PHYSICS

A First Step Toward Wiring Up a Quantum Computer

By delivering precise laser pulses to two trapped beryllium ions, researchers have soldered a connection for quantum information

The technology of quantum computers has not quite gotten routine enough to obey Moore's Law—the much-cited principle that the number of transistors packed onto an ordinary or "classical" computer chip doubles every 18 months. But after 3 years, a team at the National Institute of Standards and Technology (NIST) has achieved an initial doubling, going from a single cold, trapped ion functioning as a "qubit"—the active element of a quantum computer—to two ions.

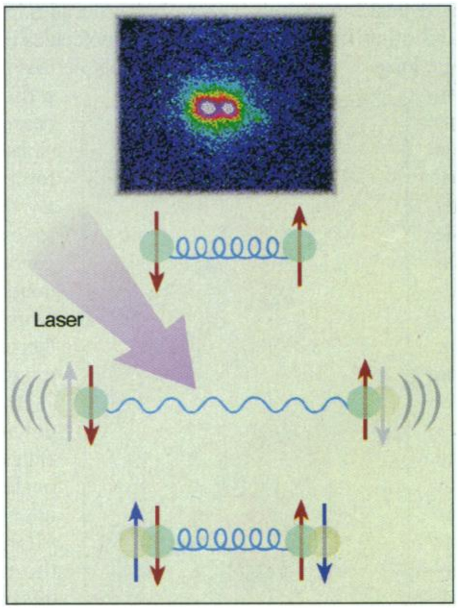
That's a bigger leap than it sounds. The math works differently in the quantum world: Just 40 qubits would make a computer that is more powerful, in some respects, than the very largest classical machines. Moreover, the step from one ion qubit to two is a critical one because it shows that qubits can be wired together through the ephemeral quantum-mechanical connection known as entanglement. The one-ion work, says Raymond Laflamme of Los Alamos National Laboratory in New Mexico, showed "that quantum computation is not crazy." But the new paper by NIST's Quentin Turchette and others in the 26 October issue of *Physical Review Letters* "is definitely a major step in the direction of building a quantum computer with an ion trap."

Although the quantum microworld promises undreamed-of power for computing, it also seems destined to tie language in knots. In the classical world, an object can be in only one position or orientation at a time, but an atom's position or quantum-mechanical "spin" can have several different values at once. Quantum mechanics allows all of those potential states to persist until the system is measured or disturbed, when it collapses into just one of the possibilities.

If an "up" spin represents 0 and a "down" spin 1, a single qubit can have two values at the same time. Two qubits, in turn, can store and compute with four different combinations of values, and the power of a quantum computer "rises exponentially in the number of qubits that it processes," says Gerard Milburn of the University of Queensland in Australia.

To perform a computation, the states of separate qubits have to be linked, or entangled. Entangled quantum states have values that depend on each other; an operation on one affects the other. In the past, entangling atoms or photons has been a hit-or-miss operation, although one quantum computing scheme—based on manipulating the spins of atomic nuclei in a liquid with pulses of radio-frequency (RF) energy—has already entangled the equivalent of several qubits to perform calculations (*Science*, 17 January 1997, p. 307).

Many researchers think thermal confusion will probably stop the liquid computer from ever going beyond seven or eight qubits, however. The best bet to reach 30 or 40 qubits first, most researchers agree, is a scheme whipped up in 1995 by Ignacio Cirac and Peter Zoller of the Institute for Theoretical Physics at the University of Innsbruck in Austria. The scheme relies on a row of chilled ions in a trap made of a combination of RF and static electric fields. The spins of the ions provide the qubits, and the row of ions can be nudged with lasers so that they rock back and forth like the sound waves in a flute, at discrete, quantized frequencies. Cirac and Zoller proposed that the motion could be used as a kind of wire to pass quantum information between ions, entangling them.



Altered states. By stimulating an accordionlike motion, a laser pulse "entangles" the possible spin states (arrows) of two trapped ions (top) into two independent relationships (blue and red).

A laser pulse of just the right frequency, Cirac and Zoller suggested, would set up resonances between the internal states and the rocking—in essence, encoding the rocking with the ions' internal quantum states to create links between the internal states of the ions. "So if you want some particular entangled state at some time, you can apply the appropriate laser pulses," says Turchette.

But transmitting quantum information along this "wire" requires a dexterity akin to walking a tightrope while balancing a teacup on one's nose: Slight perturbations from the outside world, called "decoherence," can stop the show cold. Three years ago, for example, Chris Monroe and David Wineland of NIST swapped quantum information between the internal states of a single ion and one of its rocking or "motional" states. This state was too susceptible to outside disturbances to serve as a quantum wire, however.

In the new work, Turchette teamed up with Monroe, Wineland, and five others to exploit a slightly different motional state, which arises when two or more ions share the trap. They enlisted the motion—a kind of stretching and shrinking—to entangle the spins of two beryllium ions into two distinct relationships that existed simultaneously until the spins were measured. In one, the spin of ion 1 was up and that of ion 2 was down. In the other, ion 1 was down and ion 2 was up.

Getting the ions entangled still required some clever tricks, as the team has not found a convenient way to focus separate laser beams on ions just micrometers apart. Instead, the team relied on spatial variations in the strength of the trap's RF waves to tune the interaction of the individual ions with the laser. Wherever the RF was more powerful, the ion jiggled more violently, reducing its interaction with the light. A separate electric field slid the ions slightly off-center in the trap to vary their interactions with the RF field so that the laser could put them into different spin states.

Finally, the team made a series of measurements to verify that the two relationships of spin states existed simultaneously. The NIST demonstration is "the first time anyone's been able to make 'entanglement on demand,'" says Richard Hughes of Los Alamos.

Next, the NIST team will try to address ions individually with lasers, rather than relying on the RF trick, which should let them entangle larger groups of ions. "There are a lot of technical things to deal with here," says Turchette. But theorists have been decidedly cheered by the first step in what could become a quantum Moore's Law. "The step from one [ion] to two has been really hard," says Zoller. "But once they have it, going from two or three up to five or 10 should be a much easier task."

–JAMES GLANZ

SOURCE: QUENTIN TURCHETTE