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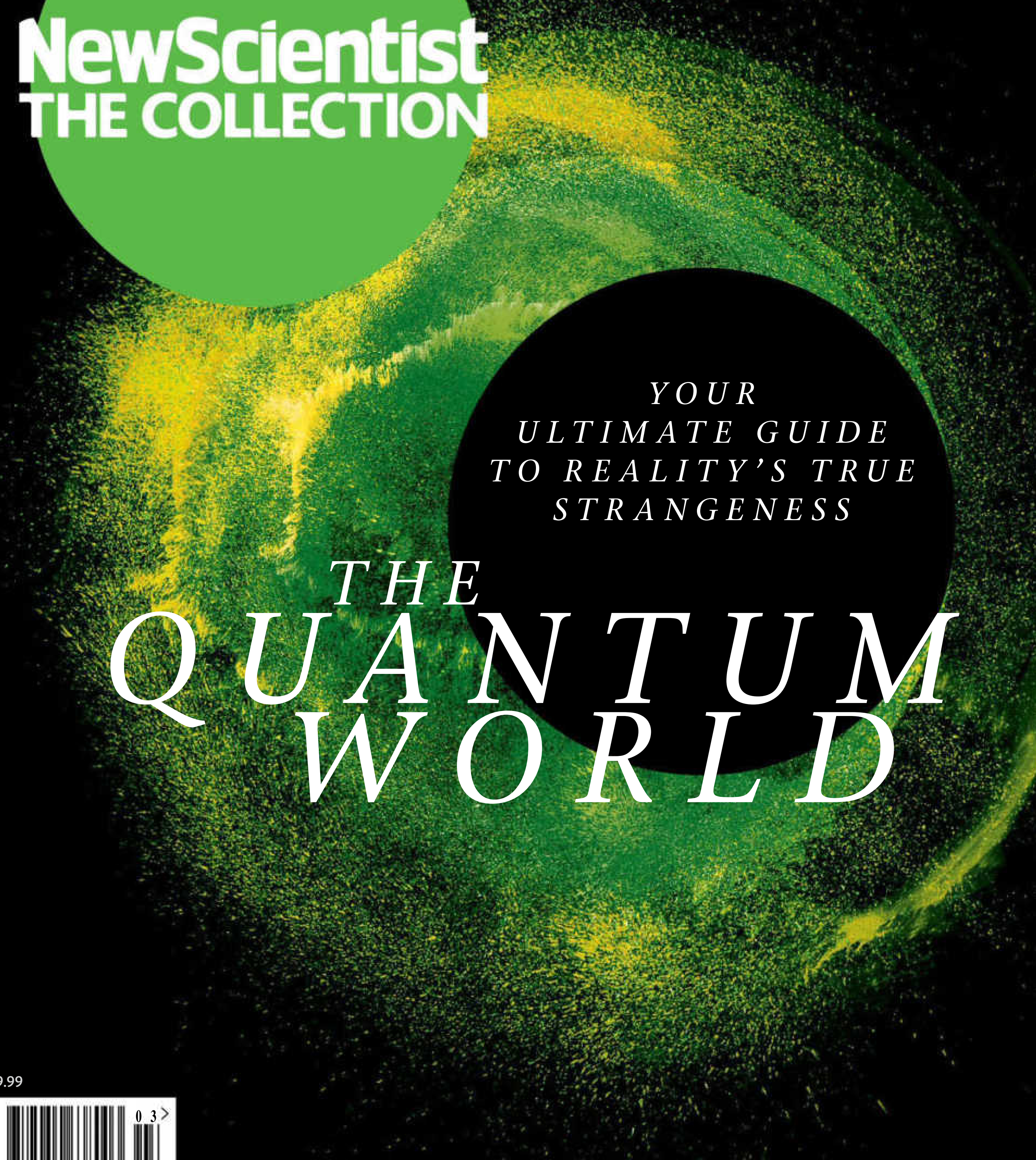

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NEW SCIENTIST THE COLLECTION
110 High Holborn,
London WC1V 6EU
+44 (0)20 7611 1202
enquiries@newscientist.com

Editor-in-chief Graham Lawton
Editor Michael Brooks
Art editor Craig Mackie
Pictures New Scientist picture desk
Subeditor Hannah Joshua
Graphics Dave Johnston
Production editor Mick O'Hare
Project manager Henry Gomm
Publisher John MacFarlane

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displayads@newscientist.com

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Welcome to the weird

IT IS something of a tragedy that Lewis Carroll died just as quantum theory was being born. The author of *Alice's Adventures in Wonderland* had a wonderful eye for the absurd, and learning about quantum oddities would have given him enormous pleasure.

It was Carroll, after all, who gave us strange shrunken worlds that require one to believe six impossible things before breakfast. He came up with a cat that disappeared, leaving its grin hanging in the air. His world is one where the unfolding of events is always "curiouser and curiouser", a phrase that fits the quantum world of atoms, electrons and photons of light perfectly.

Shrink down to these scales, and you will find objects that exist in two places at once, share seemingly telepathic links and even change their properties if they think they are being watched. Physicists have laboured for a century to make sense of all this, though it has been a labour of love. We revel in quantum weirdness in the same way Carroll's readers revel in the world Alice found by following the White Rabbit.

This issue of *New Scientist: The Collection* goes down the rabbit hole, through the looking glass and beyond – a mesmerising journey through the quantum world.

We open with a survey of quantum theory's strangest phenomena. Here you will meet a field that isn't there, see liquids that climb out of their containers, encounter telepathic electrons and particles that live a separate existence from their properties, like the Cheshire cat and its smile. For the most part there is no way to explain them, but we can state what we see, and make attempts to understand what the observations mean.

Chapter 2 goes deeper in search of meaning. What can we infer from all of this? Is reality a mathematical illusion? Are there such things as space and time? Are we, as non-quantum beings, limited in our perception?

Of course, that assumes we really are non-quantum. In chapter 3 we explore the role quantum physics may play in biology, from birds' navigation skills to the extraordinary capabilities of the human mind. None of this is quite as hard-set as physicists would like, but it has moved beyond the realms of speculation. Our experiments are now probing the idea that evolution really has taken advantage of the weirdness.

And if nature has given itself quantum superpowers, maybe we can follow suit. Chapter 4 details our quantum creations: technologies that exploit the strange rules of the very small. We now have computers that carry out all possible calculations at once, government secrets protected by the laws of nature and tiny machines that investigate those laws in an attempt to make sense of it all.

A complete understanding of the quantum world may be beyond us, however – at least until we have a way to mesh quantum theory with our understanding of what happens on cosmic scales. Chapter 5 is all about this search for a quantum universe, a quest that involves diving into black holes, creating quantum time machines and exploring the role quantum laws played in bringing the universe into existence. Our end goal, it turns out, may be reached by going back to the beginning of everything. Carroll would be delighted: it surely doesn't get curiouser than that.

Michael Brooks, Editor

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CONTRIBUTORS
Anil Ananthaswamy
is a consultant for *New Scientist*
Stephen Battersby
is a consultant for *New Scientist*
Michael Brooks
is a consultant for *New Scientist*
Mark Buchanan
is a consultant for *New Scientist*
Jon Cartwright
is a writer based in Bristol, UK
Matthew Chalmers
is a writer based in Bristol, UK
Marcus Chown
is a consultant for *New Scientist*
Stuart Clark
is a consultant for *New Scientist*
Sophie Hebden
is at the University of Leicester, UK
Rowan Hooper
is managing editor at *New Scientist*
Justin Mullins
is a consultant for *New Scientist*
Richard Webb
is features editor at *New Scientist*

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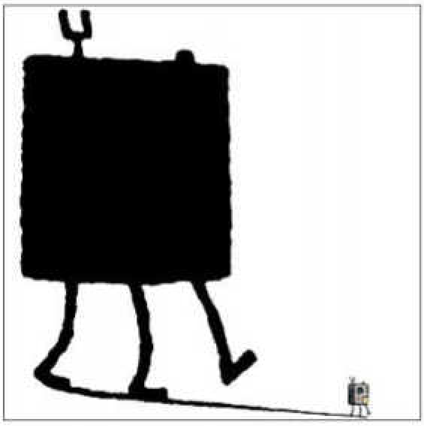

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Our quantum cosmos

CHAPTER ONE

THE QUANTUM WORLD

Weirdest of the weird

From undead cats to particles popping up out of nowhere, from watched pots not boiling – sometimes – to ghostly influences at a distance, quantum physics delights in demolishing our intuitions about how the world works. **Michael Brooks** tours the quantum effects that are guaranteed to boggle our minds

Both and neither

Wave-particle duality

IT DOES not require any knowledge of quantum physics to recognise quantum weirdness. The oldest and grandest of the quantum mysteries relates to a question that has exercised great minds at least since the time of the ancient Greek philosopher Euclid: what is light made of?

History has flip-flopped on the issue. Isaac Newton thought light was tiny particles – "corpuscles" in the argot of the day. Not all his contemporaries were impressed, and in classic experiments in the early 1800s the polymath Thomas Young showed how a beam of light diffracted, or spread out, as it passed through two narrow slits placed close together, producing an interference pattern on a screen behind just as if it were a wave.

So which is it, particle or wave? Keen to establish its reputation for iconoclasm, quantum theory provided an answer soon after it bowled onto the scene in the early 20th century. Light is both a particle and a wave – and so, for that matter, is everything else. A single moving particle such as an electron can diffract and interfere with itself as if it were a wave, and believe it or not, an object as large as a car has a secondary wave character as it trundles along the road.

That revelation came in a barnstorming doctoral thesis submitted by the pioneering quantum physicist Louis de Broglie in 1924. He showed that by describing moving particles as waves, you could explain why they had discrete, quantised energy levels rather than the continuum predicted by classical physics.

De Broglie first assumed that this was just a mathematical abstraction, but wave-particle duality seems to be all too real. Young's classic wave interference experiment has been reproduced with electrons and all manner of other particles (see diagram, page 8).

We haven't yet done it with a macroscopic object such as a moving car, admittedly. Its de Broglie wavelength is something like 10^{-38} metres, and making it do wave-like things such as diffract would mean creating something with slits on a similar scale,

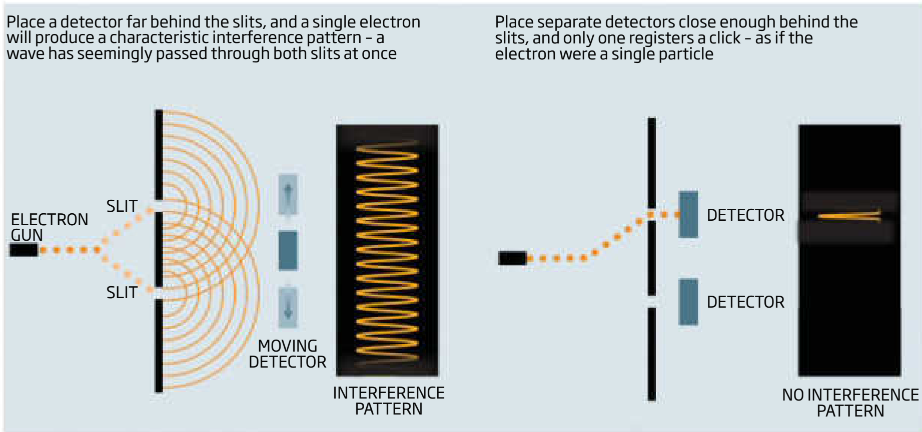
ALL ARTWORK MATT W. MOORE

a task way beyond our engineering capabilities. The experiment has been performed, though, with a buckyball – a soccer-ball-shaped lattice of 60 carbon atoms that, at about a nanometre in diameter, is large enough to be seen under a microscope.

All that leaves a fundamental question: how can stuff be waves and particles at the same time? Perhaps because it is neither, says Markus Arndt of the University of Vienna Austria, who did the buckyball experiments in 1999. What we call an electron or a buckyball might in the end have no more reality than a click in a detector, or our brain's reconstruction of photons hitting our retina. "Wave and particle are then just constructs of our mind to facilitate everyday talking," he says.

One in two

Updated versions of Thomas Young's classic double-slit experiment show how particles also look like waves – depending on how you detect them



"Both waves and particles might be just constructs of our mind to facilitate everyday talking"

Off the boil

The quantum Zeno effect

"A WATCHED pot never boils." Armed with common sense and classical physics, you might dispute that statement. Quantum physics would slap you down. Quantum watched pots do refuse to boil – sometimes. At other times, they boil faster. At yet other times, observation pitches them into an existential dilemma whether to boil or not.

This madness is a logical consequence of the Schrödinger equation, the formula concocted by Austrian physicist Erwin Schrödinger in 1926 to describe how quantum objects evolve probabilistically over time.

Imagine, for example, conducting an experiment with an initially undecayed radioactive atom in a box. According to the Schrödinger equation, at any point after you start the experiment the atom exists in a mixture, or "superposition", of decayed and undecayed states.

Each state has a probability attached that is encapsulated in a mathematical description known as a wave function. Over time, as long as you don't look, the wave function evolves as the probability of the decayed state slowly increases. As soon as you do look, the atom chooses – in a manner in line with the wave function probabilities – which state it will reveal itself in, and the wave function "collapses" to a single determined state.

This is the picture that gave birth to Schrödinger's infamous cat. Suppose the radioactive decay of an atom triggers a vial of poison gas to break, and a cat is in the box with the atom and the vial. Is the cat both dead and alive as long as we don't know whether the decay has occurred?

We're not sure. All we know is that tests with larger and larger objects – including a resonating metal strip big enough to be seen under a microscope – seem to show that they really can be induced to adopt two states at once.

The weirdest thing about all this is the implication that just looking at stuff changes how it behaves. Take the decaying atom: observing it and finding it undecayed resets the system to a definitive state, and the Schrödinger-equation evolution towards "decayed" must start again from scratch.

The corollary is that if you keep measuring often enough, the system will never be able to decay. This possibility is dubbed the quantum Zeno effect, after the Greek philosopher Zeno of Elea, who devised a famous paradox that "proved" that if you divided time up into ever

Something for nothing

The Casimir effect

"NOTHING will come of nothing," King Lear admonishes Cordelia in the eponymous Shakespeare play. In the quantum world, it's different: there, something comes of nothing and moves the furniture around.

Specifically, if you place two uncharged metal plates side by side in a vacuum, they will move towards each other, seemingly without reason. They won't move a lot, mind. Two plates with an area of a square metre placed one-thousandth of a millimetre apart will feel a force equivalent to just over a tenth of a gram.

The Dutch physicist Hendrik Casimir first noted this minuscule movement in 1948. "The Casimir effect is a manifestation of the quantum weirdness of the microscopic world," says physicist Steve Lamoreaux of Yale University.

It has to do with the quantum quirk known as Heisenberg's uncertainty principle, which essentially says the more we know about some things in the quantum world, the less we know about others. You can't, for instance, deduce the exact position and momentum of a particle simultaneously. The more certain we are of where a particle is, the less certain we are of where it is heading.

A similar uncertainty relation exists between energy and time, with a dramatic consequence. If space were ever truly empty, it would contain exactly zero energy at a precisely defined moment in time – something the uncertainty principle forbids us from knowing.

It follows that there is no such thing as a vacuum. According to quantum field theory, empty space is actually fizzing with short-lived stuff that appears, looks around a bit, decides it doesn't like it and disappears again, all in the name of preventing the universe from violating the uncertainty principle. For the most part, this stuff is pairs of photons and their antiparticles that quickly annihilate in a puff of energy. The tiny electric fields caused by these pop-up particles, and their effect on free electrons in metal plates, might explain the Casimir effect.

Or they might not. Thanks to the uncertainty principle, the electric fields associated with the atoms in the metal plates also fluctuate. These variations create tiny attractions called van der Waals forces between the atoms. "You can't ascribe the Casimir force solely either to the zero point of the vacuum or to the zero point motion of the atoms that make up the plates," says Lamoreaux. "Either view is correct and arrives at the same physical result."

Whichever picture you adopt, the Casimir effect is big enough to be a problem. In nanoscale machines, for example, it could cause components in close proximity to stick together.

The way to avoid that might be simply to reverse the effect. In 1961, Russian physicists showed theoretically that combinations of materials with differing Casimir attractions can create scenarios where the overall effect is repulsion. Evidence for this strange "quantum buoyancy" was announced in January 2009 by physicists from Harvard University who had set up gold and silica plates separated by the liquid bromobenzene.

smaller instants you could make change or motion impossible.

And the quantum Zeno effect does happen. In 1990, researchers at the National Institute of Standards and Technology in Boulder, Colorado, showed they could hold a beryllium ion in an unstable energy configuration rather akin to balancing a pencil on its sharpened point, provided they kept re-measuring its energy.

The converse "anti-Zeno" effect – making a quantum pot boil faster by just measuring it – also occurs. Where a quantum object has a complex arrangement of states to move into, a decay into a lower-energy state can be accelerated by measuring the system in the right way. In 2001, this too was observed in the lab.

The third trick is the quantum Hamlet effect, proposed in 2009 by Vladan Pankovic of the University of Novi Sad, Serbia. A particularly intricate sequence of measurements, he found, can affect a system in such a way as to make the Schrödinger equation for its subsequent evolution intractable. As Pankovic puts it: to be decayed or not-decayed, "that is the analytically unsolvable question".

Love the quantum bomb

The Elitzur-Vaidman bomb tester

A BOMB triggered by a single photon of light is a scary thought. If such a thing existed in the classical world, you would never even be aware of it. Any photon entering your eye to tell you about it would already have set off the bomb, blowing you to kingdom come.

With quantum physics, you stand a better chance. According to a scheme proposed by the Israeli physicists Avshalom Elitzur and Lev Vaidman in 1993, you can use quantum trickery to detect a light-triggered bomb with light – and stay safe a guaranteed 25 per cent of the time.

The secret is a device called an interferometer. It exploits the quantumly weird fact that, given two paths to go down, a photon will take both at once. We know this because, at the far end of the device, where the two paths cross once again, a wave-like interference pattern is produced in a suitably-placed detector (see "Both and neither", page 7).

To visualise what is going on, think of a photon entering the interferometer and taking one path while a ghostly copy of itself goes down the other. In Elitzur and Vaidman's thought experiment, half the time there is a photon-triggered bomb blocking one path (see diagram, right). Only the real photon can trigger the bomb, so if it is the ghostly copy that gets blocked by the bomb, there is no explosion – and nor is there an interference pattern at the other end. In other words, we have "seen" the bomb without triggering it.

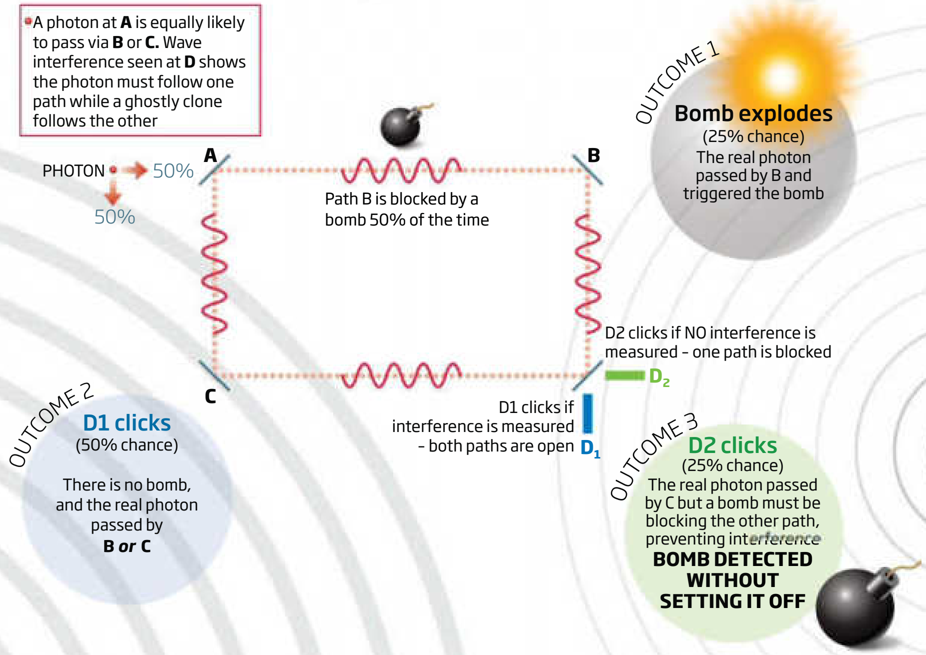
Barely a year after Elitzur and Vaidman proposed their bomb-testing paradox, physicists at the University of Vienna, Austria, had brought it to life – not by setting off bombs, but by bouncing photons off mirrors.

In 2000, Shuichiro Inoue and Gunnar Björk of the Royal Institute of Technology in Stockholm, Sweden, used a similar technique to show that you could get an image of a piece of an object without shining light on it – something that could revolutionise medical imaging. "It would be very useful for something like X-ray scanning, if there were no radiation damage to the tissue because no X-rays actually hit it," says physicist Richard Jozsa of the University of Cambridge.

Josza is the brains behind perhaps the most eye-rubbing of such tricks: using a quantum computer to deliver the output of a program even when you don't run the program. As the team that implemented his idea in 2005 showed, quantum physics does at least retain some semblance of classical decency: to deliver a sensible answer, the computer does need to be switched on.

Bomb disposal

Light can be used to detect a light-triggered explosive device – without necessarily triggering it



"The computer retains a semblance of classical decency: to deliver a sensible answer, it must be switched on"

Spooky action at a distance

Entanglement

ERWIN SCHRÖDINGER called it the "defining trait" of quantum theory. Einstein could not bring himself to believe in it at all, thinking it proof that quantum theory was seriously buggy. It is entanglement: the idea that particles can be linked in such a way that changing the quantum state of one instantaneously affects the other, even if they are light years apart.

This "spooky action at a distance", in Einstein's words, is a serious blow to our conception of how the world works. In 1964, physicist John Bell of the European Organization for Nuclear Research (CERN) in Geneva, Switzerland, showed just how serious. He calculated a mathematical inequality that encapsulated the maximum correlation between the states of remote particles in experiments in which three "reasonable" conditions hold: that experimenters have free will in setting things up as they want; that the particle properties being measured are real and pre-existing, not just popping up at the time of measurement; and that no influence travels faster than the speed of light, the cosmic speed limit.

As many experiments since have shown, quantum mechanics regularly violates Bell's inequality, yielding levels of correlation way above those possible if his conditions hold. That pitches us into a philosophical dilemma. Do we not have free will, meaning something, somehow predetermines what measurements we take? That is not anyone's first choice. Are the properties of quantum particles not real – implying that nothing is real at all, but exists merely as a result of our perception? That's a more popular position, but it hardly leaves us any the wiser.

Or is there really an influence that travels faster than light? Cementing the Swiss reputation for precision timing, in 2008 physicist Nicolas Gisin and his colleagues at the University of Geneva did an experiment. They showed that, if reality and free will hold, the speed of transfer of quantum states between entangled photons held in two villages 18 kilometres apart was somewhere above 10 million times the speed of light.

Whatever the true answer is, it will be weird, and will almost certainly confuse us further. Welcome to quantum reality.

I met a field that wasn't there

The Aharonov-Bohm effect

HERE'S a nice piece of quantum nonsense. Take a doughnut-shaped magnet and wrap a metal shield round its inside edge so that no magnetic field can leak into the hole. Then fire an electron through the hole.

There is no field in the hole, so the electron will act as if there is no field, right? Wrong. The wave associated with the electron's movement suffers a jolt as if there were something there.

Werner Ehrenberg and Raymond Siday were the first to note that this behaviour lurks in the Schrödinger equation (see "Off the boil", page 8). That was in 1949, but their result remained unnoticed. Ten years later Yakir Aharonov and David Bohm, working at the University of Bristol, UK, rediscovered the effect and for some reason their names stuck.

So what is going on? The Aharonov-Bohm effect is proof that there is more to electric and magnetic fields than is generally supposed. You can't calculate the size of the effect on a particle by considering just the properties of the electric and magnetic fields where the particle is. You also have to take into account the properties where it isn't. Confused? Well, we are dealing with quantum theory.

Casting about for an explanation, physicists decided to take a look at a property of the magnetic field known as the vector potential. For a long time, vector potentials were considered just handy mathematical tools – a shorthand for electrical and magnetic properties that didn't have any real-world significance. As it turns out, they describe something that is very real indeed.

The Aharonov-Bohm effect showed that the vector potential makes an electromagnetic field more than the sum of its parts. Even when a field isn't there, the vector potential still exerts an influence. That influence was seen unambiguously for the first time in 1986 when Akira Tonomura and colleagues in Hitachi's laboratories in Tokyo, Japan, measured a ghostly electron jolt.

Although it is far from an everyday phenomenon, the Aharonov-Bohm effect might prove to have uses in the real world – in magnetic sensors, for example, or field-sensitive capacitors and data storage buffers for computers that crunch light.

Miracle matter

Superconductors, superfluids and supersolids

FORGET radioactive spider bites, exposure to gamma rays, or any other accident favoured in Marvel comics: in the real world, it's quantum theory that gives you superpowers.

Take helium, for example. At room temperature, it is normal fun: you can fill floaty balloons with it, or inhale it and talk in a squeaky voice. At temperatures below around 2 kelvin, though, it is a liquid and its atoms become ruled by their quantum properties. There, it becomes super-fun: a superfluid.

Superfluid helium climbs up walls and flows uphill in defiance of gravity. It squeezes itself through impossibly small holes. It flips the bird at friction: put superfluid helium in a bowl, set the bowl spinning, and the helium sits unmoved as the bowl revolves beneath it. Set the liquid itself moving, though, and it will continue gyrating forever.

That's fun, but not particularly useful. The opposite might be said of superconductors. These solids conduct electricity with no resistance, making them valuable for transporting electrical energy, for creating enormously powerful magnetic fields – to steer protons around CERN's Large Hadron Collider, for instance – and for levitating superfast trains.

We don't yet know how all superconductors work, but it seems the uncertainty principle plays a part (see "Something for nothing", page 9). At very low temperatures, the momentum of individual atoms or electrons in these materials is tiny and very precisely known, so the position of each atom is highly uncertain. In fact, they begin to overlap with each other to the point where you can't describe them individually. They start acting as one superatom or superelectron that moves without friction or resistance.

"At room temperature, helium is normal fun. Close to absolute zero, though, it becomes super-fun"

All this is nothing in the weirdness stakes, however, compared with a supersolid. The only known example – and even this is controversial – is an experiment where solid helium was cooled to within a degree of absolute zero and at around 25 times normal atmospheric pressure.

Under these conditions, the bonds between helium atoms are weak, and some break off to leave a network of "vacancies" that behave almost exactly like real atoms. If things are just right, these vacancies form their own fluid-like Bose-Einstein condensate. This could, in particular circumstances, pass right through the normal helium lattice – meaning the solid flows, ghost-like, through itself.

So extraordinary is this superpower that Moses Chan and Eun-Seong Kim of Pennsylvania State University in University Park checked and re-checked their data on solid helium for four years before eventually publishing in 2004.

"I had little confidence we would see the effect," says Chan. He has since decided the results can be explained away without supersolidity, but Kim, who now heads the Center for Supersolid and Quantum Matter Research at the Korea Advanced Institute of Science and Technology, remains convinced. Superpowers are always trouble. ■

WHAT DOES IT ALL MEAN?

It is tempting, faced with the full-frontal assault of quantum weirdness, to trot out the notorious quote from Nobel prize-winning physicist Richard Feynman: "Nobody understands quantum mechanics."

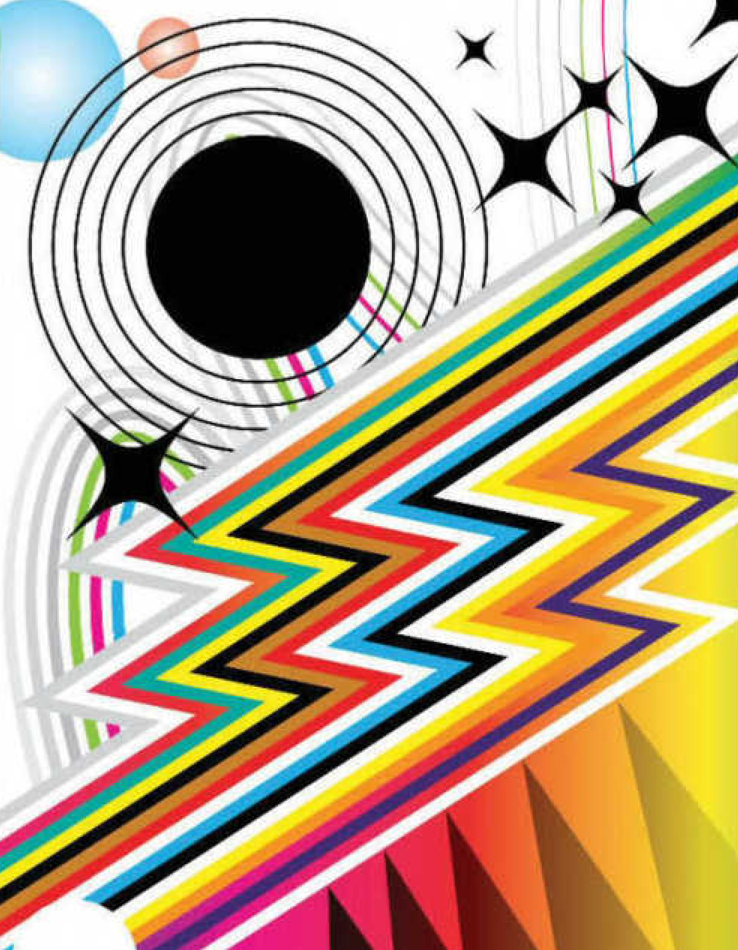
It does have a ring of truth to it, though. The explanations attempted here use the most widely accepted framework for thinking about quantum weirdness, called the Copenhagen interpretation after the city in which Niels Bohr and Werner Heisenberg thrashed out its ground rules in the early 20th century.

With its uncertainty principles and measurement paradoxes, the Copenhagen interpretation amounts to an admission that, as classical beasts, we are ill-equipped to see underlying quantum reality. Any attempt we make to engage with it reduces it to a shallow classical projection of its full quantum richness.

Lev Vaidman of Tel Aviv University, Israel, like many other physicists, touts an alternative explanation. "I don't feel that I don't understand quantum mechanics," he says. But there is a high price to be paid for that understanding - admitting the existence of parallel universes.

In this picture, wave functions do not "collapse" to classical certainty every time you measure them; reality merely splits into as many parallel worlds as there are measurement possibilities. One of these carries you and the reality you live in away with it. "If you don't admit many-worlds, there is no way to have a coherent picture," says Vaidman.

Or, in the words of Feynman again, whether it is the Copenhagen interpretation or many-worlds you accept, "the 'paradox' is only a conflict between reality and your feeling of what reality ought to be".



Quantum shadows

Is material reality made of particles or waves? Take your pick, says **Anil Ananthaswamy** – but you'll be wrong

"IF YOU haven't found something strange during the day," John Archibald Wheeler is said to have remarked, "It hasn't been much of a day." But then, strangeness was Wheeler's stock in trade. As one of the 20th century's leading theoretical physicists, the things he dealt with every day – the space- and time-bending warpings of Einstein's relativity, the fuzzy uncertainties and improbabilities of quantum physics – were the sort to boggle the minds of most mere mortals.

Even so, one day in 1978 must have been quite something for Wheeler. That was when he first lit on a very strange idea to test how photons might be expected to behave. Half a century earlier, quantum physics had produced the startling insight that light – everything in the quantum world, in fact – has a dual character. Sometimes it acts as if made of discrete chunks of stuff that follows well-defined paths – particles. At other times, it adopts the more amorphous, space-filling guise of a wave. That led to a question that exercised Wheeler: what makes it show which side, and when?

It took a while for the test Wheeler devised to become experimental reality. When it finally did, the answer that came was strange enough. Now, though, the experiment has been redone with a further quantum twist. And it's probably time to abandon any pretence of understanding the outcome. Forget waves, forget particles, forget anything that's one or the other. Reality is far more inscrutable than that.

For centuries, light has illuminated our ideas of the material world. The debate about its nature, wave or particle, goes back to the philosophers of ancient Greece, and has featured luminaries such as Newton, Descartes and Einstein on one side or the other. By the dawn of the 20th century, the result was best described as a scoring draw, with both sides having gathered significant support (see "Duelling over duality", page 14).

Quantum physics broke the deadlock essentially by saying that everyone was right. The apparent proof comes with a quantum version of an experiment first performed by the English physicist Thomas Young in 1803, ironically to support the wave theory of light. Young shone light on a screen with two tiny, parallel slits in it. On another screen a distance behind the first, he saw alternating vertical fringes of light and dark that seemed incontrovertible proof of light's wave character. Water waves passing through two narrow openings in a sea wall diffract and interfere in a similar way, sometimes constructively amplifying and sometimes destructively reducing each other beyond.

"The idea that physical reality depends on an observer's whim bothered the likes of Einstein no end"

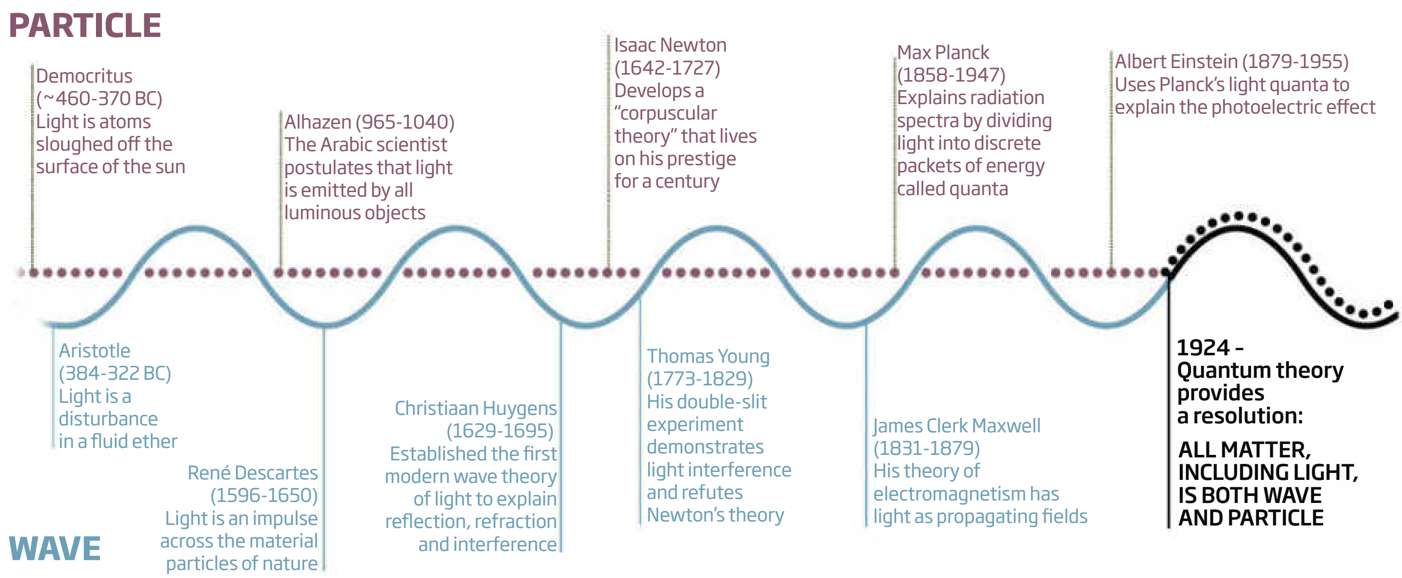
The strangeness starts when you lower the light intensity to the point at which only a single photon enters the experimental setup at any one time. In 1905, Einstein had strongly suggested that a single photon is a particle, and indeed, place a detector at one or other of the slits and you hear the beep, beep of single particles hitting it. But remove the particle detector and place a light-collecting screen – a kind of long-exposure camera – a distance behind the slits, and the same pattern of light and shade that Young had observed slowly builds up. It is as if each photon is an interfering wave that passes simultaneously through both slits. The same happens with other quantum particles: electrons, neutrons, atoms and even 60-carbon-atom buckyballs.

For Niels Bohr, the great Danish pioneer of quantum physics, this "central mystery" was nothing less than a principle of the new theory, one he called the complementarity principle. Quantum objects such as photons simply have complementary properties – being a wave, being a particle – that can be observed singly, but never together. And what determines which guise an object adopts? Bohr laid out a first outline of an answer at a grand gathering of physicists at the Istituto Carducci on the shores of Lake Como in Italy in September 1927: we do. Look for a particle and you'll see a particle. Look for a wave and that's what you'll see.

The idea that physical reality depends on an observer's whim bothered Einstein no end. Does the moon's existence depend on observers too, he once asked. "No reasonable definition of reality could be expected to permit this," he huffed in a famous paper he co-authored in 1935 with Boris Podolsky and Nathan Rosen. Einstein favoured an alternative idea of an underlying but as-yet inaccessible layer of reality containing hidden influences that "told" the photon about the nature of the experiment to be performed on it, changing its behaviour accordingly. ›

Duelling over duality

Philosophers and physicists have flip-flopped on whether light is a wave or a particle all the way back to ancient Greece

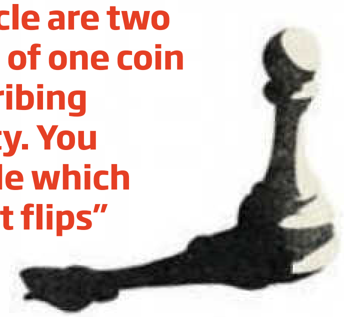


There is more to this than wild conspiracy theory. Imagine an explosion that sends two pieces of shrapnel in opposite directions. The explosion obeys the law of conservation of momentum, and so the mass and velocity of the pieces are correlated. But if you know nothing of momentum conservation, you could easily think that measuring the properties of one fragment determines the properties of the other, rather than both being set at the point of explosion. Was a similar hidden reality responsible for goings on in the quantum world?

This is where Wheeler's thought experiment came in. Its aim was to settle the issue of what told the photon how to behave, using an updated version of the double-slit experiment. Photons would be given a choice of two paths to travel in a device known as an interferometer. At the far end of the interferometer, the two paths would either be recombined or not. If the photons were measured without this recombination – an "open" interferometer – that was the equivalent of putting a detector at one or other of the slits. You would expect to see single particles travelling down one path or the other, all things being equal, splitting 50:50 between the two (see "Neither one nor the other", opposite).

Alternatively, the photons could be measured after recombination – a "closed" setting. In this case, what you expect to see depends on the lengths of the two paths through the interferometer. If both are exactly the same length, the peaks of the waves arrive at the same time at one of the detectors and interfere constructively there: 100 per cent of the hits appear on that detector and none on the other. By altering one path length, however, you can bring the wave fronts out of sync and vary the interference at the first detector from completely constructive to totally destructive, so that it receives no hits. This is equivalent to scanning across from a bright fringe to a dark one on the interference screen of the double slit experiment.

"Wave and particle are two sides of one coin describing reality. You decide which way it flips"



Wheeler's twist to the experiment was to delay choosing how to measure the photon – whether in an open or a closed setting – until after it had entered the interferometer. That way, the photon couldn't possibly "know" whether to take one or both paths, and so if it was supposed to act as a particle or a wave.

Or could it?

It was almost three decades before the experiment could actually be done. To make sure there was no hidden influence of the kind favoured by Einstein, you needed a very large interferometer, so that no word of the choice of measurement could reach the photon, even if the information travelled at light speed (anything faster was expressly forbidden by Einstein's own theory of relativity). In 2007, Alain Aspect and his team at the Institute of Optics in Palaiseau, France, built an interferometer with arms 48 metres long. The result? Whenever they chose at the last instant to measure the photons with a closed interferometer, they saw wave interference. Whenever they chose an open interferometer, they saw particles.

There was no getting round it. Wave and particle behaviours really do seem to be two sides of one coin. As to which way it flips – well, you decide. "Isn't that beautiful?" said Aspect in a 2012 public lecture at the Physics@FOM conference in Veldhoven, the Netherlands. "I think there is no other conclusion to draw from this experiment."

Unless, of course, you make things even stranger. In December 2011, Radu Ionicioiu of the Horia Hulubei National Institute for R&D in Bucharest, Romania, and Daniel Terno of Macquarie University in Sydney, Australia, proposed extending Wheeler's thought experiment. Their new twist was that the decision of how to measure the photon, as a particle or as a wave, should itself be a quantum-mechanical one – not a definite yes or no, but an indeterminate, fuzzy yes-and-no.

Infinite shades of grey

There is a way to do that: you use light to control the detector designed to probe the light. First you prepare a "control" photon in a quantum superposition of two states. One of these states switches the interferometer to an open, particle-measuring state, and the other to a closed, wave-measuring state. Crucially, you only measure the state of the control photon after you have measured the experimental "system" photon passing through the interferometer. As far as you are concerned, the system photon is passing through an interferometer that is both open and closed; you don't know whether you are setting out to measure wave or particle behaviour. So what do you measure?

This time, it took only a few months for the experimentalists to catch up with the theorists. But when three independent groups, led by Chuan-Feng Li at the University of Science and Technology of China in Hefei, Jeremy O'Brien at the University of Bristol, UK, and Sébastien Tanzilli at the University of Nice, France, performed different versions of the experiment in 2012, the results were unnerving – even to those who consider themselves inured to the weirdnesses of quantum physics.

The answer is, what you see depends on the control photon. If you look at the measurements of the system photons without ever checking the corresponding measurements of the control photons – so never knowing what measurement you made – you see a distribution of hits on the two detectors that is the signature neither of particles or waves, but some ambiguous mixture of the two. If particle is black and wave is white, this is some shade of grey.

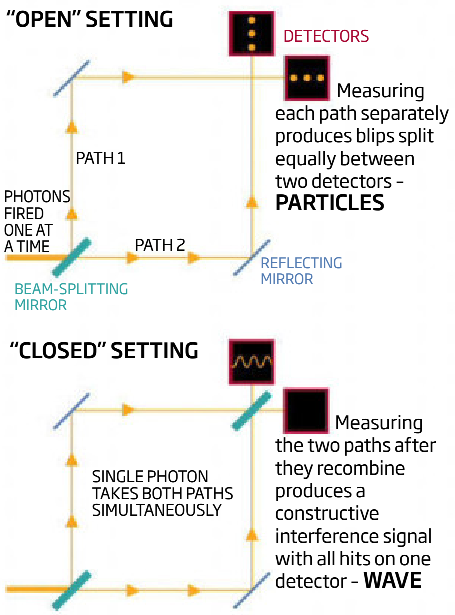
Do the same, but this time looking at the control photon measurements as well, and it is like putting on a pair of magic specs. Grey separates clearly into black and white. You can pick out the system photons that passed through an open interferometer, and they are clearly particles. Those that passed through a closed interferometer look like waves. The photons reveal their colours in accordance with the kind of measurement the control photon said you made.

It gets yet stranger. Quantum mechanics allows you to put the control photon not just in an equal mix of two states, but in varying proportions. That is equivalent to an interferometer setting that is, say, open 70 per cent of the time and closed 30 per cent of the time. If we measure a bunch of system photons in this configuration, and look at the data before putting on our magic specs, we see an ambiguous signature once again – but this time, its shade of grey has shifted closer to particle black than wave white. Put on the specs, though, and we see system photons 70 per cent of which have seemingly – but clearly – behaved as particles, while the remaining 30 per cent acted as waves.

What does this mean for our understanding of reality? In one sense, the results leave Bohr's side of the argument about quantum reality stronger. There is a tight correlation between the state of the control photon, representing the nature of the measurement, and the system photon, representing the state of reality. Make for more of a particle measurement, and you'll measure something more like a particle, and vice versa. As in earlier experiments, a hidden-reality theory *à la* Einstein cannot explain the results.

Neither one nor the other

According to how it is set up, an interferometer can be used to "prove" light is particles, waves – or nothing of the sort



If you don't know whether the interferometer is open or closed, something is measured – but it looks like neither PARTICLE nor WAVE

But in another sense, we are left grappling for words. "Our experiment defies the conventional boundaries set by the complementarity principle," says Li. Ionicioiu agrees. "Complementarity shows only the two ends, black and white, of a spectrum between particle and wave," he says. "This experiment allows us to see the shades of grey in between."

So, has Bohr been proved wrong too? Johannes Kofler of the Max Planck Institute of Quantum Optics in Garching, Germany, doesn't think so. "I'm really very, very sure that he would be perfectly fine with all these experiments," he says. The complementarity principle is at the heart of the "Copenhagen interpretation" of quantum mechanics, named after Bohr's home city, which essentially argues that we see a conflict in such results only because our minds, attuned as they are to a macroscopic, classically functioning cosmos, are not equipped to deal with the quantum world. "The Copenhagen interpretation, from the very beginning, didn't demand any 'realistic' world view of the quantum system," says Kofler.

The outcomes of the latest experiments simply bear that out. "Particle" and "wave" are concepts we latch on to because they seem to correspond to guises of matter in our familiar, classical world. But attempting to describe true quantum reality with these or any other black-or-white concepts is an enterprise doomed to failure.

It's a notion that takes us straight back into Plato's cave, says Ionicioiu. In the ancient Greek philosopher's allegory, prisoners shackled in a cave see only shadows of objects cast onto a cave wall, never the object itself. A cylinder, for example, might be seen as a rectangle or a circle, or anything in between. Something similar is happening with the basic building blocks of reality: to us, they are elusive, shifting shadows. "Sometimes the photon looks like a wave, sometimes like a particle, or like anything in between," says Ionicioiu. In reality, it is none of these things. What it is, though, we do not have the words or the concepts to express.

Now that is strange. And for quantum physicists, all in a day's work. ■

Matter of interpretation

The fertile wilds of the quantum world have provided us with a menagerie of fascinating ideas. **Michael Brooks** visits the quantum zoo

A CENTURY, it seems, is not enough. One hundred years ago this year, the first world physics conference took place in Brussels, Belgium. The topic under discussion was how to deal with the strange new quantum theory and whether it would ever be possible to marry it to our everyday experience, leaving us with one coherent description of the world.

It is a question physicists are still wrestling with today. Quantum particles such as atoms and molecules have an uncanny ability to appear in two places at once, spin clockwise and anticlockwise at the same time, or instantaneously influence each other when they are half a universe apart. The thing is, we are made of atoms and molecules, and we can't do any of that. Why? "At what point does quantum mechanics cease to apply?" asks Harvey Brown, a philosopher of science at the University of Oxford.

Although an answer has yet to emerge, the struggle to come up with one is proving to be its own reward. It has, for instance, given birth to the new field of quantum information that has gained the attention of high-tech industries and government spies. It is giving us a new angle of attack on the problem of finding the ultimate theory of physics, and it might even tell us where the universe came from. Not bad for a pursuit that a quantum cynic – one Albert Einstein – dismissed as a "gentle pillow" that lulls good physicists to sleep.

RICHARD WILKINSON

Unfortunately for Einstein quantum theory has turned out to be a masterpiece. No experiment has ever disagreed with its predictions, and we can be confident that it is a good way to describe how the universe works on the smallest scales. Which leaves us with only one problem: what does it mean?

Physicists try to answer this with "interpretations" – philosophical speculations, fully compliant with experiments, of what lies beneath quantum theory. "There is a zoo of interpretations," says Vlatko Vedral, who divides his time between the University of Oxford and the Centre for Quantum Technologies in Singapore.

No other theory in science has so many different ways of looking at it. How so? And will any one win out over the others?

Take what is now known as the Copenhagen interpretation, introduced by the Danish physicist Niels Bohr. It says that any attempt to talk about an electron's location within an atom, for instance, is meaningless without making a measurement of it. Only when we interact with an electron by trying to observe it with a non-quantum, or "classical", device does it take on any attribute that we would call a physical property and therefore become part of reality.

Then there is the "many worlds" interpretation, where quantum strangeness is explained by everything having multiple existences in myriad parallel universes. Or you might prefer the de Broglie-Bohm interpretation, where quantum theory is considered incomplete: we are lacking some hidden properties that, if we knew them, would make sense of everything.

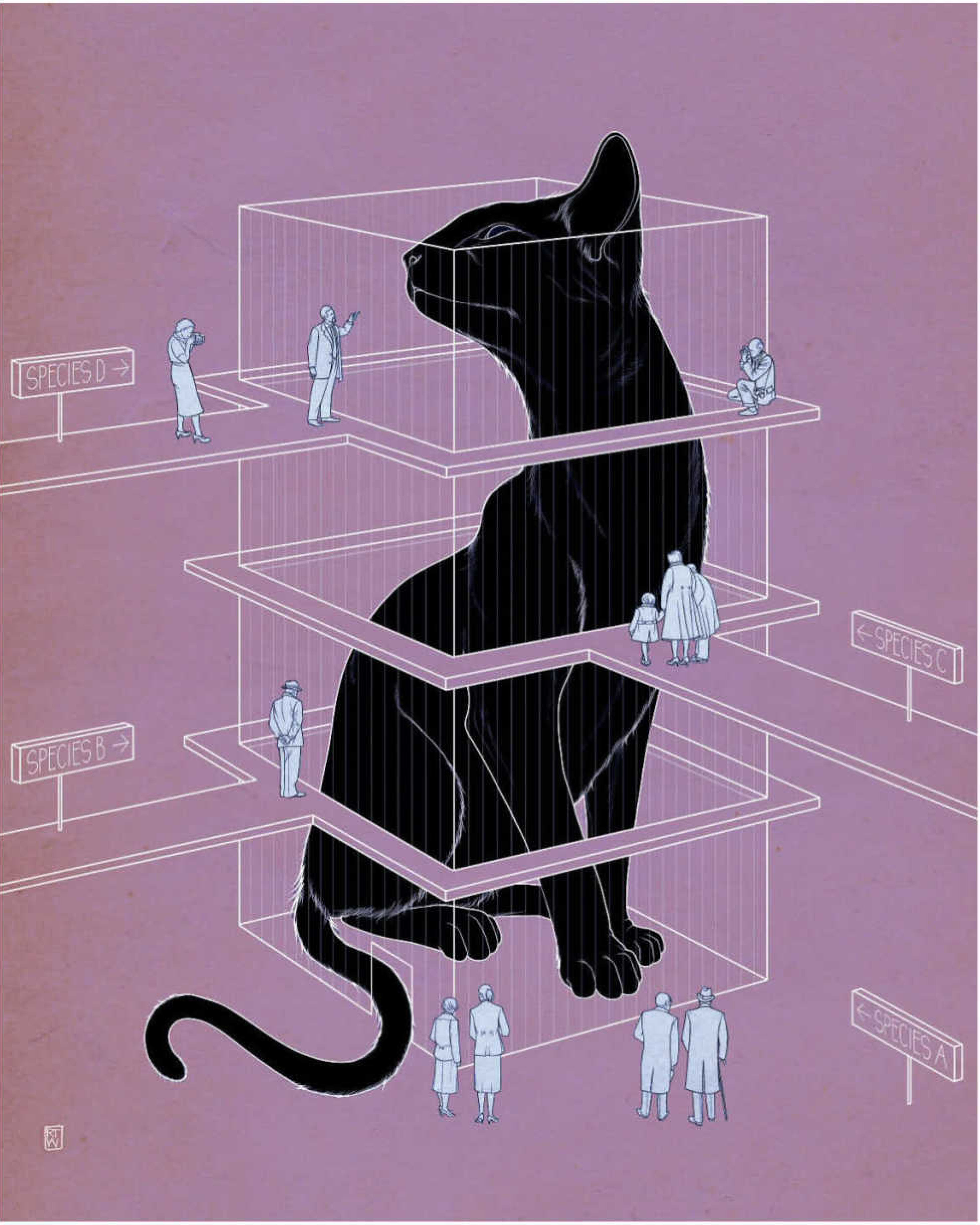
There are plenty more, such as the Ghirardi-Rimini-Weber interpretation, the transactional interpretation (which has particles travelling backwards in time), Roger Penrose's gravity-induced collapse interpretation, the modal interpretation… in the last 100 years, the quantum zoo has become a crowded and noisy place (see pages 18 and 19).

For all the hustle and bustle, though, there are only a few interpretations that seem to matter to most physicists.

Wonderful Copenhagen

The most popular of all is Bohr's Copenhagen interpretation. Its popularity is largely due to the fact that physicists don't, by and large, want to trouble themselves with philosophy. Questions over what, exactly, constitutes a measurement, or why it might induce a change in the fabric of reality, can be ignored in favour of simply getting a useful answer from quantum theory.

That is why unquestioning use of the Copenhagen interpretation is sometimes known as the "shut up and calculate" interpretation. "Given that most physicists just want to do calculations and apply their results, the majority of them are in the shut up and calculate group," Vedral says. ›



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Species: Copenhagen

Distinguishing feature
Measurement plays a key role in changing quantum states

Status Healthy

This approach has a couple of downsides, though. First, it is never going to teach us anything about the fundamental nature of reality. That requires a willingness to look for places where quantum theory might fail, rather than where it succeeds. "If there is going to be some new theory, I don't think it's going to come from solid state physics, where the majority of physicists work," says Vedral.

Second, working in a self-imposed box also means that alternative applications of quantum theory are unlikely to emerge. The many perspectives we can take on quantum mechanics can be the catalyst for new ideas. "If you're solving different problems, it's useful to be able to think in terms of different interpretations," Vedral says.

Nowhere is this more evident than in the field of quantum information. "This field wouldn't even exist if people hadn't worried about the foundations of quantum physics," says Anton Zeilinger of the University of Vienna in Austria.

At the heart of this field is the phenomenon of entanglement, where the information about the properties of a set of quantum particles becomes shared between all of them. The result is what Einstein famously termed "spooky action at a distance": measuring a property of one particle will instantaneously affect the properties of its entangled partners, no matter how far apart they are.

Species: Transactional

Distinguishing feature
Quantum sources emit waves that travel forwards and backwards in time

Status Uncertain

Species: Penrose

Distinguishing feature
Outcome of experiments is a result of gravitational interactions

Status Under investigation

When first spotted in the equations of quantum theory, entanglement seemed such a weird idea that the Irish physicist John Bell created a thought experiment to show that it couldn't possibly manifest itself in the real world. When it became possible to do the experiment, it proved Bell wrong and told physicists a great deal about the subtleties of quantum measurement. It also created the foundations of quantum computing, where a single measurement could give you the answer to thousands, perhaps millions, of calculations done in parallel by quantum particles, and quantum cryptography, which protects information by exploiting the very nature of quantum measurement.

Species: Many worlds

Distinguishing feature
All quantum possibilities play out in a multiplicity of universes

Status Healthy

Both of these technologies have, understandably, attracted the attention of governments and industry keen to possess the best technologies – and to prevent them falling into the wrong hands.

Physicists, however, are actually more interested in what these phenomena tell us about the nature of reality. One implication of quantum information experiments seems to be that information held in quantum particles lies at the root of reality.

Adherents of the Copenhagen interpretation, such as Zeilinger, see quantum systems as carriers of information, and measurement using classical apparatus as nothing special: it's just a way of registering change in the information content of the system. "Measurement updates the information," Zeilinger says. This new focus on information as a fundamental component of reality has also led some to suggest that the universe itself is a vast quantum computer.

However, for all the strides taken as a result of the Copenhagen interpretation, there are plenty of physicists who would like to see the back of it. That is largely because it requires what seems like an artificial distinction between tiny quantum systems and the classical apparatus or observers that perform the measurement on them.

Vedral, for instance, has been probing the role of quantum mechanics in biology: various processes and mechanisms in the cell are quantum at heart, as are photosynthesis and radiation-sensing systems (see "The weirdness inside us", page 62). "We are discovering that more and more of the world can be described quantum mechanically – I don't think there is a hard boundary between quantum and classical," he says.

Species: Shut up & calculate

Distinguishing features
Lack of interest in deep meanings; focus on applied research

Status Robust

Considering the nature of things on the scale of the universe has also provided Copenhagen's critics with ammunition. If the process of measurement by a classical observer is fundamental to creating the reality we observe, what performed the observations that brought the contents of the universe into existence? "You really need to have an observer outside the system to make sense – but there's nothing outside the universe by definition," says Brown.

That's why, Brown says, cosmologists now tend to be more sympathetic to an interpretation created in the late 1950s by Princeton University physicist Hugh Everett. His "many worlds" interpretation of quantum mechanics says that reality is not bound to a concept of measurement.

Instead, the myriad different possibilities inherent in a quantum system each manifest in their own universe. David Deutsch, a physicist at the University of Oxford and the person who drew up the blueprint for the first quantum computer, says he can now only think of the computer's operation in terms of these multiple universes. To him, no other interpretation makes sense.

Not that many worlds is without its critics – far from it. Tim Maudlin, a philosopher of science based at New York University in New Jersey, applauds its attempt to demote

Species: Modal

Distinguishing feature
Quantum systems simultaneously possess a set of well and poorly defined physical properties, with any particular property shifting in and out of sharp definition

Status Endangered

Species: De Broglie-Bohm

Distinguishing feature
Hidden variables carry missing information about quantum states

Status Conservation needed

measurement from the status of a special process. At the same time, though, he is not convinced that many worlds provides a good framework for explaining why some quantum outcomes are more probable than others.

When quantum theory predicts that one outcome of a measurement is 10 times more probable than another, repeated experiments have always borne that out. According to Maudlin, many worlds says all possible outcomes will occur, given the multiplicity of worlds, but doesn't explain why observers still see the most probable outcome. "There's a very deep problem here," he says.

Deutsch says these issues have been resolved. "The way that Everett dealt with probabilities was deficient, but over the years

Species: Sum over histories

Distinguishing feature
Quantum systems take all possible paths, with differing probabilities that average out to measured value

Status Popularity limited

many-worlds theorists have been picking away at this – and we have solved it," he says.

However Deutsch's argument is abstruse and his claim has yet to convince everyone. Even more difficult to answer is what proponents of many worlds call the "incredulous stare objection". The obvious implication of many worlds is that there are multiple copies of you, for instance – and that Elvis is still performing in Vegas in another universe. Few people can stomach this idea.

Persistence will be the only solution here, Brown reckons. "There is a widespread reluctance to accept the multiplicity of yourself and others," he says. "But it's just a question of getting used to it."

Deutsch thinks this will happen when technology starts to use the quantum world's stranger sides. Once we have quantum computers that perform tasks by being in many states at the same time, we will not be able to think of these worlds as anything other than physically real. "It will be very difficult to maintain the idea that this is just a manner of speaking," Deutsch says.

He and Brown both claim that many worlds is already gaining traction among cosmologists. Arguments from string theory, cosmology and observational astronomy have led some cosmologists to suggest we live in one of many universes. In 2010, Anthony Aguirre of the University of California, Santa Cruz, Max Tegmark of the Massachusetts Institute of Technology and David Layzer of Harvard University laid out a scheme that ties together ideas from cosmology and many worlds.

But many worlds is not the only interpretation laying claim to cosmologists' attention. In 2008, Anthony Valentini of Imperial College London suggested that the cosmic microwave background radiation (CMB) that has filled space since just after the big bang might support the de Broglie-Bohm interpretation. In this scheme, quantum particles possess as yet undiscovered properties dubbed hidden variables.

The idea behind this interpretation is that taking these hidden variables into account would explain the strange behaviours of the quantum world, which would leave an imprint on detailed maps of the CMB. Valentini says that hidden variables could provide a closer match with the observed CMB structure than standard quantum mechanics does.

Though it is a nice idea, as yet there is no conclusive evidence that he might be onto something. What's more, if something unexpected does turn up in the CMB, it won't be proof of Valentini's hypothesis, Vedral reckons: any of the interpretations could claim that the conditions of the early universe would lead to unexpected results.

"We're stuck in a situation where we probably won't ever be able to decide experimentally between Everett and de Broglie-Bohm," Brown admits. But, he adds, that is no reason for pessimism. "I think there has been significant progress. A lot of people say we can't do anything because of a lack of a crucial differentiating experiment but it is

Species: Ensemble

Distinguishing feature
Theory says nothing about individual particles, but instead what happens when measurements are made on a group of particles

Status Rare

"Many worlds says there are multiple copies of you – and that Elvis is still performing in Vegas in another universe"

Species: Ghirardi-Rimini-Weber

Distinguishing feature
Particles in unstable states spontaneously collapse into stable states at a particular rate

Status Uncertain

Species: Von Neumann-Wigner

Distinguishing feature
Consciousness leads to experimental results

Status Highly contentious

definitely the case that some interpretations are better than others."

For now, Brown, Deutsch and Zeilinger are refusing to relinquish their favourite views of quantum mechanics. Zeilinger is happy, though, that the debate about what quantum theory means shows no sign of going away.

Vedral agrees. Although he puts himself "in the many worlds club", which interpretation you choose to follow is largely a matter of taste, he reckons. "In most of these cases you can't discriminate experimentally, so you really just have to follow your instincts."

The idea that physicists wander round the quantum zoo, choosing a favourite creature on a whim might seem rather unscientific, but it hasn't done us any harm so far.

Quantum theory has transformed the world through its spin-offs – the transistor and the laser, for example – and there may be more to come, such as encryption-busting quantum computers (see "Quantum computing best buys", page 87). Having different interpretations to follow gives physicists ideas for doing experiments in different ways. If history is anything to go by, keeping an open mind about what quantum theory means might yet open up another new field of physics, Vedral says. "Now that really would be exciting." ■

I'm rich.

I'm a *movie* star.

I'm king of the

I'm also poor. I'm homeless.

Lots of me are dead.

LUCAS SIMÕES

I'm Rowan Hooper.

world.

I'M NONE of these. Not in this universe. But in the multiverse I'm all of them, and more.

I'm not a megalomaniac or a fantasist, but I do have a fascination with what-ifs. In the many-worlds interpretation of quantum mechanics, every decision I take in this world creates new universes: one for each and every choice I could possibly make. There's a boundless collection of parallel worlds, full of innumerable near-copies of me (and you). The multiverse: an endless succession of what-ifs.

In one of those worlds, I've just written a paragraph which explains that more clearly.

This worries me. If many worlds is correct – and many physicists think it is – my actions shape the course not just of my life, but of the lives of my duplicates in other worlds.

"In the many-worlds interpretation, when you make a choice the other choices also happen," says David Deutsch, a quantum physicist at the University of Oxford. "If there is a small chance of an adverse consequence, say someone being killed, it seems on the face of it that we have to take into account the fact that in reality someone will be killed, if only in another universe."

Should I feel bad about the parallel Rowans that end up suffering as a result of my actions? If I drive carelessly here, I might get a fine, but one of my other selves might crash and kill himself. Or worse, kill my parallel family. How am I supposed to live with the knowledge that I am just one of umpteen Rowans in the multiverse, and that my decisions reach farther than I can ever know?

You might think I should just ignore it. After all, the many-worlds interpretation says I'll never meet those other versions of me. So why worry about them?

Well, most of us try to live by a moral code because we believe the things we do affect other people, even ones we'll never meet. We worry about how our shopping habits affect workers in distant countries; about as-yet-unborn generations suffering for our carbon emissions. Deutsch points out that we readily › accept that attempted murder has moral implications, albeit less serious than actual murder. So why shouldn't we afford some consideration to our other selves?

Max Tegmark, professor of physics at the Massachusetts Institute of Technology, understands my quandary. A leading advocate of the multiverse, he's thought long and hard about what it means to live in one. "I feel a strong kinship with parallel Maxes, even though I never get to meet them. They share my values, my feelings, my memories – they're closer to me than brothers," he says.

Taking the cosmic perspective makes it difficult for Tegmark to feel sorry for himself: there's always another Max who has it worse than him. If he has a near-miss while driving, he says he takes the experience more seriously than he did before he knew about the multiverse. "The minimum tribute I can pay to that dead Max is to really think through what happened and learn some lessons."

Tegmark is obviously a multiverse believer. Once, he would have been an outsider. When many-worlds was first proposed by Hugh Everett, then a graduate student at Princeton University, it met with a scornful reception. Everett struggled to get it published, and eventually left academia in disgust. But its elegant explanations for some puzzling quantum phenomena have convinced more and more physicists over the past 50 years.

Multi-universe physics has the same kind of experimental basis as dinosaurs

"Multi-universe physics has the same kind of experimental basis as the theory that there were once dinosaurs," says Deutsch.

Nor can we avoid its consequences. Every time we make a decision that involves probability – such as whether to take an umbrella in case of rain – our decision causes the universe to branch, explains Andreas Albrecht at the University of California, Davis. In one universe, we take the umbrella and stay dry; in another, we don't, and we get wet. The fundamental variability of the universe forces such choices upon us. "There's no escaping them," says Albrecht.

That's a momentous realisation. We're living in a time akin to Copernicus realising that Earth wasn't at the centre of the universe, or when Darwin realised that humans were not created separately from the other animals. Both of those realisations reshaped our conception of our place in the universe, our philosophy and morality. The multiverse looks like the next great humbler of humanity.

"That these worlds are actually out there somewhere, but we cannot access them: I think that's an amazing and remarkable thing," says physicist Seth Lloyd, a colleague of Tegmark's at MIT. "It's sort of distressing really." Why, I ask: because it diminishes humanity's status even more?

"No, not for that reason. I've always enjoyed the gradual marginalisation of humanity," he says. "No, it was somehow tidier to have the universe *be* the cosmos. But actually now I'm liking it more, now that you've pointed out that it's really like the ultimate step in the marginalisation of human beings. I think that's much better. I enjoy that."

Enjoyable though the multiverse might be as a concept, it's tough for us humans to get our heads around its implications – even for physicists themselves. When Tegmark's wife was in labour with Philip, their eldest son, he found himself hoping that everything would go well. Then he admonished himself.

"It was going to go well, and it was going to end in tragedy, in different parallel universes. So what did it mean for me to hope that it was going to go well?" He couldn't even hope that the fraction of parallel universes where the birth went well was a large one, because that fraction could in principle be calculated. "So it doesn't make any sense to say 'I'm hoping something about this number'. It is what it is."

Hope, it turns out, is the next casualty of the multiverse. You make a decision, and you end up on a branch of the multiverse with a "good" outcome, or you find yourself on a "bad" branch. You can't wish your way on to a good one. Tegmark acknowledges this is not easy to live with. "It's tough to get your emotions to sync with what you believe," he says.

Too tough for me. How am I meant to live without hope?

Slippery concept

What do other non-specialists make of the multiverse? When Hugh Everett died in 1982, aged just 51, his teenage son Mark found his body. I asked him if his father's work had influenced him. "Although I consider ›

FOUR ASPECTS OF THE MULTIVERSE

1

THE WAVE FUNCTION

This mathematical entity describes the properties of any quantum system. Such properties - an atom's direction of spin, say - can take several values at once, in what is known as quantum superposition. But when we measure such a property we only get a single value - in the case of spin, it is either up or down.

In the traditional Copenhagen interpretation of quantum mechanics, the wave function is said to "collapse" when the measurement is taken, but it isn't clear how this happens. (Schrödinger's famous cat, neither alive nor dead until someone looks inside its box, illustrates this.) In the multiverse, the wave function never collapses: rather, it describes the property across multiple universes. In this universe, the atom's spin is up; in another universe, it's down.

myself an Everettian by default, it's all beyond me for the most part, having inherited none of my father's mathematical smarts," says Mark, long-time frontman of the band Eels. "How can I grasp any of it except in small moments? I'm having a hard enough time dealing with this world lately. I only hope some of the other worlds are easier for me to figure out."

I know how he feels. Perhaps a philosopher can help me take a broader perspective. I turn to David Papineau of King's College London. "Say you put your money on a horse that you think is a very good bet," he says. "It turns out that it doesn't win, and you lose all your money. You think, 'I wish I hadn't done that.' But you brought benefits to your cousins in other universes where the horse won. You've just drawn the short straw in finding yourself in the universe where it lost. You didn't do anything wrong. There's no sense that the action you took earlier was a mistake."

2

WAVE-PARTICLE DUALITY

In the landmark experiment, photons are sent one at a time towards a pair of slits, with a phosphorescent screen behind them. Take a measurement at either slit, and you'll register individual photons passing particle-like through one or the other. But leave the apparatus alone, and an interference pattern will build up on the screen, as if each photon had passed through both slits simultaneously and diffracted at each, like a classical wave.

This dual character has been described as the "central mystery" of quantum mechanics. In the Copenhagen interpretation, it is down to wave function collapse. Left to its own devices, each photon would pass through both slits simultaneously: the measurement at the slit forces it to "choose". One way to explain the interference pattern through many worlds, by contrast, is that each photon only ever goes through one slit - the pattern comes about when a photon interacts with its clone passing through the other slit in a parallel universe.

Hmm. I doubt "I didn't make a mistake" would get much traction with my partner if I bet all our savings on a horse this afternoon and find myself on the "wrong" branch. But then, that wouldn't be the sensible thing to do – and one of the great attractions of Everett's interpretation, according to Papineau, is that it's not "messy", as long as you act rationally.

With orthodox thinking, there are two ways of evaluating risky actions, he explains. First, did you make the choice that was most in line with the odds? If we needed money, and my stake had been proportionate, it might have been. Second, did it work out well? There are any number of reasons it might not – the horse might fall, or just defy the odds and trail in last.

It offends Papineau that these two ways of being "right" – choosing wisely and getting lucky – don't go hand-in-hand. "The idea that the right thing to do might turn out to have been the wrong thing seems to me to be a very ugly feature of orthodox thinking," he says. This doesn't arise in the many-worlds interpretation, where every choice is made and every outcome occurs. That leaves no place for hope or luck, but nor does it leave room for remorse. It's an elegant, if cold-blooded, way to look at things.

This elegance has always been part of the multiverse's appeal. In quantum mechanics, every object in the universe is described by a mathematical entity called a wave function, which describes how the properties of subatomic particles can take several values simultaneously. The trouble is, this fuzziness vanishes as soon as we measure any of those properties. The original explanation for this – the so-called Copenhagen interpretation – says the wave function collapses to a single value whenever a measurement is made.

Hugh Everett called this enforced separation of the quantum world from the everyday, classical one a "monstrosity", and decided to find out what happened if the wave function did not collapse. The resulting mathematics showed that the universe would split every time a measurement is made – or in human terms, whenever we make a decision with multiple possible outcomes. That's the many-worlds interpretation.

God of elegance

For Don Page, a theoretical physicist at the University of Alberta in Edmonton, Canada, this elegance goes far beyond human actions. Page is both a hard-core Everettian and a committed Christian. Like many modern physicists, he agrees with Everett's stance that collapsing the wave function is unnecessarily complicated. What's more, for Page it has a happy side effect: it explains why his God tolerates the existence of evil.

"God has values," he says. "He wants us to enjoy life, but he also wants to create an elegant universe." To God the importance of elegance comes before that of suffering, which, Page infers, is why bad things happen. "God won't collapse the wave function to cure people of cancer, or prevent earthquakes or whatever, because that would make the universe much more inelegant."

For Page, that is an intellectually satisfying solution to the problem of evil. And what's more, many worlds may even take care of free will. Page doesn't actually believe we have free will, because he feels we live in a reality in which God determines everything, so it is impossible for humans to act independently. But in the many-worlds interpretation every possible action is actually taken. "It doesn't mean that it's fixed that I do one particular course of action. In the multiverse, I'm doing all of them," says Page.

There are limits to Page's willingness to leave his fate to the multiverse, however. Seth Lloyd once offered him $1 million to play quantum Russian roulette, which is a good game for a multiverse aficionado: you can't lose (see below right). Page thought about it, then declined: he didn't like the thought of his wife's distress in the worlds where he died.

Like Tegmark, Page seems to values the multiverse for the perspective it offers.

"God wants us to enjoy life. But he also wants to create an elegant universe"

"One of my teenage children wants to get a motorcycle, which my wife and I think is pretty dangerous," Page says. "But if I say: 'Okay, maybe most of the time you'd survive, but there's going to be some part of you, some branch, in which you get seriously maimed in a motorcycle accident'... Maybe I'll try it."

Double Deutsch

I'm somewhat relieved to find that even many-worlds experts ultimately behave in much the same way as people who know nothing of it. But I've also realised that it shapes the way they think about their decisions. Perhaps it's more natural for us to think about how our actions affect our "other selves" than about the arid probabilities of risk and reward.

If anyone's going to buck this trend, it's surely David Deutsch, probably the most hard-core of Everettians. Surely he can give me the last word on what it means to live in › the multiverse. He does, but it is by no means the answer I was expecting.

"Decision theory in the multiverse tells us that we should value things that happen in more universes more, and things that happen in fewer universes less," he explains. "And it tells us that the amount by which we should value them more or less is, barring exotic circumstances, exactly such that we should behave as if we were valuing the risks according to probabilities in a classical universe." So the right thing to do remains the right thing to do.

So has my quest been for nothing? Not at all. For one thing, Deutsch's approach could be wrong, a possibility he accepts, though he is adamant the multiverse exists. But if he's right, his conclusion only reinforces what his peers have been telling me: the best way to live in the multiverse is to think carefully about how you live your life in this one.

Thinking of what-ifs as having some kind of reality can help us to do that. Tegmark says many worlds has made him think differently about life. He sometimes fears doing something because it feels too big a deal. But then he realises that in the grander context of the multiverse, it's not big at all – that gives him a booster shot of determination and he just does it. "The multiverse has definitely made me a happier person," he says. "It's given me courage to take chances to be bold in life."

I hope it will do the same for me. We might not stop feeling hope or remorse, but the multiverse can help put those feelings in perspective. And while the multiverse may not require a change in our morality, it can help us think harder about our choices and actions. The cosmos reaches far further than we ever appreciated. But so, it seems, do we. ■

3

QUANTUM COMPUTING

Though quantum computers are in their infancy, they are in theory incredibly powerful, capable of solving complex problems far faster than any ordinary computer. In the Copenhagen interpretation, this is because the computer is working with entangled "qubits" which can take many more states than the binary states available to the "bits" used by classical computers. In the multiverse interpretation, it's because it conducts the necessary calculations in many universes at once.

4

QUANTUM RUSSIAN ROULETTE

This amounts to playing the role of Schrödinger's cat. You'll need a gun whose firing is controlled by a quantum property, such as an atom's spin, which has two possible states when measured. If the Copenhagen interpretation is right, you have the familiar 50-50 odds of survival. The more times you "play", the less likely you are to survive.

If the multiverse is real, on the other hand, there always will be a universe in which "you" are alive, no matter how long you play. What's more, you might always end up in it, thanks to the exalted status of the "observer" in quantum mechanics. You would just hear a series of clicks as the gun failed to fire every time - and realise you're immortal. But be warned: even if you can get hold of a quantum gun, physicists have long argued about how this most decisive of experiments would actually work out.

An experiment showing that quantum particles can lose their identity is redefining reality. **Anil Ananthaswamy** reports

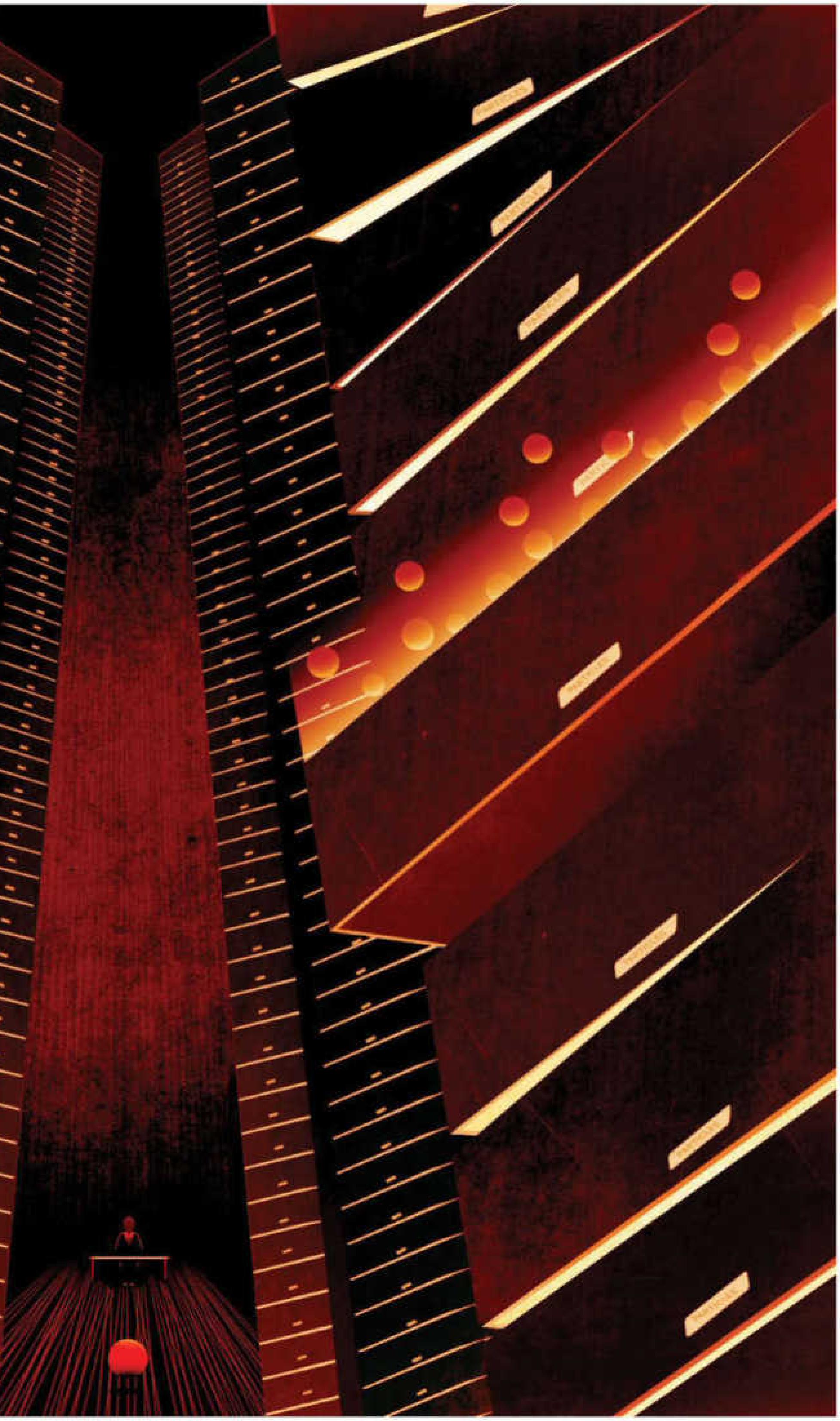
LOST and FOUND


MATT MURPHY

AS WEIRD as the quantum world is, in 2013 something happened in the shadow of the French Alps that caused even hardened quantum physicists to do a double take. At the Institut Laue-Langevin in Grenoble, where a nuclear reactor spews out the world's most intense beam of neutrons, physicists made these particles perform a trick that until now had only existed in the fevered imaginations of theorists. In doing so, they have upset our notion of reality.

The international team of physicists coaxed the neutrons to shed their quantum properties, getting the particles to go one way and their spins another way. It's as if you took one path and your personality another. Theorists have predicted the possibility of such strange behaviour for more than a decade. They even named it the quantum Cheshire cat phenomenon, after the cat in *Alice's Adventures in Wonderland*, which would disappear leaving only its grin behind. Now, for the first time, the quantum Cheshire cat is smirking at us in experiments, posing fundamental questions about the nature of the quantum world.

Quantum theory emerged in the 1920s and it remains wildly successful. No experiment has ever disagreed with its predictions and we can be confident that it is an accurate description of the microscopic world of atoms



and their constituents. It is a strange description, for sure: quantum particles can be in two places at once, spin clockwise and anticlockwise at the same time, or instantaneously influence each other from across the universe.

Why the microscopic world should behave this way while everyday objects do not is still very much a mystery. "We don't believe that there is a deep intuitive understanding of quantum mechanics, and that's the reason why we keep making these shocking discoveries," says Jeff Tollaksen of Chapman University in Orange, California.

That leaves theorists and experimentalists free to push the boundaries of quantum theory, looking for clues as to what makes it tick. One such push began 50 years ago, when Yakir Aharonov, who is also now at Chapman, asked a very basic question: does time in quantum mechanics have to flow from the past to the present, as our intuition suggests? The answer, at least mathematically, is no.

Two-way time

Aharonov and his colleagues Peter Bergmann and Joel Lebowitz fashioned a theory called the time-symmetric formulation of quantum mechanics, which defies common-sense notions of time. In their 1964 paper, they showed how the state of a quantum system could be affected both by events in the past and events in the future. Time flowed both ways. The theory was mathematically equivalent to standard quantum mechanics, where time flows one way, yet suggested that nature was different. "It was the first paper that eliminated the assumption that at the deep microscopic level there was an asymmetry in time similar to the way we human beings experience it," says Tollaksen.

So much for the theory. When it came to testing the idea, experimentalists faced a serious problem. In the classical world, an object can exist in one state or another: it can either spin clockwise or anticlockwise. But in the quantum world, particles can spin clockwise and anticlockwise at the same time. Experiments have confirmed that such "superpositions" really do exist, yet we don't see them directly because the very act of measuring them forces the particle into one state or the other. Such "strong" measurements obliterate the quantum nature of the particle and, because of this, it is impossible to test whether an event in the future will affect a particle in the present.

This might have been the end of the story,

> **"Both the past and future can influence a particle in ways that are truly bizarre"**

had Aharonov and colleagues not discovered that reports of death in the quantum world are an exaggeration. In a seminal theory paper in 1988, they showed that it is possible to make a different kind of measurement, one that doesn't destroy the quantum state. As long as the device that's doing the measuring interacts extremely weakly with the particle, you can glean something more about it without forcing it into one state or the other. The trade-off for saving the particle's quantum nature is that this "weak measurement" comes with a great deal of uncertainty.

This means that one weak measurement isn't particularly useful. But who says you can't do more? The trick, Aharonov's team found, is to make weak measurements on an ensemble of identical particles. The uncertainty means that each generates a different value. But if you plot lots of them, they produce a bell-shaped curve whose peak denotes the state of the quantum particles. So weak measurements offer a way to test time symmetry.

Needless to say, the weak measurement idea did not go down well. "At first there was complete disbelief," recalls Aharonov.

But time and technology have helped his case. Over the past decade, weak measurements have gone from theory to reality. Such experiments have allowed us to study aspects of the quantum world that were previously thought impossible, such as measuring the wave function that describes a particle. Jeff Lundeen of the University of Ottawa in Ontario, Canada, and his colleagues did exactly this in 2011 on a vast collection of identical photons.

While experimentalists were figuring out how to do weak measurements in the 1990s, Tollaksen began working for his PhD with Aharonov on the theoretical foundations of quantum mechanics. Aharonov had shown that both the past and future can conspire to influence a particle in ways that are truly bizarre. In one example, his mathematics showed that a particle whose spin is exactly +½ or -½ when you make a strong measurement on it can have a spin of 100 when you make a weak measurement.

Even stranger, Aharonov and Tollaksen found that the past and future can lead to a particle and its properties going their separate ways. The quantum Cheshire cat was born.

Lost property

When Tollaksen published his PhD thesis in 2001, he laid out their thought experiment. It begins with a step called pre-selection that involves preparing a large number of neutrons with identical spins.

These particles are sent one by one into a device called an interferometer. The first stop in the interferometer is a beam splitter, which as the name suggests splits the beam into two. Each neutron is now in that crazy state of quantum superposition where it traverses both paths at once. Both paths contain equipment that lets you make a weak measurement. The paths are eventually brought together and the beams recombined in such a way that some neutrons exit through one output path, while the others exit via a different path (see illustration, below). On one of the output paths, the particles are subjected to a strong measurement, such as measuring what spin direction the neutrons now have. Only some will have the desired value. These particles are said to be post-selected. The experimenter discards all other neutrons that don't satisfy the post-selection criterion.

Now comes the weirdness. Pre- and post-selection amount to tinkering with the past and future respectively. If you look at only those neutrons that were post-selected, the maths says that all these neutrons took one path inside the interferometer whereas their spins went along the other path. It's as if you had two boxes – one full of the particles without their properties and the other full of their properties but not the particles. "That definitely should cause you to pause," says Tollaksen.

That's all very well on paper, but would the quantum Cheshire cat appear in reality? To find out, researchers would have to make weak measurements on neutrons – something that no one has done to this kind of particle or any other kind of matter. So Tollaksen teamed up with experimenters from the Vienna University of Technology in Austria who specialise in testing quantum mechanics using neutrons.

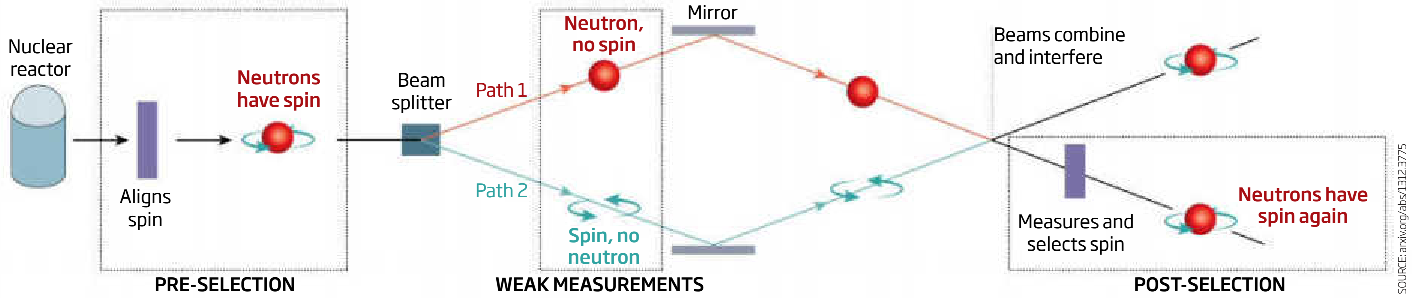
In Grenoble, the Vienna team used a feeble magnetic field and a weakly interacting neutron absorber to make the weak measurements. They found that when they put the absorber in one path of the interferometer (say left), there was a discernible effect at the output. But when they put it in the right path, it had no such effect. The neutrons were travelling in one path only.

Next, the experimenters introduced a weak magnetic field near each arm of the interferometer, to interact with the spin of the neutrons. When they did this in the left path, there was no change in the interferometer's output. If they introduced the magnetic field in the right path, though, there was a change: the magnetic field had interacted with the spin. In other words, they had confirmed that the spin had chosen the path not taken by the parent neutron. They had separated the cat from its grin.

The results are recent and radical enough that no one really knows what this might lead to. However, some are willing to speculate. Say

Quantum Cheshire cat

Yuji Hasegawa and his colleagues have brought a thought experiment called the quantum Cheshire cat to life. They have found that it is possible to separate neutrons' quantum mechanical spin from the particles themselves



MATT MURPHY

you want to measure something called the electric dipole moment of a neutron, which reflects how the charged quarks that make up the particle are distributed. Theories that try to explain why the universe has matter but no discernible antimatter left from the big bang also predict that the neutron has a tiny electric dipole moment.

All efforts to measure it have thus far found nothing. But the neutron has a strong magnetic moment – and this potentially messes up such experiments. "If I can separate the magnetic moment of the neutron from the neutron, I can do a very delicate experiment to check whether it has a very weak electric dipole moment," says Aharonov.

Peter Geltenbort of the Institut Laue-Langevin studies the fundamental properties of neutrons and is intrigued by the promise of the quantum Cheshire cat. "This is a really nice piece of experimental physics," he says. "In terms of ongoing attempts to measure the neutron's electric dipole moment, it would be extremely exciting to apply such a technique and, if successful, it would undoubtedly increase the sensitivity of our measurements."

And these aren't the only properties that neutrons can lose, according to Aharonov. "The only thing that cannot be separated from a particle is its mass. What defines where the particle lives is its mass," he says. "Everything else is like the smile of the cat. You can separate it from the cat."

Because there is nothing to stop you from making quantum Cheshire cats from photons, electrons and even atoms, Tollaksen thinks there might be uses in quantum computing. One of the challenges in quantum computing is to isolate particles from external disturbances that destroy the all-important superposition of states. The quantum Cheshire cat phenomenon could separate the more susceptible properties of particles from the particles themselves, leading to more stable quantum computers.

"We're only just beginning to understand the quantum Cheshire cat's implications"

"We can open a completely new kind of physics. I'm only beginning to understand the implications," says Aharonov.

There is of course the bigger question of what all this says, if anything, about the nature of reality. It depends on what you make of the values thrown up by weak measurements. "That's the elephant in the room," says Aephraim Steinberg of the University of Toronto, Canada, who studies weak measurement experiments. "What do these values really tell us about the physical world?"

If you ascribe physical reality to weak values, a particle really can have an absurd spin. A neutron can really be in one path and its spin in the other. "I believe that these are true physical properties of quantum systems," says Aharonov. "When you pre- and post-select quantum systems, you see a completely new reality."

Quest for elegance

Not everyone is ready to accept this strange new reality. "The interpretation of these measurements is non-trivial, even tricky," says Johannes Kofler of the Max Planck Institute of Quantum Optics in Garching, Germany. "The Cheshire cat paradox arises only when you give a physical meaning to the observed weak values – which is challenged and debated in the community."

Where does this leave the time-symmetric formulation of quantum mechanics in which the future influences the present? Steinberg remains cautious. "I think it's easy to overinterpret that language. I'm not going to claim that when I dig up a dinosaur bone today, it causes that dinosaur to have gotten killed 65 million years ago. I wouldn't say that the future is influencing the past. I'd say that information about the future gives us information about the present or the past."

Tollaksen, however, points out that with the time-symmetric formulation, the calculations needed to predict the weak values in experiments like the quantum Cheshire cat are simple and elegant. Trying to do the same with traditional quantum mechanics, where time flows one way, is unwieldy, even inelegant. Often in physics the quest for elegance has led to a clearer understanding of reality. But it's too early to tell if that reality involves time symmetry, Steinberg says.

What's clear is that finally observing the quantum Cheshire cat is challenging our intuitions about matter. We don't yet know what it means for an atom to be separated from its properties. The first clues might come when experimentalists succeed in measuring the electric dipole moment of a neutron by separating it from its magnetic moment. That would be momentous in more ways than one, giving us a glimpse of a reality that, as with almost everything in quantum mechanics, defies common sense. Curiouser and curiouser hardly covers it. ■

PAUL BLOW

Uncertainty entangled

Could quantum weirdness spell the end for Heisenberg's notorious principle, asks Anil Ananthaswamy

SOME middle-aged men have trains in their attics. Niels Bohr had Werner Heisenberg. In the winter of 1926-1927, the brilliant young German was working as Bohr's chief assistant, billeted in a garret at the top of the great Dane's Copenhagen institute. After a day's work, Bohr would come up to Heisenberg's eyrie to chew the quantum fat. They often sat up late into the night, in intense debate over the meaning of the revolutionary quantum theory, then its infancy.

One puzzle they pondered were the trails of droplets left by electrons as they passed through cloud chambers, an apparatus used to track the movements of charged particles. When Heisenberg tried calculating these seemingly precise trajectories using the equations of quantum mechanics, he failed.

One evening in mid-February, Bohr had left town on a skiing trip, and Heisenberg had slipped out to catch some night air in the broad avenues of Faelled Park, behind the institute. As he walked, it came to him. The electron's track was not precise at all: if you looked closely, it consisted of a series of fuzzy dots. That revealed something fundamental about quantum theory. Back in his attic, Heisenberg excitedly wrote his idea down in a letter to fellow physicist Wolfgang Pauli. The gist of it appeared in a paper a few weeks later: "The more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa."

Thus Heisenberg's notorious uncertainty principle was born. A statement of the fundamental unknowability of the quantum world, it has stood firm for the best part of a century. But for how much longer? Rumblings are abroad that a second quantum principle – entanglement – could sound the death knell for uncertainty. Is it goodbye Heisenberg, hello quantum certainty?

The profound implications of the uncertainty principle are hard to overstate. Think of our classical, clockwork solar system. Given perfect knowledge of the current positions and movements of its planets and other bodies, we can predict their exact positions and movements any time in the future with almost perfect accuracy. In the quantum world, however, uncertainty does away with any such ideas of perfect knowledge revealed by measurement (see "Fuzzy logic", page 32). Its assertion that there are pairs of "complementary" quantities such as position and momentum, where exact knowledge of one precludes knowing the other at all accurately, also undermines any concept of predictable cause and effect. If you cannot know the present in its entirety, you can have no idea what the future might bring.

Since that Copenhagen winter, generations of physicists have tugged at Heisenberg's principle, giving it a tweak here or a new formal expression there as we have learned more about the vagaries of quantum measurements and the exchange of quantum information. The now-favoured version of the principle was constructed in 1988 by two Dutch physicists, Hans Maassen and Jos Uffink, using concepts from the theory of information devised by the American mathematician Claude Shannon and others in the years following the second world war.

Squeezed entropy

Shannon had shown how a quantity that he termed entropy, by analogy with the measure of thermodynamic disorder, provided a reliable indicator of the unpredictability of information, and so quite generally of uncertainty. For example, the outcome of the most recent in a series of coin tosses has maximal Shannon entropy, as it tells you nothing about the result of the next toss. Information expressed in a natural language such as English, on the other hand, has low entropy, because a series of words provides clues to what will follow.

Translating this insight to the quantum world, Maassen and Uffink showed how it is impossible to reduce the Shannon entropy associated with any measurable quantum quantity to zero, and that the more you squeeze the entropy of one variable, the more the entropy of the other increases. Information that a quantum system gives with one hand, it takes away with the other.

But is that always the case? Not according to Mario Berta, a quantum information theorist at the California Institute of Technology in Pasadena, and his colleagues. Quantum entanglement can have a distinctly weird effect on uncertainty.

Suppose an observer called Bob creates a pair of particles, such as photons of light, whose quantum states are somehow entangled. Entanglement means that even though these states are not defined until they are measured, measuring one and giving it a definite value will immediately pin down the state of the other particle. This happens even if the distance between the two particles is too great for any influence to travel between them without breaking the cosmic speed ›

"Over a series of measurements, quantum weirdness squeezes uncertainty to zero"

limit set by light – the seemingly impossible process decried by Einstein as "spooky action at a distance".

Bob sends one of these entangled photons to a second observer, Alice, and keeps the other close by him in a quantum memory bank – a suitable length of optical fibre, say. Alice then randomly measures one of a pair of complementary variables associated with the photon: in this case, polarisations in two different directions. Her measurement will be governed by the usual rules of quantum uncertainty, and can only ever be accurate to within a certain limit. In Maassen and Uffink's terms, its entropy will be non-zero. Alice tells Bob which of the quantities she measured, but not the value that she obtained.

Now comes the central claim. Bob's job is to find out the result of Alice's measurement as accurately as possible. That is quite easy: he just needs to raid his quantum memory bank. If the two photons are perfectly entangled, he need only know which quantity Alice measured and measure it in his own photon to give him perfect knowledge of the value of Alice's measurement – better even than Alice can know it. Over the course of a series of measurements, he can even squeeze its associated entropy to zero.

Berta's group published their work in July 2010. Just a few months later, two independent teams, led by Robert Prevedel of the European Molecular Biology Laboratory in Heidelberg, Germany, and Chuan-Feng Li of the University of Science and Technology of China in Hefei, performed the tests. They worked: uncertainty could be reduced to previously unachievable levels simply by increasing entanglement. "The experiments are in perfect agreement with our theoretically derived relation," says Berta. "We were surprised how quickly the experiments were realised."

So is uncertainty's grip finally loosening? Initial reactions have been cautious. "This is a very beautiful and important extension of the Maassen-Uffink uncertainty relations," says Paul Busch, a quantum theorist at the University of York, UK, who was not involved with any of the teams. Uffink himself, a researcher at the University of Utrecht in the Netherlands, agrees. "It is admirable work," he says, "but there is of course a 'but'."

That "but", Uffink says, is that even if Bob is armed with entanglement and quantum memory, the experiments show only that it is possible for him to predict precisely the result of either of the two possible measurements that Alice makes – not both at the same time.

Uncertainty is dead

To both Uffink and Busch, the thought experiment devised by Berta and his team is reminiscent of the famous "EPR" thought experiment devised in 1935 by Einstein and his colleagues Boris Podolsky and Nathan Rosen. It, too, came to a similar conclusion: that entanglement could remove all uncertainty from one measurement, but not from both at once. In keeping with Einstein's general scepticism about quantum weirdness, he interpreted the tension between the two principles as indicating that quantum mechanics was incomplete, and that a hidden reality lying beneath the quantum world was determining the outcome of the experiments.

While that debate is now largely considered settled , the latest work opens up an entirely new perspective. Traditionally, debates about the validity of the uncertainty principle and the interpretation of the EPR experiment have remained distinct. Now there is another possibility: not that uncertainty is dead, but that there is a relationship between uncertainty and entanglement that has previously not been fully appreciated.

"They are different sides of the same coin," says Busch. Where two particles are perfectly entangled, spooky action at a distance calls the shots, and uncertainty is a less stringent principle than had been assumed. But where there is no entanglement, uncertainty reverts

FUZZY LOGIC

In the 1927 paper that introduced the uncertainty principle to the world, Werner Heisenberg established that there are pairs of quantities in the quantum world that cannot both be measured to an arbitrary level of precision at the same time.

One such pair is position and momentum – essentially a measure of a quantum particle's movement. If you know a particle's position x to within a certain accuracy Δx, then the uncertainty Δp on its momentum p is given by the mathematical inequality $\Delta x \Delta p \geq \hbar/2$. Here, $\hbar$ is a fixed number of nature known as the reduced Planck constant.

This inequality says that, taken together, Δx and Δp cannot undercut $\hbar/2$. So in general, the more we know about where a particle is (the smaller Δx is), the less we can know about where it is (the larger Δp is), and vice versa.

The uncertainty principle also applies to other pairs of quantities such as energy and time, and the spins and polarisations of particles in various directions. The energy-time uncertainty relation is the reason why quantum particles can pop out of nothingness and disappear again. As long as the energy, ΔE, they borrow to do that and the time, Δt, for which they hang around don't bust the uncertainty bound, the fuzzy logic of quantum mechanics remains satisfied.


SEGRE COLLECTION/AMERICAN INSTITUTE OF PHYSICS/SPL

Werner Heisenberg, quantum uncertainty pioneer, in 1927

to the Maassen-Uffink relation. The strength of the Berta interpretation is that it allows us to say how much we can know for a sliding scale of situations in between, where entanglement is present but less than perfect. That is highly relevant for quantum cryptography, the quantum technology closest to real-world application, which relies on the sharing of perfectly entangled particles. The relation means there is an easier way to test when that entanglement has been disturbed, for example, by unwanted eavesdroppers, simply by monitoring measurement uncertainty.

As for the duel between uncertainty and entanglement, it ends in a draw, with the two principles becoming the best of friends after the event. "Because they are now part and parcel of the same mathematical scheme, you can't pick one and say this is logically superior to the other, or the other way around, because everything is logically connected somehow," says Busch.

But, he says – there is another "but" – while that is true within the confines of quantum theory, we might be able to tell which is the stronger principle by zooming out and considering a mathematical framework more general than that of quantum theory.

A game that Stephanie Wehner played can help explain. Along with Jonathan Oppenheim of University College London, Wehner, a researcher at the Delft University of Technology in the Netherlands, played it with 12-year-old kids in a cafe. She gave them a board with two squares, and gave one child a zoo of two tigers and two elephants. The child could place one tiger on each square, one elephant on each square, or a tiger on one and an elephant on the other. Without looking, a second kid had to guess which animal was on one of the squares.

"It made them understand why it's not possible to win all the time," says Wehner. Without some illicit sharing or extraction of information, they could only hope to guess right half the time.

The significance of the game is that it expresses questions of uncertainty and entanglement in terms of information retrieval. Guessing an animal or a photon state correctly depends on the correlation between information already held and information being sought. Entanglement provides a way to increase that correlation – effectively, to cheat.

Long live uncertainty

Oddly, though, even the weird "non-locality" embodied by entanglement does not guarantee success. Yet it is possible to envisage theories that do not break any laws of physics – in particular, the strict condition that no influence should travel faster than light, laid down in Einstein's special theory of relativity – and still allow you to be right 100 per cent of the time. What stops us from attaining this perfection? It is an important question, and one that goes to the heart of our attempts to try and understand how all the various counterintuitive properties of quantum theory fit together.

Oppenheim and Wehner's answer, published in 2010, is disarmingly simple: the uncertainty principle.

It is a satisfying twist to the story. Within the confines of quantum theory, entanglement can help to break down uncertainty, allowing us to be more certain about the outcome of certain experiments than the uncertainty principle alone would allow. On this level, entanglement comes up trumps. But zoom out and ask how the confines of quantum theory are set, and it seems that it is the uncertainty principle that stops things in the quantum world being weirder and more correlated than they already are. Uncertainty rules, and puts entanglement in a straitjacket. "It shows quite clearly that the uncertainty principle is far from dead," says Busch.

Iwo Bialynicki-Birula, a physicist who did seminal work reformulating the uncertainty principle in terms of information in the 1970s, once wrote that every physical theory has an eye-catching equation that can grace a T-shirt. Where relativity has $E = mc^2$, quantum mechanics has its uncertainty relation. Heisenberg's baby, born in an attic, could be adorning T-shirts for a while yet. ■

MATT MURPHY

State of mind

It's not quantum theory that's uncertain, says **Matthew Chalmers** – it's you

SNATCH a toy from the tiniest of infants, and the reaction is likely to disappoint you. Most seem to conclude that the object has simply ceased to exist. This rapidly changes. Within the first year or so, playing peekaboo also becomes fun. As babies, we soon grasp that stuff persists unchanged even when we are not looking at it.

Granted, at that age we know nothing of quantum theory. In the standard telling, this most well-tested of physical theories – fount of the computers, lasers and cellphones that our adult souls delight in – informs us that reality's basic building blocks take on a very different, nebulous form when no one is looking. Electrons, quarks or entire atoms can easily be in two different places at once, or have many properties simultaneously. We cannot predict with certainty which of the many possibilities we will see: that is all down to the random hand of probability.

That's not the way our grown-up, classical world seems to work, and physicists have been scrabbling around for the best part of a century to explain the puzzling mismatch. To no avail. Faced with reality at its most fundamental, we end up babbling baby talk again.

David Mermin thinks he has something sensible to say. An atomic physicist at Cornell University in Ithaca, New York, he has spent most of his half-century-long career rejecting philosophical musings about the nature of quantum theory. But he's had an epiphany. The way to solve our quantum conundrums is to abandon the ingrained idea that we can ever achieve an objective view of reality. According to this provocative idea, the world is not uncertain – we are.

The idea that an objective, universally valid view of the world can be achieved by making properly controlled measurements is perhaps the most basic assumption of modern science. It works well enough in the macroscopic, classical world. Kick a football, and Newton's laws of motion tell you where it will be later, regardless of who is watching it and how.

Kick a quantum particle such as an electron or a quark, though, and the certainty vanishes. At best, quantum theory allows you to calculate the probability of one outcome from many encoded in a multifaceted wave function that describes the particle's state. Another observer making an identical measurement on an identical particle might measure something very different. You have no way of saying for sure what will happen.

So what state is a quantum object in when no one is looking? The most widely accepted answer is the Copenhagen interpretation, so named after the site of many early quantum musings. Schrödinger's notorious cat illustrates its conclusion. Shut in a box with a vial of lethal gas that might, or might not, have been released by a random quantum event such as a radioactive decay, the unfortunate feline hangs in limbo, both alive and dead. Only when you open the box does the cat's wave function "collapse" from its multiple possible states into a single real one.

This opens a physical and philosophical can of worms. Einstein pointedly asked whether the observations of a mouse would be sufficient to collapse a wave function. If not, what is so special about human consciousness? If our measurements truly do affect reality, that also opens the door to effects such as "spooky action at a distance" – Einstein's dismissive phrase to describe how observing a wave function can seemingly collapse another one simultaneously on the other side of the universe.

LOST IN SPACE

From a human perspective, physics has a problem with time. We have no difficulty defining a special moment called "now" that is distinct from the past and the future, but our theories cannot capture the essence of the moment. The laws of nature deal only with what happens between certain time intervals.

David Mermin of Cornell University claims to have solved this problem using a principle similar to the one he and others have applied to quantum theory (see main story). We should simply abandon the notion that an objectively determinable space-time exists.

Instead of forming a series of slices or layers that from some viewpoint correspond to a "now" or "then", Mermin's space-time is a mesh of intersecting filaments relating to the experiences of different people.

"Why promote space-time from a 4D diagram, which is a useful conceptual device, to a real essence?" he asks. "By identifying my abstract system with an objective reality, I fool myself into regarding it as the arena in which I live my life."

Things such as an interval of time or the dimensionality of space, after all, are not stamped on nature for us to read off; a newborn baby has no conception of them. They are merely useful abstractions we develop to account for what clocks and rulers do. Some of these high-level abstractions we construct for ourselves as we grow up, others were constructed by geniuses and have been passed on to us in school or in books, says Mermin. "And some of them, like quantum states, most of us never learn at all."

Then there is the mystery of how atoms and particles can apparently adopt split personalities, but macroscopic objects such as cats clearly can't, despite being made up of atoms and particles. Schrödinger's intention in introducing his cat was to highlight this inexplicable division between the quantum and classical worlds. The split is not only there, but also "shifty", in the words of quantum theorist John Bell: physicists contrive to put ever-larger objects into fuzzy quantum states, for instance – so we have no set way of defining where the boundary lies.

The Copenhagen interpretation simply ignores these quantum mysteries, famously leading Mermin to dub it the "shut up and calculate" approach in an article he wrote in 1989. He counted himself as an adherent. Although alternatives did exist – such as the many worlds interpretation, which suggests the universe divides into different paths every time anything is observed – none quite seemed to crack the central mystery.

Frequently wrong

Now Mermin thinks one does. It is not his idea: in fact, he spent more than a decade arguing against it with its originators, Carlton Caves of the University of New Mexico in Albuquerque, Christopher Fuchs of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, and Rüdiger Schack of Royal Holloway, University of London.

Known as quantum Bayesianism, its ideas stem from reassessing the meaning of the wave function probabilities that seemingly govern the quantum world (see diagram). Conventionally, these are viewed as "frequentist" probabilities. In the same way that you might count up many instances of a coin falling heads or tails to conclude that the odds are 50/50, many measurements of a quantum system tell you the relative frequency of its multiple states cropping up.

Despite its limitations, not least when dealing with single, isolated events, frequentist probability is popular throughout science for the way it turns an observer into an entirely objective counting machine. But an alternative, older approach to probability was devised by English clergyman Thomas Bayes in the 18th century. This is the sort of probability that crops up in a statement such as "there's a 40 per cent chance of rain today". Its value is not objective or fixed, but a fluid assessment based on many changing factors, such as current air pressure and how similar weather systems developed in the past. Acquire a new piece of information – see a bank of threatening cloud when you open the curtains in the morning, for example – and you might well update your prognosis to a 90 or 100 per cent chance of rain. The actual likelihood of rain has not changed; but your state of knowledge about it has.

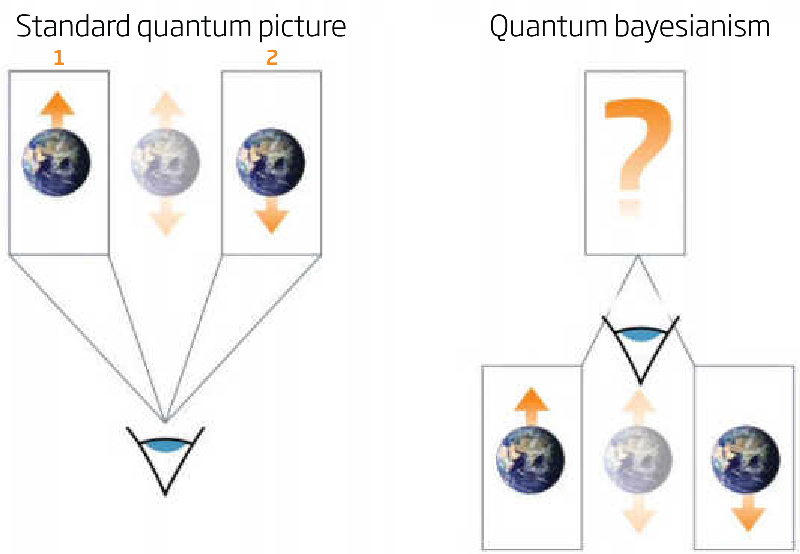
The central argument of quantum Bayesianism, or QBism, is that, by applying this more subjective type of probability to the quantum world, whole new vistas open up. Measure the spin of an invisible electron, say, and you acquire new knowledge, and update your assessment of the probabilities accordingly, from uncertain to certain. Nothing needs to have changed at the quantum level. Quantum states, wave functions and all the other probabilistic apparatus of quantum mechanics do not represent objective truths about stuff in the real world. Instead, they are subjective tools that we use to organise our uncertainty about a measurement before we perform it. In other words: quantum weirdness is all in the mind. "It really is that simple," says Mermin.

Mind you, it took six weeks of intense discussions with Fuchs and Schack in South Africa to finally convince Mermin that he had been a QBist all along. In November 2013, they published their conclusions together.

For Mermin, the beauty of the idea is that the paradoxes that plague quantum mechanics simply vanish. Measurements do not "cause" things to happen in the real world,

Uncertain uncertainty

According to quantum Bayesianism, quantum fuzziness just reflects our lack of knowledge of the world



Objects in the quantum world exist in a fuzzy combination of states. The act of measuring forces them to adopt a specific state (1 or 2)

The quantum states are all in our minds – they are just a fluid tool we use to understand our variable experiences of the world whatever that is; they cause things to happen in our heads. Spooky action at a distance is an illusion too. The appearance of a spontaneous change is just the result of two parties independently performing measurements that update their state of knowledge.

As for that shifty split, the "classical" world is where acts of measurements are continuous, because we see things with our own eyes. The microscopic "quantum" world, meanwhile, is where we need an explicit act of measurement with an appropriate piece of equipment to gain information. To predict outcomes in this instance, we require a theory that can take account of all the things that might be going on when we are not looking. For a QBist, the quantum-classical boundary is the split between what is going on in the real world and your subjective experience of it.

End of observers

Quantum theorist William Wootters of Williams College in Williamstown, Massachusetts, thinks this is the most exciting interpretation of quantum theory to have emerged in years, and points to historical precedents. "It addresses Schrödinger's concern that our own subjective experience has been explicitly excluded from physical science, and both requires and provides a place for the experiencing subject," he says.

Others are less keen. Carlo Rovelli of Aix-Marseille University in France proposed a similar, less extreme, observer-dependent idea called relational quantum mechanics in 1996. He worries that QBism relies too much on a philosophy espoused by German philosopher Immanuel Kant in the 18th century – that there is no direct experience of things, only that which we construct in our minds from sensory inputs. "I would prefer an interpretation of quantum theory that would make sense even if there were no humans to observe anything," he says.

Antony Valentini of Clemson University in South Carolina also thinks it moves things in the wrong direction. He paints a picture of someone setting up equipment to measure the energy of a particle, and then going off for a cup of tea. During the tea break, did the pointer on the equipment's dial have no definite orientation? A QBist would say maybe not, you can't tell – even though experience tells us a macroscopic object such as a pointer does always have a definite orientation. That view can't be taken seriously, says Valentini. "A physical theory should try to describe the physical world, not just some body of talk."

Schack counters that there is only one world out there, and we must find a way of unifying our classical and quantum interpretations of it – even if it means accepting we have no objective connection to reality in either sphere. "QBism abandons the idea that nature can be described adequately from the perspective of a detached observer," he says.

For him the strongest sign that QBism is on the right track is a thought experiment called Wigner's friend. Imagine you are standing outside a closed room where a friend is about to open the box containing Schrödinger's cat. Your friend witnesses a clear outcome: the cat is either alive or dead. But you must assign a set of probabilities based on a superposition of all the possible states of the cat and the reports your friend might make of it. Who's right?

"The beauty of the idea is that the paradoxes of quantum theory just vanish"

Both, say QBists: there is no paradox if a measurement outcome is always personal to the person experiencing it.

With all the zeal of a convert, Mermin has sought to convince detractors by applying QBist reasoning to the problems of an entity that has nothing to do with quantum theory, and nothing to do with probability: space-time (see "Lost in space", above left).

But Caslav Brukner of the University of Vienna in Austria wonders how far such approaches can take us. "I do not see in QBism the power to explain why quantum theory has the very mathematical and conceptual structure it does," he says. Other theories about the world at its most fundamental could have similar Bayesian underpinnings – so why specifically does quantum theory come up with the right answers? Like many who have inspected the undercarriage of quantum mechanics, Brukner would prefer to reconstruct it from a core set of principles or axioms.

You might wonder whether all this matters, given that quantum theory does such a stupendous job of describing the world and supplying us with technological innovation. After all, modern life would be almost unrecognisable without the products of quantum theory. Regardless of this, says Rovelli, our lack of intuitive understanding hampers our search for some greater theory that can embrace all of physics from the smallest to the largest scales. "If we want to better understand the world, for instance, for quantum gravity or for cosmology, it does matter," he says.

Faced with the prospect of abandoning scientific objectivity, the temptation to shut up and calculate might be as strong as ever. But perhaps quantum Bayesianism provides a way to have our cake and eat it. Shifting quantum theory's weirdness into our own minds doesn't diminish our power to calculate with it – but might just make us shut up about how shocking it all is. ■

The
SECRET LIFE *of* REALITY

The reason quantum reality is so different from our everyday experiences could be right under our feet, says Michael Brooks

THE quantum realm has always seemed worlds apart from general relativity, Einstein's theory of gravity. Though both were created at similar times, one rules at the atomic scale and smaller; the other reigns supreme across the cosmos. This is one reason why physicists are wrestling in their efforts to meld quantum theory and relativity into a theory of everything that shows how the universe works at a fundamental level.

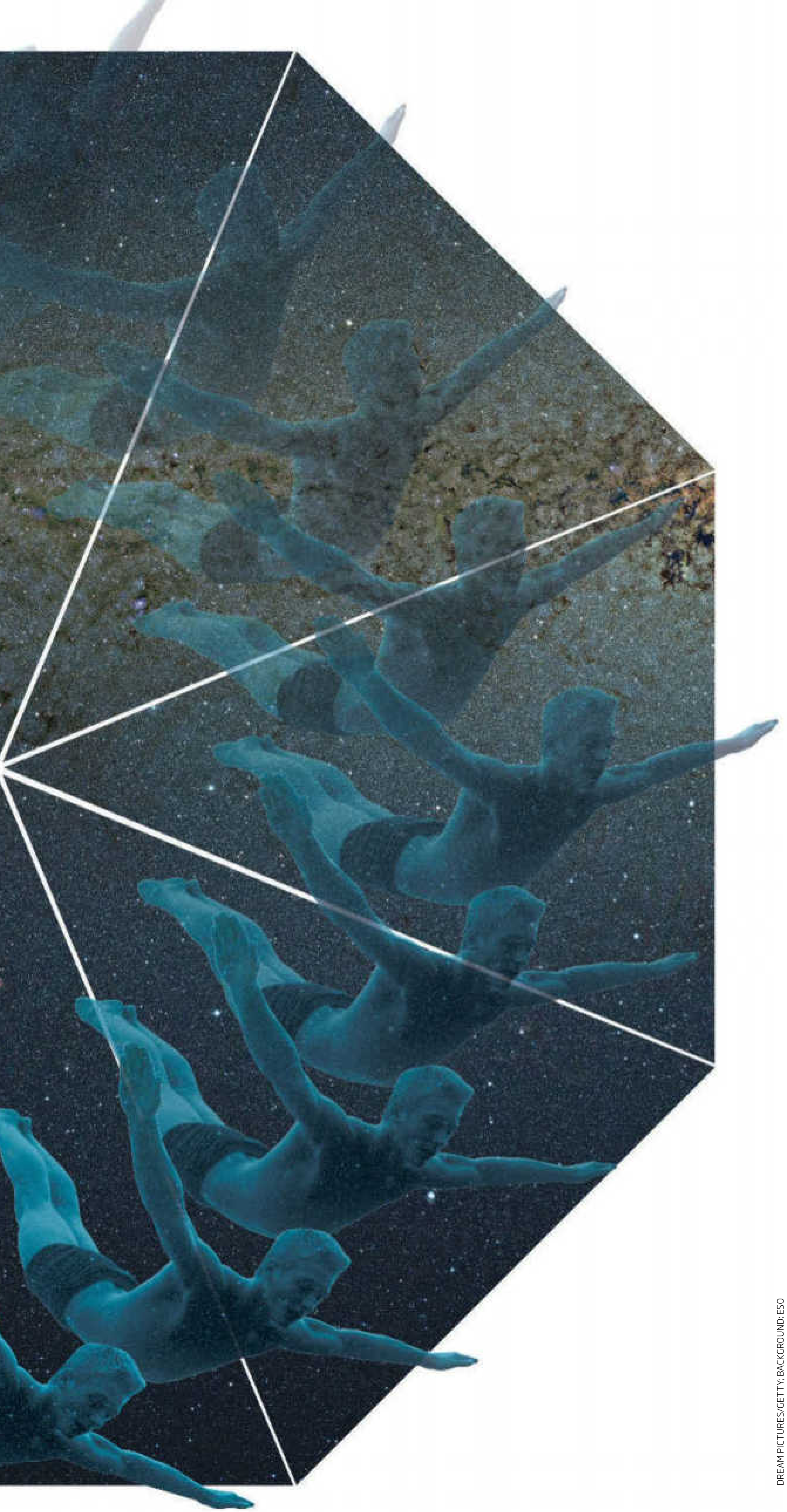
So far, all the attention has focused on schemes that come into play under the high-energy conditions that existed just after the big bang. The trouble is, experimenting with such theories is incredibly difficult. "The tests for it are way off," says Roger Penrose at the University of Oxford. "You have to build an accelerator the size of the solar system – that's not on the cards at all."

Perhaps, though, the quantum world has more in common with relativity than we think. According to Penrose, we've actually been doing experiments for decades that combine quantum theory and gravity. With a few tweaks, they might offer a different way to the revelations we seek. "It looks a much more promising route to the truth about how the universe actually works."

How can this be? Well, until now the interplay between some of the best known oddities of physics has largely been ignored. Take the fact that atoms and small molecules can exist in two places at once, a phenomenon known as superposition. This famous ability is a key feature of quantum reality and has been demonstrated in countless experiments. Yet it turns out that some fundamental questions about the role of gravity in superposition have never been asked, let alone answered.

Asking those questions, and finding out the answers, would enable us to open the door on an understanding of the universe in its entirety. They might also shed light on one of the biggest mysteries of science: what causes the transition between the weird quantum world and the everyday "classical" reality we experience. What were once impossible-looking puzzles might not be too far from a solution. "We're way closer than we've ever been," says Cisco Gooding, who earned his PhD at the University of British Columbia (UBC) in Vancouver, Canada.

The enigma is, in many ways, quite simple to lay out. Here's a starter: general relativity says that mass distorts space and time in



DREAM PICTURES/GETTY; BACKGROUND: ESO

a way that causes things around it to feel the attractive force we know as gravity (see "Weighty matters", page 40). So, in superposition, is an atom's mass creating two distinct distortions in space-time – and thus exerting a gravitational pull on itself?

Here's another: special relativity says that an atom moving through space will have a unique experience of the flow of time. This phenomenon is known as time dilation. But if a moving atom is in superposition, the time dilation must occur along two different paths at once, and will be different on each path. So when the superposition ends and the two become one again, have they aged differently?

More fundamentally, it is questionable whether general relativity even allows superposition. "There's a conflict here," says Penrose. "You can't have a superposition of two gravitational fields: that's illegal."

It is worth pointing out that we have seen nothing wrong with general and special relativity so far: experimental tests show they are correct.

Sudden collapse

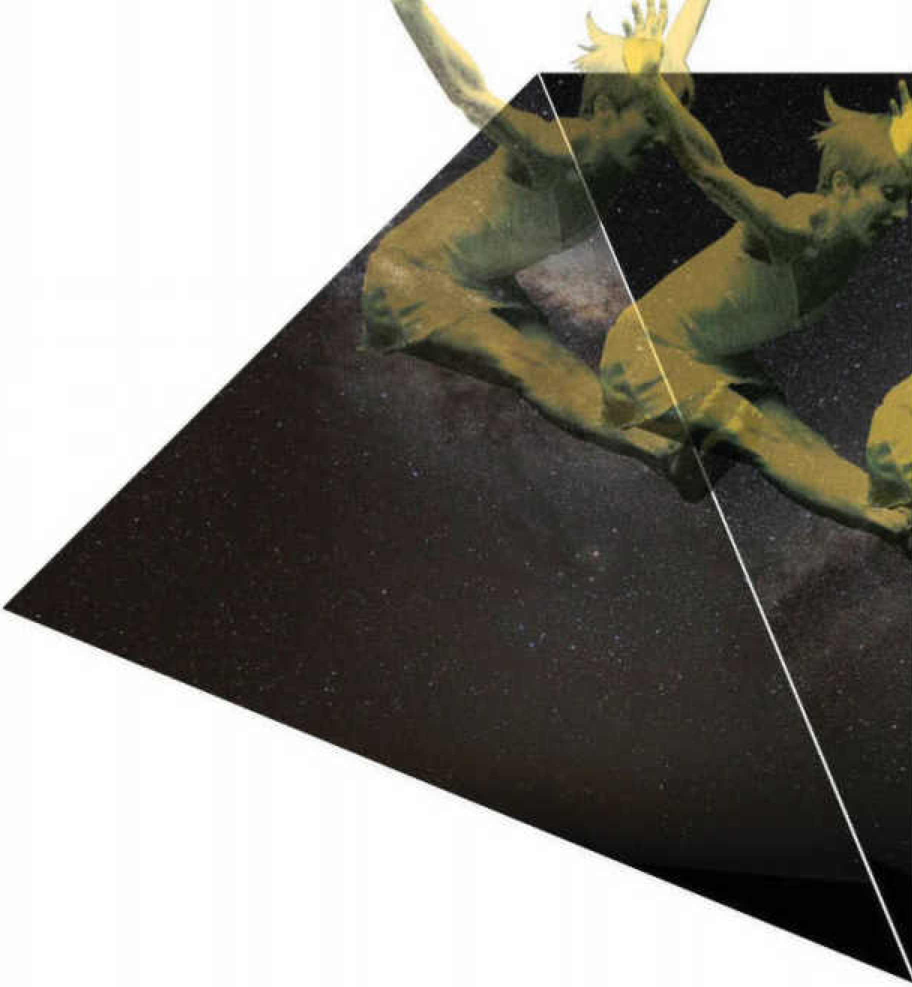
Quantum theory works similarly well, even though its ideas are odder. Superposition, for example, works because of a phenomenon called quantum coherence. This is what allows quantum objects to split their existence, characteristics and properties between spatial locations, different kinds of movement or even between different particles entirely.

The real problem is that these two theories only work separately. Quantum theory has nothing to say about the properties of the space and time its particles pass through. And relativity says nothing about the properties of those particles. When you try to combine them, they simply butt up against one another. "How do you go from one to the other?" says Miles Blencowe of Dartmouth College in Hanover, New Hampshire. "We don't have a quantum theory of gravity."

And that is why the new generation of experiments in "gravitationally induced decoherence" can't come soon enough for Penrose and others.

Decoherence is the name quantum researchers give to the falling apart of quantum coherence. You can put an atom – even a lot of atoms – in a spatial superposition, for instance, but it doesn't last. Eventually, the superposition "collapses", and the atom is suddenly in only one place.

The classic way to investigate quantum superposition is to fire an atom at a



screen with two slits, also known as an interferometer. The atom can go through either, but experiments show that if no one is measuring which slit it passes through, it will actually go through both. The result is an "interference pattern" that forms in a detector placed behind the slits. This reveals a series of well-defined patches where the atoms appear to hit the detector, alternated with blank spaces where no atom seems to land. The only explanation for such a pattern is that each atom splits in two, with one part going through each slit, then interfering before it reaches the detector.

Even weirder things happen if you equip this interferometer with another detector sited so that it can tell which slit the atom went through. The mere presence of this detector causes decoherence and destroys the interference pattern. It seems that the atom only behaves oddly when no one – or nothing – is looking.

Ticking atoms

There are many ideas for why such a thing might happen. Most are to do with information loss: reading the atom's path forces the atom to choose one path or the other and prevents it taking both. Experiments have shown that there doesn't even have to be a detector: heating the atom up, so that it emits thermal photons that could be used to infer its position, seems to be enough to weaken the interference pattern.

No one really knows what to make of this. It is made even worse by the discovery that large collections of atoms seem to be unable to exist in superposition. We have made interference patterns with molecules composed of hundreds of atoms, but the more massive they get, the shorter-lived the superposition. This has led some to suspect that gravity might be the real reason why massive collections of atoms – including us – are not quantum.

Testing this idea is far from easy because superpositions of atoms are such delicate things. But our ability to protect them from heat, vibrations and other disturbances has come on leaps and bounds, meaning we can start to get to get to grips with gravity's role.

For instance, Gooding and his former supervisor at UBC, Bill Unruh, are planning to look at how an atom in a superposition experiences time as it flies through different paths in an interferometer and then recombines to produce an interference pattern. An atom can be thought of as a tiny oscillator, a bit like a clock's pendulum. Send an atom into an interferometer and "it's a little clock that is ticking differently, and when it comes back together, those two clocks don't necessarily agree with each other," says Gooding. "We should see some sort of clash between each of their individual notions of time evolution." That should be enough to degrade the interference pattern in predictable and detectable ways.

Igor Pikovski at Harvard University has another plan based on time anomalies. Working with Caslav Brukner's group at the University of Vienna in Austria, they think we could put a clock in a superposition of two different heights from the ground. That would mean the two parts of the superposition exist in different parts of the Earth's gravitational field.

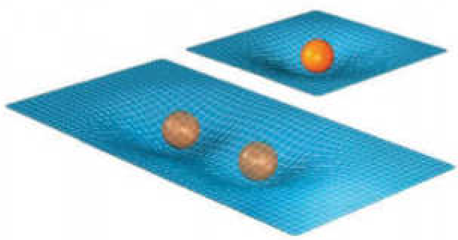
According to general relativity, clocks run faster in a weaker gravitational field. That's why, over your lifetime, your head ages 300 nanoseconds seconds more than your feet. For a one-atom clock in a superposition, this creates a problem – as the two times diverge, the atom will be forced back to being at one height or the other. "The fact that the atom records different time in different places gives away information on the atom's position," Pikovski says. "This destroys the coherence." In other words, time dilation due to gravity can explain why we do not see quantum superpositions in our everyday world.

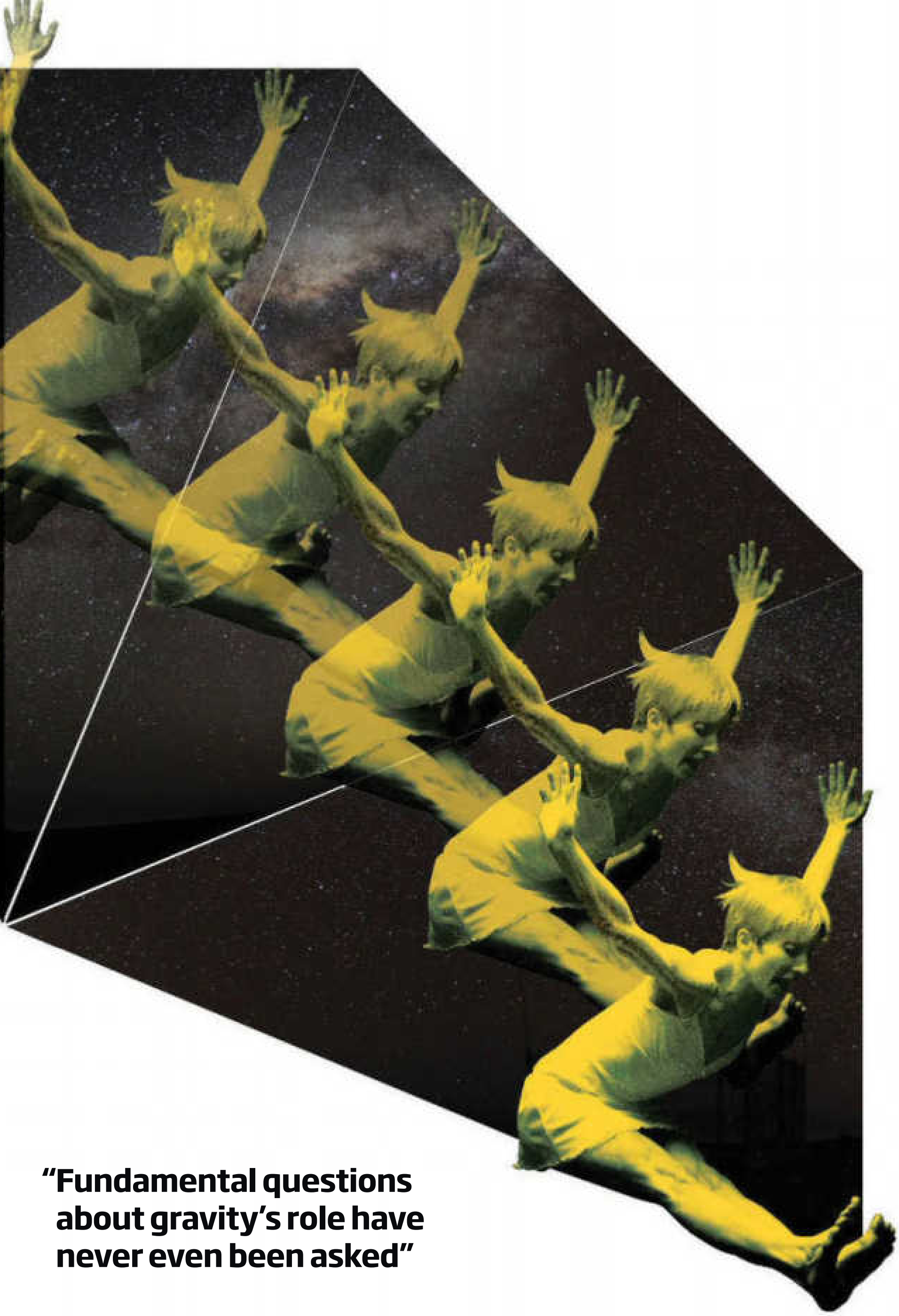
This can be tested using "atomic fountain" techniques that push atoms upwards through microwave fields to create ultra-accurate interferometers. It will involve some tweaks to existing experiments, but not too many. "It's not something that can be done now, but it's possible soon," Pikovski says.

Other experiments under development involve a different kind of superposition. Dirk Bouwmeester at the University of California, Santa Barbara, and Markus Aspelmeyer at the University of Vienna are

Weighty matters

All objects leave their mark in space-time, but how would a particle that can be in more than one place at the same time affect it?





DAVID SACKS/GETTY; BACKGROUND: ESO

"Fundamental questions about gravity's role have never even been asked"

independently making mirrored cantilevers. These structures look rather like springboards that exist in two configurations at once. When a photon in superposition hits the mirror, it can put the cantilever into a superposition of being both vibrating (as if a diver had just left the springboard) and undisturbed.

This was first achieved a few years ago. Now Penrose believes that each part of the superposed springboard should create so much gravity for the other that they collapse back into one. "It's hand-waving to a degree," he says, "but something certainly goes wrong."

The challenge now for Bouwmeester and Aspelmeyer's teams is to make the superpositions last long enough to investigate the decohering effects of gravity. One of the problems with the diving boards is that it is hard to disconnect them from their environment. This results in superpositions collapsing because of vibrations transmitted through the apparatus, rather than gravity.

Making and studying superpositions of large objects – large in quantum terms anyway – is new territory for researchers. And not surprisingly, there are other ideas for why reality ceases to be quantum at larger scales. One suggestion is that we need to revise quantum theory itself. A souped-up version of it says that superpositions are impossible for objects composed of more than a certain number of particles because of a phenomenon called spontaneous localisation, which suggests that the distribution of mass – its density – is what matters.

We may find out that particular answer fairly soon. Markus Arndt's group at the University of Vienna has been repeating the double-slit interferometer experiment with ever larger objects. Arndt believes that spontaneous localisation would kick in with particles of a mass of somewhere between 100,000 and 100 million atomic mass units in his apparatus (one amu is equivalent to 1/12th the mass of a carbon-12 atom).

We need to rule out spontaneous localisation before pointing the finger at gravity. "It's difficult to promise when this will be," he says. They are currently superposing objects of 10,000 amu, and working towards 100,000 – the lower limit of where spontaneous localisation is thought to happen. We will then have a nail-biting passage through to 100 million amu, when we would be able to rule it out.

Theory of everything

Of course, experiments will be the final arbiter of this. And in the end, all these techniques have their own challenges. "Nobody on the planet can actually do any of this yet," Arndt says. It's still a good time for theorists in this field, he quips. "We can't constrain them."

So, really, all the pressure is on the experimenters. Not that they are guaranteeing any quick solutions. Aspelmeyer reckons there is a long road ahead – and that's just the bit he can see. "It could be long, very long or impossible," he says.

And people disagree about how much such work will illuminate the search for a theory of everything. Many believe that such a theory is as distant a prospect as ever. But Gooding is an optimist. One of the good things about these experiments, he says, is that they don't involve making anything up. We've tested general relativity and quantum mechanics under these conditions, and they work. "If we can demonstrate something from just those theories then we have a good reason to believe that effect is real," he says. "If we demonstrated it from string theory there would always be a nagging thought in your mind that maybe it's something to do with the assumptions of string theory."

He thinks that we could have answers within 10 years. And that is very good progress. Until fairly recently, it didn't look as if we'd ever be able to test gravity's quantum interactions. "It's now looking like something that's actually doable, not something that has absolutely no chance of ever being observed," Gooding says. ■

JON KRAUSE

CHAPTER TWO

THE QUANTUM WORLD

How can a theory that works so well have such unnatural foundations? **Richard Webb** examines the bedrock of quantum mechanics

Mind the gap

PHYSICS, its practitioners will proudly tell you, is the most fundamental of sciences. Its theories and laws distil the workings of the real world – of particles and planets, heat and light – into stark, sweeping statements of universal validity. Think Newton's law of gravity, which describes with equal assurance how an apple falls and Earth orbits the sun, or the laws of thermodynamics that govern how energy flows. These physical laws are generally couched in the language of mathematics, to be sure. But this is merely a convenient shorthand. The mathematical quantities are ciphers, proxies for the tangible objects of the real, physical world and their measurable properties.

That was all true until quantum theory arrived on the scene. Quantum theory is odd, not just because its weird predictions are a source of consternation for physicists and philosophers, but because its mathematical structures bear no obvious connection to the real world, as far as we can see. "We do not have a source for the mathematical formalism of quantum mechanics," says Caslav Brukner of the University of Vienna in Austria. "We do not have a nice physically plausible set of principles from which to derive it." Quantum physics might be quantum – but as far as we can tell it isn't physics.

Brukner and a small band of physicists want to change that. Their efforts may lead to a better understanding of quantum reality, or expose weaknesses in the theory that will teach us a new and potentially weirder language with which to describe the world. Either way, it is an ambitious quest.

If you want to devise a physical theory, there is a traditional recipe to follow. First, you make observations about how the world works. Next you sieve the data to pick out any patterns. If anything catches your eye, you dress it up in mathematical language. The proof of the theory is in its predictions. If it can tell us further details of how the world works, you have a winning formula.

Newton's theory of gravity is a classic example. It is embodied in one simple equation, which says that two bodies will experience a mutual attraction that increases with their masses and decreases as the square of the distance between them. It was the centrepiece of his monumental work *Principia*, published in 1687. Its origins, though, reach back almost a century earlier, to the first truly precise observations of the

"Quantum physics might be quantum – but as far as we can tell it isn't physics"

motions of celestial bodies, made by the Danish astronomer Tycho Brahe.

After Brahe's death, his one-time assistant Johannes Kepler spent years poring over the data. Eventually he was able to show that the motions could be described by three "laws" governing the nature and geometry of planetary orbits. It was Newton's mathematical genius that extracted from these the single equation from which almost all facets of planetary motion can be derived.

Here, as in the other laws of classical mechanics derived in the *Principia*, mathematics and physics work in perfect tandem. Physical quantities such as force, mass or acceleration are expressed as numbers that can be measured, and the correspondence between the real and the abstract is obvious, seamless and intuitive.

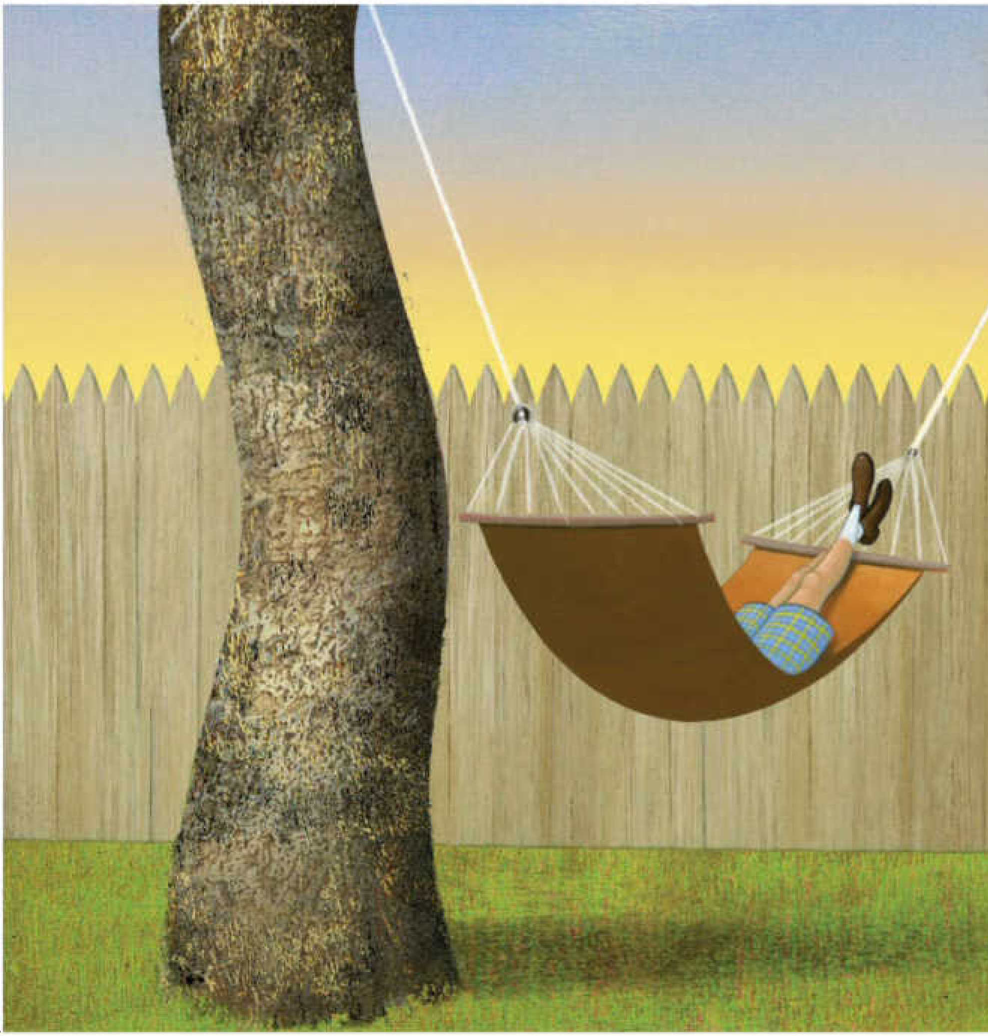
Not so with quantum theory. Although it was initially inspired by an idea rooted in the real world – that energy came in small packets called quanta – by the time luminaries such as Erwin Schrödinger and Werner Heisenberg had finished its mathematical formulation, the theory had acquired a life of its own (see "Where did it all go wrong?", page 46).

If it ain't broke

Gone was any certain correspondence between mathematical variables and physical properties. In their place were abstruse objects such as wave functions, state vectors and matrices, all acting in an unreal mathematical environment called Hilbert space – a higher-dimensional, complex version of normal three-dimensional space.

Bizarrely, though, these abstractions work. Follow a set of mathematical rules laid down by the founders of quantum theory and you can make physical predictions that are confirmed time and time again by experiment. Particles that pop up out of nothingness only to disappear again, objects whose physical states can become "entangled" and can influence each other instantaneously over vast distances, cats that remain suspended between life and death as long as we don't look at them: all of these flow from the mathematical formulation of quantum theory, and all seem to be true reflections of how the world works.

Does it matter that we don't know why? Surrounded by lasers, microchips and other trappings of quantum technology, we might be tempted to say if the theory ain't broke, don't fix it. Why worry about a few little wrinkles in the explanation of it all?



JON KRAUSE

That is okay up to a point, says Martin Plenio of the University of Ulm in Germany. "Quantum mechanics is, in our range of experience, a correct theory. It is sort of fine and we don't know what is better." But there are niggles that make him and others itch for something new. One is the great unfinished business of unifying quantum theory with general relativity, Einstein's resolutely classical theory of gravity. "Quantum mechanics and general relativity don't like each other," says Plenio.

Many physicists see that as the fault of gravity, and have expended vast energies on untested constructions such as string theory that try to dress up gravity in a quantum costume. An alternative view is that, for all its successes, quantum theory might actually be the problem. As long as we do not know what the physical basis of quantum theory is, that possibility remains both real and hard to test.

"Hypothetical theories that obey only the cosmic speed limit turn out to be weirder than quantum mechanics"

So how do we set about finding what makes quantum theory tick? Most of the recent work has homed in on one central yet unexplained feature of quantum physics – the degree of "correlation" between the states of unconnected bodies that the theory does, or does not, allow.

In our day-to-day world, we are accustomed to the idea that two events are unlikely to be correlated unless there is a clear connection of cause and effect. Pulling a red sock onto my right foot in no way ensures that my left foot will also be clad in red – unless I purposely reach into the drawer for another red sock. In 1964, John Bell of the CERN particle physics laboratory near Geneva, Switzerland, described the degree of correlation that classical theories allow. Bell's result relied on two concepts: realism and locality.

Realism amounts to saying that the properties of an object exist prior to, and independent of, measurement. In the classical world, that second sock in my drawer is red regardless of whether or not I "measure" its state by looking at it. Locality is the assumption that these properties are independent of any remote influence.

In the quantum world, these are dangerous assumptions. "It turns out that either one or both of Bell's principles must be wrong," says Brukner. If quantum effects were visible in our everyday world, I might well find that my pulling on a red sock leads to the colour of the sock left in my drawer automatically changing to red.

The mathematical framework developed by Bell and others allows us to quantify how correlated quantum theory allows seemingly unrelated objects to be. Considerably more than in classical physics, it seems – yet not half as correlated as they could be. In 1994, Sandu Popescu, now at the University of Bristol, UK, and Daniel Rohrlich, now at Ben Gurion University of the Negev in Beersheba, Israel, considered a hypothetical theory that obeyed just one rule – that cause and effect cannot propagate faster than the speed of light. Intriguingly, they found that any such theory would permit even greater correlation than even quantum theory allows.

A world with this degree of interconnection would be weird indeed. I might find that by selecting a red sock from my drawer in the morning, I had predetermined the colour not just of my other sock, but that of my shirt, underpants and of the bus I ride to work. As Gilles Brassard of the University of Montreal, Canada, and his colleagues showed in 2006, in such a maximally correlated world certain problems in communication and computation reduce to implausible trivialities.

Information correlation

That might not be a good thing. David Gross of the University of Cologne, Germany, and colleagues have demonstrated that everything in this world would be so correlated that nothing could evolve, which raises the paradoxical question of how the correlations themselves could have developed.

How is this relevant? If we could only understand why quantum theory allows precisely the degree of correlation it does, we would have a much better grasp of the underlying physics. "We know that quantum correlations can be stronger than classical," says Plenio. "But then there is the question, why aren't quantum correlations even stronger? Is there any physical principle that says quantum correlations must have the upper bound they do?"

"Either we are missing something very significant or other theories are around us too"

Popescu and Rohrlich had shown that the principle of "relativistic causality" alone was not the answer: the cosmic speed limit set in Einstein's relativity can produce theories that allow greater correlation than quantum mechanics. That prompted Marek Zukowski of the University of Gdansk, Poland, and colleagues to suggest in 2009 that a tighter variant of the principle might do the trick.

They call their idea "causality of information access". It states that if you send me a certain number of bits of information, the maximum amount of information I can access is that number of bits – a truism in both the classical and the quantum worlds. "Say I want to send you a part of my nine-digit home phone number in an encoded form," says Zukowski. "If I send you information about the first three digits, you can only decode the first three digits."

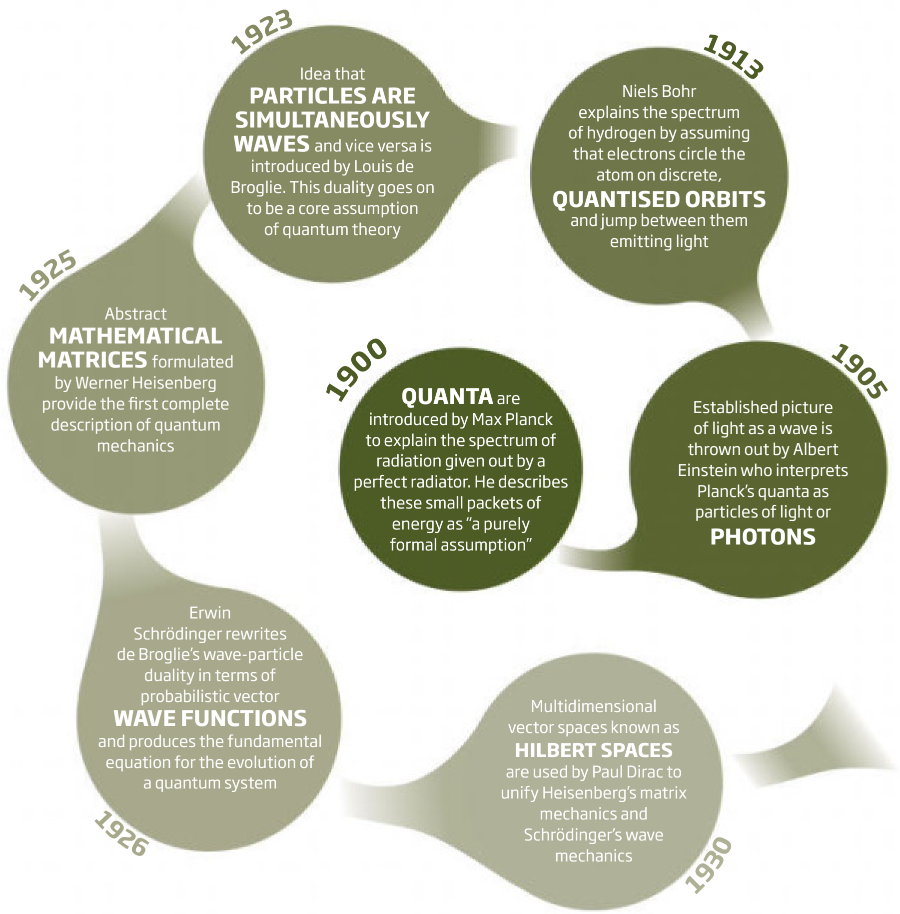
In a world where information causality does not apply, the correlations between the digits would be so strong that if you knew the first three bits, you could deduce any three digits of the original number.

It is an intriguing idea, and it narrows down considerably the maximum level of correlations that a theory can sustain, but not all the way down to the quantum limit. To define quantum theory uniquely would seem to require some other principle, too.

In 2001, Lucien Hardy, then at the University of Oxford, took a subtly different, more laborious tack. Rather than trying to pick out a single principle that reduces correlations between remote particles to the levels of quantum mechanics, he aimed to develop

Where did it all go wrong?

Quantum theory's grip on reality has always been tenuous



from scratch a full set of physically plausible axioms that defined quantum theory alone.

What he came up with was a series of five rules, some physical and some more mathematical in nature, which together defined quantum theory.

Unfortunately, though, Hardy's axioms are also compatible with systems of mathematical constructs other than quantum theory. "That suggests one of two things," says Brukner. "Either we are missing something very significant to define quantum theory, or these other theories are all around us too."

Together with his colleague Borivoje Dakic, Brukner has explored the first of these options further. They formulated their own three rules that describe how, according to experiments, quantum theory works in the case of the simplest possible quantum system – a quantum bit or "qubit" that is in a mixture, or superposition, of two possible states. If any of the rules applied to quantum theory alone, it would rule out other theories that happen to be consistent with Hardy's axioms.

The defining feature

The first rule is that this qubit can slide smoothly and continuously between the two states in its superposition. This is sufficient to distinguish quantum theory from classical physics, where such effortless reversible transitions are not possible, but does not rule out a weirder theory.

The second rule is that whatever superposition state the qubit is in, you can only ever extract one bit of information from it – you can only measure it in one state at once.

The third rule applies only to composite systems of two or more qubits. Knowing the probabilities that the individual qubits are in a particular state plus the probabilities of correlations between them tells you the state of the whole system. This encapsulates the property of entanglement between remote quantum states that experiments show holds in the real world.

And it turns out that this last feature – entanglement – might hold the key. Only a theory precisely as correlated as quantum theory can obey all the axioms and produce the kind of entanglement observed in nature. Less correlated theories don't create entanglement at all, while weirder theories produce a situation where, for example, you might measure the state of all the qubits in a system, know the correlations between them, and still not be able to say what state the whole system is in. "Entanglement is the unique feature, and it comes out of the three axioms," says Brukner.

If true, that is at best half an answer. Why is entanglement the defining feature? Brukner hazards a guess. "In many materials around us, the ground states are entangled with each other. Perhaps matter would not be stable without entanglement," he says.

Others are less convinced, and see the physics behind quantum theory as far from solved. Brukner's scheme takes the traditional route in which observations determine axioms determine theory, but that assumes our observations represent a complete and true picture of how the world works.

There is another possibility: observation might actually be leading us astray. Miguel Navascues, who has joined Brukner at the University of Vienna, is trying to find out what maximum level of correlation a reasonable physical theory can sustain if a different constraint is imposed – the requirement that quantum physics reduces to classical physics at macroscopic scales, say. He, too, is finding a maximum well above the quantum bound. That leads him to speculate that lurking somewhere, unprobed by experiment, is evidence that a theory weirder than quantum mechanics is the "right" answer – a theory that might even be capable of incorporating gravity into its framework. This would be a golden discovery, heralding a major step forward in physics. "That is what I think," he says. "But we are a long way away from proving that."

As long as niggling doubts about quantum theory's status remain, such an outcome is not unthinkable. A century ago, a few loose ends in classical physics eventually caused the whole tapestry to unravel. Betting the same thing might happen to quantum physics – now is that so weird? ■

What lies beneath

Does quantum weirdness really exist, or is it just a cover for something deeper? **Anil Ananthaswamy** investigates

WHEN Rupert Ursin stood in the darkness at the highest point of La Palma in the Canary Islands he found it scary. "Really scary," he says. It was less the blackness stretching out towards the Atlantic Ocean some 15 kilometres away. It was more the sheer technical challenge ahead – and perhaps just a little because of the ghosts he was attempting to lay to rest.

Ursin and his colleagues from the Institute for Quantum Optics and Quantum Information in Vienna, Austria, were there that night to see if they could beam single photons of light to the 1-metre aperture of a telescope on the island of Tenerife, 144 kilometres away. Even on a fine day, when Teide, Tenerife's volcanic peak, is clearly visible from La Palma, that would be a feat of mind-boggling precision. Attempting it in the dark seemed ludicrous. "At night you don't know where the other island is," says Ursin. "You are lost; you have no clue what to do."

In daylight, though, zillions of photons zinging around would have made their experiment impossible. And so, on moonless nights, the researchers would switch off the lights in their lab and slip outside to a night sky lit only by the Milky Way.

For what? To attempt to settle one of the longest-running debates in modern physics. To dispose of yet another ambiguity in our basic understanding of how nature ticks. To answer one of the most fundamental questions of all: is quantum reality real?

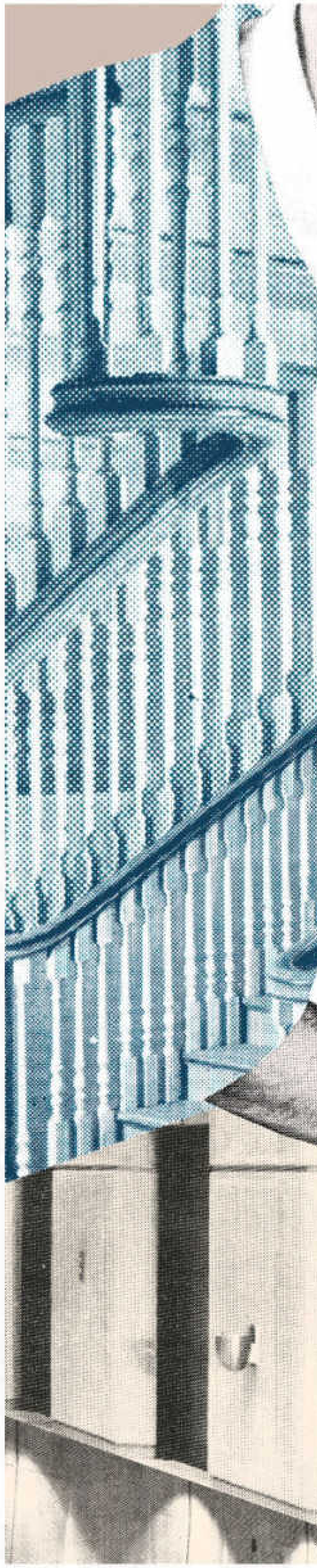
It was back in the mid-1920s that two big beasts of modern physics, Niels Bohr and Albert Einstein, first locked horns on this question (see "Quantum duellists", page 51). By then it had become clear that classical physics could not explain a litany of small-scale phenomena, such as how light interacts with matter, or why orbiting electrons don't spiral inwards and crash into the atomic nucleus.

The new theory of quantum mechanics could, but it was a bitter pill to swallow. Gone were the old certainties and straight-down-the-line relations between cause and effect of the clockwork, Newtonian universe. In their place was a fuzzy world populated by particles that were simultaneously waves, that influenced each other seemingly without reason, and which could apparently exist in many states at once until the watchful eye of an observer disturbed them.

For Bohr, if we could not get our heads round that, then the problem lay in our heads, not with quantum mechanics. Distasteful as it might be to our classically attuned brains, the theory was a complete, fundamental description of how the world worked.

Einstein disagreed. He thought the weirdness of quantum mechanics meant the theory was missing something. He became convinced that a deeper layer of reality lurked beneath its surface, governed by as-yet undiscovered "hidden variables" that worked according to rules familiar from classical physics (see "Einstein's hidden world", page 50).

Bohr and Einstein's debate continued – firmly, decorously and with no definitive answer – for decades. It wasn't until 1964, after both men had died, that the first hint of a resolution appeared. It came courtesy of John Bell, a 36-year-old researcher at ›



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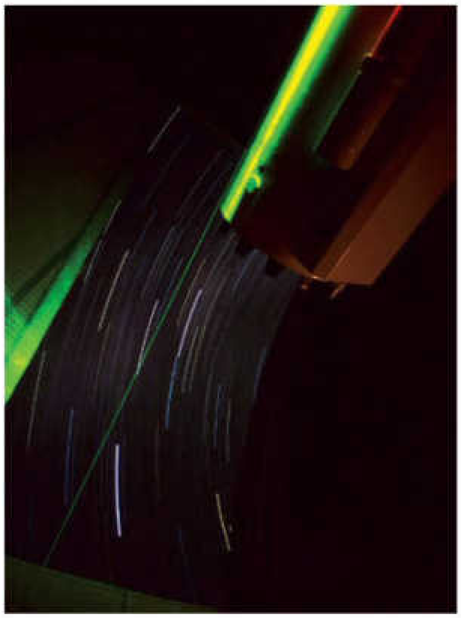
CERN, the European laboratory for particle physics near Geneva, Switzerland. His insight was that Bohr and Einstein's almost philosophical argument could be reformulated mathematically.

Bell began by considering particles that are correlated, in the sense that measuring the properties of one tells you the properties of the other. The existence of such correlations is not in itself surprising: if laws such as the conservation of energy or momentum hold, we expect that properties such as the speed or position of particles emitted from the same source at the same time will be related. But Bell derived a mathematical expression, called an inequality, to describe the maximum amount of correlation possible if two conditions dear to our classical intuitions, but seemingly violated by quantum mechanics, held: realism and localism. Realism embodies the idea that any measurable property of an object exists at all times, and its value doesn't depend on someone observing it. Localism assumes that these properties are only affected by nearby things, and cannot be influenced by anything remote.

Guiding light: the tracking laser of the Tenerife observatory



RUPERT URSIN

Here, then, was a test for physicists to get their teeth into. All that was needed was an experiment to measure how intertwined two particles from the same source were. If their correlations busted Bell's inequality by a significant amount, then realism, localism or both had failed, and the weirdness of quantum mechanics really did exist: the particles were in some mysterious way "entangled". If Bell's inequality was satisfied, however, then something real, local and classical-like was pulling the strings: Einstein's hidden variables, for example.

Fittingly, the reality was somewhat more complex. It proved hard to implement the ideal conditions needed to test Bell's inequality, and all the experiments were proving inconclusive.

Then, in the early 1970s, a young French student named Alain Aspect came on the scene. He had just finished his mandatory military service as a teacher in Cameroon and was casting around for a PhD topic. Chancing upon Bell's paper and the history of the debate between Bohr and Einstein, he was entranced. "It was the most exciting thing for an experimentalist to test who was right," says Aspect, now at the Institute of Optics in Palaiseau, France.

So Aspect visited Bell to seek his blessing. Bell warned Aspect that many regarded investigating the roots of quantum reality as "crackpot physics", and asked him whether he had a secure job. "I did. It was small, but it was permanent," says Aspect. "They could not fire me." That security allowed Aspect to embark

"It was the most exciting thing for an experimenter to do, to test whether Bohr or Einstein was right"

on a seven-year search to find out who was right: Bohr or Einstein.

Aspect's experiments broadly followed a pattern established in previous tests of Bell's inequality. Atoms were first stimulated to emit pairs of photons that were correlated in their polarisation states. These polarisations were then measured at two separate detectors, which are by convention maintained by two characters called Alice and Bob (see diagram, opposite).

EINSTEIN'S HIDDEN WORLD

Einstein was unconvinced by quantum theory, and in 1935 he aired his concerns in a paper written with two young physicists, Boris Podolsky and Nathan Rosen, called "Can quantum-mechanical description of physical reality be considered complete?".

In it, they formulated what came to be known as the EPR paradox. For a theory to be complete, the trio argued, it must describe every element of physical reality. If a moving object has a position and a momentum, for instance, the theory should include elements, or "variables", that tell you their values.

While this works fine when talking about cars, say, in the minuscule quantum world things are not that simple. According to the notorious uncertainty principle laid down by Werner Heisenberg in 1927 you can only extract an exact value for the position of a particle when the momentum is unknown, and vice versa. This, said Einstein, invited one of two conclusions: either position and momentum do not exist simultaneously, or quantum mechanics as a description of reality is incomplete.

It got worse. An explosion that sends two pieces of shrapnel shooting off in opposite directions is easily explained by classical physics. There is an easily verifiable connection between the fragments' speed, direction and mass, one that is fixed at the time of the explosion according to the law of conservation of momentum.

An analogous quantum-mechanical situation, on the other hand, is more problematic. Imagine a particle at rest decaying into two particles that shoot off in different directions. According to the kind of interpretation of quantum physics favoured by Niels Bohr and other pioneers of quantum theory, particle properties are not clearly defined until they are measured. But measuring the position or momentum of one particle immediately sets the other's position or momentum in another part of space, even though it was previously undefined. How can this change in status be communicated instantly through space?

Not, said Einstein with a grimace, through some "spooky action at a distance", as implied by quantum mechanics. Instead he believed there must be an element of an underlying theory – a "hidden variable" – that set the results of both measurements in advance, much as conservation of momentum sets the outcome of measurements of the shrapnel fragments in the classical case. Quantum mechanics as formulated must be an incomplete description of reality, he concluded.

That depended on measuring large numbers of photon pairs to get statistically significant results. By the time Aspect, together with his students Philippe Grangier and Jean Dalibard, was ready to perform his definitive tests, advances in laser technology were making that an easier task. "By 1980, I had by far the best source of entangled photons in the world," says Aspect. Whereas it had previously taken hours or even days to get the number of photons required, he could now get them in just 1 minute.

It was still painstaking work. But by 1982 the researchers had the most convincing retort yet in the quantum reality debate. There was no doubting the results. Bohr was right; Bell's inequality was violated. The world is just as weird as quantum theory says it is. "It was thrilling," says Aspect.

Niggling doubts

End of story? Not a bit of it. Experiments are rarely entirely conclusive, and – influenced no doubt by Einstein's reputation – niggling doubts remained that perhaps nature had fooled the experimenters into thinking quantum theory was the true answer. Even if the measured correlations exceeded Bell's maximum, there were enough loopholes in the experiments to leave wiggle room for something other than quantum mechanics to be the cause.

"The question of whether nature is local, realistic or quantum-mechanical is so deep and so important that we should try to do these experiments as cleanly and as loophole-free as possible," says Johannes Kofler, a theorist at the Max Planck Institute of Quantum Optics in Garching, Germany. "It's really all about ruling out conspiracy theories of nature against us."

Aspect's experiments had already done sterling work in trying to close one loophole that Bell had identified – the locality loophole. Unless the detectors used by Alice and Bob are far enough apart to prevent communication between them at light speed or below, some influence might propagate through a hidden layer of reality, telling Alice's detector the outcome of Bob's measurement before she performs her own, say, and maybe even fiddling with her detector's settings to change the outcome. "If you allow such a communication, it would be easy to violate Bell's inequality in local realism," says Kofler.

The highly efficient source of entangled photons and superior optics used by Aspect had enabled his team to separate ›

QUANTUM DUELLISTS

Albert Einstein
Born Ulm, Germany, 14 March 1879
Died Princeton, New Jersey, 18 April 1955

In his annus mirabilis of 1905, Einstein not only came up with his special theory of relativity and the mass-energy equivalence equation $E = mc^2$, but also became the first person to ascribe a physical reality to the quantum, a concept introduced by Max Planck five years earlier.

Einstein described the liberation of electrons from an illuminated metal's surface – the photoelectric effect – in terms of the action of tiny, discrete packets of light energy: photons. It was for this insight that he received the Nobel prize for physics in 1921.

HULTON/GETTY GAMMA-KEYSTONE/GETTY

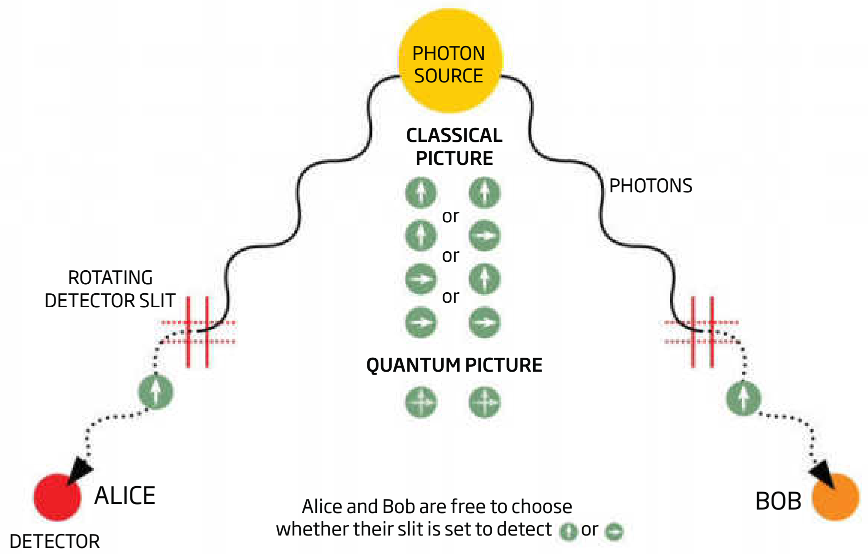
Niels Bohr
Born Copenhagen, Denmark, 7 October 1885
Died Copenhagen, Denmark, 18 November 1962

In 1913, Bohr used the principle of quantisation to postulate that electrons in atoms can exist only in discrete energy states, and thus explained the spectrum of light emitted by a hydrogen atom. This work ensured he followed Einstein to the Nobel prize for physics in 1922.

Bohr went on to develop the principle of complementarity, the bedrock of the dominant "Copenhagen" interpretation of quantum theory. This states that the quantum world is both wave- and particle-like; it is the act of measurement that causes it to show one face or the other.

Too correlated by half

If quantum theory is right, two photons emitted from the same source at the same time will both be in two polarisation states at once – allowing measurement of one to influence measurement of the other



If they both choose the setting that lets only ↑ through, what is the probability that both, one of them or neither will register a photon?

CLASSICAL EXPECTATION

Alice	↑	↑	○	○
Bob	↑	○	↑	○
Probability	¼	¼	¼	¼

Alice and Bob's measurements are independent, so each combination is expected to be equally likely

EXPERIMENTAL REALITY

Alice	↑	↑	○	○
Bob	↑	○	↑	○
Probability	½	0	0	½

If Alice registers a hit, so does Bob and vice versa – evidence of **spooky action at a distance**

Alice and Bob by about 6 metres. That gave them just enough time to change the settings of the detectors after the photons had left the source, hopefully stymieing any attempt of a hidden communication channel to ambush the experiment.

That was cunning, but not quite cunning enough. The team had only nanoseconds to change the detectors' settings, which was not enough time to change them randomly. Instead, they had to use a predictable, periodic pattern. If some hidden channel did exist, then over time the detectors used by Alice and Bob might figure out each other's settings and again trip up the experiment.

To nip that sort of thing in the bud, in 1998 Gregor Weihs, Anton Zeilinger and their colleagues strung Alice and Bob 400 metres apart over their university campus in Innsbruck, Austria, using optical fibres to connect the detectors to a photon source placed between the two. That gave them about 1.3 microseconds' grace after the photons were fired to switch the detector settings randomly. To close the locality loophole even tighter, atomic clocks ensured that Alice and Bob's measurements were made within 5 nanoseconds of each other – quick enough to prevent a hidden message being transferred. The test showed clear violations of Bell's inequality. Quantum mechanics reigned supreme.

And yet it still wasn't a final answer. As the locality loophole closed, attention shifted to other loopholes. One was the fair-sampling, or detection, loophole. The photon detectors used in all the experiments were inefficient

EDA AKALTUN

and sampled only a small fraction of the photons sent out by the source. What if only a small subset of photons were sufficiently correlated to violate Bell's inequality, and the detectors just happened to be sampling those? Implausible, perhaps, but not impossible.

This loophole was first closed in 2001 by a group led by David Wineland at the National Institute of Standards and Technology in Boulder, Colorado. Instead of photons, the researchers entangled a pair of beryllium ions, each of which could exist in a quantum-mechanical superposition of two energy states. Depending on which state an ion was in, it scattered either very many or very few photons. By probing the ions with a laser and measuring the variation in photon counts, the ions' states could be determined with almost 100 per cent efficiency.

Again, the correlations found between the beryllium ions' states were far greater than could be explained by anything other than quantum mechanics. But this, too, came with a caveat: at the point of measurement, the ions were only 3 micrometres apart. Although the detection loophole was closed, the locality loophole remained open.

COLLAPSE OF REALITY

Even as the main loopholes in tests of quantum mechanics are closed (see main story), others open up. Take the "collapse locality" loophole, the brainchild of Adrian Kent at the University of Cambridge.

According to many interpretations of quantum theory, a pair of entangled photons exists in a superposition of quantum states until the point of measurement, at which point it collapses into a specific state. The experiments performed so far have assumed this collapse to be instantaneous. But it isn't. In interpretations that require events to be registered by human consciousness for states to collapse, it takes as much as 0.1 seconds.

That means one quantum state could potentially signal its collapse to another remote location before the second state's collapse could be registered. To close this loophole, real humans would have to record the events and be spaced more than 0.1 light-seconds apart – about 30,000 kilometres, more than twice Earth's diameter.

"It seems far-fetched," says Nobel laureate Anthony Leggett of the University of Illinois at Urbana-Champaign. "But on the other hand if you had told me back in 1985 that by 2010 people were going to be doing this kind of experiment over 100 kilometres, I'd have said you must be joking."

Freedom to choose

Besides, there was another subtle loophole to be considered. Tests of Bell's inequality generally assume that researchers have the freedom to choose their detectors' settings. But do they? What if the source of particles has some way of influencing the settings on the detectors used by Alice and Bob, again through some hidden layer of reality? By exploiting this "freedom of choice" loophole the source could emit photons that mimicked the entanglement of quantum mechanics.

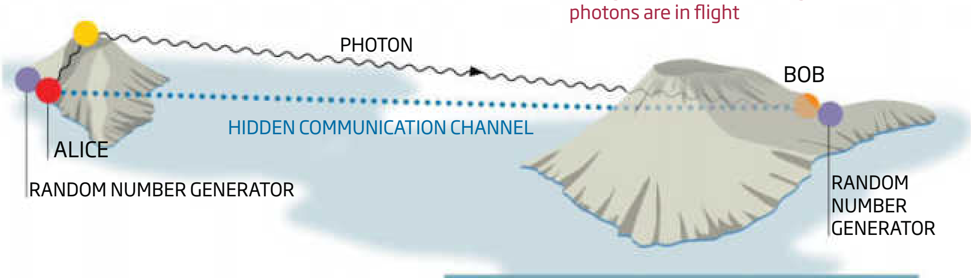
That brings us to the Canary Islands. The aim of shooting photons from La Palma to Tenerife – an experiment combining the expertise of Ursin, Kofler, Zeilinger and others – was to close the freedom of choice loophole while also keeping the locality loophole tightly shut. While one entangled

Picking holes

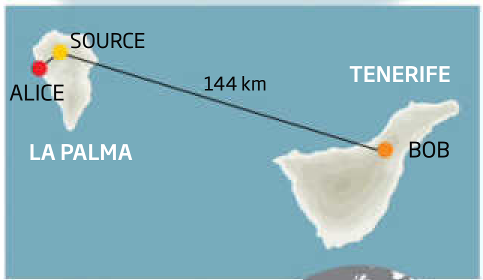
The Canary Island experiment aims to close possible loopholes in experiments designed to show whether the quantum-mechanical property of entanglement, or **spooky action at a distance**, really exists

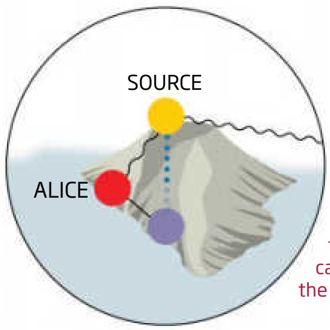
THE LOCALITY LOOPHOLE: Light-speed "communication" through a hidden layer of reality might tell Bob's detector what Alice measured and change his settings accordingly

SOLUTION: Keep the detectors far apart and use random number generators to change the detector settings while the photons are in flight



THE FREEDOM OF CHOICE LOOPHOLE: The source of photons might tweak the settings of one or other of the detectors by influencing the random number generators





SOLUTION: Put Alice's random number generator far away from the source, so no influence can pass between the two before the photon is detected

RESULT OF CLOSING THESE LOOPHOLES: ONE MEASUREMENT STILL SEEMS TO INFLUENCE THE OTHER

photon was beamed over the Atlantic to Bob in 479 microseconds, the other was pinged 6 kilometres down an optical fibre to Alice, reaching her in 29.6 microseconds. Random number generators triggered the detector settings for Alice and Bob once the photons were in transit (see diagram, right).

To ensure freedom of choice for Alice, her random number generator was kept 1.2 kilometres away from the photon source, and the random number generation and emission of photon pairs were timed so one could not influence the other. On Tenerife, the random number generator chose the setting for Bob's detector before the photon arrived from La Palma, ensuring that the source couldn't influence Bob's choice – assuming no influence travels faster than a photon.

The result? Yet again, the experiment violated Bell's inequality spectacularly.

With that, all three major loopholes – locality, fair-sampling and freedom of choice – have seemingly been closed. Has the debate between Einstein and Bohr finally been settled, in Bohr's favour?

Perhaps. While some are keeping things interesting by discovering ever more nuanced loopholes (see "Collapse of reality", left), nitpickers noted that no one experiment had closed all three major loopholes simultaneously. That is no longer the case: a group of researchers at the Technical University of Delft has now done it (see "Trust no one", page 100). The outcome of the experiment was exactly as expected. And why wouldn't it be? "It would really be a very weird sort of conspiracy of nature if everything had worked when you closed two of the three loopholes in one experiment, and then when you closed three simultaneously, things went awry," says Nobel laureate Anthony Leggett of the University of Illinois at Urbana-Champaign.

More provocative is the question of whether we are actually at liberty to close the freedom of choice loophole. Do we really have free will? What if we live in a completely deterministic world, where even the outcome of a quantum random number generator is preordained? That would make us mere pawns in a greater game, an idea known as superdeterminism. "If the universe runs deterministically, there is nothing you can do as an experimentalist," says Kofler.

But for the vast majority of physicists that is not the prime concern, says Leggett. The point is that a local-realistic hidden variable theory, as preferred by Einstein, is not a viable description of nature. While quantum mechanics may not be the last word, it is certainly the best description of reality we have right now.

So, was Einstein wrong? That is missing the point, says Zeilinger. "Yes, Einstein was wrong about reality," he says. "And I'd give a lot to hear his comments on the situation." But by forcing us to examine the basis of quantum mechanics so closely, Zeilinger says, Einstein's concerns have delivered us a theory that, however weird, is better rooted in reality than any that preceded it. We may not have solved the problem of what quantum theory means for our picture of reality, but at least we know what questions to ask.

Motivation enough for dark nights atop La Palma, scanning a black horizon for a distant photon target. If the ghosts of Bohr and Einstein had been haunting those starlit vigils, then they would both have had cause for quiet satisfaction: Bohr that the researchers had once again confirmed his world view; Einstein for ensuring they had taken the road to the summit at all. ■

REALITY CHECKED

Something is fundamentally wrong with our understanding of the quantum universe. But what, asks Michael Brooks

AT FIRST, it looks like an ordinary mirror. But it's not. It is "half-silvered". Half of the light that hits it is reflected. The other half passes straight through.

This is not in itself extraordinary. Any time you look out of a window and see the room you are sitting in partially reflected, you're seeing a similar effect. Special beam-splitting mirrors are part of any teleprompter, and you can buy them online without breaking the bank if you really want to.

It's what they do to the individual photons of light that's the strange thing. Peer too closely, and these looking glasses might destroy your very perception of reality. They could leave you unsure where or even who you are, and make you question whether you exist at all. They might even so skew your notions of cause and effect that they leave you wondering whether you, rather than the mirror, are to blame for all this. The question is whether science gets any more profound than what happens at a half-silvered mirror. "I don't think it does," says Terry Rudolph, a physicist at Imperial College London.

The culprit, as usual when we find ourselves assailed by doubt and racked with existential fear, is quantum theory. Quantum theory is our best stab yet at delivering a picture of how material reality works at the smallest scales, and its predictions have been confirmed time and time again by experiment. It's just that the reality it describes seems to bear little relation to… well, reality.

For a start, quantum reality is unpleasantly random. Take the atoms of something as apparently real as us. According to quantum theory, when in isolation they are never definitely in any one place. There is only ever a certain probability of finding an atom at point X, a different probability of finding it at Y, and yet another of finding it at Z. As long as you don't ask where it is, an atom exists in a "superposition" of all the possible places it might be. Ask the question – make a measurement – and the atom will reveal itself to be somewhere, but you won't necessarily be able to predict where.

That weirdness reaches its apogee at the half-silvered mirror. Let light hit the mirror in the right way, and it is not just the light beam that is split, but individual photons. They become in effect two photons. One of them passes through the mirror, and the other is reflected.

Each of these photons has particular properties, for example spin – a quantum-mechanical quantity that can be envisaged rather like a rotation in space. But something very odd happens when you decide to measure these spins one after the other. You can do this over and over again, each time measuring the two spins relative to different things – the lab floor, the direction of the prevailing wind outside, the direction in which a fly is walking across the ceiling above. After a while, a chill runs down your spine. A pattern emerges: each time, the outcome of the second measurement depends on how you chose to make the first measurement.

This is something we cannot explain with normal, classical conceptions of reality. It is entanglement: the ability of quantum objects that were once related to apparently influence each other's properties when subsequently separated, even by a long way. Spooky action at a distance, in Einstein's words, though Erwin Schrödinger was kinder, calling it "the characteristic trait of quantum mechanics".

It is tempting to seek succour in some "normal" physical explanation for this, as Einstein did, and so maintain our standard perceptions of reality. There must be some undetected influence that flies between the two photons. Something physical must


MARIE LUISE EMMERMAN

pass from one to inform the other of the information that has been extracted.

Whatever form that influence might take – a photon, some other exchanged particle or perhaps a type of wave? – a good guess is that it will not travel faster than the speed of light. Thanks to Einstein's relativity, that is always seen as a kind of fundamental speed limit to any kind of usable information flying through the universe. Having that limit prevents all sorts of unpleasant consequences. "We would have weird situations, weird violations of causality, if there were superluminal signalling," says Rudolph. Any faster-than-light channel might also be open to hijacking for nefarious purposes: you could use it to transmit information backwards in time. Allow violations of relativistic causality, and we could all be lottery millionaires.

Hidden physical influences of the less outlandish sort, which obey relativity, can be tested for relatively easily. First you separate two entangled photons by a huge distance. The second photon is sent away – to the International Space Station (ISS), say – with instructions to carry out a measurement at a precise time. An instant before that measurement occurs, you measure the first photon. Time it right, and there is not enough time for any influence to travel between the two, even at the speed of light.

> "You go to try to find the causes of these strange quantum correlations, but somehow they're just not there"

Nobody has yet done the ISS test, but we have done similar things many times on Earth. Each time, when the report of the second measurement comes back, the weird influence has still been felt. The second photon responds to measurements as if it were aware of what happened to the first. Experiments performed by Nicolas Gisin and his colleagues at the University of Geneva in Switzerland in 2008 showed that any spooky influences travelling 18 kilometres through a fibre-optic network must be travelling at a minimum of 10,000 times the speed of light . The experiments have also been done over hundreds of kilometres in free air with similar results, and there are ambitious plans to repeat them in space.

Shaken and stirred

So where does this leave us? Perhaps shaken by these strange tales of unexplained correlations, you might also be stirred to accept another explanation, however far-fetched it seems at first. Relativity only forbids an influence propagating above light speed when it carries information. So what if some weird phenomenon unknown to physicists could break relativity, connect two entangled particles, while being information-free?

We have even less idea what that sort of influence might look like. Chances are it doesn't matter: this escape route back to normality has also been blocked off. Together with Gisin and others, Jean-Daniel Bancal, now at the Centre for Quantum Technologies in Singapore, worked through what would happen within a network of four senders and receivers that could synchronise their measurements of entangled photons. In this theoretical set-up, influences could travel through space-time at whatever speed they liked, just as long as they contained no information.

And it failed to reproduce reality. There was no way any physical mechanism of any stamp could produce the quantum correlations seen in experiments unless hidden influences within the network could also send information at above light speed. If we trust in relativity, that leaves us with a problem. "It pushes the weirdness further than we thought," says Bancal. "You go to try to find the causes of these correlations, but somehow they're just not there."

Gisin is even more forthright in his

conclusion. For him, it means that the dimensions of reality we move in cannot possibly contain the explanation for a more fundamental quantum reality. "There is no story in space and time that tells us how the correlations happen," he says. "There must exist some reality outside of space-time."

Unless there is something fundamental that we have wrong. Violations of relativity are frowned upon because they violate our ideas of causality. We humans are suckers for causal order, looking back in time to trace the cause of any event. Even more basically, we are determined determinists, blithely assuming that every event actually has a cause. That seems to work reasonably well in our large-scale everyday world, but when it comes to the nitty-gritty of the underlying quantum reality, can we be so sure?

Out of order

Theorist Caslav Brukner and his colleagues at the University of Vienna in Austria set out to investigate whether quantum systems are subject, in theory, to the same causal laws as the rest of us. They started off from the classic situation in which two independent observers, Alice and Bob, make a measurement on a photon. The twist Brukner and his team added was quantum uncertainty, a principle that fundamentally constrains the amount of information you can extract from a quantum system – including information about time.

Brukner describes the scenario they uncovered as akin to having Alice walk into a room and find a message written by Bob. She erases it, and writes a reply – then Bob comes in to write the original message that Alice has just replied to. In effect, just as quantum particles can be in two or more places at once, so seemingly can this particle be in two or more moments at once. The system can be simultaneously in the states "Alice came into the room before Bob" and "Bob came into the room before Alice". "We cannot say whether Alice's measurement is ahead of Bob's measurement, or the other way round," says Brukner.

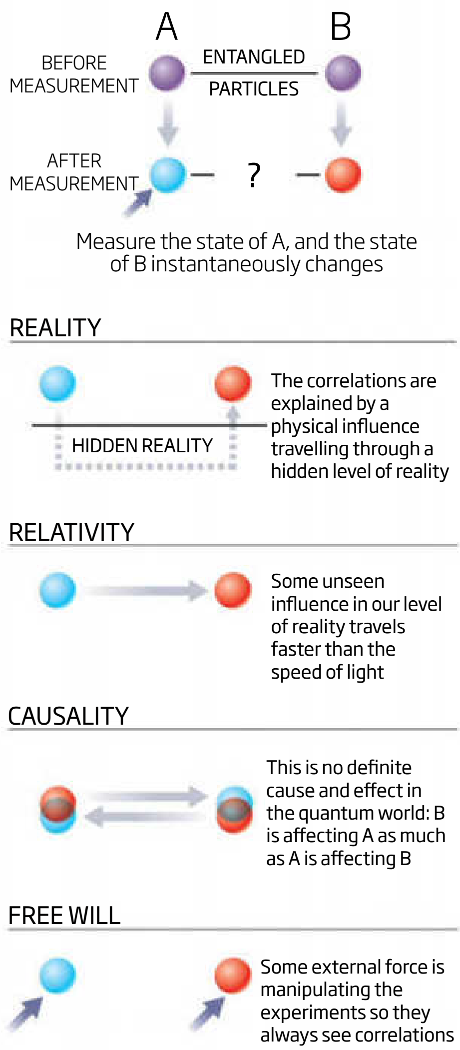
Brukner is already thinking about ways to test the results of these theoretical calculations in experiment, but it won't be easy, he says. Given the delicate nature of quantum states, any attempt to measure a quantum-mechanical superposition of causal orders destroys that superposition, collapsing it into a definite causal order.

Even without experimental confirmation,

"Just as quantum particles can be in two places at once, so seemingly can they be in two moments at once"

Beyond weird

The strange correlations between quantum objects, however far apart they are, can only be explained by abandoning some fundamental assumption



though, he thinks the conclusion is clear. "Causal order is not a fundamental property of nature," he says. Causality is only restored when the parameters of the experiment are tweaked to make the particle behave more like familiar, classical particles. That leads him in the same sort of direction as Gisin. We live in space-time, and experience causal order within it, yet causal order is not apparently fundamental to quantum theory. If we accept quantum theory as the most fundamental description of reality that we have, it means that space-time itself is not fundamental, but emerges from a deeper, currently inscrutable quantum reality.

If we accept quantum theory, that is. All the havoc quantum theory wreaks with cherished notions of reality, relativity and causality raises a natural question: is quantum theory itself the problem? For all its successes, perhaps all that randomness, uncertainty and spooky influence is just because quantum mechanics is incomplete. As currently formulated, at least, it might simply not supply all the information we need to explain why things are as they are. An analogy might be made with the laws of thermodynamics. They provide a foolproof, high-level description of how things work – heat always passes from the hotter to the cooler – while saying nothing about the underlying dynamics of individual atoms that makes that happen.

To investigate this possibility, Roger Colbeck of the University of York, UK, and Renato Renner of the Swiss Federal Institute of Technology (ETH) in Zurich have taken a look at what would happen in those classic Alice-and-Bob-type experiments if an underlying theory were to provide an additional, arbitrary amount of information about the correlations between two entangled particles. Do the outcomes of the measurements look any less random and unpredictable?

The short answer is no. In any situation where both Alice and Bob can independently choose the type of measurement they make on their particle, additional information doesn't make their predictions of what will happen in experiments any more accurate than if they use quantum theory. The mysterious unpredictability of quantum mechanics has nothing to do with incomplete information, it seems.

"The randomness is intrinsic," says Colbeck. Deep down, the universe is spontaneous. Fundamentally, there is no reason why a quantum particle has the properties it does: there is no hidden influence, no cast-iron cause and effect, no missing information. Things are as they are; there is no explanation.

"Some people find this very depressing," Colbeck says. So depressing, in fact, that it leads them to question an even more fundamental assumption about reality and our relation to it. It lies in a little clause in the way most investigations of quantum reality and quantum measurements, including Colbeck and Renner's, are set up. Let's go back to the first experiment, the one with the photons at the half-silvered mirror. To measure the direction of the photons' spins, you must first choose something to measure them relative to – the lab, the wind, the fly on the ceiling. Your choice influences the outcome of the measurement. But what if it is not actually your choice? What if something else were forcing your hand, making you perform the experiments such that the correlations always appear?

This takes us into the domain of human free will, a slippery territory where philosophers are usually more abundant than physicists. It sounds vaguely loopy, yet some serious physicists think that a lack of free will – that we are participants in something of a cosmic puppet show – might be the best way to save us from all the weirdness and loss of relativity and causality implied by quantum correlations.

Nobel laureate Gerard 't Hooft of the University of Utrecht in the Netherlands, for example, is one who finds the idea of quantum correlations that defy notions of space and time "difficult to buy". He thinks the answer might instead lie in an extreme form of determinism in which human minds are set on a trajectory of choices, such as what to make a quantum measurement relative to, from which they are powerless to deviate.

In thrall to ourselves

Others are less impressed. "Invoking conspiratorial correlations among all the brains, measuring instruments, and subatomic particles in the universe to make it 'look like' quantum mechanics is true is vastly stranger than the thing it's supposedly trying to explain," says Scott Aaronson, a quantum physicist at the Massachusetts Institute of Technology. In essence, he says, there is little difference between invoking something like that and invoking a superhuman deity.

Rudolph doesn't have an answer – no one does. But he reckons the problem is that we are still hopelessly anthropocentric.

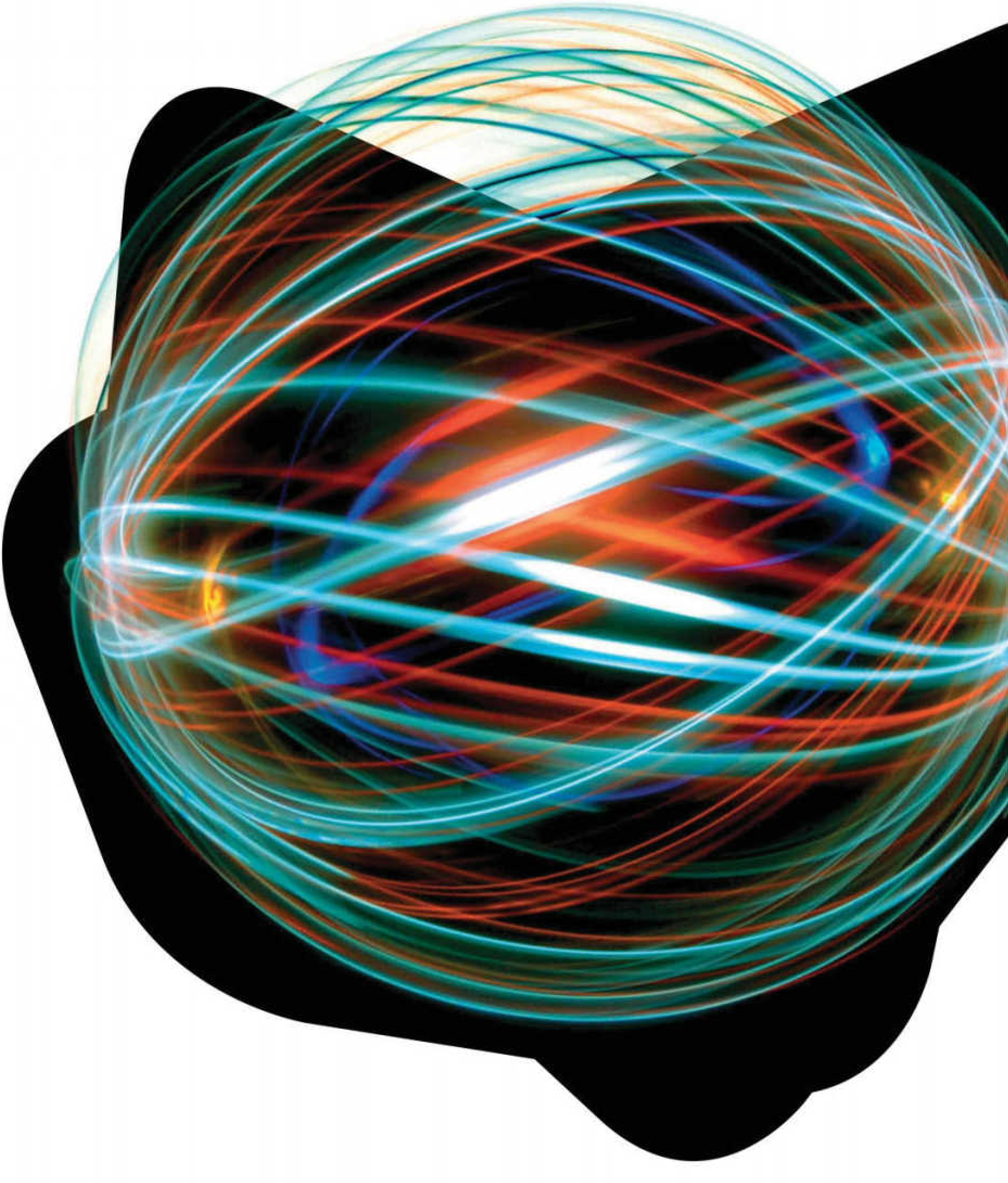
MARIE LUISE EMMERMAN

"One solution might be that there is no free will – we are all participants in something of a cosmic puppet show"

The growing disconnection between our experience of the world and the results of quantum experiments, he says, are simply a modern version of the ever-more complex epicycles that Ptolemy and those who followed him used to explain the motions of the heavenly bodies. The problem back then was that we could only see the planets as revolving around Earth; it took Copernicus to turn things around, and suddenly all was plain and simple.

Perhaps we have constructed theories such as relativity and quantum theory with a similarly limited view, in thrall this time to a sense of space and time that might not exist beyond ourselves. "We think time and position and so on are important variables for describing the world because we evolved to perceive them," says Rudolph. "But whatever is going on down there doesn't seem to worry about them at all."

So there you have it. When the light shines on that the half-silvered mirror, what we see is hardly a reflection of the world as we would like to know it. The trouble is, nature has no interest in how we would like things to be. Put simply, our conceptions of reality, relativity, causality, free will and space and time can't all be right. But which ones are wrong? ■



Ghost in the atom

An ethereal presence has haunted quantum theory since its early days – but could this cipher actually be real, asks **Marcus Chown**

ANDREW HALL

A BOAT trip on Lake Zurich seemed like the perfect way to unwind after intense discussions about the hot topic of the moment, quantum theory. Appropriate, too, given that all the physicists present were talking about an idea Erwin Schrödinger had put forward a few months earlier. He had suggested that all quantum particles, from atoms to electrons, could be described by intangible entities that spread out through space much like ripples on a lake's surface. He called them wave functions.

When Schrödinger had first published his insights in March 1926, theorists had been thrilled. Symbolised by the Greek letter psi, the wave function gave them a way to apply their much-loved mathematics of waves to the quantum world. And it worked, neatly explaining why electrons in atoms have the energies they do. Yet there was a problem, summed up by a cheeky verse penned on the boat trip:

Erwin with his psi can do
Calculations quite a few
But one thing has not been seen:
Just what does psi really mean?

Now, 90 years on, quantum theory is still our very best description of the microscopic world of atoms and their constituents. It has given us lasers, computers and nuclear reactors, and even tells us how the sun shines and why the ground beneath our feet is solid. Yet the wave function remains an enigma, a ghost at the heart of the atom. To most physicists, it is little more than a convenient way of calculating how quantum systems such as atoms should behave. Few have considered it in any sense real.

It might now be time to rethink those attitudes. A group of physicists based in the UK has looked again at the wave function, and think they have the proof that there is more to it than meets the eye. The ghost in the atom may yet prove to be more real than we ever imagined.

The emergence of the wave function as a central element of quantum theory was by no means an overnight thing. The theory was born in 1900 when German physicist Max Planck found that he could explain the baffling spectrum of light emerging from a hot furnace only if the vibrational energy of the atoms giving out the light came in discrete chunks, or quanta. Planck himself thought this was merely a convenient mathematical device. It was left to one Albert Einstein to recognise that quanta were real five years later. He showed that the light streaming out of the atoms that make up matter consists of untold trillions of these tiny energy packets, now better known as photons.

Einstein's idea flew in the face of hundreds of experiments showing that light was like a ripple spreading on a lake or pond. The only plausible explanation was that somehow light must be both a wave and a stream of particles. In 1923, French physicist Louis de Broglie took this idea and ran with it, proposing that just as light waves could behave like particles, the fundamental particles of matter could behave like waves.

De Broglie imagined an electron as a "matter wave" rippling through space. But as the idea was fleshed out mathematically, that interpretation was quietly dropped. The waves associated with quantum particles were waves alright, but they appeared to be totally abstract things, unlike any waves anyone had ever imagined.

All waves can be described mathematically – a ripple across a pond, for example, is a disturbance in water; its wave function › describes its shape at any point and time, while something called the wave equation predicts how the ripple moves. Schrödinger realised from de Broglie's work that actually every quantum system has a wave function associated with it, though he struggled to explain what the disturbance would be in the case of an atom or an electron. Even so, Schrödinger's work led to a radical new picture of the quantum world as a place in which certainties give way to probabilities.

Schrödinger's wave function is central because it encodes all the possible behaviours for a quantum system. Picture the simple case of an atom flying through space. It is a quantum particle, so you cannot say for sure where it will go. If you know its wave function, however, you can use that to work out the probability of finding the atom at any location you please. That is good enough for most physicists, who believe the wave function to be merely a probability distribution – a statistical summary of what large numbers of measurements would tell you about the whereabouts of the particle. But is that the full story?

An example helps to highlight the subtle difference between a purely mathematical and a physically real wave function. Say you arrive at a lake into which a large number of plastic bottles have been thrown. You notice that there are places where the bottles bunch up and places where there are very few bottles. By counting the number of bottles at different locations, you could create a probability distribution, which allows you to estimate the chance of finding a bottle at each point.

But suppose you notice that the bottles are most common where the amplitude of the real waves in the lake peak. Now you realise that the probability distribution is not the last word – there is a mechanism behind it. Real, physical waves have driven the bottles to their particular locations.

Back in quantum theory, we can similarly ask if the quantum wave function is merely a probability distribution or the manifestation of a real, underlying wave. The key to answering that question is to come up with a thought experiment in which the two possibilities produce different outcomes. That isn't so easy, and theorists have struggled for years to formulate the question in a tractable way.

Eventually, however, Matthew Pusey and Terry Rudolph of Imperial College London, with Jonathan Barrett of Royal Holloway University of London, achieved a significant breakthrough. They imagined a hypothetical theory that completely describes a single quantum system such as an atom but, crucially, without an underlying wave telling the particle what to do.

Abstract reality

Next they concocted a thought experiment to test their theory, which involved bringing two independent atoms together and making a particular measurement on them. What they found is that the hypothetical wave-less theory predicts an outcome that is different from standard quantum theory. "Since quantum theory is known to be correct, it follows that nothing like our hypothetical theory can be correct," says Rudolph.

Some colleagues are impressed. "It's a fabulous piece of work," says Antony Valentini of Clemson University in South Carolina. "It shows that the wave function cannot be a mere abstract mathematical device. It must be real – as real as the magnetic field in the space around a bar magnet."

The UK trio's work has also received support from Lucien Hardy at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada, where Pusey is also now based. Using slightly different assumptions, he has obtained a similar result indicating the reality of the wave function.

The conclusion appears inescapable. Quantum theory makes no sense if the wave function is merely a probability distribution. Instead, the wave function has to be a real thing associated with a single quantum system, informing it how to behave. "Under seemingly benign assumptions, you cannot escape the wave function being 'real'," says Rudolph.

Valentini agrees with this interpretation. "There is a definite reality underpinning quantum theory," he says. Not everyone shares his conviction, however. Some point to problems with the team's "benign" assumptions. One is the notion that a quantum system has true properties even before any measurement has been made on it. The pioneers of quantum theory, Niels Bohr and Werner Heisenberg, famously maintained

THE WAY THEY TELL IT

Historically, there have been more than a dozen different interpretations of what quantum theory means. The chief problem is reconciling the many possibilities for a quantum particle's state that are encoded in its wave function with the fact that we can only ever measure one of them. If the wave function is indeed associated with something physically real, that would favour certain ways of achieving that trick.

One interpretation given a fillip by the latest work (see main story) would be the "many worlds" interpretation put forward by US physicist Hugh Everett in 1957. According to this view, all those possibilities encoded in the wave function are actualities that play out in parallel realities. We observe only one of these possibilities because we are confined to one reality – one branch of the wave function. That wave function, with all its parallel strands, is ultimate reality.

Another interpretation in which the wave function is real is the "collapse interpretation". Here, the wave function contains all possibilities until some random event inherent to the wave function collapses it down to one possibility.

Yet another is the de-Broglie-Bohm "pilot wave" theory, proposed in 1927, the year after Schrödinger devised his equation. De Broglie maintained that every quantum particle possesses an invisible pilot wave, which runs alongside it and tells the system how to behave. He even used the interpretation to predict that particles of matter would display wave phenomena such as interference, something also observed in 1927.

Despite this success, pilot wave theory fell out of favour. It was supplanted by the view of Niels Bohr and Werner Heisenberg, who believed that the wave function encapsulates merely what we can know about reality rather than reality itself. If that turns out not to be the case, the pilot wave interpretation could be in with a shout again.


ANDREW HALL

that there was no real world out there and that quantum properties were brought into existence by the very act of measurement. Taken to its extreme view, the Bohr-Heisenberg view implies that the universe did not exist until we came on the scene to observe it. “But that was then and this is now,” says Valentini. These days the consensus among most quantum theorists is that the universe, electrons and atoms exist even when they are not being measured.

Pusey and his colleagues also suppose that the two atoms in their thought experiment are truly independent of each other, so that a measurement made on one does not affect the other. They also take for granted that the laws of cause and effect hold, so that a measurement made on an atom at, say, 3 pm does not affect its state earlier at 1 pm.

Valentini argues that these are reasonable assumptions to make. To violate them would require a kind of universal web of interactions in which almost every system in the universe influences every other system at different times as well as different places. “It seems simpler to accept the quantum wave as real, just as classically it is simpler to accept the electromagnetic field as real,” he says.

"Taken to its extreme, the old view implied the universe did not exist until we observed it"

So what does it mean if Pusey’s team and Hardy are right and the wave function is real? On the one hand, they have overturned almost 90 years of thinking by showing that the wave function is part and parcel of a single quantum system. On the other, if the wave function is real, it is a very weird kind of real. According to the mathematics, Schrödinger’s wave function encodes everything there is to know about a single particle in three dimensions. But things get more complicated very quickly. The wave function for two particles exists in an abstract six-dimensional space and for three particles, it exists in nine dimensions, and so on. “We need to expand our imaginations, widen our view of what constitutes fundamental reality,” says Valentini.

He draws parallels with the time when no one believed in an electric field, which permeates all of space and tells charged particles such as electrons how to behave. Without the intermediary of an electric field, it was tremendously difficult to predict how charged particles would react with each other. “Similarly, people might not like to believe in a wave function that lives in an abstract space and tells quantum systems how to behave,” says Valentini. The new work, however, proves that it is difficult to find a theory which predicts the behaviour of quantum systems without that property.

That could have implications for how we interpret the seemingly counter-intuitive predictions of quantum theory, a major source of debate ever since the theory’s inception (see “The way they tell it”, left). Valentini believes it could be the most important shift in the foundations of quantum theory since physicist John Bell argued that quantum theory allows something then thought scarcely believable – that making a measurement on a particle could instantaneously influence another particle on the other side of the globe. It was another 18 years before Alain Aspect at the University of Paris South in France proved experimentally that Bell’s theorem was correct.

In the interim, the abstract notion had surprisingly practical applications, such as protocols for transmitting cryptographic signals securely using quantum mechanics. Only now are the implications of Bell’s work being fully realised by governments and banks seeking the ultimate in data security. It may take just as long before the ideas of Pusey and his colleagues are vindicated – or not, as the case may be. The experiments are difficult, but not impossible, and some have been done that confirm things are on the right track. However, loopholes remain. An experiment that would silence all the criticisms is still a way off.

Valentini remains enthusiastic. “I certainly hope that the new work will lead to the discovery of new phenomena,” he says. Most importantly, however, he thinks it will open up new avenues in research into the foundations of quantum theory. “You’ve seen nothing yet,” he says. “Mark my words, this will run and run.” ■

CHAPTER THREE

THE QUANTUM WORLD

The weirdness inside us

Do the strange laws of quantum physics also determine how living organisms work? **Michael Brooks** investigates a controversial claim

EVER felt a little incoherent? Or maybe you've been in two minds about something, or even in a bit of delicate state. Well, here's your excuse: perhaps you are in thrall to the strange rules of quantum mechanics.

We tend to think that the interaction between quantum physics and biology stops with Schrödinger's cat. Not that Erwin Schrödinger intended his unfortunate feline – suspended thanks to quantum rules in a simultaneous state of being both dead and alive – to be anything more than a metaphor. Indeed, when he wrote his 1944 book *What is Life?*, he speculated that living organisms would do everything they could to block out the fuzziness of quantum physics.

But is that the case? Might particles that occupy two states at once, that interact seemingly inexplicably over distances and exhibit other quantum misbehaviours actually make many essential life processes tick? Accept this notion, say its proponents, and we could exploit it to design better drugs, high-efficiency solar cells and super-fast quantum computers. There's something we need to understand before we do, though: how did the quantum get into biology in the first place?

On one level, you might think, we shouldn't be surprised that life has a quantum edge. After all, biology is based on chemistry, and chemistry is all about the doings of atomic electrons – and electrons are quantum-mechanical beasts at heart. That's true, says Jennifer Brookes, who researches biological quantum effects at Harvard University. "Of course everything is ultimately quantum because electron interactions are quantised."

On another level, it is gobsmacking. In theory, quantum states are delicate beasts, easily disturbed and destroyed by interaction with their surroundings. So far, physicists have managed to produce and manipulate them only in highly controlled environments at temperatures close to absolute zero, and then only for fractions of a second. Finding quantum effects in the big, wet and warm world of biology is like having to take them into account in a grand engineering project, says Brookes. "How useful is it to know what electrons are doing when you're trying to build an aeroplane?" she asks.

Might this received wisdom be wrong? Take smell, Brookes's area of interest. For decades, the line has been that a chemical's scent is determined by molecular shape. Olfactory receptors in the nose are like locks opened only with the right key; when that key docks, it triggers nerve signals that the brain interprets as a particular smell.

Is that plausible? We have around 400 differently shaped smell receptors, but can recognise around 100,000 smells, implying some nifty computation to combine signals from different receptors and process them into distinct smells. Then again, that's just the sort of thing our brains are good at.

A more damning criticism is that some chemicals smell similar but look very different, while others have the same shape but smell different. The organic compound benzaldehyde, for example, comes in two almost identical molecular arrangements, vanillin and isovanillin, that have very distinctive smells.

There is an alternative explanation. Around 70 years ago, even before the lock-and-key mechanism was suggested, the distinguished British chemist Malcolm Dyson suggested that, just as the brain constructs colours from different vibrational frequencies of light radiation, it interprets the characteristic frequencies at which certain molecules vibrate as a catalogue of smells.

The idea languished in obscurity until ›

SEAN RODWELL

1996, when Luca Turin, a biophysicist then at University College London, proposed a mechanism that might make vibrational sensing work: electron tunnelling. This phenomenon results from the basic fuzziness of quantum mechanics, and is a staple of devices from microchips to microscopes. When an electron is confined in an atom, it does not have an exactly defined energy but has a spread of possible energies. That means there is a certain probability that it will simply burrow through the energy barrier that would normally prevent it escaping the atom.

Turin's idea is that when an odorous molecule lodges in the pocket of a receptor, an electron can burrow right through that molecule from one side to the other, unleashing a cascade of signals on the other side that the brain interprets as a smell. That can only happen if there is an exact match between the electron's quantised energy level and the odorant's natural vibrational frequency. "The electron can only move when all the conditions are met," Turin says. The advantage, though, is that it creates a smell without the need for an exact shape fit.

It was a controversial notion. In 2007 Brookes, then also working at University College London, and colleagues showed that the mechanism is physically plausible: the timescales are consistent with the speed with which the brain responds to smell, and the signals generated are large enough for the brain to process. And in January 2011 Turin, then at the Alexander Fleming Biomedical Sciences Research Centre in Vari, Greece, and his colleagues delivered what looks like evidence for vibrational sensing. They showed that fruit flies can distinguish between two types of acetophenone, a common base for perfumes, when one contains normal hydrogen and the other contains heavier deuterium. Both forms have the same shape, but vibrate at different frequencies. That sensitivity can only mean electron tunnelling, says Andrew Horsfield of Imperial College London, a co-author on Brookes's paper: in classical models of electron flow the electron would not be sensitive to the vibrational frequency. "You can't explain it without the quantum aspect."

Smell is not the only thing that proponents of quantum biology think it might explain: there's also the mechanism that powers the entire animal kingdom. We all run on adenosine triphosphate, or ATP, a chemical made in cells' mitochondria by moving electrons through a chain of intermediate molecules. When we attempt to calculate how speedily this happens, we hit a problem. "In nature the process is much faster than it should be," says Vlatko Vedral, a quantum physicist at the University of Oxford.

Vedral thinks this is because it depends on the quality of "superposition" which allows the sort of quantum-mechanical wave that describes electrons to be in two places at once. He reckons quantum omnipresence might speed the electrons' passage through the reaction chain. "If you could show superposition is there and it's somehow also important for the electron flow, that would be very interesting," he says.

Vedral's first calculations support the idea, but he says it is too early to make any claims. It is hard to estimate all the parameters involved in electron transport, and it is possible that the classical calculations just used the wrong numbers. "And as yet we have no experimental proof," he says. Such proof might be quite close by – in how plants and some bacteria get their energy. It seems photosynthesis might be very much a quantum game.

Quantum marines

Direct evidence that this is so came in 2007, when a group led by Graham Fleming at the University of California, Berkeley, took a close look at photosynthesis in the green sulphur bacterium *Chlorobium tepidum*. They detected "beating" signals characteristic of quantum wave interference in the photosynthesising centres of bacteria cooled to 77 kelvin. In January 2010, a group led by Gregory Scholes of the University of Toronto, Canada, showed a similar effect at room temperature in light-harvesting proteins from two marine algae.

This is a trick we might like to learn from. Although photosynthesis is not particularly efficient overall, the initial stage of converting incoming photons into the energy of electrons within a photosynthesising organism's light-gathering pigment molecules is extremely effective. When sunlight is weak, plants are able to translate more than 90 per cent of photons into an energy-carrying electron;

BIRD'S EYE VIEW

Another instance of quantum effects in biology might be in how birds sense Earth's magnetic field. In 2004, Thorsten Ritz of the University of California, Irvine, showed how magnetic disturbances that would only show up on systems that could detect transitions between particular quantum-mechanical atomic spin states could disrupt the compass of the European robin, *Erithacus rubecula*.

Ritz suggested that birds come equipped with a sensor system containing spin states that flip in response to changes in Earth's magnetic field, producing signals that the bird's brain in some way detects. But how?

The first proposal was that some apparatus in the eye initiates a chemical response. But this would require a constant, fast flipping of spins to keep chemical information flowing, whereas the birds seemed to maintain delicate spin states for extraordinarily long times of up to 100 microseconds.

According to the late Marshall Stoneham of University College London and his colleagues, the problem might be overcome if the birds used something similar to a human visual peculiarity that detects light polarisation. Known as Haidinger's brush, this superimposes a faint, yellow bow-tie shape on our visual field, and is thought to result from the way blue light-absorbing lutein molecules are arranged in concentric circles within our eye. Stare at a blank piece of paper and a polarising filter or a blank document on a laptop screen and you can see it for yourself.

Stoneham calculated that a magnetic field could produce a similar distortion in a bird's visual field, the orientation of which would change with a change in magnetic field. Crucially, that would occur only if quantum states lasted long enough to affect many of the bird's light sensing molecules at the same time. Birds might see the result, Stoneham suggested, in a kind of head-up display similar to that embedded in the windscreens of some luxury cars. As yet, there is no experimental proof for the idea.

in strong sunlight plants have to dump about half the energy to avoid overheating.

Scholes's explanation for this is that when sunlight hits electrons, they are kicked into a quantum superposition that allows them to be in two places at once. That effectively "wires" light-gathering molecules to the reaction centre where the photosynthesis takes place for a few hundred femtoseconds. During that time, an electron can, according to quantum rules, take all paths between the two places simultaneously. Probing the process more closely causes the superposition to collapse – and reveals the electron to have taken the path that lost it the least energy.

Might we take a leaf out of biology's book? Scholes thinks so. "Every year there are thousands of papers published on energy transfer," he says. "It sounds harsh but we haven't learned a thing apart from the obvious." A better understanding of what is going on might also help us on the way to building a quantum computer that exploits coherent states to do myriad calculations at once. Efforts to do so have so far been stymied by our inability to maintain the required coherence for long – even at temperatures close to absolute zero and in isolated experimental set-ups where disturbances from the outside world are minimised. Currently, quantum computing takes place in laboratories that are isolated from electric and magnetic fields, from vibrations that might impart unwanted energy to the system and within refrigerators that remove as much thermal energy as possible.

This remains the central conundrum for the physicists studying quantum aspects of biology. If we can't do these things in our isolated labs, how can a leaf in your less-than-isolated garden do it? If only the European robin could do more than warble chirpily. Perhaps then it could tell us – and explain its own apparent quantum superpowers, too (see "Bird's eye view", below left).

At the moment we have little more than educated guesses. One is that it is simply a wonder of evolution. Scholes thinks that proteins around algae's light-harvesting equipment might have evolved structures that shield disturbances from the environment and so allow processes within to exploit the magic of quantum physics to give them a selective advantage. Vedral thinks something similar, although why and how nature would do this, he says, is "completely unclear".

Turin shrugs his shoulders, too. "Life's 4 billion years of nanoscale R&D will have engineered many miracles," he says. We should learn to accept what we see and try to mimic it, he says – and not just in solar cells and quantum computers. While what makes a drug effective or ineffective is far from clear, for instance, we do know that the operation of things like neurotransmitters in our brains depends on redox reactions, which are all to do with electron flow. If those flows occur in weirder ways than we have hitherto imagined, that could open up a new path to design drugs to treat some of our most pernicious ailments.

Others think nature is leading us up the garden path. Is photosynthesis, for example, really made more efficient by exploiting quantum interference and superposition effects? "I think the jury is still out on this question," says Robert Blankenship of Washington University in St Louis, Missouri. "I think it is possible that, depending on the details of the system, it could just as easily decrease the efficiency." Simon Benjamin, a colleague of Vedral's at the University of Oxford, wonders how we can really put long-lived quantum states to work if indeed they do pop up in natural systems. "It's certainly too early to be making dramatic claims," he says.

All those stepping gingerly around this new field agree that caution is needed – yet there is a palpable sense of excitement. Max Planck first discovered quantum theory more than a century ago because of odd observations that could be explained in no other way. That led to the laser and the semiconductor and all the technological revolutions they have seeded. To the optimists, it seems that quantum biology is at that early stage of inexplicable observations. Turin for one believes something big is emerging. "I can't help thinking we are seeing just a small part of a far, far bigger iceberg," he says. ■

> "Every year thousands of papers are published on energy transfer. It sounds harsh but we haven't learned a thing"

A bit in ~~owt~~two minds

The human brain's peculiar computing abilities could be down to quantum fuzziness finds Michael Brooks

MATTHEW FISHER was wary of how his peers would react to his latest project. In the end he was relieved he wasn't laughed out of court. "They told me that this is sensible science – I'm not crazy."

Certainly nothing in Fisher's CV says crazy. A specialist in the quantum properties of materials, he worked at IBM and then at Microsoft's Research Station Q developing quantum computers. He is now a professor at the Kavli Institute for Theoretical Physics at the University of California Santa Barbara. In 2015 he won a share of the American Physical Society's Oliver E. Buckley prize in condensed matter physics, many recipients of which have gone on to win a Nobel.

The thing was, he had broached a subject many physicists would rather simply avoid.

"Does the brain use quantum mechanics? That's a perfectly legitimate question," says Fisher. On one level, he is right – and the answer is yes. The brain is composed of atoms, and atoms follow the laws of quantum physics. But Fisher is really asking whether the strange properties of quantum objects – being in two places at once, seeming to instantly influence each other over distance and so on – could explain still-perplexing aspects of human cognition. And that, it turns out, is a very contentious question indeed.

The most basic objection comes from Occam's razor, the principle that says the simplest explanation is usually the best. In this view, current non-quantum ideas of the brain's workings are doing just fine. "The evidence is building up that we can explain everything interesting about the mind in terms of interactions of neurons," says philosopher Paul Thagard of the University of Waterloo in Ontario, Canada. Physicist David Deutsch of the University of Oxford agrees. "Is there any need to invoke quantum physics to explain cognition?" he asks. "I don't know of one, and I'd be amazed if one emerges."

Fisher is less sure, pointing out that current ideas about memories are far from watertight – for example, that they are stored in the architecture of neuron networks or in the junctions between neurons. "My gut instinct is that neuroscience has lots of things that remain puzzling," says Fisher. So why not see if there are better quantum explanations?

Perhaps because we've been here before. In 1989, Oxford mathematician Roger Penrose proposed that no standard, classical model of computing would ever explain how the brain produces thought and conscious experience. The suggestion intrigued a lot of people, not least an Arizona-based anaesthetist called Stuart Hameroff, who suggested a specific way for quantum effects to get involved.

The crux of the idea was that microtubules – protein tubes that make up neurons' support structure – exploit quantum effects to exist in "superpositions" of two different shapes at once. Each of these shapes amounts to a bit of classical information, so this shape-shifting ›

EIKO OJALA

quantum bit, or qubit, can store twice as much information as its classical counterpart.

Add entanglement to the mix – a quantum feature that allows qubit states to remain intertwined even when not in contact – and you rapidly build a quantum computer that can manipulate and store information far more efficiently than any classical computer. In fact, Penrose suggested, the way such a computer can arrive at many answers simultaneously, and combine those answers in different ways, would be just the thing to explain the brain's peculiar genius.

Penrose and Hameroff collaborated on the idea, and they and others kicked it around as a sensible proposal for a while. But holes soon began to appear.

From a physicist's perspective, the most fundamental problem was coherence time. Superposition and entanglement are both extremely fragile phenomena. Think of a human pyramid of performers crossing a high wire on a unicycle and you get the idea. The slightest disturbance and their grip slips. In the case of a quantum system, it will "decohere" to a bog-standard classical state if disturbed by heat, a mechanical vibration or anything else. The information stored in the quantum states is generally lost to the surrounding environment.

This problem has hampered attempts over the past two decades by physicists, Fisher included, to engineer a quantum computer of any significant size (see "Quantum computer best buys", page 87). Even in cryogenically cooled and mechanically isolated conditions, it's a struggle to keep qubit networks coherent for long enough to do anything beyond the capabilities of classical computers.

In the warm, wet brain, with its soup of jiggling, jostling molecules, it becomes almost impossible. Neurons hold information for microseconds at a time or more while processing it, but calculations suggest that the microtubule superpositions would last only between 10^{-20} and 10^{-13} seconds. Neurophilosopher Patricia Churchland summed up what came to be the mainstream view: "Pixie dust in the synapses is about as explanatorily powerful as quantum coherence in the microtubules," she wrote in 1996.

> "Maintaining quantum effects in the warm, wet brain should be impossible"

Fisher shared that scepticism. "When they started talking about microtubules, I knew immediately it didn't make sense," he says. "It's impossible to work with quantum information unless you can control it and keep it from entangling with the environment."

But equally, he thought, wouldn't it be odd if evolution hadn't worked that out? Life has had billions of years to "discover" quantum mechanics, and its exquisite molecular apparatus gives it the means to exploit it. Even if electrical impulses among neurons within the brain – something well described by classical physics – are the immediate basis of thought and memory, a hidden quantum layer might determine, in part, how those neurons correlate and fire.

Fisher's personal interest in the subject began in a rather roundabout way, while wondering about the persistence of mental illness among people close to him, as well as the efficacy of the drugs used to treat them. "No one truly knows how any of the psychiatric pharmaceuticals work," he says. There's a reason for that. It would require a much better understanding of what the drugs are trying to modify: the human mind.

The initial focus of Fisher's interest was lithium, an ingredient of many mood stabilising drugs. As he combed the scientific literature, he happened across one particular report from 1986 that gave him pause for thought. It described an experiment in which rats were fed one of the two stable isotopes of lithium: lithium-6 and lithium-7. When it came to grooming, nursing of pups, nest-building, feeding and several other measures, those fed lithium-6 were enormously more active than control groups or those fed lithium-7.

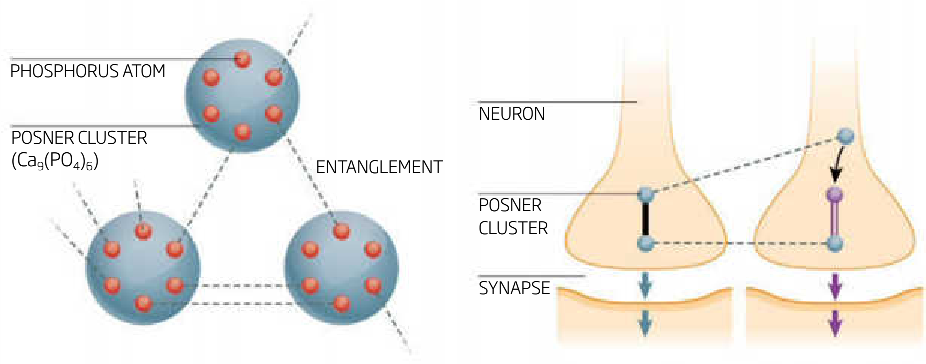
It was this paper that led Fisher to think it might be time to open the whole quantum cognition can of worms once again. All atomic nuclei, like the fundamental particles that make them up, have a quantum-mechanical property called spin. Crudely, spin quantifies how much a nucleus "feels" electric and magnetic fields; the higher the spin, the greater the interaction. A nucleus with the very lowest possible spin value, 1/2, feels virtually no interaction with electric fields and only a very small magnetic interaction. So in an environment such as the brain, where electric fields abound, nuclei with a spin of 1/2 would be peculiarly isolated from disturbance.

Spin-1/2 nuclei are not common in nature, but here's the thing. The spin value of lithium-6 is 1, but in the sort of chemical environment found in the brain, a water-based salt solution, the presence of the water's extra protons is known to make it act like a spin-1/2 nucleus. Experiments as long ago as the 1970s had noted that lithium-6 nuclei could hold their spin steady for as long as 5 minutes. If there is an element of quantum control to the brain's computation, Fisher reasoned, lithium's calming effects might be down to the incorporation of these peculiarly coherent nuclei into the brain's chemistry.

And not just that. Lithium-6 does not occur naturally in the brain, but one nucleus with a spin-1/2 does, and it is an active participant in many biochemical reactions: phosphorus. The seed in Fisher's mind was beginning to

Joined-up thinking

Posner clusters thought to be found in the brain contain six phosphorus atoms whose nuclear spin states can be quantum entangled – perhaps influencing how we think and remember



Change the spin state of one entangled phosphorus atom and the state of its entangled partner changes too – regardless how far apart they are

Entangled Posner clusters involved in chemical signalling in one brain neuron could **induce similar reactions in another neuron** sprout. "If quantum processing is going on in the brain, phosphorus's nuclear spin is the only way it could occur," Fisher says.

After exhaustive calculations of the coherence times of various phosphorus-based molecules in biological settings, Fisher went public with a candidate qubit. It is a calcium phosphate structure known as a Posner molecule or cluster. It was identified in bone mineral in 1975 and has also been seen floating around when simulated body fluids – that is, water with added biological molecules and mineral salts – are concocted in the lab. When Fisher estimated the coherence time for these molecules, it came out as a whopping 10^5 seconds – a whole day.

He has also identified at least one chemical reaction in the brain that he thinks would naturally manufacture entangled, coherent states between nuclear spins within Posner molecules. It is a process involved in calcium absorption and fat metabolism that uses an enzyme called pyrophosphatase. This enzyme breaks down structures made of two interlinked phosphate ions, producing two single ions. Theoretically, at least, the nuclear spins in these two ions should be quantum entangled. Release them into the fluid surrounding the cells, and they can combine with calcium ions to form Posner molecules.

If this is all correct, the brain's extracellular fluid could be awash with complex clusters of highly entangled Posner molecules. Once inside the neurons, these molecules could begin to alter the way the cells signal and respond, starting to form thoughts and memories (see diagram, left).

Fisher published the details of his proposal in *Annals of Physics* in 2015. Much of it, he admits, is highly speculative. "I'm still at the stage of telling stories," he says. "I have to get some experiments done."

The c-word

The first test will be whether Posner molecules exist in real extracellular fluids. If they do, can they be entangled? Fisher envisages testing this in the lab by inducing the chemical reactions suspected to entangle phosphorus nuclear spins, pouring the resulting solution into two test tubes and looking for quantum correlations between light given out from the two. Observe such correlations, and you might just begin to make a case for quantum cognition. "That test can be done, and I'll make sure it is done," says Fisher.

Penrose is – perhaps predictably – excited by the story so far. "Stuart Hameroff and I

SUPERSTOCK

Quantum control of the brain is controversial

have been of the opinion that nuclear spins might be an important ingredient of long-term memory for quite a while," he says. "Matthew Fisher's idea could well provide a very positive contribution to this picture."

Penrose still pins his colours to his microtubule hypothesis, however, seeing the new proposal as a mere add-on that allows for lasting memory. "The phenomenon of

> "The idea that the brain is too messy for quantum effects is simple-minded"

consciousness is much more likely to be connected with the quantum actions of interconnected microtubules," he says.

For Penrose, consciousness has to do with gravity acting on quantum states and thus causing them to decohere; microtubules are more massive than nuclei, and thus more likely to be the cause of this interaction, he says. Fisher would rather not go down this road, and says he has studiously avoided any mention of the c-word – consciousness – in his paper, concentrating instead on better-defined concepts such as memory.

His proposal might not be crazy, but does it do enough to convince sceptics to look again for quantum effects in the brain? Thagard declares himself open-minded. He points to evidence that has accumulated in the past quarter-century showing that other biological processes, such as photosynthesis, involve long-lived coherent quantum states. Vlatko Vedral of the University of Oxford also sees some value in Fisher's work. The idea that a warm, wet brain is too messy to have useful coherences is "simple-minded", he says. Beyond that, he is not sure what exact part Fisher's mechanism might play. "But at least he has suggested experiments that might be able to probe this issue further," he says.

If there is any hint of success, Fisher has plenty of ideas lined up to test. There's the lithium question, and also whether related spin effects might explain mercury's influence on the brain – the phenomenon that became known as mad hatter disease, because hat-making traditionally involved prolonged exposure to mercury. Some commonly abundant isotopes of mercury have non-zero nuclear spin and might decohere phosphorus nuclear spins if caught inside a Posner molecule.

The questions keep coming. Does a bang on the head induce memory loss because it causes decoherence? Is nuclear spin the reason you can change brain states with transcranial magnetic stimulation, which fires a magnetic field across the brain? Fisher is working with neuroscientists and molecular biologists at Stanford University in California, where he spent a sabbatical, to address such questions. Most have taken a lot of convincing, he admits.

Johnjoe McFadden, a molecular biologist at the University of Surrey in Guildford, UK, is one researcher who remains to be persuaded. He once again invokes Occam's razor. "There are too many bits of it that need to hold together to make a coherent story," he says. "If any one aspect goes missing, it all falls apart."

Thagard, too, is waiting for the fall. "Do you need that extra level of explanation to account for interesting psychological phenomena? I don't think so," he says. But that's no reason not to seriously evaluate such proposals, he adds. "One of the great strengths of science is that people try different approaches and you get competing explanations. That's all good. I'm just putting my money on a different one."

Fisher meanwhile is putting his money where his mouth is: he has spent $20,000 of his own cash filing a patent on treating depression and similar mental conditions with compounds enriched in lithium-6. Perhaps appropriately, though, he remains in two minds about whether it will lead anywhere. "Could quantum cognition make sense of these things that are missing from our understanding of neuroscience?" he asks reflexively. "Maybe, yes." ■

Quantum sense

The weird logic in particles' behaviour applies surprisingly well to the way we think. **Mark Buchanan** finds the "you" in quantum

THE quantum world defies the rules of ordinary logic. Particles routinely occupy two or more places at the same time and don't even have well-defined properties until they are measured. It's all strange, yet true – quantum theory is the most accurate scientific theory ever tested and its mathematics is perfectly suited to the weirdness of the atomic world.

Yet that mathematics actually stands on its own, quite independent of the theory. Indeed, much of it was invented well before quantum theory even existed, notably by German mathematician David Hilbert. Now, it's beginning to look as if it might apply to a lot more than just quantum physics, and quite possibly even to the way people think.

Human thinking, as many of us know, often fails to respect the principles of classical logic. We make systematic errors when reasoning with probabilities, for example. Physicist Diederik Aerts of the Free University of Brussels, Belgium, has shown that these errors actually make sense within a wider logic based on quantum mathematics. The same logic also seems to fit naturally with how people link concepts together, often on the basis of loose associations and blurred boundaries. That means search algorithms based on quantum logic could uncover meanings in masses of text more efficiently than classical algorithms.

It may sound preposterous to imagine that the mathematics of quantum theory has something to say about the nature of human thinking. This is not to say there is anything quantum going on in the brain, only that "quantum" mathematics really isn't owned by physics at all, and turns out to be better than classical mathematics at capturing the fuzzy and flexible ways that humans use ideas, says Aerts. "The mathematics of quantum theory turns out to describe this quite well."

It's a finding that has kicked off a burgeoning field known as "quantum interaction", which explores how quantum theory can be useful in areas having nothing to do with physics, ranging from human language and cognition to biology and economics. And it's already drawing researchers to major conferences.

One thing that distinguishes quantum from classical physics is how probabilities work. Suppose, for example, that you spray some particles towards a screen with two slits in it, and study the results on the wall behind (see diagram, page 72). Close slit B, and particles going through A will make a pattern behind it. Close A instead, and a similar pattern will form behind slit B. Keep both A and B open and the pattern you should get – ordinary physics and logic would suggest – should be the sum of these two component patterns.

"These experiments demonstrate that people aren't logical, at least by classical standards"

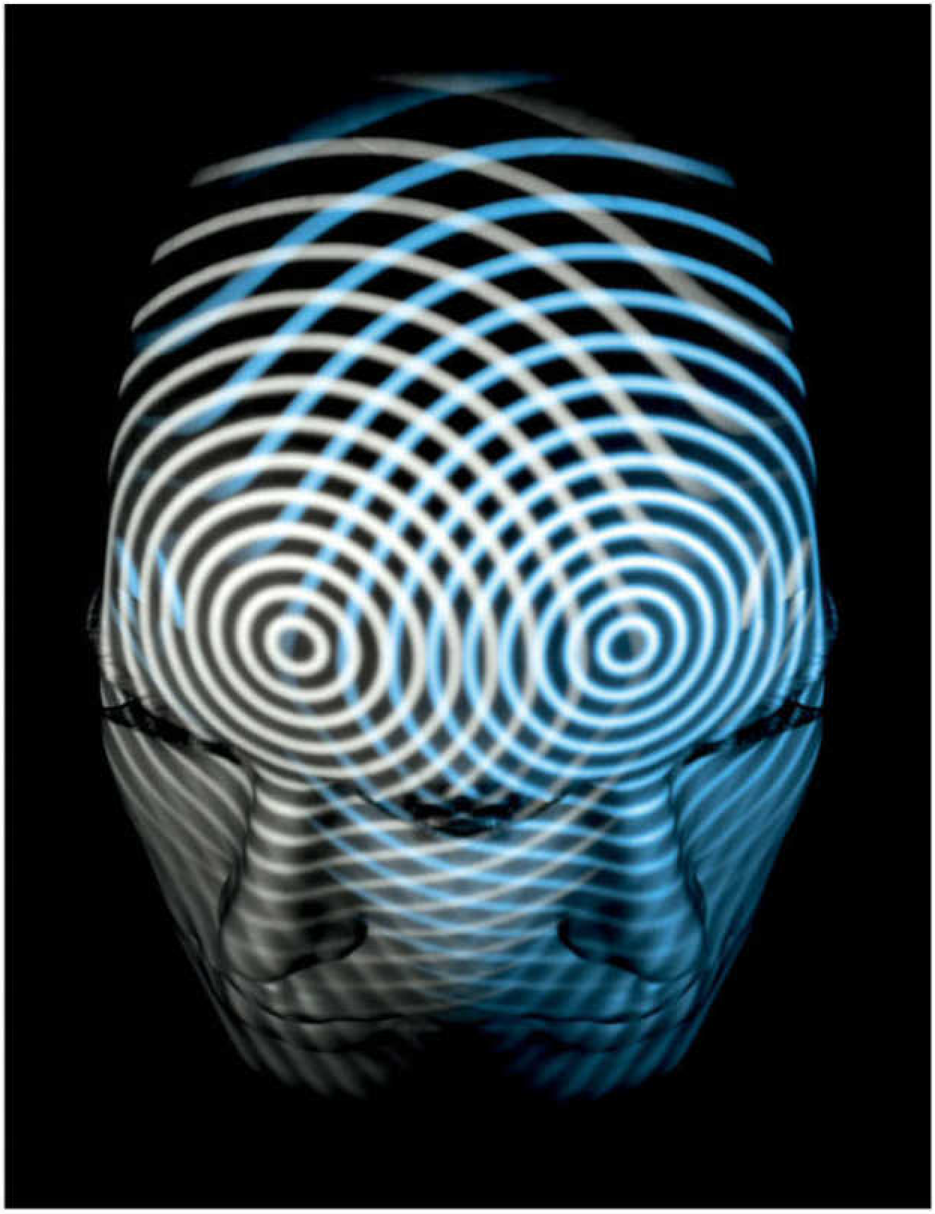
But the quantum world doesn't obey. When electrons or photons in a beam pass through the two slits, they act as waves and produce an interference pattern on the wall. The pattern with A and B open just isn't the sum of the two patterns with either A or B open alone, but something entirely different – one that varies as light and dark stripes.

Such interference effects lie at the heart of many quantum phenomena, and find a natural description in Hilbert's mathematics. But the phenomenon may go well beyond physics, and one example of this is the violation of what logicians call the "sure thing" principle. This is the idea that if you prefer one action over another in one situation – coffee over tea in situation A, say, when it's before noon – and you prefer the same thing in the opposite situation – coffee over tea in situation B, when it's after noon – then you should have the same preference when you don't know the situation: that is, coffee over tea when you don't know what time it is.

Remarkably, people don't respect this rule. In the early 1990s, for example, psychologists Amos Tversky and Eldar Shafir of Princeton University tested the idea in a simple gambling experiment. Players were told they had an even chance of winning \$200 or losing \$100, and were then asked to choose whether or not to play the same gamble a second time. When told they had won the first gamble (situation A), 69 per cent of the participants chose to play again. If told they had lost (situation B), only 59 per cent wanted to play again. That's not surprising. But when they were not told the outcome of the first gamble (situation A or B), only 36 per cent wanted to play again.

Classical logic would demand that the third probability equal the average of the first two, yet it doesn't. As in the double slit experiment, the simultaneous presence of two parts, A and B, seems to lead to some kind of weird interference that spoils classical probabilities.

Other experiments show similar oddities. Suppose you ask people to put various objects, such as an ashtray, a painting and a sink, into one of two categories: "home furnishings" and "furniture". Next, you ask if these objects belong to the combined category "home furnishings or furniture". Obviously, if "ashtray" or "painting" belongs in home furnishings, then it certainly belongs in the bigger, more inclusive combined category too.



PAUL WESLEY GRIGGS

But many experiments over the past two decades document what psychologists call the disjunction effect – that people often place things in the first category, but not in the broader one. Again, two possibilities listed simultaneously lead to strange results.

These experiments demonstrate that people aren't logical, at least by classical standards. But quantum theory, Aerts argues, offers richer logical possibilities. For example, two quantum events, A and B, are described by so-called probability amplitudes, alpha and beta. To calculate the probability of A happening, you must square this amplitude alpha and likewise to work out the probability of B happening. For A or B to happen, the probability amplitude is alpha plus beta. When you square this to work out the probability, you get the probability of A (alpha squared) plus that of B (beta squared) plus an additional amount – an "interference term" which might be positive or negative.

This interference term makes quantum logic more flexible. In fact, Aerts has shown that many results demonstrating the disjunction effect fit naturally within a model in which quantum interference can play a role. The way we violate the sure thing principle can be similarly explained with quantum interference, according to economist Jerome Busemeyer of Indiana University in Bloomington and psychologist Emmanuel Pothos of City University in London. "Quantum probabilities have the potential to provide a better framework for modelling human decision making," says Busemeyer.

The strange links go beyond probability, Aerts argues, to the realm of quantum uncertainty. One aspect of this is that the properties of particles such as electrons do not exist until they are measured. The experiment doing the measuring determines what properties an electron might have.

Hilbert's mathematics includes this effect by representing the quantum state of an electron by a so-called "state vector" – a kind of arrow existing in an abstract, high-dimensional space known as Hilbert space. An experiment can change the state vector arrow, projecting it in just one direction in the space. This is known as contextuality and it represents how the context of a specific experiment changes the possible properties of the electron being measured.

Mixed meaning

The meaning of words, too, changes according to their context, giving language a "quantum" feel. For instance, you would think that if a thing, X, is also a Y, then a "tall X" would also be a "tall Y" – a tall oak is a tall tree, for example. But that's not always the case. A chihuahua is a dog, but a tall chihuahua is not a tall dog; "tall" changes meaning by virtue of the word next to it. Likewise, the way "red" is defined depends on whether you are talking about "red wine", "red hair", "red eyes" or "red soil". "The structure of human conceptual knowledge is quantum-like because context plays a fundamental role," says Aerts.

These peculiar similarities also apply to how search engines retrieve information. Around a decade ago, computer scientists Dominic Widdows, now at technology company Grab in Bellevue, Washington, and Keith van Rijsbergen of the University of Glasgow, UK, realised that the mathematics they had been building into search engines was essentially the same as that of quantum theory.

It didn't take long for them to find they were on to something. An urgent challenge is to get computers to find meaning in data in much the same way people do, says Widdows. If › you want to research a topic such as the "story of rock" with geophysics and rock formation in mind, you don't want a search engine to give you millions of pages on rock music. One approach would be to include "-songs" in your search terms in order to remove any pages that mention "songs". This is called negation and is based on classical logic. While it would be an improvement, you would still find lots of pages about rock music that just don't happen to mention the word songs.

Widdows has found that a negation based on quantum logic works much better. Interpreting "not" in the quantum sense means taking "songs" as an arrow in a multidimensional Hilbert space called semantic space, where words with the same meaning are grouped together. Negation means removing from the search pages that shares any component in common with this vector, which would include pages with words like music, guitar, Hendrix and so on. As a result, the search becomes much more specific to what the user wants.

"It seems to work because it corresponds more closely to the vague reasoning people often use when searching for information," says Widdows. "We often rely on hunches, and traditionally, computers are very bad at hunches. This is just where the quantum-inspired models give fresh insights."

That work is now being used to create entirely new ways of retrieving information. Widdows, working with Trevor Cohen at the University of Texas in Houston, and others, has shown that quantum operations in semantic Hilbert spaces are a powerful means of finding previously unrecognised associations between concepts. This may even offer a route towards computers being truly able to discover things for themselves.

To demonstrate how it might work, the researchers started with 20 million sets of terms called "object-relation-object triplets", which Thomas Rindflesch of the National Institutes of Health in Bethesda, Maryland, had earlier extracted from a database of biomedical journal citations. These triplets are formed from pairs of medical terms that frequently appear in scientific papers, such as "amyloid beta-protein" and "Alzheimer's disease", linked by any verb that means "associated with".

"It may even offer a way towards computers being able to discover things for themselves"

The researchers then create a multidimensional Hilbert space with state vectors representing the triplets and applied quantum mathematics to find other state vectors that, loosely speaking, point in the same direction. These new state vectors represent potentially meaningful triplets not actually present in the original list. Their approach makes "logical leaps" or informed hypotheses about pairs of terms, which are outside the realms of classic logic but seem likely promising avenues for further study. "We're aiming to augment scientists' own mental associations with associations that have been learned automatically from the biomedical literature," says Cohen.

Going on a hunch

He and his colleagues then asked medical researchers to use the approach to generate hypotheses and associations beyond what they could come up with on their own. One of them, molecular biologist Graham Kerr Whitfield of the University of Arizona in Phoenix, used it to explore the biology of the vitamin D receptor and its role in the pathogenesis of cancer. It suggested a possible link between a gene called *ncor-1* and the vitamin D receptor, something totally unexpected to Kerr Whitfield, but now the focus of experiments in his lab.

Yet one big question remains: why should quantum logic fit human behaviour? Peter Bruza at Queensland University of Technology in Brisbane, Australia, suggests the reason is to do with our finite brain being overwhelmed by the complexity of the environment yet having to take action long before it can calculate its way to the certainty demanded by classical logic. Quantum logic may be more suitable to making decisions that work well enough, even if they're not logically faultless. "The constraints we face are often the natural enemy of getting completely accurate and justified answers," says Bruza.

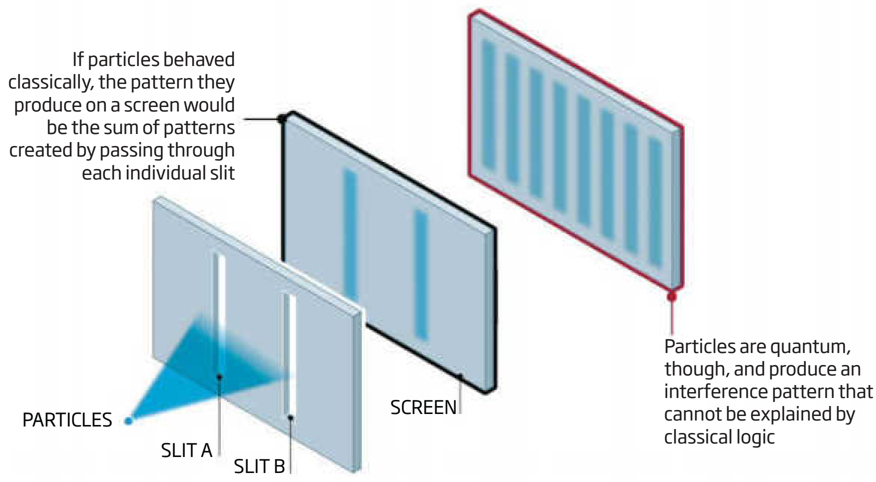
This idea fits with the views of some psychologists, who argue that strict classical logic only plays a small part in the human mind. Cognitive psychologist Peter Gardenfors of Lund University in Sweden, for example, argues that much of our thinking operates on a largely unconscious level, where thought follows a less restrictive logic and forms loose associations between concepts.

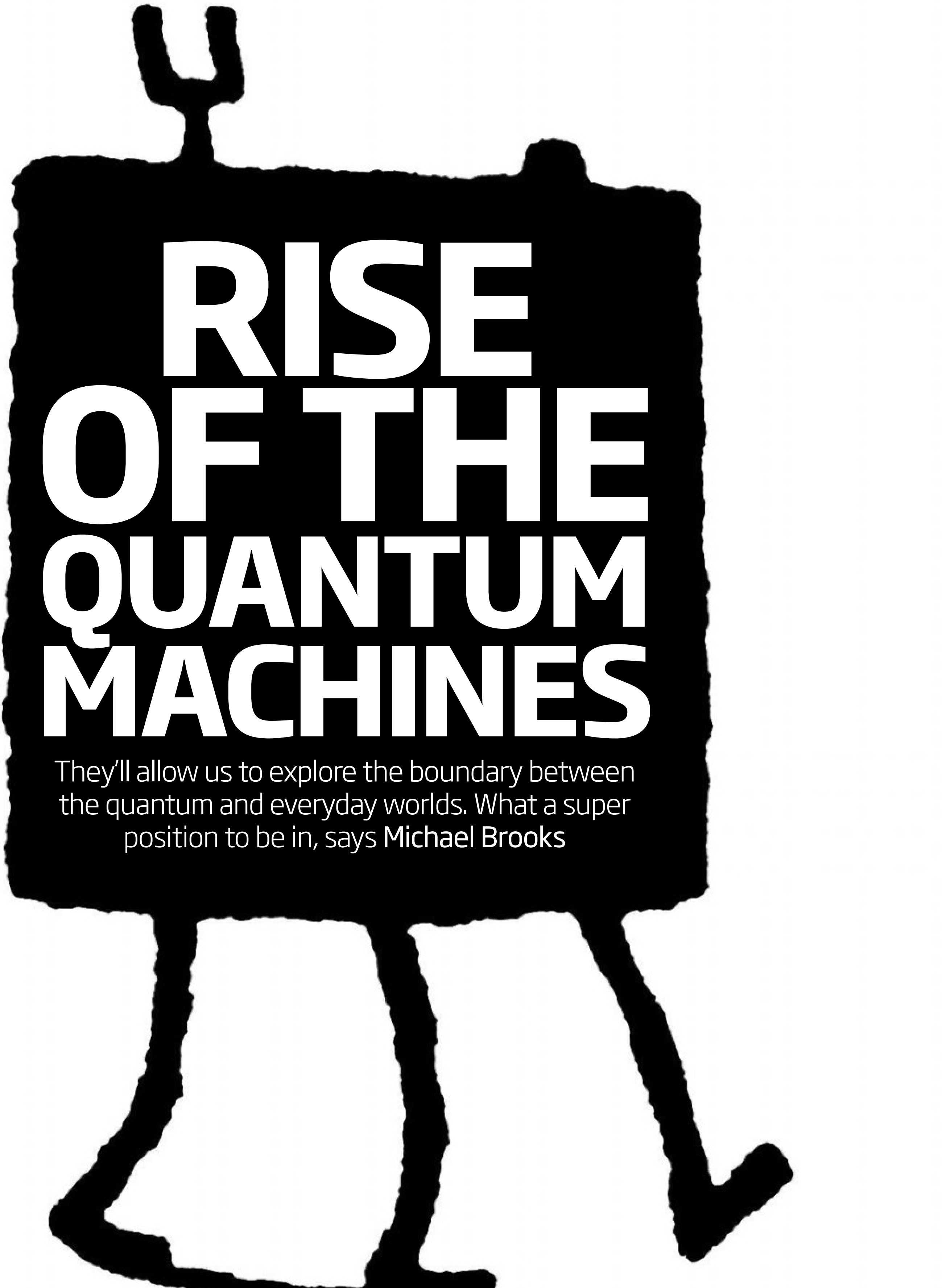
Aerts agrees. "It seems that we're really on to something deep we don't yet fully understand." This is not to say that the human brain or consciousness have anything to do with quantum physics, only that the mathematical language of quantum theory happens to match the description of human decision-making.

It does raise an interesting possibility, though. Perhaps humans, with our seemingly illogical minds, are uniquely capable of discovering and understanding quantum theory. To be human is to be quantum. ■

The famous double slit experiment

This experiment illustrates the difference between quantum and classical mathematics





RISE OF THE QUANTUM MACHINES

They'll allow us to explore the boundary between the quantum and everyday worlds. What a super position to be in, says Michael Brooks

CHAPTER FOUR

THE QUANTUM WORLD

QUANTUM theory is our most successful theory of physics. There is not one shred of experimental evidence that doesn't fit with its predictions. So why, if it ain't broke, is a growing number of researchers expressing a desire to fix it?

"Everything depends on whether you believe quantum mechanics is going to go on describing the physical world perfectly to whatever level you push it," says Nobel laureate Anthony Leggett, who studies the quantum world at the University of Illinois at Urbana-Champaign.

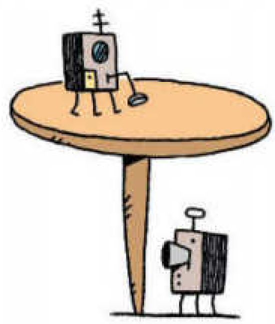
Leggett thinks it won't, that there are too many issues with quantum theory to think it anything more than an approximation of reality. "I'm inclined to put my money on the idea that if we push quantum mechanics hard enough it will break down and something else will take over – something we can't envisage at the moment," he says.

The question is, how hard can we push it? Experiments have never had the sensitivity to pinpoint a weak spot in quantum mechanics. But thanks to a breakthrough in 2010, that is beginning to change. A new swathe of experiments is coming onto the scene that should be up to the job. Welcome to the dawn of the quantum machines.

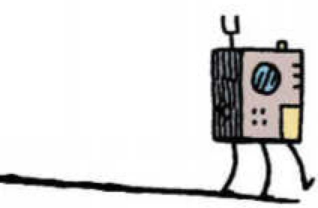
Such machines are promising to patch a gaping hole in every experiment that has ever been used to back up our view of the quantum world. Take the simple process of measuring a photon's spin. Thanks to the strange nature of the quantum world, it can actually be spinning in two directions at once, a phenomenon known as superposition. When we use a detector to measure the spin, however, the superposition disappears and we register a spin occurring in one direction or the other.

Quantum theory does not explain why this happens. "We don't really understand the measurement process," admits Stephen Adler at the Institute for Advanced Study in Princeton, New Jersey.

"These machines are promising to patch a gaping hole in every experiment ever made"



TOM GAULD



If you want to know how little we know, ask a roomful of physicists what goes on when we measure a particle's properties. All will be able to calculate the result of the measurement, but the explanation they give will differ wildly. Some will tell you that new parallel universes necessarily sprang into being. Others will say that, before a measurement is performed, talk of particles having real properties is meaningless. Still others will say that hidden properties come into play.

Another group will tell you that they deal with physics, not philosophy, and dismiss the question without giving you an answer. It has been thus for more than 80 years. "These conceptual challenges are still not understood at all," says Markus Aspelmeyer at the University of Vienna in Austria. "We're still right at the beginning."

Experiments investigating the quantum world have traditionally focused on what are known as interferometers. Researchers fire a single quantum particle, such as a photon, towards two apertures in a screen. Common sense says the photon has to go through one aperture or the other. However, as long as you don't measure which aperture it went through, something remarkable happens.

At a screen on the far side of the twin slits, an interference pattern forms. This can only occur if the photon goes through both slits at the same time and interferes with itself. In other words, as long as nobody is watching, the photon exists in two different places at once.

A measurement changes everything, however. If you set up the experiment so you can see which slit the photon goes through, the interference pattern disappears; the photon will have gone through one slit or the other, but not both.

The situation is analogous to one of the most famous thought experiments in physics, that of Schrödinger's cat. Here, an unfortunate feline is sealed in a box with a vial of poison and a lump of radioactive metal. When the metal emits a radioactive particle, it triggers a mechanism which will break the vial, killing the cat. But because the box is sealed, there is no measurement, and the particle remains in a superposition of emitted and not emitted. According to quantum logic, the cat is therefore alive and dead at the same time.

Schrödinger came up with this bizarre scenario to show that there was something wrong with quantum theory. There's no way, he said, that something as non-quantum as a cat can be in a superposition of alive and dead – whether it is being observed or not.

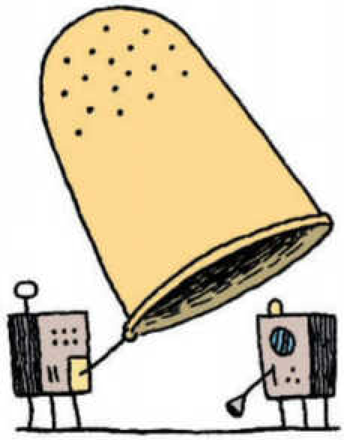
Others beg to differ. Markus Arndt at the University of Vienna has demonstrated that carbon-70 molecules can go through two slits at once, too. Though these ball-shaped molecules aren't quite as substantial as cats, they can nonetheless be seen through a microscope.

Tuning forks

Such interferometer experiments have been extremely useful in teaching us about what constitutes a measurement. It turns out that measurement doesn't have to be a deliberate action. Experiments have shown that if conditions allow an observer to infer which slit the photon went through – if, say, there were stray photons in the apparatus that could bounce off the test photon and thus give away its position – the superposition will disappear. This destruction, or collapse, of the superposition is known as decoherence.

Exploring when decoherence occurs has allowed us to find out more about what makes the quantum world tick. However, there is still an enormous amount we don't know. And here we are running up against a difficult logistical problem.

Pushing at the boundary between the quantum world and that of classical physics means using ever larger molecules to see where decoherence destroys superposition. But the bigger the molecule, the harder it is to control outside forces and stop them from disrupting the molecule's delicate quantum state. For large molecules, uncontrolled decoherence effects rule, spoiling the very effect you want to measure. ›



"Building the first quantum machine has taken years of painstaking work"

This is where the quantum machines come in. At the moment, they don't look like much. The biggest of them is little more than a sliver of aluminium about 50 micrometres in length. It functions as an oscillator, something like a quantum tuning fork. The key is its mass. Even the relatively large clusters of carbon atoms Arndt sends through his interferometer are lightweights compared with the mass that quantum machines will have (see "Mass matters", opposite). "They operate at masses which are orders of magnitude larger than even the most massive clusters we are using," Arndt says.

This is useful because the mass of a quantum object plays an important role in several alternative explanations of how the quantum world works. For several years now, Dirk Bouwmeester at the University of California, Santa Barbara (UCSB), has been building a quantum machine to test an idea put forward by mathematician Roger Penrose of the University of Oxford. In 2003, Penrose suggested that gravity might cause superposition collapse. If this were so and heavy, or extremely close, objects were found to be unable to sustain being in two places at once, this could help us understand the inner workings of the quantum world and the measurement problem.

Testing such ideas, however, will require quantum machines of almost incomprehensible sensitivity. The necessary apparatus involves mirrors 10 micrometres across that weigh just a few trillionths of a kilogram. It's a difficult experiment, Bouwmeester says, and may yet take another few years to complete.

His experiment calls for the mirrors themselves to be put into a superposition – in other words, in two different places at once. Verifying that, however, will mean measuring how much they are deflected by a photon that is itself in a superposition. If Bouwmeester's calculations are correct, the deflection will be less than a billionth of a millimetre.

Though Bouwmeester's machine is years away from telling us anything, another quantum machine is up and running: the aforementioned quantum tuning fork, created by Aaron O'Connell and his colleagues at UCSB. In 2010 they reported that they had managed to get it to rest peacefully in its ground state.

This was not easy to achieve – it has taken years of painstaking work – but it means that, like an atom, the oscillator is in a state in which it will absorb energy only in distinct incremental amounts, or quanta. Its movements are so minute that adding a single quantum of energy will affect its motion or change its position. And, also like an atom, it can exist in a superposition.

O'Connell's team have managed to put their sliver of aluminium into a superposition of oscillating and not oscillating. They did this by putting the oscillator next to a tiny electric circuit that exhibits strange quantum behaviour, such as forcing current to move through it in two different directions at once. Being in the vicinity of this strange behaviour made the oscillator pick up similarly strange quantum states.

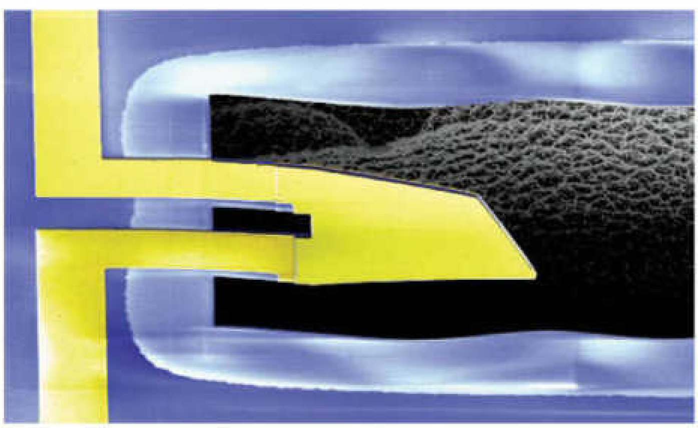
The experiment is a move towards a genuinely macroscopic case of something being in two places at once. If we can get there, it would be the mechanical analogue of a cat being alive and dead.

There is still some way to go before we are quite ready to resolve the paradox of Schrödinger's cat. Though the oscillator is large enough to see with the naked eye, the difference between its static and oscillating positions is tiny, just 10^{-16} metres. To see a meaningful deviation from standard quantum mechanics, the separations would have to be at least an order of magnitude larger – possibly a lot more, Arndt reckons.

Nevertheless, says Arndt, the breakthrough is "really stunning". He, like everyone else, is excited to see what might come of this new age of quantum machines. "The first key applications are improved tests of the foundations of quantum physics," he says.

This could be done by watching the behaviour of such oscillators under various conditions, such as different temperatures and oscillation frequency. Placing it next to different kinds of quantum circuits and using various ways of protecting it from the environment might also expose hitherto unseen quantum behaviours. Because the quantum machine is so unusually large, it

AARON D. O'CONNELL AND ANDREW N. CLELAND, UC SANTA BARBARA



One way to test quantum theory is with this sliver of aluminium

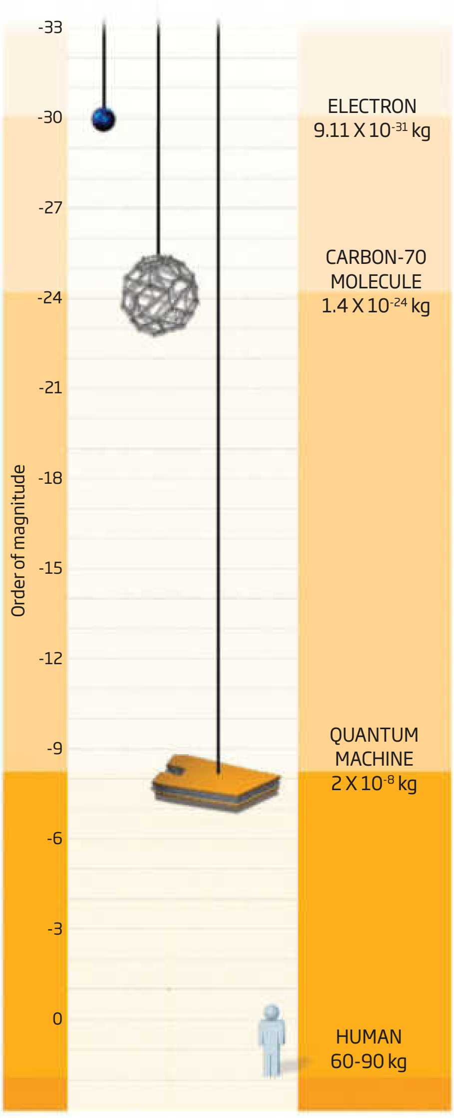
is possible that it will do things that quantum theory does not predict.

O'Connell's group has not seen any deviations from the basic Schrödinger equation that describes the quantum world yet. "It seems to work just fine, from what we've seen so far," says John Martinis, who leads the team.

But these are only the first of a new wave of tests. In 2009, Adler and Angelo Bassi of the University of Trieste in Italy pointed out that a quantum machine could test a proposal made by a group of physicists at Trieste more than a decade ago: that the Schrödinger equation is

Mass matters

Quantum machines are orders of magnitude more massive than anything that has demonstrated quantum behaviour before, such as electrons and molecules



only an approximation of a deeper theory, and that adding a term to it that describes random noise might make it more accurate.

In this "continuous spontaneous localisation" model, the random noise is linked to the mass of the objects involved and it is this rather than the measurement process that causes the decoherence. Adler and Bassi have shown how this could be tested – and how it might reveal something new about the universe.

What is this noise? Electromagnetic hiss? Chaotic Brownian motion of the particles? Something entirely unknown to physics? It's not clear, Adler says, but the latter possibility is the most likely if their model turns out to be right. "There could be a new cosmological field," he says. "At present it's not detectable and it's going to be very hard to detect."

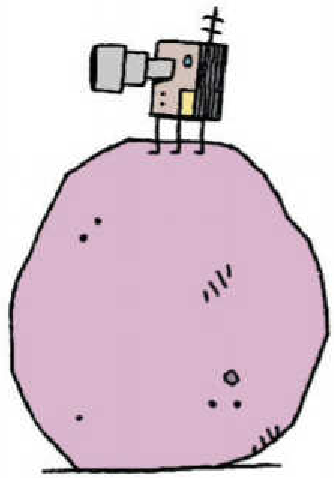
The idea of a new field permeating space sounds far-fetched, but Bouwmeester reckons we shouldn't rule anything out. "We know a lot but we are far from having understood everything," he says, pointing to the surprising conclusion from astronomical observations that the universe is filled with dark energy and dark matter. "There is room for some very big surprises."

A deeper theory

And, as Adler points out, it's no more fanciful an idea than saying quantum stuff is inherently incomprehensible – that it is a matter of mysterious measurement processes or new universes forming every time a particle is detected to be doing one thing and not another. "Make the superposition collapse a real process and you don't have to explain it away through interpretations," he says.

Another test on the horizon has been devised by Charles Wang and his colleagues at Aberdeen University in the UK. This quantum machine is not a microfabricated piece of aluminium, but a gas of super-chilled atoms designed to check whether the quantum uncertainty principle is responsible for the collapse of superpositions.

First formulated by Austrian physicist Werner Heisenberg, the uncertainty principle has become a central tenet of quantum theory. It says that empty space is fizzing with particles that pop in and out of existence due to uncertainties in the energy of the vacuum. In 2000, Ian Percival of Queen Mary, University of London, suggested that these ghostly entities could affect the way subatomic particles form superpositions and interact with each other.



Wang and colleagues are tightening and – where technology allows – testing this idea. They propose that the energy inherent in empty space will affect the movements of an ultra-cold gas of atoms, called a Bose-Einstein condensate. Though they are still working out the exact implications, Wang thinks this approach could reveal a previously unconsidered influence on the quantum world.

Any, or none, of the schemes could change the way we view the quantum world and the way we interact with it. If mass and gravity turn out to be affecting quantum behaviour, that might tell us something about the elusive theory of quantum gravity that physicists are trying so hard to create (see "Where worlds collide", page 104). Penrose reckons we will eventually be forced to combine Schrödinger's equation describing quantum particles, an understanding of the measurement process, and the principles of Einstein's theory of gravity into one theory, and that each of these three aspects of reality will then be seen as nothing more than an approximation to a deeper fundamental truth.

It is a tantalising prospect - especially in an age of big physics. Bouwmeester is excited that, while so much public attention is focused on the high-energy potential of the Large Hadron Collider at CERN, near Geneva, Switzerland, the quantum machines might tell us something more fundamental about the universe. "Most theorists would probably not expect big things to come out of the type of experiments we are doing," he says. "They probably think we have to go to huge energies to resolve such fundamental issues."

Though the road ahead looks to be a bumpy one, everyone is excited about quantum machines opening up an alternative vista. It's a chance to probe the quantum world with a "new and unexplored regime", Aspelmeyer says. "This is really testing quantum physics in its extremes." ■

Honey, I shrunk the proton

Curious goings-on at the heart of the atom may point to an unknown force of nature. Jon Cartwright reports

ANDREW HALL

ONE quadrillionth of an inch. If you lost that off your waistline, you wouldn't expect a fuss. Then again, you are not a proton.

Until recently, it was unthinkable to question the size of the proton. Its radius is so well known that it appears on lists of nature's fundamental constants, alongside the speed of light and the charge of an electron. So when Randolf Pohl and his colleagues set out to make the most accurate measurement of the proton yet, they expected to just put a few more decimal places on the end of the official value. Instead this group of more than 30 researchers has shaken the world of atomic physics. Their new measurement wasn't just more accurate, it was decidedly lower. The proton had apparently been on a diet.

Freak results do turn up from time to time in physics. Witness the furore in 2011 over the neutrinos that appeared to travel faster than light and whose unbelievable powers were traced months later to a dodgy cable connection. Yet the proton puzzle first came to light in 2009, and several experiments later we are running out of ways to explain how the particle can have seemingly shrunk. No experimental flaws have been found. The theory has been checked and rechecked. Physicists are now facing the possibility that an unknown phenomenon is at work. Has a big problem with a tiny particle revealed a brand new force of nature?

"As Sherlock Holmes would put it, 'Once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth'," says Itay Yavin, a particle physicist at McMaster University in Hamilton, Canada. "That is new physics."

It wouldn't be the first time we have had to rethink the physics inside the atom. Rewind 100 years and the atom is pictured as a miniature solar system, with negative electrons as planets orbiting a sun-like bundle of positive protons and neutrons at the centre. Holding it all together is a force – not the gravity that influences the whole solar system, but electromagnetism.

After quantum mechanics emerged in the 1920s, electromagnetism came to be seen as particles of light – photons – hopping from electrons to protons, and vice versa. Quantum theory did a fair job of predicting the energy of various electron orbits, but on the fine details it proved a little too crude. So by the end of the 1940s, a more refined theory had taken over: quantum electrodynamics, or QED for short.

QED showed that to predict orbital energies precisely, you had to consider all the ways an electron could emit photons. For instance, an electron might emit a photon then immediately reabsorb it. Or it might emit two photons at once. Or, en route to the nucleus, a photon might temporarily split into a particle-antiparticle pair. In fact, QED showed that there are infinite possibilities, all of which help to determine the electron orbits by varying amounts.

To predict the energy of a particular orbit, you don't need to add up all these possibilities – you would be there forever. Instead, by considering the biggest QED contributions first, then the next biggest and so on, you can progressively make your prediction more accurate. QED is like a box of measuring tools: to get a rough measurement you might start off with a metre stick, but to improve precision you might get out a centimetre rule, and finally a pair of callipers.

Today QED has grown into one of science's most revered theories, largely thanks to the precision with which it can predict orbital energies – in some cases to just a few parts in a million. But physicists are never satisfied. "Just because a theory is good at explaining all current measurements, doesn't mean it's the 'true' one," says Pohl, who works at the Max Planck Institute for Quantum Optics in Garching, Germany.

Pohl's group set out to develop even more precise QED predictions, to see if they would still withstand experimental scrutiny. But it wasn't a case of simply getting out the QED callipers. According to quantum mechanics, particles such as electrons and protons are vague creatures, more like clouds of charge than solid objects. This means that an electron can even veer inside a proton, where it will feel less of the electromagnetic attraction it feels on the outside. The net result is that the proton's size subtly changes the electron's energy.

Getting the finest QED predictions, then, requires taking into account the proton's size. In fact, QED itself offers a way to size up the proton, by making use of the hydrogen atom and a difference in the energies that its lone electron can take. First measured in 1947 by US physicists Willis Lamb and Robert Retherford, this shift is called the Lamb shift.

All you have to do is predict the Lamb shift via QED, measure its actual value, then put any "error" down to the size of the proton. Since the late 1990s, experimenters have used this trick to nail down the proton radius to within 0.1 per cent of 0.877 femtometres – about one 10-billionth the thickness of a human hair.

It's an impressive feat, but not so good for testing QED. The trouble is that the energy shift due to the proton size is about the same size as the QED corrections under test, a bit like using a ruler with millimetre divisions to measure something that's about a millimetre long and expecting the result to be accurate. What's needed is an atom in which the proton has a much bigger influence on the Lamb shift.

Enter a very different kind of hydrogen atom: "muonic" hydrogen in which the electron is replaced by its weightier cousin the muon. Muons have the same electrical charge as electrons, but they are 200 times heavier. As a result, the muon orbits hydrogen's central proton 200 times closer than an electron and therefore spends longer inside the proton's cloud. This means that the proton has a bigger effect on the Lamb shift in muonic hydrogen than normal hydrogen. "You can measure the proton radius in muonic hydrogen 10 times better than anywhere else," says Pohl.

Muon mystery

To test their idea, Pohl's group set off for the Paul Scherrer Institute (PSI) in Villigen, Switzerland. Here, a special low-energy particle accelerator fed muons into hydrogen gas, so that they swapped places with the electrons normally orbiting the hydrogen atoms. It was a laborious process, and it wasn't until seven years later, in June 2009, that the Lamb shift finally appeared in their results.

It wasn't where Pohl's team expected it. The result implied that the proton radius was 0.841 femtometres, some 4 per cent lower than in regular hydrogen. "We were running around for four days in a manic depression," says Pohl. "Like, is it a background signal? Or could it really be?"

Others were just as shocked. Suddenly, precision testing of QED had been yanked from the spotlight and replaced with a bit-part actor – the proton's size. "My first reaction was doubt – it was a new technique, there was easily something going wrong," says Jan Bernauer at the Massachusetts Institute of Technology. "It was clear, pretty soon after, that this was not the case."

"Electrons and protons are vague creatures, more like clouds than solid objects"

Because the proton has such a big effect in muonic hydrogen, Pohl and his colleagues were able to measure the radius accurately and so their measurement was unlikely to be wrong. But there is little urge to point the finger at the measurements based on regular hydrogen, either: they have back up. Since the 1950s, physicists have fired electrons at a stationary hydrogen atom to measure the proton's size (see "Proton problem", below right). By angling the gun towards the proton from either side, they can detect when the electrons begin to scatter, and thereby mark out the proton's boundary.

Electron-scattering measurements of the proton radius were never accurate enough for precision tests of QED. Still, at least three independent measurements have been made, all of which support the value of the proton radius extracted from the Lamb shift in regular hydrogen. Bernauer has performed some of them and is sure they are correct. He has equal faith in the PSI group's work. "I'm convinced there's nothing wrong with their experiment," he says. "It's really clean. Either you get something out, or you don't."

Perhaps the protons are actually changing size. According to quantum chromodynamics, the theory that describes the inner workings of a proton, the idea isn't totally implausible. It says that a proton can sometimes distort when receiving a photon from an orbiting electron – a bit like how the oceans gravitate towards our orbiting moon to form tides. Such a distortion can unsettle the normal hopping of photons from electrons or muons to protons, and in turn affect the Lamb shift.

In 2012, theorists Judith McGovern and Michael Birse at the University of Manchester in the UK decided to see if such distortion could explain away the proton puzzle, but found that it was dozens of times too feeble. "It wasn't well known before, and some people had speculated that it might conceivably be large enough," says McGovern. "To my mind, we've pretty convincingly shown that it can't."

The mathematics of QED has also come under scrutiny, but here an answer seems even less likely. QED has established itself as such a bedrock theory that one of its creators, the US theorist Richard Feynman, once called it "the jewel of physics". In any case, says Krzysztof Pachucki at the University of Warsaw in Poland, the calculations have been repeated by hundreds of scientists worldwide. "People tend to ask, are the QED calculations wrong?" he says. "But for muonic hydrogen, the calculations are very elementary. It's hard to believe there's a mistake."

As if to rub salt into the wound, in January 2013 Pohl and colleagues published a new

> "To rub salt into the wound, the new, smaller, measure of the proton radius is twice as accurate"

measurement that almost doubles the accuracy of their smaller value of the proton radius. Now, with all traditional avenues of explanation blocked, there seems to be only one route left: physics beyond the current standard model of particle physics.

A fresh force

Ever since the standard model was formulated in the early 1970s, physicists have known it isn't the last word on particles and forces. Yet evidence of new phenomena has proved frustratingly hard to come by. Has the orbit of muons in and around protons revealed clues where other experiments, even those at powerful accelerators, have failed?

There is already a good reason to think something is amiss with muons. For the past 15 years, physicists at Brookhaven National Laboratory in New York have been measuring the muon's "g-factor", an abstract parameter that is related to another fundamental quantum property of particles called spin. Like the Lamb shift, the g-factor is predicted by QED, and for the electron this prediction agrees with experiment to a whopping 10 significant figures, making it the best agreement between theory and experiment in all of physics. However, that's not the case for the muon's g-factor: this disagrees with predictions so much that there's a 99.9 per cent chance that new physics is at work.

Combine these odds with the proton puzzle, and the muon appears to be telling us something. Theorists believe that a new force could be binding the muon extra tightly to the proton. Such a force would skew the Lamb shift in muonic hydrogen, making the proton appear smaller than it actually is. But modelling such a force is like trying to satisfy an impossibly fussy customer.

For starters, the force needs to affect muons much more than electrons. Next, it needs to be strong enough to account for the proton puzzle, but not so strong as to override the dominant force of electromagnetism in QED. Finally, there is the thorny matter of neutrinos. These fleeting particles hardly interact with other matter, so there cannot be any extra force acting on them we are not aware of already. "The moment you touch neutrinos, your model is dead," says theorist Maxim Pospelov at the University of Victoria in Canada.

Despite these tough constraints, various new forces that would fit the bill have been proposed. In 2011, Yavin and his colleague David Tucker-Smith at Williams College in Williamstown, Massachusetts, came up with a force that could explain not just the proton puzzle, but the g-factor discrepancy too. The force would be carried by a new particle with about one-tenth the mass of the proton.

Later in 2011, Pospelov and others proposed a more intriguing force-carrier: the dark photon. This particle would be invisible to humans, but it would act as the glue that binds dark matter, an elusive substance thought to make up about 85 per cent of all matter in the universe. Dark photons are already being searched for in the debris of certain particle smashers, such as at Jefferson Laboratory in Newport News, Virginia.

Or perhaps the answer isn't a new force at all. In 2013, Li-Bang Wang and Wei-Tou Ni at the National Tsing Hua University in Taiwan suggested that the muon might be bound tighter to the proton by some extra gravity leaking in from another dimension. That would help to explain the errant proton radius, though not the g-factor result.

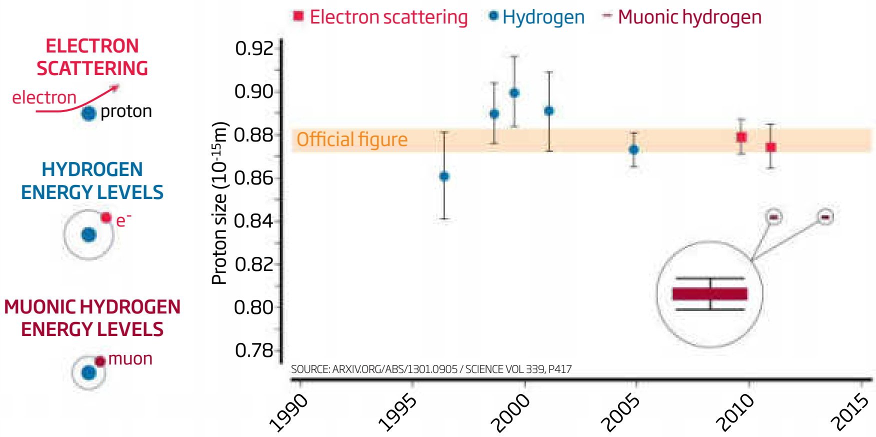
Yet all of these explanations have something missing: elegance. "I find them all a little contrived," says Pospelov. "The explanations are not very economical, not very natural."

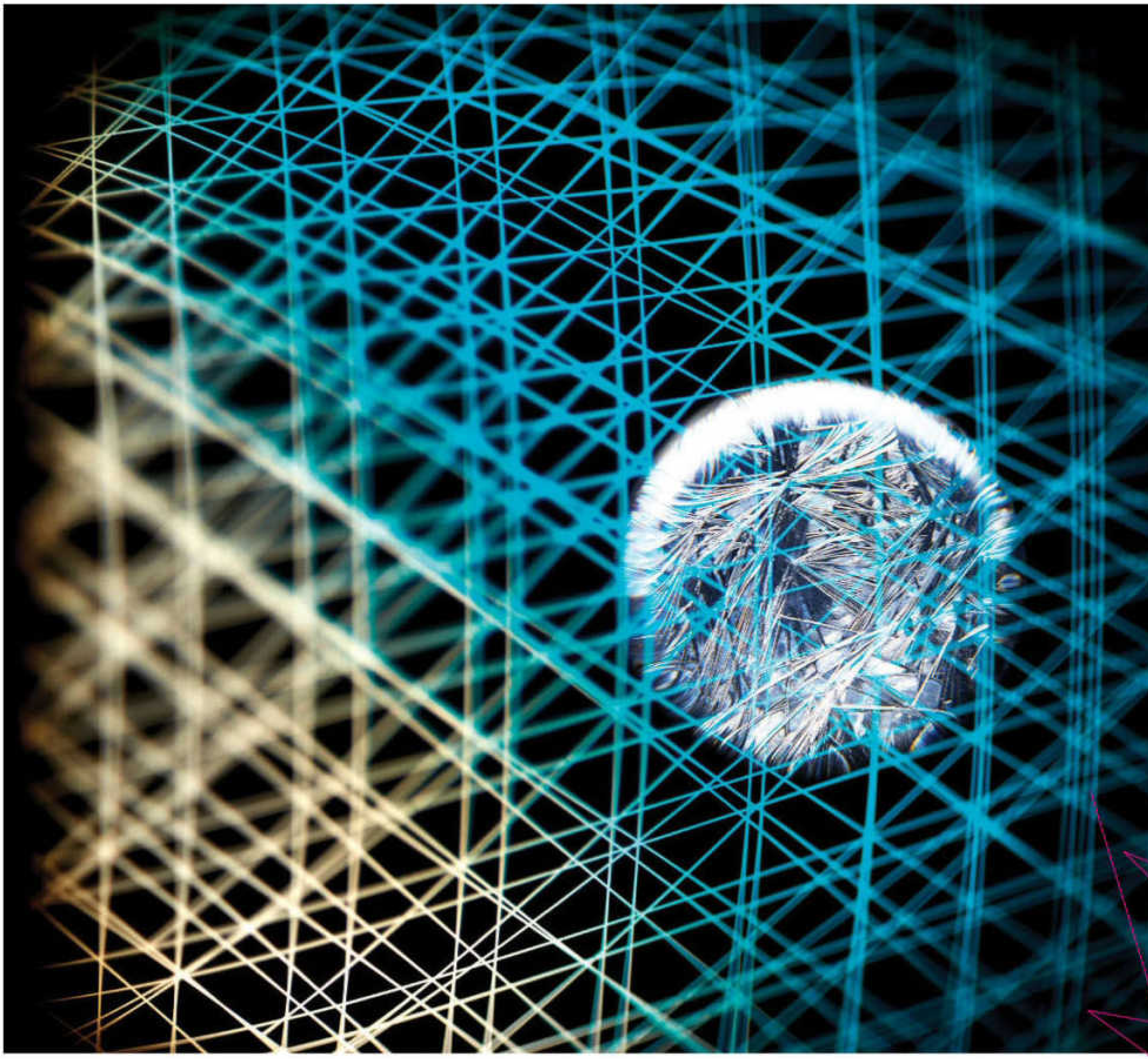
And this is the problem with the proton puzzle. Whichever way physicists turn, the path looks as if it will lead them right back to where they started. There is some hope in the next round of experiments at PSI, which employ the scattering method to determine the proton radius, using muons in place of electrons. In principle, this is the final piece of the jigsaw and will be able to show whether the issue is with the mathematics, or with the proton itself. But the results are yet to come in.

"None of the explanations seems likely, which is what makes the puzzle so interesting," says Ron Gilman at Rutgers University in New Jersey. "It's like a horse race – but not only can you not tell which horse is likely to win, you're worried none of them will even finish." ■

Proton problem

Three techniques have been used to measure the proton's radius, but the most accurate way – using muonic hydrogen – gives a much smaller result than the others

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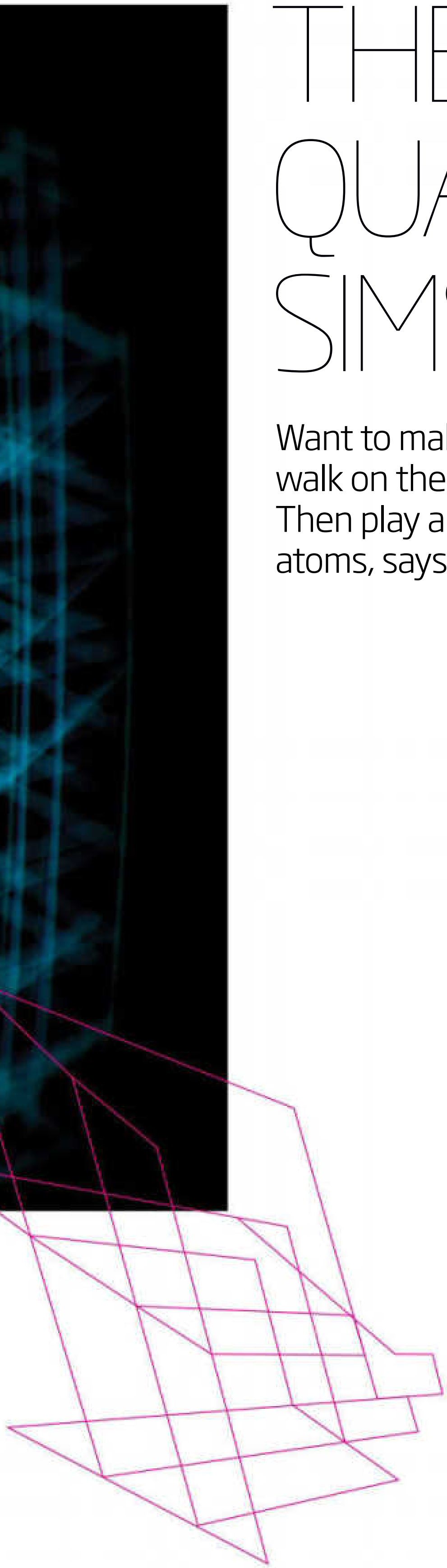


THE QUANTUM SIMS

Want to make a superconductor, or walk on the surface of a neutron star? Then play around with ultracooled atoms, says **Michael Brooks**

STEP into Martin Zwierlein's lab and you step out of this world. Not quite literally, but there's a lot within its walls that you won't find outside its doors. On one day you might find his team playing with a quark-gluon plasma, a searingly hot substance that only naturally existed in the universe's first split second. Drop by the next week, and they will be messing about on the surface of a neutron star. Sometimes they'll even be creating stuff that has never been made anywhere in the universe.

But there is more to this than physicists at play. The stuffs that the researchers at the Massachusetts Institute of Technology are studying have something in common, something they share with a lot of everyday materials: they are fiendishly, inscrutably, impossibly complex. Swipe the touchscreen of your mobile phone and, as an electrical pulse passes from your finger and brings it to life, a random mosaic of chemical bonds breaks and reforms. How does that work in detail? Or how exactly does that magnet keep your shopping list stuck to the refrigerator? Or what makes some materials lose all electrical resistance below a certain temperature and become superconductors? Get that to happen at close to room temperature, and our world would be revolutionised: we would have a way of storing energy for ever, for free.

If only. Trying to model the myriad effects and influences in all these situations soon leaves us floundering. "We know the ingredients: they're super-easy to write down," says Zwierlein. "But give that to a computer and it will explode."

That's why his group and a few others dotted around the globe are working on plan B. They hope to get straight to the heart of the matter – by unleashing the full power of the quantum simulator.

Quantum simulation is an idea first floated in a lecture given in 1981 by the revered US physicist Richard Feynman. He pointed out that conventional, classical computers are a window on the world with a restricted view. They demand ruthless logic and concrete instructions: if *x*, then *y*; move this binary digit here; add these two numbers; subtract; print, that kind of thing. Quantum physics, on the other hand, is all maybes and probablys. Particles have undefined locations or spins, and can be spookily influenced by a legion of other ghost particles around them.

How can we model such countless effects and avoid meltdown? Feynman answered in typically ebullient fashion: "Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical." Three decades later, though, we're not particularly far on in our efforts to build a general computer that works according to the precepts of quantum physics. That is largely because of huge technical difficulties.

But to simulate some quantum problems it turns out that you don't actually need anything we would recognise as a conventional computer. In fact, you don't need to actually calculate much at all. That's because the complex rules and influences of quantum physics work in the same way for all particles – for atoms, electrons, whatever. To unlock the secrets of an intransigent quantum system, all you need is to make a more pliant, physical mimic.

Atomic egg boxes

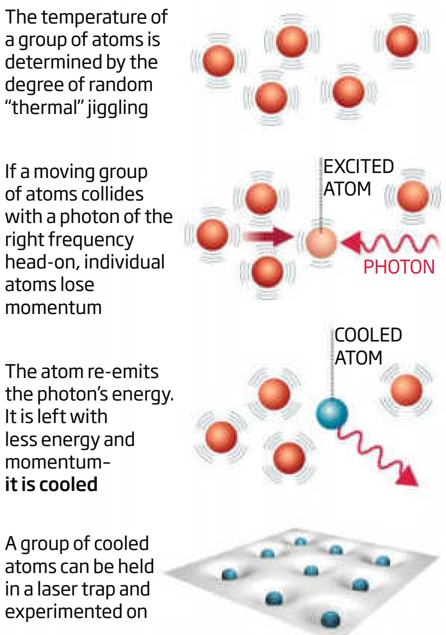
There are several candidates: photons of light, or trapped ions, for example. Perhaps the most effective quantum simulator, though, is an ultracold atomic gas. A criss-cross of laser beams confines a million or so atoms in a landscape of neighbouring hollows that is rather like a quantum egg box. The action of the lasers cools down the atoms' normal thermal jiggling so they have a temperature just billionths of a degree above absolute zero – cold enough for their behaviour to be › cleanly described using the laws of quantum mechanics (see diagram, below).

It's a fiddly technique that we're just beginning to master. "There's an explosion of people with the ability to locate, measure and control individual atoms," says Ian Spielman of the National Institute of Standards and Technology in Gaithersburg, Maryland. Once the atoms are becalmed, you can use further pulses of light to change their environment and behaviour, for example pushing some of them to sit in a "superposition" between two neighbouring quantum states. "You can tickle them in all kinds of ways," says Zwierlein.

The gentle laser massaging allows you to conjure phenomena beyond a classical computer's ken – such as what happens in some extreme astrophysical environments. "With the right combination of lasers you can create scenarios like those in neutron stars," says Kai Bongs, who runs a quantum simulation lab at the University of Birmingham, UK. Neutron stars pack in more than the mass of our sun in a ball just 10 to 15 kilometres across. They form when the cores of certain stars collapse in on themselves during their final supernova explosion. The remnant's super-strong gravity and magnetic fields make for extremely complex interactions – far too complex for any conventional computer to model in detail.

Cooling with light

Lasers can be used to cool atoms down to within a fraction of a degree above absolute zero



In February 2012, Zwierlein's group recreated a neutron star within a gas of ultracold lithium-6 atoms. Thanks to the value of their quantum-mechanical spin, these atoms, like neutrons, belong to the class of particles known as fermions. Quantum rules forbid fermions from getting too close to each other. The atomic simulation showed how this prevented the atoms condensing beyond a certain point – reproducing how the collapse of a neutron star stops beyond a certain density.

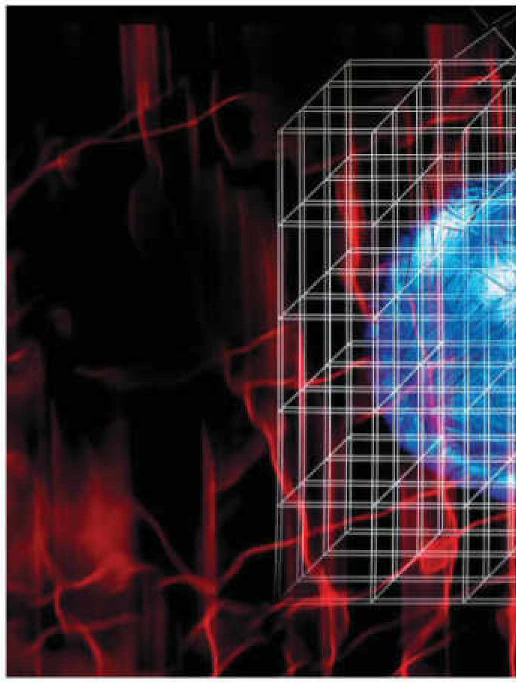
We can get similar lab-based insights on the quark-gluon plasma, the hugely energetic state of matter that existed shortly after the big bang and which gave rise to today's particles. Experiments at vast accelerators at Brookhaven National Laboratory in New York state, and latterly at CERN's Large Hadron Collider near Geneva, Switzerland, have succeeded in recreating the real thing by bashing together ions of heavy atoms such as lead with such force that they disintegrate.

Zwierlein and his team's "Little Fermi Collider" aims to create exactly the same physics, but using more manageable particles at a fraction of the temperature and price. Their first results, published in 2011, were encouraging. Magnetic forces drove together two clouds, each of around 100,000 lithium atoms. They first repelled, then repeatedly bounced off each other and finally merged – at an extremely slow rate precisely matching that predicted by theoretical models of the quark-gluon plasma.

Hunting the Higgs

And how about the grandest particle prize of all, the Higgs boson? In 2012 Immanuel Bloch of the Max Planck Institute for Quantum Optics in Garching, Germany, and his team observed a wave of energy in a cloud of ultracold rubidium-87 atoms that exactly mimicked the mathematics of a Higgs boson. If that sounds a little weak, bear in mind that no one at CERN has ever actually seen a Higgs boson either, just the energy signature of particles thought to derive from it. In effect, Bloch's team had spotted an ultracold analogue of the elusive particle months before the real thing was spotted at CERN in July 2012.

These first successes suggest that quantum simulation really does, as Feynman hoped, provide a viable way of teasing out the behaviour of any quantum system, however

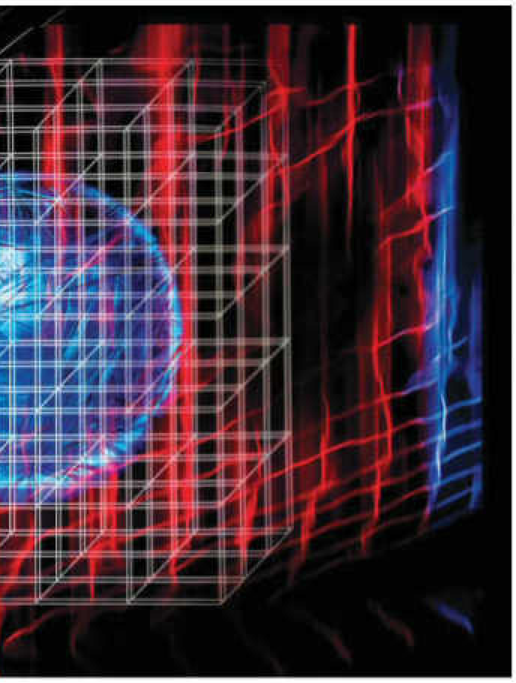


complex. "Quantum simulation is beginning to come of age," says Spielman. And that means it might get to grips with some far less esoteric quantum problems.

One of those is magnetism. Magnetism arises when the spins of atoms inside crystals of metals such as iron align in particular ways, but the details are complex, hindering the search for new magnetic materials. Christopher Monroe and his team at the University of Maryland, Baltimore, are working on simulating the transition to a magnetic state using trapped ions. Their experiments involve 26 ions so far. A dozen more and they will have reached the limit of what is calculable with a classical computer.

With luck the lessons can be applied to other practical quantum systems – that pattern of bond formation in your touchscreen, for example. The interest in magnetism is just a stepping stone to something bigger, too. That's because of clues contained in a set of equations known as the Hubbard model. This describes how materials move between insulating and conducting behaviour, and it suggests a key to the enigma of high-temperature superconductivity. "The model predicts a magnetic phase that is supposed to kick in before the superconductivity sets in," says Bongs.

Superconductors are materials that lose all resistance to electricity when cooled below a certain temperature. Materials that pull off this trick close to absolute zero have been known about for a century, and pretty well understood for half of that. But materials that do the same thing at higher temperatures remain a mystery. A number of "cuprate" superconductors become superconducting at



temperatures near 140 kelvin, around halfway between absolute zero and room temperature.

The idea is that, by setting a lattice of atoms to behave according to the Hubbard model's equations, we can then twiddle the knobs of the simulation – by altering the magnetic field, how densely the atoms are packed, the ratio of atoms with different spins, and so on – and look for behaviours that resemble the onset of magnetism and superconductivity. Do that, and in theory it's just a case of fiddling about with the same parameters to show us how we might produce the same effects at higher temperatures.

In practice, it's not that simple. For a start, says Bloch's colleague Ignacio Cirac, the temperature of our existing ultracold simulators is still too high. That seems harsh for an environment that, at a few billionths of a degree above absolute zero, is the most frigid we know. This is not about absolute physical temperature, however. Rather, it is about "Fermi temperature" – roughly speaking, the temperature at which half of a conducting material's free electrons are free enough to wander about and transport energy. Every superconducting material has a set temperature when this happens, and it is usually many times higher than the temperature above which a material ceases to superconduct.

A perfect simulation requires that the ratio of Fermi temperature to working temperature in the ultracold gas is about the same as the ratio of the material's Fermi temperature to its superconducting temperature. To get the ratio right, the working temperature of the gas needs to drop by a further factor of 5 or so. That's a tough ask. Lowering the temperature means the atoms must interact more. Like the neutrons of a neutron star, electrons are fermions, so they don't like getting too up close and personal – and the same applies to a fermionic gas designed to simulate them.

That means workarounds are needed. "People are getting really creative," says Zwierlein. His team, for instance, has tested an idea dreamed up by Peter Zoller's team at the University of Innsbruck, Austria: mix fermions with more sociable bosons in the simulator. In such a scheme, the fermions stay bound in the egg-box lattice, while the bosons roam, interact and lose energy through collisions, reducing the overall temperature.

Zwierlein's gas of fermionic lithium-6 atoms also has some promising characteristics. The temperature at which the atoms begin mimicking superconductivity is a full 16 per cent of the gas's Fermi temperature, rather than just a tiny fraction – meaning a superconductor with equivalent properties would be expected to superconduct at way above room temperature. That makes it a milestone in our quest for room temperature superconductors, says theorist Wilhelm Zwerger of the Technical University of Munich in Germany.

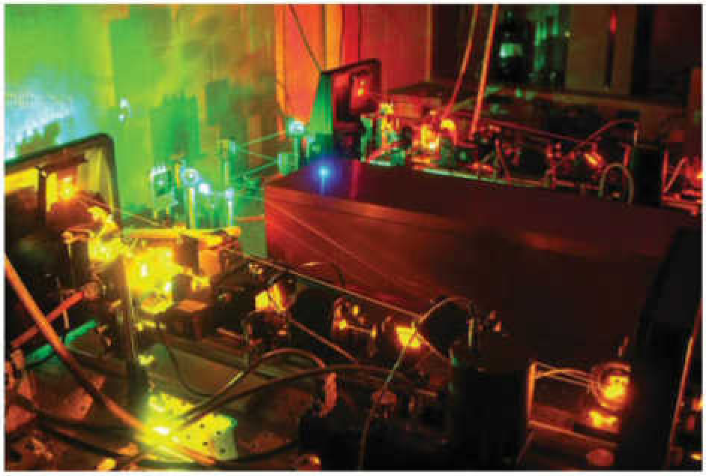
"Ultracold simulators are still too hot – harsh as that seems for an environment a few billionths of a degree above absolute zero"

Yet the true beauty of the simulator approach in the quest for new and better materials such as superconductors is its flexibility. Traditionally researchers have had to design a potentially promising material, grow it in the lab and measure its properties – only to find it is a dud. Mimic a superconductor with a gas of ultracold atoms, however, and you can scan through hundreds of slightly different atomic recipes at different simulated temperatures, all in a couple of days. "That's a profound difference," says Spielman.

It also means that theorists are finally getting some real-world checks on their models. "They can't just come up with a random number – for the first time, it has to be tested through experiment," says Zwierlein. Bongs is similarly enthusiastic. "Cold atoms allow us to access something that's hardly accessible in nature."

That same point makes Cirac sound a note of caution. When it comes to phenomena that have never been observed before, such as room-temperature superconductivity, we still won't be 100 per cent sure that the quantum simulator is not sending us on a wild goose chase until we can actually make the equivalent material. "If you knew the result, you wouldn't need the simulator," he says.

Nevertheless, there is a whole new avenue of possibilities to explore. Feynman ended his talk on quantum simulation with the words, "By golly it's a wonderful problem, because it doesn't look so easy." Three decades on, we're under no illusions. Progress has been slow and hard-won, with plenty of stubborn hurdles remaining. No one in this field is in it for the easy ride. But in Feynman's terms, though it still doesn't look so easy, it's starting to look doable, dammit. ■



Just chilling: quantum simulators need laser cooling and control

QUANTUM COMPUTING BEST BUYS

Fed up of failing to factorise? Is your optimisation not optimal? Simulations running slow? **Michael Brooks** is here to solve your problems

IS THERE anything more to quantum computers than talk, talk, talk? You might have given up waiting – after all, it's been more than 30 years since physicist Richard Feynman came up with the idea. He wanted to harness spooky quantum effects to seriously surpass the processing power of any normal computer. In that time, normal computers have become around a billion times faster. Quantum computers, by contrast, are still struggling with primary school arithmetic.

At long last, though, there's good news. In laboratories around the world, researchers have been beavering away, and they can't help feeling there's magic in the air. "Some aspects of this field are getting tantalisingly close," says Matthias Steffen of IBM's quantum computing division based in New York. You can even buy a quantum computer right now – maybe – but you'll need deep pockets. It doesn't matter what apps you're planning to run, this much computational horsepower doesn't come cheap.

With that warning in place, let *New Scientist* help you make an informed choice – whether you're an online game freak looking to take multiplayer to a whole new level, an engineering powerhouse looking to stay one step ahead, or a security service worried about keeping the nation's secrets under lock and key. Over the next five pages you'll find out what they can do, what different kinds are on offer, and whether you'll have to turn the back bedroom into a cryogenic coolant plant.

GETTING STARTED

Baffled by how a quantum computer is supposed to work? Don't worry, some of the biggest brains in physics can't figure it out either. Some say such computers run in a swathe of parallel universes; others claim they transcend all normal notions of space and time. Whatever the truth, here's a rundown of the basics.

QUBIT:

Ordinary computers use "bits" to process information. The basic unit of quantum computing is the qubit. These are physical systems that can exist in two different states, so they can represent the 1s and 0s that make up the binary code computers run.

> "Superconductor or spin? That's like deciding between Apple or Android"

A qubit might be an electron held in a magnetic field, or a photon that is polarised so its spin can be easily manipulated. Preparing qubits, as well as reading and writing to them, involves some hardcore hardware. Depending on your choice of technology, you might need a ruby laser, a non-linear crystal or even a pink diamond.

SUPERPOSITION:

This is where the magic happens! The advantage a qubit has over a normal bit is that it can be put into a superposition state, being 0 and 1 at the same time. But this is tricky to pull off – any stray heat, electromagnetic noise or physical bump can knock it out again. So you'll have to invest in some serious refrigeration, tinfoil shielding and tiptoe around your quantum computer, or invest in a state of the art vibration containment system.

Even then, you can only run the computer for a limited time before the superposition collapses. You'll want to check out this "coherence time" carefully, as well as evaluating how many errors are created.

ENTANGLEMENT:

Okay, we lied, this is where the magic really happens. Thanks to what Einstein termed spooky action at a distance, two subatomic particles can become inextricably interlinked, or entangled. The link lets you manipulate multiple qubits at once. That's what makes quantum computers so kickass: just eight qubits, held in superposition and entangled, can simultaneously represent every number from 0 to 255, letting you carry out many operations at once.

So that's the other thing to look for when weighing up a purchase: how many entangled qubits can your chosen machine manage at once? Don't set your sights too high. At the moment, 14 is the record, achieved in 2012 by Rainer Blatt's group at the University of Innsbruck in Austria.

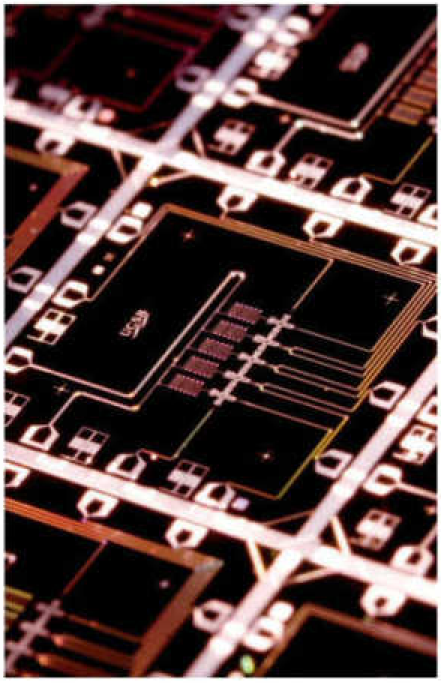
ERROR CORRECTION:

Even normal computers make mistakes. Sometimes a bit can be buffeted by a voltage spike or a passing cosmic ray, changing it from a 0 to a 1, say. Processors deal with this by keeping copies, but this isn't an option for qubits, thanks to a law called the no-cloning theorem.

Fortunately there are error correction algorithms to get around this. The drawback is that these need a lot of qubits, anything between 100 and 10,000 times as many as needed for the actual computation you're trying to perform. Happily, our ability to assemble arrays of qubits for error correction has come on leaps and bounds. And error rates have been creeping downwards too. In June 2014, IBM unveiled error correcting code that is well suited to the large arrays of qubits expected to outperform regular machines. Essentially we're where we need to be to start building interesting quantum computers.

Where the magic happens

D-WAVE



HARDWARE

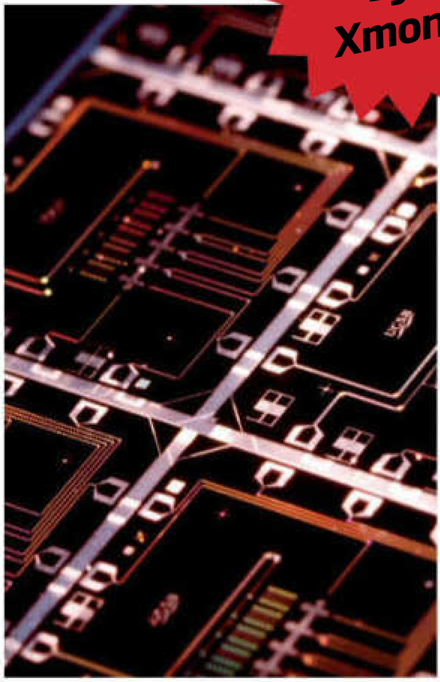
Spin or superconductor? That's the "Apple or Android?" of the quantum computing world. Superconducting qubits have been around longer, but spin's the ultracold new thing – and there are a few wild-card options to boot. Here's what you need to know.

SUPERCONDUCTING QUBITS:

This is the grandaddy of all quantum computer tech. Back in 1962, Cambridge physicist Brian Josephson showed that putting a small gap into a strip of superconductor – a material that has zero resistance to the flow of electricity at low temperatures – has a surprising effect. For example, superconducting loops incorporating such a "Josephson junction" let current flow clockwise and anticlockwise simultaneously. That's a superposition of states – just what you need for a qubit.

What's more, these systems are manufactured on the mainstay material of the tech industry: silicon. "That allows you to use standard lithographic tools," says Steffen. "You're not in thrall to natural systems, and once you can do a handful of ›

Powered by Xmons



UCSB

qubits on a chip reliably, you should be able to put many more onto the same chip." That makes superconducting a good choice for the buyer looking for a tried-and-tested solution to their quantum computing needs.

If you're sold on this approach, you still have a choice to make: transmon or Xmon? Transmons are loop-shaped and, at the moment, up to nine of them can be linked together. A standard transmon can maintain its coherence for around 50 microseconds – long enough to be used in quantum circuits. What's more, coherence times twice that length, and transmon arrays of 10 to 20 loops, are just around the corner, according to Göran Wendin of Chalmers University in Gothenburg, Sweden.

The Xmons created by a team at the University of California, Santa Barbara (UCSB), are cross-shaped superconducting qubits made from sapphire sitting on aluminium. The UCSB group can connect up five of these to create an array that corrects its own errors, and are working on a nine qubit array. UCSB's John Martinis, who is now working in collaboration with Google, thinks they can power ahead: "My challenge to the group is to double the number of qubits every year." That's a big ask: the architecture and the kinds of algorithms the machine will run still need work.

SPIN QUBITS:

If you're more of an early adopter, you might check out what Andrea Morello's group is up to at the University of New South Wales (UNSW) in Sydney, Australia. Their single atom of phosphorus sitting inside a silicon chip may not sound as impressive as a quintuplet of superconducting loops, but it certainly has its advantages.

Morello's team is able to put the atom's spin in a superposition, manipulate this blurred quantum state and then read it out by applying a microwave pulse. Morello says the team has maintained coherence for "tens of seconds" – plenty of time to run the kinds of quantum apps being dreamed up. There's scope for going longer, too. Researchers at Simon Fraser University in Burnaby, Canada, have managed to get their phosphorus-in-silicon rig to hold for nearly 40 minutes at room temperature. They also preserved the superposition while cycling the material between room temperature and 4.2 kelvin.

At the moment, the UNSW group is squeezing two qubits out of a single atom, using the phosphorus nucleus as the first and one of its electrons as the second. In June 2014, they announced that they could now couple two atoms together and read out all four spins, although they haven't yet managed to manipulate them. Once they can, they aim to have a handful of qubits that will let them start making quantum calculations. But that will take several years, and the wait for apps will be even longer.

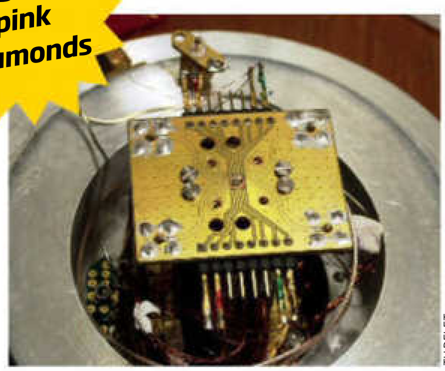
Some researchers are looking for a more high-end solution – which is where those diamonds come in. When certain diamonds are formed, a nitrogen atom can sneak into the place of a carbon atom to give the gem a slight pink colouring and, at the same time, leave an empty space nearby in the crystal lattice. This combination of nitrogen plus "vacancy" (NV) can be used to create a qubit; the vacancy has distinct quantum energy levels that can be put into superposition using a pulse of laser light. Further pulses can manipulate the state and read out the result of the operation.

In May 2014, researchers from the Delft University of Technology in the Netherlands managed to teleport quantum information between two diamonds that were 3 metres apart. This is a baby step towards quantum computing in the cloud and a quantum internet.

Before we get ahead of ourselves, there's a catch. You can't manufacture these blingtastic NV qubits to order. Putting hundreds of them together, as would be necessary for a useful quantum computer, would give a noisy output. But that's not a deal-breaker. Last year, a team led by Simon Benjamin at the University of Oxford showed that you can put just a few NV qubits together in a "cell", then link those cells together with photons that act as the input and output bits. Even at room temperature, the cell can maintain coherence for around a second, and the noisy photon network that connects cells can tolerate a 10 per cent error rate without crashing.

"Information has been quantum teleported between two diamonds"

Blingtastic pink diamonds

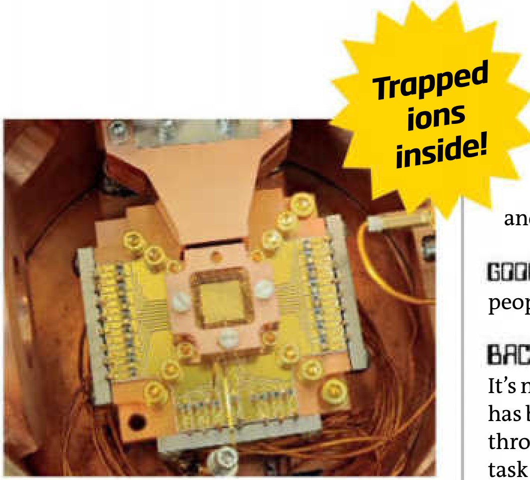


TU DELFT

ALSO AVAILABLE:

If you're really into bleeding-edge technology, there are a few other options to consider. Ion trap quantum computing is actually the market leader when it comes to entanglement. This technique has linked together a whopping 14 qubits made from ions – typically ytterbium – held in carefully shaped electromagnetic fields and manipulated with laser or microwave pulses. But that's still a long way from a useful computer, and researchers are finding it tricky to scale up.

You would have to be brave to put all your money on photonic quantum computing,



NIST

too. Photons look like they would make good qubits: they are easily superposed and stay coherent for good lengths of time. But although it's possible to work with particles that move at the speed of light, it isn't easy.

Topological quantum computing, where qubits are encoded in the way subatomic particles move past one another, has its pluses too – it's particularly resistant to environmental disturbances for one thing. Microsoft is beginning to invest heavily in it, but it won't be in the shops any time soon. Maybe one to consider when your first quantum computer starts to look a little vintage.

VERDICT: Superconducting qubits might attract those who like to play it safe, but spin could just overtake it during the next decade. Everything else is for die-hard experimenters only.

APPS

Hardware is important, but what really matters is the software. So what will you be able to run on your quantum computer? Here's our pick of the best apps in the pipeline.

FACTORISATION:

This is the killer app for quantum computers: finding the factors of a large number. Why? To find a factor, normal computers have to try every possible combination, which takes an incredibly long time. Because of this, factorisation algorithms are used to protect data in situations ranging from banking to internet databases.

Two decades ago, mathematician Peter Shor devised an algorithm that could break such security with ease. However, Shor's algorithm only works on quantum computers and so far the largest number that has been factorised is 21. Don't you dare sneer – when this app takes off it'll put the revelations of WikiLeaks and the capabilities of the NSA to shame.

GOOD FOR: Anyone who wants to read other people's secrets.

BACKWARD SEARCH:

It's no wonder Google's PageRank algorithm has been such a money-spinner; searching through an unsorted database is a colossal task for ordinary computers. If there are N possibilities, a standard computer will, on average, find what you're looking for in a time related to $N/2$. Bell Labs researcher Lov Grover showed in 1996 that a quantum computer with the right algorithm can speed up the process, taking a time that is related to the square root of N. It works by fiddling with the qubits to make the object of the search the most likely outcome of a measurement on their superposition.

GOOD FOR: Budding dot-com billionaires, people in need of plumbers.

QUANTUM SIMULATION:

Where it all started. If you want to a simulate a complex quantum system – a large molecule, say – there's just too much detail for a normal computer, no matter how powerful. So as Richard Feynman realised in 1982, you need a quantum computer. For example, if you have one photon to represent each particle in the system you want to simulate, such as an atomic nucleus, then you can put them through a series of quantum gates that mimic interactions. Handy if you don't have the maths or equipment to try it for real.

GOOD FOR: Impoverished chemistry students, entrepreneurs searching for everyday superconductors, nuclear warhead designers.

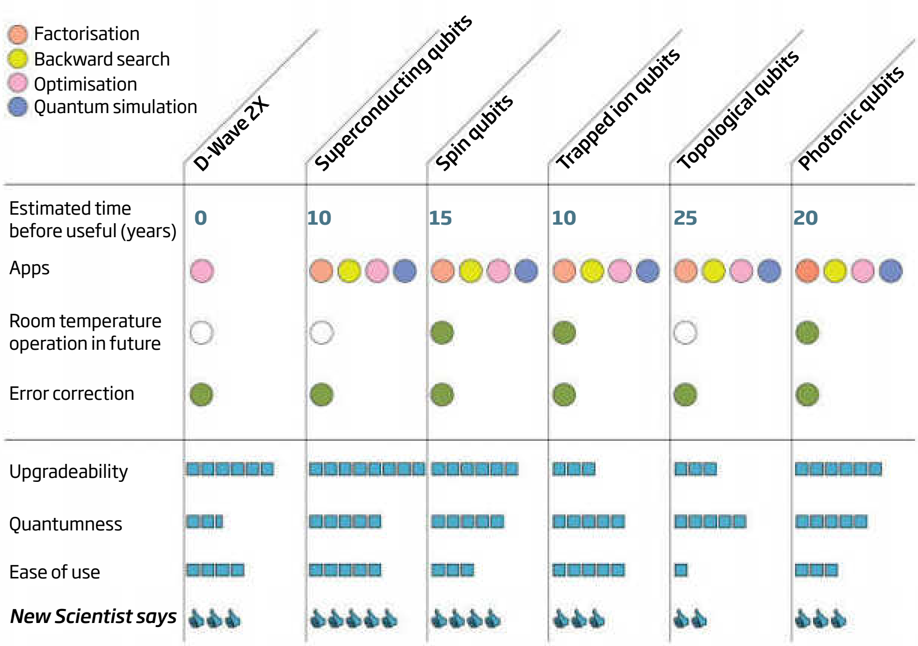
OPTIMISATION:

If you want to baffle a computer, ask it to work out the best shape for the front end of an aeroplane. There are so many variables to consider that you'll be dead and gone long before it spits out an answer. This kind of problem is perfect for quantum ›

> "You can buy a quantum computer today – if you have $10 million spare"

Which quantum computer is right for you?

There are many types to choose from. Here's how they compare and our all-important verdict



"annealing", named after the process of shaping materials by cycles of heating and cooling.

Annealing is a way of representing all the different possibilities and their consequences as a landscape of hills and valleys; the ideal solution is the lowest point in that landscape. A quantum computer can survey the whole landscape at once, while a classical machine must run through it repeatedly. That's the idea, anyway – no one really knows if it'll actually work that way.

QUANTUM OR QUICKSILVER?

Can't wait to get your hands on a shiny new quantum computer? The good news is that you can buy one today, if you have $10 million to spare. The bad news is nobody knows if it actually is one.

D-Wave Systems of Burnaby, Canada, is the upstart breaking in on the quantum action. Its flagship model, known as D-Wave 2X, contains 1000 superconducting loops of niobium metal, each containing a Josephson junction.

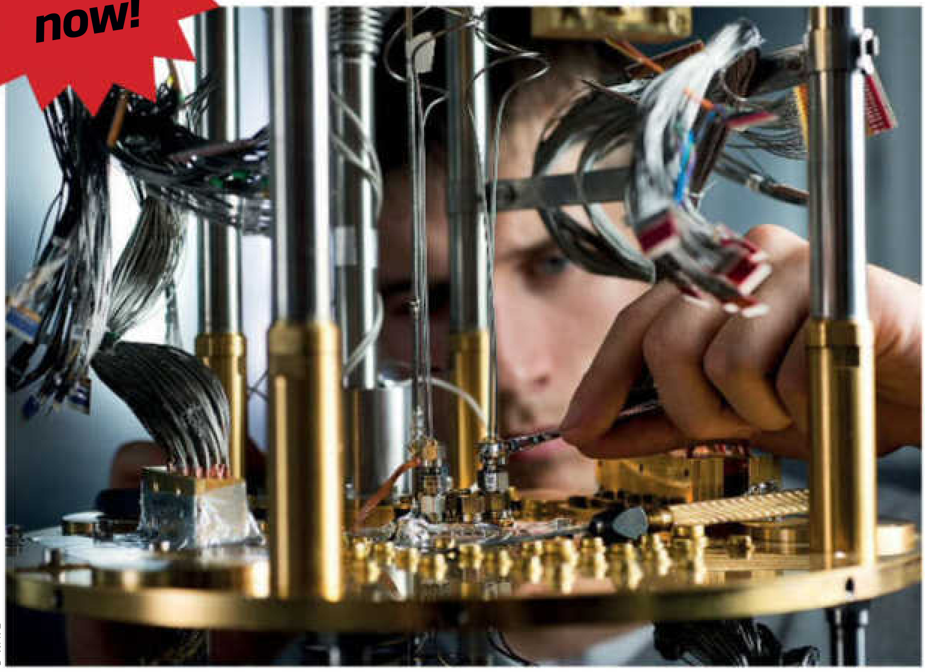
But be warned, this is no quantum laptop. The whizzy-looking black box it's housed in, along with its supporting cryogenic system and supercomputer interface, fills a room 10 metres squared. Perhaps surprisingly then it runs on just 25 kilowatts, less than a thousandth of the power devoured by Tianhe-2, the world's fastest supercomputer.

A full thousand-qubit performance would leave rivals in the dust, but D-Wave doesn't worry about being able to address each qubit individually, with having all the qubits entangled together or even operating properly as Josephson junctions. So it's not clear that they actually are qubits, and tests have proved inconclusive as to whether it really outperforms ordinary computers.

"We're not in the business of trying to prove whether it's quantum or not," says Bo Ewald, President of D-Wave US. "We don't know how much coherence we've got." Tests on previous models that had 512 qubits showed that somewhere between eight and 40 qubits were entangled. Ewald believes all the loops are entangled, but doesn't want to spend megabucks proving it: "Trying to measure this means turning it into an experimental physics device. We're more focused on just using it as a computer."

It's a computer with only one application: an optimisation algorithm that searches for the best solution to a given problem. That's enough for D-Wave's first two customers.

Available to buy now!

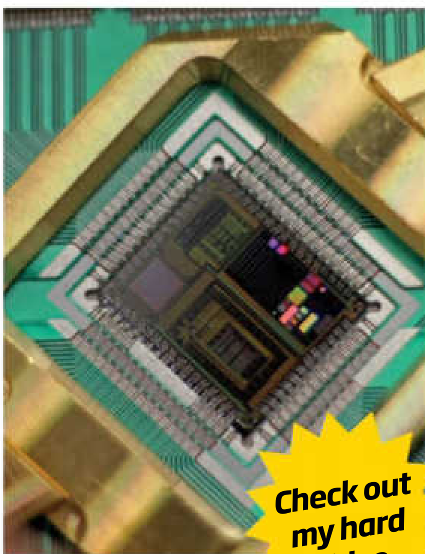


D-WAVE

Google is using it in machine learning for its head-mounted display Google Glass; so far it has put the D-Wave machine to work finding quicker ways to recognise certain objects in an image. Those can be transplanted back into traditional computers, making them more efficient at the task.

Lockheed Martin is using the machine to find out where its aircraft software might go wrong. The company gives its aircraft control system a bad result – such as the aircraft nose going in the wrong direction when the pilot pulls up on the stick – and asks the D-Wave machine to look for input scenarios that might lead there.

D-Wave thinks it'll find more customers in medical imaging, financial planning and delivery scheduling, but the company is open to offers. It might also be worth noting that Google has now started investing in other quantum technologies: in September the company announced a partnership with UCSB to build an Xmon-based quantum computer.



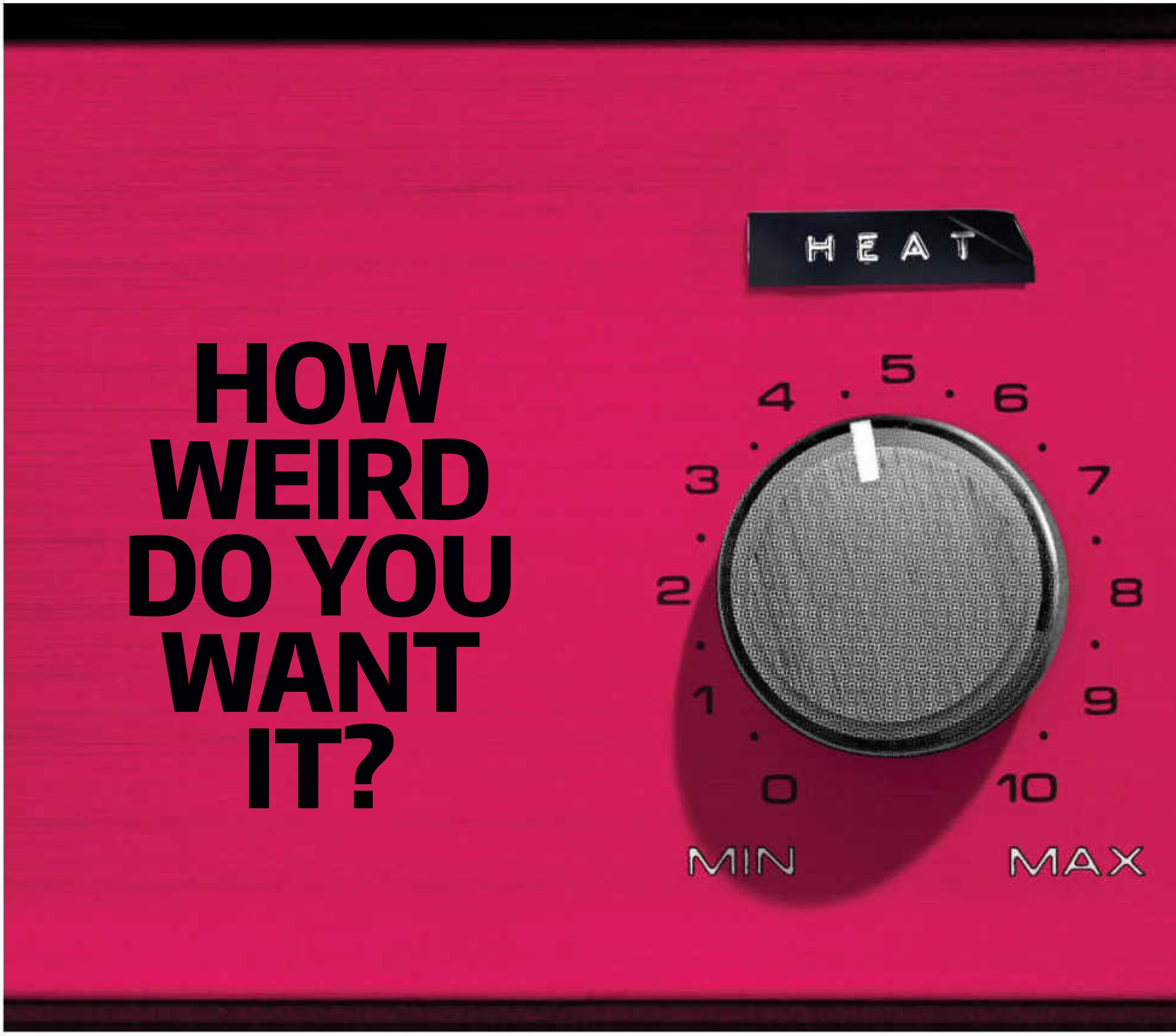
D-WAVE

Check out my hard drive

THE VERDICT

First things first: a quantum computer is definitely something that should be on your wishlist. The question is, which one is right for you? Right now the field is wide open. The experts say it's not clear which platform will win out and make it to market, but the smart money is on a hybrid that uses one technology for the computing and another for the networks to connect it up. Exactly when that will happen – D-Wave and a few experimental and very specialised machines aside – is up in the air. Insiders say you might not be taking delivery of your general-purpose quantum computer until 2024 or even later. But it'll be worth the wait to get hold of a machine that can wipe the floor with anything we have today. Don't forget, though: such power comes with a hefty price tag. Better start saving. ■

HOW WEIRD DO YOU WANT IT?



To really control the quantum world, make some noise, shouts Michael Brooks

RAYMOND LAFLAMME works in a magnificent-looking building. The Quantum-Nano Centre on the University of Waterloo campus in Ontario, Canada, boasts an exterior whose alternating strips of reflecting and transparent glass are designed as metaphors for the mysterious nature of the quantum world. Inside, it is even more impressive. Its labs are so well isolated from the outside world that an earthquake will barely move their floors. No electric or magnetic fields can get in where they aren't wanted, and the temperature is controlled to within a single degree. That's especially impressive, considering that human beings bring their hot bodies into the centre to perform experiments at temperatures close to absolute zero.

What a shame, then, if all this cutting-edge engineering proves entirely superfluous. Laflamme heads the university's quantum computing institute. Ironically, he was among the first researchers to show why quantum computing might not require the kinds of isolation we once thought. If the latest raft of results is anything to go by, the key to accessing the quantum world may lie not in avoiding disturbance, but embracing it.

Our emerging understanding of the way quantum systems are connected suggests that there is much more to being quantum than we realised. Researchers have given this phenomenon the name quantum discord. If it turns out to be all that it currently seems, discord may finally tell us what it really means

to be quantum. Its benefits won't just be abstract, though. Discord could change our view of biology, computing, measurement and – of course – the nature of reality itself.

Be warned: discord is a tricky concept. The first person to define it was Wojciech Zurek of the Los Alamos National Laboratory in New Mexico. Zurek had been looking at the effects of measurement on quantum systems. One of the oddest things about quantum objects is that, until you measure where they are, they exist in many places at the same time.

Zurek wanted to understand how a measurement turns a quantum object into a "classical" everyday object that has a fixed, distinctly un-weird existence. We know that a quantum system becomes classical if you make repeated measurements on it, or measure it with brute force. Zurek proposed that there was a quantifiable entity – discord – lost during this process. According to him, discord is, effectively, the "measure of quantumness".

The notion garnered very little attention. Then a few months later, Vlatko Vedral of the University of Oxford saw something similar – albeit from a different direction. He was looking at the total information that you can theoretically extract from a pair of particles that interact to create an "entangled" pair. When two quantum particles are entangled, some of the information about each one is held in the other. You can only fully describe each one's properties by describing the complete pair.

Yet Vedral got a shock when he worked through the mathematics, examining where all the information came from. The information held in the entanglement and the classical information "did not add up to the total in the system", he says. "This really was surprising." The missing information, he believes, is a measure of the discord in the system.

One reason it was so surprising is because we have long considered entanglement as the distilled essence of the quantum world's weirdness. That's because you can entangle a pair of atoms, put them at opposite sides of the universe and perform a measurement on one that will affect the outcome of a later

“ENTANGLEMENT’S SPOOKY LINK IS TERRIBLY DELICATE”

measurement on the other, even though there is no physical link between them.

Einstein dismissed this as “spooky action at a distance” and said it showed the mathematics of quantum theory needed some work – there must, he said, be additional information about the atoms that hadn’t been included in the equations.

Unfortunately for Einstein, entanglement was proved real in the 1980s. Since then, quantum researchers have become rather obsessed by it. What Schrödinger hailed as the defining trait of quantum theory has been championed as the key to superfast computing, unbreakable cryptography and unravelling the nature of space and time.

It is all because entanglement is an astonishing resource for manipulating quantum information. If Alice and Bob share an entangled pair of photons, Alice can put Bob’s photon into any state she chooses just by performing a particular measurement on her photon.

The trouble is, putting entanglement to work has proved remarkably difficult. Its spooky link is terribly delicate: entangle two atoms and you have to isolate them from all sources of disturbance. Vibrations, heat, light, collisions with atoms in the air; these can all break the link – hence the stringent requirements of Laflamme’s workplace.

So, is there a way to do strange and useful quantum things without all the hassle? That’s where discord comes into its own.

The reason disturbances are such a problem to entanglement is that interaction with a hot or noisy environment carries away some of the quantum information that is necessary to fully describe the system. That’s a big problem for entanglement, which can hardly tolerate any information loss. But when entanglement breaks, you can still have discord: a network of weaker – but nonetheless useable – links that contain information about the properties of the system. What’s more, discord is a lot more tolerant than entanglement: it thrives on noise. “Some types of noise actually increase the discord,” says Gerardo Adesso of the University of Nottingham, UK.

To explain why, we need to understand that quantum states can exist in various levels of purity. For something like a photon, the purest state is like a coin rolling along on its edge – perfectly upright but highly vulnerable. Only in this state can photons be entangled. Think of entanglement as rolling two pure-state coins through a pair of narrow vertical slots into a box that exchanges information between the coins.

The purest quantum state is like a coin rolling upright

MIKE STONE / ALAMY

Not every quantum state can pass through such a stricture. “Mixed” states are less well-defined: the photon would be more like a coin that is wobbling from side to side as it rolls forward. It won’t be able to roll through the entanglement box’s vertical slots, but it can still pass through a wider gap. As it does, it might interact with the walls. Those knocks will set the walls ringing, and any other photon using that channel will gain a sense of the “wobble”. In that way, a noisy environment can actually increase the amount of shared information.

Entangled no more

So while disturbances from the environment will cause pure states to become mixed, destroying any entanglement, mixed states not only tolerate the knocks, they can also gain information from them. They can’t contain as much information as entanglement, but still a potentially useful amount. It is a kind of entanglement lite, in that once two particles share some discord, you can manipulate one to change the other. The spectrum of possible changes is more limited than with entanglement, but it can still be harnessed for processing information.

Take Laflamme’s discovery. In 1998, working with Emmanuel Knill of the University of Colorado in Boulder, he showed that quantum computation didn’t need entanglement.

The pair did this in a mathematical thought experiment. First, they imagined a collection of quantum particles where all but one is in a mixed state. The remaining particle is in a pure state, but because there is only one, the system contains no entanglement. Then Knill and Laflamme looked for an information-processing task this collection of particles could perform quicker than any known classical algorithm.

They found one. It has to do with computing the energies of the system; not the most heart-stopping of tasks, but a demonstration, nonetheless, of the fact that you can get quantum speed-up without entanglement.

The speed-up came from interacting the mixed-state particles with the pure-state particle and then, at the end, measuring the resulting pure state. Nearly a decade later, Animesh Datta, then at the University of Oxford, and colleagues, showed that the quality we now define as quantum discord is at the heart of this scenario. The quantity of information shared between them all depends on the discord links that exist between the mixed states in the system.

To reprise the coin analogy, Datta, who has since moved to the University of Warwick, UK, showed that the process is like passing the pure-state coin through one of the mixed-state coins’ wide slots, while the other slot contains one of the mixed-state particles. If the pure-state coin happens to brush against the wall, it will pick up a little of the information left by the mixed-state coins’ more robust contact with the wall. Finally, you read the information in the pure-state coin, and you’ll find out something about the mixed-state coins that have influenced each other and the apparatus.

In other words, when the process is carried out correctly, a final measurement on the pure-state atom can harness the information processing potential of the other atoms, despite their being in a mixed state.

Subsequent experiments by Andrew White at the University of Queensland in Brisbane, Australia, not only proved this to be true; they also showed that you can even dilute the purity of the pure state. As long as there is some discord, there is some computing advantage over a classical machine.

This is a huge discovery. It demotes entanglement to an interesting tool for exploiting the quantum world – but not an essential one. Because discord is so much easier to achieve, it is entirely possible that we will do without entanglement in our attempts to build quantum technologies. "I would say there are at least a dozen quite distinct applications where discord is useful," says Zurek. "It is too good a tool not to use when it is needed."

Such revelations will have a huge impact on the field of quantum computing. In almost every explanation you will have read – including those in this publication – the power of entanglement will have been invoked as the reason quantum computers can compute beyond what is classically possible. It's time to rip up that explanation, according to discord proponents. Entanglement, Laflamme says, may even be a by-product of quantum computing, not the source of its power. "We know there is more to quantum information processing than entanglement," Laflamme says. "It's not the answer to everything."

Adesso is already working on technologies that exploit discord. He has developed highly sensitive quantum measurement devices that operate without any of the restrictions required to get similar entanglement-based devices to work. Using a technique he and his colleagues refer to as quantum estimation, they interact a quantum system containing discord-filled mixed states with whatever system is being measured. By monitoring changes in the mixed states of their probe, they make a highly sensitive measurement of, say, the phase properties of a photon. That might give us more sensitive and robust interferometers, creating high-precision gravitational wave detectors or atomic clocks.

Quantum plants

Then there are the potential applications in the physics of complex materials. Understanding what creates unexpected properties, such as sudden phase changes at certain temperatures, may come down to discord and other interconnections in the material. "We are just beginning to understand their ramifications," says Ujjwal Sen of the Harish-Chandra Research Institute, Allahabad, India.

Discord might also be a useful tool for exploring the nascent field of quantum biology (see "The weirdness inside us", page 62). Research has thrown up hints that quantum tricks help plants to photosynthesise and some birds to navigate. This has been so surprising largely because these systems operate in the warm, wet and noisy natural environments that we try to get away from in all our quantum technology systems. It was always a mystery how entanglement could be at work in such environments, but now we know it doesn't have to be.

The fact that quantum discord can not only tolerate but also be increased by noise causes Adesso to suspect that evolution might have put it to work. "I think that living systems are very likely to have a very robust exploitation of quantum effects, so there will be discord involved in this for sure."

It is not yet clear how far this strange phenomenon's influence might stretch. "Is discord the answer to everything? We don't know," Laflamme admits. "Discord tells us there is more to quantum mechanics than we've thought about – that there are many pieces of the puzzle we don't understand. But exactly where it can go, what it can tell us about the world, where we can use it – that's still not totally clear."

Another thing that's still not clear to everyone is how revolutionary discord really is, if at all. Stephanie Wehner at the Delft University of Technology in the Netherlands sounds a note of caution: discord has been overblown, she says. She fears that it is merely a way of rephrasing what we already know, and that it might distract people from digging for deeper truths about the quantum world. "Quantum information theory offers much more powerful ways to study the subtleties of quantum versus classical," she says.

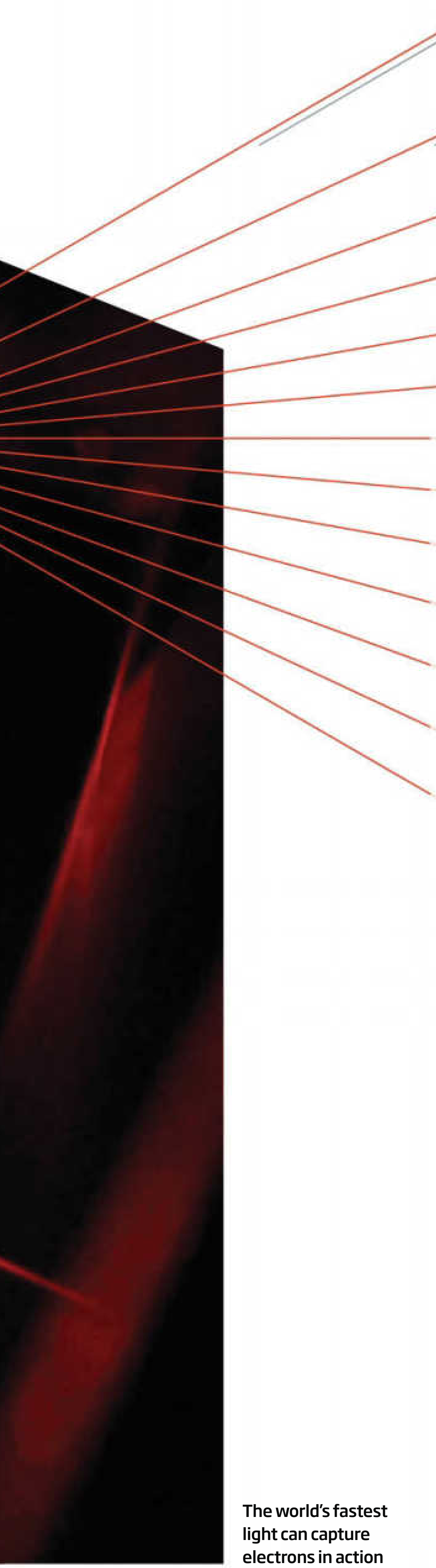
Still, the idea of discord has opened our eyes, Laflamme says. We have a new angle of attack on understanding the difference between classical and non-classical worlds – why it is, for instance, that quantum systems can exist in two places at once but we can't. It could mark a technological turning point. "This is great: a young scientist in this field can think about quantum information processing in a whole different way from my generation," Laflamme says. Just don't tell the people who worked so hard to create his fancy building. ■

"DISCORD TELLS US THERE IS MORE TO QUANTUM MECHANICS THAN WE'VE THOUGHT ABOUT"

It's the shortest story ever told – but it takes some quick-fire wizardry to catch atomic electrons on camera. Stephen Battersby reports

The flash

THORSTEN NAESER/MPQ



The world's fastest light can capture electrons in action

IT IS a realm more alien to our experience than the heart of the sun or the other side of the universe, separated from us by a great gulf not of distance, but of brevity. To the inhabitants of this superfast world, the beat of a human heart is as imperceptibly slow as the drift of the continents is to us.

The world is the atom, and its denizens electrons. Their mercurial movements can be over in just attoseconds – billionths of a billionth of a second – yet they drive our electronic devices, every chemical reaction in nature and every thought in our heads.

What wouldn't we give to capture them in action. Understand how electrons move, and we might control reactions better, design more effective drugs and better materials for generating energy, and boost today's sluggish computers to warp speed.

The premiere of such high-speed action movies is fast approaching. As yet the camera work is a little shaky and the picture somewhat grainy, but the technical finesse of the electron film-franchise can only improve with time. Soon we could be watching movies of the microworld in ultimate slow-mo.

It was the late 19th century when photographic pioneer Eadweard Muybridge felt the urge to witness what is merely a blur before our unaided eyes. Famously he captured the motion of a horse galloping, proving the disputed notion that there is a moment in each stride when all four hooves are off the ground. Muybridge used a tripwire as a trigger for his cameras, and then put a series of stills together onto a glass disc. Spinning the disc within his primitive film projector, the zoopraxiscope, he produced an illusion of motion.

The same principle has kept movie-goers happily fooled ever since. It illustrates the central paradox of film-making: to make motion flow visibly, you first have to freeze it. For a speeding horse, that means a fast shutter on your camera. Eventually, though, mechanical shutters reach their limits, and film or detectors get too little light in the brief exposure to reveal anything. Then what you need is a strobe light that provides intense illumination for just a split second. In the 19th and early 20th century, electric sparks were used to provide such flashes, capturing the motion of sound waves, speeding bullets and other fleeting phenomena.

Sparks can last just a few nanoseconds, but even that is far too ponderous to illuminate the attosecond world of electron movements. "These are the fastest motions outside of the atomic nucleus," says Ferenc Krausz of the Laboratory for Attosecond Physics in Garching, Germany. Capturing them needs the right kind of flashlight to generate ultrabrief, ultrabright pulses of light that can freeze electrons in action.

That means a laser – in particular, one that produces many different frequencies of light. Carefully manipulated, these will periodically all come into step, reinforcing one another in a sudden burst of light that is over in a trice.

In the late 1980s, Ahmed Zewail of the California Institute of Technology in Pasadena developed such a flashlight to watch chemical reactions unfold on timescales of femtoseconds – millionths of a billionth of a second. He observed the making and breaking of bonds and the formation of ephemeral intermediate molecules, and received the 1999 Nobel prize in chemistry for his efforts.

"It is the central paradox of film-making: to make motion flow visibly, you first have to freeze it"

Getting any faster posed a fundamental problem, however. Light is made of oscillating electric and magnetic fields, and for a light pulse to exist at all its field must rise from zero to a peak and fall back again. The shortest-wavelength lasers produce light in the visible and infrared regions of the electromagnetic spectrum, where one wave cycle lasts just a few femtoseconds. There seemed no chance of making a laser pulse any shorter.

Not so. Around the time that Zewail was doing his seminal work, some laser physicists began to see strange, short bursts of › ultraviolet light emerging when they hit certain gases with a powerful blast of infrared laser light. Ken Kulander and his team at the Lawrence Livermore National Laboratory in California worked out what was going on. Bright light means strong fields, and if a laser pulse is intense enough, its electric field can rip an electron from an atom. Then, as the field reverses, the kidnapped electron is hurled back towards its atom, emitting its excess energy as a high-frequency ultraviolet or X-ray photon as it slams back in and is recaptured.

This process, called high-harmonic generation, is a little like twanging an elastic strap to create a burst of high-frequency sound waves. Crucially, the rip and the re-collision both happen on very short timescales, lasting much less than a single laser oscillation. Master the fiddly details and you might use an infrared laser to produce X-ray flashes just attoseconds long.

It worked. In 2001 Krausz's group, together with Paul Corkum at the University of Ottawa, Canada, demonstrated that high-harmonic

"A deal of quantum post-production wizardry goes into making a sensible electron picture"

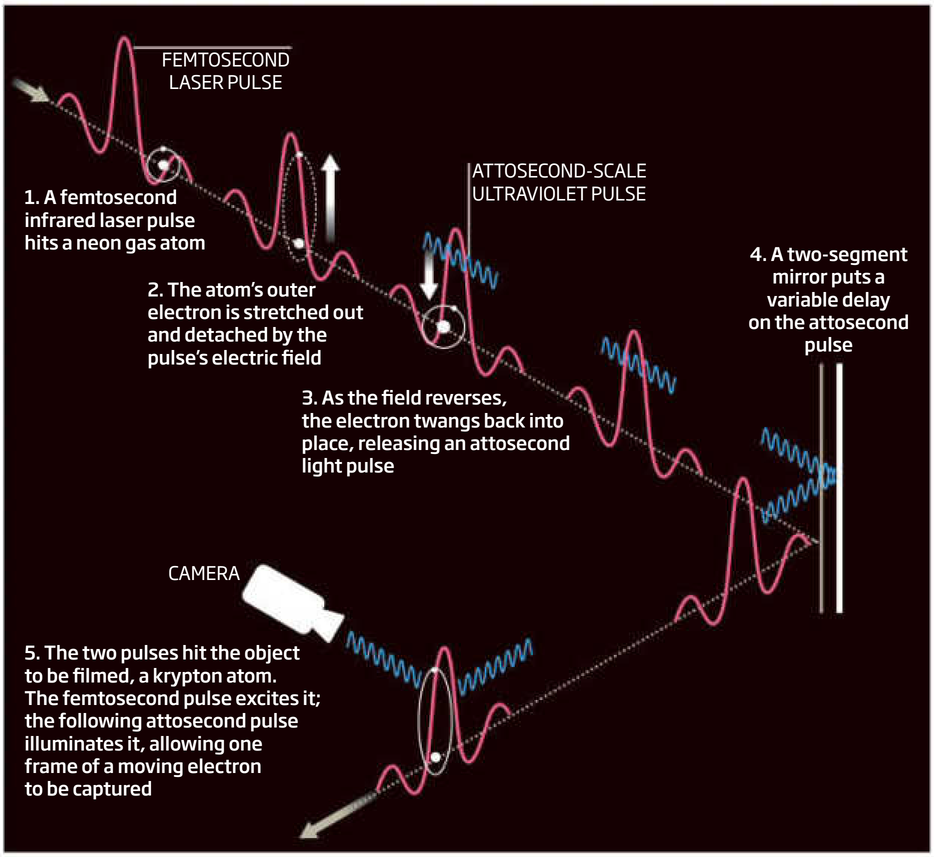
generation could produce flashes of light lasting about 650 attoseconds, showing for the first time that the femtosecond barrier had been broken. Since then, they and others have trimmed the fastest flashes down to about 80 attoseconds.

This, finally, was a camera-flash fast enough to snap an electron in action. And in 2010 Krausz's team did just that. They tuned an infrared laser to create a pulse lasting less than 3 femtoseconds – just a couple of wave cycles – and fired it through neon gas to create high harmonics. Neon atoms grip their electrons tightly, resisting until close to the peak of the intense laser pulse, and so generate the briefest and highest-frequency light.

The twanging of this electron created an

Making an atomic motion picture

A fast enough flash of light can capture a freeze-frame of a moving electron



ultraviolet pulse lasting less than 150 attoseconds. It is combined with the infrared pulse to hit a nearby sample of krypton gas. This double whammy is vital. Most of the time, an electron bound to an atom sits in an unchanging energy state. To catch one being interesting, you must first throw something at it to provoke it to move, and then snap its picture a moment later.

That is, in a rudimentary fashion, what the two-pulse method does – with an additional trick to take account of the blisteringly quick timescale. To delay the ultraviolet flash very precisely with respect to the infrared pulse, Krausz's team has developed a special two-part mirror. The outer part focuses the broad infrared laser beam onto the krypton to excite its electrons, while the central part is movable, adding a slight, variable delay to the narrow ultraviolet flash used to take the picture. With a series of different delays in repeated experiments, you get a series of snapshots that can be run together to reveal motion.

A deal of post-production wizardry still goes into making a sensible picture. An electron is not a sharply defined object, but a blurred-out beast, its hazy presence described by a quantum wave function. This wave function adopts various states, or orbitals, each with a different fuzzy outline and energy. Recording the frequencies of ultraviolet light absorbed at a given instant reveals the electron's energy and quantum state, which tells you the orbital's shape. Krausz and his team used some CGI trickery to convert this quantum information into a movie of a krypton ion's outermost electron wobbling its way from dumb-bell to doughnut shape and back again. The shot of around 40 "frames" lasts about 6 femtoseconds.

Similar quantum cunning lies behind a film reel produced in March 2011 by Corkum and his group. In the instant between having an electron ripped off and slammed back on again, an ionised atom or molecule can be in more than one quantum state. These states interfere with one another, resulting in a series of short flashes that automatically provide snapshots of electron action in the molecule.

Just as Muybridge's original film reel of a galloping horse is a little primitive to modern eyes, these short movies are hardly 3D IMAX immersive experiences. But at a million thrills per nanosecond they are action-packed – and promise some profound insights into the workings of nature.

Take the frailties of our existence, for example. "The energy and information transport in biomolecules is based on charge transfer," says Reinhard Kienberger of the Technical University of Munich. "But we don't know exactly how that happens – we only know that if it doesn't work right then people get sick." The same goes for the signalling process in our nerves, a particular target for Krausz. He wonders whether it's a purely electronic process involving just charge transfer from one molecule to another, or whether it is also chemical, involving the movements of whole atoms. "No one knows, but we now have the tools to study such questions," he says.

There is still a hurdle to be jumped before such experiments become reality. The immensely strong electric fields of attosecond light pulses tend to destroy delicate biological samples. The Garching team hopes to find a way of sticking molecules onto a surface in a way that holds them tight and protects them from electrical disintegration.

THORSTEN NAESER/MPQ

Ultrafast light could give us some control of atomic dynamics

More than just voyeurs

At Imperial College London, Jon Marangos and his research group are training their own flashlight, which currently delivers pulses as short as 250-attoseconds, on different targets. Among other things, they are looking at the mechanism behind radiation damage in biomolecules. Radiation damage is thought to begin when a high-energy photon knocks an electron out of a molecule, leading to a chain of events that breaks bonds, damages molecules and may lead to cancerous tissue. No one is too sure about the details of this process on the shortest time scales. "That could have important implications for how radiation damage proceeds," says Marangos.

Eventually he also hopes to watch photosynthesis in action. This process begins when a photon of sunlight excites an electron in chlorophyll, but exactly how does that electron's motion lead to the chemical changes that make sugar out of water and carbon dioxide? "It is possible that we are missing key steps," says Marangos – for instance the mooted role of collective quantum excitations in making the whole thing work. If we can find out, it could enable us to develop artificial photosynthesis to generate power or directly create fuels. It could even help us to bioengineer plants to increase the efficiency of natural photosynthesis.

Ultimately we would like to become more than just voyeurs of the attoworld. We would like to manipulate it, too. That might involve, for example, steering an excited electron to a particular site in a molecule, perhaps to break a bond at a certain place and trigger a chemical change in a specific way. "Perhaps we can make new molecules that would not be possible otherwise," says Marangos. Krausz's group is trying to use attosecond laser pulses to modify the optical and electronic properties of microchip components so they switch on and off 100,000 times faster than is possible today. All the indications are encouraging. "We are very excited about this," he says.

Time will tell. As others look to even faster times (see "Beyond the atto", left), Krausz now has his eye on the ultimate subatomic film-maker's goal: real documentary movies, rather than footage created by computer wizardry from an absorption spectrum and some quantum mechanics. It's not going to be easy, as everyone involved in this field will attest. To see the fine spatial detail of an atomic process, you need light of a wavelength shorter than the size of individual electron orbitals, much smaller than a nanometre. That means producing much higher-energy photons.

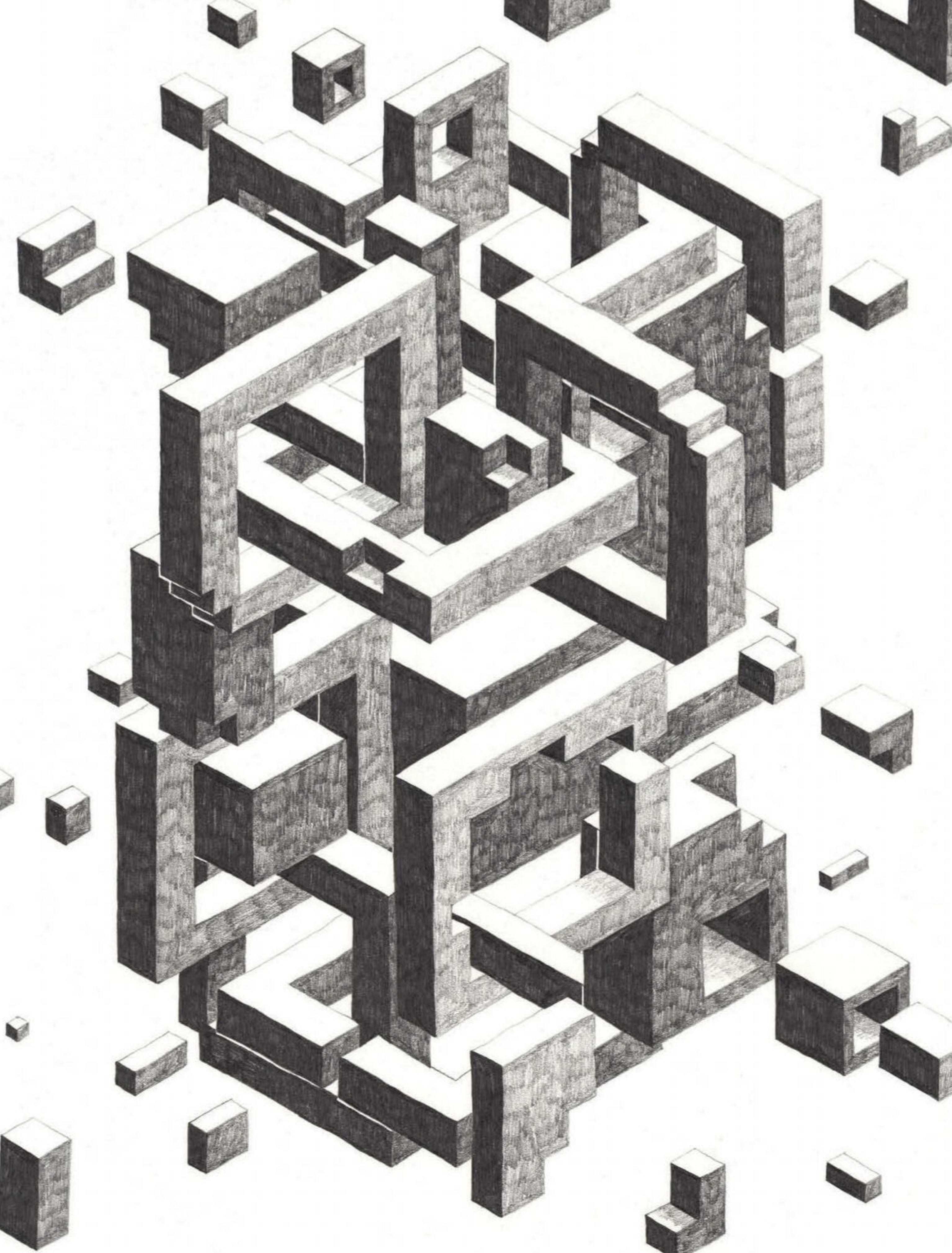
Krausz says he has a few technical barriers to surmount before he can produce and manipulate that ultimate light, but he is confident they will be overcome. "Then the long-held dream will come true," he says. Coming soon to theatres near you: the shortest story ever told. ■

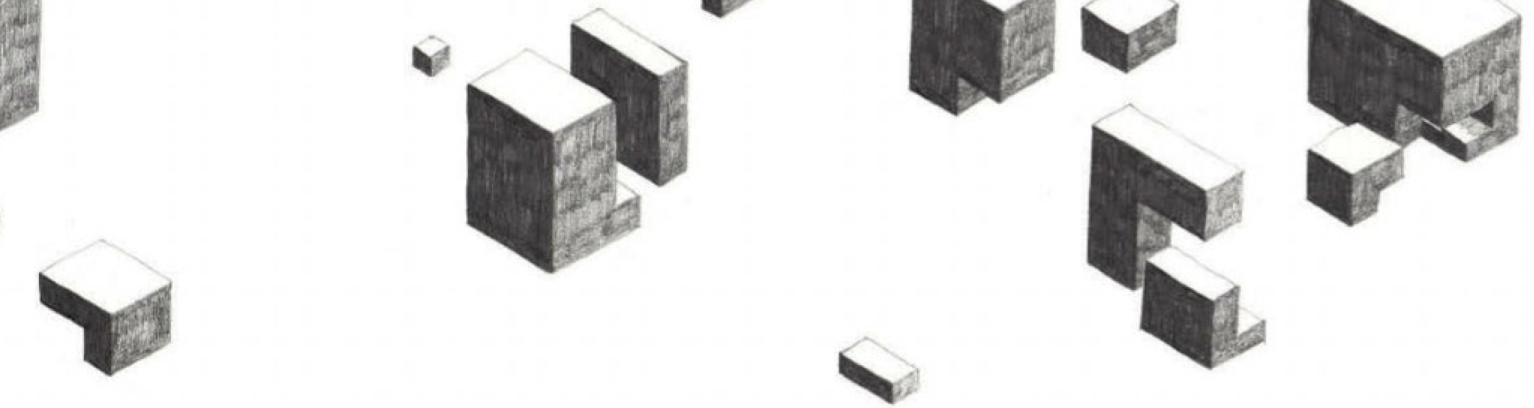
BEYOND THE ATTO

How low can we go - can we make light pulses much shorter even than 1 attosecond? Perhaps, if research from the group of Henry Kapteyn and Margaret Murnane at the JILA research institute in Boulder, Colorado, is anything to go by. They are investigating how to make high harmonic light (see main story) from a long-wavelength infrared laser. The longer wave cycle means that an electron ripped from the atom by the light is accelerated for longer before the field reverses, gaining more energy before it is pinged back. The result is extremely high-energy X-rays that could be packed into a pulse of just a few attoseconds or fewer.

Ferenc Krausz's group at the Laboratory for Attosecond Physics in Garching, Germany, is following the same lead. Achieving the very highest energies turns out to be particularly tricky, though. The infrared pulse rips out some electrons even before it reaches its central peak, resulting in messy interference. Krausz has a workaround that involves combining three separate infrared laser pulses so that interference cancels most of them out, leaving almost all of the power in a single wiggle of the wave.

Is there much point in these blisteringly fast pulses? After all, nothing much of interest in nature is faster than the attosecond movements of electrons. "A sub-attosecond pulse might allow for some control of atomic dynamics not previously possible," says Kapteyn. "But in most cases this is an inconsequentially short period of time." He is instead looking to the potential of longer pulses from a desktop X-ray laser that came online in December 2015. "Its spatial resolution is a thousand times better than an ordinary medical X-ray," says Kapteyn. His group has been collaborating with electronics companies to picture the digital bits written on a disc drive, and watch the effects of heat flow in nanoscale components.





JAMIE MILLS

TRUST NO ONE

Need to share a secret? You'll want a cipher that's as strong as the laws of physics, says Michael Brooks

THE Romans had a saying in praise of a reliable man: "You can trust him in the dark." But as Julius Caesar realised when several members of his inner circle stabbed him to death, sometimes the best course of action is to trust no one.

Throughout history, people have been burned by misplaced trust. Users of the extramarital affairs website Ashley Madison, whose details were leaked in 2015, are a good example. Their spouses are another. But as far as cybersecurity is concerned, we are finally poised to create a world in which trust is optional. The development taking us there is called device-independent quantum cryptography. Once it is perfected, you will be able to buy a secure device from your worst enemy and still be certain that no one is spying on the messages you send using it. "You don't have to trust anyone," says Artur Ekert, the University of Oxford physicist whose innovations in cryptography led to the idea.

This perfectly secure future can't arrive quickly enough, as present-day cryptographic systems are in a precarious state. The security of all of our online purchases, bank transactions and personas rely on a single shaky assumption: that certain mathematical operations are hard to do. The best known of our modern encryption systems is called RSA. To encode data, it builds a key from two very large prime numbers. These are kept secret, but their product – a number thousands of binary digits long – is public knowledge. Data can be encoded using this public key, but only those with knowledge of the original numbers can decrypt it. RSA's security relies on the fact that there is no known shortcut to find the two starting numbers. The only ways to do it are almost interminable processes, such as trying all the possibilities one by one.

Or so we hope. "We cannot prove that these problems are inherently difficult," Ekert says. It's not impossible that someone will discover a procedure allowing a conventional computer to quickly factorise the product of two huge primes. Maybe they already have and they're cleverly keeping it secret. If such an algorithm ever came to light, internet transactions would collapse, and financial deals and top secret government communications would be exposed. "It would truly be a catastrophe," says Michele Mosca of the Institute for Quantum Computing in Waterloo, Canada. "It's like a Y2K problem, except we don't know precisely when it might happen."

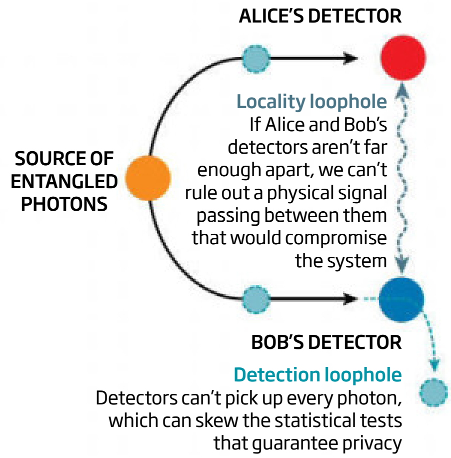
Even if we could prove that the factorisation problem is beyond the abilities of traditional computers, there are still quantum computers to consider. Because they compute using quantum phenomena they could consider all the possible primes at once. In 1994 mathematician Peter Shor, now at the Massachusetts Institute of Technology, showed this would be a speedy process. Simple quantum computers already exist and advanced machines able to realise Shor's idea can't be far off.

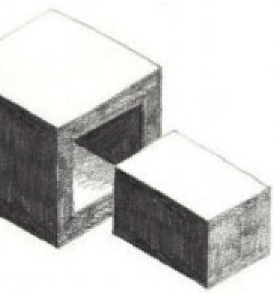
One way to reinvigorate our privacy is to fight fire with fire and employ quantum cryptography. This promises the ability to create keys that are entirely random, entirely unpredictable and totally inaccessible to spies.

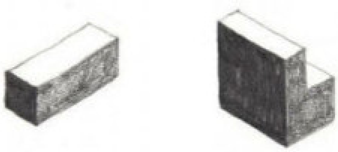
Quantum cryptography hinges on the rules that govern particles like photons or electrons. Their properties, including polarisation for instance, take multiple values at once, only snapping into sharp definition when measured. Use these properties as a basis for encryption and you preclude any attempt to peek at your key: that would change the result of the measurement, in effect destroying the key's tamper-proof seal. The technique has already been used to protect hospital data, ›

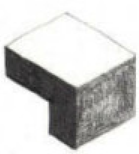
Talking in secret?

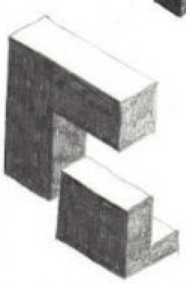
Alice and Bob like to encrypt messages using entangled photons, but two loopholes can compromise privacy











financial transactions and voting in the Swiss general elections.

Current systems use a protocol where the person transmitting the key, usually referred to as Alice, releases a polarised photon and makes a measurement on it before sending it. Her listening partner, usually referred to as Bob, chooses a particular way to make a measurement of that polarisation, and then he and Alice use an unencrypted channel to compare the sort of measurements they did. This allows them to create one digit of a private key for use in encrypting messages. To build the entire key, Alice and Bob simply repeat the process.

You might think that's good enough, yet this type of quantum cryptography has weaknesses. "You always have to make some assumptions about certain pieces of equipment," says Vadim Makarov, one of Mosca's colleagues in Waterloo. Makarov is an expert at showing that those assumptions matter, having broken into many "secure" systems around the world. He is the first to admit that you have to go to fantastic lengths to exploit these weaknesses, but when it comes to state secrets, say, or large bank transactions, who's to say nobody would?

One example of such a vulnerability is known as the detection loophole. It arises because the efficiency of photon detectors is never perfect, making practical quantum cryptography a bit like sending multiple copies of your key via an army of couriers to an office that occasionally shuts for lunch. Alice has to send far more photons than would otherwise be necessary, because Bob can't detect them all. This intermittent detection means Alice and Bob can't be certain that their apparatus is working securely.

It's not impossible to dream up ways of solving these technical hitches, but there's another more subtle problem that comes as an unavoidable side dish and which takes us to the heart of the problem with trust.

Imagine you have bought a state-of-the-art quantum cryptography system. It might well come complete with a shiny certificate guaranteeing its security, but how do you know the manufacturer hasn't built in a covert back door that allows them to read and sell your secrets?

It's hardly unthinkable. As soon as a new encryption technology becomes available, governments, corporations and intelligence agencies look for – and may even demand – a hidden flaw that they can exploit. Maybe your machine is programmed to spit out a key matching what someone somewhere has on file. Or perhaps there is a side-channel that logs a copy of any key you generate.

Here's where device-independent cryptography comes in. It started when Ekert came up with a smart new form of quantum cryptography in 1991.

This protocol also uses a stream of photons and, just as before, Alice creates a string of random numbers by measuring a property of each. The twist is that this time Bob has a separate stream of photons from the same source, and his photons are "entangled" with Alice's. Entangled photons are generated in pairs, and their properties are subtly connected. If Alice has one of a pair, and Bob has the other, they can perform measurements on their respective photons that will help them create each digit of a shared key.

"How do you know the device hasn't got a back door that will leak your secrets?"

So random

Until 2004, Ekert's idea was just another way of doing quantum cryptography, subject to the same old loopholes (see "Talking in secret?", left). But that changed when Antonio Acín of the Institute of Photonic Sciences in Barcelona, Spain, and colleagues realised that this version of cryptography contained a way to check the trustworthiness of the manufacturer. The implications are profound: with this protocol, you could buy the machine from your worst enemy and still be certain that it couldn't leak your secrets. "It came as a surprise to me," Ekert says. "Sometimes your inventions can be cleverer than you are."

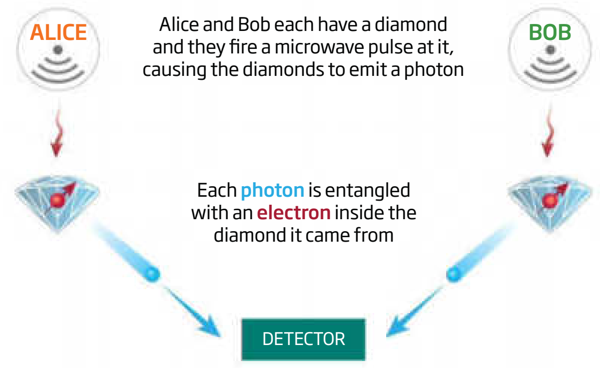
The rules of quantum theory say that the link between two entangled particles is "monogamous": there is no correlation with anything else and so no information can escape to an eavesdropper. Acín's neat insight was that you can prove whether this is the case using something known as a Bell test.

First set out by physicist John Bell in 1964, the test aims to determine whether two sets of numbers are more highly correlated than can be achieved by chance. "The more they are correlated together, the less they can be correlated with anything outside," Ekert says.

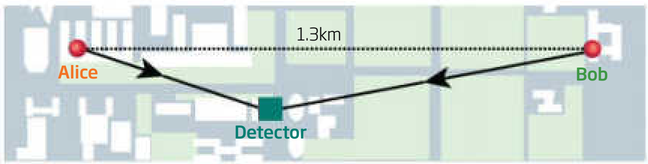
If your system passes the Bell test, you have a cast-iron guarantee of three things. First, that your key is generated on the fly and thus not predictable. Second, that its digits have an inherent randomness, and thus can't be guessed. Third, and perhaps most importantly, that no one is tapping into your

Privacy guaranteed

Earlier this year an experiment beat the loopholes that compromise the security of existing quantum cryptography



If the two photons arrive at the detector simultaneously, the entanglement gets transferred: now the electron in Alice's diamond is entangled with the electron inside Bob's diamond. This allows Alice and Bob to have entangled particles without needing to exchange them – and that closes the loopholes



Aerial view of experiment at Delft University, the Netherlands

key transmission using a back door. If they were, the correlations would be tainted.

There was just one problem with the scheme: no one had built a fully watertight experimental set up to conduct the Bell test. It comes down to the same problems that plague today's versions of quantum cryptography, plus one more that comes into play now we're dealing with entanglement.

This final problem is called the locality loophole. The worry is that there might be some as yet undiscovered signal relaying information between the entangled particles. If there were, that would invalidate our assumptions about randomness and open up the possibility of some genius adversary tapping the signal.

It might seem like madness to be concerned about all this, but there are two good reasons to push ahead. For one thing, get this right and we would have totally eliminated the need for trust. And for another, this is where the story of quantum cryptography intersects with physicists' quest to prove quantum theory is a full and accurate description of reality. Here is an opportunity to slay the lingering doubt about whether there is something beneath the spooky links between entangled particles.

Proving that there isn't would involve a Bell test where the locality and the detection loopholes are simultaneously closed. In the 51 years since Bell published his test researchers did one or the other, but no one had done both at the same time. It's surprisingly hard to do, according to Stephanie Wehner of Delft University of Technology in the Netherlands. "It's like saying I can ride a bike and I can juggle, so I must be able to juggle while riding a bike," she says. "It's not as easy as you might think."

But in 2015 Wehner and her colleagues finally performed a loophole-free Bell test. The crucial idea they harnessed in their experiment is called entanglement swapping.

"It's like a Y2K problem except we don't know when it will happen"

The Delft team set up two diamonds, 1.3 kilometres apart on their campus. Imagine our hypothetical Alice being stationed at one, Bob at the other. Each diamond contained a defect known as a nitrogen vacancy centre. Hitting an electron located there with a microwave pulse produces a photon that is entangled with the electron. The team arranged things so that pulses hit both diamonds at roughly the same time and their respective photons shot off to a detector in the middle. Here's the smart bit: if the photons arrived at that central detector exactly in sync, the entanglement would swap from being between each person's electron-photon pair to being shared between the electrons. Now Alice and Bob have a pair of entangled electrons that haven't travelled anywhere (see "Privacy guaranteed", left).

Because electrons are much easier to detect than photons, the experiment easily closed the detection loophole. And because the electrons were so far apart, the researchers had a 4-microsecond window in which to measure their correlations – plenty of time in 21st-century physics – and prove that any physical signal that could have created them would have needed to travel faster than light. Since this is forbidden by the laws of general relativity, of course, that took care of the locality loophole.

Under wraps

Thanks to this ingenuity, the correlations passed the Bell test, and we know that they are not due to detector errors, nor to a communication that has a hackable physical mechanism. "That feels good," says Wehner's college Bas Henson who led the project. Finally, we have closed the loopholes; quantum theory has passed the test and we know it can be used to create a certifiably safe cryptographic system.

There are still a few wrinkles. Familiar ones that have always hindered cryptographers. An enemy might break into your office and steal your key, for instance. "Physical security is always an issue," Mosca says. "If I can look into your lab and see the plain text, then I don't need to break your cipher." Makarov points to another caveat: the key distribution might be device-independent, but other parts of the system could be compromised. "You have to trust that no ingredient at the end stations contains some malicious piece," he says.

Those eternal issues aside, though, we have finally reached the end of the road for perfecting security. It will take time to move from proof of principle to application: implementing the protocol is still hard work for now. The Delft team achieved 245 entanglement events in 9 days – not exactly a useful rate for generating a cryptographic key, which might need to be thousands of digits long. But things are improving. "We expect to be able to make entanglement 100,000 times faster in the near future," says Henson.

Since Henson and his colleagues achieved their loophole-free Bell test, other groups have managed it too, using various different means. These successes suggest that device independent quantum cryptography, the last word in secret messaging, does now appear to be within our grasp. The quantum part provides an unbreakable protocol; the device-independence takes the reliability of the supplier out of the equation. "In terms of being able to verify physical security, it's the best," says Mosca. Ekert agrees: the Bell test routine is so simple anyone can use it. "You don't even have to understand physics." ■

Where worlds collide

Our two great theories of reality could soon be slugging it out far above our heads, says Sophie Hebden

IT IS a meeting point, this vast expanse of near-nothingness hundreds of kilometres above our planet's surface. Here, Earth's gravity is too weak for atmospheric gases to linger, but the absolute emptiness of outer space has not yet quite begun. Human activity is ever-present. Satellites wink and blink, monitoring, directing, communicating.

These satellites too are a meeting point. Deep within their sensors and electronic circuits, electrons and photons dance to the tune of our most fundamental theory of nature's workings: quantum theory. Its fuzzy uncertainties and instantaneous influences provide a peerless description of matter on the smallest scales. But to predict how a satellite itself will move – or any large body, from falling apples to stars, galaxies and the universe itself – we must call on a very different mathematical construction: the rigid, space-warping equations of Einstein's theory of gravity, general relativity.

These two theories really don't get along. In fact they are fundamentally, mutually antagonistic. So what happens when one trespasses on the other's territory? To find out, there is only one way to go. We must take our quantum experiments into relativity's realm – that marginal zone far above our heads.

If we have as yet failed to find a chink in the armour of quantum theory or relativity, it is not for want of trying. The space-warping quirks of relativity that lead to deviations from Newton's earlier theory of gravity only become obvious on very large scales, but our passive observations of distant planets, stars and galaxies have yet to deliver anything incompatible with Einstein's ideas. We can test quantum theory's weirdness more directly here on Earth, with the same result – which was much to Einstein's distaste.

ALEXANDER KENT

Take experiments performed by Anton Zeilinger of the University of Vienna, Austria, and his team over the past few years, beaming photons of light great distances in the Canary Islands. In quantum theory, particles such as photons exist as wave functions, probabilistic entities depicted as being in all their possible quantum states at once. When they are measured, however, they "collapse" into a definite state. What's more, the effect known as entanglement allows the fates of two or more particles to be intertwined. By measuring the state of one particle, you can collapse the wave function of another, seemingly instantaneously, however far away.

Einstein was dismissive of this "spooky action at a distance", preferring to think that some hidden, physical influence connected the measurements. Yet working on moonless, still nights to beam one of an entangled pair of photons 144 kilometres between the islands of La Palma and Tenerife, Zeilinger and his team observed just the correlated collapse in the photons' states that quantum theory dictated (see "What lies beneath", page 48).

Such trickery is already in practical use. An eavesdropper cannot listen in on information encoded in entangled quantum states without collapsing them, thus revealing the interception. Cryptographic keys written in photon polarisation states are now used to encode and decode messages in small-scale fibre-optic networks set up by government agencies, research labs and commercial companies worldwide.

This has its limits, though. Beyond 100 kilometres or so, absorption within fibre-optic cables tends to disturb any quantum information transmitted along it, rendering it useless. Unlike for classical information, we do not have any reliable way to boost quantum signals along their route. If we want to be enjoying the fruits of secure, global quantum communication any time soon, we will have to beam the signals via satellite.

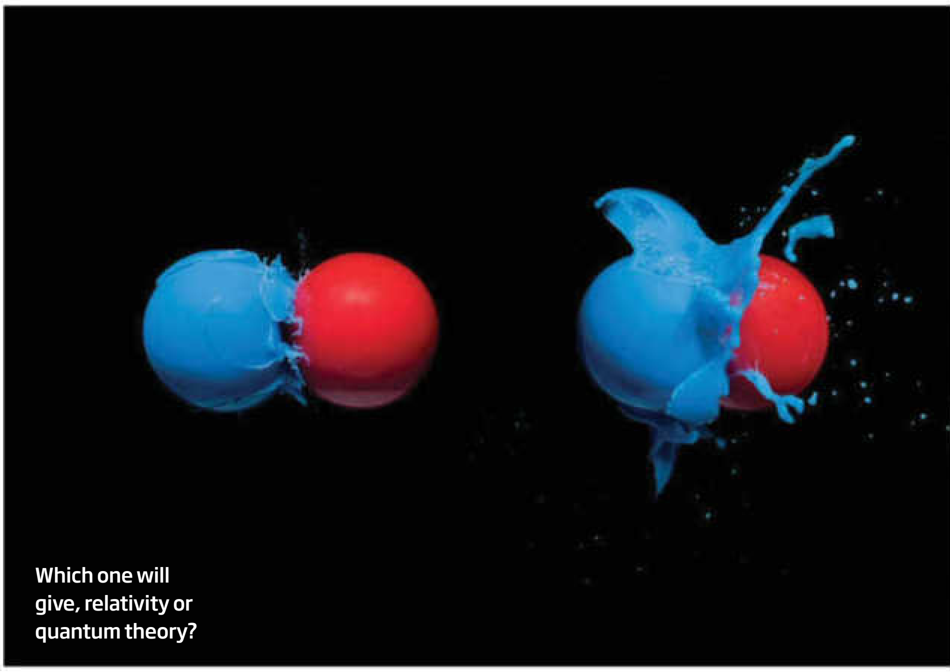
That gives a practical edge to a very fundamental question. "We've seen entanglement work over macroscopic distances, but is it going to work forever?" asks Giovanni Amelino-Camelia, a theorist at the Sapienza University of Rome in Italy. And there is good reason to believe that the sky might indeed be the limit.

Conflicting clocks

Entanglement as we know it on Earth relies on quantum theory's assumption that space and time form an impassive, unchanging background against which events such as measurements simply take place. Perform a measurement in one place, and observe a correlated effect in another, and you can be reasonably sure the one influenced the other. But in relativity's realm, space and time are, well, relative. Time appears to tick more slowly and space to contract for objects moving at high speeds relative to one another. The closer an object is to a large source of gravity, the slower its clock will run.

Such effects are negligible on Earth's surface, but GPS systems routinely correct for them as their signals bounce to and from satellites. And they could mean, for example, that the order in which things happen in › quantum experiments is no longer so clear cut. How do relativistic effects change things such as entanglement, if at all?

It is not the first time we have posed that question, but previous proposals to answer it have been frustrated. Zeilinger has been in discussions with the European Space Agency since 2002 about putting an entangled-photon source on the International Space Station so that he can fire them down to detectors on Earth. As yet, ESA has no firm plans to launch such a mission. A proposal in 2010 for a quantum link-up to a microsatellite sent into low Earth orbit by the Canadian Space Agency was eventually passed over, although "the possibility of doing fundamental science with the satellite remains", says one of the scientists involved, David Rideout of the University of California, San Diego. A NASA-funded mission to create entangled particles in orbit, co-ordinated by the Centre for Quantum Technologies in Singapore, has a prototype photon source in orbit now, but is not yet producing entangled particles.



Which one will give, relativity or quantum theory?

Satellite state

Enter the new, muscular player in all things space: China. An erstwhile student of Zeilinger's, Jian-Wei Pan of the University of Science and Technology of China in Hefei, is now leading a team developing the Quantum Science Satellite, the world's first dedicated quantum space probe. Due to launch in the second half of 2016, it will have a sun-synchronous orbit: it will pass over locations on Earth at the same time each day at an altitude of 600 kilometres.

Zeilinger is in on the project too. The first aim is to share a quantum cryptographic key via satellite between the Chinese Academy of Sciences in Beijing and Zeilinger's institute in Vienna. This will be used to decrypt a secure intercontinental phone call between the two – if things pan out. "The pressure's going up, we have a lot of challenges to overcome," says Yuao Chen of the Chinese team. Collisions with air molecules that disrupt the photon beams should be less of a problem than in the Canary Islands experiments: by going up and down, the photons travel less distance in the thickest layers of the atmosphere. Even so, only one of every million entangled particles transmitted is expected to make it to the detector.

The real problem is that the satellite will only be visible to the ground stations in China and Europe for a few minutes at a time as it shoots overhead at 8 kilometres per second. It will require a sure aim to lock the laser beams to the passing satellite. Pan and his team have been getting their eye in using a hot air balloon to simulate the vibrations, random movements and changes in altitude of a space platform, and a moving van with a rotating turntable to model the satellite's rapid fly-by.

The Chinese team is also investigating whether it is possible to make detectors that are sensitive enough to pick up entangled photons during the day – a decisive step to making a practical worldwide secure quantum communications network. "I find it fascinating, having done fundamental research for so many years, that we are moving closer to applications now," says Zeilinger. "It's a completely new game."

One, perhaps, with completely unknown rules. "We're not expecting entanglement to break down," says Zeilinger. But at the very least we can expect some ticklish questions. Beam a pair of entangled photons up to two satellites moving at speed towards one another, and measure them concurrently from the point of view of Earth, then to each of the two satellites the other's measurement appears to have happened first (see diagram, below). So which measurement caused the wave functions to collapse?

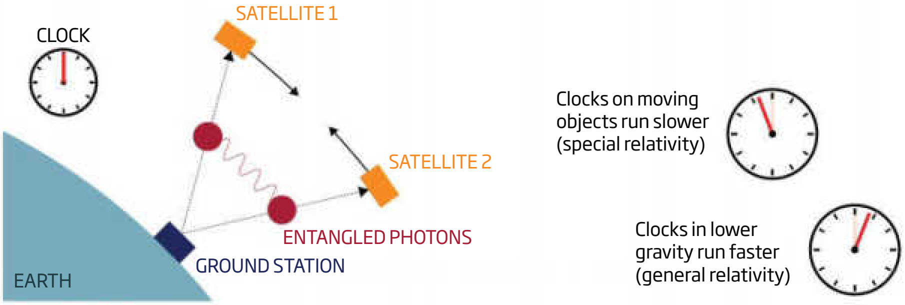
The hope is that by doing the measurements we can find out, and so bore more deeply into vexed questions of cause, effect and reality in the quantum world. Is a wave function a real object, and its collapse a process that happens in space and time? Or is it merely a mathematical shorthand for our state of knowledge of a quantum system, with the real action happening on a level we have not yet penetrated? Einstein favoured the second view, sparking a debate that continues to this day. "It's still very controversial, how to reconcile wave function collapse with our usual notions of reality and causality," says Rideout.

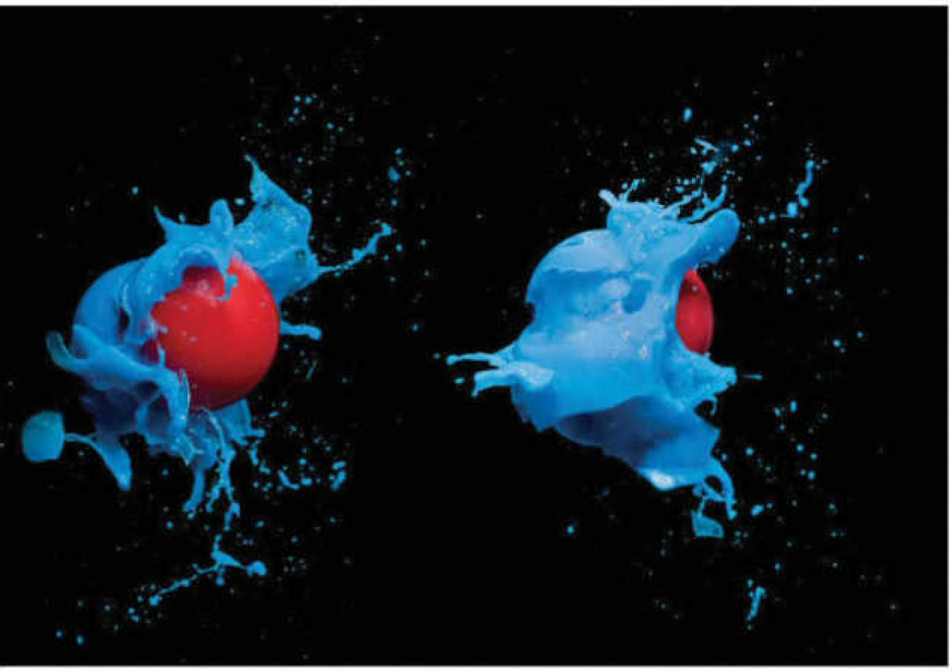
Others are not so sure that entanglement won't just break down at some point. Calculations published in 2013 by Tim Ralph of the University of Queensland in Brisbane, Australia, and his colleagues suggest that the relativistic time-stretching of a few hundred femtoseconds involved in sending one of an entangled pair of photons from the ground to

Which came first?

Imagine sending entangled photons to a pair of orbiting satellites

Einstein's relativity makes it difficult to tell the order in which the photons are detected





> "Quantum experiments in space are a completely new game – one, perhaps, with unknown rules"

a satellite just 200 to 300 kilometres up could be enough to do just that. But the calculated effect only really kicks in for short, well-defined photon pulses that are themselves less than about 100 femtoseconds long. That should not be a problem for the initial Chinese experiments, which will use a continuous beam, but it is something to watch out for.

For a dedicated test, Ivette Fuentes, a quantum theorist based at the University of Nottingham in the UK, and her colleagues propose analysing the entanglement between Bose-Einstein condensates. These large collections of atoms, chilled to near absolute zero, behave as one quantum system. The idea is to hold entangled condensates in two separate satellites, and then kick one into a different orbit. Calculations indicate that the acceleration needed for a change in orbital radius of just 400 metres would disturb a condensate enough to noticeably degrade its entanglement. A typical satellite manoeuvre changes orbital radius by as much as 60 kilometres – enough to completely disrupt the transmission of information in a future quantum network.

"From a theoretical point of view, we've shown that there are effects, but we need to confirm this with experiment," says Fuentes. And to test effects in space, we need to go to space: on Earth, we are limited to experiments in "drop towers" where condensates fall a maximum of 100 metres or so.

Entanglement is not the only quantum phenomenon we need to examine carefully in relativity's realm, either. Interferometer experiments on Earth, in which single photons are pinged along two paths of equal length, then made to combine at the other end, have seemingly confirmed that quantum objects can be in two places at once. In space, the idea would be to repeat the experiment along two different paths, one straight up to a satellite and along to a second, and one along close to Earth's surface and then up to the second satellite. The two photons will have passed along paths identical in everything but the average strength of gravity along them. What happens then?

Long-sought prize

We don't know, but that is exactly the point, says Ralph. "Something different might happen. It's very important to do these sorts of experiments to see if they really behave the way we expect them to." He has been discussing how such an experiment might be made reality with researchers from the European and Canadian space agencies, among others.

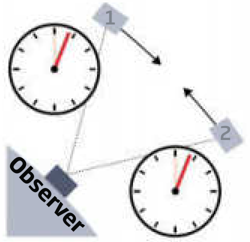
Quite apart from their relevance to any future satellite quantum-information network, deviations from what quantum theory or relativity predict could deliver a long-sought prize: the first whiff of a greater theory that might allow them to set aside their differences and unite. Theorists are not short of suggestions in the form of grand constructs such as string theory, but testing them was long believed beyond our technological capabilities. "Quantum gravity research was a free-for-all, the best theories were decided by a show of hands," says Amelino-Camelia.

In the late 1990s, he was among the first to point out an observable effect that a very large quantum experiment in space might just catch. Over distances of less than about 10^{-35} metres, at the Planck scale, most theories of quantum gravity predict that space-time no longer acts like a smoothly flowing continuum, as Einstein's relativity would have it. This bumpiness could have a slow cumulative effect on the polarisation of photons, randomly knocking them slightly out of kilter.

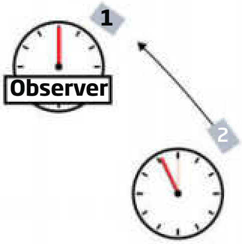
If the most optimistic models turn out to be right, we could see an effect by beaming polarised photons from the ground to a satellite in a low Earth orbit. At the worst, though, we would need to put a detector billions of light years away. "We have to be prudently pessimistic: we are just opening a window; it will only work if we are lucky," says Amelino-Camelia. Yet even a no could be a significant result, allowing us to start ruling out those theories that predict larger, albeit still small, effects.

But the possibility of one of these experiments presenting evidence of anomalous effects provides all the motivation he needs to take quantum tests into relativity's realm high above us. "If we get a yes, it will resound in the history of physics forever." ■

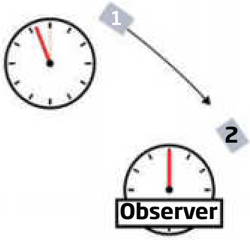
To an observer on the ground, it seems that clocks on both satellites are running fast. The two measurements might appear to take place at the same time



An observer on sat 1 will feel stationary, and the clock on the approaching sat 2 will seem to be running slow. So a measurement at sat 2 will appear to happen first



To an observer on sat 2, sat 1's clock is running slower and so the measurement at sat 1 appears to happen first



EDWARD KINSELLA

Zombie universe

Did the quantum world freeze into weirdness at the big bang, asks Jon Cartwright

AS ENDINGS go, it is a bit of an anticlimax. As the universe enters old age, its stars burn out. Slowly, the temperature across the cosmos reaches equilibrium. With no heat flowing, thermodynamic laws make it impossible to transfer energy in a useful way. Nothing interesting or productive happens any more. Everything creaks to a standstill.

This "heat death" of the universe was a favoured topic of the gloomier sort of 19th-century physicist. These days, we console ourselves that, if it is to happen, it will not be for many, many multiples of the current age of the universe.

Antony Valentini, a theoretical physicist at Clemson University in South Carolina, is less sanguine. For the past two decades, he has championed the idea that something like heat death has already happened – not in our layer of reality, admittedly, but on an underlying level that we are hard-pressed to see.

Fundamental physics is not short of eccentric and unworkable proposals, and it is easy to dismiss such a bold suggestion. But there are aspects of Valentini's idea that make some of his peers believe he might just be on to something. Just as a thermodynamic heat death would prevent us from doing anything useful with energy in the distant future, if Valentini's "quantum death" has happened, it could explain our puzzling inability to fully get to grips some of aspects of nature – those to do with quantum behaviour. "He's well respected and taken seriously," says Carlo Rovelli of Aix-Marseille University in France.

Now Valentini thinks he may have seen the first evidence for this theory, etched in the afterglow of the big bang. Strange as it might seem, quantum death might breathe new life into our understanding of reality.

It is almost 90 years since luminaries of theoretical physics, among them Albert Einstein, Niels Bohr, Werner Heisenberg and Erwin Schrödinger, gathered in Brussels to try and make sense of the bizarre results then emerging from atomic physics. At the 1927 Solvay conference, it was becoming clear that subatomic entities such as electrons could appear both as localised particles or as fuzzy, spread-out waves. Which one you saw depended on how you measured them.

Quite generally, quantum objects seemed to exist in a haze of indecision before anyone observed them. The newly apparent quantum property of spin, for instance, could take one of two values, conventionally termed "up" and "down". Until you tried to pin down the spin of something like an electron, it seemed to have both values at once, randomly choosing which guise to reveal only at the final moment.

This fuzziness, it later became clear, even extends from one quantum entity to another. If two electrons are born together, measuring one appears to instantaneously alter the state of the other, regardless of whether they are separated by metres, kilometres or even light years. Einstein in particular was not a fan of this "entanglement", damning it with the phrase "spooky action at a distance".

Shut up and calculate

Mathematically, though, all of this was no problem. As the pioneers of quantum physics showed, a quantum system, be it a single electron or an entangled pair, could be described by a "wave function" containing information on all the system's possible properties such as spin (see "Ghost in the atom", page 58). Just like tossing a die, you couldn't be certain which side of the wave function would show itself when you made a measurement. But a deft mathematical trick – simply squaring the wave function – ›

"Quantum death could explain our puzzling inability to get to grips with quantum reality" made it possible to calculate the probability that different sides would show up.

Such sleights of hand have allowed us to build solid technologies on fuzzy quantum foundations, from lasers to computers, solar cells and nuclear reactors. But we are left wondering what it all means. Before measurement, is an electron really a smeared-out cloud of probability, everything and nothing at once, as the wave function suggests? And how can it know what its partner is doing on the other side of the room – or galaxy?

After the 1927 meeting, most physicists settled on a common answer. Known fondly as the "shut up and calculate" school of thought, it is more formally the Copenhagen interpretation, after the institution at which Bohr, its prime mover, worked. It says that quantum mechanics is just a tool to help us predict the goings-on of the world, rather than necessarily being a description of reality itself. It works – just don't ask why.

"The usual answer is quantum theory works – just don't ask why"

Valentini is not the first to think this is a cop-out. The 1927 meeting gave air to several rival interpretations – a fact often glossed over, he says, because historical accounts were written mainly by advocates of the victorious Copenhagen interpretation, such as Heisenberg and Bohr. "The standard history you read in the textbooks is very skewed," he says.

Valentini's visions of quantum death began with one of those early rival theories. It was the brainchild of the French physicist Louis de Broglie, and unlike the Copenhagen interpretation makes a clear statement about what is real in the quantum world. Every particle exists in a definite location and with definite properties at all times, and is guided by an equally real "pilot wave". Entangled electrons are linked by a pilot wave so that a wiggle at one end – the manipulation of one of the electrons during a spin measurement, for instance – causes an instantaneous wiggle at the other, changing the other electron's properties, too. What we see as spooky action at a distance is the result of a complex, tangled web of pilot waves linking things on a level hidden from view.

The attraction of pilot-wave theory à la de Broglie is that it makes exactly the same predictions as standard quantum mechanics, and so like that theory agrees with all experimental results to date. But this is a double-edged sword: it means there is also no way to test whether it is a better description of reality than quantum mechanics. Given that the theory suggests mysterious, inscrutable layers of reality, most physicists have preferred to stay tight-lipped in Copenhagen.

But something left Valentini unsatisfied. Einstein's reservations notwithstanding, there is now no serious doubt spooky action exists: we exploit connections between entangled particles to create virtually uncrackable techniques for transferring information securely. The strange thing is that, although we know any "communication" between the particles must occur at many thousands of times the speed of light, we can't exploit the connection to actually send messages that fast. This central feature of quantum theory is, for us, strangely redundant. Einstein's cast-iron rule that nothing physical moves faster than light speed remains.

The reason, Valentini first realised in the early 1990s, lies in the probabilities that come from squaring the wave function. Do this calculation for many pairs of entangled electrons, and each electron in the pairs will turn out to be spin-up in exactly half of the instances, and spin-down in the other half. This equal split is crucial. Were it anything else – 100:0, 80:20, or even 51:49 – tampering with the electrons on one side could induce a noticeable change in those on the other that would count as an instant transfer of information (see diagram, right).

Such a 50:50 split seems an extraordinarily finely poised state for the universe to assume. In Valentini's eyes, it cried out for a physical mechanism to make it just so. Orthodox quantum mechanics says the universe runs purely on probability: it simply is the way it is with no reason to believe it hasn't always been like that. Pilot waves would make things a little different.

This is where thermodynamics comes in. Look at individual molecules in a canister of gas, and they are likely all to be at the same temperature and spread out over the available volume, in the same sort of deathly equilibrium the whole universe will some day seek out. Equally, experience tells us it is unlikely the molecules started out like this. When first injected into the canister, they

Out of the valley of death

Allow information to travel faster than light speed, and almost anything becomes possible. You can communicate instantaneously across galaxies, tap even the most secure quantum network and perhaps even build number-crunchers so powerful they would surpass even our wildest dreams of a super-powerful quantum computer.

In Antony Valentini's model of quantum death (see main story), such mayhem would have been over within the first instant of the universe's birth. But perhaps, as Valentini proposed in 2001, some particles managed to pull away from the mob in the aftermath of the big bang, and so avoid sudden quantum death.

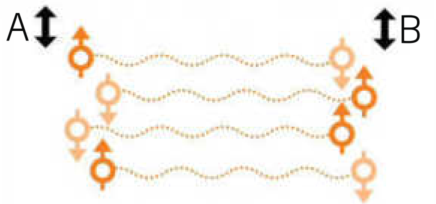
To do this, such relic particles would have had to be incredibly elusive – every sort of particle that we have detected so far, even the slippery neutrino, interacts with other matter too strongly. One possibility is the graviton, the hypothetical, massless particle responsible for the force of gravity.

The chances of detecting one of these in the foreseeable future is next to zero, given the vast detectors we must already build to bag a handful of neutrinos. A more likely possibility is a partner of the graviton, the gravitino. While these are also thought to be near impossible to detect directly, they could decay into other particles, such as photons, that satellite observatories might spot. These decay products ought to inherit the quirks of the universe before quantum death. Catch a bunch, entangle them and share them between two distant parties, and you would have a recipe for faster-than-light communication.

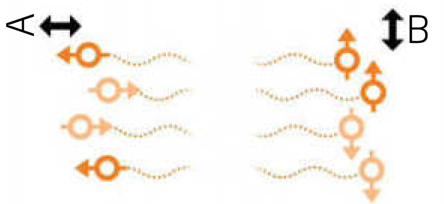
Unlimited chat

In today's quantum world, measuring the spin of entangled pairs of particles produces "up" and "down" with equal probability. This might not have been the case in the early universe, before a process of "quantum death" occurred. If so, faster-than -light communication was once possible

After quantum death (now)



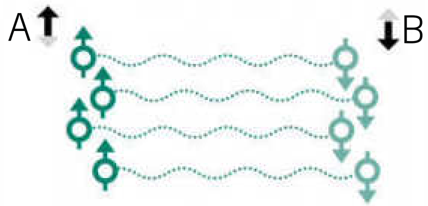
Alice measures her particles' spins to be up or down with equal probability. In every case, Bob's entangled particles adopt the opposite spin



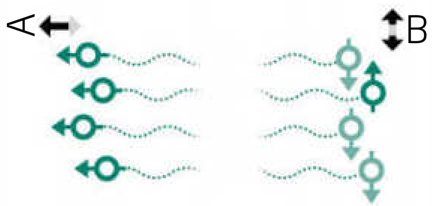
Alice now rotates her equipment by 90°. This breaks the direct correlation between each pair of particles. But Bob still measures half up, half down – there is no change in his measurement, overall:

No communication

Before quantum death



Without the equal probability rule, Alice might measure all her entangled particles to be spin up – in which case Bob measures all spin down



If Alice now breaks the correlation, with no equal probability rule there is no restriction on what Bob's spins can be. His measurements are different to before so he instantly knows Alice has rotated her equipment:

Faster-than-light communication

would have been in some non-equilibrium state, perhaps concentrated near the inlet.

In the same way, Valentini argues, the big bang produced a universe in a non-equilibrium quantum state. In those first moments, particle properties could have been highly ordered, with all the up spins in one place, and all the down spins in another. But the intense heat and violence made for an extraordinarily tangled web of

> "The tangled early universe would naturally have wanted to relax"

pilot waves that would naturally want to relax into a simpler state. Within a tiny fraction of a second, the pilot waves piloted the universe there. Unlike the long throes of thermodynamic death, quantum death came in an instant.

Valentini's extension of de Broglie's pilot-wave theory shows that those suspicious equal-probability splits, and our related inability to make use of spooky action at a distance, are not conspiracy or fine-tuning. They are the natural end for a universe starting out in any other quantum configuration.

Most physicists have no truck with any situation in which information can be transferred faster than light speed, which would have been the case in Valentini's early universe. It would overturn cherished concepts that have proved their worth over the past century, such as the idea that time is relative, with no one clock beating out the pulse of the universe. "To me it's very worrisome," says theorist Daniel Sudarsky of the National Autonomous University of Mexico. "It would change our whole conception of the nature of space-time."

Relics from the time before quantum death might live on in our current universe, potentially still causing mayhem with our notions of what physics does and doesn't allow (see "Out of the valley of death", left). Whether that is the case or not, Valentini thinks he has seen clues that reinvigorate the whole idea of quantum death.

Soon after the big bang, while in the throes of quantum death, the universe is thought to have undergone a short-lived burst of breakneck expansion known as inflation, which amplified tiny differences in density to give the seeds of the stars and galaxies we see today. We don't yet have any evidence for inflation, although researchers are looking for it in the polarisation patterns of the cosmic microwave background, which is the sea of radiation left over from the big bang that fills all of space. In 2007, Valentini predicted that inflation would also have magnified any density fluctuations that hadn't yet reached quantum equilibrium. Their odd distributions should be imprinted in the microwave background as a slight loss of power at longer wavelengths. In 2013, data from the European Space Agency's Planck satellite gave the first conclusive evidence that such a power deficit exists. "It's good news," says Valentini. "Qualitatively, it fits."

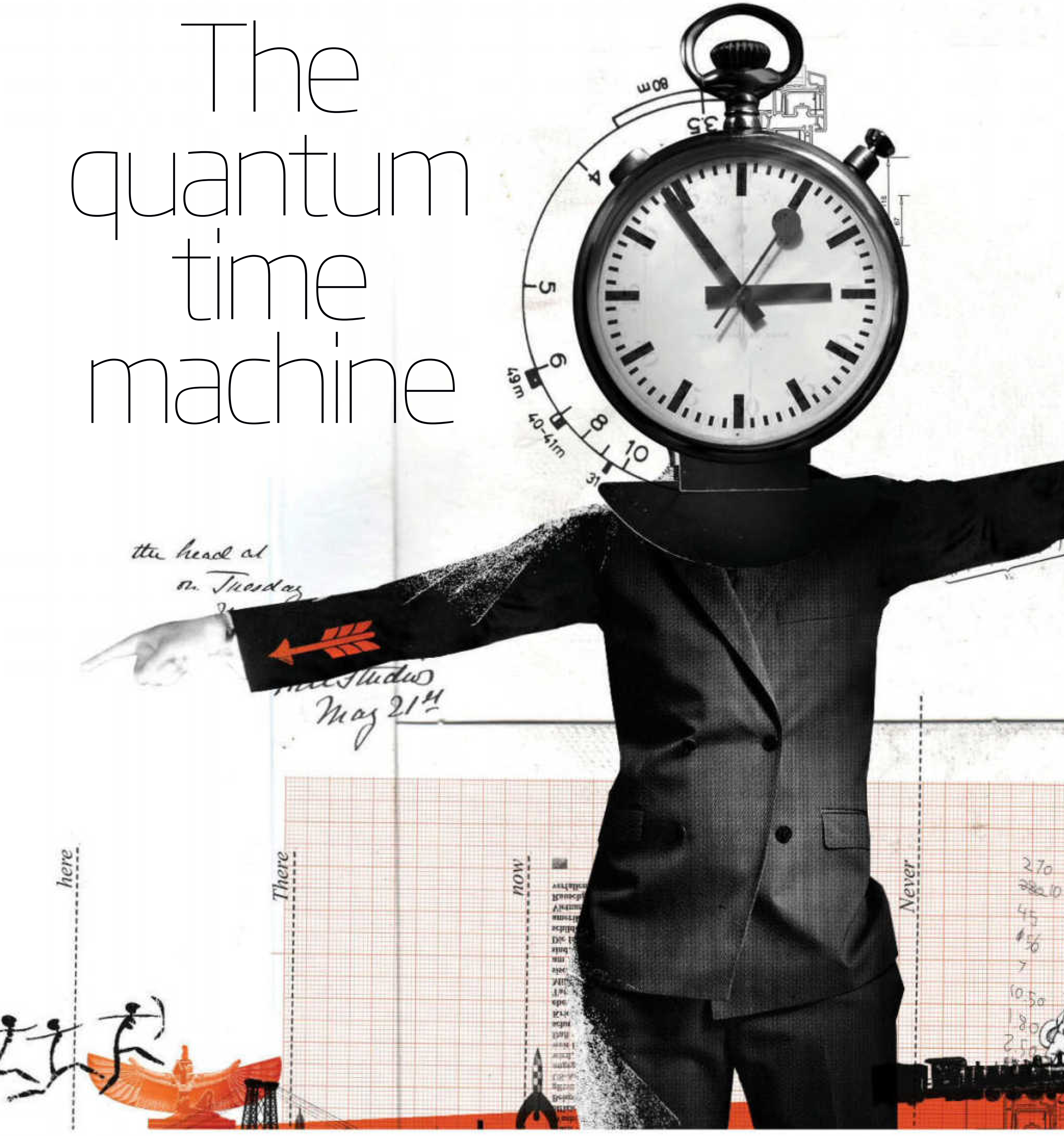
Not everyone agrees. Glenn Starkman, of Case Western Reserve University in Cleveland, Ohio, says there were already hints of a power deficit in data from Planck's predecessor, NASA's Wilkinson Microwave Anisotropy Probe. Valentini would have known about this, he says, which makes his prediction retrospective – and therefore unconvincing. "He needs to come up with a distinguishing prediction for something we haven't already measured," Starkman says.

Valentini takes on board such scepticism. Together with his Clemson colleague Samuel Colin, he is working on a more detailed prediction about how features in the cosmic microwave background should vary with its wavelength. This would concern not only power, but also anisotropy – a lopsidedness in the distribution of fluctuations across the sky. There is good reason to aim for this. "It'd be like killing two birds with one stone," he says. "With two pieces of evidence, there will be a considerably stronger case."

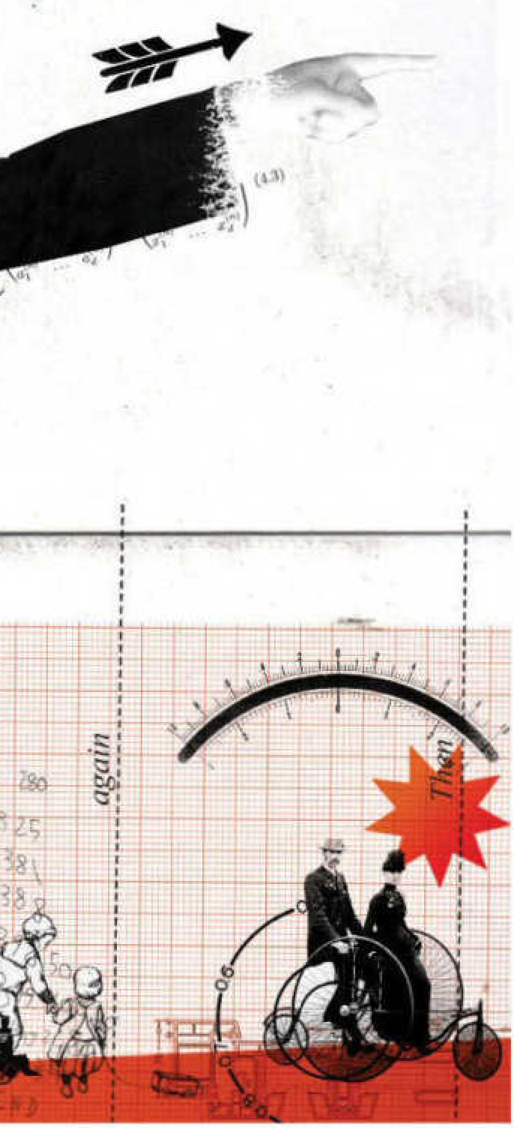
Valentini appeals to common sense. After all, thermodynamics allows us to perform useful work – it is only after the prophesied heat death that nature will get lazy. Does it not make sense, he asks, that our inability to exploit what quantum theory offers is the result of an analogous quantum death?

"What has always puzzled me is that there's this kind of conspiracy," says Valentini. "On one hand, quantum theory seems to be fundamentally non-local – something is going on faster than light. On the other, you can't actually use it to send a signal. And just intuitively, it seems to me that there is something going on behind the scenes." ■

The quantum time machine



Who says you need wormholes or black holes to see time travel in action? **Justin Mullins** goes back to the future



MARIE LUISE EMMERMANN

CHATTING about time travel in a room overlooking a verdant quadrangle at the Massachusetts Institute of Technology seems strangely appropriate. The building dates from 1916 and looks its age: the high ceilings, echoing corridors and musty offices with heavy wooden doors have changed little in that time. If it weren't for a computer screen in the corner, the room's interior could almost date from that time.

The office belongs to Seth Lloyd, one of the world's leading theorists on quantum mechanics. We are talking about a paper he and his colleagues have published. It describes a subtle twist on time travel. This kind of paper crops up every few years, and usually focuses on some kind of thought experiment that uses logic and reasoning, rather than equipment, to describe how time travel could occur for real.

Except, there is always a caveat; the unfortunate time traveller must journey to the edge of a black hole to perform the feat, for example. So there is never an experimental test of the ideas. It is all good fun and usually worth a few column inches, but there is rarely anything to get your teeth into.

Lloyd has come up with an alternative way of looking at the problem using quantum mechanics, so I am keen to hear about his thought experiment and, of course, to learn about the inevitable caveat. He is telling me how photons could travel back in time when he says something extraordinary: "...and we've done the experiment," he says casually. "You've seen that paper too, haven't you?"

I stare disbelievingly. For a split second, it seems time stops still. "The experiment?" I think. As Lloyd continues, his story becomes even more amazing. Not content with just thinking about sending photons into the past, the experiment is a physical recreation of the famous "grandfather paradox". This is the mind-twisting problem in which a time traveller visits the past and kills his grandfather before his grandmother is even in the picture, meaning the time traveller will never exist and so cannot have travelled into the past to kill his grandfather.

I am stunned. We have been trying to get our heads around time travel for centuries. Now Lloyd and his collaborators have identified an approach to the problem that opens up the strange world of time travel to experiments.

What is so tantalising about time travel is that there seems to be nothing to prevent it. As far as the laws of physics are concerned, time can run forwards or backwards. But time travel of the kind that Marty McFly gets up to in the movie *Back to the Future* is a different kettle of fish. It requires an object to go back in time while everything else keeps creeping forward. Still, there is no shortage of ideas about how this might happen.

Most of them focus on the fabric of space-time as the medium of travel. According to Einstein's general theory of relativity, space-time is a kind of substance that can be squeezed and stretched like a giant sheet of rubber. A massive object like a star deforms this fabric causing everything in its vicinity to feel the pull towards it.

Twist space-time enough, however, and strange things can happen. If the sheet becomes folded, for example, regions that are ordinarily far apart suddenly become connected, setting up a loop called a "closed time-like curve" that would allow a time traveller to repeatedly visit the same point in space and time (see diagram, page 114).

"Quantum particles such as photons and electrons are not bound by the arrow of time"

The first person to show how relativity leads to closed time-like curves was the Austrian mathematician Kurt Gödel. His 1949 blueprint for a time machine required the whole universe to be rotating. Many related ideas have been put on the table since then, ranging from long strands of energy known as cosmic strings to rotating black holes and tunnels through space-time called wormholes.

Quantum physics entered the scene when theorists began asking how a quantum particle would fare if it were to make a leap into the past. In 1991, the British physicist David Deutsch put this question on a firm theoretical footing. He imagined a particle that travels back and destroys its former self, creating a grandfather-type paradox.

Against all expectation, Deutsch went on to solve the paradox. He did so by invoking the "many worlds" interpretation of quantum mechanics in which the instant the particle enters the closed time-like curve, the universe splits in two. In one universe, the particle survives having failed to kill itself; in the other, it is destroyed. By invoking multiple › universes, Deutsch cunningly avoids the grandfather paradox and resolves one of the fundamental problems with time travel. But many physicists feel uneasy with the many worlds idea because it spawns an unimaginably huge number of other universes and is unnecessarily complex.

Lloyd and his colleagues have taken a different approach to quantum time travel, using the fact that quantum particles such as photons and electrons are not bound by the arrow of time.

The mathematics of quantum theory says that the quantum state that describes them evolves both forwards and backwards in time. This odd state of affairs has led to some researchers claiming that the normal rules of causality don't apply, so things that happen in a quantum particle's future will affect its past.

One of the first people to show this was John Wheeler at Princeton University. He showed that the classic "double slit" experiment, where an unobserved photon passes through two slits simultaneously, can be affected by a measurement that takes place after the experiment is ostensibly finished.

"The experiment behaves as a time travel simulator, making it possible to do extraordinary things"

The wave characteristics of the unobserved photon means it passes through both slits at once. If it is observed as it goes through the slits, experiments have shown that it will take on particle-like qualities and only go through one. Wheeler wanted to know what happens if you delay your decision to look at the wave or particle nature of the photon until long after it has passed through the slits.

He suggested that using a pair of distant telescopes to look back at the slits would also force the photon to take on particle-like properties. This selection of a property after the main part of the experiment is effectively over is known as "post-selection". Post-selection may sound unsettling. However, experiments by Jean-François Roch at the Ecole Normale Supérieure in Cachan, France, and others have shown that post-selection really does change the properties of a photon up to a few nanoseconds into the past.

According to the Copenhagen interpretation of quantum theory, there is no objective reality until a measurement is made. But we are beginning to learn that even that reality may be a moveable feast: the past state of a quantum particle has no more reality than its future state. Which is why post-selection has an effect. In other words, everything is up for grabs. In theory, the post-selection process could even change the entire history of the universe.

Lloyd and Aephraim Steinberg, of the University of Toronto, Canada, say this peculiar property of the quantum world might be the key to a working time machine. Our daily experiences tell us that the conditions given at the beginning of an experiment will determine its outcome. But if quantum particles can't discriminate between things that affect them forward and backward in time, that means specifying a final condition can determine what happens before it. "Mathematically, there's no reason why final conditions can't be 'givens' as well and everything has to follow logically from them," Steinberg says.

Instant teleportation

It is exactly this sort of thinking that led physicists Charles Bennett at IBM Research in Yorktown Heights, New York, and Ben Schumacher at Kenyon College in Gambier, Ohio, to suggest that quantum mechanics could be used to build a time machine by making use of quantum teleportation, a phenomenon that has been demonstrated experimentally countless times. The process exploits a curious quantum property called entanglement, by which two particles, such as photons, become so closely linked that they share the same existence. Entangled particles are special because a measurement on one immediately influences the other, no matter how far away it is.

Now imagine that you want to teleport a third space-travelling particle from A to B. The trick is to make a pair of entangled particles and place one of them at A and one at B, then carry out a set of measurements at both locations. If you do this just right, you can use this "spooky action at distance", as Einstein called it, to ensure that the second particle ends up in a state that is exactly the same as the "space traveller".

In fairness, the traveller hasn't physically moved, but the quantum information that completely describes the traveller has made the trip instead and this allows the second particle at B to take on the traveller's identity.

The curious thing about teleportation is that it occurs instantly. In this process, the quantum information moves from point A to point B, so it is natural to think that the measurements at A set the journey in motion.

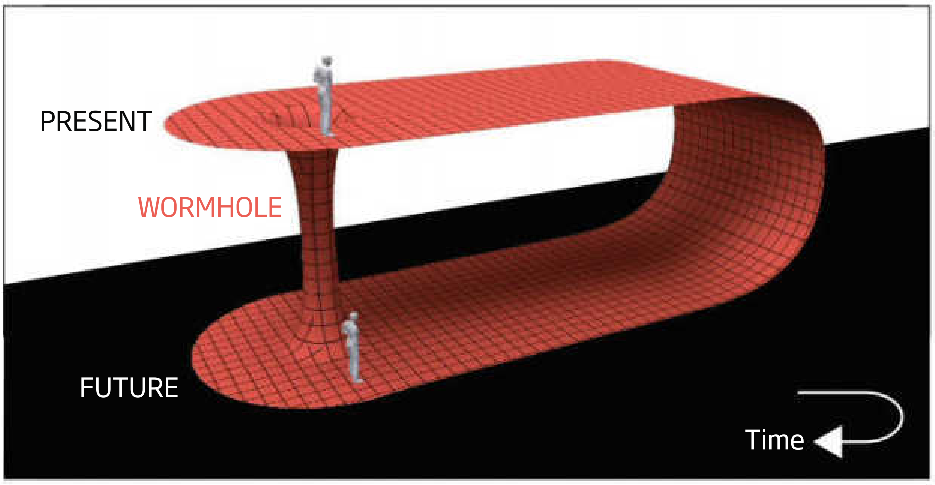
But because teleportation happens instantaneously, it is just as valid to think that the measurement at point B triggers the journey, even though it takes place moments later (see diagram, below right). This is post-selection in action and it is a feature that quantum physicists use all the time to do things like quantum computation. It is this ambiguity between cause and effect that Steinberg and Lloyd exploit in their time-travel simulator. "In essence, the time travel is just teleportation," says Steinberg.

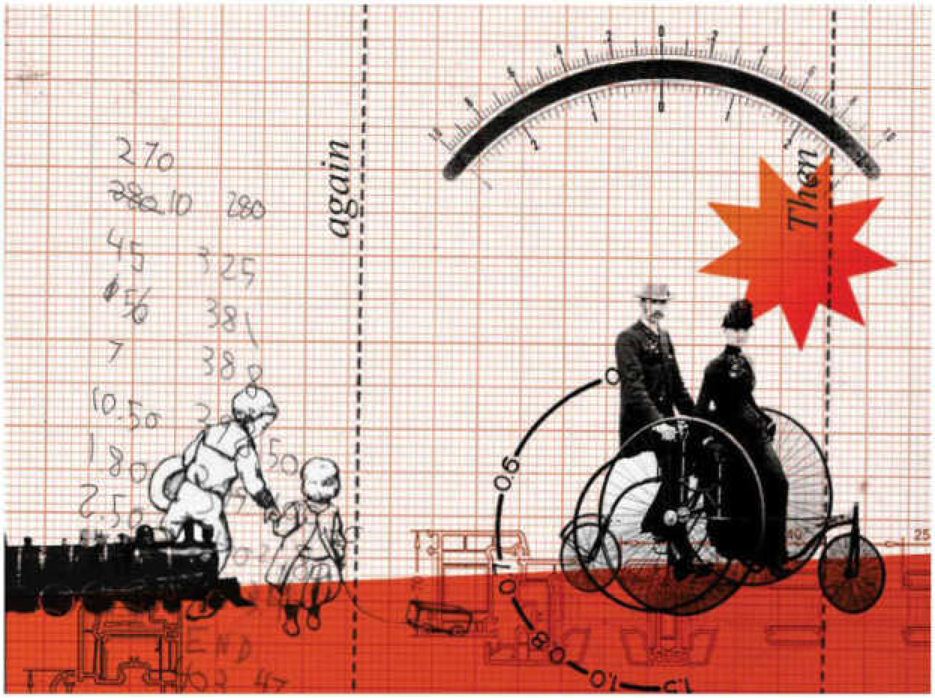
Is it an exaggeration to call this time travel? Perhaps – in the same way that quantum teleportation transports a quantum state and not a material object. Yet Lloyd and Steinberg argue that the logic of post-selected teleportation is the same as for time travel, so their experiment is a time travel simulator. And while that may not be as exciting as a time machine that can send us back to the dinosaurs, it is possible to do extraordinary things with it.

The first thing Lloyd and Steinberg's team did was to simulate the grandfather paradox by sending a photon back to kill itself. To do this, the team used teleportation, but with a crucial twist. Conventional quantum teleportation is guaranteed to give you a replica of the state that you intend to send. What Steinberg and Lloyd wanted to know is whether this would work for photons intent on killing themselves with a quantum gun.

Two ways to time travel

Time travel is possible in theory through a tunnel in space-time (below) or using quantum mechanics (right)





MARIE LUISE EMMERMANN

To work, their simulator required two additional features: a quantum gun that sometimes fires, and a means for the teleportation itself to fail. The team also decided that, rather than entangle two photons, as often happens in quantum teleportation, they would entangle two attributes of a single photon. The photon's polarisation would represent the photon's "present" and its direction would represent the "past". Next, they gave the photon a quantum gun that can either fire or fail. This device, called a wave plate, can flip the photon's polarisation, or not. Because the photon's polarisation and direction are entangled, giving the photon such a gun affects the "past".

Now, how to ensure that the teleportation sometimes fails? That is easier, as teleportation has an in-built failure mechanism. Unless you make your measurements in a particular way, it only works 25 per cent of the time. So there are four possible outcomes from the team's experiment, depending on the combined status of the teleportation and gun.

When this experiment is done, something interesting happens: every single time the time travel works, the gun fails to go off. And when time travel fails, the gun works. To put this in the language of the grandfather paradox, as long as there is some chance of your gun misfiring and the assassination failing, time travel may work. "You can point the gun but you can't pull the trigger," says Lloyd.

Clearly time travel has some important implications, not least for the nature of free will and our ability to exercise it. Time travellers may be somehow prevented from even thinking about shooting their grandfathers or perhaps they can make the decision to shoot only to be foiled in some other way. "Nature wouldn't care much whether it interferes with my synapses or with the workings of my Colt 45," says Steinberg.

While the idea of a time travel simulator is a jaw-dropper for many people, the work has so far made little impression on quantum physicists. That is because the experiment does exactly what quantum mechanics predicts – there is no controversy over how teleportation works or how bits of quantum information, or qubits, behave. "Sure, it's fun, but everyone knew perfectly well what the outcome was going to be," says Scott Aaronson, a computer scientist also at MIT.

Testing times

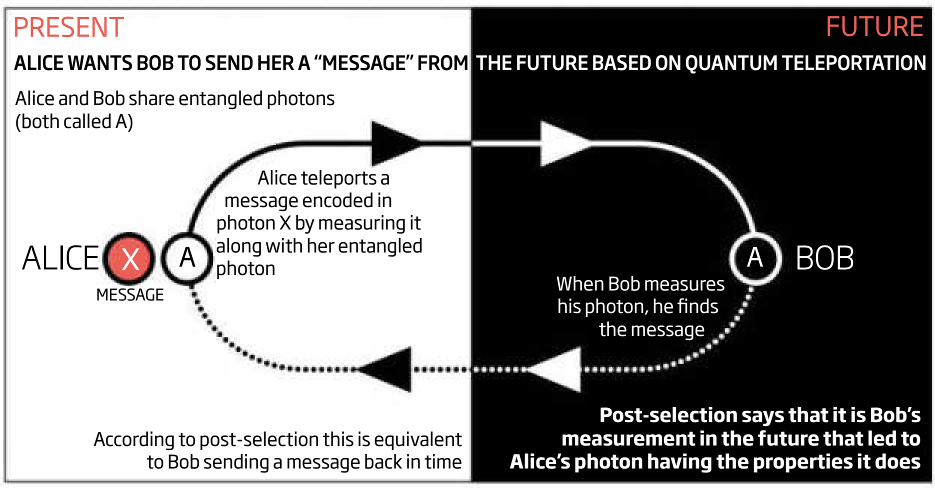
Lloyd and Steinberg have a different take. They say that thinking about time travel in this way raises important questions and provides significant new insights. For a start, it can actually be tested in the lab, unlike Deutsch's closed time-like curves. And while post-selection may feel like cheating, that could just be because we are biased towards a specific direction for time.

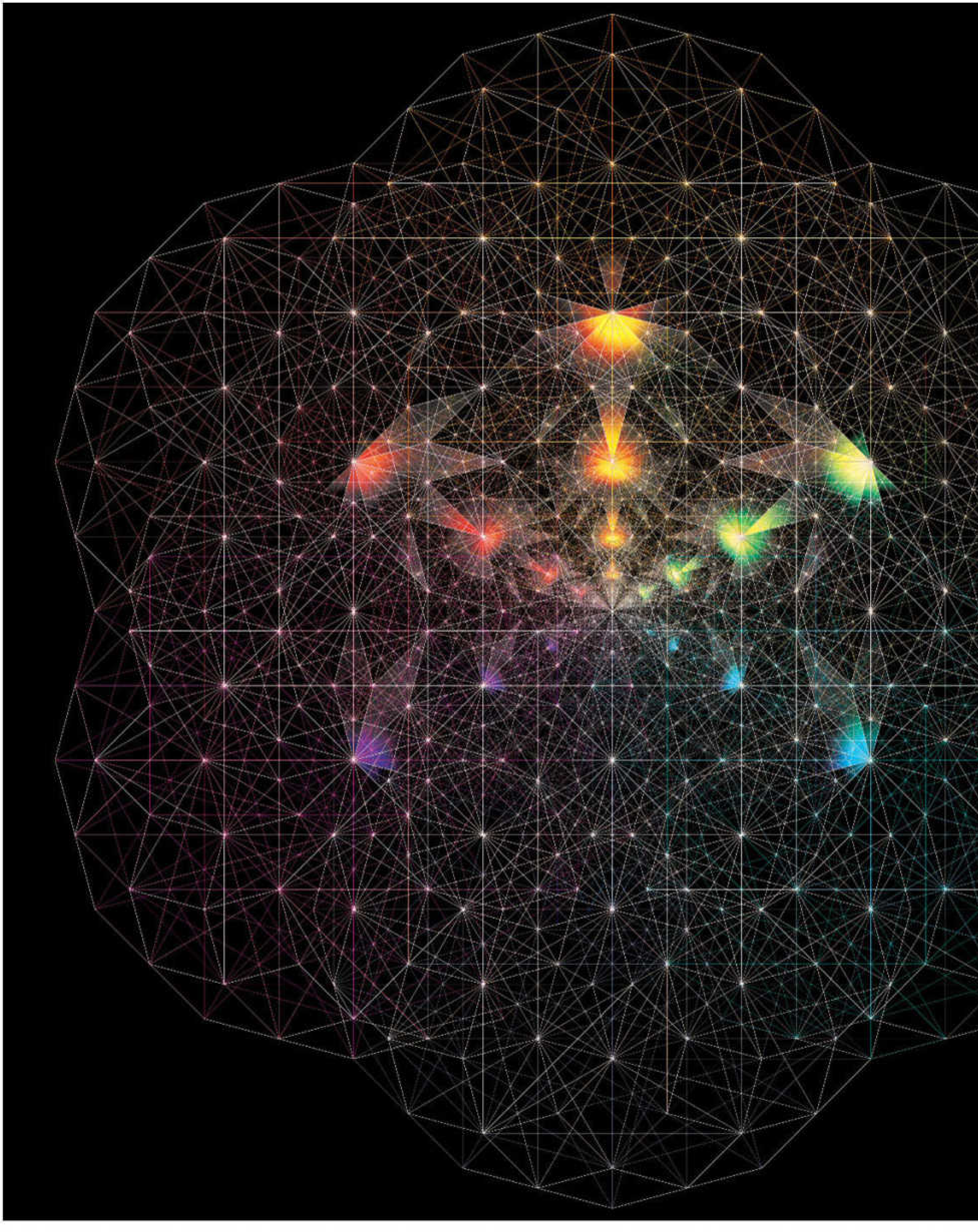
While Lloyd and Steinberg's experiment simulates time travel, one question remains. Is it really possible to time travel without black holes?

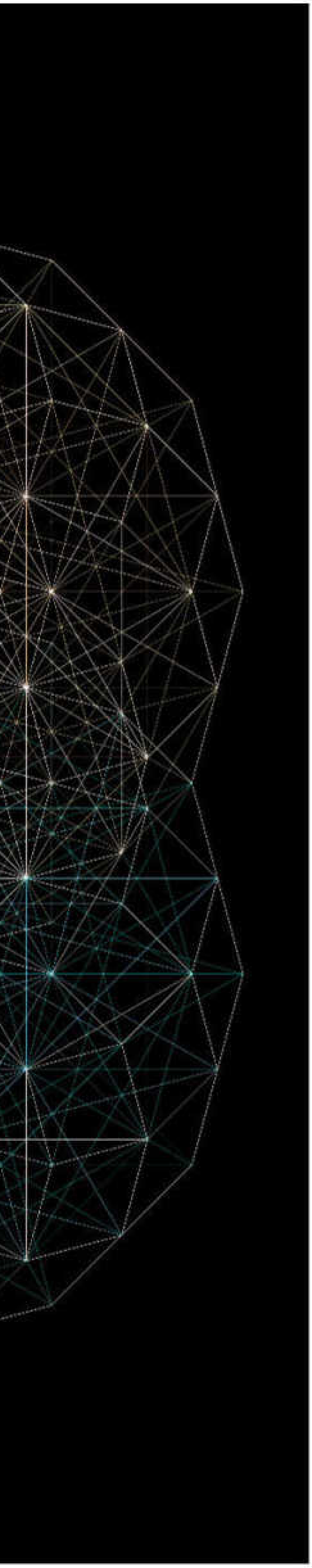
According to certain formulations of quantum mechanics, the answer is yes. One of the most troubling aspects of quantum mechanics is that it is so incompatible with general relativity. Solving this problem will be essential to creating a "final theory" of physics. For decades, physicists have tried to combine the two into a quantum theory of gravity and failed. While many lay the blame with relativity, others suspect that the problem is really to do with the incompleteness of quantum mechanics.

This has motivated alternative formulations of quantum mechanics. Aram Harrow, now a colleague of Lloyd's at MIT, points out that these can skew quantum mechanical measurements in the same way that post-selection does, meaning that time travel is viable in theory. So far, physicists have no evidence for such formulations of quantum mechanics, though that is not to say that there aren't places in the universe where they might operate.

So back to the original problem: will time travel be possible? Maybe, but chatting about time travel in a room overlooking a verdant quadrangle at the Massachusetts Institute of Technology seems strangely appropriate. The building dates from 1916... ■







ANDY GILMORE

ENTANGLED UNIVERSE

Weird connections through space-time might be the warp and weft of reality. **Anil Ananthaswamy** pulls at the threads

IT WAS a cryptic email that Juan Maldacena pinged across the US to fellow physicist Leonard Susskind back in 2013. At its heart lay a single equation: "ER = EPR". The message clicked with its recipient. "I instantly knew what he was getting at," says Susskind. "We both got quite excited."

Excited, because that one equation promises to forge a connection between two very different bits of physics first investigated by Albert Einstein almost 80 years ago. Excited, because it could help resolve paradoxes swirling around those most befuddling of cosmic objects, black holes, and perhaps provide a route to a unified theory of physics. Excited, because it might even answer one of the most fundamental questions of all: what is reality made of?

The origins of the story lie precisely a century ago. In November 1915, Einstein presented the final form of his revolutionary theory of gravity to the Prussian Academy of Sciences in Berlin. The general theory of relativity overturned notions of gravity that stretched back as far as Isaac Newton's day. It said that everything that happens in the cosmos at large – be it an apple falling from a tree on Earth or the distant whirling of a cluster of galaxies – happens because stuff follows invisible contortions in space and time that are caused by the presence of other stuff. Gravity follows from the geometry of a warped space-time.

In the past century, general relativity has never failed an experimental test. Yet the suspicion has grown that it is missing something. The theory describes space-time as a malleable yet smooth and featureless backdrop to reality. Problems start when a great agglomeration of matter folds this cosmic fabric so tightly that a black hole singularity arises – an object with a gravitational pull so great that nothing can escape, not even light.

Black holes are a prediction from the earliest days of general relativity. But in the 1970s, physicists Jacob Bekenstein and Stephen Hawking derived a strange result about them: black holes have a temperature, and hence a property called entropy. This takes us into the realms of quantum theory where everything, be it forces or matter, comes in discrete chunks. Entropy measures how many ways you can organise a system's various constituents – the arrangement of atoms in a gas, for example. The greater the number of possible configurations, the higher the entropy.

Hole in the theory

But if a black hole is just an extreme scrunching of smooth space-time, it should have no substructure, and thus no entropy. For Susskind, of Stanford University in California, this contradiction points to a hole in Einstein's theory. "We know that general relativity is incomplete," he says. "Its inability to account for the entropy of black holes is probably the most obvious incompleteness of the theory."

That's a turn up for the books. In his lifetime, Einstein levelled a similar charge at quantum theory. In May 1935, the *New York Times* ran a story with the headline "Einstein Attacks Quantum Theory", reporting on a paper Einstein had written with Boris Podolsky and Nathan Rosen. It brought to light a weird property of the quantum world in › which two particles could instantly influence each other, even if they were at opposite ends of the universe. In Einstein's view, this "spooky action at a distance" – quantum entanglement, as it became known – was preposterous. It was a clear sign there was something missing from the quantum description of reality.

But quantum theory has breezed through even more precise experimental tests than those devised for general relativity. And it is the very property that Einstein discovered – entanglement – that continues to expose the contradictions between the two theories. Allowing quantum entanglement and general relativity to cohabit in the contorted space-time around black holes yields unpleasant and unsustainable consequences. For example, information seems to be destroyed – an impossibility according to quantum physics – or the black hole becomes surrounded by a blazing "firewall" of energetic particles (see "Paradox regained", left).

So we need some way to square the two schools of thought – to quantise space-time and form a quantum theory of gravity. Susskind and Maldacena, who works at the Institute of Advanced Studies in Princeton, have long been leading lights in perhaps the most promising field with this aim: string theory. It replaces the point-like particles of current quantum theories with wiggling strings of infinitesimal size, and suggests space-time has a grainy substructure – you can't keep chopping it indefinitely into smaller and smaller pieces.

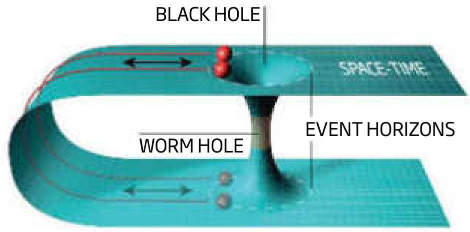
But if string theory does hold the answer, it's well hidden. The theory has more than 10^{500} solutions, each describing a different sort of universe – making it nigh-on impossible to find the one solution that corresponds to the geometrically flat, expanding space-time filled with the exact complement of fundamental particles we observe around us.

A startling insight from Maldacena in 1997 gave new hope. He conjectured that string theory equations describing gravity in some volume of space-time were just the same as a set of quantum equations describing the surface of that volume. If you could solve the surface equations, you could get a viable theory describing gravity inside.

This "Maldacena duality" was a bold leap – but physicists found that it held. "The funny thing was that it was not proven, and it was

Quantum web

The fabric of reality might be woven from quantum entanglement



"Wormholes" connecting two black holes in different parts of space-time can exist - but only if particles on the black holes' surfaces are quantum entangled

difficult to even understand why this was happening," says theorist Mark Van Raamsdonk of the University of British Columbia in Vancouver, Canada. "It was very mysterious."

In 2001, Maldacena himself provided an intriguing example, going back to a paper written by – you guessed it – Einstein, again with Rosen, and again in 1935. This one exposed another peculiarity of black holes. It showed how something that looked like two separate black holes from the outside might be connected on the inside. This interior connection formed a shortcut through space-time, and came to be known as an Einstein-Rosen bridge – or in common parlance, a wormhole.

Chewing gum wormhole

The really odd thing, though, was that Maldacena's duality showed that such a wormhole would only form if the outsides of the black holes were quantum-entangled.

By 2009, the underlying mathematics was sufficiently well developed for Van Raamsdonk to explore further. Entanglement is not an on/off thing – it can exist in varying degrees. So what would happen if you were to slowly reduce the amount of entanglement between the black holes' surfaces to nothing? The answer was rather like pulling at two ends of a piece of chewing gum. "The two sides get further apart, and what's connecting them is this really thin piece of gum, and eventually it snaps," he says. The wormhole becomes

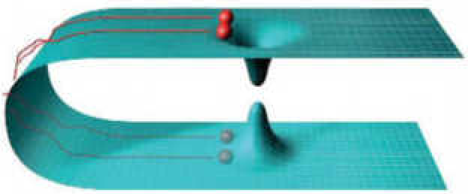
PARADOX REGAINED: THE BLACK HOLE PROBLEM

In the 1970s, Stephen Hawking showed that black holes emit radiation. The mechanism has to do with quantum mechanics, which allows pairs of quantum-entangled particles to spontaneously pop into existence. When this happens near a black hole's event horizon, one particle may travel outwards, while the other goes towards the black hole. The result is a steady stream of outgoing particles, called Hawking radiation.

If no new matter falls into the black hole, this emission means the black hole will eventually evaporate. But matter is information, and in quantum theory information is sacrosanct: it can never be destroyed. So if a black hole evaporates, what happens to the matter, and therefore information, that fell into it?

One possible solution to this "black hole information loss paradox" is the idea that information escapes with the Hawking radiation. But in 2012, Joseph Polchinski and Don Marolf of the University of California, Santa Barbara, and colleagues showed this option creates other problems. General relativity demands that the space-time around a black hole's horizon should be smooth and featureless. It turns out that for this to be the case and for information not to be lost, a Hawking particle on its way in would have to be entangled with all other Hawking particles that left the black hole at all earlier times, rather than just its partner outside the horizon.

This offends a fundamental quantum rule known as "monogamy of entanglement" - that a quantum particle can only ever be fully entangled with one particle at a time. But if you break the polyamorous entanglement of Hawking particles, an energetic "firewall" of radiation forms at the event horizon. That, unfortunately, goes against the tenets of general relativity. Paradox preserved.



Break the entanglement, and the wormhole snaps too, suggesting entanglement is the thread that binds space-time together

thinner until it breaks, and you have two unconnected bits of space-time (see diagram, above). Reverse the process – increase the entanglement – and the wormhole starts to form again.

It took a few more years for the penny to finally drop in Maldacena's mind, and for him to make the suggestion laid out in that excited email. ER = EPR. ER – the paper Einstein wrote with Rosen in 1935 introducing the concept of wormholes. EPR – the paper he wrote with Podolsky and Rosen the same year introducing the concept of entanglement. What if, asked Maldacena, wormholes and entanglement are in fact two sides of the same coin: the same physics in two different guises?

The immediate attraction was that the principle seemed to get rid of those pesky paradoxes involving firewalls around black holes (see "Paradox lost", right). But it also provided some form of explanation for the phenomenon Van Raamsdonk's work had exposed, in which space-time in the form of wormholes could be created and destroyed simply by tweaking the amount of entanglement.

"It's pointing to a statement that is really quite dramatic," says Van Raamsdonk. "Space-time is really just some geometrical manifestation of entanglement." Maldacena comes to the same conclusion. "There is a very close connection between quantum mechanics and space-time," he says. "The continuity of space-time, which seems to be something very solid, could come from the ghostly properties of entanglement."

Susskind speculates further. Quantum entanglement is a form of information, and so "space-time is a manifestation of quantum information", he says.

Heady stuff. But does that really mean that when quantum entanglement exists between two particles – as can easily be made to happen, say between photons in a lab experiment – they are connected by a microscopic wormhole? Or that we live on a backdrop that is nothing more than the 1s and 0s of entangled information?

The short answer is we don't know. One very big caveat is that all of the work linking entanglement with space-time so far has been done with a space-time that isn't expanding. Van Raamsdonk and others are working to extend the results to the sort of expanding, accelerating space-time that makes our cosmos.

But for those involved, this is the most positive lead yet towards a theory of quantum gravity that can unify the forces of nature. The ER = EPR principle is something "that a theory of quantum gravity should obey", says Maldacena. Susskind thinks so too. "We are sure that these things are going to be part of the final story," he says. "But I don't think we have a clear picture of what that final story is yet."

Others are less convinced. Joe Polchinski and Don Marolf are physicists at the University of California, Santa Barbara, and part of the team that exposed the black hole firewall paradox. Polchinski is concerned that the ER = EPR idea will end up modifying a central principle of quantum theory, known as superposition. Exemplified by Schrödinger's cat, this principle explains that a quantum system can exist in two different states at the same time. When quantum objects become entangled, they also enter a superposition.

At first glance, the ER = EPR hypothesis would mean quantum systems that become entangled, and therefore enter a superposition, suddenly gain a wormhole – a conjuring trick the superposition principle doesn't obviously allow. That's problematic, says Polchinski. "Quantum mechanics is weird, but it works," he says. "When you give up superposition, it's just weird."

Still, he remains open to the eventuality. "In the history of science, things that seemed absolute in many important cases have turned out to be not absolute," he says – Newton's law of gravitation, for example. "Maybe superposition is one of them." Maldacena says that it's too early to say if their work is threatening the superposition principle, because the mathematics hasn't been worked out in detail.

Marolf for his part isn't convinced the ER = EPR equality works in all circumstances: Susskind and Maldacena have shown how to avoid the firewall only for a particular entangled state of black holes. "You might think that it shows how to get out of the [firewall] paradox for any highly entangled state, but that's not true," says Marolf.

Given that Einstein developed the ideas of both wormholes and entanglement, one can only wonder what he would have made of it all. "My guess is that the old Einstein would have said poppycock," says Susskind – after all, Einstein spent much of his later years arguing for a hidden reality that wasn't subject to the vagaries of quantum mechanics. "But the young Einstein apparently had a much more flexible mind. My guess [is] that the young Einstein would have embraced these ideas, loved them." ■

PARADOX LOST: THE BLACK HOLE SOLUTION

The main problem with the black hole paradox is the idea of quantum monogamy - a particle can only be entangled with one other particle at a time (see "Paradox regained", left). This means that three quantum systems - say a particle inside a black hole's event horizon, a particle outside it, and a third far, far away – can't all be entangled at the same time.

But physicists Juan Maldacena and Leonard Susskind argue that this can be resolved if the particles just inside the horizon and the particles far away are connected via a wormhole. When a wormhole connects two objects, one must lie to the future of the other.

So, although these two particles might be entangled, their entanglement doesn't necessarily conflict with the entanglement of the particle inside the horizon and its immediate partner outside the horizon - because they aren't all happening at the same time. Uncomfortable apparitions such as blazing firewalls at the event horizon disappear. Paradox removed.

QUANTUM BOUNCE

CAN EXPLODING BLACK HOLES REVEAL THE TRUE FABRIC OF SPACE-TIME? STUART CLARK PICKS AT THE SEAMS

ON 2 NOVEMBER 2012, an intense burst of radio waves flashed across the skies above the Caribbean island of Puerto Rico. There was no spectacular fireworks display visible to human eyes, but the signal was captured by the 305-metre-wide radio dish of the Arecibo Observatory, nestled among the island's forest-covered peaks.

Radio astronomers had been waiting for one of these for a while: a fast radio burst. Lasting only a few thousandths of a second, these super-bright pulses are thought to come from deep space, and are extremely rare. The Arecibo burst was only the eleventh ever detected. There was a suspicion that all previous readings, from a single radio telescope in Australia, were down to a technical glitch.

They weren't. But what these strange pulses are remains a mystery. Some think they come from super-dense stars or black holes dancing with those stars. Some have even floated the idea – one few people are willing to buy – that they could be "hailing signals" from aliens.

The latest idea is that they could encode something equally astonishing: a signal from black holes behaving in an entirely new way. If so, it would transform our understanding of these most enigmatic cosmic objects, and mark the beginning of the end of a quest to reconcile two fundamentally irreconcilable descriptions of the physical universe. It might even explain the beginning of it all.

"That's our big excitement for all this," says theorist Hal Haggard of Bard College in Red Hook, New York, who has worked on the theory. "But I'm being a little cautious."

The idea grows out of the rift between general relativity, which explains how space and time curve to create gravity, and quantum theory. Quantum theory describes the behaviour of natural force fields, such as those associated with electricity and magnetism, and the subatomic particles, or quanta, that make up those fields. To do this, it assumes that space and time are a fixed and rigid framework through which these fields pass – while general relativity, formulated by Einstein almost exactly 100 years ago, insists that space and time are malleable fields in their own right. But if space-time is a field, presumably quantum theory must apply, meaning it can be subdivided into little bits.

It's a fundamentally confusing picture, and nowhere does that become more dramatically apparent than in our attempts to understand black holes. These regions of space-time in which matter is so dense and gravity so overwhelming that nothing can escape are, in essence, the ultimate cosmic trash compactors. Once something falls in, whether it's a photon or an idealistic NASA pilot thrown off course by a Hollywood scriptwriter, it never comes out.

At least this is what general relativity tells us. According to Einstein's theory, all matter

BOSE COLLINS

ends up at the centre of the black hole where it forms a singularity: a pinprick of infinite density at which the laws of physics break down. This is where today's cosmologists disagree with Einstein. "No physicist really believes that is what happens," says Haggard.

Hence the search for a successful theory of quantum gravity, which would explain how gravity behaves over extremely small distances, such as those in the centre of a black hole. The problem is, we have no clue what such a theory would look like. General relativity has never flunked a test; no one has ever measured a signal that it can't neatly explain. Until we do, theorists are working in the dark.

"We are in dire need of a guiding light to show us the correct path to quantum gravity," says theorist Thomas Sotiriou at the University of Nottingham, UK. "It would be one of the most important discoveries you could make." Hence the interest in the fast radio bursts. "If you could observe a black hole doing something that does not come from general relativity, that would be a revolution," says Sotiriou.

LOOPY BITS

The new idea comes from work Haggard did with Carlo Rovelli, a theoretical physicist at the University of Aix-Marseille, France. Rovelli is one of the founders of a model for a unified theory known as loop quantum gravity. It proposes that space-time is made of interlocking loops that form a fabric akin to chain mail. When seen from afar, this fabric looks smooth and continuous, but viewed close up it is woven from tiny, indivisible pieces. These loops would be the fundamental quanta of space-time; nothing could be smaller.

When Rovelli and Haggard considered what loop quantum gravity would mean for black holes, they came up with a startling conclusion: a black hole would eventually reach a density at which loopy bits of space-time could shrink no more. According to their calculations, published in 2014, there would be no singularity. Instead the loops would generate an outward pressure, resulting in a "quantum bounce" – an explosion that would destroy the black hole.

This is not the first time physicists have toyed with black holes doing unexpected disappearing tricks. Stephen Hawking suggested a mechanism based on the laws of thermodynamics, which govern heat and energy, that would make a black hole evaporate, albeit over a stupendous length of time. More recently, Abraham Loeb of Harvard University suggested that black holes could appear to explode if they were surrounded by a veil of matter that suddenly dissipated.

Rovelli and Haggard's bouncing black holes are different. Most importantly, their quantum bounce would create a white hole, a massive object that spews out particles and radiation. "It's like running a movie of a black hole in reverse," he says. "The white hole emits particles but never absorbs them."

Haggard has calculated that white holes are possible under the mathematical rules laid out by the equations of general relativity for the behaviour of space-time. But that does not mean a black hole actually does turn into its belching alter ego. "Stitching together different space-time solutions does not prove it is possible for a black hole to evolve into a white hole," says Sotiriou.

Haggard and Rovelli think the transition could be the result of a quantum phenomenon called tunnelling, which allows subatomic particles to spontaneously change from one state to another. Quantum tunnelling underlies nuclear fusion, among other things. In our sun, it allows protons to overcome an otherwise insurmountable energy barrier in order to fuse and release energy.

It is not so crazy to think that quantum gravity could be subject to the same peculiar ways. Haggard and Rovelli's idea is that all the matter collapsing to form a black hole

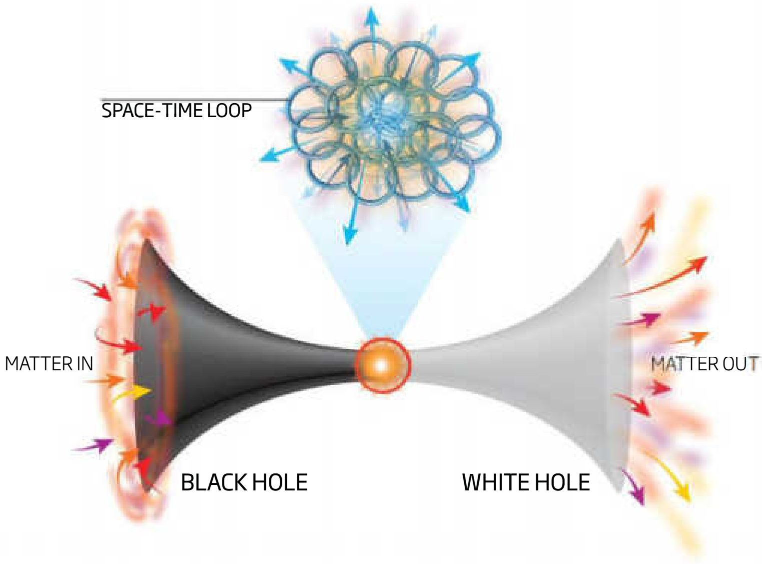
"AT STAKE ARE NOT ONLY BLACK HOLES AND SPACE-TIME, BUT THE START OF EVERYTHING"

singularity can never actually reach that point. As it approaches the size of an individual space-time loop, the probability that the entire black hole undergoes a quantum tunnelling event becomes greater and greater, until boing! It suddenly becomes a white hole (see diagram, below).

Not everyone is convinced: Sotiriou for one thinks the process is too much of a conceptual leap. "That definitely goes against conventional wisdom," he says. "I think that needs clarification before this idea can be taken seriously."

Ultimate rebound

According to the theory of loop quantum gravity, space-time is made of tiny, indivisible loops. As a black hole collapses, the pressure of these loops could cause it to rebound explosively, forming a "white hole" that spews out matter



The best way to persuade the doubters would be to spot a black hole in the throes of such an explosive reversal. In 2014, Rovelli and two colleagues – Aurélian Barrau at the University of Grenoble in France and Francesca Vidotto of Radboud University in Nijmegen, the Netherlands – set out to determine how such an event would make itself known.

They got together at a conference in Trieste, Italy, and calculated that an exploding black hole would generate signals at a wavelength equal to its diameter. In that sense, black holes are rather like loudspeakers: larger ones transmit longer wavelengths, or lower pitches, than smaller versions. Assuming that the exploding specimens were primordial black holes – a class of small black hole thought to have formed in the gravitationally violent aftermath of the big bang – they came up with a wavelength of a few millimetres. In other words, the expected signal was on the boundary between infrared and radio waves.

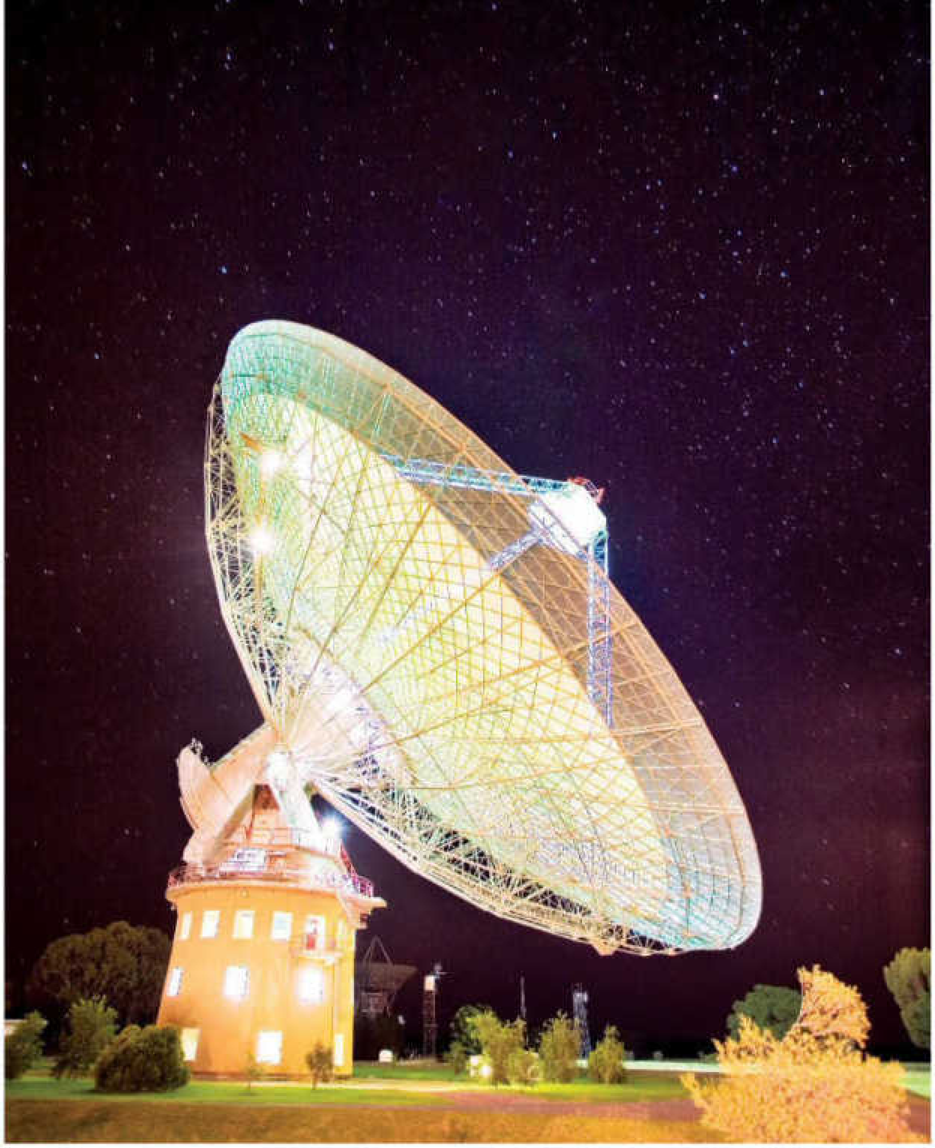
This rang a bell for Vidotto. She thought back to the mysterious ping from the Arecibo Observatory, and realised that its wavelength was in the same ballpark as their prediction for a signal from bouncing black holes.

That was especially exciting given how rare these events seem to be. Fast radio bursts were discovered in 2006, when radio astronomer Duncan Lorimer, then newly arrived at the University of West Virginia in Morgantown, was sifting through an old set of data from the Parkes Observatory in New South Wales, Australia. One signal stood out. "We just didn't know what to make of it, it was so bright," says Lorimer. After a further hard look, he concluded that the signal was not a technical snafu and almost certainly came from the far reaches of the universe – although he could not figure out what had produced it.

Only nine more of these fast radio bursts have been detected since, all from Parkes data, leading to questions about whether it was a quirk of the telescope – that is, until 2012 and the Arecibo signal.

It is easy to see why Rovelli and his colleagues are energised by that burst, which was announced to the world in 2014. But though their predictions for an exploding black hole signal and the fast radio bursts so far are a close match, they are not a perfect one. Then again, the calculations are based on an estimate for the mass of a black hole, which is in turn based on an estimate of how long a bounce would take.

Narrowing things down means tweaking the theory to take into account effects such



YURY PROKOPENKO/GETTY

Australia's Parkes Observatory saw most of the mysterious radio bursts

as time dilation. Under the laws of relativity, time slows down in a gravitational field. The stronger the force field produced by a massive object, the slower time will run. A clock on a spacecraft orbiting 10,000 kilometres above Earth runs faster than a clock on the surface because the planet's gravitational field weakens with distance. So in a black hole, where the field is about as strong as it can be, time pretty much comes to a standstill – for an outside observer at least.

The twist is that we experience time passing at the same rate wherever we are. So let's imagine you could witness a quantum bounce from inside a black hole. For you the explosion would take milliseconds, but for anyone outside it would appear to take billions of years because the black hole generates such a strong gravitational field.

Now consider that the more massive the black hole, the stronger its gravity and so the greater the extent of the time dilation, meaning bigger black holes would appear to take longer to bounce. This gives Rovelli and his colleagues a potential way to test their hypothesis. Primordial black holes are generally tiny, isolated objects, their size fixed at their birth shortly after the big bang. If the theory is right, they are like ticking time bombs whose clock is set by their mass. The smaller ones will experience less time dilation, and so from our perspective will explode earlier in cosmic history. These explosions should also generate fast radio bursts at shorter wavelengths.

In other words, distant fast radio bursts should have shorter wavelengths than nearby ones – a pattern we would not expect to observe if the bursts had any other origin. "If we saw this, it would be extremely strong confirmation for our idea," says Rovelli.

At the moment, all known fast radio bursts have been relatively close, so the change of wavelength with distance cannot yet be tested. Also, with only 11 of them, there are too few for any serious statistical analysis. So now it is a waiting game. Over time, researchers hope to detect more fast radio bursts and build up a proper data set. No one knows how long that might take.

Another type of signal thought to be produced by exploding black holes might offer an alternative route to validation: blasts of super-high-energy photons known as gamma rays. Much like radio bursts, the precise gamma ray signal emitted by an exploding black hole is determined by the total amount of matter and energy contained within. The signals would be distinct from the gamma ray bursts that astronomers regularly see, and right now we wouldn't be able to detect them.

There is, however, an observatory currently under consideration: the Cherenkov Telescope Array, which would boast more than a hundred telescopes spread over two sites in Spain and Chile. It should be capable of spotting these signature bursts but will not be ready until 2023, assuming it gets the go-ahead.

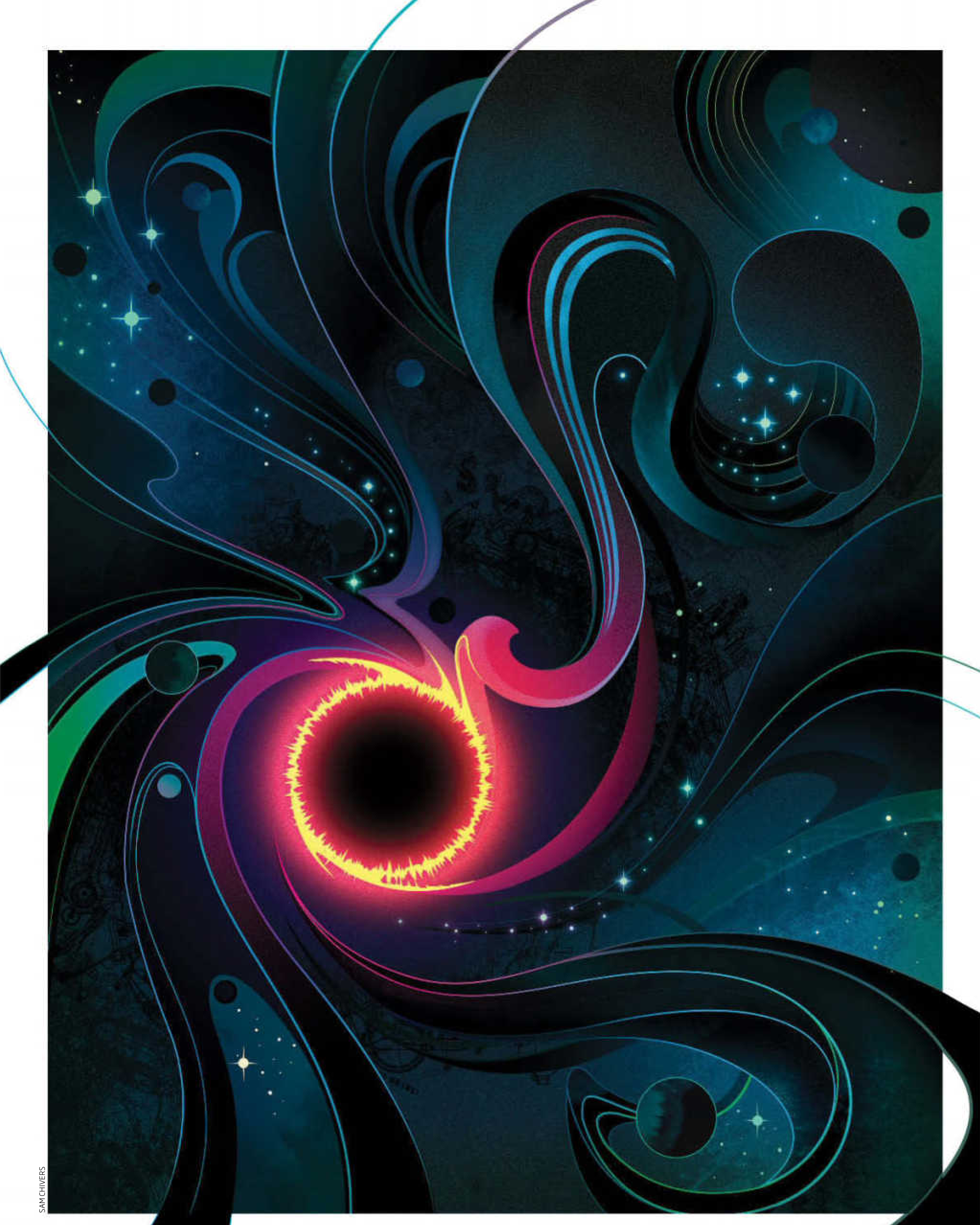
BIG BOING?

There is a lot at stake here – our understanding of not just black holes and space-time, but also the origin of the universe. There is only one other place where general relativity predicts a singularity arising: at the very moment of the big bang. But if the granularity of space-time prevents singularities happening in the first place, how did our cosmos come about? Perhaps not with a big bang, but with a big boing.

The big bounce hypothesis has been around for a while, and says that our universe was not born of an explosion that came out of nothing, but from a previous universe that collapsed. The new idea fits with that picture: as all the matter in that doomed cosmos came together in a catastrophic crunch, an enormous quantum bounce would have taken place once it reached the scale of the individual loops of space-time. This would have set our big bang in motion.

Lest anyone gets too carried away, however, there are more prosaic ideas to consider. Lorimer thinks fast radio bursts are most probably produced by young versions of rapidly-spinning neutron stars known as pulsars. This idea is "perfectly consistent with what we see", he says, and is "grounded in things that we really understand".

If so, it's a little disappointing. After all, it would resign us to yet another false start for quantum gravity. But then perhaps the mysterious signals really are the call sign of a distant alien civilisation. Maybe, if we ask them very nicely indeed,they can tell us where we are going wrong. ■



SAM CHIVERS

Ring of fire

Falling into a black hole has never been more dangerous. Anil Ananthaswamy reports from a safe distance

"PARADOXES are good in physics," reflects John Preskill. "They help to point the way towards important discoveries." Quantum mechanics and Einstein's theories of relativity offer plenty to choose from. There's the cat that can be dead and alive at the same time. Or the *Back to the Future*-style time traveller who kills his own grandfather, rendering his own birth impossible. Or the twins who disagree on their age after one returns from a near light-speed trip to a neighbouring star. Each perplexing scenario forces us to examine the fine print of the problem, thereby advancing our understanding of the theory behind it. A case in point is Einstein, whose own theories came from trying to resolve the paradoxes of his time.

Now Preskill, a theoretical physicist at the California Institute of Technology in Pasadena, is scratching his head over the latest one to surface. Nicknamed the black hole firewall paradox, it comes about when you consider what happens to someone falling into a black hole.

With the nearest black hole more than 1000 light years away, the question is very much a theoretical one. Yet just by studying such a possibility, physicists are hoping to make a breakthrough in their efforts to combine general relativity and quantum mechanics into a theory of quantum gravity – one of the most intractable problems in physics today.

Black holes have long been fertile breeding grounds for paradoxes. Back in 1974, Stephen Hawking, along with Jacob Bekenstein of the Hebrew University in Jerusalem, Israel, famously showed that black holes are not entirely black. Instead, they radiate energy known as Hawking radiation comprising photons and other quantum particles – an agonisingly slow process that eventually causes the black hole to evaporate completely.

Hawking spotted a problem with this picture. The radiation seemed so random that he surmised it couldn't carry any information about the stuff that had fallen in. So as the black hole evaporates, the information it holds must eventually disappear. Yet this is in direct conflict with a central tenet of quantum physics, which says that information cannot be destroyed. The black hole information paradox was born.

Over the decades, physicists have struggled with this paradox. Hawking thought that black holes destroyed information and the answer was to question quantum mechanics. Others disagreed. After all, Hawking's idea came from his efforts to meld general relativity and quantum mechanics – a mathematical feat so elusive that he was forced to make approximations. Preskill even made a bet with Hawking that black holes don't destroy information.

Several arguments suggest that Hawking was wrong. One of the most compelling comes from thinking about what happens as the evaporating black hole gets smaller and smaller. If information can't escape or be destroyed, then more and more has to be stored in an ever-shrinking volume. But if this is the case, quantum theory says the probability for making a tiny black hole increases from virtually nothing to almost infinity wherever matter collides against matter. "You should ›

"You're sailing along through space-time and then, bam! you hit this firewall and burn up"

have seen it at the Large Hadron Collider, you should have seen it at Fermilab, you should have seen it in tiny room-sized particle accelerators from the 1930s," says Don Marolf, a theorist at the University of California in Santa Barbara (UCSB). "You should see it when you go and jump up and down on the grass."

Obviously that hasn't happened. The other possibility – that matter and the information it carries can leak out from a black hole – is unlikely. Any material that falls in would need to travel faster than light to escape the black hole's fearsome gravity.

Perhaps, instead, the answer lies with the Hawking radiation itself. Maybe it isn't so featureless. "A common reaction was that Hawking had simply been careless," says Joseph Polchinski, also at UCSB. "It wasn't that information was lost, it was that he hadn't kept track of it enough."

Yet all early efforts to do away with the paradox proved unsuccessful. "Hawking had identified a really deep problem," says Polchinski.

As it happened, Hawking changed his mind in 2004, partly due to work by an Argentinian physicist called Juan Maldacena (see "Hawking's change of heart", right). Black holes don't destroy information after all, he conceded. He honoured the bet he made with Preskill and presented him with an encyclopaedia of baseball, which Preskill likened to a black hole, because it was heavy and it took effort to get information out of it.

Into the abyss

Attention soon shifted to wondering how information could get out of a black hole. This isn't an easy question to answer. And it is by exploring these issues that the black hole firewall paradox has come into sharp focus.

A firewall is the catchy new term for something physicists have long suspected might happen if information escapes from a black hole. To understand the argument, we need a simplified picture of Hawking radiation. The vacuum of space-time is constantly producing pairs of virtual particles, which pop into existence and just as quickly disappear. This picture changes near the black hole's event horizon, considered the point of no return for anything falling in. Occasionally one of the pair is sucked into the black hole while the other escapes. It is a rare particle that flees a black hole, but it is these that constitute Hawking radiation.

Now if Hawking radiation is carrying out quantum information, then that creates a problem. One of Hawking's great insights was to show how quantum theory, general relativity and thermodynamics are all linked at a black hole. This means that the paired particles just inside the event horizon would become immensely energetic as information is transferred to their partners outside, creating a wall of fire hot enough to burn up anything, or anyone, falling into the black hole.

This dramatically contradicts anything general relativity tells us about black holes. In fact, such firewalls seemed so preposterous that physicists started looking for ways to transfer information out of the black hole without such transgressions.

One possibility has been put forward by Steve Giddings, also at UCSB. Building on work done by Samir Mathur of Ohio State University, Giddings developed a simple model of a black hole. The work showed that if quantum theory breaks down in the vicinity of the event horizon, then it is possible to transfer information from within the black hole to distant outside regions, and thus avoid creating a firewall.

The trouble is, for it to work, Giddings had to relax the law that forbids faster-than-light information transfer. Another problem was that he couldn't say exactly where in space-time quantum theory should break down. Still, it was a tantalising idea.

Enter Polchinski and his students Ahmed Almheiri and James Sully, who are now both at Stanford University in California. They reckoned they could crack the problem by combining Giddings's model with earlier work carried out by Leonard Susskind at Stanford.

That meant reconciling the model with three postulates put forward by Susskind, which many physicists hold dear. One is, of course, that information is not lost as a black hole evaporates. The others relate to thought experiments using two observers called Alice and Bob who are approaching a black hole. Intrepid Alice crosses the black hole event horizon. Cautious Bob stays outside.

According to the second postulate, Bob sees nothing unusual as he sits outside the black hole. The third postulate says that Alice also sees nothing amiss as she crosses the event horizon. That's because the event horizon is not a physical boundary, it is just an ordinary patch of vacuum in an ordinary patch of space-time that curves gently.

Polchinski and his colleagues failed in their attempt to reconcile all three – if information wasn't lost then the firewall still existed and Alice ended up burning to a crisp. But that didn't deter them. "You first try to do something, and if you fail to do it, you try to prove that it is impossible," says Polchinski.

Their colleague Marolf joined them in this effort and their work led to a paper, published in 2012, showing that the postulates cannot all be true simultaneously. It caused a storm of controversy; 200 papers discuss the work, including one that says the answer is to ignore gravity.

If Hawking radiation does carry quantum information out of the black hole, as many think it does, then quantum mechanics has a few things to say about it. Let's say particle A of Hawking radiation comes out early in the life of the hole. Quantum theory says that particle A shares a spooky connection, or is entangled, with another

HAWKING'S CHANGE OF HEART

It was string theorist Juan Maldacena who made the breakthrough that eventually led to Stephen Hawking changing his mind about black holes and information (see main story). In 1997, Maldacena used the mathematics of string theory to show that the theory of gravity that describes the insides of a black hole is equivalent to the quantum theory that describes the black hole's surface. It sounds esoteric, yet Maldacena's work is remarkable. While we don't yet know a theory of gravity that describes the black hole in its entirety, we do know how to work with quantum theory on the surface. What that means is that quantum mechanics is valid at a black hole's surface and that as the hole evaporates it doesn't lose information. One caveat is that the type of space-time Maldacena studied is different from the space-time of our universe, but his result is so compelling that physicists are loath to quibble.

RICHARD KAIL/SCIENCE PHOTO LIBRARY

Hawking radiation causes black holes to evaporate

Hawking radiation particle that emerges later in the life of the black hole.

Now, think about particle B, which exists much later than A. Particle B is one of a pair of particles, B and C, produced at the horizon, and C has fallen into the black hole. Space-time at the horizon is assumed to be nothing special, just gentle gravity and low curvature. This demands that the virtual particles produced at the horizon be entangled with each other. So B must be entangled with C. But since early and late Hawking radiation must be entangled, B is also entangled with A.

Unfortunately this violates another cherished principle of quantum mechanics known as the monogamy of entanglement. Simply speaking, it says that particle B can be entangled with A or C, but not both.

So the conundrum has come full circle. If we want to get information out of a black hole, A must be entangled with B. If we want the vacuum of space-time to be ordinary at the event horizon – which is what allows Alice to slip into the black hole without bursting into flames – then B must be entangled with C. Something has to give. Is it going to be quantum mechanics or general relativity?

Take quantum mechanics and its prediction that information is conserved. Could this be wrong? Polchinski doesn't think that is possible because of Maldacena's work, which is one of the strongest mathematical statements in favour of leaving quantum mechanics as it is. What's more, quantum mechanics is a theory that has been extremely well tested, and even tiny changes put it at odds with experimental results.

The other option is to call into question the state of the vacuum at the horizon. Messing with monogamy could be avoided if particles B and C on either side of the horizon aren't entangled. But destroying this entanglement leaves the black hole's event horizon in an agitated thermal state and re-instates the firewall. Instead of floating across the event horizon without drama, Alice would face instant incineration by temperatures as high as 10^{32} kelvin.

This has dismayed Marolf. General relativity says crossing a black hole's event horizon should be uneventful. "A firewall would be a strong violation of general relativity," he says. "In that struggle between general relativity and quantum mechanics, general relativity loses badly. I feel bad about that, because I think of myself as a relativist by training."

"In the struggle between general relativity and quantum mechanics, relativity loses badly"

Fresh thinking

He's not alone in finding it unpalatable. "You are sailing along fairly fine in this very smooth space-time, and all of a sudden, bam! you hit this firewall and just burn up," says Preskill. "It's pretty crazy."

Nonetheless, the firewall is the best explanation if black holes transfer information into the Hawking radiation. Susskind remains sceptical of firewalls, but he has argued that they could represent the migration of the singularity, which in traditional black hole physics lies at the centre of the black hole, to the horizon.

Even if firewalls do form, Susskind differs on when they might form. For instance, for a black hole with the radius of a proton, Polchinski, Marolf and colleagues say that firewalls would form 10^{-20} seconds after the formation of the black hole, while in Susskind's view it would take as long as the age of the universe.

Regardless of when firewalls form, if they do, then space-time as we know it may terminate at the horizon. "If the entire black hole horizon becomes this firewall that cuts off the interior, maybe the interior just doesn't exist," says Marolf.

The paradox would also be resolved if there is something special about space-time near a black hole, so that information can be transferred faster than the speed of light. Maybe Giddings and Mathur were on to something, although that would be another blow to relativity.

The upshot of all this is that more than 40 years after Hawking proposed the black hole information paradox, the problem hasn't gone away. It has just made physicists look deeper at their theories. "I am as confused as I was 20 years ago," says Polchinski.

Preskill says this isn't a bad thing. "There is always a fourth possibility: none of the above, something we haven't thought of. Any way it shakes down, it's going to be interesting," he says. "All the options are crazy, that is what's so wonderful about the situation." ■

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