

features

In the beginning was the bit



Illustration: Aude Van Ryn

And after that came the rest of the weird world, says Hans Christian von Baeyer

"NOBODY understands quantum mechanics," lamented Richard Feynman. But Anton Zeilinger at the University of Vienna aims to prove him wrong. His research group has demonstrated the futuristic phenomena of quantum teleportation and quantum encryption, and these successes have encouraged Zeilinger to search for the essence of quantum mechanics--the irreducible kernel from which everything else flows. He believes that he has found it. If he is right, all the mysteries of the quantum world will turn out to be inescapable consequences of a single, simple idea.

Quantum theory describes the world with astonishing precision, whether applied to elementary particles a hundred thousand times smaller than atoms or to currents in superconducting rings a billion times larger. And yet it seems to present a catalogue of intertwined conundrums. The most fundamental is quantisation, the notion that energy, spin and other quantities only come in discrete steps. Another enigma is the probabilistic nature of the quantum world, at odds with the classical world of definite physical properties. Then there is entanglement, the profound connectedness of objects and processes across large distances, and superposition, the astonishing proposition that an electron can be both here and there, a current can flow simultaneously clockwise and anticlockwise, and a cat can be both dead and alive, until you look to see which.

Physicists have anxiously devised one philosophical interpretation of quantum mechanics after another. In the Copenhagen interpretation, the outcome of an experiment is only revealed when the quantum system interacts with a macroscopic apparatus in the laboratory, which eliminates all possibilities but one. The many-worlds interpretation insists that all possible outcomes of an experiment actually occur in as many parallel universes, but as we only occupy a single branch of the hydra-headed multiverse, we experience only one outcome. Or, if you prefer, there's the guiding wave interpretation, which assigns an undetectable "pilot wave" to each particle to steer it along a perfectly determined path. Altogether there are at least eight serious and reputable interpretations of the theory, which implies that no single one is convincing.

Zeilinger thinks that before we can truly understand quantum theory, it must be connected in some way to what we know and feel. The problem, he says, is the lack of a simple underlying principle, an *Urprinzip*. All the other major theories of physics are based on such principles--pithy, comprehensible maxims that anchor the formulae in the everyday world.

Take the science of heat. Though highly mathematical and abstract, thermodynamics is based on two basic principles that can be described in colloquial terms. The first law of thermodynamics is just the conservation of energy: it means that there are no perpetual motion machines. The second law of thermodynamics is simply the statement that heat tends to flow from warm objects to cooler ones. When the stuff called energy was invented to quantify these laws, it was strange and undefinable, and even today we don't know what energy is. Yet energy quickly became a robust term in daily conversation and government policy.

The special theory of relativity is also based on two principles, namely, "Inside a speeding transatlantic jet, you have no way of knowing how fast you are going," and "The speed of light shone from this jet is the same as the speed of light from a stationary source." That second statement is counterintuitive, but it is simple to understand and turns out to be a stubborn experimental fact. And general relativity, Einstein's theory of gravity, is based on the thought that a freely falling person feels no weight. None of these theories suffer from the confusions of quantum mechanics.

Now Zeilinger proposes to rebuild quantum mechanics on a similar basis, to put it in terms that need no debatable philosophy.

Perhaps it is no surprise that the terms he uses are those of information. We live in the age of information. We depend increasingly on information technology, our schools teach information processing and information science, and our industry and commerce are information based. But until now, the concept of information has only hovered on the edge of physics.

About a decade ago, John Archibald Wheeler urged that information should take centre stage. What we call reality, he thinks, arises from the questions we ask about it and the responses we receive. "Tomorrow, we will have learned to understand and express all of physics in the language of information," he said.



Illustration:
Aude Van
Ryn

The atom of information is the bit--the quantity contained in the answer to a yes or no question. If experiments are questions we ask of nature, then the simplest of them have yes or no answers: "Did the photon arrive here, or not?", "Did the counter click, or not?" We can also ask more complex questions, but they can always be built up from simpler yes or no questions like these.

Zeilinger's conceptual leap is to associate bits with the building blocks of the material world. In quantum mechanics, these building blocks are called elementary systems, and the archetypal elementary system is the spin of an electron. The only possible outcomes of measuring an electron's spin are "up" and "down". You can choose any axis to measure the spin along--vertical, horizontal or tilted--but once that axis is chosen, only the two results are possible, as if the electron were a spinning top that can be one way up or the other, but can't point to any intermediate direction. These outcomes could just as well be labelled "yes" and "no", or, in the fashion of digital computers, "1" and "0".

This system is far more general than it seems. The formulae that describe it apply, unchanged, to every conceivable quantum-mechanical system characterised by just two states--from polarised light and molecules with just two energy levels to counterrotating currents in a superconducting ring. Not forgetting that touchstone of quantum mechanics, the two-slit experiment (see "Two becomes one").

Zeilinger avoids the question "What is an elementary system?" and asks instead, "What can be said about an elementary system?" His conclusion is simply stated: *an elementary system carries one bit of information.*

It sounds innocuous. But the consequences of Zeilinger's principle promise to be breathtaking. In the first place, it contains the fact that the world is quantised--the very starting point of quantum mechanics. Because we can only interrogate nature the way a lawyer interrogates a witness, by means of simple yes-or-no questions, we should not be surprised that the answers come in discrete chunks. Because there is a finest grain to information there has to be a finest grain to our experience of nature. This is why electrons are restricted to fixed energy levels in atoms, why light comes in pieces we call photons, and perhaps, ultimately, why the Universe seems to be made out of discrete particles. To the question, "Why does the world appear to be quantised?" Zeilinger replies, "Because information about

the world is quantised."

Less obviously, Zeilinger's principle leads to the intrinsic randomness found in the quantum world. Consider the spin of an electron. Say it is measured along a vertical axis (call it the z axis) and found to be pointing up. Because one bit of information has been used to make that statement, no more information can be carried by the electron's spin. Consequently, no information is available to predict the amounts of spin in the two horizontal directions (x and y axes), so they are of necessity entirely random. If you then measure the spin in one of these directions, there is an equal chance of its pointing right or left, forward or back. This fundamental randomness is what we call Heisenberg's uncertainty principle.

In order to progress beyond a single elementary system, Zeilinger's principle has to be generalised. He proposes simply that two elementary systems carry exactly two bits of information, and N systems carry N bits. This gives us a natural explanation for one of the most fundamental and puzzling features of quantum mechanics--entanglement.

When, say, two electrons are entangled, it is impossible even in principle to describe one without the other. They have no independent existence. This seems bizarre until you use Zeilinger's principle. Concentrating on their spins, a two-electron system contains two bits. For example, they might be "The spins in the z direction are parallel," and "The spins in the x direction are antiparallel". The two bits are thereby used up, and the state is completely described--yet no statement is made about the direction of spin of one electron or the other. The entire description consists of relative statements, or correlations. This means that as soon as one spin is measured along a certain direction, the other one is fixed, even if it happens to be far away.

Zeilinger's single, simple principle leads to these three cornerstones of quantum mechanics: quantisation, uncertainty and entanglement. What, then, of the more formal elements of quantum mechanics such as wave functions and Schrödinger's equation--the bread and butter of atomic physicists? The road promises to be long and steep, but Zeilinger and his student [^]Caslav Brukner, have now begun the ascent.

Physicists use Schrödinger's equation to work out how a particle will behave in a given situation. It governs the evolution of things called wave functions, inside a bizarre abstract arena called Hilbert space. Because Hilbert space makes use of imaginary numbers, based on the square root of minus one, these numbers--the amplitudes of the wave functions--have to be squared to produce a real, observable quantity, such as the probability of a particle being in a given place. It is not an intuitively obvious way of describing things.

Zeilinger and Brukner discard it. Instead, they introduce a three-dimensional space they call information space. The relationship between 2D Hilbert space and 3D information space is a bit like the relationship between an accurate perspective drawing and a real, three-dimensional object. This new

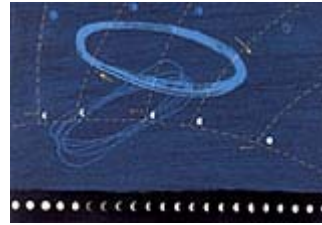


Illustration: Aude Van Ryn

space is much closer to our reality, as its axes correspond to the answers of yes or no questions about an elementary system. An electron's spin can be measured, or quantised, along the x , y , or z axes of real space, which gives the three dimensions of information space a clear correspondence with reality. In other two-state systems the connections are not so obvious, but three independent propositions will always exhaust the possibilities.

Any quantum system has to describe how states change over time, so the point in information space has to move. It seemed natural to Zeilinger and Brukner to have the point move as if it were a real, classical object. So they used the mechanical equation that governs the motion of bullets and billiard balls. When translated back into its equivalent form in Hilbert space, it turns out to be none other than Schrödinger's equation.

Their next aims are to generalise this approach from one elementary system to many, and to find a way to include continuous variables such as position and speed. Eventually, they must find a way to account for the information contained in quantities like mass and charge.

Even if this programme succeeds, physicists may dismiss it as old wine in new bottles. Why should they adopt the principle if it doesn't tell us anything new? But in fact it already does. In October 1999, Zeilinger and Brukner turned their theory around to propose a new measure of information.

A new theory of quantum information is needed if we are to handle the quantum computers of the future. This technology promises one day to perform calculations far faster than ordinary computers can, by exploiting the ability of quantum systems to be in more than one state at a time.

Physicists call the building blocks of their planned quantum computers "qubits". A qubit is simply an elementary system such as an electron spin. Because a qubit can be in a superposition of 1 and 0, it must hold not only classical information, but some more elusive quantum kind of information too. Many practitioners feel that ordinary information theory must be contained in quantum information theory.

The number of classical bits in a system has traditionally been evaluated using a formula derived by the American engineer Claude Shannon. Say your system is a hand of cards. If you wanted to e-mail a friend to describe your hand, Shannon's

formula gives the minimum amount of information you'd need to include. But Zeilinger and Brukner noticed that it doesn't take into account the order in which different choices or measurements are made.

This is fine for a classical hand of cards. But in quantum mechanics, information is created in each measurement--and the amount depends on what is measured when--so the order in which different choices or measurements are made does matter, and Shannon's formula doesn't hold. Zeilinger and Brukner have devised an alternative measure that they call total information, which includes the effects of measurement. For an entangled pair, the total information content in the system always comes to two bits.

Without Shannon's theory, progress in telecommunications during the second half of the 20th century would have been far slower. Perhaps total information will become as important in the 21st century.

Zeilinger's principle is a newborn baby. If its fate is anything like that of Planck's century-old energy quantum, years will pass before it grows up and gains acceptance in the mainstream of physics. But if it does, it will transform physics as thoroughly as its venerable predecessor.

Further reading:

- "A Foundational Principle for Quantum Mechanics" by Anton Zeilinger, *Foundations of Physics*, vol 29, p 631 (April 1999)
- www.quantum.at

Two becomes one

According to Richard Feynman, there is one experiment that exposes "the only mystery" of quantum mechanics. Light from a single source is split into two beams that travel along different paths. Where the beams recombine, two detectors measure how the two waves interfere with each other: detector S fires if the beams interfere constructively and detector D fires if they interfere destructively, cancelling each other out. For a beam with no interference, either S or D will fire, each with a 50-50 probability. When the two paths have the same length, the waves will be in phase where they recombine and the beams will interfere constructively, so detector S keeps firing and D never fires.

Now suppose the light is so feeble that photons can only travel through the apparatus one at a time. That interference

remains. The startling implication is that each photon has to travel along both paths simultaneously. The same goes for beams of electrons, neutrons, atoms, or molecules. Zeilinger has even seen this happening to buckyballs--big, football-shaped carbon molecules.

But if instruments are installed to measure which path the photons travel down, the detectors start firing randomly: interference is destroyed. How, except by magic, can this be reconciled with the previous experiment on the same apparatus? How do photons know whether to go down only one path, or both?

Zeilinger's answer is that our choice of measurement is putting that information into the photon. But it can only carry one bit. So if we arrange the experiment so that the photon is destined to trigger detector S, that bit is used up, and we can have no knowledge of which path it traversed. On the other hand, if we decide to know which path it travelled, we cannot predict whether S or D will fire.

This experiment highlights another troubling aspect of quantum mechanics, called the measurement problem. Each photon seems to undergo a mysterious metamorphosis from a quantum wave to a classical particle in the act of measurement. But according to Zeilinger's principle, we simply cannot know enough about the photon to call it either wave or particle. Zeilinger's elementary system is no more than a carrier of information.

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