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Quantum control: How weird do you want it?

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Entanglement used to be the gold standard of the quantum world's weirdness, now a new and noisy phenomenon could give us all the benefits with less of the fuss

RAYMOND LAFLAMME works in a magnificent-looking building. The Quantum-Nano Centre on the University of Waterloo campus in Ontario, Canada, boasts an exterior whose alternating strips of reflecting and transparent glass are designed as metaphors for the mysterious nature of the quantum world. Inside, it is even more impressive. Its labs are so well isolated from the outside world that an earthquake will barely move their floors. No electric or magnetic fields can get in where they aren't wanted, and the temperature is controlled to within a single degree. That's especially impressive, considering that human beings bring their hot bodies into the centre to perform experiments at temperatures close to absolute zero.

What a shame, then, if all this cutting-edge engineering proves entirely superfluous. Laflamme heads the university's quantum computing institute. Ironically, he was among the first researchers to show why quantum computing might not require the kinds of isolation we once thought. If the latest raft of results is anything to go by, the key to accessing the quantum world may lie not in avoiding disturbance, but embracing it.

Our emerging understanding of the way quantum systems are connected suggests that there is much more to being quantum than we realised. Researchers have given this phenomenon the name quantum discord. If it turns out to be all that it currently seems, discord may finally tell us what it really means to be quantum. Its benefits won't just be abstract, though. Discord could change our view of biology, computing, measurement and – of course – the nature of reality itself.

Be warned: discord is a tricky concept. The first person to define it was Wojciech Zurek of the Los Alamos National Laboratory in New Mexico. Zurek had been looking at the effects of measurement on quantum systems. One of the oddest things about quantum objects is that, until you measure where they are, they exist in many places at the same time.

Zurek wanted to understand how a measurement turns a quantum object into a "classical" everyday object that has a fixed, distinctly un-weird existence. We know that a quantum system becomes classical if you make repeated measurements on it, or measure it with brute force. Zurek proposed that there was a quantifiable entity – discord – lost during this process. According to him, discord is, effectively, the "measure of quantumness".

The notion garnered very little attention. Then a few months later, Vlatko Vedral of the University of Oxford saw something similar – albeit from a different direction. He was looking at the total information that you can theoretically extract from a pair of particles that interact to create an "entangled" pair. When two quantum particles are entangled, some of the information about each one is held in the other. You can only fully describe each one's properties by describing the complete pair.

To control the quantum world, make some noise

Yet Vedral got a shock when he worked through the mathematics, examining where all the information came from. The information held in the entanglement and the classical information "did not add up to the total in the system", he says. "This really was surprising." The missing information, he believes, is a measure of the discord in the system.

One reason it was so surprising is because we have long considered entanglement as the distilled essence of the quantum world's weirdness. That's because you can entangle a pair of atoms, put them at opposite sides of the universe and perform a measurement on one that will affect the outcome of a later measurement on the other, even though there is no physical link between them.

Einstein dismissed this as "spooky action at a distance" and said it showed the mathematics of quantum theory needed some work – there must, he said, be additional information about the atoms that hadn't been included in the equations.

Unfortunately for Einstein, entanglement was proved real in the 1980s. Since then, quantum researchers have become rather obsessed by it. What Schrödinger hailed as the defining trait of quantum theory has been championed as the key to superfast computing, unbreakable cryptography and unravelling the nature of space and time.

It is all because entanglement is an astonishing resource for manipulating quantum information. If Alice and Bob share an entangled pair of photons, Alice can put Bob's photon into any state she chooses just by performing a particular measurement on her photon.

The trouble is, putting entanglement to work has proved remarkably difficult. Its spooky link is terribly delicate: entangle two atoms and you have to isolate them from all sources of disturbance. Vibrations, heat, light, collisions with atoms in the air; these can all break the link – hence the stringent requirements of Laflamme's workplace.

So, is there a way to do strange and useful quantum things without all the hassle? That's where discord comes into its own.

The reason disturbances are such a problem to entanglement is that interaction with a hot or noisy environment carries away some of the quantum information that is necessary to fully describe the system. That's a big problem for entanglement, which can hardly tolerate any information loss. But when entanglement breaks, you can still have discord: a network of weaker – but nonetheless useable – links that contain information about the properties of the system. What's more, discord is a lot more tolerant than entanglement: it thrives on noise. "Some types of noise actually increase the discord," says Gerardo Adesso of the University of Nottingham, UK. To explain why, we need to understand that quantum states can exist in various levels of purity. For something like a photon, the purest state is like a coin rolling along on its edge – perfectly upright but highly vulnerable. Only in this state can photons be entangled. Think of entanglement as rolling two pure-state coins through a pair of narrow vertical slots into a box that exchanges information between the coins.

Not every quantum state can pass through such a stricture. "Mixed" states are less well-defined: the photon would be more like a coin that is wobbling from side to side as it rolls forward. It won't be able to roll through the entanglement box's vertical slots, but it can still pass through a wider gap. As it does, it might interact with the walls. Those knocks will set the walls ringing, and any other photon using that channel will gain a sense of the "wobble". In that way, a noisy environment can actually increase the amount of shared information.

Entangled no more

So while disturbances from the environment will cause pure states to become mixed, destroying any entanglement, mixed states not only tolerate the knocks, they can also gain information from them. They can't contain as much information as entanglement, but still a potentially useful amount. It is a kind of entanglement lite, in that once two particles share some discord, you can manipulate one to change the other. The spectrum of possible changes is more limited than with entanglement, but it can still be harnessed for processing information.

Take Laflamme's discovery. In 1998, working with Emmanuel Knill of the University of Colorado in Boulder, he showed that quantum computation didn't need entanglement.

The pair did this in a mathematical thought experiment. First, they imagined a collection of quantum particles where all but one is in a mixed state. The remaining particle is in a pure state, but because there is only one, the system contains no entanglement. Then Knill and Laflamme looked for an information-processing task this collection of particles could perform quicker than any known classical algorithm.

They found one. It has to do with computing the energies of the system; not the most heart-stopping of tasks, but a demonstration, nonetheless, of the fact that you can get quantum speed-up without entanglement.

The speed-up came from interacting the mixed-state particles with the pure-state particle and then, at the end, measuring the resulting pure state. Nearly a decade later, Animesh Datta of the University of Oxford and colleagues showed that the quality we now define as quantum discord is at the heart of this scenario. The quantity of information shared between them all depends on the discord links that exist between the mixed states in the system.

To reprise the coin analogy, Datta showed that the process is like passing the pure-state coin through one of the mixed-state coins' wide slots, while the other slot contains one of the mixed-state particles. If the pure-state coin happens to brush against the wall, it will pick up a little of the information left by the mixed-state coins' more robust contact with the wall. Finally, you read the information in the pure-state coin, and you'll find out something about the mixed-state coins that have influenced each other and the apparatus.

In other words, when the process is carried out correctly, a final measurement on the pure-state atom can harness the information processing potential of the other atoms, despite their being in a mixed state.

Subsequent experiments by Andrew White at the University of Queensland in Brisbane, Australia, not only proved this to be true; they also showed that you can even dilute the purity of the pure state. As long as there is some discord, there is some computing advantage over a classical machine.
This is a huge discovery. It demotes entanglement to an interesting tool for exploiting the quantum world – but not an essential one. Because discord is so much easier to achieve, it is entirely possible that we will do without entanglement in our attempts to build quantum technologies. "I would say there are at least a dozen quite distinct applications where discord is useful," says Zurek. "It is too good a tool not to use when it is needed."

Such revelations will have a huge impact on the field of quantum computing. In almost every explanation you will have read – including those in this magazine – the power of entanglement will have been invoked as the reason quantum computers can compute beyond what is classically possible. It's time to rip up that explanation, according to discord proponents. Entanglement, Laflamme says, may even be a by-product of quantum computing, not the source of its power. "We know there is more to quantum information processing than entanglement," Laflamme says. "It's not the answer to everything."

Adesso is already working on technologies that exploit discord. He has developed highly sensitive quantum measurement devices that operate without any of the restrictions required to get similar entanglement-based devices to work. Using a technique he and his colleagues refer to as quantum estimation, they interact a quantum system containing discord-filled mixed states with whatever system is being measured. By monitoring changes in the mixed states of their probe, they make a highly sensitive measurement of, say, the phase properties of a photon. That might give us more sensitive and robust interferometers, creating high-precision gravitational wave detectors or atomic clocks.

Quantum plants

Then there are the potential applications in the physics of complex materials. Understanding what creates unexpected properties, such as sudden phase changes at certain temperatures, may come down to discord and other interconnections in the material. "We are just beginning to understand their ramifications," says Ujjwal Sen of the Harish-Chandra Research Institute, Allahabad, India.

Discord might also be a useful tool for exploring the nascent field of quantum biology. Recent research has thrown up hints that quantum tricks help plants to photosynthesise and some birds to navigate. This has been so surprising largely because these systems operate in the warm, wet and noisy natural environments that we try to get away from in all our quantum technology systems. It was always a mystery how entanglement could be at work in such environments, but now we know it doesn't have to be.
The fact that quantum discord can not only tolerate but also be increased by noise causes Adesso to suspect that evolution might have put it to work. "I think that living systems are very likely to have a very robust exploitation of quantum effects, so there will be discord involved in this for sure."

It is not yet clear how far this strange phenomenon's influence might stretch. "Is discord the answer to everything? We don't know," Laflamme admits. "Discord tells us there is more to quantum mechanics than we've thought about – that there are many pieces of the puzzle we don't understand. But exactly where it can go, what it can tell us about the world, where we can use it – that's still not totally clear."

Another thing that's still not clear to everyone is how revolutionary discord really is, if at all. Stephanie Wehner at the Centre for Quantum Technologies in Singapore sounds a note of caution: discord has been overblown, she says. She fears that it is merely a way of rephrasing what we already know, and that it might distract people from digging for deeper truths about the quantum world. "Quantum information theory offers much more powerful ways to study the subtleties of quantum versus classical," she says.
Still, the idea of discord has opened our eyes, Laflamme says. We have a new angle of attack on understanding the difference between classical and non-classical worlds – why it is, for instance, that quantum systems can exist in two places at once but we can't. It could mark a technological turning point. "This is great: a young scientist in this field can think about quantum information processing in a whole different way from my generation," Laflamme says. That's all very well, Ray. Just don't tell the people who worked so hard to create your fancy building.

This article appeared in print under the headline "How weird do you want it?"
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