Quantum Weirdness Now a Matter of Time

Bizarre quantum bonds connect distinct moments in time, suggesting that quantum links — not space-time — constitute the fundamental structure of the universe.

By George Musser

In November, construction workers at the Massachusetts Institute of Technology came across a time capsule 942 years too soon. Buried in 1957 and intended for 2957, the capsule was a glass cylinder filled with inert gas to preserve its contents; it was even laced with carbon-14 so that future researchers could confirm the year of burial, the way they would date a fossil. MIT administrators plan to repair, reseal and rebury it. But is it possible to make it absolutely certain that a message to the future won't be read before its time?

Quantum physics offers a way. In 2012, Jay Olson and Timothy Ralph, both physicists at the University of Queensland in Australia, laid out a procedure to encrypt data so that it can be decrypted only at a specific moment in the future. Their scheme exploits quantum entanglement, a phenomenon in which particles or points in a field, such as the electromagnetic field, shed their separate identities and assume a shared existence, their properties becoming correlated with one another's. Normally physicists think of these correlations as spanning space, linking far-flung locations in a phenomenon that Albert Einstein famously described as "spooky action at a distance." But a growing body of research is investigating how these correlations can span time as well. What happens now can be correlated with what happens later, in ways that elude a simple mechanistic explanation. In effect, you can have spooky action at a delay.

These correlations seriously mess with our intuitions about time and space. Not only can two events be correlated, linking the earlier one to the later one, but two events can become correlated such that it becomes impossible to say which is earlier and which is later. Each of these events is the cause of the other, as if each were the first to occur. (Even a single observer can encounter this causal ambiguity, so it's distinct from the temporal reversals that can happen when two observers move at different velocities, as described in Einstein's special theory of relativity.)

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The time-capsule idea is only one demonstration of the potential power of these temporal correlations. They might also boost the speed of quantum computers and strengthen quantum cryptography.

But perhaps most important, researchers hope that the work will open up a new way to unify quantum theory with Einstein's general theory of relativity, which describes the structure of space-time. The world we experience in daily life, in which events occur in an order determined by their locations in space and time, is just a subset of the possibilities that quantum physics allows. "If you have space-time, you have a well-defined causal order," said Časlav Brukner, a physicist at the University of Vienna who studies quantum information. But "if you don't have a well-defined causal order," he said — as is the case in experiments he has proposed — then "you don't have space-time." Some physicists take this as evidence for a profoundly nonintuitive worldview, in which quantum correlations are more fundamental than space-time, and space-time itself is somehow built up from correlations among events, in what might be called quantum relationalism. The argument updates Gottfried Leibniz and Ernst Mach's idea that space-time might not be a God-given backdrop to the world, but instead might derive from the material contents of the universe.

How Time Entanglement Works

To understand entanglement in time, it helps to first understand entanglement in space, as the two are closely related. In the spatial version of a classic entanglement experiment, two particles, such as photons, are prepared in a shared quantum state, then sent flying in different directions. An observer, Alice, measures the polarization of one photon, and her partner, Bob, measures the other. Alice might measure polarization along the horizontal axis while Bob looks along a diagonal. Or she might choose the vertical angle and he might measure an oblique one. The permutations are endless.

The outcomes of these measurements will match, and what's weird is that they match even when Alice and Bob vary their choice of measurement — as though Alice's particle knew what happened to Bob's, and vice versa. This is true even when nothing connects the particles — no force, wave or carrier pigeon. The correlation appears to violate "locality," the rule that states that effects have causes, and chains of cause and effect must be unbroken in space and time.

In the temporal case, though, the mystery is subtler, involving just a single polarized photon. Alice measures it, and then Bob remeasures it. Distance in space is replaced by an interval of time. The probability of their seeing the same outcome varies with the angle between the polarizers; in fact, it varies in just the same way as in the spatial case. On one level, this does not seem to be strange. Of course what we do first affects what happens next. Of course a particle can communicate with its future self.

The strangeness comes through in an experiment conceived by Robert Spekkens, a physicist who studies the foundations of quantum mechanics at the Perimeter Institute for Theoretical Physics in Waterloo, Canada. Spekkens and his colleagues carried out the experiment in 2009. Alice prepares a photon in one of four possible ways. Classically, we could think of these four ways as two bits of information. Bob then measures the particle in one of two possible ways. If he chooses to measure the particle in the first way, he obtains Alice's first bit of information; if he chooses the second, he obtains her second bit. (Technically, he does not get either bit with certainty, just with a high degree of probability.) The obvious explanation for this result would be if the photon stores both bits and releases one based on Bob's choice. But if that were the case, you'd expect Bob to be able to obtain information about both bits — to measure both of them or at least some characteristic of both, such as whether they are the same or different. But he can't. No experiment, even in principle, can get at both bits — a restriction known as the Holevo bound. "Quantum systems seem to have more memory, but you can't actually access it," said Costantino Budroni, a physicist at the University of Siegen in Germany.

The photon really does seem to hold just one bit, and it is as if Bob's choice of measurement retroactively decides which it is. Perhaps that really is what happens, but this is tantamount to time travel — on an oddly limited basis, involving the ability to determine the nature of the bit but denying any glimpse of the future.

Another example of temporal entanglement comes from a team led by Stephen Brierley, a mathematical physicist at the University of Cambridge. In a paper last year, Brierley and his collaborators explored the bizarre intersection of entanglement, information and time. If Alice and Bob choose from just two polarizer orientations, the correlations they see are readily explained by a particle carrying a single bit. But if they choose among eight possible directions and they measure and remeasure the particle 16 times, they see correlations that a single bit of memory can't explain. "What we have proven rigorously is that, if you propagate in time the number of bits that corresponds to this Holevo bound, then you definitely cannot explain what quantum mechanics predicts," said Tomasz Paterek, a physicist at Nanyang Technological University in Singapore, and one of Brierley's co-authors. In short, what Alice does to the particle at the beginning of the experiment is correlated with what Bob sees at the end in a way that's too strong to be easily explained. You might call this "supermemory," except that the category of "memory" doesn't seem to capture what's going on.

What exactly is it about quantum physics that goes beyond classical physics to endow particles with this supermemory? Researchers have differing opinions. Some say the key is that quantum measurements inevitably disturb a particle. A disturbance, by definition, is something that affects later measurements. In this case, the disturbance leads to the predicted correlation.

In 2009 Michael Goggin, a physicist who was then at the University of Queensland, and his colleagues did an experiment to get at this issue. They used the trick of spatially entangling a particle with another of its kind and measuring that stand-in particle rather than the original. The measurement of the stand-in still disrupts the original particle (because the two are entangled), but researchers can control the amount that the original is disrupted by varying the degree of entanglement. The trade-off is that the experimenter's knowledge of the original becomes less reliable, but the researchers compensate by testing multiple pairs of particles and aggregating the results in a special way. Goggin and his team reduced the disruption to the point where the original particle was hardly disturbed at all. Measurements at different times were still closely correlated. In fact, they were even more closely correlated than when the measurements disturbed the particle the most. So the question of a particle's supermemory remains a mystery. For now, if you ask why quantum particles produce the strong temporal correlations, physicists basically will answer: "Because."

Quantum Time Capsules

Things get more interesting still — offering the potential for quantum time capsules and other fun stuff — when we move to quantum field theory, a more advanced version of quantum mechanics that describes the electromagnetic field and other fields of nature. A field is a highly entangled system. Different parts of it are mutually correlated: A random fluctuation of the field in one place will be matched by a random fluctuation in another. ("Parts" here refers both to regions of space and to spans of time.)

Even a perfect vacuum, which is defined as the absence of particles, will still have quantum fields. And these fields are always vibrating. Space looks empty because the vibrations cancel each other out. And to do this, they must be entangled. The cancellation requires the full set of vibrations; a subset won't necessarily cancel out. But a subset is all you ever see.

If an idealized detector just sits in a vacuum, it will not detect particles. However, any practical detector has a limited range. The field will appear imbalanced to it, and it will detect particles in a vacuum, clicking away like a Geiger counter in a uranium mine. In 1976 Bill Unruh, a theoretical physicist at the University of British Columbia, showed that the detection rate goes up if the detector is accelerating, since the detector loses sensitivity to the regions of space it is moving away from. Accelerate it very strongly and it will click like mad, and the particles it sees will be entangled with particles that remain beyond its view.

In 2011 Olson and Ralph showed that much the same thing happens if the detector can be made to accelerate through time. They described a detector that is sensitive to photons of a single frequency at any one time. The detector sweeps through frequencies like a police radio scanner, moving from lower to higher frequencies (or the other way around). If it sweeps at a quickening pace, it will scan right off the end of the radio dial and cease to function altogether. Because the detector works for only a limited period of time, it lacks sensitivity to the full range of field vibrations, creating the same imbalances that Unruh predicted. Only now, the particles it picks up will be entangled with particles in a hidden region of time — namely, the future.

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Olson and Ralph suggest constructing the detector from a loop of superconducting material. Tuned to pick up near-infrared light and completing a scan in a few femtoseconds (10^{-15} seconds), the loop would see the vacuum glowing like a gas at room temperature. No feasible detector accelerating through space could achieve that, so Olson and Ralph's experiment would be an important test of quantum field theory. It could also vindicate Stephen Hawking's ideas about black-hole evaporation, which involve the same basic physics.

If you build two such detectors, one that accelerates and one that decelerates at the same rate, then the particles seen by one detector will be correlated with the particles seen by the other. The first detector might pick up a string of stray particles at random intervals. Minutes or years later, the second detector will pick up another string of stray particles at the same intervals — a spooky recurrence of events. "If you just look at them individually, then they're randomly clicking, but if you get a click in one, then you know that there's going to be a click in the other one if you look at a particular time," Ralph said.

These temporal correlations are the ingredients for that quantum time capsule. The original idea for such a contraption goes back to James Franson, a physicist at the University of Maryland, Baltimore County. (Franson used spacelike correlations; Olson and Ralph say temporal correlations may make it easier.) You write your message, encode each bit in a photon, and use one of your special detectors to measure those photons along with the background field, thus effectively encrypting your bits. You then store the outcome in the capsule and bury it.

At the designated future time, your descendants measure the field with the paired detector. The two outcomes, together, will reconstitute the original information. "The state is disembodied for the time between [the two measurements], but is encoded somehow in these correlations in the vacuum," Ralph said. Because your descendants must wait for the second detector to be triggered, there's no way to unscramble the message before its time.

The same basic procedure would let you generate entangled particles for use in computation and cryptography. "You could do quantum key distribution without actually sending any quantum signal," Ralph said. "The idea is that you just use the correlations that are already there in the vacuum."

The Nature of Space-Time

These temporal correlations are also challenging physicists' assumptions about the nature of space-time. Whenever two events are correlated and it's not a fluke, there are two explanations: One event causes the other, or some third factor causes both. A background assumption to this logic is that events occur in a given order, dictated by their locations in space and time. Since quantum correlations — certainly the spatial kind, possibly the temporal — are too strong to be explained using one of these two explanations, physicists are revisiting their assumptions. "We cannot really explain these correlations," said Ämin Baumeler, a physicist at the University of Italian Switzerland in Lugano, Switzerland. "There's no mechanism for how these correlations appear. So, they don't really fit into our notion of space-time."

Building on an idea by Lucien Hardy, a theoretical physicist at the Perimeter Institute, Brukner and his colleagues have studied how events might be related to one another without presupposing the existence of space-time. If the setup of one event depends on the outcome of another, you deduce that it occurs later; if the events are completely independent, they must occur far apart in space and time. Such an approach puts spatial and temporal correlations on an equal footing. And it also allows for correlations that are neither spatial nor temporal — meaning that the experiments don't all fit together consistently and there's no way to situate them within space and time.

Brukner's group devised a strange thought experiment that illustrates the idea. Alice and Bob each toss a coin. Each person writes the result of his or her own toss on a piece of paper, along with a guess for the other person's outcome. Each person also sends the paper to the other with this information. They do this a number of times and see how well they do.

Normally the rules of the game are set up so that Alice and Bob do this in a certain sequence. Suppose Alice is first. She can only guess at Bob's outcome (which has yet to occur), but she can send her own result to Bob. Alice's guess as to Bob's flip will be right 50 percent of the time, but he will always get hers right. In the next round, Bob goes first, and the roles are reversed. Overall the success rate will be 75 percent. But if you don't presume they do this in a certain sequence, and if they replace the sheet of paper with a quantum particle, they can succeed 85 percent of the time.

If you try to situate this experiment within space and time, you'll be forced to conclude that it involves a limited degree of time travel, so that the person who goes second can communicate his or her result backward in time to the one who goes first. (The Time Patrol will be relieved that no logical paradoxes can arise: No event can become its own cause.)

Brukner and his colleagues at Vienna have performed a real-world experiment that is similar to this. In the experiment, Alice-and-Bob manipulations were carried out by two optical filters. The researchers beamed a stream of photons at a partially silvered mirror, so that half the photons took one path and half another. (It was impossible to tell, without measuring, which path each individual photon went down; in a sense, it took both paths at once.) On the first path, the photons passed through Alice's filter first, followed by Bob's. On the second path, the photons navigated them in reverse order. The experiment took quantum indeterminacy to a whole new level. Not only did the particles not possess definite properties in advance of measurement, the operations performed on them were not even conducted in a definite sequence.

On a practical level, the experiment opens up new possibilities for quantum computers. The filters corresponding to Alice and Bob represent two different mathematical operations, and the apparatus was able to ascertain in a single step whether the order of those operations matters — whether A followed by B is the same as B followed by A. Normally you'd need two steps to do that, so the procedure is a significant speedup. Quantum computers are sometimes described as performing a series of operations on all possible data at once, but they might also be able to perform all possible operations at once.

Now imagine taking this experiment a step further. In Brukner's original experiment, the path of each individual photon is placed into a "superposition" — the photon goes down a quantum combination of the Alice-first path and the Bob-first path. There is no definite answer to the question, "Which filter did the photon go through first?"— until a measurement is carried out and the ambiguity is resolved. If, instead of a photon, a gravitating object could be put into such a temporal superposition, the apparatus would put space-time itself into a superposition. In such a case, the sequence of Alice and Bob would remain ambiguous. Cause and effect would blur together, and you would be unable to give a step-by-step account of what happened.

Only when these indeterminate causal relations between events are pruned away — so that nature realizes only some of the possibilities available to it — do space and time become meaningful. Quantum correlations come first, space-time later. Exactly how does space-time emerge out of the quantum world? Brukner said he is still unsure. As with the time capsule, the answer will come only when the time is right.

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