with 95% of the pore diameters between 0.5 nm and 0.75 nm, simulations indicate that pores greater than 0.55 nm in diameter may allow salt through. Additionally, larger sheets are more prone to larger-than-desired pores and defects. And growing graphene sheets by chemical vapor deposition makes the cost of a nanoporous graphene membrane much higher than that of a polymer membrane.

Even with improved membrane technology, desalination will still be plagued by environmental problems. Disposing of the concentrated brine left behind after desalination is no simple matter. Pumping it back into the ocean changes the region's salinity and harms ocean life. Also of concern are the copper and chlorine that get added to seawater at various stages in the desalination process. They help to control bacterial growth and reduce corrosion but remain in the discharged brine.[6]

Rachel Berkowitz

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Teleportation for device-scale quantum computing

Trapped ions interact with help from an entangled pair of messengers.

A quantum computer will need a method to perform logic operations on qubits that are physically distant. Gate teleportation, proposed 20 years ago,[1] does just that. It takes an approach similar to teleporting a qubit (see the article by Charles Bennett, PHYSICS TODAY, October 1995, page 24) and uses entangled particles, or messengers, to teleport a logic gate that executes the operation. The messengers are entangled beforehand, and each one travels to a qubit and ropes it into the entangled state. Gate teleportation may also help deal with error propagation (see the article by John Preskill, PHYSICS TODAY, June 1999, page 24).

In a modern classical computer, a switch uses many electrons, $N \sim 10^5$ or more. Provided the number of electrons doesn't deviate by more than $\sqrt{N}$, the gate works flawlessly—typical failure rates are less than 10^{-18}. In a quantum logic gate, any error in the input carries over to the output, and the gate can't correct itself. The best isolated two-qubit quantum gate operations in trapped ions have an error rate of 10^{-3}. A quantum computation that enlisted more than a modest 1000 gates would always fail—without quantum error correction, that is.

To correct errors, a quantum computer needs redundancy: The more qubits encoding the same information, the less likely all, or even a majority, of them will err. A practical device would use many physical qubits to encode every logical qubit in the computation and require millions of physical qubits total. But a device that large can't have all its qubits in close proximity. Gate teleportation is one way for qubits to interact without the inherently slow process of migrating distant qubits together.

Now the Ion Storage Group at NIST in Boulder, Colorado, has demonstrated gate teleportation in trapped ions.[2] The experiment was led by Dietrich Leibfried, Andrew Wilson, and David Wineland. Gate teleportation serves as a test case for many necessary features of a trapped-ion quantum computing architecture that can be scaled to thousands or even millions of qubits (see the article by Ignacio Cirac and Peter Zoller, PHYSICS TODAY, March 2004, page 38).

Making it happen

Fifteen years ago, Guang-Can Guo of the University of Science and Technology of China and his collaborators demonstrated

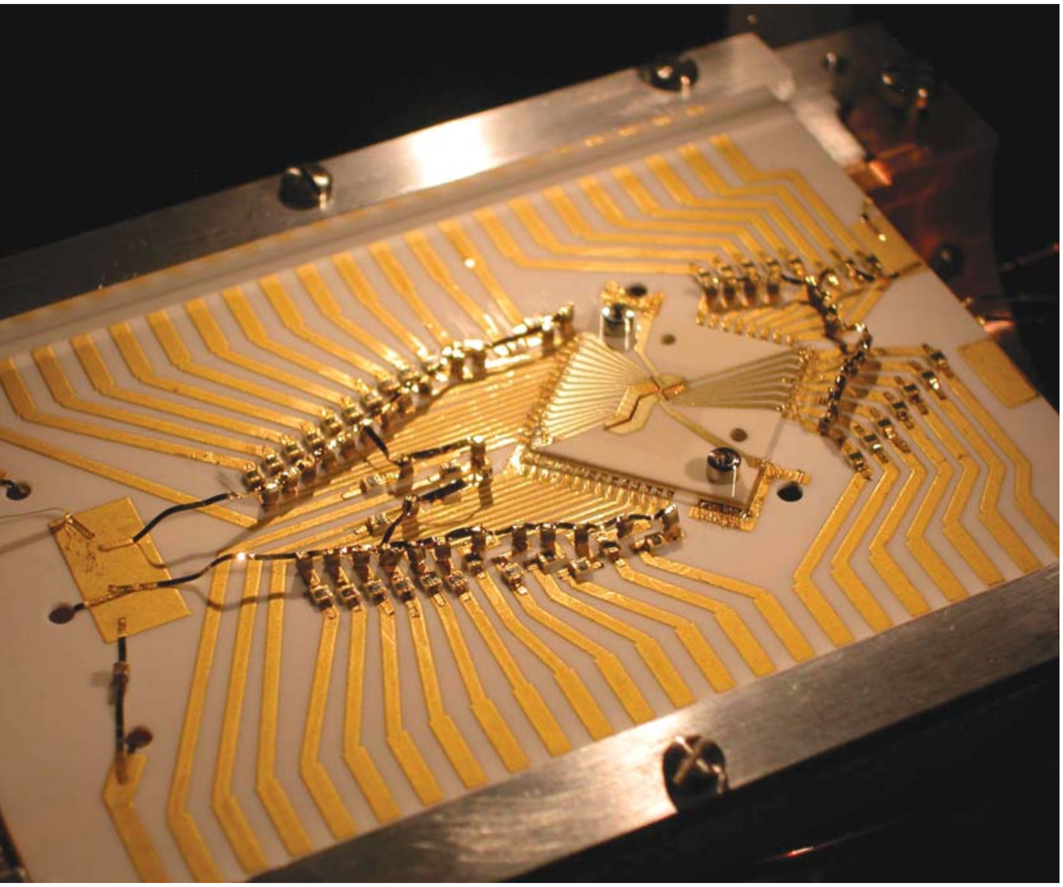

FIGURE 1. NIST'S TRAPPED-ION DEVICE uses electrodes to shuttle around ions trapped in potential wells. The interaction zone, where ions are exposed to a laser, is near the center of the about 15 mm × 15 mm square region on the right. (Courtesy of Brad Blakestad.)

that they could teleport gates in a photonic system probabilistically.[3] To move from probabilistic to deterministic gate teleportation requires real-time measurement and the communication of that classical information from one qubit to the other. That's because only a specific state of the messengers teleports the correct gate. For deterministic gate teleportation, therefore, the messenger state must be measured and adjusted if it is not the one desired. Deterministic gate teleportation was demonstrated a year ago in superconducting qubits[4] by Yale University's Robert Schoelkopf and colleagues. In that work, the researchers used superconducting microwave cavities as the logic qubits and a type of superconducting qubit, called a transmon, as the messengers.

The NIST researchers built a device that implements qubits using ions stored in potential wells that can be brought together, separated, and moved around the device, including to an interaction zone where qubits are exposed to laser fields. Using the device, the team deterministically teleported a controlled-NOT (CNOT) logic gate, similar to the classical exclusive-OR (XOR) gate, in which a target qubit's spin flips only if a control qubit's spin has a specific orientation. A CNOT operation paired with single-qubit rotations can perform any possible operation in quantum computing. Wineland and his colleagues demonstrated a CNOT gate in 1995 on a single beryllium ion in a harmonic trap, with the ion's electronic state as one qubit and its vibrational state as the other.[5]

The new device, shown in figure 1, requires two specific capabilities. First, physical manipulations such as shuttling, separation, and recombination of the ions must be accurate and reliable. Second, ions of different types must be capable of entanglement so that they can take on specialized roles, such as memory storage or helping in error correction. The second capability is crucial, and the NIST team accomplished it only a few years ago through a laser-driven direct CNOT operation on Be^+ and Mg^+ ions.[6] The biggest technical achievement in the new study is implementing all of those things in a single device.

Gate performance

In the gate-teleportation experiment, NIST postdocs Yong Wan and Daniel Kienzler, now at ETH Zürich, perform a CNOT operation on two Be ions (B1 and B2 in figure 2) kept over 300 μm apart. First, they prepare B1 and B2 in a superposition of spin states and entangle two magnesium ions (M1 and M2) to use as messengers. M1 is shuttled off to B1, where a local CNOT operation entangles B1, M1, and M2. A measurement of M1's spin removes it from the entangled state and leaves B1 and M2 entangled. If M1's spin is up, B1 and M2 are in the desired state. If M1's spin is down, M2's spin is flipped to achieve the desired state. Afterward, M2, which has been shuttled to B2, is entangled with B2 through another local CNOT, and a measurement of M2's spin leaves B1 and B2 entangled. After a conditional phase flip on B1 if M2 is spin down, the teleported CNOT gate between B1 and B2 is complete.

The sequence performs as expected for an ideal CNOT 85–87% of the time—Schoelkopf and colleagues obtained a similar fidelity, 79%, in their study on superconducting qubits.[4] In NIST's trapped-ion platform, the error rate for each of the steps when performed together in the same device was higher than the best rate for any one operation in isolation. The largest error contribution, about 4%, came from entangling M1 and M2. Notably, the error was about the same, or less, for entanglement between different types of ions: It is only about 3% for the CNOT between B1 and M1. The current error rate is too high to put the gate to work in practically useful quantum computers. However, researchers now know which steps in trapped-ion devices need the most improvement.

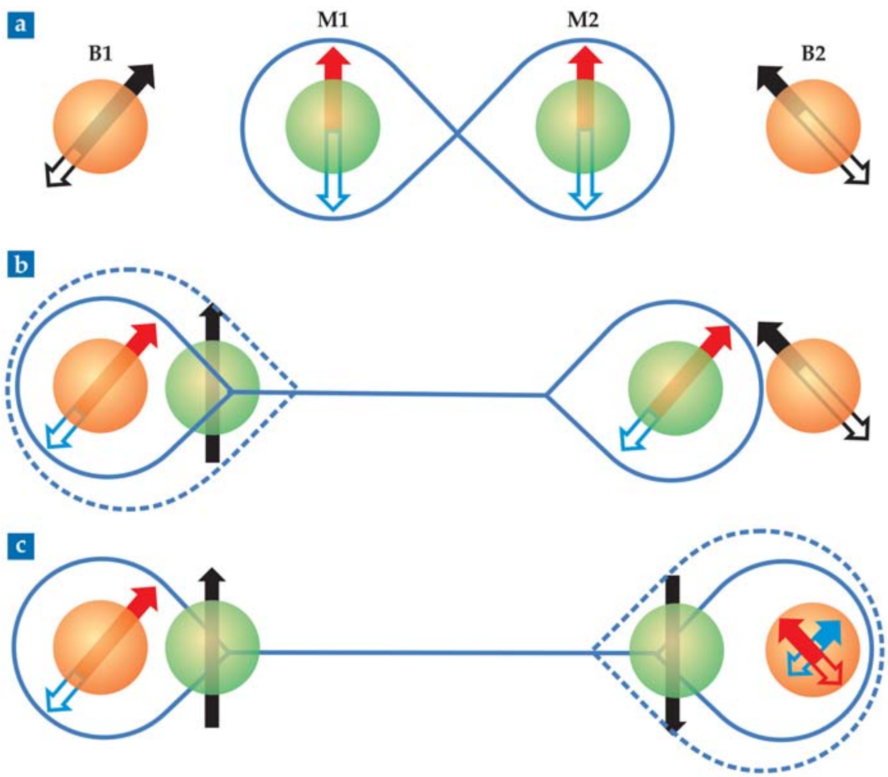

FIGURE 2. GATE TELEPORTATION BETWEEN TWO QUBITS, beryllium ions B1 and B2 (orange), requires messengers, magnesium ions M1 and M2 (green). **(a)** The messengers are prepared in an entangled state of spin-up and spin-down. B1 and B2 are each in a superposition of spin-up and spin-down and are too far apart to interact directly. **(b)** A local CNOT operation brings B1 into the entangled state, and a measurement on M1 removes it from the entangled state. **(c)** A similar process on B2 and M2 yields the desired CNOT gate operation between B1 and B2. (Courtesy of Dietrich Leibfried.)

Quantum computing platforms

Gate teleportation can be a test for the pros and cons of different quantum computing platforms—for example, architectures based on superconducting qubits or trapped-ion qubits. "Development of large-scale quantum computing is such a massive undertaking that devices will likely be a hybrid of different technologies," says Leibfried. "There probably won't be a single winner, and therefore, in this field it's crucial to advance multiple platforms."

The group's device needs improvement before the number of qubits can be increased significantly, but it is a major step toward the quantum charge-coupled device (QCCD), a proposed architecture for quantum computing using trapped ions. Presented in 1998, the QCCD houses many interconnected ion traps. Changing the voltages on its electrodes shuttles ions from trap to trap, and regions are set aside for memory storage or interaction with other ions. Overall, it is similar to the device used for gate teleportation but accommodates more qubits.

In the proposed QCCD, entangled pairs of ions for gate teleportation can be churned out in a dedicated part of the device, stockpiled in advance, split up, and shipped throughout the device. With messengers ready to go, gate operations would not need to wait for ion qubits to be moved together. The same entangled messenger states can teleport many different kinds of gates, and used messengers can be entangled again and redeployed.

Heather M. Hill

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