Researchers use measurements to generate quantum entanglement and teleportation

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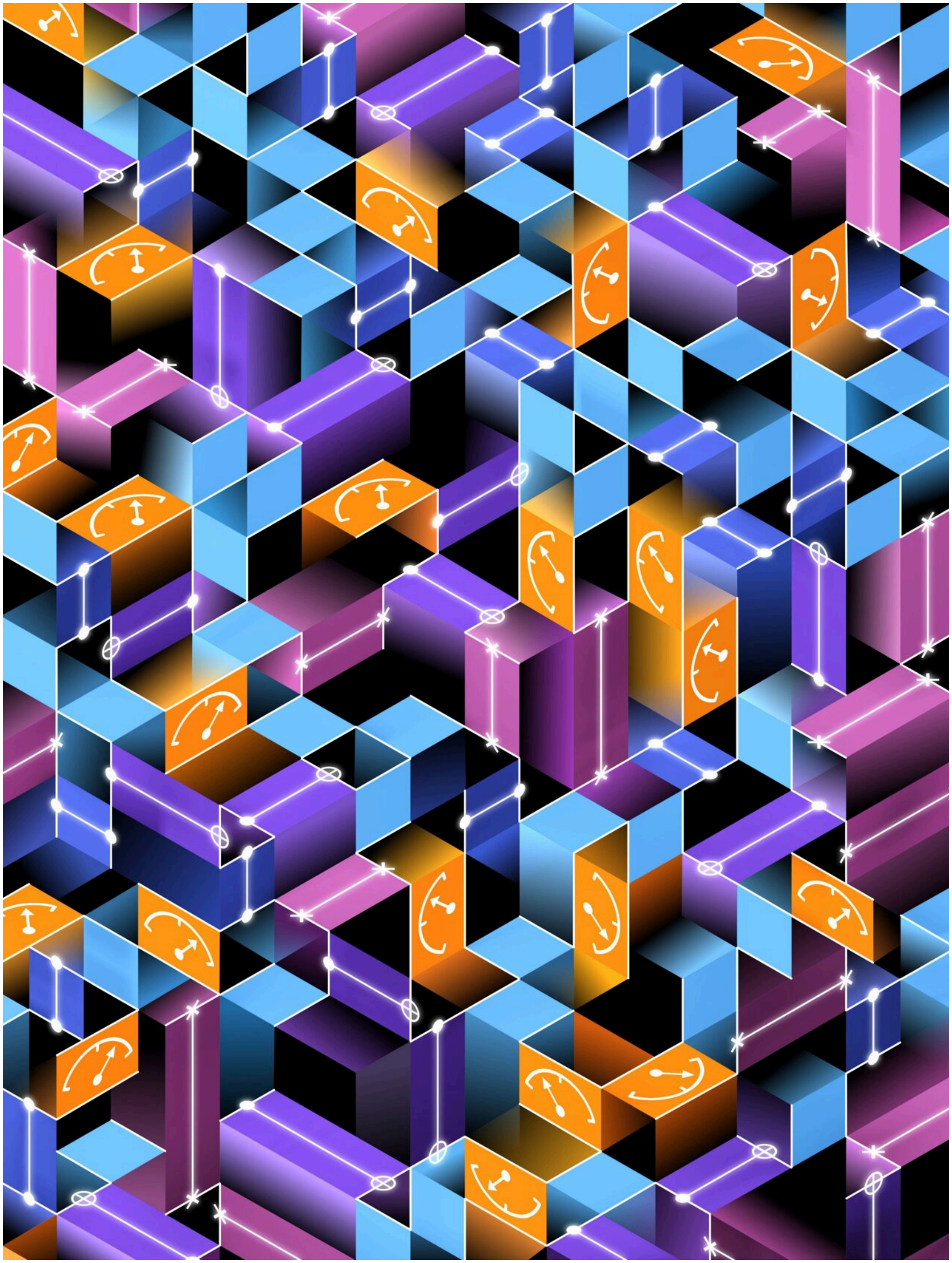

The researchers at Google Quantum AI and Stanford University explored how measurements can fundamentally change the structure of quantum information in space-time. Credit: Google Quantum AI, designed by Sayo-Art

Quantum mechanics is full of weird phenomena, but perhaps none as weird as the role measurement plays in the theory. Since a measurement tends to destroy the "quantumness" of a system, it seems to be the mysterious link between the quantum and classical world. And in a large system of quantum bits of information, known as "qubits," the effect of measurements can induce dramatically new behavior, even driving the emergence of entirely new phases of quantum information.

This happens when two competing effects come to a head: interactions and measurement. In a quantum system, when the qubits interact with one another, their information becomes shared nonlocally in an "entangled state." But if you measure the system, the entanglement is destroyed. The battle between measurement and interactions leads to two distinct phases: one where interactions dominate and entanglement is widespread, and one where measurements dominate, and entanglement is suppressed.

As reported in the journal *Nature*, researchers at Google Quantum AI and Stanford University have observed the crossover between these two regimes—known as a "measurement-induced phase transition"—in a system of up to 70 qubits. This is by far the largest system in which measurement-induced effects have been explored.

The researchers also saw signatures of a novel form of "quantum teleportation"—in which an unknown quantum state is transferred from one set of qubits to another—that emerges as a result of these measurements. These studies could help inspire new techniques useful for quantum computing.

One can visualize the entanglement in a system of qubits as an intricate web of connections. When we measure an entangled system, the impact it has on the web depends on the strength of the measurement. It could destroy the web completely, or it could snip and prune selected strands of the web, but leave others intact.

To actually see this web of entanglement in an experiment is notoriously challenging. The web itself is invisible, so researchers can only infer its existence by seeing statistical correlations between the measurement outcomes of qubits. Many, many runs of the same experiment are needed to infer the pattern of the web. This and other challenges have plagued past experiments and limited the study of measurement-induced phase transitions to very small system sizes.

To address these challenges, the researchers used a few experimental sleights of hand. First, they rearranged the order of operations so that all the measurements could be made at the end of the experiment, rather than interleaved throughout, thus reducing the complexity of the experiment. Second, they developed a new way to measure certain features of the web with a single "probe" qubit.

In this way, they could learn more about the entanglement web from fewer runs of the experiment than had been previously required. Finally, the probe, like all qubits, was susceptible to unwanted noise in the environment. This is normally seen as a bad thing, as noise can disrupt quantum calculations, but the researchers turned this bug into a feature by noting that the probe's sensitivity to noise depended on the nature of the entanglement web around it. They could therefore use the probe's noise sensitivity to infer the entanglement of the whole system.

The team first looked at this difference in sensitivity to noise in the two entanglement regimes and found distinctly different behaviors. When measurements dominated over interactions (the "disentangling phase"), the strands of the web remained relatively short. The probe qubit was only sensitive to the noise of its nearest qubits.

In contrast, when the measurements were weaker and entanglement was more widespread (the "entangling phase") the probe was sensitive to noise throughout the entire system. The crossover between these two sharply contrasting behaviors is a signature of the sought-after measurement-induced phase transition.

The team also demonstrated a novel form of quantum teleportation that emerged naturally from the measurements: by measuring all but two distant qubits in a weakly entangled state, stronger entanglement was generated between those two distant qubits. The ability to generate measurement-induced entanglement across long distances enables the teleportation observed in the experiment.

The stability of entanglement against measurements in the entangling phase could inspire new schemes to make quantum computing more robust to noise. The role that measurements play in driving new phases and physical phenomena is also of fundamental interest to physicists.

Stanford professor and co-author of the study, Vedika Khemani, says, "Incorporating measurements into dynamics introduces a whole new playground for many-body physics where many fascinating and new types of non-equilibrium phases could be found. We explore a few of these striking and counter-intuitive measurement induced phenomena in this work, but there is much more richness to be discovered in the future."

More information: Pedram Roushan, Measurement-induced entanglement and teleportation on a noisy quantum processor, *Nature*

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