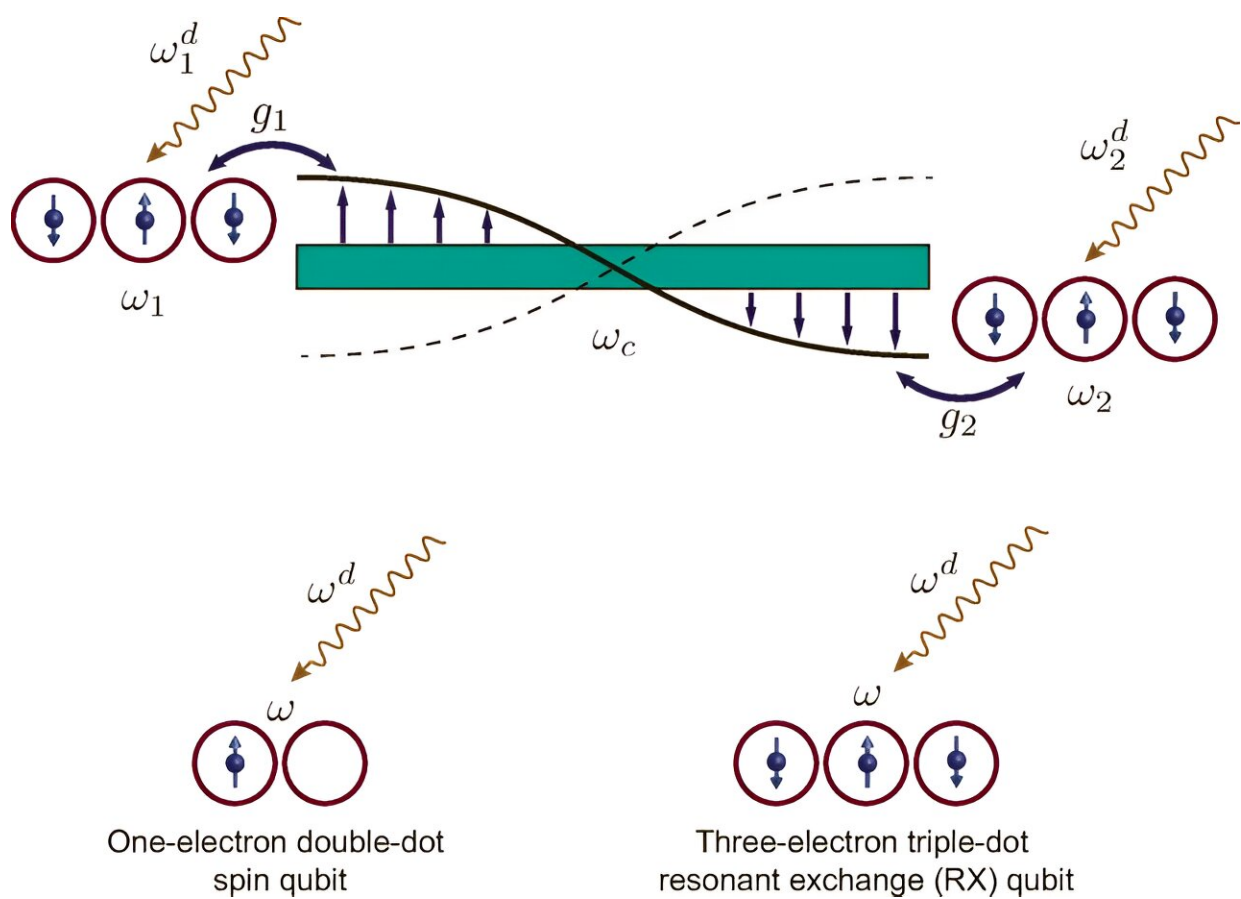


Theoretical research holds promise for advancing modular quantum information processing

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Schematic illustration of a system for cavity-mediated coupling of two parametrically driven quantum dot spin qubits via sidebands. Credit: *PRX Quantum* (2024). DOI: 10.1103/PRXQuantum.5.020339

The operation of a quantum computer relies on encoding and processing information in the form of quantum bits—defined by two states of quantum systems such as electrons and photons. Unlike binary bits used in classical computers, quantum bits can exist in a combination of zero and one simultaneously—in principle allowing them to perform certain calculations exponentially faster than today's largest supercomputers.

To reach their full potential, quantum computers need millions of quantum bits, or qubits. But a challenge arises as quantum information processing systems are scaled to many qubits. Highly complex electronics are needed to control even a few qubits and scaling that complex circuitry represents a major hurdle.

In recent theoretical research, a team of physicists, led by University of Rhode Island professor Vanita Srinivasa, envisions a modular system for scaling [quantum processors](#) with a flexible way of linking qubits over long distances to enable them to work in concert to perform quantum operations. The ability to carry out such correlated or "entangling" operations between linked qubits is the basis of the enhanced power quantum computing holds compared with current computers.

A new [paper](#) on their research, co-authored by Srinivasa, Jacob M. Taylor of the University of Maryland and the National Institute of Standards and Technology, and Jason R. Petta of the University of California, Los Angeles, was recently published in the journal *PRX Quantum*.

"Each qubit in a quantum computer operates at a specific [frequency](#). Realizing the capabilities unique to a quantum computer relies on being able to control each qubit individually via a distinct frequency, as well as to link pairs of qubits by matching their frequencies," said Srinivasa, director of URI's Quantum Information Science program and an assistant professor of physics.

"As a quantum processor is scaled to larger numbers of qubits, being able to simultaneously achieve both of these operations for every qubit becomes very challenging. In our work, we describe how applying oscillating voltages effectively generates extra frequencies for each qubit in order to link multiple qubits without having to match all of their original frequencies. This allows qubits to be linked while simultaneously allowing each qubit to retain a distinct frequency for individual control."

Using semiconductors to build quantum processors is in principle very promising for scaling qubits to large numbers. The advanced semiconductor technology that exists today forms the basis for fabricating chips with billions of tiny transistors and can be harnessed to make qubits that are compact in size, Srinivasa said. Additionally, storing qubits in an internal property of electrons and other semiconductor particles known as spin provides enhanced protection from the quantum information loss inherent in every quantum computing platform.

However, scaling up a quantum processor by simply adding more and more spin qubits and their associated control circuitry to a single array of qubits is very challenging in practice. The theoretical work by Srinivasa and her colleagues addresses this problem by providing a step-by-step guide that shows multiple ways to entangle spin qubits over long distances with flexibility in matching their frequencies.

The resulting flexibility opens a pathway to semiconductor-based modular [quantum information](#) processing, which represents an alternative approach for building many-qubit systems using small arrays of qubits—modules—that can already be made today, and connecting them with robust, long-range entangling links.

"This approach to scaling is like building a larger system using fixed-size

LEGO blocks, which are like individual modules, and connecting them using longer pieces that are strong enough to maintain the connection between the blocks for a sufficient time before external influences break the links," Srinivasa said.

"Provided fast and reliable long-distance links between qubits are available, such a modular approach allows scaling while providing more space for the spin qubit control circuitry." Fully modular semiconductor-based quantum processors have yet to be demonstrated.

While there are many types of qubits and a corresponding variety of ways for them to interact, the researchers chose to study quantum dot-based spin qubits that interact through microwave photons in a superconducting cavity. Quantum dots are atom-like structures created to confine electrons—and other particles used to define qubits—to small spaces within semiconductors and control them individually by applying voltages. Likewise, superconducting cavities are fabricated structures that confine photons but are much larger than [quantum dots](#), with a size set by the wavelength of microwaves.

Recent experiments have demonstrated long-distance links between quantum dot spin qubits using microwave cavity photons. (The first demonstration for two spin qubits in silicon was achieved by co-author Jason Petta's experimental research group.)

However, tuning all of the qubit and photon frequencies so they precisely match and can exchange energy—a condition called resonance—to establish a link has been a problem even at just the two-qubit level, the paper says. To address this problem, the researchers present a highly tunable approach for linking qubits using [microwave photons](#) that does not rely on simultaneous resonance among all original qubit and cavity frequencies.

In their paper, the researchers provide comprehensive guidelines for tailored long-distance entangling links that allow flexibility by making multiple frequencies available for each qubit to become linked with microwave cavity photons of a given frequency, "like multiple keys that can fit a given lock," Srinivasa said.

Extra frequencies can be generated by applying an oscillating voltage to each spin qubit that moves the spins back and forth in the quantum dots. If this back-and-forth motion is fast enough, two sideband frequencies—one higher and one lower in frequency than the original qubit frequency—are created for each qubit in addition to their characteristic frequency.

The addition of the sideband frequencies results in three ways to tune each qubit into resonance with microwave cavity photons, and consequently nine different conditions under which two qubits can be linked.

This flexibility in resonance conditions would make it much easier to add qubits to a system because they do not all need to be tuned to the same frequency. Furthermore, the nine ways for two qubits to be linked enable several different types of entangling operations to be selected simply by setting the oscillating voltages appropriately, without having to modify the structure of either the quantum dots or the cavity photons.

The versatility in types of entangling links enables an expanded set of elementary quantum operations with which to perform calculations. Finally, the researchers show that their proposed entangling method is less sensitive to leakage of photons out of the cavity than previous approaches, allowing for more robust long-distance links between spin qubits.

"The combination of flexibility in matching frequencies, versatility in

tailoring the types of quantum entangling operations between qubits, and reduced sensitivity to cavity photon leakage renders our proposed sideband frequency-based approach promising for realizing a modular quantum processor using semiconductor qubits," Srinivasa said.

"I am excited for the next step, which is to apply these ideas to real quantum devices in the laboratory and find out what we need to do to make the approach work in practice."

More information: V. Srinivasa et al, Cavity-Mediated Entanglement of Parametrically Driven Spin Qubits via Sidebands, *PRX Quantum* (2024). [DOI: 10.1103/PRXQuantum.5.020339](https://doi.org/10.1103/PRXQuantum.5.020339)

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