

Quantum perspective

Our efforts to see reality from multiple points of view at once are revealing the strange part we all play in creating it, says **Amanda Geffer**

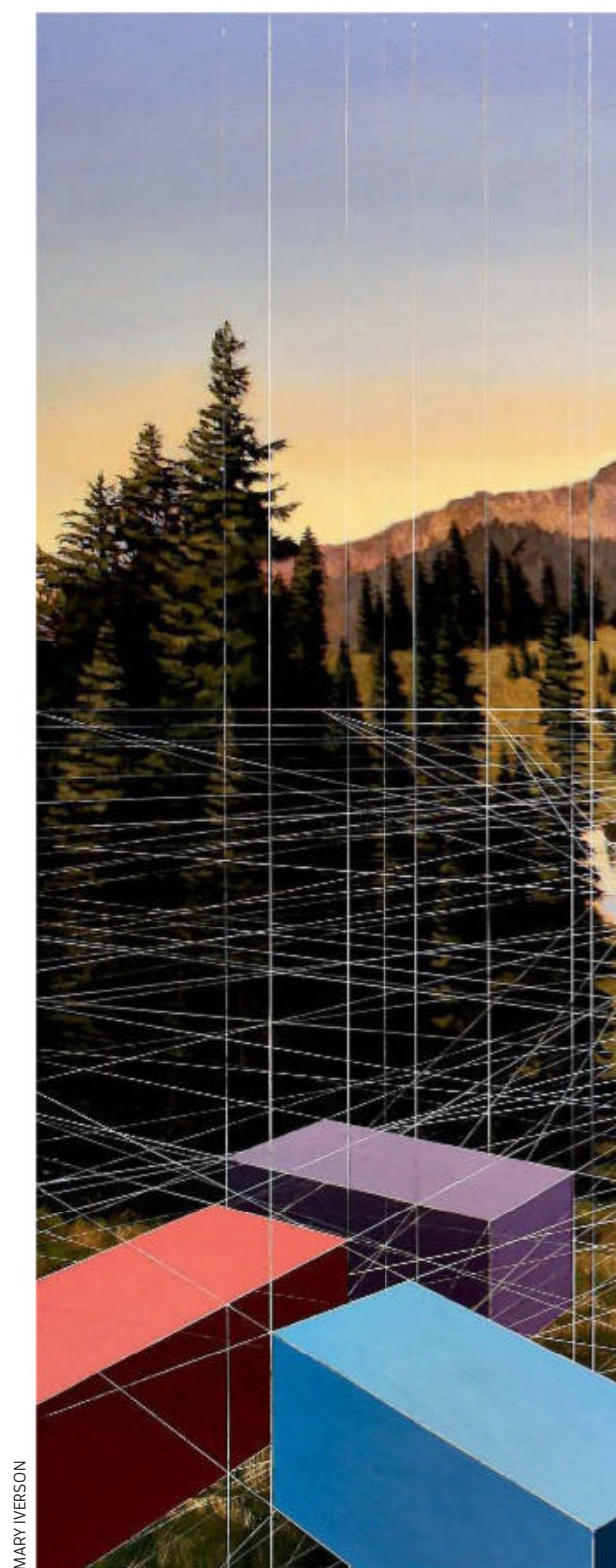
IMAGINE approaching a Renaissance sculpture in a gallery. Even from a distance, it looks impressive. But it is only as you get close and walk around it that you begin to truly appreciate its quality: the angle of the jaw, the aquiline nose, the softness of the hair rendered in marble.

In physics, as in life, it is important to view things from more than one perspective. As we have done that over the past century, we have had plenty of surprises. It started with Albert Einstein's theory of special relativity, which showed us that lengths of space and durations of time vary depending on who is looking. It also painted a wholly unexpected picture of the shared reality underneath – one in which space and time were melded together in a four-

dimensional union known as space-time.

When quantum theory arrived a few years later, things got even weirder. It seemed to show that by measuring things, we play a part in determining their properties. But in the quantum world, unlike with relativity, there has never been a way to reconcile different perspectives and glimpse the objective reality beneath. A century later, many physicists question whether a single objective reality, shared by all observers, exists at all.

Now, two emerging sets of ideas are changing this story. For the first time, we can jump from one quantum perspective to another. This is already helping us solve tricky practical problems with high-speed communications. It also sheds light on





whether any shared reality exists at the quantum level. Intriguingly, the answer seems to be no – until we start talking to each other.

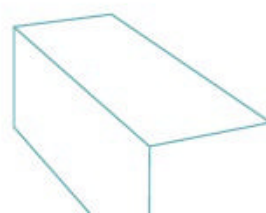
When Einstein developed his theory of relativity in the early 20th century, he worked from one fundamental assumption: the laws of physics should be the same for everyone. The trouble was, the laws of electromagnetism demand that light always travels at 299,792 kilometres per second and Einstein realised this creates a problem. If you were to race alongside a light beam in a spaceship, you would expect to see the beam moving far slower than usual – just as neighbouring cars don't look to be going so fast when you are zipping along the motorway. Yet if that

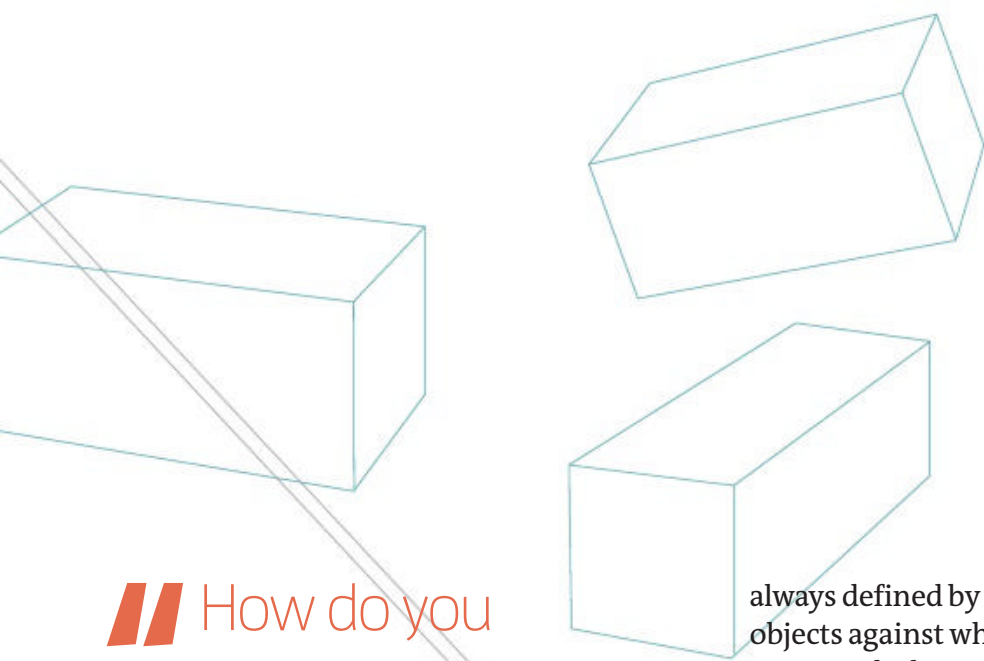
// In the quantum world, there has never been a way to reconcile different perspectives and glimpse the shared reality beneath

was the case, the laws of physics in that perspective would be violated.

Einstein was convinced that couldn't happen, so he was forced to propose that the speed of light is constant for everyone, regardless of how fast they are moving. To compensate, space and time themselves had to change from one perspective to the next. The equations of relativity allowed him to translate from one observer's perspective, or reference frame, to another, and in doing so build a picture of the shared world that remains the same from all perspectives.

He went on to develop these ideas into general relativity, which remains our best theory of gravity. But it isn't the whole story. In Einstein's writings, reference frames are ➤





// How do you measure time with a clock that is entangled, or distance with a ruler that is in multiple places at once?

always defined by “rods and clocks”, physical objects against which space and time are measured. These objects are, however, governed by a different theory altogether.

Quantum theory deals with matter and energy and is even more successful than relativity. But it paints a deeply unfamiliar picture of reality, one in which particles don’t have definite properties before we measure them, but exist in a superposition of multiple states. It also shows that particles can become entangled, their properties intimately linked even over vast distances. All this puts the definition of a reference frame on shaky ground. How do you measure time with a clock that is entangled, or distance with a ruler that is in multiple places at once?

Quantum physicists usually avoid this question by treating measuring instruments as if they obey the classical laws of mechanics developed by Isaac Newton. The particle being measured is quantum; the reference frame

isn’t. The dividing line between the two is known as the Heisenberg cut. It is arbitrary and it is moveable, but it has to be there so that the measuring device can record a definite result.

Consider Schrödinger’s cat, the thought experiment in which an unfortunate feline is in a box with a radioactive particle. If the particle decays, it triggers a hammer that breaks a vial that releases a poison that kills the cat. If it doesn’t, the cat lives. You are outside the box. From your perspective, the contents are entangled and in a superposition. The particle both has and hasn’t decayed; the cat is both dead and alive. But, as in relativity, shouldn’t it be possible to describe the situation from the perspective of the cat?

This conundrum has long bothered Časlav Brukner at the Institute for Quantum Optics and Quantum Information in Vienna, Austria. He wanted to understand how to see things from multiple points of view in quantum theory. Following Einstein’s lead, he started from the assumption that the laws of physics must be the same for everyone, and then developed a way to mathematically switch between quantum reference frames. If we could describe a situation from either side of the Heisenberg cut, Brukner suspected that some truth about a shared quantum world might emerge.

Think inside the box

What Brukner and his colleagues found in 2019 was a surprise. When you jump into the cat’s point of view, it turns out that – just as in relativity – things have to warp to preserve the laws of physics. The quantumness previously attributed to the cat gets shuffled across the Heisenberg cut. From this perspective, the cat is in a definite state – it is the observer outside the box who is in a superposition, entangled with the lab outside. Entanglement was long thought to be an absolute property of reality. But in this new picture, it is all a matter of perspective. “What is quantum and what is classical depends on the choice of quantum reference frames,” says Brukner.

Jacques Pienaar at the University of Massachusetts says all this allows us to rigorously pose some fascinating questions. Take the well-known double-slit experiment, which showed that a quantum particle can

Flying qubits

Networks of cables that carry quantum information are already being set up around the world as a prototype quantum internet. These networks transport information in the form of qubits, or quantum bits, which can be encoded in the properties of particles – typically in a quantum property called spin. One person sends a stream of particles to another, who then measures their spin to decode the message.

Except, not so fast. To be a useful means of communication, these particles must travel at close to the speed of light. At such speeds, a particle’s spin gets “quantum entangled” with its momentum in such a way that if the receiver only measures the spin, information will be lost. “This is serious,” says Flaminia Giacomini at the Perimeter Institute in Canada. “The qubit is the basis for

quantum information, but for a particle moving at very high velocities, we can no longer identify a qubit.” As if that weren’t enough of a problem, each qubit doesn’t move at one definite speed: thanks to quantum mechanics, it is in what is known as a superposition of velocities.

The rules of quantum reference frames developed by Časlav Brukner (see main story) could be the answer. Giacomini has shown how the rules can be used to jump into the particle’s reference frame, even when the particle is in a superposition. From that perspective, it is the rest of reality that is whizzing past in a blurred superposition. Armed with knowledge of how the qubit sees the world, you can then determine the mathematical transformation to perform on the particle to recover the information in the original qubit.

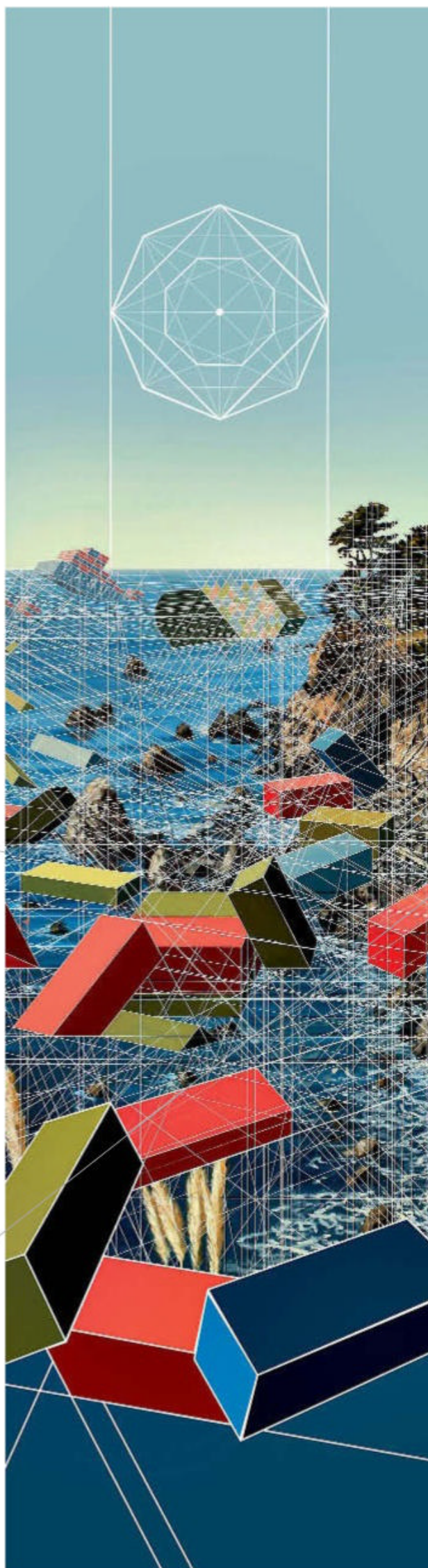
travel through two slits in a grating at once. “We see that, relative to the electron, it is the slits themselves that are in a superposition,” says Pienaar. “To me, that’s just wonderful.” While that might all sound like mere theorising, one thing that gives Brukner’s ideas credence is that they have already helped solve an intractable problem relating to quantum communication (see “Flying qubits”, left).

Quantum reference frames do have an Achilles’ heel though, albeit one that might ultimately point us to a deeper appreciation of reality. It comes in the form of “Wigner’s friend”, a thought experiment dreamed up in the 1950s by physicist Eugene Wigner. It adds a mind-bending twist to Schrödinger’s puzzle.

Faced with the usual set-up, Wigner’s friend opens the box and finds, say, that the cat is alive. But what if Wigner himself stands outside the lab door? In his reference frame, the cat is still in a superposition of alive and dead, only now it is entangled with the friend, who is in a superposition of having-seen-an-alive-cat and having-seen-a-dead-cat. Wigner’s description of the cat and the friend’s description of it are mutually exclusive, but according to quantum theory they are both right. It is a deep paradox that seems to reveal a splintered reality.

Brukner’s rules are no help here. We can’t hop from one side of the Heisenberg cut to the other because the two people are using different cuts. The friend has the cut between herself and the box; Wigner has it between himself and the lab. They aren’t staring at each other from across the classical-quantum divide. They aren’t looking at one another at all. “My colleagues and I were hoping that the Wigner’s friend situation could be rephrased in quantum reference frames,” says Brukner.

// Alice and Bob’s communication may forge the structure of space-time



But so far, that hasn’t been possible. “I don’t know,” he sighs. “There’s a missing element.”

Hints as to what that might be are coming from work by Flavio Mercati at the University of Burgos in Spain and Giovanni Amelino-Camelia at the University of Naples Federico II in Italy. Their research seems to suggest that by exchanging quantum information, observers can create a shared reality, even if it isn’t there from the start.

The duo were inspired by research carried out in 2016 by Markus Müller and Philipp Höhn, both then at the Perimeter Institute in Waterloo, Canada, who imagined a scenario in which two people, Alice and Bob, send each other quantum particles in a particular state of “spin”. Spin is a quantum property that can be likened to an arrow that can point up or down along each of the three spatial axes. Alice sends Bob a particle and Bob has to figure out its spin; then Bob prepares a new particle with the same spin and sends it back to Alice, who confirms that he got it right. The twist is that Alice and Bob don’t know the relative orientation of their reference frames: one’s x-axis could be the other’s y-axis.

If Alice sends Bob just one particle, he will never be able to decode the spin. Sometimes in physics, two variables are connected in such a way that if you measure one precisely, the other no longer exists in a definite state. This tricky problem, known as the Heisenberg uncertainty principle, applies to particles’ spin along different axes. So if Bob wants to measure spin along what he thinks is Alice’s x-axis, he has to take a wild guess as to which axis that really is – if he is wrong, he erases all the information. The pair can get around this, however, if they exchange lots of particles. Alice can tell Bob, “I’m sending you 100 particles that are all spin ‘up’ along the x-axis.” As Bob measures more and more of them, he can begin to work out the relative orientation of their reference frames.

Here is where it gets interesting. Müller and Höhn realised that, in doing all this, Alice and Bob automatically derive the equations that enable you to translate the view from one perspective to another in Einstein’s special relativity. We tend to think of space-time as the pre-existing structure through which observers communicate. But Müller and Höhn flipped the story. Start ➤

Does space-time commute?

In ordinary space, it isn't the journey that matters so much as the destination. If you're trying to arrive at a given place, it makes no difference whether you head 5 kilometres south and then 3 kilometres west, or vice-versa. That is because the coordinates "commute"; they get you to the same spot regardless of the order.

At very small scales to which quantum theory applies, this might not be true. In quantum theory, measuring a particle's position erases information about its momentum. Similarly, it could be that the order in which movements are made could affect the structure of space. If this is so, it makes no sense to talk about space-time as a fixed arena.

Physicists Flavio Mercati and Giovanni Amelino-Camelia think they have a way to find out whether space-time commutes. They were inspired by research that imagined two people exchanging quantum particles and measuring their properties to deduce their relative orientation (see main story). What would happen, Mercati and Amelino-Camelia asked, if this game were played for real?

As the people exchange more and more particles, their uncertainty about their orientation should decrease. But will it ever get to zero? In ordinary space-time, it will. But if space-time is non-commutative, some uncertainty will always remain, since their orientation is ever so slightly rewritten with each measurement. The pair might have to exchange trillions of particles before we will have an answer – but Mercati thinks it is worth a try.



with observers sending messages, and you can derive space-time.

For Mercati and Amelino-Camelia, who first came across the work a few years ago, that flip was a light-bulb moment. It raised a key question that turns out to have a crucial bearing on Brukner's work: are Alice and Bob learning about a pre-existing space-time or is the space-time emerging as they communicate?

Make some space

There are two ways in which the latter could play out. The first has to do with the trade-off in quantum mechanics between information and energy. "To gain information about a quantum system you have to pay energy," says Mercati. Every time Bob chooses the correct axis, he loses a bit of energy; when he chooses wrong and erases Alice's information, he gains some. Because the curvature of space-time depends on the energy present, when Bob measures his relative orientation he also ends up changing the orientation a tiny bit.

There could be a more profound sense in which quantum communication creates space-time. This comes into play if space is what's called "non-commutative". If you want to arrive at a point on a normal map, it doesn't matter in which order you specify the coordinates. You can go over five and up two; or up two and over five – either way you will land on the same spot. But if the laws of quantum mechanics apply to space-time itself, this might not be true. In the same way that knowing a particle's position prevents you from measuring its momentum, going over

five might prevent you from going up two.

Mercati and Amelino-Camelia say that if space-time does work in this way, Alice and Bob's attempts to find out their relative orientation wouldn't merely uncover the structure of space-time, they would actively forge it. The choices they make as to which axes to measure would alter the very thing their communication was meant to reveal. The pair have also devised a way to test whether this is really the case (see "Does space-time commute?", left).

All this work points towards a startling conclusion: that as people exchange quantum information, they are collaborating to construct their mutual reality. It means that if we simply look at space and time from one perspective, not only do we miss its full beauty, but there might not be any deeper shared reality. For Mercati and Amelino-Camelia, one observer does not a space-time make.

That leads us back to the Wigner's friend paradox that flummoxed Brukner. In his work, observers can be treated as having perspectives on the same reality only when they are gazing at one another from across the Heisenberg cut. Or, put another way, only when it is possible for them to communicate, which is precisely what Wigner and his friend can't do. Perhaps this is telling us that until two people interact, they don't share the same reality – because it is communication itself that creates it. ■



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