The quantum world is there to exploit, says **Eugenie Samuel Reich**. But before we truly harness its power, there's one small problem to solve

Which way is up?

PITY the most famous feline in physics, Schrödinger's cat. Sealed in a box with a vial of poison, the unfortunate animal faces an uncertain future. No one knows if it is alive or dead – killed by a quantum event that causes toxic fumes to spew from the shattered vial. It is only when we open the box that we discover the cat's condition.

Thankfully Schrödinger's cat is all in the mind, a bizarre thought experiment proposed by Austrian physicist Erwin Schrödinger in 1935 to highlight the weirdness of quantum theory. Quantum mechanics says that while the cat remains unobserved in the box, it is simultaneously both dead and alive. It is the act of looking inside the box that determines its fate. But imagine you opened the box and found Schrödinger's cat lying with its eyes shut. Is it dead, or just sleeping?

This may sound like a scene from a *Monty Python* sketch, but physicists wrestling with the vagaries of the quantum world find themselves in a similarly ridiculous position. And it is no abstract difficulty: thanks to the discovery of a fundamental problem with observing quantum phenomena, researchers are now wondering whether we need to rethink how we put quantum theory to work.

We are getting used to hearing extremely upbeat predictions about how weird quantum behaviour can change the way we communicate. These forecasts have thrilled researchers in the field of optics and telecommunications because they seem to herald strange feats, such as teleporting particles across huge distances.

The first stage of teleportation relies on a seemingly supernatural link that ties quantum particles together over any distance. Known as entanglement, this intimate connection arises when two particles bump into each other or come into existence in the same process. For ever after, it is impossible to tease apart the quantum characteristics of the two particles. So if you do something to the quantum state of one particle, it inevitably, and instantaneously, affects the state of the other, no matter how far apart the particles are.

So entangled particles should be useful in quantum communication by tapping this connection between them to send encrypted messages. More exotic applications could include quantum teleportation and quantum computing.

But some theoretical physicists have recently dented the hopes researchers have for entanglement. Among them is physicist Howard Wiseman of Griffith University in Queensland, Australia. The mathematical descriptions for quantum entanglement might look fine on paper, he argues, but many of these descriptions do not relate to anything practical. Instead they refer to a kind of phantom entanglement that appears in theoretical calculations but cannot actually be measured. Such phantoms have been given the derisory name "fluffy bunnies". In effect, we are looking at Schrödinger's cat but unable to decide whether it is alive or dead. Suddenly, quantum researchers are facing the embarrassing possibility that they haven't got as close to controlling the quantum world as they thought.

So how do you overcome this problem? How do you make sure that the thing you are talking about can actually be measured? With a cat, the answer is easy: you check its breathing or try waking it up. Maybe you check for a heartbeat, or even call a vet. At least you would know what to do to assess its condition. But in the world of quantum mechanics, the solution is not always as clear-cut.

This realisation is having serious repercussions for quantum technology. To exploit entanglement, two people at distant points – conventionally dubbed Alice and Bob – need to measure the properties of those linked particles. This is where the trouble starts. Most measurements rely on discovering whether each particle is spinning with its axis pointing up or down. How does Bob know his notion of up is the same as Alice's?

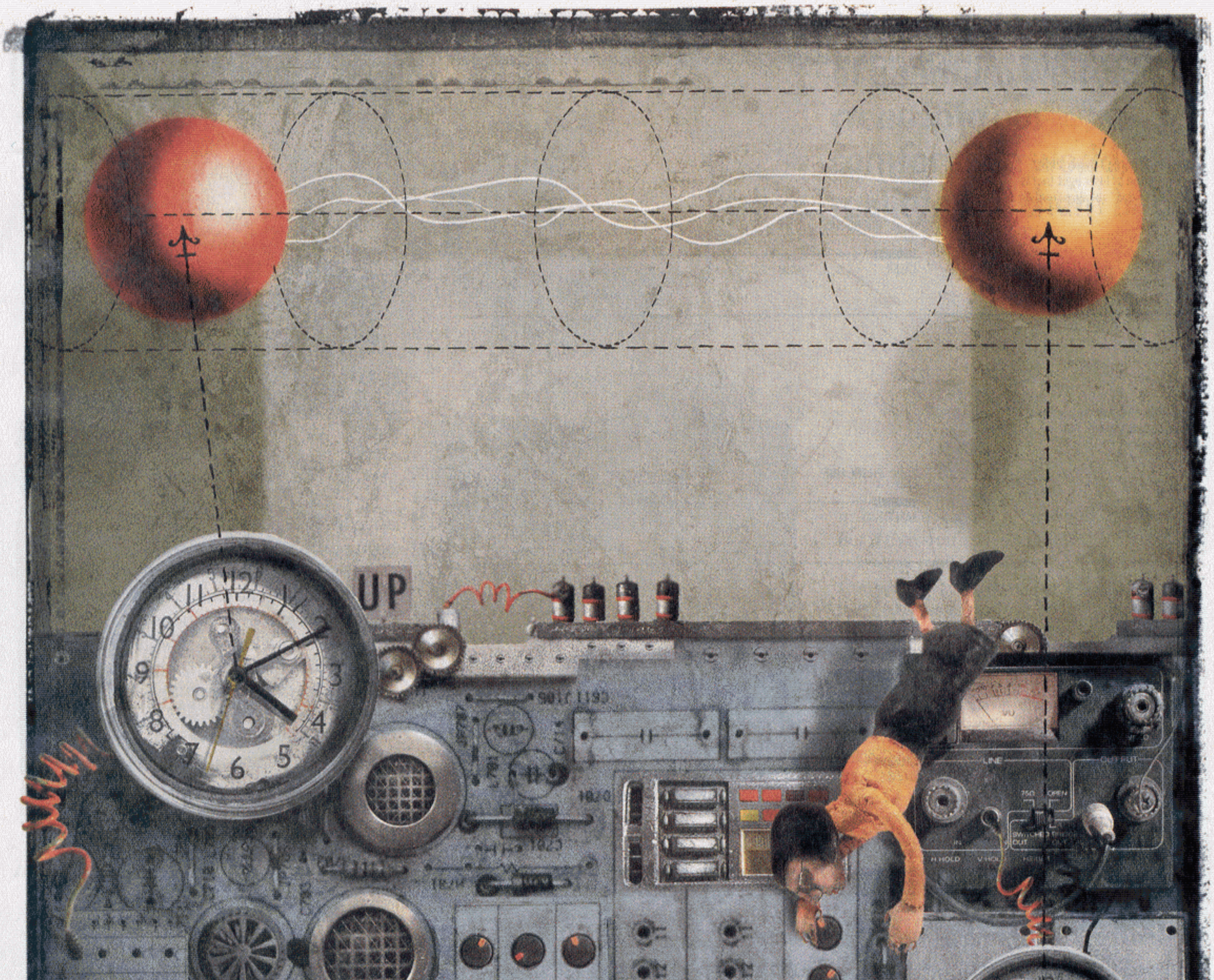
Usually, of course, Alice and Bob are on the same planet and even in the same lab. They know which way is up because it is the opposite direction to gravity's pull. They also agree on other things, like what time it is. In other words, they share the same frame of reference. "You have a reasonably good idea of time. You can count seconds. You know the difference between your head and your feet, and in a lab we have objects like clocks and rules that we can share also," says Terry Rudolph of Imperial College London.

But is that always true? It is possible to imagine a situation in which Alice and Bob don't have much in common. Maybe Alice is driving around the Sahara desert without a GPS locator, while Bob is sitting at a computer in Taiwan. Now his idea of up is ▶

Lost reality

When the theory of quantum mechanics was first developed in the 1920s, Niels Bohr and Albert Einstein had a series of prominent debates on how to make measurements. Bohr won, by arguing that the very act of measuring a thing gives it a reality that it previously did not possess.

It is this argument that Erwin Schrödinger mockingly illustrated with his infamous cat in a box. But as time went by, says Terry Rudolph, who studies the role of measurement in quantum theory at Imperial College London, people began to forget about the importance of measurement. "It got abandoned," he says. "We ended up with this very clean mathematical formulism. " And it does not necessarily correspond to reality.



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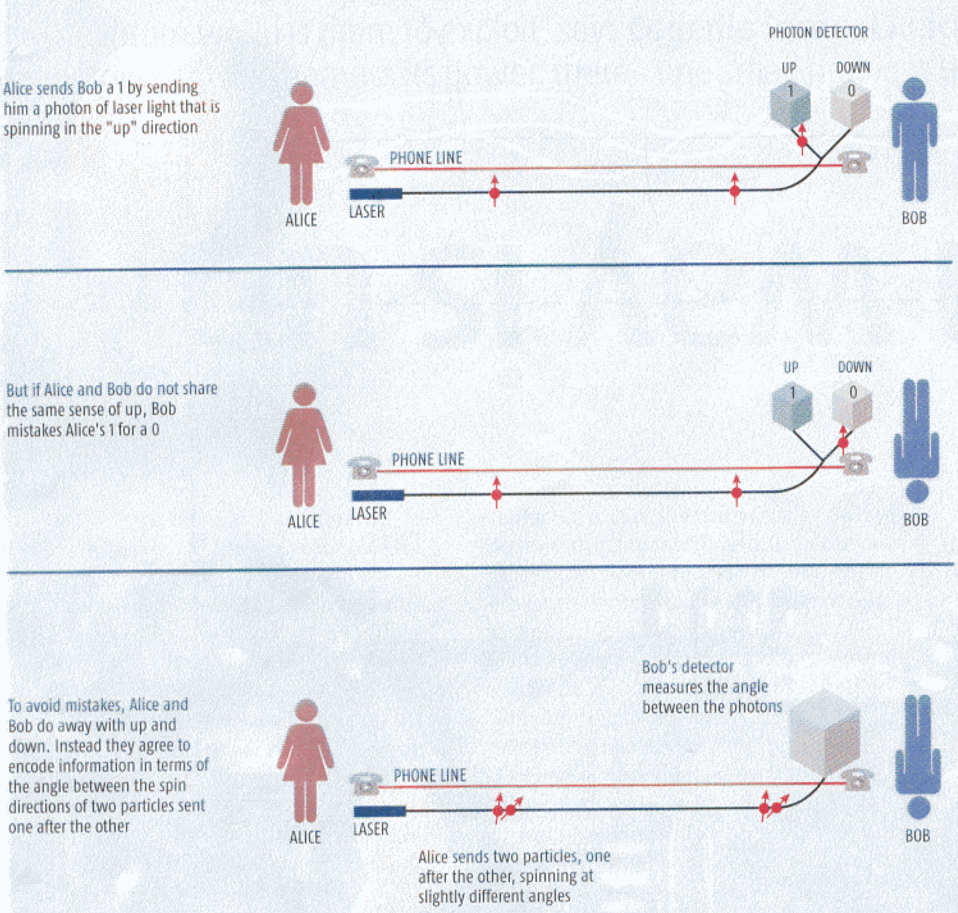
RIGHT SIDE DOWN

Quantum communication relies on one party, Alice, sending another party, Bob, a string of bits encoded in the spins of photons


Alice sends Bob a 1 by sending him a photon of laser light that is spinning in the "up" direction

But if Alice and Bob do not share the same sense of up, Bob mistakes Alice's 1 for a 0

To avoid mistakes, Alice and Bob do away with up and down. Instead they agree to encode information in terms of the angle between the spin directions of two particles sent one after the other

Bob's detector measures the angle between the photons

Alice sends two particles, one after the other, spinning at slightly different angles

directly opposite to hers because they are on opposite sides of the planet.

If quantum technologies are ever going to make it out of the lab and become useful, these measurement questions need to be cleared up. "This is why we are getting people interested in this now," Rudolph says, "because we can point out the relevance for current technology."

Recent work by Nicolas Gisin of the University of Geneva in Switzerland, and the company id Quantique, which sells quantum communication technologies, has shown that there can be serious problems with communication via optical fibres. Take a photon travelling down a fibre spinning one way. Gisin has shown the axis of its spin can drift considerably as it travels. And a person measuring a photon at one end of the fibre cannot be sure that what they measure as up is the same as the person who sent the photon.

But with so many successful quantum experiments already, can this really be an issue? Yes, says Jeff Kimble of the California Institute of Technology in Pasadena, one of the leading researchers in quantum technology (see "The key to teleportation"). "It is clear now when one is doing teleportation that everyone has to agree on a frame of reference," he says. "That is an essential requirement."

Kimble's own use of reference frames survived scrutiny, but Wiseman's crusade has targeted several other groups where researchers have discussed clever quantum effects without paying proper attention to how they might be used. But now some groups are starting to think up ways to exploit entanglement that are not so susceptible to the measuring problem. If Alice and Bob cannot agree on which way is up, why not have them communicate in terms that do not depend on sharing that information?

In March, Konrad Banaszek at the University of Oxford and colleagues at the

The key to teleportation

Jeff Kimble at the California Institute of Technology knew from the start that the success of his team's attempt to teleport a quantum state would depend on being able to prove that teleportation had indeed taken place. But he only realised later just how important it was to define a reference frame for the experiment.

In 1998 Kimble's group was the first to teleport a quantum state across a laboratory. But three years later, the claim came under attack. Rudolph and Barry Sanders of the University of Calgary in Canada argued that the team had, without meaning to, cheated. The link between quantum-entangled particles was not the only connection between Alice (the sender) and Bob (the receiver) in Kimble's lab.

In the teleportation experiment, Alice and Bob shared entangled photons of light from the same laser beam. Alice then wrote an unknown quantum state, fed to her on another laser, onto her entangled photons. The theory behind entanglement says that Bob's beam should acquire the same quantum state because his photons are entangled with Alice's. In this way, the unknown state of Alice's photons is teleported to his.

However, to help them prove that the quantum state had indeed been teleported, Kimble's group needed to make careful measurements of Alice and Bob's photons. To do this, the researchers passed a laser beam between Alice and Bob which helped to synchronise the measurements being made. Perhaps this was not spooky action at a distance after all, critics contended. Maybe the synchronisation beam had helped to communicate the unknown quantum state between Alice and Bob. Rather than teleportation, this was straightforward communication by laser.

Others leapt quickly to the Kimble group's defence. They showed that the laser beam was not acting as a communication device. It was just a way of making sure that clocks being used at both ends of the experiment were telling the same time. The critics eventually backed off, but Kimble says he realised later, thanks to them and Wiseman, how fundamental that laser beam actually was to all of teleportation. Without it, the teleportation itself had no meaning, because it is the act of measurement that gives reality to the quantum world.

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"As fast as the tentacles of quantum weirdness creep into our comfortable world, reality slaps them back"

"Perhaps quantum researchers haven't got as close to controlling the quantum world as they thought"

University of Warsaw in Poland did just that in an experiment for the first time. They sent information between two points but instead of encoding it in terms of the up and down spins of photons relative to the laboratory's frame of reference, they used the angle between the spins of entangled photons. So for example, a binary 1 might correspond to a pair of photons with spins at 180 degrees to each other, while a 0 described spins at 45 degrees. Banaszek's group sent two such photons along the same optical fibre 6 nanoseconds apart. After they had both arrived, their spins were measured at exactly the same time. From the measurement, the group could work out what bits had been received and compare their message with what had been sent.

Sometimes, of course, the spins of the photons were disturbed in transit, corrupting the message. But Banaszek's group showed that a third fewer messages are garbled using their method compared with the technique that relies on knowing the difference between up and down. That, says Banaszek, is because imperfections due to the uncertainty of which way is up no longer matter.

An even more dramatic example has come from a group led by Harald Weinfurter of the Max Planck Institute for Quantum Optics in Garching, Germany. The team has an even more complicated communication scheme that relies on the relative spins of four entangled photons. The researchers sent the four photons through a material that randomises the spins of individual photons, deliberately messing up any chance of Alice and Bob agreeing on which way is up. Despite this, they found that the information carried by their four photons arrived unharmed (*Physical Review Letters*, vol 92, p 107901). That is because although each individual spin was random, the relationship between them survived the transit.

Rob Spekkens of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, says their success was no coincidence. The difficulty of aligning Alice and Bob's positions would introduce noise to any messages they share. But if they don't need to share the same reference frame, they should be protected from this. If quantum communication technologies are to develop to the point where they can be used in a worldwide network, or even between distant points in the solar system, it may make sense to encode the information in terms of angles.

Spekkens is so intrigued by the possibilities that in July he and Stephen Bartlett of the University of Queensland in Brisbane, Australia, held the first workshop on solving reference-frame problems.

But there is still controversy over how far these solutions can go, says Mohamed Bourennane also at the Max Planck Institute, who worked on Weinfurter's experiment. He points out that while the experiment made it unnecessary for Bob and Alice to share a reference for up and down, they still needed to share an idea of time because they had to agree in advance the order in which the four photons were sent.

This raises a profound limitation that quantum researchers are still struggling to accept. Perhaps, to get the most from quantum mechanics, people will always have to share classical reference information about their set-up, something that has been agreed in advance. As fast as the tentacles of quantum weirdness creep into our comfortable world, reality seems to find a way to slap them back. ●

Further reading: "Ferreting out the fluffy bunnies: entanglement constrained by generalized superselection rules" by Howard Wiseman, Stephen Bartlett and John Vaccaro, www.arxiv.org/abs/quant-ph/0309046