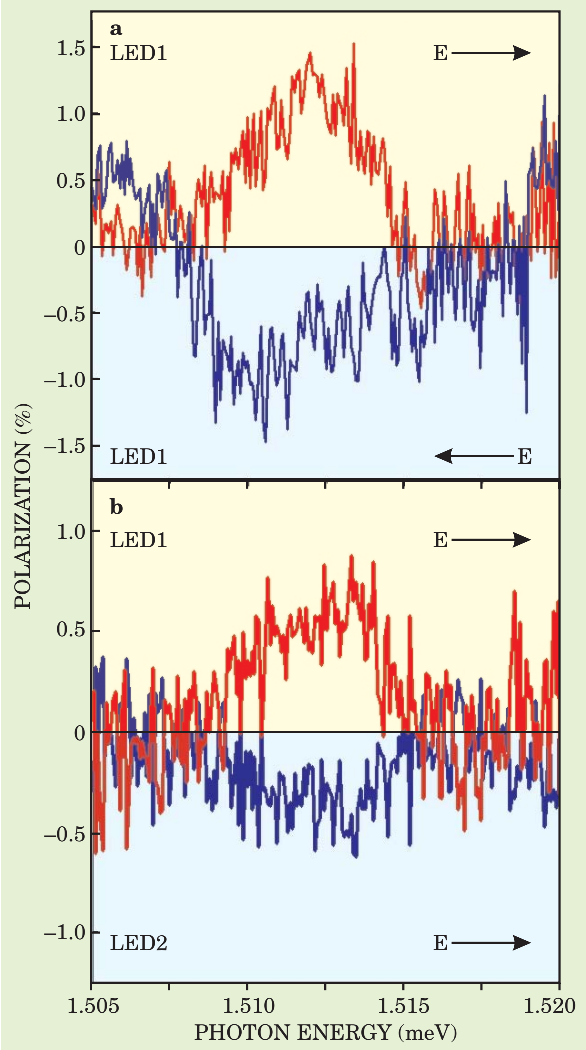

Figure 4. The light emitted by the Hitachi LEDs at a photon energy of 1.510 to 1.515 meV comes from the recombination of spin-polarized holes and electrons. The direction of the polarization reverses with the applied electric field **(a)** and is opposite at the two edges **(b)**. (Adapted from ref. 6.)

electrons, which occupy *p*-like states, have far stronger coupling than conduction band electrons, which occupy *s*-like states.

A further boost to the coupling comes from breaking the up–down symmetry of the lattice. Silicon has inversion symmetry, but GaAs does not. Confining the charge carriers in a thin layer with a strong electric field also breaks up–down symmetry and strengthens the coupling.

In the Santa Barbara experiment, the spins belong to conduction-band electrons whose spin–orbit coupling to the atoms of the GaAs lattice is weak despite the lack of inversion symmetry. Here, the spin Hall effect most likely originates extrinsically from skew scattering off impurities, rather than intrinsically from the GaAs lattice. The Santa Barbara team checked this hypothesis by repeating their experiment on a strained sample. If the effect originated in the lattice, then it should depend on the strain direction. It doesn't.

The charge carriers in the Hitachi experiment are holes whose already strong coupling to the GaAs lattice is increased by their confinement in a narrow layer. Having measured the impurity concentration in their sample, the Hitachi researchers believe it to be too low to account for the polarization they observe. The spin Hall effect in their sample is, they believe, intrinsic in origin.

The controversy surrounding the intrinsic effect doesn't stem from the effect itself, but from what happens when impurities are present. When the electric field is switched on, the spins polarize and head off to different edges of the strip. In the absence of impurities, the electrons would continue to accelerate down the strip, but in a real, impurity-ridden lattice, the electrons must decelerate to stabilize the current, either by scattering off impurities or by slamming against the sample boundary. And when the electrons decelerate, the intrinsic effect reverses direction and could, in principle, cancel itself out.

In some models, the steady acceleration caused by the field doesn't necessarily cancel the abrupt deceleration that occurs when electrons slam head-on into a few sparsely distributed impurities. But in other models, the cancellation is exact and, in some cases, originates from the lattice as well as impurities.

Even the notion of a spin current is somewhat problematic. As an electron travels through the bulk to reach the edge, its charge remains the same. But its spin, thanks to spin–orbit coupling, is not conserved. Relating spin accumulation observed at the edges to a spin current through the bulk is not straightforward.

Sankar Das Sarma of the University of Maryland in College Park has been closely following the controversy as its unfolds. "The theoretical situation is a complete mess," he says.

Charles Day

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Quantum Error Correction Demonstrated with Trapped Ions

For the first time, this necessary part of a quantum computation scheme is implemented in a system that can be scaled up.

These days it's easy to take information technology for granted: Our computers will do what they're programmed to do, the files we download will be intact, and compact discs and DVDs will deliver perfect sound and pictures. That trust is rooted in the pervasiveness of error correction: Errors inevitably creep in, through noisy transmission lines or scratches on CDs, but redundant coding of information and error-correcting procedures minimize the effect of errors on downloading pictures or on our enjoyment of Bach cantatas.

Quantum information is even more susceptible to errors than its classical counterpart. A qubit's coherent superposition of states, which underlies the potential power of quantum computers, is fragile and can be lost due to unwanted coupling to the environment. Through careful engineering, such decoherence can be reduced, but errors will always creep into a computation at a finite rate. Thus there will come a time in a quantum computation after which the results are unreliable.

Ten years ago, Peter Shor (then at Bell Labs, Lucent Technologies) and Andrew Steane (University of Oxford) showed that it is possible to protect quantum computations from error.[1] By entangling qubits with other, auxiliary qubits (called ancillae), one can detect and correct for individual errors (see the article by John Preskill in PHYSICS TODAY, June 1999, page 24). Although still vulnerable to concurrent errors, quantum error correction can increase the reliability of computations. It is viewed as an integral requirement for quantum computers.

John Chiaverini, Dietrich Leibfried, and colleagues in David Wineland's group at NIST in Boulder, Colorado, have now demonstrated quantum error correction using trapped beryllium-9 ions.[2] The viability of quantum error-correction procedures has previously been demonstrated in liquid-state nuclear magnetic resonance experiments.[3] Such systems, however, contain a limited number of qubits and can't be scaled up to the tens of qubits at which a quantum computer can outperform the largest classical computer. In addition, the ancilla qubits in NMR experiments need to be prepared in advance and can be used only once. Trapped-ion systems, in contrast, have the potential for scalable architectures (see the article by Ignacio Cirac and Peter Zoller in PHYSICS TODAY, March 2004, page 38), and the ancillae can be reset and recycled for use in multiple calculation steps.

Protecting against spin flips

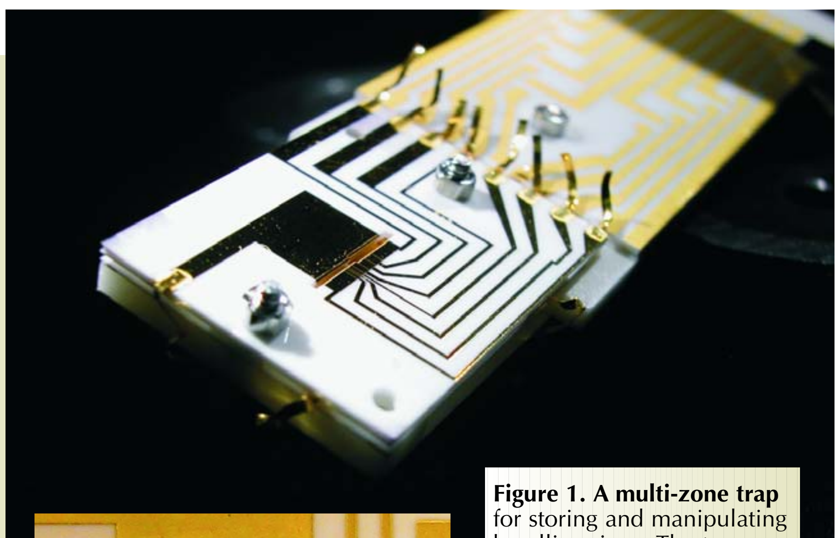
Making copies of classical bits is a straightforward way to protect classical information against errors, but quantum bits can't be cloned. Instead, quantum error-correction protocols protect information by encoding it in an entangled state with ancilla qubits. In addition to the principal qubits and the quantum operations required for the calculation, further qubits and processing steps are needed to implement the error correction. The goal is to achieve an acceptable error rate with a reasonable amount of overhead.

For the experiment, the NIST team used three ^{9}Be ions: one for the principal qubit whose quantum state was to be protected, and two for ancilla qubits. The qubits' states were two of the ions' ground-state hyperfine levels, denoted $|\downarrow\rangle$ and $|\uparrow\rangle$ in analogy to a spin-$\frac{1}{2}$ particle. The ions were loaded into a trap like that shown in figure 1. The linear trap contained several zones; by varying the voltages applied to the different trap electrodes, the experimenters could shuttle ions between the zones, separate the ions, and bring them back together as needed for the various steps in their quantum error-correction protocol. By carefully positioning the ions in the trap and using appropriately focused, tuned, and timed lasers, the NIST team could manipulate the qubits collectively or individually.

The NIST protocol was designed to detect and rectify one particular type of error: spin flips, in which any of the three qubits, after encoding, was flipped from a superposition $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$ to $\beta|\uparrow\rangle + \alpha|\downarrow\rangle$. (To protect against both spin flips and the other type of error, phase flips, in which $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$ gets changed to $\alpha|\uparrow\rangle - \beta|\downarrow\rangle$, a minimum of five qubits are needed.)

Each experimental run comprised several steps. The team first prepared the principal qubit in the quantum state to be protected. After encoding that state into an entangled superposition of all three qubits, they introduced errors by rotating the qubits in spin-space. The rotation angle θ_E represents the magnitude of the error. They then decoded the entangled state back to the principal qubit. At that point, the ancillae contained information on whether a spin-flip error had occurred. By measuring the fluorescence from the ancilla ions—a projection measurement that forces the ancillae into definite spin states and yields classical information about which qubit, if any, was flipped—the researchers could make the necessary corrections to the principal qubit.

The NIST team relied on a three-qubit phase gate, an extension of their earlier two-qubit phase gate (see PHYSICS TODAY, May 2003, page 17), as the main step in the encoding and decoding stages. Two lasers, slightly detuned from each other, were shone briefly on the ions. If the ions were all in the same spin state, the lasers had no effect. But if they were in different states, the lasers excited the center-of-mass vibrational state in the trap and forced the ions to slosh back and forth. By the time the lasers were turned off, the ions had picked up a geometrical phase that was adjusted to be exactly π. By impressing a phase that's conditional on the qubits' states, this three-qubit gate allowed the team to entangle the principal and



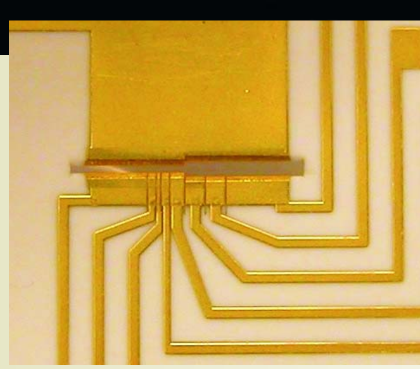


Figure 1. A multi-zone trap for storing and manipulating beryllium ions. The trap was made from two stacked, gold-plated alumina wafers; the ions are confined in the space between the wafers and between the opposing control electrodes. The inset shows the electrodes that can be used to shuttle the ions between different zones along the trap. (Photos courtesy of NIST.)

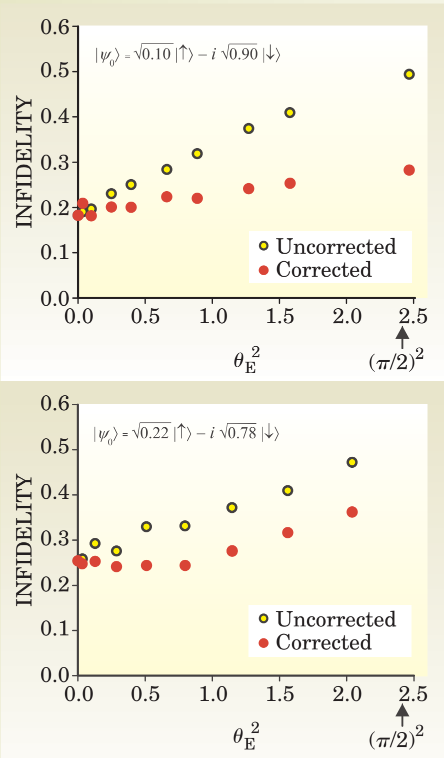


Figure 2. Quantum error correction can protect the fidelity of quantum information. Shown here are the results for qubits prepared in two different initial superpositions of spin-up $|\uparrow\rangle$ and spin-down $|\downarrow\rangle$. In each case, the qubit—either by itself or with error correction—was rotated by an angle θ_E and then read. For small values of θ_E, the probability of a spin flip, or infidelity, was linear in θ_E^2 without error correction. With error correction, the infidelity was quadratic in θ_E^2 for small θ_E. The state preparation, encoding, and decoding steps introduced a chance of a spin flip even with no rotation. (Adapted from ref. 2.)

ancilla qubits in a single operation.

The NIST protocol should protect an initial quantum state against individual spin-flip errors, but it is still vulnerable to multiple spin flips. Figure 2 shows the effectiveness of the NIST procedure for protecting two different initial states of the principal qubit. The various steps in the procedure weren't perfect, and they contributed about a 20% chance of a spin flip even in the absence of an applied error. But as expected, the error correction reduced the infidelity—the likelihood of observing a flipped qubit—from a linear dependence on θ_E^2 to a quadratic dependence, for small θ_E^2. And for a certain range of θ_E, the protocol helped to protect the principal qubit even from the preparation, encoding, and decoding infidelities.

Scalable quantum computers

An important result to come out of quantum information theory is the accuracy-threshold theorem, which states that if the error rate is below some threshold value, any calculation can be performed with any desired accuracy using a reasonable amount of resources—an amount that scales polynomially instead of exponentially with the size of the calculation. What that threshold value is for trapped-ion systems isn't known, but the NIST researchers acknowledge that their fidelity isn't high enough yet. "To get higher fidelity, we need to solve some tough engineering problems," says Leibfried, "but we don't see any fundamental complications." Still, says Raymond Laflamme of Canada's Institute for Quantum Computation, "This is an important step toward demonstrating that we can control quantum systems at will."

The report of error correction follows demonstrations, by the NIST team and by Rainer Blatt's group at the University of Innsbruck, of another important technique for quantum information processing with trapped ions: the teleportation of a quantum state from one ion to another.[4] Much work still needs to be done, but trapped ion systems appear to be edging closer to scalable quantum computation.

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