nor one that appeared at a single moment in time. Pask's analysis is based on the *Principia*'s third edition, which was published four decades after the celebrated year of 1687. That might not matter too much if Newton himself had been responsible for all the revisions, but it was Roger Cotes, a young astronomy professor at Cambridge, who forced Newton to confront his mistakes and corrected many of them for him. Newton's attitude was surprisingly lackadaisical. "Such errors as do not depend upon wrong reasoning can be of no great consequence and may be corrected by the Reader," he pontificated from his superior position as president of the Royal Society. Undeterred, the more perfectionist Cotes – dismissed in one short paragraph by Pask as irrelevant – bombarded Newton with letters for years, repeatedly challenging his experimental results as well as his theoretical calculations, and refusing to accept any attempts to fudge the evidence.

In contrast, I imagine many practising scientists will welcome this book, which is effectively a guided translation of the *Principia*'s geometrical arguments into modern mathematical language. Yet even here, Pask's devotion to his hero sometimes tempts him to be misleading. An emeritus professor of mathematics at the University of New South Wales, Australia, he knows the differences between Galilean invariance and special relativity, yet he is so keen to claim Newton as the originator of everything that he implicitly elides them. Albert Einstein abhorred the meaningless cocktail-party phrase "Everything is relative" bandied about by artists and writers, but unwary readers could easily deduce from this book that special relativity is merely a modification of the classical theory.

Pask's devotion sometimes tempts him to be misleading

People who are convinced that Newton was the first great scientist have to face the tricky truth that Newton was deeply religious, which didn't just mean going to church on Sundays. Pask omits to point out that Newton could never have subscribed to modern relativity theory because for him, there had to be an absolute time and space: they were God Himself, and He was immanent throughout the universe. Today's Newtonianism is deterministic, but that feature was introduced by Pierre Laplace, the self-styled French Newton, at the end of the 18th century. To the disdain of Leibniz and other critics, Newton posited a God who intervened from time to time by sending in comets with animated tails. Newton derived the concept of an active nature, a "perpetual worker", from his alchemical studies – a crucial topic ignored in this study.

Newton remains one of science's most revered figureheads. Yet paradoxically, he would have been appalled by modern Newtonian models of the cosmos, because they leave no place for spirit. He wasn't even a scientist (a word not invented until 1833), but a natural philosopher who regarded the Bible, alchemy and experimentation as three related routes towards God. And he broke all the rules in the scientific code of behaviour by sometimes twisting the facts to fit his preconceptions – a tendency that is, regrettably, occasionally shared by Pask.

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Kate Brown

Alices in a nuclear Wonderland

Oak Ridge National Laboratory/Department of Energy/AIP Emilio Segrè Visual Archives

New perspective Women made up a significant portion of the workforce on the Manhattan Project but their stories are rarely heard. Here, operators in the Y-12 calutron control room at Oak Ridge National Laboratory (c. 1945) produce enriched uranium.

The Girls of Atomic City: the Untold Story of the Women Who Helped Win World War II
Denise Kiernan
2013 Touchstone Books £16.67/ $27.00hb 373pp

Denise Kiernan's *The Girls of Atomic City* tells the story of a dozen women who left rural America in the early 1940s and tumbled suddenly, like Alice down the rabbit hole, into the nascent US military-industrial complex, with all its regulations, factory discipline, dangers and surveillance. These women, along with thousands of others like them, made up the major part of the labour force of the factory in Oak Ridge, Tennessee, that enriched uranium for the Manhattan Project's first atomic bomb. Kiernan narrates the story from the perspective of these ill-informed young women, who worked in blackout security conditions with no information about what they were doing, or why.

In this accessible account, each woman's story, derived from Kiernan's oral interviews, is spliced together with that of the others. To provide some of the background that "the girls" themselves lacked at the time, Kiernan intersperses their personal stories with chapters on "tubealloy" – the code name for uranium. These chapters give the standard account of the Manhattan Project, featuring the big men whom Kiernan refers to as "The General" (Leslie Groves), "The Scientist" (J Robert Oppenheimer) and "The Engineer" (Kenneth Nichols). For this master narrative, Kiernan draws on a couple of dozen archival documents, and relies heavily on the book *City Behind a Fence* by Charles Johnson and Charles Jackson, along with Peter Bacon Hales' masterful *Atomic Spaces*.

The tales of "the girls" frequently stress their naivety, ignorance and fear of security officials. However, in writing about them, Kiernan focuses on conventional "women's issues" to the point where, at times, the prose descends to the mundane. For example, when Celia Szapka and a few of her fellow northerners stopped at a café near the end of their journey to Oak Ridge, Kiernan writes, "One menu item puzzled them…None had heard of any such thing as 'grits'." Kiernan explains that Szapka's Polish mother had cooked mostly potatoes, rather than the cornmeal porridge that was (and is) a staple of southern American food.

Celia liked the grits, and in the book they form part of her "arrival" story – one of many stories in the book to contain first impressions of Oak Ridge. This muddy town of hutments, prefab housing and corrugated steel structures took shape quickly, accommodating 75 000 new residents in just a few months, but in Kiernan's account, the reader learns less about the effects of placing a dangerous plant in the middle of a rural community or about the women's work, and much more about their food, dating, wardrobe, weddings and families. *The Girls of Atomic City*, as a consequence, reads like *Physics World* welded to *Good Housekeeping*.

This is a shame because Kiernan provides some fascinating material that adds to the history of the Manhattan Project. Rosemary Maiers, who had worked as a nurse at Oak Ridge's first medical clinic, related to Kiernan the story of a young naval ensign who suffered a nervous breakdown at the plant and started to do exactly what was forbidden: he talked, babbling on and on about the secret plant and the weapons it was going to produce. Afraid to release the voluble young man to medical care away from the nuclear reservation, the site psychiatrist Eric Clarke commandeered an apartment and locked the sailor in, treating him with electric shock therapy.

Kiernan also recounts how some women, just out of high school, operated the plant's array of "calutrons" – the large electromagnetic separators built to disentangle U-238 from U-235. The women challenged the male scientists at Ernest Lawrence's lab in Berkeley, California, where the calutron was invented, to a race to see who could generate more "product" (enriched uranium) per run. The "girls" handily beat the California PhDs. Lawrence explained his team's loss with condescension, rationalizing that his crew was always fiddling with the dials trying to make the calutrons run faster and smoother, while the girls stayed on task precisely following directions. Kiernan doesn't question why, then, the PhDs, with all their extra knowledge and expertise, didn't in fact succeed in producing more enriched uranium, more quickly.

Later in the book, Kiernan provides intriguing new material on the story of Ebb Cade, a black employee who, after landing in the Oak Ridge hospital following a car crash, was deployed as a human lab rat. Expecting that Cade would soon die of his injuries, Manhattan Project doctors injected a sizable dose of plutonium into his veins to see how much lodged in his body. For this part of her story, Kiernan quotes from an oral history by Karl Morgan, a health physicist. Morgan described how Robert Stone, one of the leading lights of the Manhattan Project medical programme, told him about the opportunity the badly injured Cade presented when he was checked into the hospital: "Karl, do you remember that [racial epithet] truck driver that had this accident some time ago?" Stone then laid out how they planned to take samples of bone, liver and other organs from Cade's body after his death.

When Cade refused to expire, Stone and the other doctors nevertheless held off setting his broken bones for 90 days in order to let the plutonium travel through his body before taking bone samples during surgery. As another consolation prize, they extracted 15 teeth, which they determined Cade no longer needed, as sample material. Kiernan recounts how in Morgan's version, Cade, clearly suspicious of his "treatment" at the hospital, ran away as soon as he was ambulatory, taking with him his valuable plutonium-laced urine, faeces and organs. Unfortunately, much of the incriminating material of this story is buried in the endnotes. More distressing, Kiernan describes the event and lets it lie, undigested, for her readers to figure out just what this episode means to her larger history.

Kiernan describes the event and lets it lie, undigested, for her readers to figure out just what this means

So what is the message of *The Girls of the Atomic City*? Kiernan doesn't directly state it, but she implies that she is adding to the trope of the "greatest generation" – the journalist Tom Brokaw's description of the Americans who grew up with the deprivations of the Great Depression and made a decisive contribution to the war effort. Kiernan is right to suggest that women, too, numbered among the Americans who worked, sacrificed and soldiered on selflessly for a just cause, although she is by no means the first to do so. But in seeking to balance between "commemoration and celebration", Kiernan draws back from assessing the impact of this pioneering nuclear-weapons community on democracy, civil rights and public health. While she sporadically acknowledges that there were problems – including the loss of civil rights, incessant surveillance, segregation, gender and racial discrimination, medical experimentation on unwitting human subjects and (though Kiernan does not address it) residents being unknowingly subjected to toxic and radioactive contaminants – her narrative choices unfortunately lead the reader to feel a lot like Alice, lost in a historical Wonderland with little direction or analysis.

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Web life: *Voices of the Manhattan Project*

URL: www.manhattanprojectvoices.org

So what is the site about?

Voices of the Manhattan Project was launched in October 2012 with the aim of preserving the memories and experiences of scientists and other workers who participated in the US-led effort to build an atomic bomb during the Second World War. Backed by two non-profit organizations, the Atomic Heritage Foundation and the Los Alamos Historical Society, the site hosts a rich archive of audio and video interviews with Manhattan Project veterans, as well as written transcripts.

Who are the interviewees?

There are a few famous faces in the collection, including Roy Glauber, who won the Nobel Prize for Physics in 2005 for his work on quantum optics; John Wheeler, the theorist who coined the term "black hole" and influenced a whole generation of physicists; and Alvin Weinberg, who later became director of Oak Ridge National Laboratory. However, most of those interviewed are relatively obscure figures, and their stories are all the more fascinating for it. A good example is an interview (http://ow.ly/sz8kV) that the journalist Stephen L Sanger conducted in 1989 with a husband-and-wife pair, Vincent and Clare Whitehead. The Whiteheads met when they were both working in military intelligence at the plutonium plant at Hanford, Washington, and Vincent's story, in particular, makes a useful counterpoint to Richard Feynman's better-known tales of playing pranks on security personnel at Los Alamos. "There was a code name given to each piece of apparatus, and some of those professors, for Christ's sake, would just in the clear say the description," Whitehead recalls with disgust, before joking "Have you ever tried to get an egg back into a hen?"

How is the site organized?

As well as searching for the names of specific interviewees, it is also possible to filter the collection according to common themes such as "Security and secrecy" or "Environmental impact" and by the location where people worked. The location filter is interesting because it highlights the scale of the Manhattan Project. In addition to interviews with those who worked at the well-known facilities in Hanford, Oak Ridge and Los Alamos, the archive also incorporates the experiences of people employed at a chemical plant in Colorado, the University of Cambridge, UK, and at universities across the US. There is even an interview with one Robert Furman, who, as an assistant to the project's military chief, General Leslie Groves, participated in the Alsos Mission to locate and capture German atomic scientists in Europe during the spring of 1945.

Why should I visit?

Most of today's physicists are too young to have worked on the Manhattan Project, or even to remember the era in which it took place. In 2014, as people across Europe commemorate the centenary of the outbreak of the First World War – a conflict that is now almost entirely beyond the reach of living memory – it makes sense to listen, while we still can, to those who lived through this crucial aspect of the war that followed on the heels of that earlier fight. Indeed, several of the people whose oral histories can be found in the site's archive have already died, making their interviews all the more precious.

Between the lines

iStock/goktugg

Physics in wartime The problem with being an "apolitical" scientist under a murderous dictatorship.

Morally ambiguous science

Werner Heisenberg was not a Nazi, but his willing service to Hitler's government as the head of Germany's wartime atomic weapons project has proved a lasting stain on his character. Max Planck was the dean of pre-war German science and a man whose personal decency impressed all who knew him, yet he was notably quiet in the face of Nazi repression. The chemical physicist Peter Debye left Germany for the US in 1940, but his departure may have been driven by academic politics rather than moral principles. These ambiguities of character – along with many others – are explored thoroughly and thoughtfully in Philip Ball's book *Serving the Reich: the Struggle for the Soul of Physics Under Hitler*. Ball focuses on Heisenberg, Planck and the lesser-known Debye because they are neither villains nor heroes. Unlike their fellow Nobel laureates Philipp Lenard and Johannes Stark, who dismissed relativity and quantum theory as a "Jewish conspiracy", they did not allow ideology to influence their work; however, they did seem to regard their pursuit of scientific truth as a licence to ignore the momentous events taking place around them. The idea that scientists should "rise above politics" still has its adherents today, but in some of the book's best passages, Ball calls it into question. The biggest problem with the behaviour of Heisenberg, Planck and Debye is not, he suggests, that they failed to actively resist the Nazis. After all, he writes, "it is a brave person who asserts without hesitation that he or she would have done better". Instead, it is their failure even to engage with the idea that they, as scientists, bore some responsibility for the work they did and the regime under which they did it. Being an "apolitical scientist" is itself a political decision, Ball argues, and as his book demonstrates, it is not always the right one.

- 2013 Bodley Head £20.00 320pp

One universe, one community

The roots of radio astronomy can be traced to the Second World War, when pioneers such as Edward "Taffy" Bowen, Bernard Lovell and Martin Ryle were all part of the British radar effort. In his book *A Single Sky: How an International Community Forged the Science of Radio Astronomy*, the science historian David Munn explores how the development of this then-new discipline was shaped by the attitudes of such early pioneers and their wartime experiences. The book's central thesis (and the source of its striking title) is that the early radio astronomers were unusually communitarian by nature. Unlike the "fractious" world of science as a whole, Munn writes, "the radio astronomers saw a single sky, unifying both nations and disciplines". One reason for this, he suggests, is the novelty of the field and its associated technologies. It is easy to forget that before 1945, the idea that a telescope could look like a radar dish rather than a supercharged version of something William Herschel might have used was little short of revolutionary. At the outset, astronomers and radar physicists had relatively little in common, but the technological demands of the new field forced them to collaborate very closely, and Munn argues that such close collaboration tended to foster a broad respect for people with different, but equally valuable, skills. The field's interdisciplinary nature also encouraged a trans-national outlook, since the scarcity of scientists equipped with the required skills tended to mean people got hired irrespective of where they were from. (The decision by the US National Science Foundation to recruit an Australian, Joe Pawsey, to lead its new National Radio Astronomy Observatory in 1961 is a good example.) This international flavour, in turn, helped the nascent radio-astronomy community to buck the Cold War trend for yoking science to the needs of the military-industrial complex. These are all interesting ideas, but the academic and occasionally clunky writing style of *A Single Sky* means that readers will need a keen personal interest in radio astronomy to persevere with Munn's analysis.

- 2013 MIT Press £23.95/$34.00hb 256pp

The last word on nothing

The latest collection of material from the archives of *New Scientist* magazine isn't about why penguins' feet don't freeze (2006) or whether polar bears get lonely (2008). Instead, it's about nothing. Cosmological nothing, mathematical nothing, quantum nothing – whatever flavour of nothing you fancy, *Nothing* probably has it. The book features essays by 22 different scientists and science journalists on various aspects of nothingness, including the nothing that preceded the Big Bang and the nothing embodied in the mathematical concept of zero. Not all of the essays are about physics or mathematics, however. For example, one thread of essays concerns medications that contain "nothing" – placebos, in other words. Each essay is relatively short, which makes *Nothing* an excellent companion for those stray moments when you'd otherwise be doing, well, nothing.

- 2013 Profile Books £7.99pb 256pp

Careers

A lasting legacy

Michael Conti-Ramsden describes how a physics degree and the Great Exhibition of 1851 helped turbocharge a career based on solving practical problems in chemical engineering

Michael Conti-Ramsden

Practical matters Michael Conti-Ramsden made use of an industrial fellowship to further his career.

Like most 18 year olds applying to study physics, I didn't have a clear vision of where my degree would take me – although I did know that it would provide me with transferable skills that I could use in a variety of careers. However, my undergraduate degree in natural sciences (physics) at the University of Bath included a "sandwich year" in industry, which helped me to realize that I wanted to use my physics background in a commercial environment.

Today, as the product development manager of an engineering start-up firm, Arvia Technology, I get a real buzz out of employing the basic principles, mathematics and modelling skills I have learned to solve real-world problems. By working with engineers and scientists from diverse fields, I get to use these skills to develop solutions that help drive business growth in the UK.

A path into engineering

Although my initial sandwich-year placement at a laser micro-machining company ended prematurely when the firm went into administration – not the best start to my interaction with industry! – I was fortunate enough to land an alternative placement at the Joint European Torus (JET) in Culham, Oxfordshire. I became part of the heating and fuelling department at JET, and it was there that I really got the bug for deploying my knowledge of physics to solve industrial problems. I was working with talented people and am proud to say that the cooling manifold design I helped to develop for the JET's neutral beam injectors was actually incorporated into the final project.

This was my first interaction with applied science, and from that point on I was hooked. I went back to finish my degree at Bath, graduating with first-class honours. But unlike some of my peers, I turned away from a possibly lucrative career in banking and financial consultancy. Instead, I applied to an engineering doctorate (EngD) programme at the University of Manchester. Incorporated within this programme is a diploma in enterprise management, which develops the basic skills required to commercialize novel technologies and manage their development. These skills are taught via a series of interactive courses that focus on key skills such as assessing the market potential for innovative products and developing business plans.

Students also work with a sponsoring company that helps steer their PhD-level research over the four years of the degree. My sponsor (and my current employer) was Arvia – a start-up company in Daresbury that, at the time, specialized in a technology for removing organic compounds such as dyes and pesticides from wastewater. Working within a start-up environment was interesting. I had to balance limited time and funds with commercial pressures and scientific principles, which meant that problems had to be approached from a slightly different direction from what I was used to.

But the work itself was somewhat of a departure from physics, since my EngD focused on exploring whether a wastewater treatment process could be applied to malodorous gases produced by industrial plants and sewage-treatment facilities. The move from physics into a chemical-engineering role meant that I faced a steep learning curve, but while I had to learn some new vocabulary and processes, there wasn't so much of a gulf as one might think. The language of mathematics to describe systems and processes is common to both fields and I was able to apply the principles I learned and developed from one to the other.

Turbocharging a career

One year into my EngD, my programme manager suggested putting me forward for an Industrial Fellowship with the Royal Commission for the Exhibition of 1851. I confess that I was unaware of this organization at the time, but as I learned more, I was increasingly attracted by its aims. Held in London early in the Victorian era, the Great Exhibition of 1851 celebrated the best in modern industrial technology and design, and after it closed, its surplus funds were given to a reconstituted Royal Commission for the purpose of "increasing the means of industrial education and extending the influence of science and art upon productive industry".

The fellowships are one way that the 1851 Commission continues to fulfil this mission, and since becoming a beneficiary of the programme, I have gradually realized that its work aligns pretty much exactly with what I want to do with my own career. I also liked the fact that the fellowship itself was focused on developing a patented product or process in conjunction with a PhD or EngD.

My fellowship application had to be

made in consultation with Arvia and the university, and to be honest, since being accepted, I haven't looked back. The funding meant that all my university fees and 50% of my stipend were paid; the award is worth £80 000 over three years, and the university department is awarded an additional £10 000 grant upon completion. The fellowship also covered up to £3500 worth of travel expenses each year, and this really turbocharged my career since it enabled me to travel extensively and attend conferences all over the world. For example, at the World Water Congress in 2011, I met Roberto Narbaitz, an environmental engineer at the University of Ottawa and a globally recognized expert on electrochemical regeneration of carbonaceous adsorbents. He has since visited Arvia and we hope to work on projects together in the future.

The language of mathematics to describe systems and processes is common to both physics and chemical engineering

Continued benefits

From my EngD work on malodorous gases, we concluded that although Arvia's technology could be used to remove odours, it was not economical or worth pursuing from a business point of view. However, the data I collected – together with the conclusions drawn in four publications – also had a more promising outcome as they showed that Arvia's platform is good at removing dangerous organic species from aqueous waste. This discovery helped refocus the company's strategy in the water industry, and a patent is pending.

After completing my thesis, I was offered consultancy work and then a permanent job with Arvia at the beginning of January 2013. Since then I have been promoted to product development manager and I am now responsible for how we develop our technology and key accounts, including our contracts with the US Department of Energy and other major players in the nuclear industry.

Throughout this time, I have kept up my links with the 1851 Commission. Their support and network has given me access to powerful and influential scientists and engineers for advice and business opportunities. Both the commissioners themselves and the other industrial fellows provide an unparalleled "hive-mind" for discussing ideas, and also a contact book that I will call on throughout my career. The commission's aim of extending the influence of science on the productive industries has become part of my life and something that I strive for all the time.

Michael Conti-Ramsden is product development manager of Arvia Technology, www.arviatechnology.com, and an alumnus of the 1851 Royal Commission's Industrial Fellowship scheme, www.royalcommission1851.org.uk

Once a physicist: Dan Trueman

Dan Trueman is a composer, Hardanger fiddle-player and a co-founder of the Princeton Laptop Orchestra

What sparked your interest in physics?
My father, Larry Trueman, is a theoretical physicist at Brookhaven National Laboratory, and either through genetics or exposure (or both) I've been interested in physics for as long as I can remember.

Why did you decide to switch to music?
I had been playing violin since I was four, and my family is very musical, so I was surrounded by it (also for as long as I can remember). As an undergraduate, I struggled to balance these competing interests, and when I was filling out applications to graduate school in physics, a good friend of mine who had just started grad school in chemistry at the Massachusetts Institute of Technology told me that, realistically, I'd have to quit playing violin at any serious level while pursuing graduate studies in physics. I vividly remember dumping the applications in the trash sometime later, after realizing I just wasn't ready to do that. I also think I realized that I was just better at music than I was at physics.

What is a Hardanger fiddle?
The Hardanger fiddle is a traditional Norwegian instrument that has been around for at least as long as the violin. It is distinguished by a set of sympathetic strings that run underneath the main strings (through the middle of the bridge and under the fingerboard); these strings resonate variably, depending on the notes you play, and give the fiddle a magical, warm and sparkling quality. I fell in love with the sound of the instrument and the strangeness of the traditional dance music that it is associated with when I first heard it.

You're also a co-founder of a very non-traditional music group, the Princeton Laptop Orchestra (PLOrk).
The orchestra directly follows my interest in the Hardanger fiddle. One of the things that struck me about the Hardanger was how small changes in instrument design could radically change its expressive and creative possibilities. For instance, I can change the tuning of the instrument slightly from the norm, so that running my fingers through familiar patterns yields unfamiliar melodies and chords. So, my work with laptops in music has been focused on trying to build digital instruments that are inspired by old instruments such as the Hardanger fiddle, the violin and the piano, yet exploit the new possibilities afforded by computation.

With PLOrk, each player has a hemispherical speaker that can roughly approximate the way conventional instruments fill rooms with sound (I helped develop these speakers with a computer scientist at Princeton, as part of a larger research project). What's nice about this is that every player has their own sound source, and we can just gather wherever and make music together in a familiar old-fashioned way.

What are you working on now?
I'm currently finishing a set of études for what I call the "prepared digital piano". This instrument uses a conventional 88-key MIDI piano keyboard and can sound like a familiar piano, but it has a set of "preparations" or simple algorithms attached to the "strings" – this is all done in a laptop – that cause it to respond differently. For instance, the tuning of the virtual strings might change as you play, creating chords that are tuned "perfectly" using exact ratios. I am also just beginning a big new piece in collaboration with the Irish *sean-nós* singer Iarla Ó Lionáird and the poet Paul Muldoon.

How (if at all) has your background in physics influenced you as a musician and composer?
There are obviously specific fields, such as acoustics and Fourier analysis, which have come into play for me over the years. I also feel that the general sense of discipline that the pursuit of physics involves has been important to me. I remember my father working out equations on his yellow pad, while also conversing with experimentalists about the design of collider experiments, and while I never reached the point where I could really understand the physics, the process feels familiar; I am constantly working things out on paper or in code, and then trying to bring them to life in the real world with musicians, and I try to be as disciplined and honest about the results as physicists need to be. Finally (and I hope this doesn't seem too fuzzy to the physicists reading this), there have been aesthetic lessons from physics that have stayed with me – lessons having to do with symmetry or the lack thereof, elegance, simplicity and abstraction grounded in the messiness of reality, and just the overwhelming impression that the world has some truly intractable and beautiful problems to solve.

Any advice for today's physics students?
When I was studying physics, I felt that I could go anywhere with it. At the time, I thought that meant I might pursue, say, atmospheric sciences or engineering after my physics degree, but it has provided a wonderful background for musical pursuits as well. I'm not sure this qualifies as "advice", but recognizing that the study of physics is about much more than just physics is important, and might help when in the throes of trying to complete a problem set.

Careers and people

Spotlight on: Péter Mészáros

As an astrophysicist, Péter Mészáros – who was recently awarded the 2013 Einstein Professorship by the Chinese Academy of Sciences – is best known for co-developing the standard theoretical model of gamma-ray bursts. Working with the University of Cambridge astrophysicist Martin Rees and Bohdan Paczynski of Princeton University, Mészáros helped formulate a model that suggests that gamma-ray bursts will be followed by "afterglows" in the X-ray and optical region of the electromagnetic spectrum. The trio's predictions were confirmed in February 1997 when the Italian–Dutch BeppoSAX satellite and the Canary Islands-based William Herschel Telescope observed afterglows from one such burst.

Mészáros was born in Argentina to Hungarian-refugee parents, and he received his Master's degree in physics from the National University of Buenos Aires in 1967. He then moved to the US, earning a PhD in astronomy from the University of California, Berkeley, in 1972. In 1983 he joined the faculty at Pennsylvania State University, where he remains today.

Movers and shakers

Alan Haigh, an alumnus of the JET fusion project and current head of the European Commission (EC) Research Fund for Coal and Steel, has been appointed head of department in the EC's Innovation and Networks Executive Agency, which is part of the "Horizon 2020" Europe-wide research programme that launched in December 2013.

Particle physicist **Tejinder Virdee** of Imperial College London has won the 2013 GG2 Man of the Year Award from the Asian Media and Marketing Group, which prepares an annual list of the most influential British Asians.

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Scottish Doctoral Training Centre
in Condensed Matter Physics

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The Faculty of Physics, Mathematics, and Computer Science at the Johannes Gutenberg University of Mainz (JGU) invites applications for an appointment at the level of

University Professor (W2 with tenure) in Experimental Physics

in the area of Electronic and Magnetic Properties of Condensed Matter Systems. The professorship will become available in 2014.

We are looking for a scientist with an internationally visible research record in the fields of electronic and magnetic properties (such as magnetism, superconductivity, topological insulators etc.) of new correlated materials. Possible research topics are static and dynamical properties of nanostructures, inorganic/molecular hybrid systems and the interaction of spin, charge and orbital degrees of freedom.

The position is embedded in the Graduate School of Excellence Materials Science in Mainz (MAINZ) and intense collaboration with existing experimental and theoretical groups at the Institute of Physics is expected. Candidates have the possibility to participate in coordinated research activities, in the Center for Innovative and Emerging Materials (CINEMA), and will have access to state-of-the-art lithography and microscopy tools.

Applicants are expected to have a Ph.D. in physics, a proven first rate research record and to possess the required pedagogical skills for teaching. Undergraduate courses are usually given in German. JGU promotes a concept of intensive tutoring and expects a high rate of presence at the university. The appointment requires participation in teaching activities and in the duties of academic administration.

JGU aims at increasing the percentage of women in academic positions and encourages in particular the application of women.

JGU is an equal opportunity employer and particularly welcomes applications from persons with disabilities.

JGU is a leading research university with a focus on Physics and Materials Sciences and is regularly ranked top 10 in Germany. At the Institute of Physics a number of large scale research activities are coordinated including the Graduate School of Excellence Materials Science in Mainz (www.mainz.uni-mainz.de) and the Excellence Research Cluster "Precision Physics, Fundamental Interactions and Structure of Matter" as part of the German Federal Excellence Initiative.

Qualified candidates are asked to submit their applications **by March 31, 2014**, including the usual documents (CV; list of publications; copies of three key publications; research proposal) as a single PDF file via the portal **http://www.phmi.uni-mainz.de/stellen**.

Applications should be addressed to

"Dekan des Fachbereichs 08, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, 55128 Mainz".

Postdoctoral Position in Atomic, Molecular, and Optical Physics, National Taiwan University

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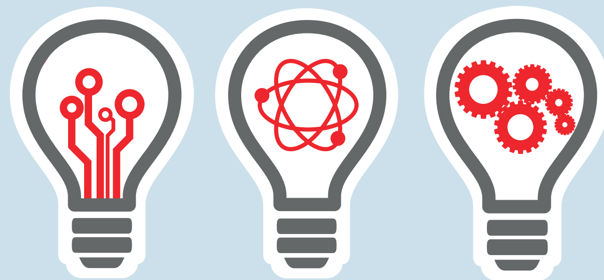

The jobs site for physics and engineering

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The Max Planck Institute for Plasma Physics in Greifswald, Germany, is seeking in the framework of its development program for young scientists for the Edge and Divertor Physics Division (Experimental Plasma Physics 4)

a graduate physicist

The research focuses on characterization and analysis of the edge and scrape-off layer plasma in the Wendelstein 7-X stellarator, with the goal of reaching a deeper understanding of the physical parameters and transport processes that determine the scrape-off layer width in both limiter and divertor configurations. The work will focus especially on the development and operation of Langmuir probes, on the data analysis of the measurements obtained from these probes, and their connection to existing theories and code predictions, for example the EMC3-EIRENE code.

The applicant is expected to have completed his or her PhD in experimental plasma physics. A proven track record of developing and operating Langmuir probes, as well as extracting new and important physics insights from these and other complementary measurements is strongly desired.
A strong scientific track record, including a number of first-authored publications in peer-reviewed physics journals, and several national and international conference contributions, including invited talks is advantageous.
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When ice grows up

A few months ago I joined the little-known fraternity of people who have opened their freezer doors, looked at their ice cube trays and said to themselves, "What the heck is *that*?"

Poking up from one of the partitions of my ice-cube tray was a needle of ice about 3 cm long and sticking nearly straight up – even though, as far as I could tell, all the gravity around me was pulling down.

My first thought was that something had dripped onto the tray from above, building up the spear of ice like dripping water builds up stalagmites on the floor of a cave. Nothing appeared to be thawing, but just to be sure, I moved aside some frozen chicken and a bag of peas and positioned my refilled ice-cube tray so that nothing was above it.

The next day brought another of the mysterious lances of ice.

At this point I did what any baffled student of science does today: I posted a photo on my blog. That was my introduction to the wonderful world of ice spikes. It turns out that several people have developed entire websites devoted to ice spikes. There are plenty of pictures, some short video clips, and a shared sense of what we all like best about science: getting to say to oneself, yet again, "Wow, isn't this cool?"

One of these sites (http://ow.ly/sdjjh) is run by Stephen Morris of the Experimental Nonlinear Physics Group at the University of Toronto. Morris's site contains tales of ice spikes developing in ice-cube trays, birdbaths and rivers downstream of a weir. There is even an amazing account from Pennsylvania's Harborcreek Historical Society of a man who, in 1963, walked 32 miles across a frozen Lake Erie and reported vertical ice "spurts" that "looked to him like telephone poles standing straight up all over the lake."

On the academic side, Morris's site also links to a paper on ice spikes that appeared in the *Physical Review* in 1921. In it, the author, one Herbert Grove Dorsey, reports, with pictures, on ice columns up to four and a half inches high. Dorsey had been thinking of ice spikes since he saw them on a tin pan of frozen water on 15 December 1916 in Gloucester, Massachusetts.

Another site, http://snowcrystals.com, has been put together by California Institute of Technology physicist Kenneth Libbrecht. He told me that he gets one or two e-mails a day – amounting to "thousands over the years" – from people who see ice spikes on a bird bath after a cold winter's night or, like me, in their ice-cube trays. (Technically, they should be called "ice parallelepiped" trays, but that's never caught on.) Anyway, one summer Libbrecht asked an undergraduate, Kevin Liu, to investigate ice spikes. After making several thousand ice cubes, Liu and Libbrecht found that the probability of ice-spike formation peaks at about –7 °C, at which point spikes form up to 35% of the time. The pair were able to increase this to almost 60% if they used a fan to circulate air in their freezer, and they also found that spikes form more frequently with mineral-free distilled water – something Libbrecht says he cannot explain.

Libbrecht and Liu published their work in the *Journal of Glaciology* and in their paper they report strong evidence for the so-called "Bally–Dorsey model" of ice-spike formation. (Bally published his work in the Swiss journal *Helvetica Chimica Acta* in 1933. Fascination with ice spikes knows no international boundaries.) This model suggests that as water in a container freezes, beginning on the surface and moving in from the edges, the expanding ice forces water through the remaining hole and up. This process creates a tube, frozen on the outside, in which liquid water travels upwards. The water then freezes at the top, thereby lengthening the tube until all the liquid is gone or the tube freezes shut. Libbrecht and Liu videotaped the formation of several spikes, and found they grew to their full height in 3–10 minutes, at a rate of "roughly" 50 μm per second. Some spikes even changed direction when disturbed, until their tubes froze shut.

I did what any baffled student of science does today: I posted a photo on my blog

For spikes to form in frozen liquids, the liquid must expand as it freezes. Water, which we take so much for granted, is one of the very few substances with this property. My research indicates that antimony and bismuth also expand as they freeze, but their freezing points are 631 and 272 °C, respectively. This suggests an interesting research programme for the next ambitious undergraduate – as long as their department owns a fire-proximity suit.

My own investigations were not nearly as hazardous. I was only able to form one more small, stubby spike about 1 cm in height, and, strangely, none at all using distilled water. But even for containers with a sizeable diameter of about 15 cm (such as my cat's feeding dish), the ice surface was rarely flat, and Libbrecht suspects this is due to similar forces on the liquid water as the surface freezes inward.

Naturally, every time I open my freezer door now, I hope to see another ice spike. Or something even stranger. Maybe this is how Heike Kamerlingh Onnes got his start.

David Appell is a science writer living in Oregon, www.davidappell.com

● Readers are invited to submit their own Lateral Thoughts. Articles should be 900–950 words, and can be e-mailed to pwld@iop.org