



QUANTUM COMPUTING WITH IONS

Researchers are taking the first steps toward building ultrapowerful computers that use individual atoms to perform calculations

By Christopher R. Monroe and David J. Wineland

KEY CONCEPTS

- Quantum computers can store and process data using atoms, photons or fabricated microstructures. These machines may someday be able to perform feats of computing once thought to be impossible.
- The manipulation of trapped ions is at the forefront of the quantum computing effort. Researchers can store data on the ions and transfer information from one ion to another.
- Scientists see no fundamental obstacles to the development of trapped-ion computers.

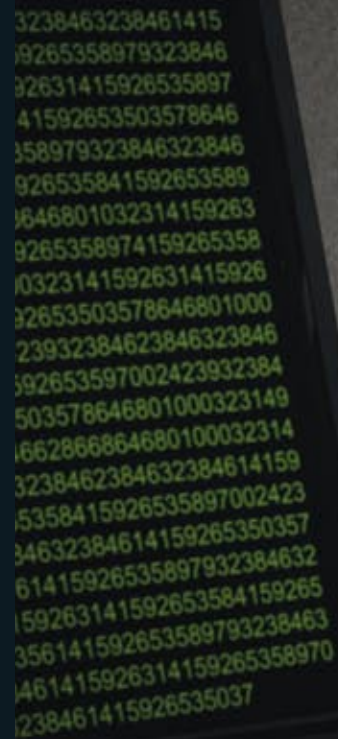
—The Editors

Over the past several decades technological advances have dramatically boosted the speed and reliability of computers. Modern computer chips pack almost a billion transistors in a mere square inch of silicon, and in the future computer elements will shrink even more, approaching the size of individual molecules. At this level and smaller, computers may begin to look fundamentally different because their workings will be governed by quantum mechanics, the physical laws that explain the behavior of atoms and subatomic particles. The great promise of quantum computers is that they may be able to perform certain crucial tasks considerably faster than conventional computers can.

Perhaps the best known of these tasks is factoring a large number that is the product of two

primes. Multiplying two primes is a simple job for computers, even if the numbers are hundreds of digits long, but the reverse process—deriving the prime factors—is so extraordinarily difficult that it has become the basis for nearly all forms of data encryption in use today, from Internet commerce to the transmission of state secrets. In 1994 Peter Shor, then at Bell Laboratories, showed that a quantum computer, in theory, could crack these encryption codes easily because it could factor numbers exponentially faster than any known classical algorithm could. And, in 1997, Lov K. Grover, also at Bell Labs, showed that a quantum computer could significantly increase the speed of searching an unsorted database—say, finding a name in a phone book when you have only the person’s phone number.

Actually building a quantum computer, how-





DAVID ENMITE (computer setup); GEORGE RETSECK (spheres)

ever, will not be easy. The quantum hardware—the atoms, photons or fabricated microstructures that store the data in quantum bits, or qubits—needs to satisfy conflicting requirements. The qubits must be sufficiently isolated from their surroundings; otherwise stray external interactions will halt their computations. This destructive process, known as decoherence, is the bane of quantum computers. But the qubits also have to interact strongly with one another and must ultimately be measured accurately to display the results of their calculations.

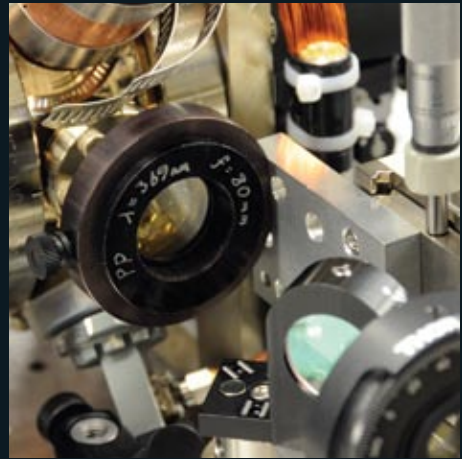
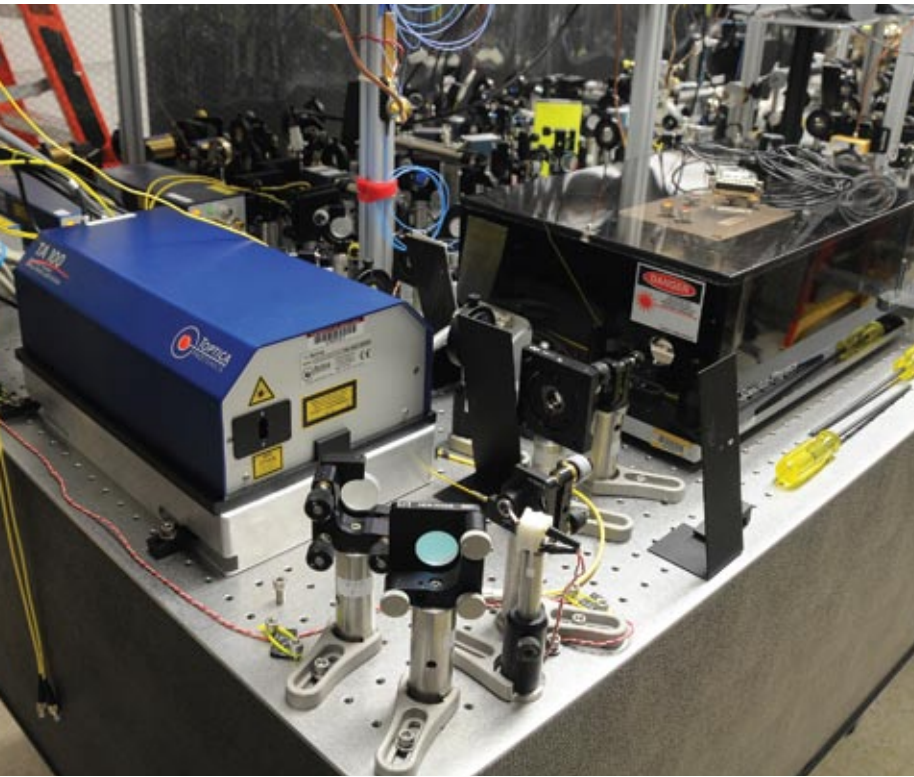
Scientists around the globe are pursuing several approaches to building the first prototype quantum computers. Our own research focuses on processing information with singly charged positive ions, atoms that have been stripped of one electron. We have trapped short strings of

ions—confining the particles in a vacuum using electric fields produced by nearby electrodes—so that they can receive input signals from a laser and share data with one another. Our goal is to develop quantum computers that are scalable—that is, systems in which the number of qubits could be increased to the hundreds or thousands. Such systems would fulfill the promise of the technology by accomplishing complex processing tasks that no ordinary computer could match.

Trapping Ions

Quantum mechanics is a theory based on waves. Just as the sound waves from two or more piano strings can merge into a chord, different quantum states can be combined into a superposition. For example, an atom may be simultaneously in two locations or in two different states of excitation.

TRAPPED-ION COMPUTERS could encode and process data with strings of ions that act somewhat like the suspended metal balls in a Newton's cradle (as seen in this artist's conception). The ions interact through oscillatory motions. Researchers can manipulate the particles by training laser beams on them.



TABLETOP EXPERIMENTS have shown the feasibility of quantum information processing. Researchers use lasers (blue device in photograph at left) to generate beams that are shunted by mirrors across the table to the apparatus containing the trapped ion (above). The laser cools the ion, draining away its kinetic energy so that investigators can easily manipulate it.

When a quantum particle in a superposition state is measured, the conventional interpretation is that the state collapses to a single result, with the probability of each possible measurement given by the relative proportions of the waves in the superposition [see box below]. The potential power of a quantum computer derives from these superpositions: unlike a conventional digital bit, which can have a value of either 0 or 1, a qubit can be both 0 and 1 at the same time. A system with two qubits can hold four values simultaneously—00, 01, 10 and 11. In general, a quantum computer with N qubits can simultaneously manipulate 2^N numbers; a collection of only 300 atoms, each storing a quantum bit, could hold more values than the number of particles in the universe!

These larger quantum superpositions are usually entangled, meaning that the measurements of the individual qubits will be correlated. Quantum entanglement can be thought of as an invisible wiring between particles that cannot be replicated in classical physics, a wiring that Einstein called “spooky action at a distance.” In our trapped-ion experiments, for example, each electrically levitated ion behaves like a microscopic bar magnet; the qubit states of 1 and 0 can correspond to two possible orientations of each atomic magnet (say, up and down). Laser cooling, which drains kinetic energy from atoms by scattering photons, brings the ions almost to rest within the trap. Because the ions reside in a vacuum chamber, they are isolated from the

[THE AUTHORS]

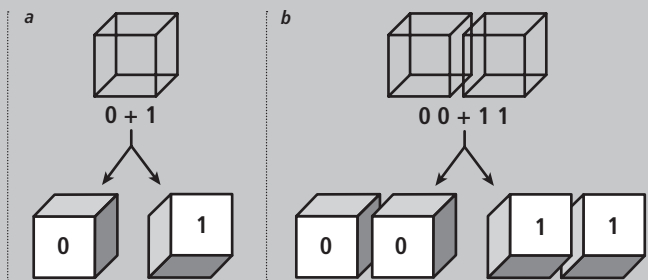


Christopher R. Monroe (left) is Bice Sechi-Zorn Professor of Physics at the University of Maryland and Fellow of the Joint Quantum Institute at Maryland and the National Institute of Standards and Technology (NIST). Monroe specializes in the electromagnetic trapping, laser cooling and quantum control of atoms and ions. **David J. Wineland** (right), who received his B.A. from the University of California, Berkeley, in 1965 and his Ph.D. from Harvard University in 1970, is leader of the Ion-Storage Group in NIST’s Time and Frequency Division in Boulder, Colo. The group has focused on laser cooling and spectroscopy of trapped atomic ions.

[ENTANGLEMENT]

SPOOKY ACTION AT A DISTANCE

The “ambiguous cube” (a) is like an ion in a superposition state—a measurement of the ion will lock it into one of two definite states (0 or 1). When two ions are in an entangled superposition (b), a measurement will force both ions into the same state (either 0 or 1) even though there is no physical connection between them.



JOINT QUANTUM INSTITUTE (optical tables); JENS ZORN (Monroe); EDIE DEWEESE (Wineland); JEN CHRISTIANSEN (illustrations). SOURCE: TAKING THE QUANTUM LEAP, BY FRED ALAN WOLF (bottom)

[BASICS]

TRUTH TABLE

A trapped-ion computer would rely on logic gates such as the controlled not (CNOT) gate, which consists of two ions, *A* and *B*. This truth table shows that if *A* (the control bit) has a value of 0, the gate leaves *B* unchanged. But if *A* is 1, the gate flips *B*, changing its value from 0 to 1, and vice versa. And if *A* is in a superposition state (0 and 1 at the same time), the gate puts the two ions in an entangled superposition. (Their state is now identical to the one shown in the box on the bottom of the opposite page.)

<i>A</i>	<i>B</i>	→	<i>A'</i>	<i>B'</i>
0	0	→	0	0
0	1	→	0	1
1	0	→	1	1
1	1	→	1	0
0 + 1		→	00 + 11	

environment, yet the electric repulsion among them provides a strong interaction for producing entanglement. And laser beams thinner than a human hair can be targeted on individual atoms to manipulate and measure the data stored in the qubits.

Over the past few years scientists have performed many of the proof-of-principle experiments in quantum computing with trapped ions. Researchers have produced entangled states of up to eight qubits and have shown that these rudimentary computers can run simple algorithms. It appears straightforward (though technically very challenging) to scale up the trapped-ion approach to much larger numbers of qubits. Taking the lead from classical computers, this effort would involve sequencing a few types of quantum logic gates, each made up of only a few trapped ions. Scientists could adapt conventional error-correction techniques to the quantum world by using multiple ions to encode each qubit. Here the redundant encoding of information allows the system to tolerate errors, as long as they occur at a sufficiently low rate. In the end, a useful trapped-ion quantum computer would most likely entail the storage and manipulation of at least thousands of ions, trapped in complex arrays of electrodes on microscopic chips.

The first requirement for making a “universal” quantum computer—one that can perform all possible computations—is reliable memory. If we put a qubit in a superposition state of 0 and 1, with the ion’s magnetic orientation pointing up and down at the same time, it must remain in that state until the data are processed or measured. Researchers have long known that ions held in electromagnetic traps can act as very good qubit memory registers, with superposition lifetimes (also known as coherence times) exceeding 10 minutes. These relatively long lifetimes result from the extremely weak interaction between an ion and its surroundings.

The second essential ingredient for quantum computing is the ability to manipulate a single qubit. If the qubits are based on the magnetic orientation of a trapped ion, researchers can use oscillating magnetic fields, applied for a specified duration, to flip a qubit (changing it from 0 to 1, and vice versa) or to put it in a superposition state. Given the small distances between the trapped ions—typically a few millionths of a meter—it is difficult to localize the oscillating fields to an individual ion, which is important because we will often want to change one qubit’s orientation without changing that of its neigh-

POWERS OF TWO

The enormous potential of trapped-ion computers lies in the fact that a system with *N* ions can hold 2^N numbers simultaneously. And as *N* increases, the value of 2^N rises exponentially.

$$2^5 = 32$$

$$2^{10} = 1,024$$

$$2^{50} = 1,125,899,906,842,624$$

$$2^{100} = 1,267,650,600,228,229,401,496,703,205,376$$

bors. We can solve this problem, however, by using laser beams that are focused on the particular qubit (or qubits) of interest.

The third basic requirement is the ability to devise at least one type of logic gate between qubits. It can take the same form as classical logic gates—the AND and OR gates that are the building blocks of conventional processors—but it must also act on the superposition states unique to qubits. A popular choice for a two-qubit logic gate is called a controlled not (CNOT) gate. Let us call the qubit inputs *A* and *B*. *A* is the control bit. If the value of *A* is 0, the CNOT gate leaves *B* unchanged; if *A* is 1, the gate flips *B*, changing its value from 0 to 1, and vice versa [see box above]. This gate is also called a conditional logic gate, because the action taken on qubit input *B* (whether the bit is flipped or not) depends on the condition of qubit input *A*.

To make a conditional logic gate between two ion qubits, we require a coupling between them—in other words, we need them to talk to each other. Because both qubits are positively charged, their motion is strongly coupled electrically through a phenomenon known as mutual coulomb repulsion. In 1995 Juan Ignacio Cirac and Peter Zoller, both then at the University of Innsbruck in Austria, proposed a way to use this coulomb interaction to couple indirectly

the internal states of the two ion qubits and realize a CNOT gate. A brief explanation of a variant on their gate goes as follows.

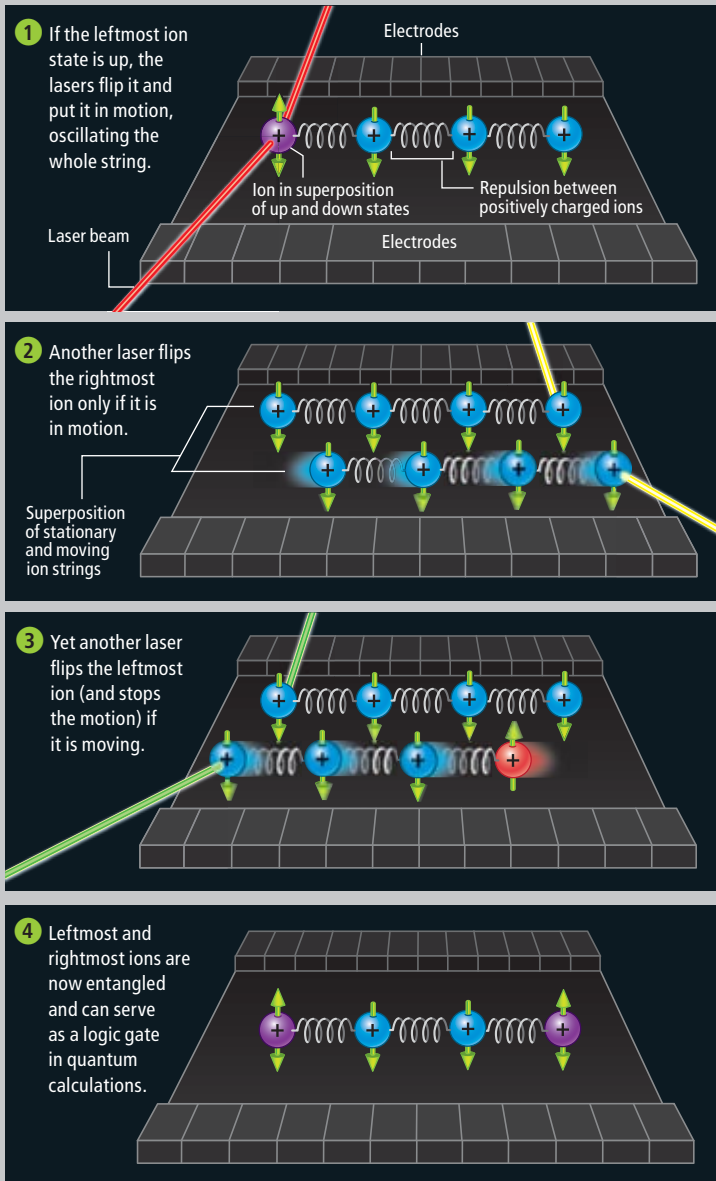
First, think about two marbles in a bowl. Assume that the marbles are charged and repel each other. Both marbles want to settle at the bottom of the bowl, but the coulomb repulsion

causes them to come to rest on opposite sides, each a bit up the slope. In this state, the marbles would tend to move in tandem: they could, for instance, oscillate back and forth in the bowl along their direction of alignment while preserving the separation distance between them. A pair of qubits in an ion trap would also experience

[ONE APPROACH]

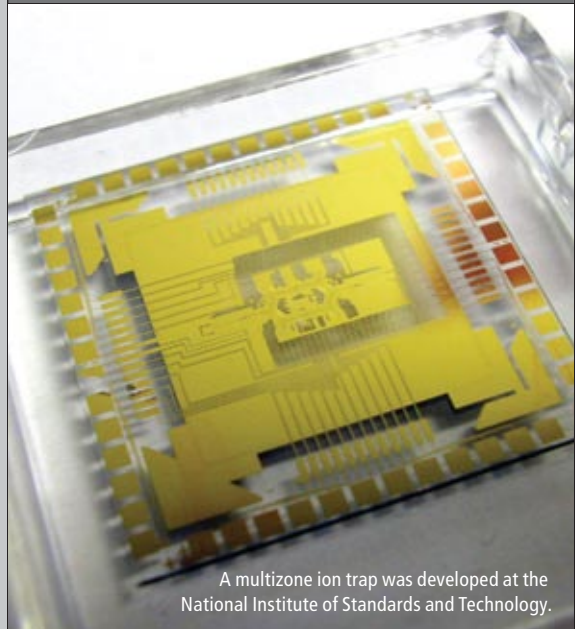
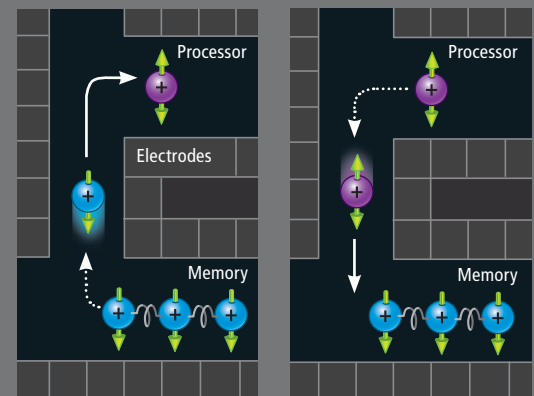
ION STRINGS

One method for building a trapped-ion computer is to connect the ions through their common motions. A string of ions is electrically levitated between two arrays of electrodes. Because the positively charged particles repel one another, any oscillatory motions imparted to one ion (say, by a laser) will move the whole string. Lasers can also flip the ions' magnetic orientations, which encode the data carried by the string—an up orientation can correspond to 1, and down can represent 0.



THE FUTURE

Scaling this system up to larger numbers of ions presents difficulties, however. It appears that longer strings—those containing more than about 20 ions—would be nearly impossible to control because their many collective modes of common motion would interfere with one another. So scientists have begun to develop gridlike traps in which ions can be moved from a string in the system's memory, say, to another string where data are being processed. The quantum entanglement of the ions allows data to be transferred from one zone of the trap to another.



JEN CHRISTIANSEN (illustrations); JASON AMINI/NIST (ion trap)

this common motion, jiggling back and forth like two pendulum weights connected by a spring. Researchers can excite the common motion by applying photon pressure from a laser beam modulated at the natural oscillation frequency of the trap [see box on opposite page].

More important, the laser beam can be made to affect the ion only if its magnetic orientation is up, which here corresponds to a qubit value of 1. What is more, these microscopic bar magnets rotate their orientation while they are oscillating in space, and the amount of rotation depends on whether one or both of the ions are in the 1 state. The net result is that if we apply a specific laser force to the ions for a carefully adjusted duration, we can create a CNOT gate. When the qubits are initialized in superposition states, the action of this gate entangles the ions, making it a fundamental operation for the construction of an arbitrary quantum computation among many ions.

Researchers at several laboratories—including groups at the University of Innsbruck, the University of Michigan at Ann Arbor, the National Institute of Standards and Technology (NIST) and the University of Oxford—have demonstrated working CNOT gates. Of course, none of the gates works perfectly, because they are limited by such things as laser-intensity fluctuations and noisy ambient electric fields, which compromise the integrity of the ions' laser-excited motions. Currently researchers can make a two-qubit gate that operates with a “fidelity” of slightly above 99 percent, meaning that the probability of the gate operating in error is less than 1 percent. But a useful quantum computer may need to achieve a fidelity of about 99.99 percent for error-correction techniques to work properly. One of the main tasks of all trapped-ion research groups is to reduce the background noise enough to reach these goals, and although this effort will be daunting, nothing fundamental stands in the way of its achievement.

Ion Highways

But can researchers really make a full-fledged quantum computer out of trapped ions? Unfortunately, it appears that longer strings of ions—those containing more than about 20 qubits—would be nearly impossible to control because their many collective modes of common motion would interfere with one another. So scientists have begun to explore the idea of dividing the quantum hardware into manageable chunks, performing calculations with short chains of ions that could be shuttled from place to place

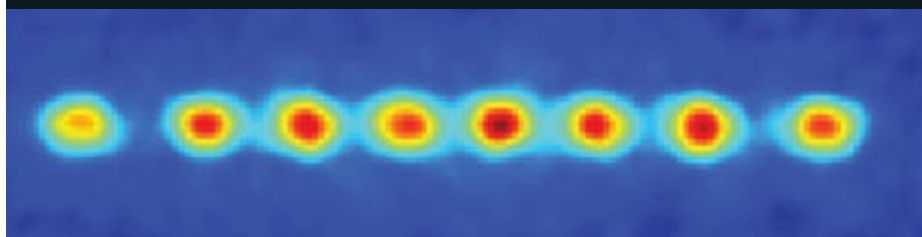
Quantum information science offers an opportunity to radically change computing. Scientists may finally realize their dream of creating a quantum machine that can tackle tasks once thought impossible.

on the quantum computer chip. Electric forces can move the ion strings without disturbing their internal states, hence preserving the data they carry. And researchers could entangle one string with another to transfer data and perform processing tasks that require the action of many logic gates. The resulting architecture would somewhat resemble the familiar charge-coupled device (CCD) used in digital cameras; just as a CCD can move electric charge across an array of capacitors, a quantum chip could propel strings of individual ions through a grid of linear traps.

Many of the trapped-ion experiments at NIST have involved shuttling ions through a multi-zone linear trap. Extending this idea to much larger systems, however, will require more sophisticated structures with a multitude of electrodes that could guide the ions in any direction. The electrodes would have to be very small—in the range of 10 to 100 millionths of a meter—to confine and control the ion-shuttling procedure precisely. Fortunately, the builders of trapped-ion quantum computers can take advantage of microfabrication techniques, such as microelectromechanical systems (MEMS) and semiconductor lithography, that are already used to construct conventional computer chips.

Over the past year several research groups have demonstrated the first integrated ion traps. Scientists at the University of Michigan and the Laboratory for Physical Sciences at the University of Maryland employed a gallium arsenide semiconductor structure for their quantum chip. Investigators at NIST developed a new ion-trap geometry in which the ions float above a chip's surface. Groups at Alcatel-Lucent and Sandia National Laboratories have fabricated even fancier ion traps on silicon chips. Much work remains to be done on these chip traps. The atomic noise emanating from nearby surfaces must be reduced, perhaps by cooling the electrodes with liquid nitrogen or liquid helium. And researchers must skillfully choreograph the movement of ions across the chip to avoid heating the particles and

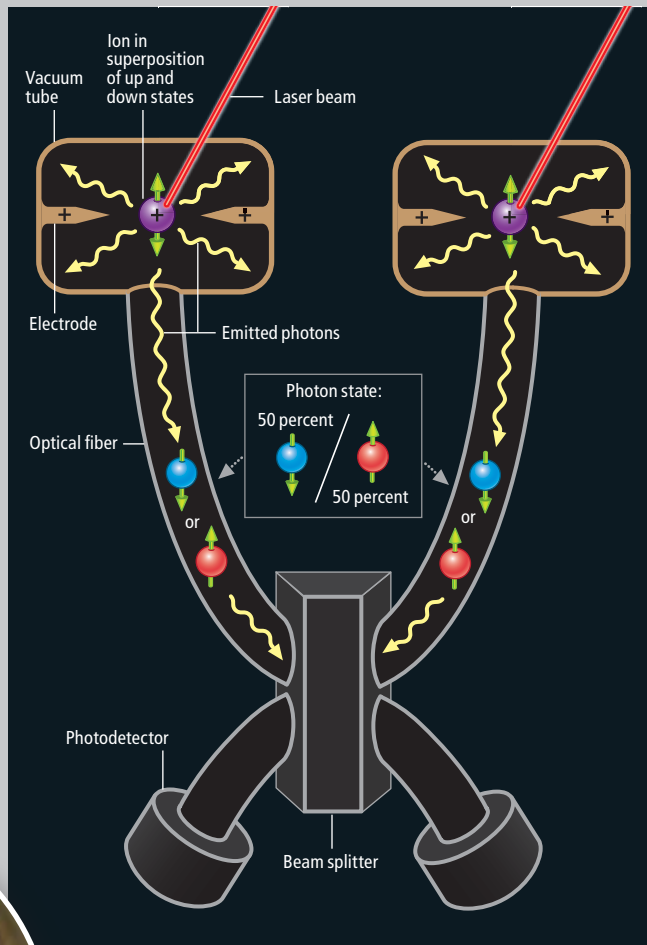
LEVITATED STRING of eight calcium ions are confined in a vacuum chamber and laser-cooled to be nearly at rest. Such a string can perform quantum calculations.



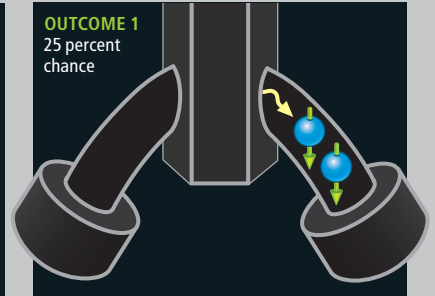
[ANOTHER METHOD]

LINKING IONS WITH PHOTONS

An alternative approach to trapped-ion computing is to link the ions using the photons they emit. Two remotely located trapped ions (purple), each isolated in a vacuum tube (photograph below), are excited with laser pulses and emit photons into optical fibers. The frequencies of the photons depend on the magnetic orientation of the ions; a photon emitted by an ion in a 50–50 superposition state—half up, half down—would be in a superposition of frequencies (half red and half blue in this example). If the photons from the two ions are in the same state, the beam splitter will shunt both to one photodetector. But if the photons are in different states, they will travel to separate detectors. Once that happens, the ions are entangled, because researchers cannot tell which ion has emitted which photon.



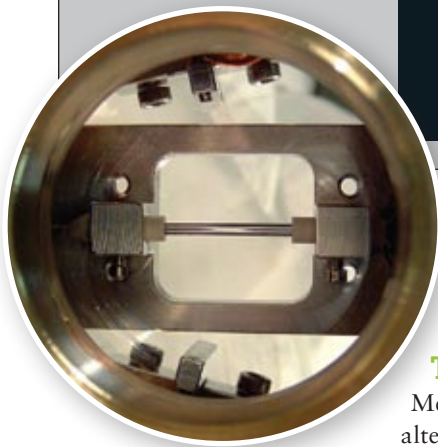
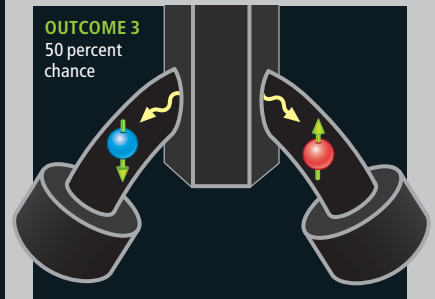
OUTCOME 1
25 percent chance



OUTCOME 2
25 percent chance



OUTCOME 3
50 percent chance



disturbing their positions. For example, the shuttling of ions around a simple corner in a T junction requires the careful synchronization of electric forces.

The Photon Connection

Meanwhile other scientists are pursuing an alternative way to build quantum computers from trapped ions, and this approach may circumvent some of the difficulties in controlling the motion of the ions. Instead of coupling the ions through their oscillatory motions, these researchers are using photons to link the qubits. In a scheme based on ideas described in 2001 by Cirac, Zoller and their colleagues Luming Duan of the University of Michigan and Mikhail Lukin of Harvard University, photons are emitted from each trapped ion so that the attributes of the photons—such as polarization or color—become entangled with the internal, magnetic qubit states of the ion emitter. The photons then

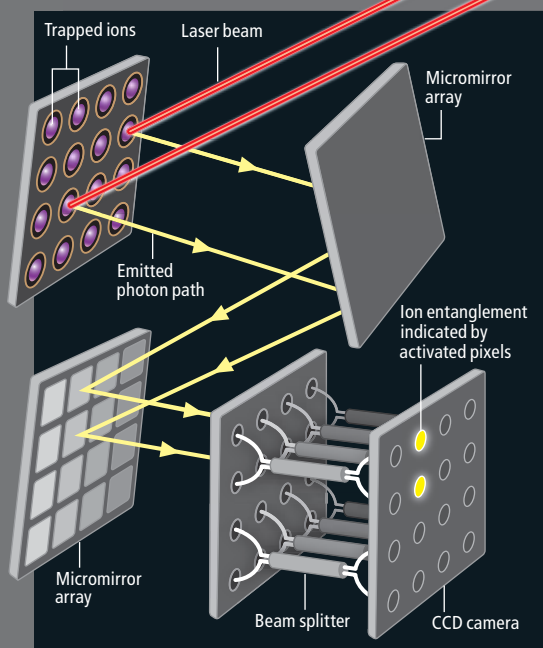
travel down optical fibers to a beam splitter, a device typically used to split a light beam in two. In this setup, however, the beam splitter works in reverse: the photons approach the device from opposite sides, and if the particles have the same polarization and color, they interfere with each other and can emerge only along the same path. But if the photons have different polarizations or colors—indicating that the trapped ions are in different qubit states—the particles can follow separate paths to a pair of detectors [see box above]. The important point here is that after the photons are detected, it is not possible to tell which ion has emitted which photon, and this quantum phenomenon produces entanglement between the ions.

The emitted photons, though, are not successfully collected or detected in every attempt. In fact, the vast majority of the time the photons are lost and the ions are not entangled. But it is still possible to recover from this type of error

JEN CHRISTIANSEN (Illustrations); STEVEN OLMSCHEK/Joint Quantum Institute and University of Maryland (Ion trap)

THE FUTURE

Researchers are excited about the photon-linking approach because it offers a relatively easy way to connect large numbers of ions. Laser beams could be directed at an array of trapped ions, and the emitted photons could travel to a bank of beam splitters. A charge-coupled device (CCD) camera could easily detect when any two ions become entangled, and each entanglement would increase the processing power of the trapped-ion computer.



by repeating the process and simply waiting for photons to be simultaneously counted on the detectors. Once this occurs, even though the ions may be widely separated, the manipulation of one of the qubits will affect the other, allowing the construction of a CNOT logic gate.

Scientists at the University of Michigan and the University of Maryland have successfully entangled two trapped-ion qubits, separated by about one meter, using the interference of their emitted photons. The main obstacle in such experiments is the low rate of entanglement generation; the likelihood of capturing these single photons into a fiber is so small that ions are entangled only a few times per minute. That rate could be increased dramatically by surrounding each ion with highly reflective mirrors in a so-called optical cavity, which would greatly improve the coupling of the ion emission with the optical fibers, but this enhancement is currently very difficult to accomplish experimental-

ly. Nevertheless, as long as the interference eventually occurs, researchers can still use the system for quantum information processing. (The procedure is comparable to getting cable TV installed in a new house: although it may take many phone calls to get the service provider to install the system, eventually the cable is hooked up, and you can watch TV.)

Furthermore, investigators can expand the quantum gate operations to large numbers of qubits by connecting additional ion emitters by optical fiber and repeating the procedure until more entangled links are established. It should also be possible to use both photon coupling and the motional coupling discussed earlier to connect several small clusters of trapped ions over remote or even global distances. This is exactly the idea behind a “quantum repeater,” in which small quantum computers are networked at periodic distances to maintain a qubit as it travels over hundreds of kilometers. Without such a system the data would usually be lost forever.

The Quantum Future

Scientists are still far from constructing a quantum computer that can take on the daunting challenges—such as factoring very large numbers—that have stymied conventional machines. Still, some features of quantum information processing are already finding uses in the real world. For example, several of the simple logic operations required for two-qubit gates can be employed in atomic clocks, which keep time based on the frequency of the radiation emitted when atoms transition between quantum states. And researchers can apply the techniques for entangling trapped ions to increase the sensitivity of measurements in spectroscopy, the analysis of the light emitted by excited atoms.

The field of quantum information science promises to radically change the rules of computing. Collections of trapped ions are at the forefront of this effort because they offer a level of isolation from the environment that is currently unmatched in most other physical systems. At the same time, through the use of lasers, researchers can readily prepare and measure entangled quantum superpositions devised with small numbers of ions. In the coming years, we look forward to a new generation of trapped-ion chips that may pave the way for quantum computers with much larger numbers of qubits. Then scientists may finally realize their dream of creating a quantum machine that can tackle Herculean tasks once thought to be impossible. ■

THE SMALL FRONTIER

Building a computer with single atoms as the memory elements is, in a sense, a natural limit of computer miniaturization. But as physicist Richard Feynman stated in his 1959 lecture entitled “There’s Plenty of Room at the Bottom”:

When we get to the very, very small world—say circuits of seven atoms—we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics.

MORE TO EXPLORE

Quantum Information Processing with Atoms and Photons.

Christopher R. Monroe in *Nature*, Vol. 416, No. 6877, pages 238–246; March 14, 2002.

Rules for a Complex Quantum World.

Michael A. Nielsen in *Scientific American*, Vol. 287, No. 5, pages 66–75; November 2002.

The Limits of Quantum Computers.

Scott Aaronson in *Scientific American*, Vol. 298, No. 3, pages 62–69; March 2008.

More information about trapped-ion computing is available at tf.nist.gov/timefreq/ion, www.jqi.umd.edu and www.iontrap.umd.edu