- Quantum theory

A HITCH HIKER'S GUIDE TO THE QUANTUM WORLD

Quantum physics is confusing. Really confusing. You just won't believe how vastly, hugely, mindbogglingly confusing it is. Fortunately, scientists have been exploring it for years now and are, finally, beginning to make some sense of it all by PHILIP BALL

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In the same way that "space is big" (as described in Douglas Adams's *The Hitchhiker's Guide to the Galaxy*), quantum physics is confounding.

Science's best minds have been puzzling away at it for over a century, pawing at the subject like Schrödinger's cat playing with a ball of cosmic string. But the bafflement is beginning to give way to understanding and we're starting to get a grasp on not only what quantum physics could mean, but what uses it could be put to.

Here are just a few suggestions for entries in what could be an early draft of a hitchhiker's guide to the quantum world. Just remember: don't panic!



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QUANTUM INTERNET

Entangled encryption and a quantum cloud could change how we share data

In the 1980s, researchers pointed out something intriguing: the laws of quantum physics should permit information that has been encoded in quantum objects – like photons, the 'quantum particles' of light – to be sent from one person to another in a totally secure way. By connecting the transmitted particles via a phenomenon called quantum entanglement, it would be impossible for some would-be eavesdropper to intercept and read the message without the recipient detecting such tampering.

This quantum cryptography was later demonstrated for light signals sent through the air or down optical fibres, and in 2007 the technique was used for secure transmission of the results of a Swiss election. Quantum cryptography has now been carried out for messages sent from China to Austria via signals bounced off a special quantum-enabled telecommunications satellite.

Now, there are plans afoot for a 'quantum internet' in which all messages are sent via fibre or satellite with secure encoding. Last year, researchers in China sent quantum-encrypted information through optical fibres between a sender and receiver more than 12km (7.5 miles) apart in an urban area. This was the first step in creating a national quantum-information grid.

QUANTUM COMPUTERS

The challenges of making a sci-fi staple a reality

Quantum computers have been a godsend to science-fiction writers in need of a machine capable of doing anything, even creating alternative realities. In truth, quantum computers have nothing like that power. Yes, today's prototypes have achieved impressive things, like performing calculations that would take conventional computers longer than the age of the Universe to complete. But these amount to party tricks: quantum computers remain some way off from tackling the most challenging of tasks, like predicting new drugs and materials or simulating the weather.

The issues lie in the immense engineering obstacles. Whereas conventional computers encode information in binary form as 1s and 0s, a quantum 'bit', or qubit, can be placed in states that are a mix of 1 and 0 (the purple spot on the qubit illustrated below). To carry out a computation, qubits must be entangled, meaning that their settings are interdependent. Sustaining an entangled state among hundreds – or even thousands – of qubits is technically hard and generally requires very low temperatures.

What's more, we have to develop ways to protect quantum computers against random errors that can occur if the state of a qubit gets flipped accidentally. With conventional computers, we can keep back-up copies of the bits, but the laws of quantum physics prohibit that for qubits.

"Error correction places a huge resource overhead on quantum computing", says Prof Anthony Laing, a physicist at the University of Bristol. In fact, current quantum computers are concerned as much with correcting errors as with running the tasks. Yet error correction methods are steadily improving and Laing says that if researchers can make components more resistant to errors, quantum computers could become radically simpler and more powerful.



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QUANTUM SENSORS

High-precision measurements will have a host of applications

Although quantum information technologies (such as computers and cryptography) tend to steal the limelight, other technologies that rely on quantum rules have been around for some time. Lasers, invented in the 1960s, exploit a quantum effect discovered by Albert Einstein in 1917.

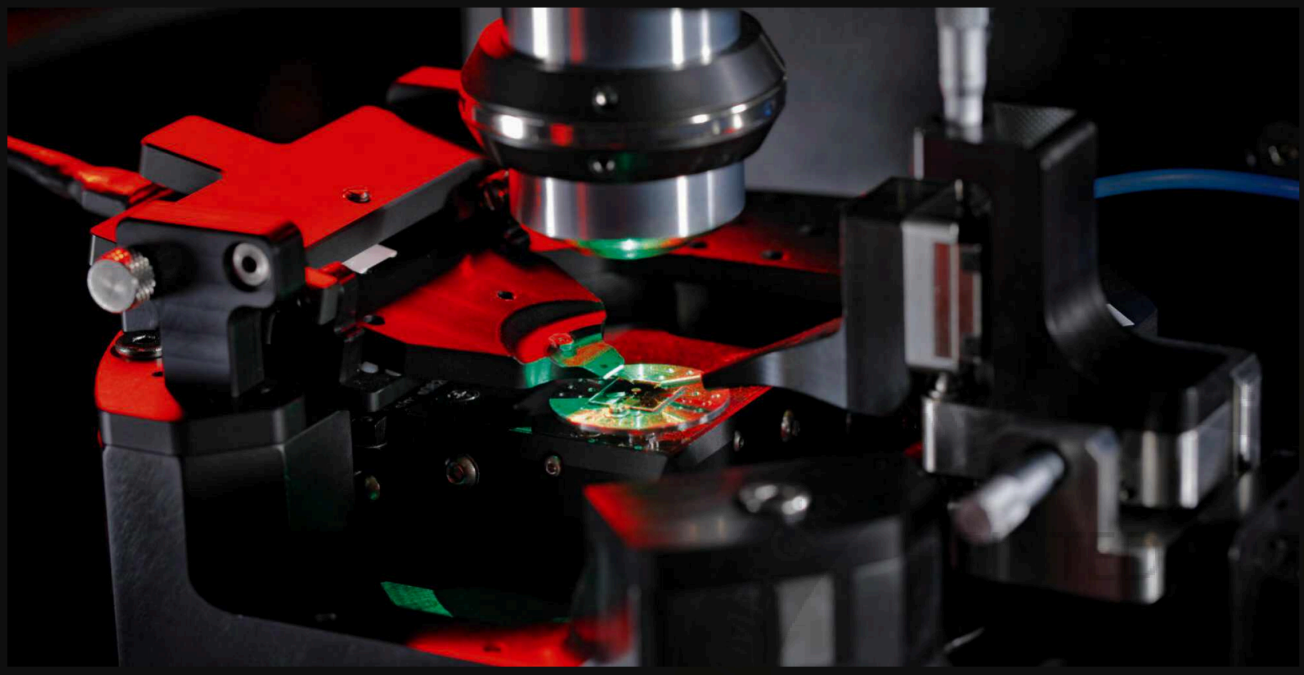
Many of the newer quantum technologies are sensors that exploit quantum effects to attain far greater accuracy than classical devices can provide. For example, electrons in atoms are forced by quantum physics to have very particular energies, each with an associated frequency. In atomic clocks we can use that frequency like the steady pulse of a pendulum, which never deviates since it's fixed not by the limits of engineering precision, but by the laws of nature. And by clever use of entanglement between atoms, even the apparent quantum limits on how accurately we can measure such a pulse can be cheated. Such highly accurate timekeeping already has applications, such as for GPS navigation.

Meanwhile, quantum magnetometers use a property called 'spin' in individual quantum particles, such as atoms embedded in crystals, to create sensors for detecting very weak magnetic fields. The fields change the spin state of the particle and this change can be detected from a shift in how the particle absorbs light. A quantum magnetometer (like the one pictured below) can be used in medicine – in brain scanning, for example – and in geological prospecting and more.

What's more, the fact that quantum particles can act like waves opens up opportunities for making extremely precise measurements of distance and movement. Such 'matter waves' can get out of step with one another if they're sent along different paths, meaning that they will interfere when brought back together. This is similar to how light waves interfere to cancel out some colours and enhance others when reflected from iridescent surfaces. By exploiting this effect, even tiny differences in path or motion become detectable.

Quantum interference is already being used in devices for measuring gravitational fields by letting clouds of cold atoms fall along different trajectories before bringing them together again. But the principle might also be used to measure acceleration for navigation systems and motion trackers. It could even test the fundamental theories of physics.

"QUANTUM MAGNETOMETERS USE A PROPERTY CALLED 'SPIN' IN INDIVIDUAL QUANTUM PARTICLES TO DETECT VERY WEAK MAGNETIC FIELDS"



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QUANTUM ENTANGLEMENT

The mindboggling web that could alter our reality

Quantum entanglement is arguably the strangest feature of quantum physics. This is the phenomenon whereby particles can seem to affect one another instantly, no matter how far apart they are. To put it another way, it's as though some properties of particles are 'nonlocal', meaning they're not confined to the particle itself.

As such, quantum entanglement seems to ignore conventional notions of space. It's as if two entangled particles simply don't notice that they're separated and behave as parts of a single quantum object.

What, though, if quantum particles aren't really objects located in space at all, but form an entangled web of interacting entities, and what we think of as space *emerges* from that web? It sounds odd, but some theoretical physicists have shown one mathematical description of a special kind of space to be equivalent to what the 'shadow' of a web of entangled particles looks like when projected onto their boundary. Imagine the entangled web as a room full of objects and space is the dappled shadows they throw onto the walls.

The basic idea is that entanglement weaves quantum objects together into what looks like ordinary space, so that the distance between them is really a measure of how entangled they are. If we can find ways to test this speculative idea, it could transform our notion of what reality is fundamentally composed of.

QUANTUM THERMO-DYNAMICS

How entanglement can be harnessed to boost energy efficiency

Thermodynamics is, in essence, the science of how efficiently machines can be made to work. Developed in the 19th century during the Industrial Revolution, it's all a matter of how well an energy source (such as coal) can be used to do work (like pumping water), given that some energy is always lost as heat.

But that doesn't take entanglement into account. Scientists now realise that the usual limits on efficiency imposed by the laws of thermodynamics might be beaten in 'quantum engines', where the component parts, which might be individual atoms, are entangled. Think of it like the improvements in efficiency that can come from having two people coordinating their actions rather than working independently.

Ultra-efficient quantum heat engines have already been demonstrated, in which the switching of atoms between quantum states can, like a steam-powered piston, be harnessed to do work. The same idea can be inverted to make quantum refrigerators. Then there are quantum batteries (an illustration of one is pictured below). With energy stored in the quantum states of atoms, these can charge more quickly and discharge more efficiently if operated in arrays of entangled copies. All these devices are microscopic, but could be useful for powering and cooling microelectronic devices on silicon chips.



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QUANTUM GRAVITY

Does quantum mechanics fit with General Relativity?

Despite quantum mechanics passing every experimental test that scientists have set for it, not everyone thinks it'll be the final word. That's because it doesn't seem to fit with the other foundational theory of physics: General Relativity, devised by Einstein to describe gravity.

According to the theory of General Relativity, space and time are smooth and continuous, whereas in quantum mechanics there's a kind of fundamental granularity to it all. Usually this doesn't matter, because quantum mechanics tends to be used for very small things, such as atoms, while General Relativity is used for very big things, like stars or the entire Universe. Still, having two theories that don't dovetail doesn't seem right.

"The quantum nature of gravity is an absolute necessity, without which the laws of nature as we know them would crumble", says Prof Claudia de Rham, a theoretical physicist at Imperial College London.

Finding a quantum theory of gravity is therefore "the biggest challenge of modern physics", according to Dr Igor Pikovski, a physicist at the Stevens Institute of Technology in New Jersey, in the US. We know that three of the four fundamental forces of nature obey quantum theory, "but we don't know if that's true for gravity," he says. "All attempts to 'quantise' Einstein's theory of gravity have so far not produced a satisfactory answer."

To that end, physicists need experiments that at least hint at what such a theory should look like. If gravity is a quantum force, then there must be a particle that 'carries' it, which physicists call the graviton. Pikovski's group and others hope to find it. "Such experiments were thought to be impossible, but this was wrong," he says. "I can imagine these experiments will materialise within a few years or a decade. It's an exciting time."

There may be another option, according to de Rham. That's to look not at the very tiny, but the very big; at the "signature of the quantum nature of gravity in the sky". Random quantum fluctuations in spacetime in the earliest moments of the Universe, when it was still tiny, should remain imprinted in features of the cosmic microwave background radiation that pervades all of space. According to de Rham, astronomers are trying to observe this quantum fingerprint across the Universe.

THE QUANTUM MEASUREMENT PROBLEM

It has been the biggest mystery in quantum theory since the beginning

It's been a hundred years since quantum mechanics was devised, yet there's still no agreement about what it actually means. The reason for this division comes down to one key issue: measurement.

Typically, if we want to know a certain property of an object – say, the speed of a tennis ball – we simply observe and measure it. If we're careful enough, we can work out the speed accurately while ensuring that the act of measuring doesn't affect the ball. In quantum mechanics, however, it seems that a measurement fundamentally changes the nature of a quantum object and what we see depends on how we look at it. So, if we observe an atom with one method, it might look like a tiny particle with a particular position in space. Look at it another way, though, and it's a spread-out wave.

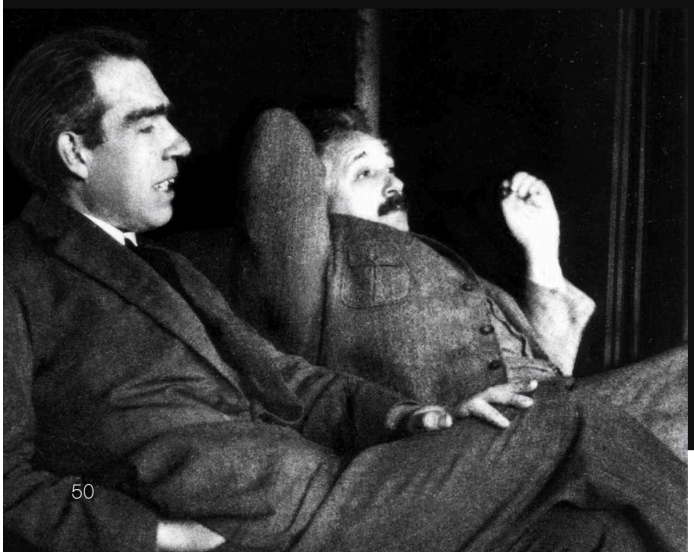
The basic problem is that quantum mechanics doesn't specify what a measurement is. All it can do is tell us the probabilities of seeing the various possible outcomes – for instance, how likely the electron is to be here or there. So how do we go from all those possible positions before the measurement, to a single location after it? And can the mere act of looking really induce that change?

One of the founders of quantum theory, Niels Bohr, famously argued with Albert Einstein (seen sitting next to Bohr in the picture below left) about that question. Einstein felt sure there had to be something we could meaningfully say about a quantum object before it's observed, but Bohr said that quantum theory is silent about that. The root of the debate was what we can consider to be real at all.

With no one able to see how to resolve the dispute, the issue went ignored for decades. It's only been since the 1970s that it became possible to carry out experiments. The results seem to exclude Einstein's view of a well-defined single reality, regardless of whether we observe it or not. That doesn't mean Bohr was right, though.

There are now many other interpretations of quantum theory vying for the crown. One insists that particles are real and can take crazy paths guided by waves in a pervasive quantum field. Another argues that all possible outcomes of a measurement are realised, but in different worlds that split off from each other when the observation is made.

While there's still no sign of any agreement, it at least no longer seems impossible to imagine that one day experiments will sift through the options and tell us what reality is really like. **SF**



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Philip is a science writer and a former editor of Nature. *He's the author of* Beyond Weird: Why Everything You Thought You Knew About Quantum Physics is... Different. *His latest book is* How Life Works: A User's Guide to the New Biology *(Picador, £22).*

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