# How New Entanglement Control at MIT Is Redefining Quantum Computing

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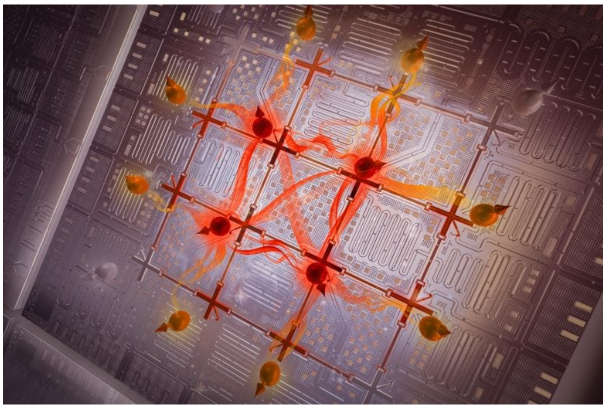

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One type of correlation that exists between quantum objects, like atomic-scale particles, is called entanglement. Though it is one of the characteristics that explains the macroscopic behavior of quantum systems, this peculiarly quantum phenomenon defies explanation by the rules of classical physics.

Gaining a greater understanding of entanglement could help scientists better grasp how information is stored and processed in quantum systems, as it is fundamental to their operation.

The fundamental components of a quantum computer are called qubits, or quantum bits. Nevertheless, creating distinct entangled states in many-qubit systems, let alone studying them, is quite challenging. Differentiating between the many entangled states might be difficult as well.

Researchers at MIT have now shown how to effectively create entanglement amongst a variety of superconducting qubits that behave in a particular way.

In recent years, scientists from the Engineering Quantum Systems (EQuS) group have worked on methods to accurately operate a quantum processor made out of superconducting circuits utilizing microwave technology. The methods presented in this work allow the processor to efficiently generate highly entangled states and transition those states between different types of entanglement, including those that are more likely to support quantum speed-up and those that do not. These control techniques are in addition to them.

"Here, we're showing that the developing quantum processors can be used as an instrument to deepen our knowledge of physics. The principal author of the study, Amir H. Karamlou '18, MEng '18, PhD '23, notes, "Although everything we did in this experiment was on a scale which can still be simulated on a classical computer, we have a good roadmap for scaling this technology and methodology beyond the reach of classical computing."

William D. Oliver, the director of the Center for Quantum Engineering, the head of the EQuS group, the Henry Ellis Warren professor of electrical engineering, computer science, and physics, and the associate director of the Research Laboratory of Electronics, is the senior author. Research Scientist Jeff Grover, postdoc Ilan Rosen, and other personnel from MIT's Electrical Engineering and Computer Science and Physics departments, as well as from MIT Lincoln Laboratory, Wellesley College, and the University of Maryland, join Karamlou and Oliver. The study was just released in the Nature journal.

Entanglement can be defined as the quantum information transferred between a subsystem of qubits and the remainder of the larger system in a large quantum system with many interconnected qubits.

A quantum system's entanglement can be classified as either area-law or volume-law according to the way this shared information scales with subsystem geometry. When there is volume-law entanglement, the degree of entanglement that exists between a qubit subsystem and the rest of the system increases in direct proportion to the subsystem's overall size.

However, area-law entanglement is contingent upon the number of common connections that a qubit subsystem has with the rest of the system. The degree of entanglement only increases along the subsystem's boundary with the larger system as it gets bigger.

Theoretically, the strength of quantum computing is associated with the creation of volume-law entanglement.

Oliver states, "We know that generating volume-law entanglement is a key ingredient to realizing a quantum advantage, even though we have not yet fully abstracted the role that entanglement plays in quantum algorithms."

Nevertheless, volume-law entanglement is also more difficult to simulate with a classical computer and practically prohibitive at scale compared to area-law entanglement.

Superconducting circuits, which are utilized to create artificial atoms, are a component of their processor. The artificial atoms are used as qubits, which are highly accurate devices that can be controlled and read out with microwave waves.

This experiment's apparatus had sixteen qubits placed in a two-dimensional grid. To ensure that each of the 16 qubits had the same transition frequency, the researchers meticulously adjusted the CPU. Subsequently, they concurrently applied a second microwave drive to each qubit.

This microwave drive creates quantum states with volume-law entanglement if its frequency matches that of the qubits. Nevertheless, the qubits show less volume-law entanglement with rising or decreasing microwave frequency, and eventually transition to entangled states that progressively follow an area-law scaling.

"Our study is a masterwork of superconducting quantum computing capabilities. In one experiment, Rosen adds, "we used the processor as a digital computing device to measure the entanglement scaling that resulted from operating it as an analog simulation device, which allowed us to prepare states with different entanglement structures efficiently."

The team worked diligently for years to carefully build up the infrastructure around the quantum processor in order to provide that control.

The crossover between volume-law and area-law entanglement was demonstrated, allowing the researchers to experimentally validate the predictions of previous theoretical studies. More crucially, this technique can be applied to identify as area-law or volume-law entanglement in a general quantum processor.

The difference between area-law and volume-law entanglement in two-dimensional quantum simulations with superconducting qubits is highlighted by the MIT experiment. Professor of theoretical physics at the University of Innsbruck Peter Zoller adds, "This beautifully complements our work on entanglement Hamiltonian tomography with trapped ions in a parallel publication published in Nature in 2023." Zoller was not involved in this work.

Pedram Roushan of Google, who was not involved in the study, states that "quantifying entanglement in large quantum systems is a challenging task for classical computers but a good example of where quantum simulation could help." Karamlou and colleagues measured the entanglement entropy of different subsystems of different sizes using a 2D array of superconducting qubits. By measuring the area-law and volume-law contributions to entropy, they may identify crossover behavior that occurs when the quantum state energy of the system is adjusted. It effectively illustrates the special insights that quantum simulators can provide.

This method could be used in the future by scientists to investigate the thermodynamic behavior of complicated quantum systems, which are currently too complex to examine analytically and are prohibitively expensive to model on even the most powerful supercomputers in the world.

"We may learn more about the nature of entanglement in these many-body systems, and the experiments we conducted in this work can be used to characterize or benchmark larger-scale quantum systems," says Karamlou.

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