Proposed modular quantum computer architecture offers scalability to large numbers of qubits

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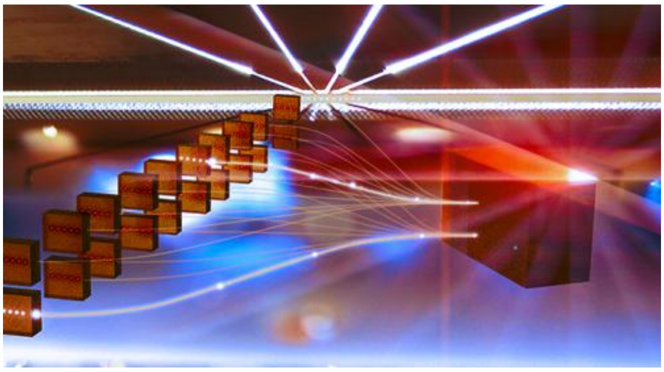

Ion qubits (shown as a crystal within trap blades) are combined in a modular design. Any set of ion modules (small cubes on left) can be connected using photonic interconnects. A switch, depicted as large cube on right, contains microelectromechanical mirrors to change connections between any arbitrary pair of modules. Credit: Graphic based on figure 1 from publication. Background is a photo of a razor blade ion trap, taken by S. Debnath. Graphic rendering E. Edwards/JQI

How do you build a universal quantum computer? Turns out, this question was addressed by theoretical physicists about 15 years ago. The answer was laid out in a research paper and has become known as the DiVincenzo criteria. The prescription is pretty clear at a glance; yet in practice the physical implementation of a full-scale universal quantum computer remains an extraordinary challenge.

To glimpse the difficulty of this task, consider the guts of a would-be quantum computer. The computational heart is composed of multiple quantum bits, or qubits, that can each store 0 and 1 at the same time. The qubits can become "entangled," or correlated in ways that are impossible in conventional devices. A quantum computing device must create and maintain these quantum connections in order to have a speed and storage advantage over any conventional computer. That's the upside. The difficulty arises because harnessing entanglement for computation only works when the qubits are almost completely isolated from the outside world. Isolation and control becomes much more difficult as more and more qubits are added into the computer. Basically, as quantum systems are made bigger, they generally lose their quantum-ness.

In pursuit of a quantum computer, scientists have gained amazing control over various quantum systems. One leading platform in this broad field of research is trapped atomic ions, where nearly 20 qubits have been juxtaposed in a single quantum register. However, scaling this or any other type of qubit to much larger numbers while still contained in a single register will become increasingly difficult, as the connections will become too numerous to be reliable.

Physicists led by ion-trapper Christopher Monroe at the JQI have now proposed a modular quantum computer architecture that promises scalability to much larger numbers of qubits. This research is described in the journal *Physical Review A*, a topical journal of the American Physical Society. The components of this architecture have individually been tested and are available, making it a promising approach. In the paper, the authors present expected performance and scaling calculations, demonstrating that their architecture is not only viable, but in some ways, preferable when compared to related schemes.

Individual qubit modules are at the computational center of this design, each one consisting of a small crystal of perhaps 10-100 trapped ions confined with electromagnetic fields. Qubits are stored in each atomic ion's internal energy levels. Logical gates can be performed locally within a single module, and two or more ions can be entangled using the collective properties of the ions in a module.

One or more qubits from the ion trap modules are then networked through a second layer of optical fiber photonic interconnects. This higher-level layer hybridizes photonic and ion-trap technology, where the quantum state of the ion qubits is linked to that of the photons that the ions themselves emit. Photonics is a natural choice as an information bus as it is proven technology and already used for conventional information flow. In this design, the fibers are directed to a reconfigurable switch, so that any set of modules could be connected. The switch system, which incorporates special micro-electromechanical mirrors (MEMs) to direct light into different fiber ports, would allow for entanglement between arbitrary modules and on-demand distribution of quantum information.

The defining feature of this new architecture is that it is modular, meaning that several identical modules composed of smaller registers are connected in a way that is inherently scalable. Modularity is a common property of complex systems, from social networks to biological function, and will likely be a necessary component of any future large-scale quantum computer. Monroe explains,"This is the only way to imagine scaling to larger quantum systems, by building them in smaller standard units and hooking them together. In this case, we know how to engineer every aspect of the architecture."

In conventional computers, modularity is routinely exploited to realize the massive interconnects required in semiconductor devices, which themselves have been successfully miniaturized and integrated with other electronics and photonics. The first programmable computers were the size of large rooms and used vacuum tubes, and now people have an incredible computer literally at their fingertips. Today's processors have billions of semiconductor transistors fabricated on chips that are only about a centimeter across.

Similar fabrication techniques are now used to construct computer chip-style ion-traps, sometimes with integrated optics. The modular quantum architecture proposed in this research would not only allow many ion-trap chips to be tied together, but could also be exploited with alternative qubit modules that couple easily to photons such as qubits made from nitrogen vacancy centers in diamond or ultracold atomic gases (the neutral cousin of ion-traps).

More information: "Large-scale modular quantum-computer architecture with atomic memory and photonic interconnects." C. Monroe, R. Raussendorf, A. Ruthven, K. R. Brown, P. Maunz, L.-M. Duan, and J. Kim. *Phys. Rev. A* 89, 022317 (2014). Published February 13, 2014. physics.aps.org/synopsis-for/1 … 3/PhysRevA.89.022317

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