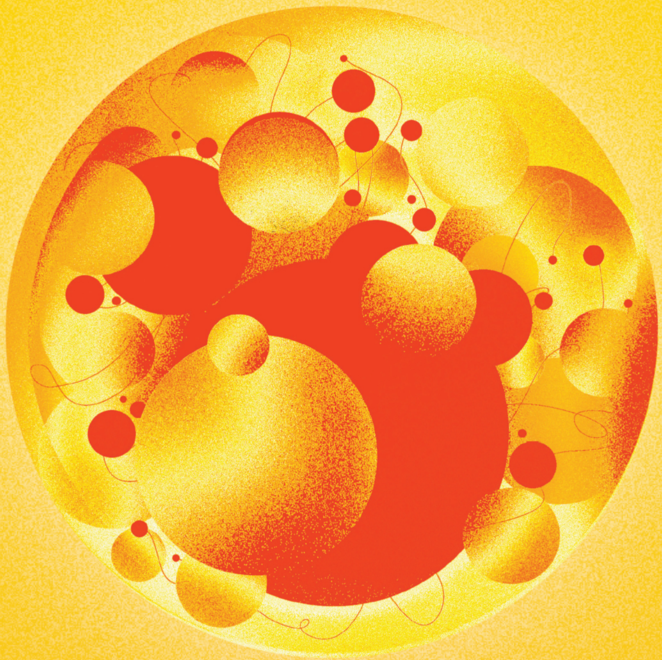
BBC

Science Focus

MAGAZINE

# INSTANT GENIUS



WHAT IS IT?

SCHRÖDINGER'S CAT

A THEORY OF EVERYTHING

# QUANTUM THEORY

FOCUS UNIVERSITY

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EST. 1992

# QUANTUM PHYSICS
## IN 10 MINUTES

Even Nobel Prize-winning physicists are baffled by this tricky subject. But John Gribbin is here to reveal why quantum physics is relevant to all our lives

### What is quantum physics for?

Quantum physics may seem like a pretty esoteric topic with no everyday practical value, but that's far from being the case. Quantum physics is the science you need to understand the behaviour of atoms, electrons and light. It therefore underpins the workings of microchips and lasers, among other things. The chemical bonds that hold strands of DNA together, and which enable the double-stranded molecules of the famous helix to unzip and make copies of themselves, operate purely in accordance with the laws of quantum physics. Quantum physics is the science of life: it doesn't get much more basic than that!

### Wave, particle or both?

The understanding of physics that scientists had reached by the end of the 19th Century is now called 'classical physics'. It describes the behaviour of the material world in terms of the laws discovered by Isaac Newton, and it describes the behaviour of light and other electromagnetic radiation (everything from radio waves to gamma rays) in terms of the wave equations of James Clerk Maxwell.

Crucially, in the world of classical physics, waves are waves and particles are particles. They interact with one another – as when an electrically charged, jiggling electron emits radio waves – but they always retain their identity. Even the General Theory of Relativity (like its simpler cousin the Special Theory of Relativity) counts as a classical theory, because it retains this distinction between waves and particles, and preserves the idea that changes happen in a continuous fashion.

When Max Planck suggested that light was made up of particles, he completely overturned classical physics

Quantum physics overturns all of that. The first clue that something other than classical physics was needed came when Max Planck found that he could only explain some aspects of the behaviour of light (such as the nature of so-called black body radiation – see 'Jargon buster' on p82) by treating light as being made up of particles, not a continuous wave. But other experiments still showed light behaving as a wave! Then it was discovered that electrons, which classical physics said were particles, behaved in some circumstances as if they were waves. Wave-particle duality, as it became known, lies at the heart of quantum physics.

### Does quantum theory rule?

Wave-particle duality is not the whole story of the split between classical physics

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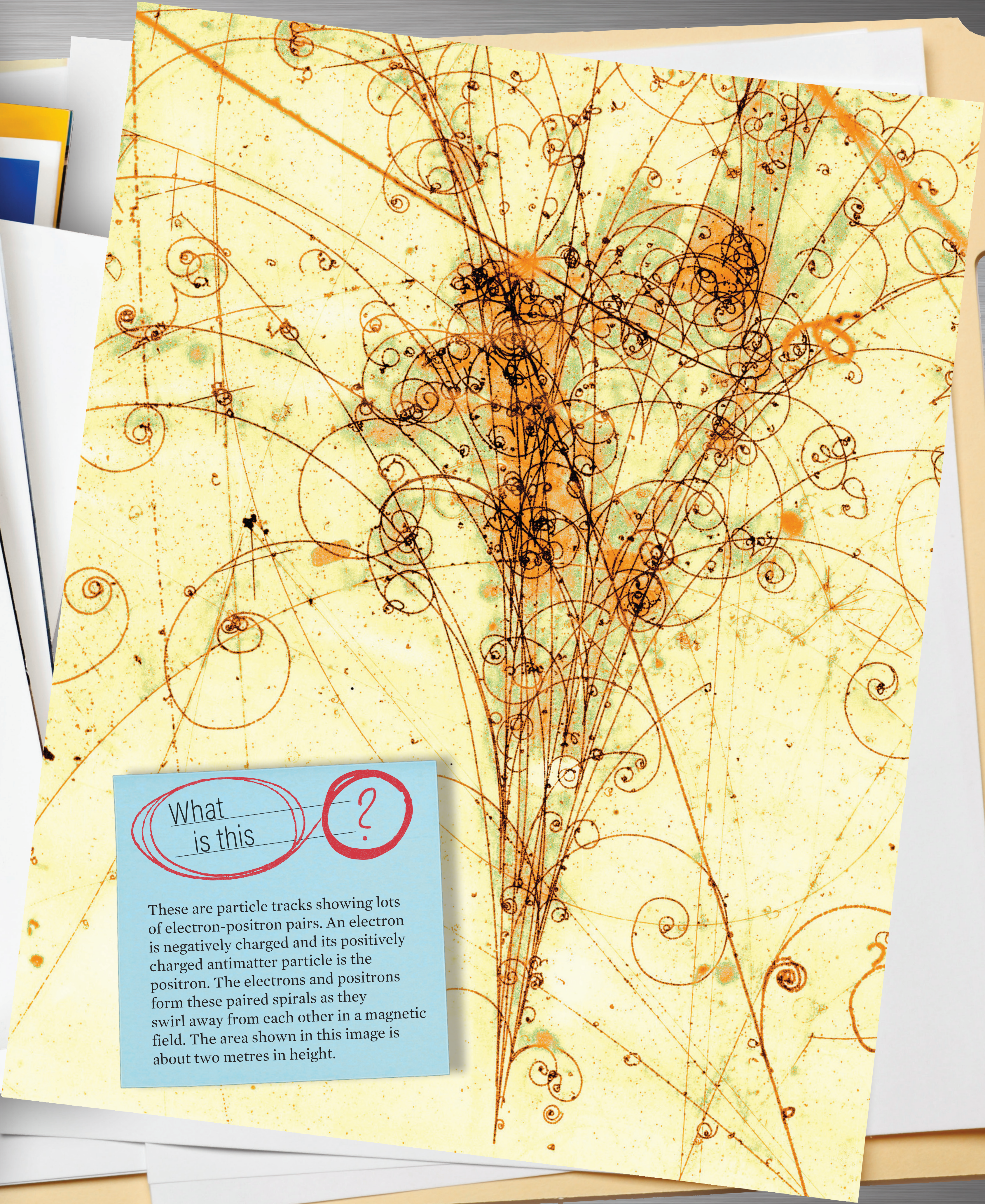
PHOTO: GETTY, SCIENCE PHOTO LIBRARY

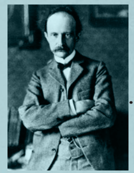


What is this?

These are particle tracks showing lots of electron-positron pairs. An electron is negatively charged and its positively charged antimatter particle is the positron. The electrons and positrons form these paired spirals as they swirl away from each other in a magnetic field. The area shown in this image is about two metres in height.

# TIMELINE

**1900**



German physicist Max Planck (1858–1947) discovers that black body radiation can be explained if light is emitted in packets of energy, now called photons. This conflicts with the accepted idea that light is a wave.

**1905**

German physicist Albert Einstein (1879–1955) explains the photoelectric effect, in which light falling on a metal surface makes photoelectrons jump out of the surface.

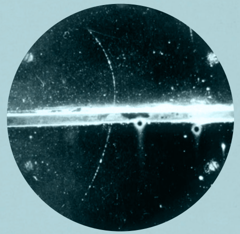
**1913**

Danish physicist Niels Bohr (1885–1962) explains the spectrum of light radiated by atoms in terms of electrons jumping between fixed energy levels, like steps on a staircase, inside the atom. This is the 'quantum leap'.

**1927**

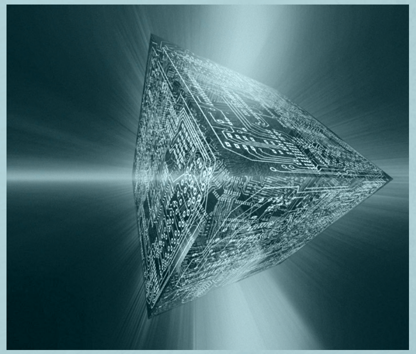
US physicist Clinton Davisson and UK physicist George Paget Thomson (pictured) share a Nobel prize for independently discovering that electrons can be diffracted like waves, confirming the reality of wave-particle duality.

**1932**



While studying cosmic ray tracks, US physicist Carl Anderson (1905–1991), sees the trace of a particle like an electron but with a positive charge. It is the positron, an antiparticle.

**1985**



David Deutsch (1953–) publishes a paper pointing out the possibility of making a true quantum computer. He predicts that they will carry out certain tasks much faster than a conventional computer can.

PHOTO: SCIENCE & SOCIETY, GETTY X2, SCIENCE PHOTO LIBRARY X2, NASA AMES/NICK BONIFAS

and quantum physics. In the world of classical physics, a particle such as an electron has a definite position in space, and is moving in a definite direction. As long as you make allowance for all the forces it encounters along the way, you can calculate everything that will ever happen to it. This applies to all particles. The classical world is said to be 'deterministic' because once you know where everything is and where it is going, you can work out the entire future and the entire past. Both are determined by the way things are now, which doesn't leave very much room for free will! This is sometimes called 'Newton's Clockwork Universe'.

But according to quantum physics, an electron is *never* located at a precise place (because of its wave nature), and it is *never* sure where it is going. This is the 'uncertainty principle' discovered by Werner Heisenberg, who found there is a trade-off. Quantum objects can either have a relatively well-defined position and a poorly defined direction, or a well-defined direction and a poorly defined position. But they can't have both. It's the price of free will.

This ties in with another key quantum physics idea – probability. You can never say precisely where a quantum entity is or where it is going, but you can use the rules of quantum physics to work out probabilities, such as the probability that an electron will follow a certain trajectory, or the probability that a sample of radioactive material will decay and spit out a particle within a certain time.

## What is a quantum?

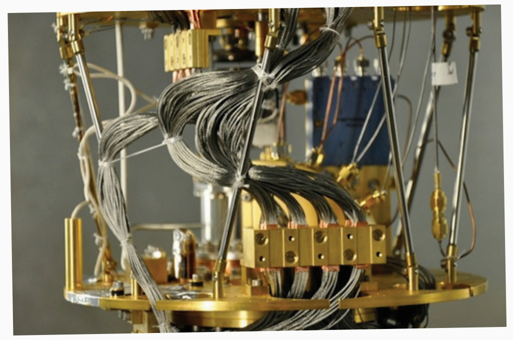
A quantum is the smallest amount of something that it is possible to have. The smallest amount of light you can have, for example, is a particle called a photon. If you have a bright light, there are many photons streaming outwards. But as you turn the light down, there are fewer and fewer photons. Eventually, there are so few photons that they can be detected one at a time. Astronomers see this happening when they build up images of very faint objects using long exposures of charge-coupled devices (CCDs). When atoms emit light, they do so by rearranging their electrons to radiate energy. Like a ball bouncing down a staircase, the electron jumps from one energy level to another inside the atom, and a photon is emitted. This jump is known as a quantum leap.

A quantum leap is the smallest change it is possible to make – something to remember next time you see the term used in advertising.

## Can we see quantum effects?

The definitive demonstration of quantum effects at work was carried out by a Japanese team in the 1980s. They took the classical experiment which 'proves' light is a wave and adapted it to electrons.

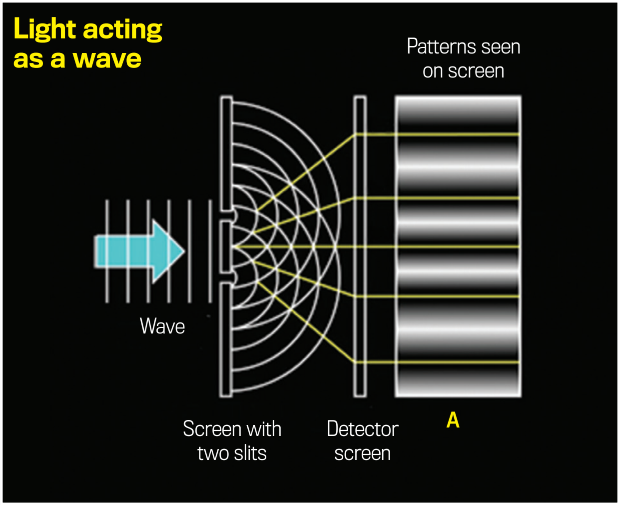
The traditional experiment involves sending a beam of light through two slits in a cardboard screen to make a pattern on

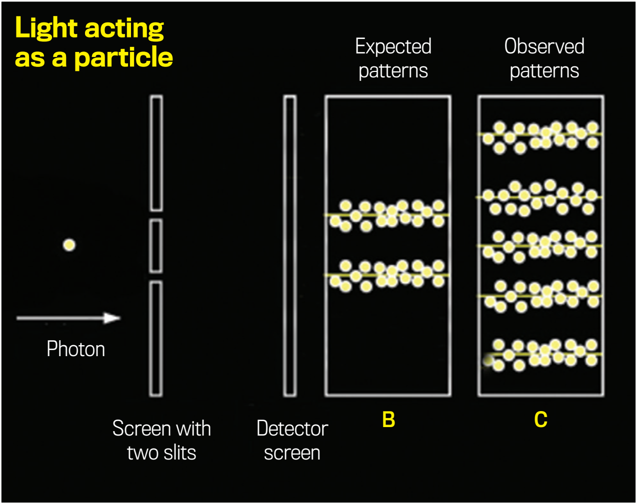


## D-Wave

Could this be the first quantum computer? Manufacturers D-Wave claim that it is, but have not revealed details of how it works. What we do know is that it's cooled to temperatures approaching absolute zero. The aim is to develop computers based on the superposition idea of quantum physics. These quantum computers will make classical computers look as primitive as an abacus.

# THE KEY EXPERIMENT





IN THE 18TH Century, debate raged as to whether light was a wave or a particle. But in 1803, English scientist Thomas Young showed that, when light is passed through two slits onto a backboard, an interference pattern appears. This is similar to what's seen when two sets of similarly generated waves collide in water (fig **A**). Light, he deduced, must be a wave. In the early 20th Century, however, Einstein and others demonstrated that light can also be seen as a stream of particles, called photons.

This is where things get tricky. When individual particles are sent one at a time through a double slit, as in Young's experiment, they should 'pile up' in two bands (fig **B**). Photons don't, though: even if you send photons through the double slit individually, an interference pattern is observed (fig **C**). Just to complicate matters, if you monitor which slit each photon is going through, the interference patterns are replaced by two bands.

The same applies to other fundamental particles, such as electrons. If that sounds a bit mind-blowing… welcome to the world of quantum physics, where 'wave-particle duality' is commonplace and where the mere act of observing can affect the outcome of an experiment.

# JARGON BUSTER

### BLACK BODY

An object that is a perfect absorber of radiation is called a black body, hence the name. But if a black body is hot, it becomes a perfect emitter of radiation. So, seemingly paradoxically, the Sun is an almost perfect black body radiator.

### DIFFRACTION

This is the process by which waves can bend around corners or spread out in all directions from a small hole or slit.

### DUALITY

This is the way that quantum entities seem to be both particle and wave. Light 'waves' are associated with particles called photons; electron 'particles' are associated with waves.

### ENERGY LEVEL

A quantum state, for example in an atom, that is associated with a particular energy. Electrons in atoms will sit on, or occupy, specific energy levels.

### QUANTUM LEAP

The change of a quantum system, such as an electron in an atom, from one energy level to another. This happens without the system (electron) passing through any in-between state.

### SUPERPOSITION

This is when a quantum system exists in a mixture of states. For example, an electron has a property called spin. On its own, the electron is in a superposition of spin up and spin down. It only 'collapses' into one state when it interacts with something. This is linked to the idea of quantum probability – there is a 50:50 chance of finding the electron in either state.

PHOTO: SCIENCE PHOTO LIBRARY X3

another screen on the far side. Like ripples on a pond, the waves started to spread out from the two slits and interfered with one another to make the distinctive pattern. In their variation on the theme, the Japanese team fired electrons, one at a time, through an equivalent setup onto a screen like a television screen, where each electron made a single spot as it arrived, showing that it was a particle. But as hundreds of electrons were fired through the experiment, one after another, the pattern of spots that built up was an interference pattern, proving that electrons are waves.

Don't worry if you find your mind boggled by this. The physicist Richard Feynman used to say that "nobody understands quantum physics" – and he had a Nobel Prize for it.

## Are there practical applications?

Applied quantum physics is everywhere around us. Computer chips, including the ones in your smartphone, are designed using quantum physics and operate on quantum principles. The lasers used to read Blu-ray discs operate on quantum principles that were first worked out by Albert Einstein 100 years ago. Physicists have developed tools known as superconducting quantum interference devices, or SQUIDs, in which electron waves travel round a ring of metal about the size of a wedding ring. These are supersensitive detectors of magnetic fields, and are used in many different applications including the MRI scanners with which doctors can 'see' inside the human body.

The most exciting application of quantum physics today is in the new field of quantum computing. Ordinary computers are based on switches that can be either on or off (0 or 1); in contrast, a true quantum computer has switches (single atoms or electrons) that can be both on and off at the same time. This is a so-called superposition, which makes the computer immensely more powerful.

## How does quantum physics explain the Sun's energy?

Stars like the Sun release energy as a result of a process called nuclear fusion. At its simplest, inside the Sun two protons (hydrogen nuclei) come together and fuse, then combine with other particles to make nuclei of helium. The helium has less mass than the particles that went into it, so energy is released in line with Einstein's famous equation, $E=mc^2$. Astronomers are able to figure out how hot the interior of the Sun must be in order to hold itself up against gravity.

But this then led to a puzzle. Because protons are positively charged, they repel each other and have to be moving very fast before they will collide and stick together. Classical physics said that the interior of the Sun is not hot enough for this to happen. Quantum physics provided the explanation. When two protons are close together, but not close enough to touch according to classical theory, quantum uncertainty means that there is a probability that they might actually touch. Another way of understanding this is to think of the protons as waves, reaching out to each other. Either way, the result is that the protons can fuse. They are said to tunnel through the barrier of classical electrical repulsion.

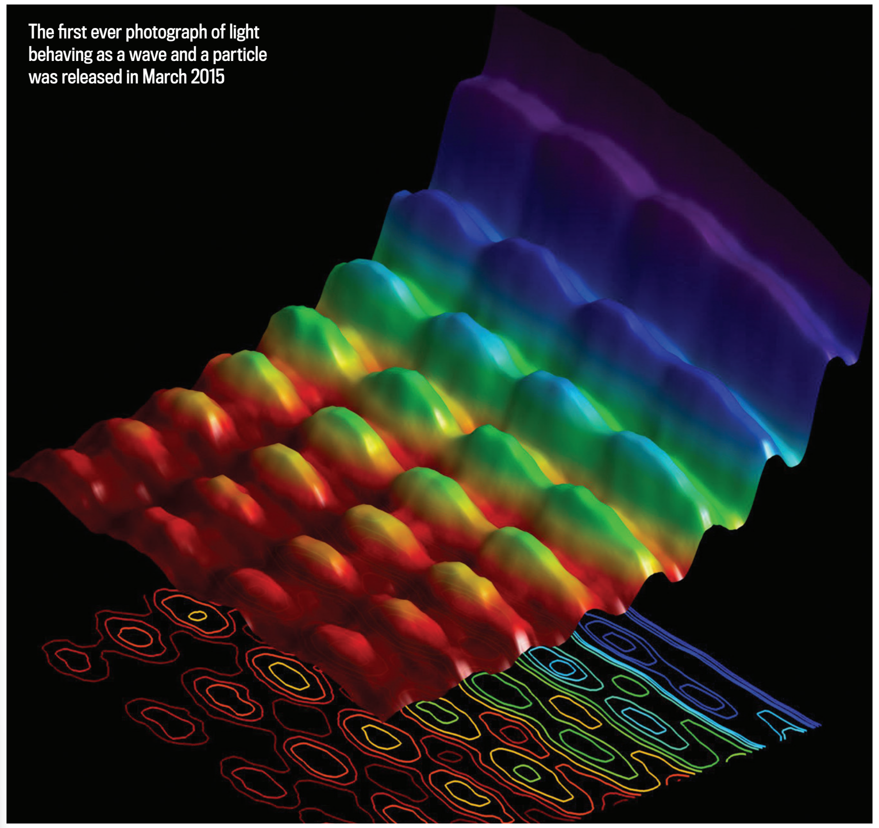
## What is antimatter?

One of the strangest predictions of quantum physics is that for every type of particle, there should be an antiparticle that has its key properties reversed. The electron, for example, has a negative charge, while its antiparticle, the positron, has positive charge.

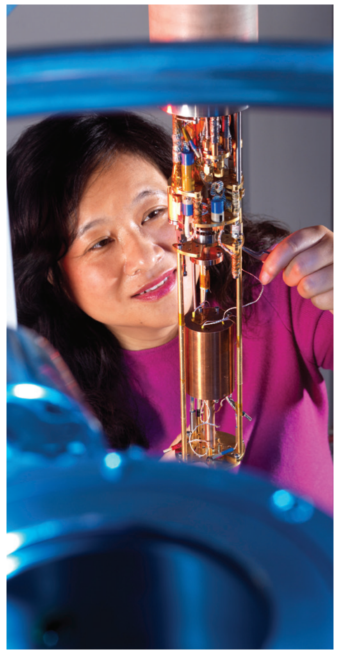
The physicist Paul Dirac was the first person to take this seriously, but when he published the idea in the 1920s he cautiously suggested that the required positive particle might be the proton, the only other particle known at the time. But in 1932 the physicist Carl Anderson discovered the tracks of positively charged particles with the same mass as electrons in a device known as a cloud chamber. This breakthrough earned him a Nobel Prize.

Dirac had been more correct than he had realised himself. It turns out that particle-antiparticle pairs (such as an electron and a positron) can be made out of pure energy in line with Einstein's equation, but when a particle and its antiparticle meet they annihilate each other in a puff of gamma rays. ■

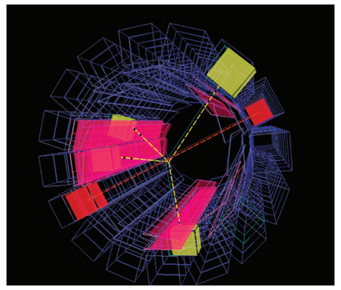
**DR JOHN GRIBBIN** is a science writer and astrophysicist



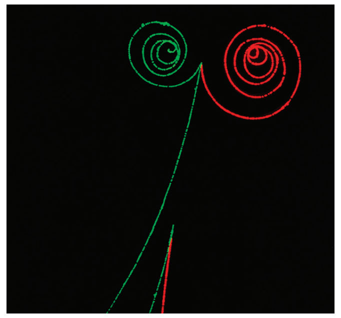
The first ever photograph of light behaving as a wave and a particle was released in March 2015



Researcher adjusting NanoSQUID device that changes temperature when hit by a photon



Model of a matter-antimatter annihilation event



Production of a matter particle, along with its corresponding antimatter

# EXPLAIN IT TO A FRIEND

### 1. SCIENCE ON A TINY SCALE

Quantum physics describes the behaviour of very small things, like electrons and atoms. That's why we don't notice weird quantum effects in everyday life. But quantum physics explains how atoms and molecules work, including molecules like DNA. We need quantum physics to do everything from designing computer chips to genetic engineering.

### 2. EVEN EXPERTS GET CONFUSED

At the quantum level the distinction between waves and particles is blurred. Everything in the quantum realm is both wave and particle at the same time. Experiments designed to measure waves find waves, while experiments designed to measure particles find particles. What you look for is what you get.

### 3. PROBABILITY IS KING

Probability rules in the quantum world. If a single quantum entity, such as an electron, has a 'choice' of options, such as which of two holes to go through, it chooses at random. Einstein hated the idea that 'God plays dice', and did not accept this. But experiments show he was wrong.

Quantum physics gives us free will! Without it you would have no choice about anything. It explains what life is and how my phone works.

IN ONE TWEET!

: Jeff Forshaw and Brian Cox :

## GUIDE TO THE COSMOS

# THE QUANTUM WORLD

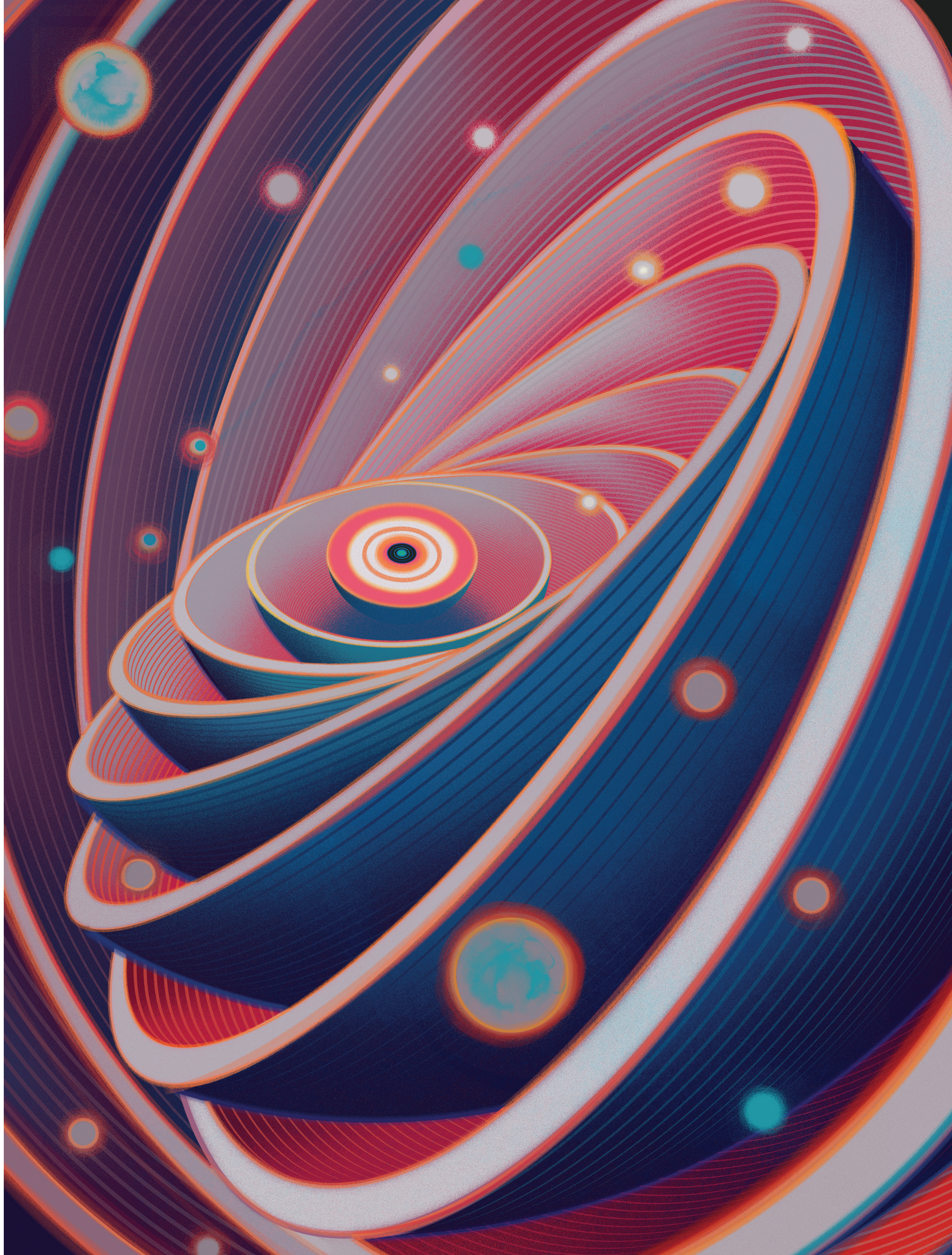
How subatomic anarchy gives rise to everything we see in our daily lives

Physicists Jeff Forshaw and Brian Cox introduce us to the biggest ideas in modern physics and cosmology. What is the nature of time? What is everything made from? What happened before the Big Bang, and how will the Universe end? We'll delve into the deepest questions concerning the very essence of space, time, matter, and reality itself...

What happens if you chop something in half, then in half again and keep on going? What do you end up with? Can you keep doing it forever? These simple-minded questions are profound and lead us into the bizarre world of quantum physics. Bizarre because, as we are about to find out, the world of tiny things is extremely different from the world of big things: it is a world where particles dance around each other according to rules ▶

Listen to episodes of *The Infinite Monkey Cage* with Brian Cox at bbc.in/monkey_cage

ILLUSTRATIONS: SAM CHIVERS, KATE COPELAND



> “As far as we can tell, quarks and electrons are not made of anything”

that completely defy common sense. Perhaps the most shocking aspect of quantum physics is that one particle can be in *several* places at the same time. (That previous sentence is worth reading a few times!) Clearly, these are no ordinary particles – they are tiny things that do not behave like miniature versions of big things.

### INTO THE RABBIT HOLE

As far as physicists can tell, everything in the Universe is made up of tiny particles. For example, the molecules in your body are made out of atoms, and each atom is composed of a central nucleus surrounded by a cloud of electrons. The nucleus is about a trillionth of a millimetre in size and inside it is a bunch of protons and neutrons, which in turn are made up of quarks. As far as anyone can tell, quarks and electrons are not made of anything smaller. That might just be because we haven't yet built a sufficiently powerful microscope to look inside them, but there is another possibility: it might be impossible to break these particles apart. For this reason, electrons and quarks are two of just a handful of different types of particle that we think of as ‘elementary’ (we will be exploring the other types of elementary particle in the next article in this series). Okay, so how do these elementary particles move around?

The first thing we need to appreciate is that it is impossible to know what a particle will do next. What we *can* know is how likely it is to do a particular thing. For example, if we know that an electron is ‘over here’ at one particular moment then we can use mathematics to calculate how likely it is to be ‘over there’ at a later time. In other words, the best we can do is compute probabilities. This is not a feature of human ignorance – rather it is a feature of the Universe that the future is inherently uncertain. So how do we calculate these probabilities in quantum physics? This is where the fun really starts.

### RESTLESS PARTICLES

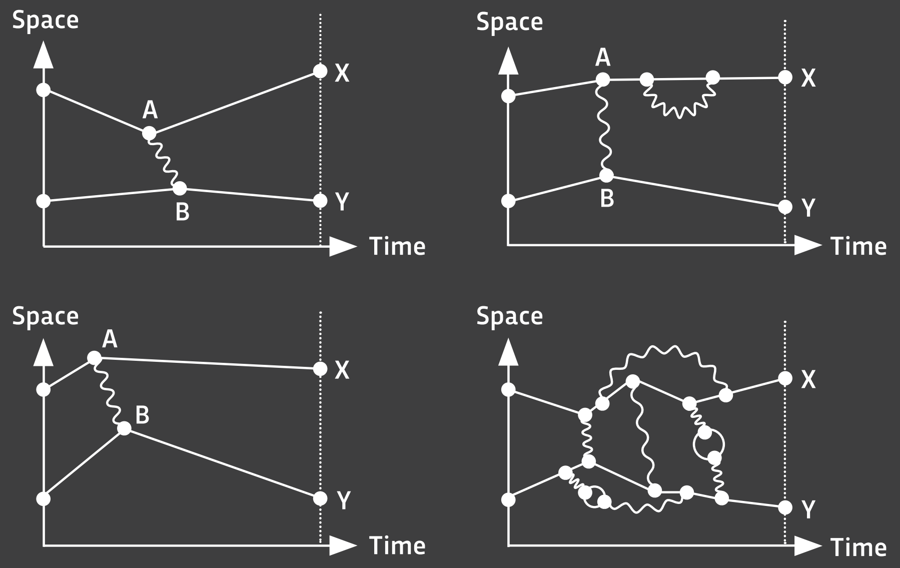
Let's plunge straight in and consider a specific example. For this, you need to look at the four pictures in ‘The key idea’ (right). These pictures show four different ways in which two electrons can travel to the points X and Y. In the top-left picture, one electron starts its journey from the upper dot on the left and the other starts its journey from the lower one. The first electron hops to point A where it does something interesting – it emits a particle of light (called a photon and denoted by the wavy line). The photon then hops from A to B, while the electron continues its journey and hops from A to X. The journey of the second electron is also interesting. It starts by hopping to point B where it absorbs the photon emitted by the first electron. After that, it hops onwards to point Y. Although this might seem quite unfamiliar, the rules of the game are really rather simple: electrons can

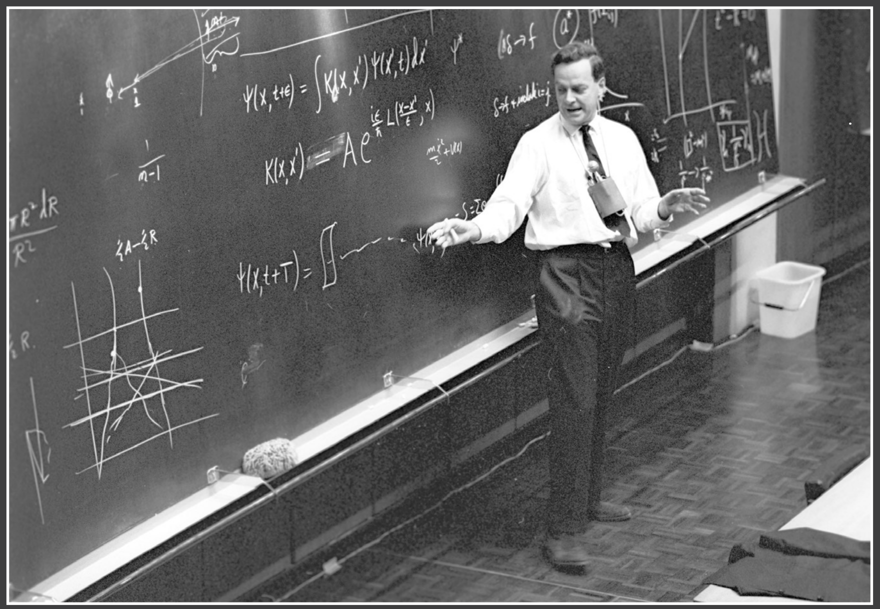
PHOTO: CERN ILLUSTRATION: SAM CHIVERS

## The key idea

### EVERYTHING THAT CAN HAPPEN DOES HAPPEN

These pictures show four different ways in which two electrons can travel from their initial positions (denoted by the two dots on the left of each picture) to the points marked X and Y. Along the way, they can exchange a photon (or photons), denoted by the wavy lines. For each picture, it is possible to compute a number, and then we must add together all of these numbers to compute the probability that the particles will actually arrive at X and Y. Although we have drawn just four pictures, there are infinite possibilities: the electrons must travel by *every* possible route in order to arrive at their destination. It's one of the most mind-boggling aspects of quantum physics.





Richard Feynman developed diagrams to help show how subatomic particles behave

## Glossary

### ELEMENTARY PARTICLE

These tiny particles aren't made up of anything smaller (to the best of our current knowledge). Everything in the Universe appears to be made up of just a handful of different types of elementary particle. Two of these – electrons and quarks – are the main ingredients of atoms.

### FEYNMAN DIAGRAM

Named after Richard Feynman, these pictures provide a way to visualise how the elementary particles move around and interact with each other. We can use the diagrams to compute the probability that something will happen to the particles.

### PROBABILITY

A number between zero and one corresponding to the odds that something will happen. For example, the probability that a rolled dice will show a six is 1/6 = 0.167. This means that on average 16.7 out of every 100 rolls will register a six. Probabilities are all that we can calculate in quantum physics. This inherent unpredictability of nature cannot be circumvented by knowing more.

### QUANTUM PHYSICS

This explains how atoms and other tiny things work. It replaces Newton's laws of motion, which fail to describe atoms. Quantum physics is counterintuitive – most remarkable perhaps is that a particle can simultaneously be both ‘here’ and ‘there’.

### UNCERTAINTY PRINCIPLE

Named after Werner Heisenberg, this is the contrary idea that the more accurately we know the location of a particle at some moment in time, the more likely it is that the particle will immediately jump far away from that point.

➤ hop from one place to another and they may or may not emit or absorb photons… that's all there is to it.

You can use these simple rules to draw your own pictures of how the electrons might hop and branch their way to points X and Y – we have shown three more possibilities. The last one (bottom-right) is quite fancy and involves lots of photons, but hopefully you can see that it is still just a matter of electrons hopping around and emitting or absorbing a photon.

Pictures like these are called Feynman diagrams (after the US physicist Richard Feynman) and they describe how particles interact with each other – in our case, the two electrons interact via the exchange of photons. In fact, all of the particles in nature interact in ways very similar to those we just described. There are a few more types of particle (other than electrons and photons), and a few more rules to consider, but the basic idea of how particles interact is the same. Nice pictures don't really amount to very much, though – we need to use them to help us calculate the probability that the electrons will end up at the specific points, X and Y. Remember, calculating the probability that something happens is the aim of the game in quantum physics.

### EVERYTHING THAT CAN HAPPEN…

The lovely feature of Feynman diagrams is that they are not just pretty pictures. They can be translated into mathematics. Specifically, for every hop an electron makes (so for every straight line in a Feynman diagram) we can assign a particular number (the size of the number depends on how big the hop is). Similarly, every time an electron emits or absorbs a photon, there is a number. All of these numbers should be multiplied together to obtain one final number for each graph. In other words, we can calculate a number for each of the four graphs in 'The key idea'. Add those numbers together and you get the probability of finding one electron at X and the other at Y*.

> Quantum theory underpins our modern world”

Now, something extremely weird is going on here. To calculate the probability that something specific happens, the rules say that we must take into account *all* of the possible ways that this thing *could* happen. In the case of our pair of electrons, it seems we have to consider that the electrons reach X and Y via all possible routes. If we used 'common sense' and supposed that each electron really travelled along only one of the possible routes, then we would not get the correct answer for the probability. It really is as if the answer to the question "how did the electrons reach X and Y?" is "they went via every possible route". If this sounds crazy to you, then you are in good company, because it runs counter to our everyday experience. Experience has fooled us into imagining 'things' uniquely exist and move around along definite trajectories through space. The possibility that this idea might be wrong is at the heart of quantum theory.

As we have seen, the rules of quantum physics are quite simple. Once we have the rules for how electrons and photons can jump around, we can draw Feynman diagrams and compute probabilities that can be tested in experiments. And these are not esoteric calculations either: they allow us to compute how atoms behave, which is crucial for understanding chemistry. They are also key to understanding how semiconductor devices work, and these form the basis of today's technology. In other words, quantum theory underpins our modern world. ➤

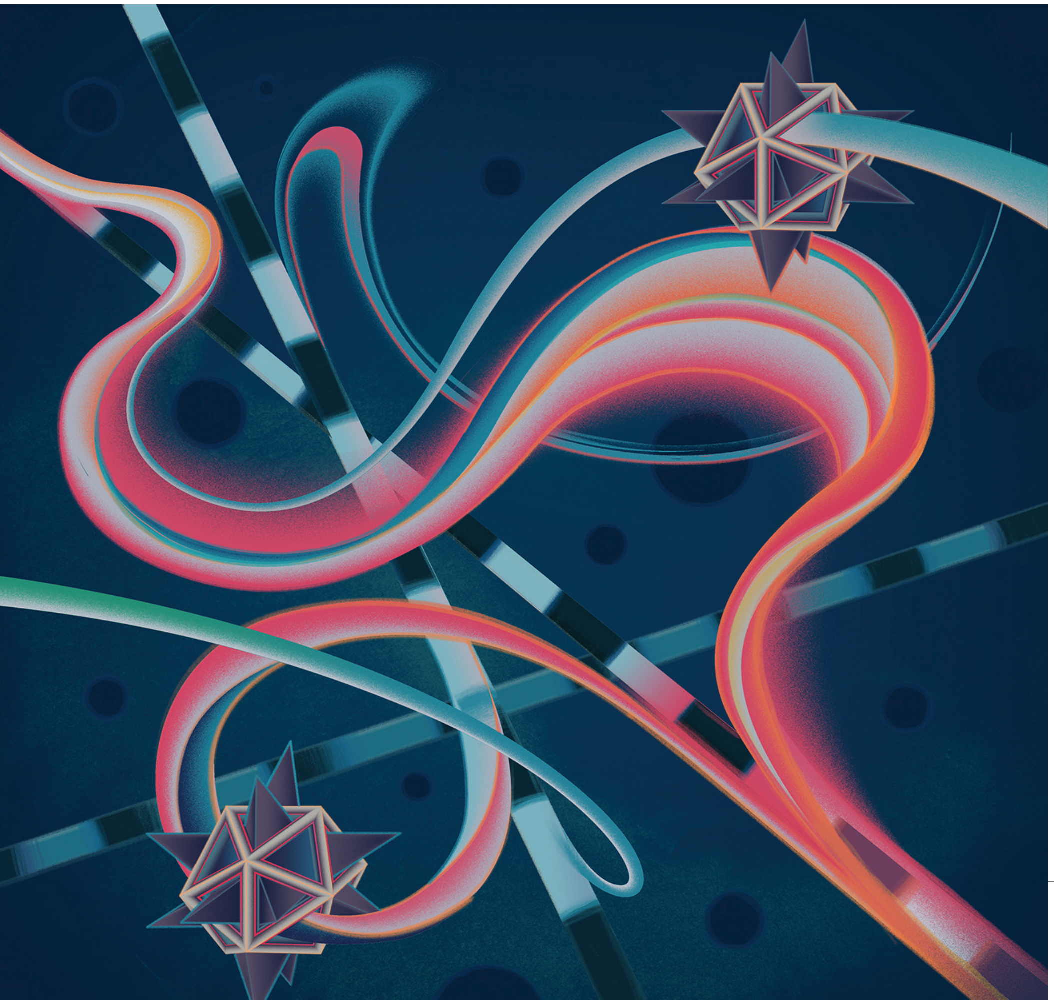


PHOTO: SCIENCE PHOTO LIBRARY ILLUSTRATIONS: SAM CHIVERS

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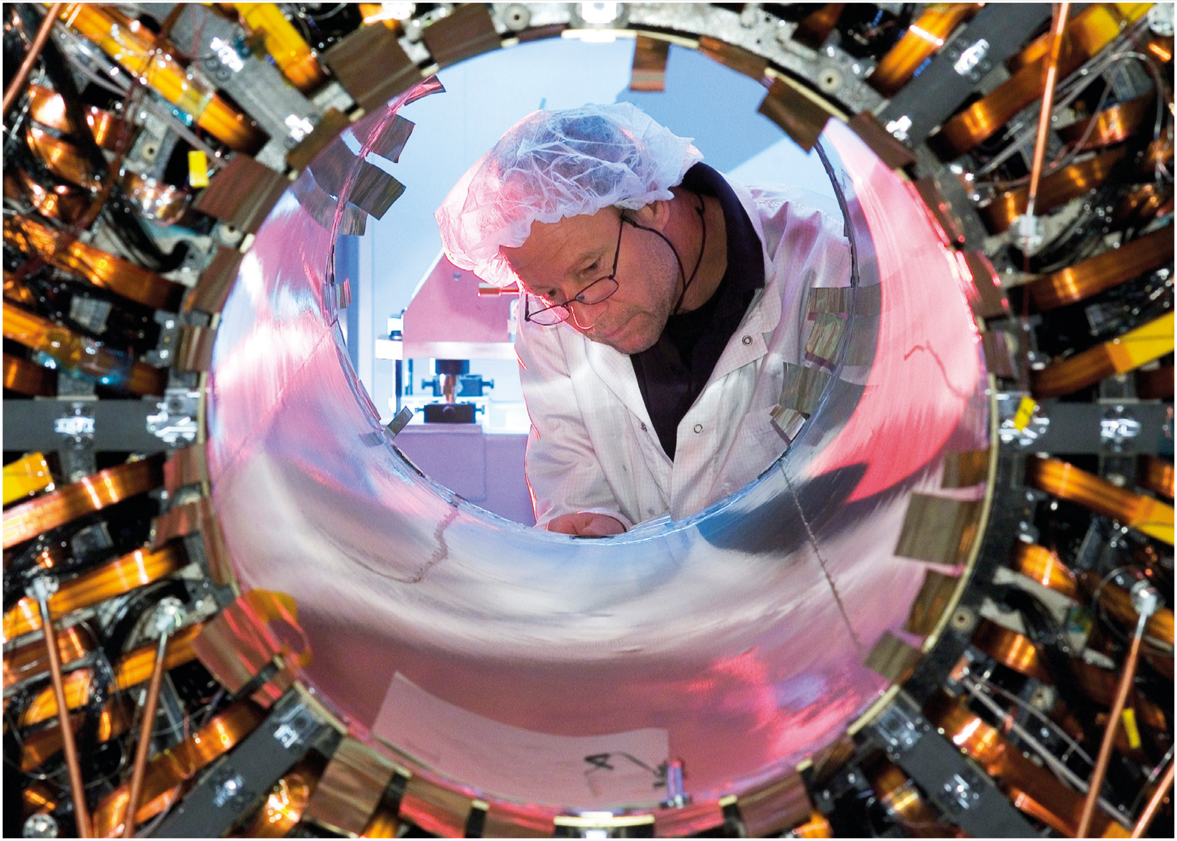
* Actually, the numbers are a special type of number known as 'complex numbers' and the probability is obtained by adding together the complex numbers for each possible route to X and Y. But to get the main idea, it isn't necessary to know about complex numbers.



An engineer works on the ATLAS experiment, which hunts for the Higgs boson as well as particles that could make up dark matter

## Quantum physics in five steps

1. Everything in the entire Universe is made up of elementary particles that constantly interact with each other. These particles include the electron, quarks and – of recent interest – the Higgs boson.

2. It is not possible for us to know exactly how these subatomic particles will move around. The best we can do is to calculate the probability of something happening.

3. To calculate the probability of an electron moving to point X, we assign a number to each route, then add the numbers together. We have to consider that the electron travels by *every* possible route.

4. Particles hop around like crazy, emitting and absorbing other particles as they go. Remarkably, the regular, orderly world that we experience emerges from this subatomic anarchy.

5. The modern world is built using technology that relies on our understanding of quantum physics, from lasers and medical scanners to the silicon chips that power our computers and smartphones.

Peter Higgs, who used purely theoretical ideas to predict the existence of a new particle in the 1960s. The particle, now termed the Higgs boson, was finally discovered using the Large Hadron Collider at CERN in 2012

> “Apart from quarks, electrons and photons, we now know that the Universe contains other elementary particles”

The trouble is that nature’s quantum rules lead to a picture of the microworld that is pretty much impossible to imagine. This is probably the biggest challenge to anyone trying to understand it. We have to concede that the way we imagine the world is limited – we simply cannot conceive of things that are both ‘alive’ and ‘dead’, or ‘here’ and ‘there’, at the same time. But it seems that this is how the world actually behaves – the Universe is far richer than our imagination can grasp. The bottom line, then, is that although the rules might be weird, they can be used to make precise mathematical predictions concerning the real world.

**THE WORLD WE SEE**

Although we have been talking about the rules governing how particles move around, we have so far been careful not to say what those rules are in any detail. That’s because the details require a knowledge of mathematics beyond what we can cover here. We can give a flavour of what’s involved, though, by asking what happens to a particle whose position in space is perfectly well known at some moment in time.

> “We simply cannot conceive of things that are both ‘alive’ and ‘dead’, or ‘here’ and ‘there’, at the same time”

Before the 1920s (which is when quantum theory first really established itself as the new order in physics), the answer to the question “what happens to a particle if it is left alone?” was thought to be self-evident: nothing happens to it; it just hangs around doing nothing. This is Isaac Newton’s first law of motion. But, for small enough particles, Newton couldn’t be more wrong.

The correct rule is that a particle, whose position is known at some moment in time, will leap off and could equally likely be found more or less anywhere else at any later instant. In fact, the particle really ought to be considered as occupying all possible locations in space simultaneously a mere moment after it is released from its original, known, location. This is the essence of Werner Heisenberg’s famous Uncertainty Principle, and such spectacularly bizarre behaviour really is the way that tiny things move around. Large things, such as sofas and washing machines, are built from tiny particles, so you might be forgiven for wondering how such anarchic behaviour at the subatomic scale can lead to the mundane behaviour of everyday objects. After all, your washing machine does tend to stay in the same place from one day through to the next.

PHOTO: CERN ILLUSTRATIONS: SAM CHIVERS

But remarkably, the anarchic rules operating at the subatomic level do lead to the everyday behaviour of big things. This is because, as we’ve already discussed, particles don’t tend to occupy precisely known locations at some instant in time. Instead, they’re in several places at once. Let’s imagine one such particle, an electron in an atom in your body, say. At any given moment in time, the electron simultaneously occupies lots of different locations surrounding the atom. To compute the chances of it being found at a position X, far from your body, some time later, we need to add together the numbers corresponding to all of the ways the electron could hop from one of its original locations to X. The magic is that, although the numbers can be big for any particular hop to X, when we add the numbers for all possible hops together we get a tiny number. In other words, the electron is highly unlikely to be observed at X, far away from its parent atom. It seems that our regular and orderly world is an emergent feature of a seething maelstrom of activity on the subatomic scale.

Apart from quarks, electrons and photons, we now know that the Universe contains other elementary particles. There are the muon and tau particles, which are like heavy versions of the electron; three types of neutrino; W and Z particles; gluons; and, of most recent interest, there is the Higgs boson and perhaps (though not yet seen) dark matter particles. All of these hop around, emitting and absorbing other particles according to a set of mathematical rules. In next month’s article, we will turn our attention to these elementary particles. We will see what role they play in shaping our Universe, and discover how the rules governing their behaviour are underpinned by the most beautiful of ideas.

**Jeff Forshaw** is professor of particle physics at the University of Manchester. He has co-authored three popular science books with Brian Cox.

**Brian Cox** is professor of particle physics at the University of Manchester and the Royal Society professor for public engagement in science. His BBC TV and radio work includes *Wonders Of The Universe*, *Forces Of Nature*, *Stargazing Live* and *The Infinite Monkey Cage*.

**DISCOVER MORE**

To learn more about the strange workings of the quantum world read Brian and Jeff’s *The Quantum Universe: Everything That Can Happen Does Happen* (£9.99, Allen Lane).

Brian and Jeff’s latest book is *Universal: A Guide To The Cosmos* (£25, Allen Lane).

# THE REAL SCHRÖDINGER'S CAT

In 1935, Erwin Schrödinger created his famous thought experiment involving a cat that is both dead and alive to illustrate a perceived flaw in the emerging field of quantum theory. Nearly a century later, the idea is not proving as absurd as he originally intended...

**WORDS:** BRIAN CLEGG

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Back in 1935, Albert Einstein and colleagues hypothesised that quantum theory predicted a remote linkage between particles, called quantum entanglement. Einstein took an instant dislike to the idea, calling it "spooky action at a distance". He hoped that the existence of quantum entanglement meant that quantum theory, which he wasn't too keen on to begin with, was somehow flawed, or not yet fully understood.

Quantum entanglement is a bizarre offshoot of quantum theory that says certain properties of a pair of particles become linked together in such a way that if you measure the value of one of them, then you instantaneously know the state of the other, even if they are separated by cosmic distances. Weird, eh? Sadly for Einstein, quantum entanglement has been demonstrated to be true many times, but so far only on a subatomic level.

Quantum theory describes the workings of the Universe's smallest known components, predicting the behaviour of electrons and atoms, molecules and photons of light. And it does so incredibly well: eminent physicist Richard Feynman pointed out that quantum theory is so accurate it's like predicting the distance between New York and Los ➲

Angeles to the width of a human hair. Yet quantum particles behave totally unlike everyday objects on a more human scale.

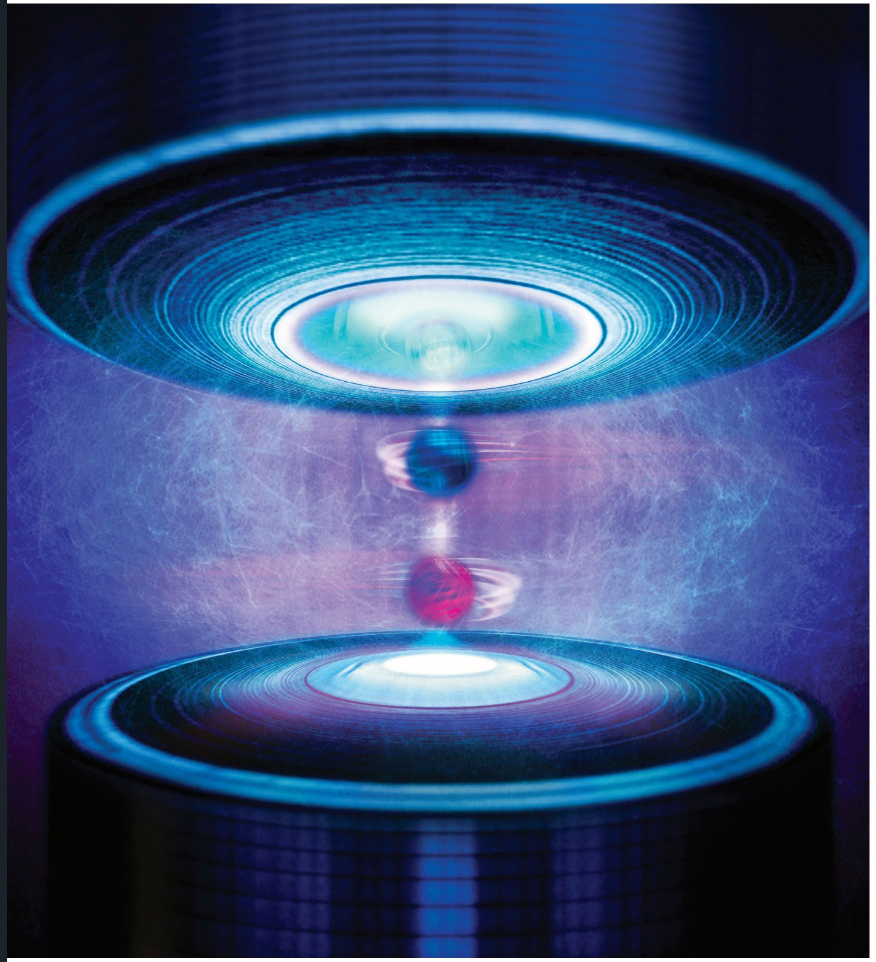
### TOO WEIRD FOR EINSTEIN

One of the key tenets underlying quantum theory is the idea that a particle can be in more than one place at any given time. Oddly, when not interacting with the world around them, or having their positions specifically measured, quantum particles don't have a specific location. Instead, all that exists is a collection of probabilities of where the particle could be at any given time – a so-called superposition of states. It is this phenomenon that leads to Schrödinger's cat (see opposite page) being both alive and dead.

This gives us a puzzling distinction between everyday macroscopic objects, which obey the predictable precision of 'classical physics', and the microscopic world of tiny objects – 'quantum physics' – where probability rules. Einstein was so appalled at this idea it led him to say: "I would rather be a cobbler, or even an employee in a gaming house, than a physicist."

When Einstein raised his objections to entanglement in the 1930s, it wasn't possible to experimentally verify it. But by the 1970s it became feasible, and successful entanglement experiments have been run many times since. There are even several practical applications of entanglement. One is quantum encryption. It takes inspiration from an idea by the American banker and cryptographer Frank Miller, who was working on the creation of an unbreakable cipher called a 'one-time pad' around 100 years ago. His idea was to give both sender and receiver a key made up of random values, but the approach was not 100 per cent secure because this key would have to be sent to both sender and receiver and so could be intercepted. However, as quantum entanglement automatically provides random values even at widely separated locations, and also makes it possible to check whether particles have remained entangled, it would be impossible for a third party to read the random key before the particles reach their destinations. Chinese researchers have tested this principle, sending entangled photons to locations 1,200 kilometres apart.

> "Einstein was so appalled at [entanglement] it led him to say: 'I would rather be a cobbler, or even an employee in a gaming house, than a physicist'"

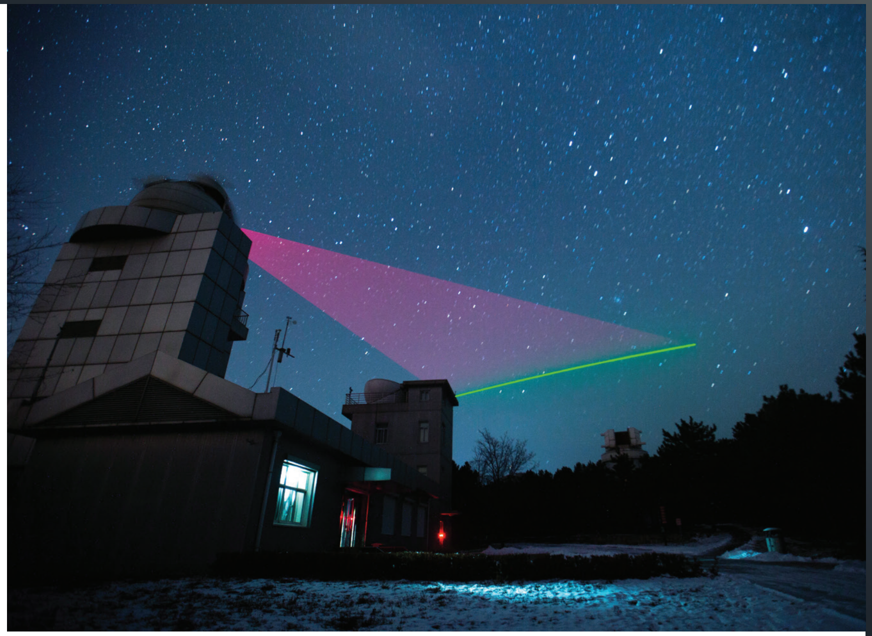


This illustration represents 'spin', which is one of the properties of subatomic particles

### TELEPORTATION DEVICE

Quantum entanglement also makes quantum teleportation possible. Without entanglement it's not possible to copy a quantum particle, because observing it will change the particle's properties into a specific state. But quantum entanglement can transfer the state from one particle to another without altering it. This is like a small-scale version of a *Star Trek* transporter, though real teleportation makes a remote copy, scrambling the original, rather than moving it.

In practice, using teleportation on people would be impractical as they contain too many atoms. But the process can transfer quantum information from place to place, which is essential when building quantum computers. In standard computing, bits have values of 0 or 1. With quantum computing, bits are replaced with qubits, combining probabilities of 0 and 1 simultaneously, making it possible for special programs to run far faster than on a conventional computer.



China's quantum satellite Micius has sent entangled photons (particles of light) from space to ground stations on Earth

Even outside of the lab, quantum phenomena are occurring all of the time. Any interaction between matter and other matter or light is a quantum process. All electronic devices rely on quantum phenomena, and even the Sun wouldn't work were it not for the probabilistic nature of the location of quantum particles enabling hydrogen nuclei to get close enough together to fuse and produce energy. There is also increasing awareness of quantum processes in biology. For example, photosynthesis, used by plants to generate energy from light, seems to use quantum effects to channel energy to the appropriate part of the plant. Entanglement also may enable pigeons and robins to navigate. These birds detect the Earth's magnetic field, apparently due to quantum entanglement in their eyes. Light coming into the eye boosts the energy of electrons. A property of the electrons called 'spin' is then influenced by tiny variations in the Earth's magnetic field, and it is thought that quantum entanglement makes it possible for the bird to build a picture by linking different electrons.

### SCALING UP

But can quantum phenomena apply to objects bigger than tiny atoms or molecules? The answer appears to be yes. Dr Simon Gröblacher of Delft University of Technology and his colleagues have entangled two microscopic silicon bars. These bars measure 10 x 1 x 0.25 millionths of a metre, making them finer than a human hair. They have tiny pockets inside them that absorb energy from laser light which causes them to vibrate. The laser light is set up in such a way that the vibrational states of the bars become linked via quantum entanglement. This is highly unusual. Usually in an object of this size, interaction between different atoms within the object, and with any atoms it comes into contact with, destroys entanglement in a process known

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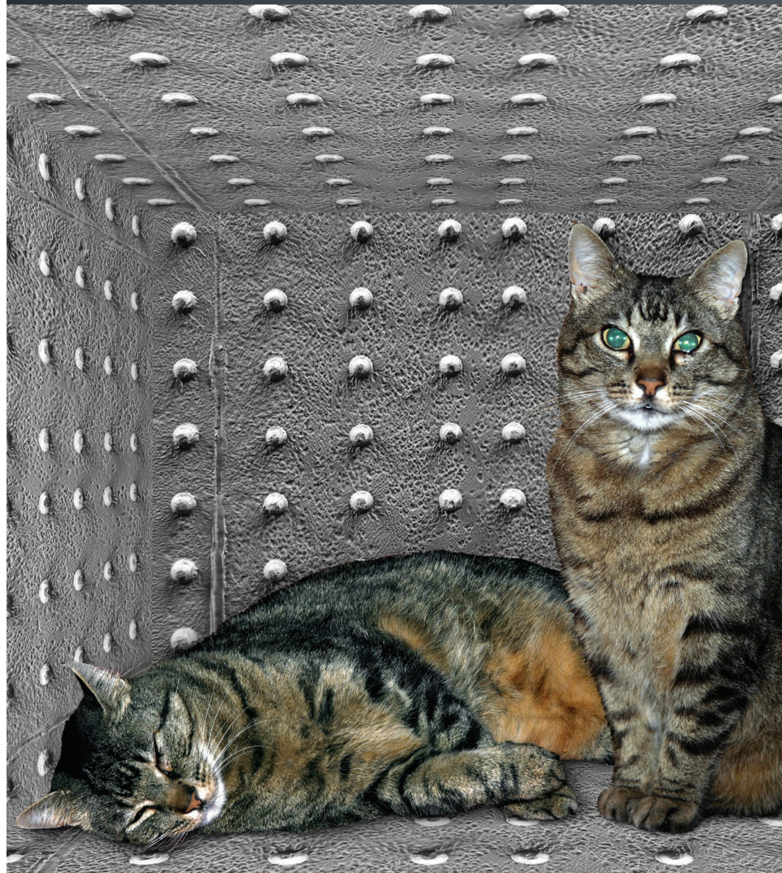
## WHAT IS SCHRÖDINGER'S CAT?

The Schrödinger's cat thought experiment demonstrates the strange nature of quantum superposition. A cat is placed in a box with a vial of poison, which will be automatically smashed if a radioactive particle decays. Radioactive decay is one of the probability-driven aspects of quantum physics. We can't say when a given particle will decay, we only know the probability of it decaying in a certain period. After some time has elapsed, an unobserved particle will be in a superposition of decayed and not decayed states. All that exists before measurement (someone looking inside the box) is the probabilities. But since the life of the cat depends on the state of the particle, does this mean the kitty is simultaneously dead and alive?

In reality, we could never witness the cat being both alive and dead – as soon as we look in the box, the cat will be in just one state. And the practicalities of the experiment don't even allow for this. For the detector to be able to release the poison it would have to interact with the particle, forcing it to be either decayed or not decayed.

Despite its limitations, Schrödinger's cat gives us a feel for the weirdness of superposition, and while such a test wouldn't be possible with a complex organism like a cat, proposed experiments with a tardigrade could bring an aspect of the Schrödinger's cat experiment closer to reality.

Schrödinger's cat: dead and alive at the same time, until it is 'fixed' into one of these states by someone observing it



## TARDIGRADES: THE WORLD'S TOUGHEST ANIMALS

**1** Tardigrades, also known as water bears or moss piglets, are a group of eight-legged animals. They are about 0.5mm long, and can be found around the world in a wide range of environments.

**2** Tardigrade means 'slow paced'. It was originally an adjective applied to tortoises, but since 1800 it has been the name of these microscopic creatures.

**3** Tardigrades can cope with extreme high and low temperatures that would kill other organisms. Some species can survive exposure to -272.15°C.

**4** If a tardigrade is dehydrated and loses up to 99 per cent of its water content, its living processes can be near-suspended for several years before being brought back to life.

**5** In 2007, dehydrated tardigrades were taken up into orbit and exposed to the vacuum and radiation of space for 10 days. On return to Earth, over two-thirds of them were successfully revived. Many died relatively soon after, but were still able to reproduce before they passed away.

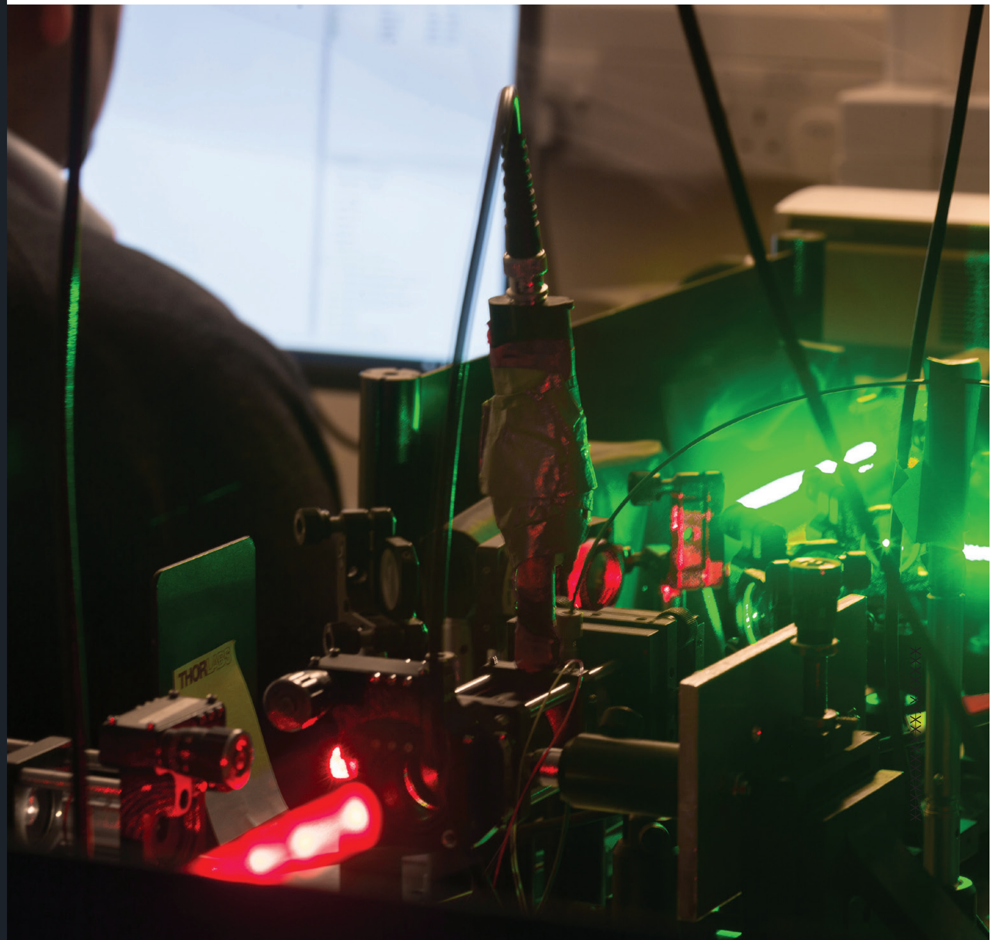
**6** Inside the cells of dehydrated tardigrades, a protein replaces the water. This forms a glass-like substance that keeps the cell structures intact.

**7** Tardigrades are among the few animals to have lived through all of our planet's big five extinction events.

▶ as 'decoherence'. So if it is possible to entangle a pair of silicon bars, how big could we go? Could we entangle living organisms?

Quantum biology is still a young field, but inspired by experiments such as Gröblacher's, some scientists are devising experiments to use quantum effects to produce superpositions and entanglement in living organisms. One group believes that this has already happened. In 2016, Dr David Coles of the University of Sheffield and his colleagues sent light bouncing across a narrow gap between two mirrors, through green sulphur bacteria. The experiment was devised to study photosynthesis, but when subsequently analysing the data, a group led by quantum physicist Dr Chiara Marletto at the University of Oxford discovered evidence that molecules inside the green sulphur bacteria had become entangled with the photons of light.

They are not 100 per cent certain of the effect, as proving entanglement would require measurements of the photons and the bacteria independently, and this wasn't possible in their particular experiment. Marletto admits that dealing with living organisms is far harder than quantum particles. "In quantum biology the molecules are very messy, and it is hard to perform accurate measurements," she says. "What one would have to do is to isolate a single biomolecule [a molecule in a biological organism] within the bacterium and demonstrate that it is entangled with light," she says.



A quantum optics setup at the University of Oxford with laser beams passing through a series of elements

GETTY, SCIENCE PHOTO LIBRARY, DAVID FISHER/OXFORD MARTIN SCHOOL

> "Entangling living bacteria is a first step towards assessing the feasibility of implementing teleportation in bacteria"

### INTO THE REAL WORLD

But if such entanglement does occur, it could possibly be a survival mechanism that the bacteria use to harvest the scarce light in the deep oceans. And if entanglement were proven, it would open up a wealth of further possibilities.

"There has been a long-standing debate about whether quantum theory applies to all scales. The experiment shows that biomolecules in living entities are perfectly capable of displaying quantum effects by being entangled with light. The remarkable thing also was that the bacteria were alive throughout the experiment," says Marletto.

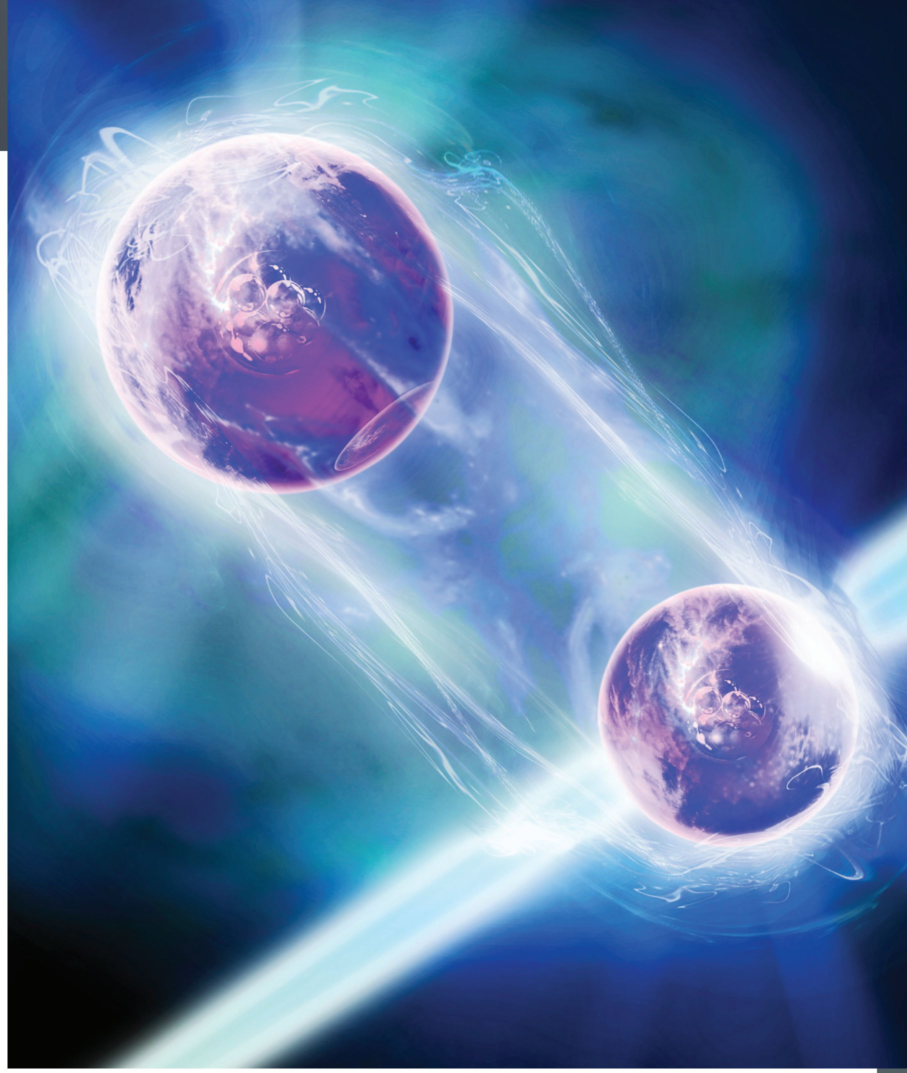
To investigate the phenomenon further, Dr Tristan Farrow, one of Marletto's colleagues, has proposed a new study to entangle a quantum property in a pair of bacteria. Although initially limited to a single property, Farrow believes the experiment could be taken further. "Entangling living bacteria is a first step towards assessing the feasibility of implementing teleportation in bacteria," he says. "Big, hot and messy systems such as biomolecules, never mind living organisms, have long been thought to be hostile environments for quantum states to survive for any meaningful length of time. We don't know whether this is always true, or whether certain sub-structures inside these complex molecules can shield quantum states from the hostile environment."

And there could be practical applications, too. "Bio-inspired quantum computing is an applied aspect of our research, aiming to reverse-engineer artificial structures inspired by biology," says Farrow. "A prime example would be an artificial leaf to harvest light energy with extreme efficiency inspired by how certain photosynthetic molecules might use quantum superpositions to transport energy captured from sunlight."

Gröblacher is also interested in experiments involving living creatures. He is currently working on putting a sheet of nitride into a superposition of states. By using a laser, it is theoretically possible to get a barely visible membrane of silicon nitride measuring around one millimetre across into a superposition of vibrations with two different amplitudes. The amplitude is related to the amount of energy carried by a wave, and is the measurement from the undisturbed position to the peak of the wave. If you apply more force, the peak – and therefore amplitude – increase. Gröblacher reckons they are within a couple of years of achieving this superposition of vibrations.

"A superposition state of these membranes would allow us to demonstrate that objects that are visible to the naked eye still behave quantum, and we can really test decoherence – the transition between classical and quantum mechanics," he says.

He then hopes to extend the experiment by placing tiny living organisms called tardigrades (see opposite page) onto the membrane of silicon nitride, putting them into superposition too. One of the remarkable abilities of tardigrades is their ability to survive being dehydrated. The tardigrades would be in their dehydrated state during the experiment so that there would be no impact on their biology. If successful, Gröblacher's tardigrades would be the closest we've come to seeing a living creature in two simultaneous states – a real-life Schrödinger's cat. ■



Subatomic particles can become entangled. Even if they are separated across great distances, a change or measurement to one particle will affect the other

**Brian Clegg** is a freelance author who has written over 30 science books. His latest is *The Graphene Revolution* (£8.99, Icon Books).

Listen to *In Einstein's Shadow*, a BBC Radio 4 series about General Relativity, quantum theory and Einstein. Presented by Brian Cox.
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INTERVIEW

# THE SEARCH FOR A THEORY OF EVERYTHING

The two main theories of physics are at odds with one another. Einstein's General Relativity explains gravity, but it contradicts quantum theory: how we understand matter, atoms and particles. Theoretical physicist **Fay Dowker** tells **Amy Barrett** why the theories are incompatible, and how she intends to bring them together...

**WHAT CHALLENGE DO PHYSICISTS FACE TODAY?**

I am working on the problem of quantum gravity. We don't have a theory of quantum gravity yet. The challenge is to find one. It's a problem because our current two best fundamental theories in physics [General Relativity and quantum theory] are not compatible with each other. It's a strong statement to say they are contradictory, but I'm not afraid of saying that. Science advances by looking at contradictions between different pieces of our understanding, and it focuses on those contradictions in order to make progress.

Science tolerates contradictions, but not forever.

**WHAT ARE THE CONTRADICTIONS INVOLVED IN THE PROBLEM OF QUANTUM GRAVITY?**

Our best theory of gravity, currently, is General Relativity. Largely formulated by Albert Einstein, according to this theory, gravitational phenomena – such as the motions of the planets around the Sun, black holes, the motions of galaxies in the Universe – are manifestations of the geometry of a fabric that we call space-time.

Space-time is four-dimensional, and it's dynamical, so it has a life of its own. It is governed by laws of physics. It bends and it warps, and it ripples, and it carries energy. It is a physical entity in our current understanding of gravity.

> "Space-time is dynamical, so it has a life of its own. It is governed by laws of physics"

The way that it bends and warps is governed by the matter in the Universe. Depending on what matter there is, then space-time responds to it. If two black holes, for example, are in orbit around each other, spiralling in towards each other, then that will predictably create ripples in this space-time fabric called gravitational waves.

But the contradiction arises because our best and most fundamental understanding of matter is quantum mechanical. One of the essential features of quantum mechanics is that quantum mechanical events are inherently unpredictable. When a quantum mechanical event happens, we don't know in advance what the outcome will be. We know what the possibilities are, but we won't know which one will happen. Like if you go to a horse race, you know that one of the horses will win, but you don't know which one in advance. That quantum mechanical feature of matter is ignored by General Relativity. There's the contradiction: quantum mechanics says that matter behaves in a stochastic or random way, but General Relativity assumes that matter behaves in a predictable way.

**SO HOW DO WE FIND A RESOLUTION TO THIS CONTRADICTION?**

There's a global community of people working on quantum gravity. It's a strange situation at the ➲

> “The idea of four-dimensional space-time is that you need four numbers to pin down not just where you are but *when* you are … a particular instance of you. I mean, you *now*”

moment, in which the experimental evidence pointing us in one direction or another in quantum gravity research is very, very scarce. It’s hard to be guided by actual observations. For example, at the time of the Big Bang, roughly 13.7 billion years ago, when the matter in the Universe was in a hot, dense state… that realm is where both gravitational and quantum effects will be important. But it’s very far from us in time. So, it’s difficult for us to probe that era to get experimental evidence of what quantum gravity should be like.

**CAN WE LOOK OUT INTO SPACE AND SEE THIS HAPPENING?**

We can. So, cosmology – which is the study of the Universe at the largest scales that we can observe – is probably the most promising area that we can look to for evidence for different approaches to quantum gravity. I am hopeful that more and more cosmological data will, in the not so distant future, start to distinguish between different approaches, and we’ll be able to be guided by that cosmological data in our research in quantum gravity.

**WHAT ARE THE DIFFERENT APPROACHES?**

I could divide them roughly into two… I mean, there’s overlap between them, and there are scientists who work on more than one approach, but roughly speaking, they can be divided into two camps. There’s one approach which comes from a tradition of particle physics, called string theory. These are physicists who have been focused on trying to understand matter at the most fundamental level, the standard model of particle physics. In string theory, the fundamental particles are conjectured to be different modes of vibration of a fundamental substance, which is one-dimensional. That’s why it’s called string theory; string is one-dimensional.

The other tradition takes the four-dimensional fabric of space-time as the starting point and to think about it as having a quantum mechanical nature. That stems from physicists working on General Relativity and gravitational physics, from which arises approaches that are more focused on space-time than they are on matter.

**FOUR-DIMENSIONAL SPACE-TIME IS QUITE HARD TO GET YOUR HEAD ROUND.**

Yes, yes, it is. It’s a new worldview, a new way of thinking about the Universe. How do you get your head around three dimensions?

**THREE DIMENSIONS IS SOMETHING THAT WE’RE ALL FAMILIAR WITH, RIGHT?**

Yes, good. But what does it mean exactly? Well, what it means is that you can think of a thing, let me say… my teacup. To tell you where it is, I have to give you three numbers, three coordinates. How high it is above the floor, how far it is from the front wall, and how far it is from the side wall. That’s what we mean by space being three-dimensional. If you want to pinpoint your position in Bristol right now on a map, you only need to give two numbers: the two coordinates of the coordinate grid on the map. So, the map of Bristol is two-dimensional, the space in this room around my teacup is three-dimensional.

The idea of four-dimensional space-time is that you need four numbers to pin down not just where you are but *when* you are. And what I mean by ‘when you are’ is not you, because you persist for many moments of time, but a particular instance of you. I mean, you *now*.

So, to say where that event is of you, you need to give four numbers. Three where you are in space, roughly speaking, and one of what time it is at that moment. Four-dimensional space-time is the collection of all these events.

**HOW DOES THAT RELATE TO QUANTUM GRAVITY?**

Well, first of all it relates to gravity. Space-time is the fundamental way that we understand gravity.

If you take all of the events in the Universe, then they form this four-dimensional fabric. The structure of that four-dimensional fabric manifests itself as gravitational phenomena. It explains gravity. It tells us why the planets orbit the Sun and why the galaxies behave as they do, why black holes exist, so this four-dimensional fabric of space-time is gravity.

Now, to understand quantum gravity, we have to understand quantum space-time. In General Relativity, space-time is smooth and continuous. But in the approach to quantum gravity that I work on, called causal set theory, the conjecture is that this smooth fabric is just an approximation to something which is fundamentally granular, bitty, pixelated. Fundamentally atomic. The word ‘atom’ means uncuttable. It’s something you can’t divide up any more. It’s conjectured to be made of fundamental events that are the smallest possible events, and you can’t cut them up any more.

Causal set is just the name we give to the mathematical, discrete, atomic object. The originator of causal set theory is my close colleague, a physicist called Rafael Sorkin.

**HOW WILL THINKING ABOUT SPACE-TIME AS GRANULAR HELP SOLVE THE PROBLEM?**

It relates to our understanding of the nature of the quantum world. There’s no consensus on how to understand quantum theory, and but one approach is called ‘the sum over histories’. It’s associated very closely with the particle physicist Richard Feynman.

In this approach, you think about a quantum system in terms of things that can happen, events, and then histories, which are very detailed ways in which that event can happen. Feynman’s sum over histories gives you a way of making predictions about those events, rules about how to calculate the probability of an event happening.

My colleagues and I are trying to base an understanding of the quantum physical world, on this sum over histories.

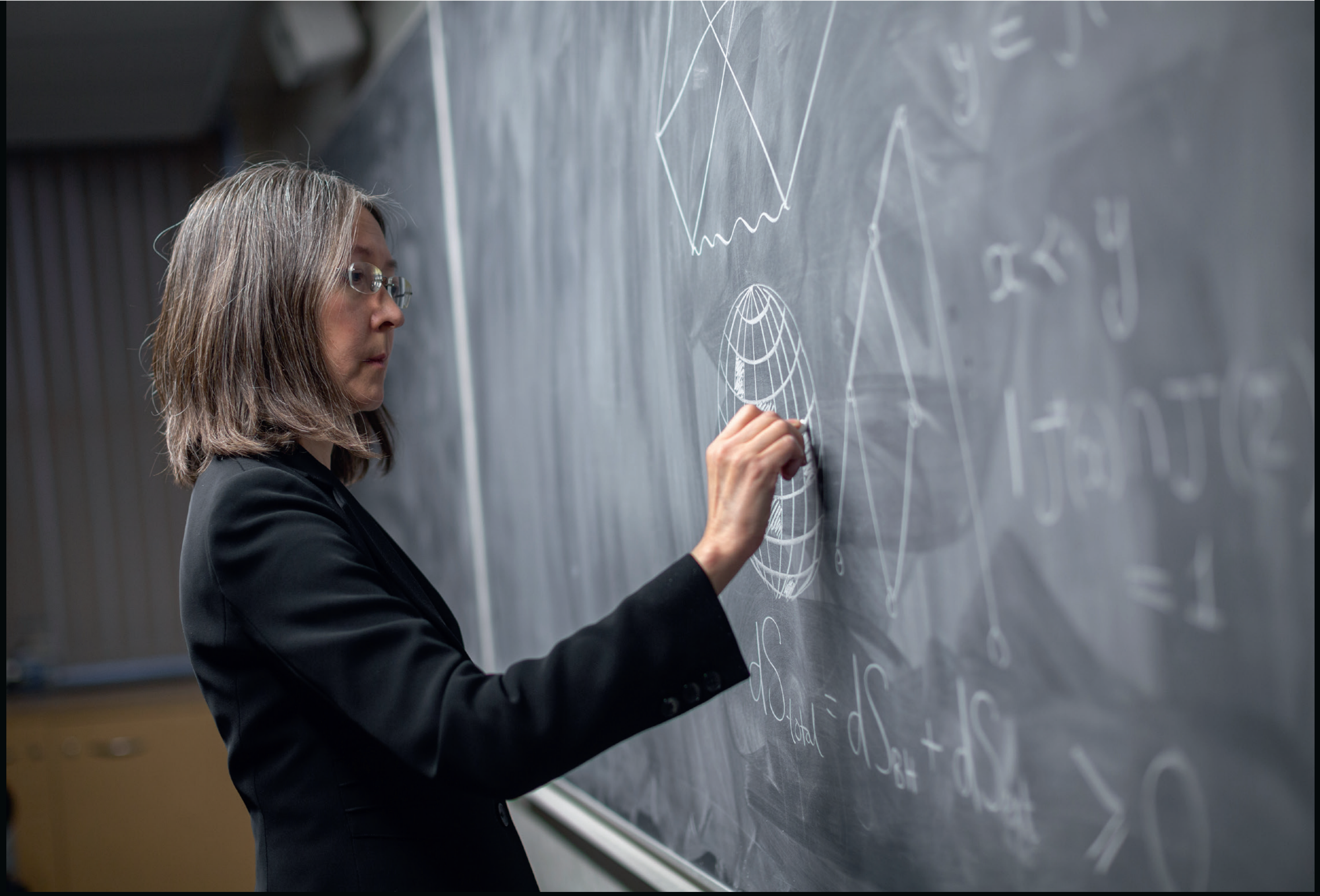
**PROF STEPHEN HAWKING WAS YOUR PHD SUPERVISOR. WHAT WAS HE LIKE?**

It was an amazing experience being his student. Stephen was a generous supervisor. He involved me in the work that he was doing, he gave me a great problem to work on, and he was approachable. I was a shy person and not good at putting myself forward, but he was not standoffish at all. He always made time for me. Even though I would often have to wait for a long time before seeing him because he was so busy, he always made it clear that science and his work and his research was a priority.

That was an important part of my PhD. The things that he taught me are still part of the way that I think about physics. The opportunities that I got from being his student also helped me enormously in my subsequent career. He just expected us to be involved in whatever he was doing at the time. I think that’s very, very encouraging for a young scientist, to feel that they’re part of something bigger. **SF**

**PROF FAY DOWKER**

Fay is a professor of theoretical physics at Imperial College London, working on several areas of theoretical physics as well as teaching and supervising students. As an undergraduate, Fay studied mathematics at the University of Cambridge. In 1990, Fay completed her PhD on space-time wormholes, under the supervision of Prof Stephen Hawking. She describes Stephen as her “teacher, mentor and friend” and delivered the eulogy at his funeral in 2018.



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**ABOVE** Prof Fay Dowker teaches theoretical physics at Imperial College London

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