NIST demonstrates data 'repair kit' for quantum computers

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A practical method for automatically correcting data-handling errors in quantum computers has been developed and demonstrated by physicists at the National Institute of Standards and Technology.
Described in the Dec. 2, 2004, issue of the journal Nature, the NIST work is the first demonstration of all the steps of error correction for quantum computers, a futuristic, potentially very powerful form of computing that uses the quantum properties of atoms or other particles as 1s and 0s for processing data. The method was implemented using ions (electrically charged atoms) as quantum bits (qubits). Ions are arguably the leading candidate for use as qubits in a quantum computer.

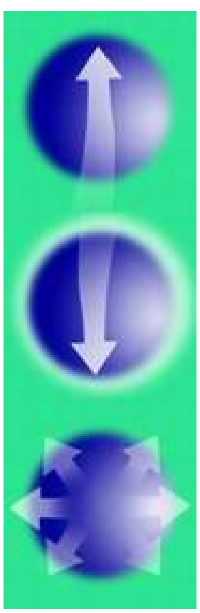

Image: An ion's quantum state can be spin up (top), spin down (middle) or a superposition state, represented graphically as any one of many possible spin directions in between up and down (bottom). Superposition states in which the spin is depicted as horizontal will be measured as spin up 50 percent of the time and spin down 50 percent of the time. Graphic credit: Kelly Talbott/NIST

Conventional computers use electronic switches that are either on or off to represent 1s and 0s that then can be stored or manipulated to make calculations. Quantum computing would use the quantum states of matter (such as magnetic properties) as 1s, 0s---or even both at once. The unusual features of the quantum world provide extra computational power, offering the prospect of carrying out a massive number of simultaneous calculations to solve problems that are impossible to solve today. Specific applications could include code-breaking of unprecedented power, faster database searching, fraud-proof digital signatures and optimization of everything from communications systems to airline schedules. But unless data-handling errors are corrected, "noise" caused by environmental disturbances, such as fluctuating magnetic fields associated with electrical equipment, could diminish any gains over today's computers.

The new NIST method helps to ensure the correctness of data during computations by creating redundant data sets, or what might be called quantum backup copies. "The basic concept is a familiar one: If someone doesn't understand what you say, you repeat it several times, and eventually they'll get it," explains physicist Dietrich Leibfried, who developed the approach and helped to demonstrate its feasibility in NIST's Boulder, Colo., laboratories.

Direct copying of qubits is prohibited by the rules of quantum mechanics, nature's instruction book for the smallest particles of matter. Like all known quantum error correction methods, the NIST method gets around this obstacle by exploiting a famously spooky (the term used by Einstein) feature of quantum mechanics that allows the "entanglement" of physically separated atoms to link their quantum properties in predictable ways. The atoms also are prepared in a special "superposition" state in which they represent both 1 and 0 at the same time.

The demonstration used three beryllium ions as qubits. One "primary" ion is entangled with two "helper" ions as part of a series of encoding steps. The primary qubit is essential to the computation; the other two are expendable. Because the three are entangled, errors in one affect the others, a condition that is reflected in the joint quantum state of all three qubits. If the quantum state of the primary qubit is accidentally changed, the mistake can be detected and corrected by reversing the steps to decode the data, and then measuring the values of the two extra qubits.

Unlike other demonstrations of quantum error correction, the NIST approach makes corrections based on actual measurements, allows qubits to be "reset" on the fly, and could be scaled up for use in quantum computers of practical size and utility. Previous demonstrations by other groups have involved correction of errors in qubits made of molecules in a liquid, without the ability to measure or reset and reuse the extra qubits needed to detect errors. The ability to "empty the trash bin," rather than simply storing mistakes somewhere in the computer, makes the NIST approach more practical.

The NIST error correction process could be incorporated into the programs executed by quantum computers. In principle, the approach could be used to maintain the fragile quantum states of ions or atoms by repeated error correction during data processing, an essential step toward scalable, reliable quantum computers. The same NIST research group previously demonstrated other essential components for a quantum computer based on atomic-ion traps.

Error correction is routine in today's computing and communications systems. For instance, a sender might periodically add up a series of sent bit values and transmit the total to the receiver. Once the same bits are received, the values are also summed at the receiver and the two totals are compared. If the totals match, there is a high probability that the bits arrived in the correct state. If the totals differ, then the data were corrupted, and the original bits are re-sent. This approach would fail in quantum information systems because measuring a qubit destroys its quantum state and effectively stops the computation. Therefore, errors need to be detected indirectly, as in the NIST method. It is not necessary to know the value of the primary qubit in order to detect an error and correct it.

To verify that the method works, NIST scientists performed many experiments with beryllium ion qubits and compared the corrected quantum states to the initial and uncorrected states. The instrumentation and procedures for manipulating qubits need to be improved to build reliable quantum computers, but such improvements seem feasible, Leibfried says. In addition, more ions and a more complex approach would be needed to correct all possible types of errors.

Source: NIST