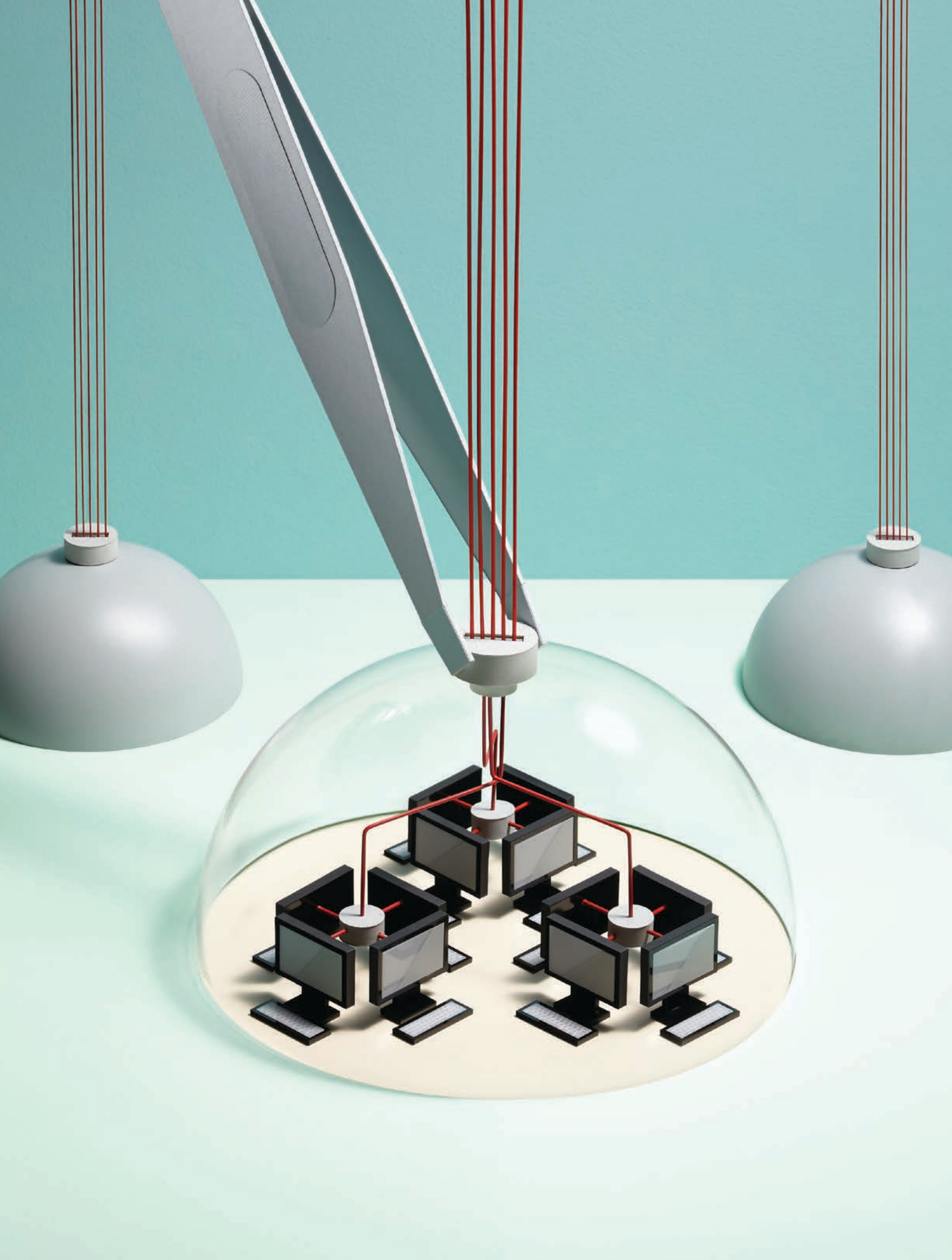
TECHNOLOGY

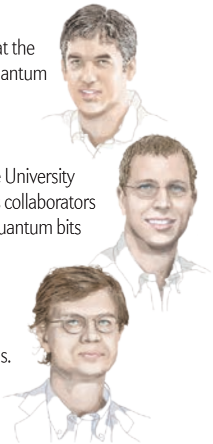
QUANTUM CONNECTIONS

Scientists are trying to make quantum computers a reality by connecting many small networks together into one large whole

By Christopher R. Monroe, Robert J. Schoelkopf and Mikhail D. Lukin

Illustration by Kyle Bean





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FOR THE PAST TWO DECADES SCIENTISTS HAVE BEEN ATTEMPTING TO HARNESS THE peculiarities of the microscopic quantum world to achieve leaps in information processing and communication ability. By exploiting several features of physics at the universe's smallest scales—that electrons are both particles and waves, that an object can be in many places at once and that two particles can maintain an eerie instantaneous connection even when separated by vast distances—quantum machines could make previously unthinkable computing, communication and measurement tasks trivial. To cite just one example, a quantum computer should be able to break "unbreakable" codes.

At the same time, quantum machines can be used for storing and communicating information such that privacy is guaranteed by the laws of physics. They can also be used to simulate processes in complex chemical and materials systems that would otherwise be intractable. And quantum systems could boost the precision of the world's most accurate timekeepers—atomic clocks—and serve as miniature precision sensors that measure the properties of chemical and biological systems at the atomic or molecular scale, with applications ranging from biology and materials science to medicine.

This potential is why technology behemoths such as Google and Intel, several start-up companies, and defense and other government agencies are betting big on the field. The academic community is also inspired: in 2015 alone, three major journals published more than 3,000 scientific papers mentioning "quantum computing" or "quantum information."

The problem is that scientists have not yet been able to build a large-scale quantum machine that realizes this promise. The challenge is that such a computer must, by definition, operate in the quantum realm, and yet when we try to build one large enough to be useful, its natural tendency is to start obeying the classical rules of the macroscopic realm.

Building a system that maintains quantum rules on a large scale and exercises the full power of quantum information processing will likely require a modular approach, where smaller, demonstrably quantum units are connected in a way that does not kill their quantum nature. Recent work has taken this so-called modular approach beyond the theoretical realm to successful tests on small scales and is paving the way for realizing the unique potential of quantum machines.

PROBABLY ZEROES AND POSSIBLY ONES

THE FIRST SUGGESTION that the quantum world could be exploited to build advanced computers came in the early 1980s from phys-

IN BRIEF

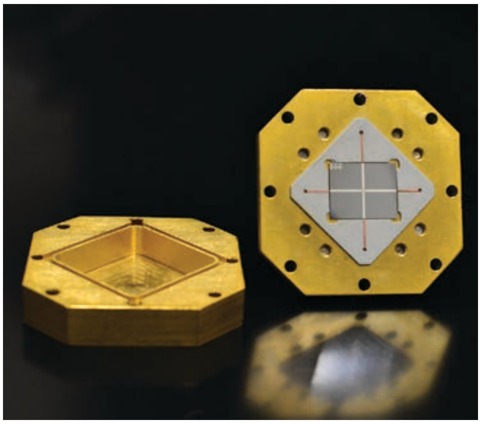
Scientists struggle to build quantum computers big enough to be useful because large collections of particles typically stop behaving quantum mechanically and start obeying classical laws.

The solution, researchers are realizing, is to construct many small quantum computers and link them together through minimal connections that do not disturb their quantum properties—an approach called modular quantum computing.

Several modular methods relying on different types of quantum bits, or qubits, have recently proved successful in small tests and could soon be scaled up into larger systems.

icists and mathematicians such as Richard Feynman of the California Institute of Technology and David Deutsch of the University of Oxford. The idea remained speculative for many years until 1994, when Peter Shor, then at AT&T Bell Laboratories, showed how a quantum computer could be used to quickly factor large numbers, igniting interest in the field. The first basic quantum computers arrived in the late 1990s and early 2000s, when researchers built simple systems consisting of several "bits" made of atoms, molecules or photons.

It is the special nature of quantum particles that can give quantum computing an advantage over its classical counterpart. Unlike classical computing, where the basic unit of information (the bit) takes a definite value of 1 or 0, the quantum unit of information, the qubit, can exist in two states at once, meaning it can represent 0 *and* 1 simultaneously. Or it can be probably 0 but possibly 1. Or equally likely to be 0 or 1. Or any other weighted combination of the two binary states. The qubit has this power because quantum particles can exist in two locations or physical states at once—a phenomenon known as superposition.


QUANTUM DEVICE: A circuit for measuring superconducting qubits is housed in a gold-plated box. These measurements can entangle qubits in separate clusters, or "modules," allowing modules to connect to form a unified quantum computer.

COURTESY OF MICHEL H. DEVORET *Yale University*

Beyond existing in two states simultaneously, qubits can be connected through a quantum property called entanglement: the ability of particles separated in space to retain a connection so that an action performed on one reverberates on the other. This property gives quantum computers a massive parallel processing ability. When a set of qubits is entangled, a simple operation on one can affect all the other qubit states. Even with just a few qubits, all those mutually dependent 0s, 1s and other superposition states create a hugely complex range of possible outcomes. Whereas a classical computer can handle only one possibility at a time, a quantum computer can effectively test all possible solutions to a problem simultaneously. Just a few hundred qubits can calculate a tableau of outcomes that exceeds the number of particles in the universe.

So far scientists have created small quantum-computing systems in many laboratories that use up to 10 qubits. But as we add qubits, it becomes ever more difficult to shield the system from the outside world—and any such interference dooms the very properties that make a quantum computer special. A quantum superposition of multiple states can exist only in isolation. Any attempt to prematurely observe or measure it will force a particle to collapse into a single state—to choose one possibility. At this point, quantum mechanics is out, and the qubits revert to the conventional bits of classical computers. In other words, the special abilities of quantum objects are typically seen only in very small systems and break down when those objects become fully connected to a larger whole—similar to the way an indie musical group might appeal most strongly to its fans when few people know of it. Large systems are usually too complex and insufficiently isolated to behave quantum mechanically—after all, we do not expect to find a baseball, or even a biological cell, in two places at the same time.

MODULAR QUANTUM SYSTEMS

THE CHALLENGE BECOMES scaling up without losing the necessary quantumness. A brute-force approach to creating a large quantum system by simply adding and wiring together qubits in one network will likely fail. This prediction is buttressed by the fate of machines developed by Canada-based company D-Wave Systems that have hundreds or thousands of individual qubits wired together. Although company officials maintain that these devices beat the calculation speeds of classical algorithms, we have found no published data that show evidence of large-scale entanglement or any speed advantage in these systems.

The modular technique, however, offers another path forward. This solution is akin to the strategy that commercial airlines exploit to manage complexity. Next time you fly, check the back of your in-flight magazine. The carrier's route map gives a rough sense of what a full-scale quantum computer might look like. Airlines do not directly connect every city with every other one, because the logistics and overhead would be prohibitive. Instead they use central hubs to create networks of indirect connections. Sacrificing direct connectivity allows them to grow and manage a much larger network of destinations.

Similarly, a modular quantum computer would not connect every qubit to every other one. Instead it would use a few qubits as hubs that would connect separate modules, akin to the way Atlanta serves as a hub connecting the southeastern U.S. to other regions.

Modular networks help to keep the number of interactions among qubits manageable while allowing each module to remain shielded from external interference. They compensate for sacrifices in direct connectivity by allowing thousands or even millions of qubits to collaborate indirectly. But unlike conventional modular systems such as multicore computer processors, which use the same type of wires between cores as those within cores, modular quantum systems may require two or more different types of linkage to achieve the necessary entanglement while maintaining isolation between the modules. Three leading modular quantum strategies, using different types of qubits, have emerged over the past decade. The three of us are independently developing these platforms, and we believe they will usher in larger quantum computers that will enable new kinds of information processing.

ATOMIC QUBITS

THE MOST NATURAL TYPE of qubit is a single atom whose electronic or nuclear energy levels (sometimes called spin states) store quantum information. Atomic qubits are fundamentally scalable because multiple atoms of the same species are virtually identical and do not need to be engineered to match. Laser beams can cool the atoms until they are nearly at rest, chilling them by transferring momentum from the atom to scattered laser light. We do all this while suspending the atoms in free space in a vacuum chamber to prevent them from interacting with anything else.

Either neutral or charged atoms (ions) can serve as qubits. To confine neutral atomic qubits, we use focused laser beams or a crisscrossed pattern of laser beams called an optical lattice; dozens of research groups throughout the world are pursuing such methods. Although it is difficult to control and couple neutral atoms at the single-qubit level, there are many promising paths forward.

As an alternative, many groups use positively charged ions—atoms with an electron removed. Ions interact strongly with one

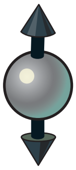
STRATEGIES

Three Ways to Build a Quantum Computer

Computers that capitalize on the bizarre laws of quantum mechanics could theoretically perform calculations that are impossible for classical computers. Yet the larger a quantum computer gets, the more difficult it becomes to preserve its quantum properties (*below*). Scientists think the solution is to build many small quantum computers and link them together into a larger whole—a strategy called modular quantum computing. The boxes at the right show three potential modular setups using three different types of quantum bits, or qubits.

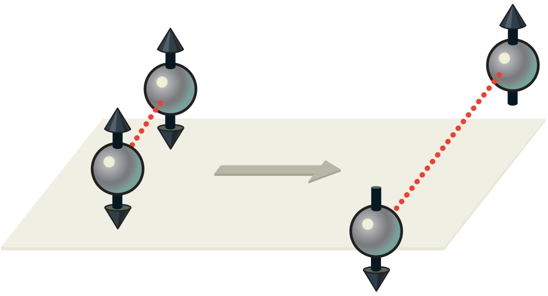
Quantum Property 1: Superposition

Atoms and subatomic particles can exist in multiple states and even multiple locations simultaneously—a state called superposition. Whereas a classical object, such as a marble, can spin in only one direction at a time, particles can be in two "spin states"—both spin up and spin down, for example—at once. By exploiting this property, quantum computers could test many possible solutions to a problem simultaneously.



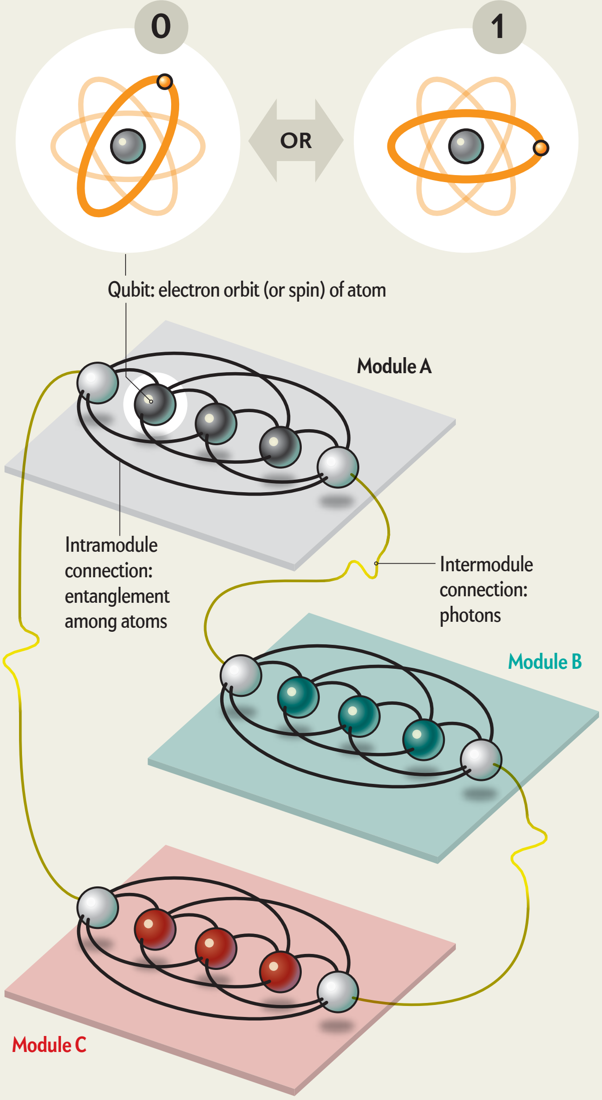
Quantum Property 2: Entanglement

Albert Einstein called it "spooky action at a distance": entanglement allows two particles to forge an instantaneous connection such that an action performed on one of them affects the other, even when they are separated in space. In the picture below, the entangled particles start out in a superposition of both up and down spin states. When an outside measurement forces the particles to "pick" a single state, the two will always pick coordinated states. Depending on the type of entanglement, if the first particle is in the spin up state, the second will always be in spin down. When multiple qubits are entangled, an operation performed on one will affect all the others instantaneously, allowing for unprecedented parallel processing.



Atomic Ion Qubits

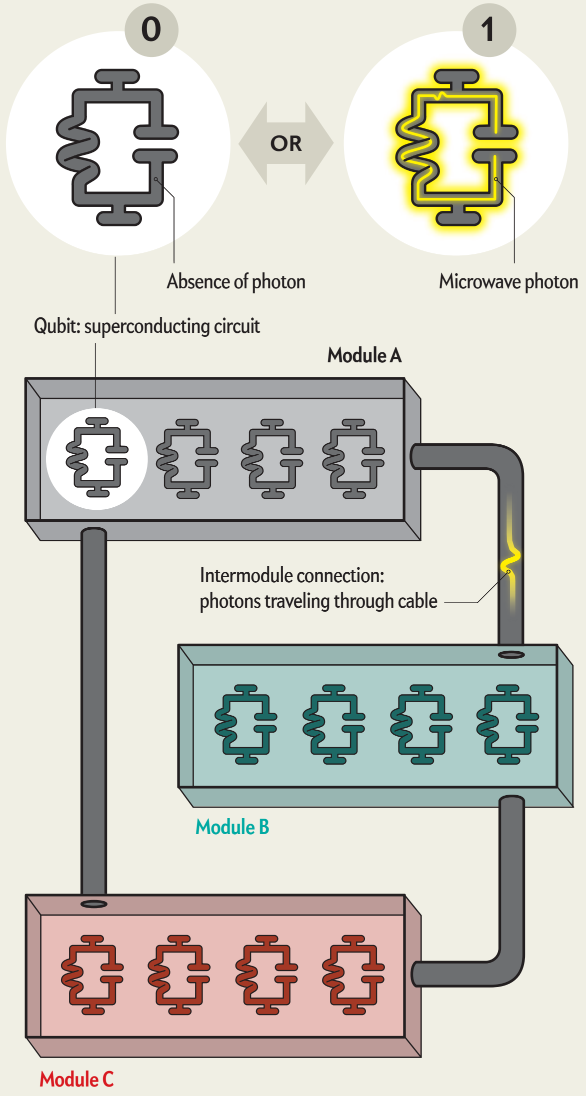
The simplest way to build a modular quantum computer is to use single atoms as qubits. Each atom can represent the binary code values of 0 or 1 (or a superposition of the two) via different electronic orbits (*top*). At the bottom is a schematic of three modules—mini quantum computers made of five atomic ions each—connected in a way that preserves each module's quantum properties. Within each module, all five ions are entangled with one another. The two end ions (*in white*) are special and can emit photons to communicate with other modules.



another through their electrical repulsion and can be confined with electromagnetic fields generated by nearby electrodes. We can laser-cool hundreds of trapped ions to form a stationary crystal of individual atoms that act like identical pendulums connected by springs. Additional control lasers can push the ions around in a way that can entangle their spin states through the vibrations of the ions, in a scheme first proposed in 1995 by Ignacio Cirac and Peter Zoller, both then at the University of Innsbruck in Austria. In the past couple of decades researchers have made astounding progress in the control and entanglement of individual trapped-ion qubits in this way. Lately groups led by one of us (Monroe), David J. Wineland of the National Institute of Standards and Technology, and Rainer Blatt of the University of Innsbruck have demonstrated high-quality entangle-

Superconducting Qubits

Another modular quantum-computing strategy uses "artificial atoms" made of superconducting circuits as qubits. These qubits are electrical circuits that can take on a value of 0 or 1 through the absence or presence of a microwave photon or an oscillating electric current running through the circuit. (When the qubit is in a state of superposition, the photon may be both "there" and "not there.") Within each module, qubits can be entangled directly with one another via trapped photons. These photons can also be sent through cables to link each module to the others.



Solid-State Spin Qubits

A third option is to make qubits out of defects in a solid-state material, such as a diamond lattice of carbon atoms. If one of the carbon atoms in the lattice is replaced by a nitrogen atom and a neighboring site is empty, the impurity is known as a nitrogen-vacancy (NV) center. The NV center and the surrounding carbon atom neighbors all become qubits, and their spin states represent 0s and 1s. Each cluster of impurities in the diamond lattice is an independent module, and modules can connect to other modules via entangled optical photons.

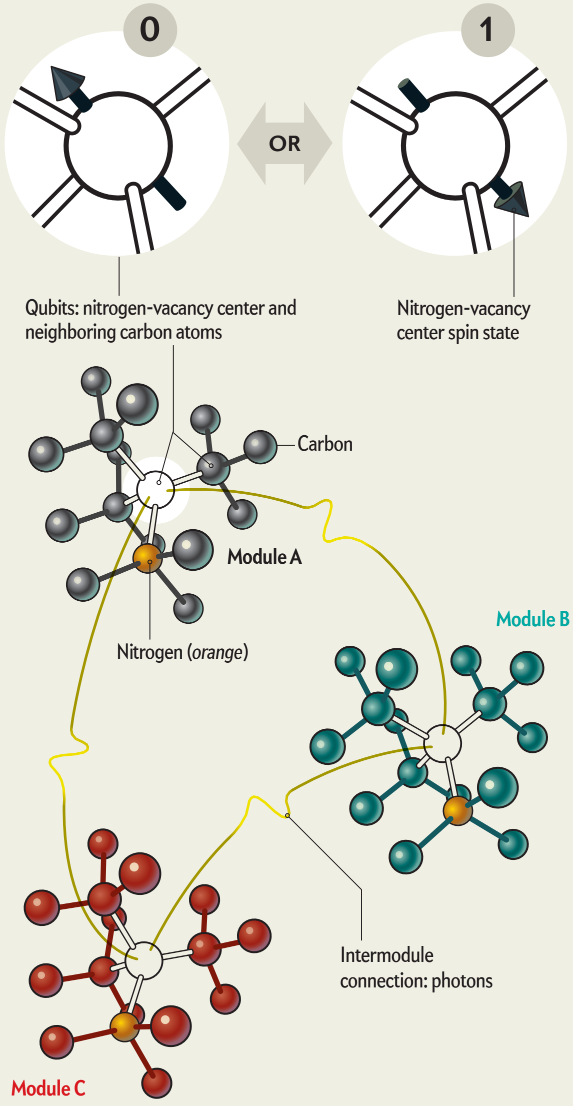
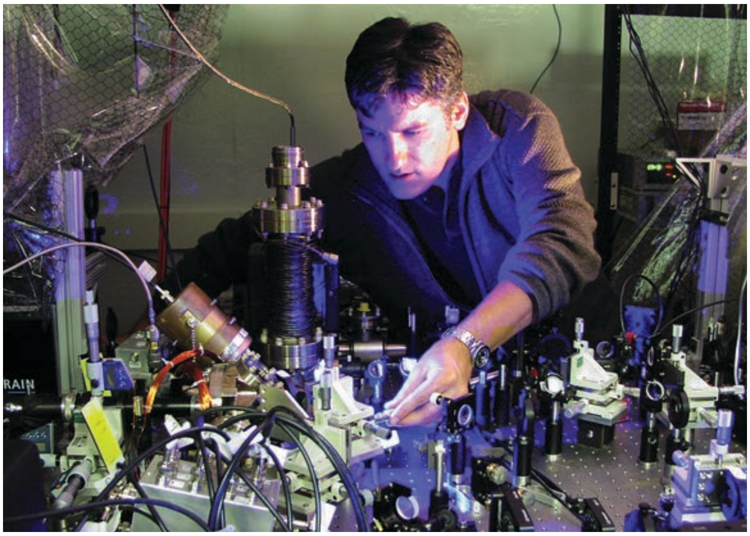


Illustration by Jen Christiansen

ment operations among up to 20 trapped-ion qubits.

Researchers have explored two ways to connect modules made of such entangled ion crystals. One is to physically move a few of the ion qubits through space, from one module to another, by passing them through a complex maze of electrodes (a method proposed in 2000 by Monroe, along with Wineland and David Kielpinski, then at NIST). The ions can be made to surf through space on an electrical field wave without disturbing their qubit state. When the ions touch down at the second module, laser pulses can induce them to form new entanglements. The two modules, each containing, say, 50 qubits, become part of a single set for computation, meaning that now 100 qubits are working together, albeit with a weak link. There is no theoretical limit to the number of modules that we can connect via this technique, which is called ion shuttling.

A difficulty with this method is controlling the complex ion traps, which consist of hundreds or thousands of precisely positioned electrodes that accomplish the shuttling. We must be able to manipulate all of the required electrode voltages to induce the ions to surf through the maze of electrodes. Notable efforts to fabricate ion-trap electrodes from silicon or other semiconductor materials in a scalable fashion are now coming from Sandia National Laboratories and Honeywell International.



LAB WORK: Author Christopher R. Monroe manipulates atomic ion qubits with lasers and confines them in a trap made of electromagnetic fields generated by electrodes.

COURTESY OF KATHERINE MONROE

The second method of connecting ion qubit modules together leaves the atoms in place. It relies on lasers to prompt ions to emit photons (particles of light) that are entangled with the ions. These photons can then transfer the entanglement between modules. This type of photonic quantum interface stems from ideas pioneered almost 20 years ago by researchers at the University of Innsbruck, Caltech and Harvard University and demonstrated 10 years ago by Monroe.

The photonic connection technique has the great advantage of allowing us to link qubit memories that may be far apart, and it can also be applied to other types of qubits, such as neutral atoms and superconducting and semiconductor qubits, as we will discuss. Moreover, we can scale up the photonic connection between modules through fiber-optic networks and switches that can allow us to reconfigure which qubits get entangled. The central hurdle for this strategy is that the qubit-photon link is typically inefficient because it requires capturing and guiding these photons. Many trials may be necessary to establish a successful connection. The best attempts so far have operated only at a rate of up to about 10 entangled links a second. Extensions of current technology, however, should be able to push this rate up by many orders of magnitude.

SUPERCONDUCTING QUBITS

ALTHOUGH ATOMS may be nature's qubits, controlling and scaling them to more complex systems poses several engineering challenges. An alternative strategy is to devise "artificial atoms" using circuits made of superconducting material. These devices contain many atoms but can behave as simple, controllable qubits, where the presence or absence of a single microwave photon or the clockwise/counterclockwise direction of a circulating current inside the circuit corresponds to the "0" or "1" states. Such quantum circuits have distinct advantages. We can tailor their properties by design and mass-produce them with the fabrication techniques of conventional integrated circuits. And remarkably, when they operate at temperatures near absolute zero, they can persist in a superposition state for long enough to serve as a robust qubit. During the past 15 years the lifetimes of these systems have improved more than a millionfold.

In the past decade work on these superconducting quantum circuits has made rapid progress, demonstrating the various necessary features for a quantum computer. Researchers at many academic labs as well as industrial players such as Google and IBM can now manipulate and entangle several superconducting qubits. With techniques called circuit quantum electrodynamics, pioneered by one of us (Schoelkopf), together with his colleagues Michel H. Devoret and Steve Girvin, both at Yale University, we can also entangle multiple qubits over long ranges by using superconducting transmission lines.

Superconducting devices lend themselves naturally to a modular architecture. We can make connections among modules within a large cryogenic device via superconducting wires and measurement devices while reducing the cross talk and interference among modules by shielding them from one another. To generate the entanglement among modules, researchers at Yale, JILA at the University of Colorado Boulder, the University of California, Berkeley, and elsewhere have developed special superconducting devices for quantum measurement.

The modular approach with superconducting qubits has a number of appealing features. Instead of building and testing one gigantic circuit, we need only mass-produce and calibrate the more modest modules and then build complexity module by module. We can eliminate or skip over defective modules and rewire the connections among modules to create different architectures. Work is also under way to develop microwave-to-optical quantum transducers and then connect distant modules via optical fiber to create long-range quantum networks or a distributed quantum computer.

SOLID-STATE SPIN QUBITS

FINALLY, A THIRD TYPE of qubit encodes information in spin states within solid-state materials. There are different models for this type of qubit, but a promising method, pursued by one of us (Lukin), as well as numerous other groups, uses defects in crystals to generate qubits. One such system is a diamond lattice of carbon atoms in which a single atom is replaced by nitrogen and a neighboring site is empty—an impurity known as a nitrogen-vacancy (NV) center. Electromagnetic pulses can control the electronic spin of this atomlike impurity. In a method pioneered by Lukin and his colleagues, the NV center reacts to the nuclear spins of its closest carbon neighbors, creating a cluster of neighboring qubits formed from the magnetic interactions among the particles. A nitrogen-vacancy impurity, though, has only so many close carbon neighbors, limiting the total number of qubits per module to fewer than a dozen.

Scaling up requires connecting multiple NV modules. If the qubits are in separate crystal lattices, we can link them by forcing each qubit to emit a photon and then meausuring the photons. But if multiple NV impurities reside within a single diamond lattice, we can also try to connect them using quantum vibrations called phonons, which can transport quantum information between impurities.

Remarkably, although manipulating information encoded in these NV center qubits is challenging, we can often do it under ambient conditions at room temperature. Techniques to observe single NV centers, pioneered in the past decade by Jörg Wrachtrup of the University of Stuttgart in Germany and Fedor Jelezko, now at the University of Ulm in Germany, have allowed scientists to work with individual electronic spin qubits. A team led by David Awschalom of the University of Chicago has been able to manipulate these qubits on nanosecond timescales, comparable to the speed of modern classical processors.

Recently Ronald Hanson and his colleagues at Delft University of Technology in the Netherlands have entangled single-NV-impurity qubits separated by more than one kilometer using entangled photons, similar to the photonic method of connecting ions discussed earlier. Currently this process is not very efficient (in the Delft experiments, the entanglement links are established at a rate of only a few times per hour), but new techniques to greatly improve it using nanoscale optical devices have recently emerged at Harvard and the Massachusetts Institute of Technology. And because we already have the means to create several qubits around a single diamond-lattice defect and store them for longer than a second in ultrapure crystals such as those grown by scientists at Element Six, NV centers show great potential for a scalable modular quantum-computing architecture.

QUANTUM FUTURE

AS A RESULT of more than 20 years of research and development in this field, scientists have experimentally tested all these modular quantum-computing approaches on small scales. The task awaiting us is to expand these techniques to larger conglomerations of qubits and modules and to start using them for interesting applications. We believe this goal is now within sight.

The quantum future is both challenging and exciting. As quantum machines grow larger, it will become increasingly difficult to both control and verify that the overall system is indeed behaving quantum mechanically. Luckily, the modular architecture allows us to test and validate individual modules and the various connections among them independently, without disturbing the entire system. Scientists have recently taken important steps toward this goal.

And even modular quantum computers of relatively modest scale may enable unique applications. They naturally provide the backbone for a "quantum Internet" composed of small quantum processors that are connected via entangled optical photons. These can serve as repeater stations that extend the reach of secure quantum communication—currently limited to about 100 kilometers because of the photon loss in conventional telecom fibers—to continental distances.

Elements of modular quantum machines are already being incorporated into some of the world's most accurate timekeepers, and their role is expected to grow in a new generation of optical atomic clocks based on neutral atoms and atomic ions. Scientists have proposed a global quantum network of such clocks to create a real-time, single international timescale, or "world clock," that would operate with unprecedented stability and accuracy.

A miniature quantum network could also serve as a precision sensor of electromagnetic fields and temperatures in complex chemical and biological systems at the nanometer scale. For example, researchers have exploited electronic and nuclear spins associated with solid-state impurities to achieve magnetic resonance imaging with the resolution of a single atom. This technique could be used to directly image individual molecules, which would inform fundamental biological and materials science and deliver new tools for medical diagnostics and drug discovery.

The time has come to stop asking whether quantum computing is possible and to start focusing on its large-scale architecture and on what it will be able to do. The truth is that we do not know how quantum computers will change the world. But with the advent of modular quantum-computing networks, we should soon begin to find out.

Disclosure of commercial ties: *Christopher R. Monroe is a co-founder and co-inventor of intellectual property that is licensed to ionQ, a start-up company focused on the development of atomic quantum computers using the methods described in this article. Robert J. Schoelkopf is a co-founder, an equity holder and an inventor of intellectual property that is licensed to Quantum Circuits, a start-up that is developing superconducting circuits for quantum computation based on techniques discussed here. Mikhail D. Lukin is a co-founder, advisory board member and a co-inventor of intellectual property that is licensed to Quantum Diamond Technologies, a start-up focused on applications of quantum sensors for medical diagnostics using research described in this article.*

MORE TO EXPLORE

Scaling the Ion Trap Quantum Processor. C. Monroe and J. Kim in *Science,* Vol. 339, pages 1164–1169; March 8, 2013.

Superconducting Circuits for Quantum Information: An Outlook. M. H. Devoret and R. J. Schoelkopf in *Science,* Vol. 339, pages 1169–1174; March 8, 2013.

Atom-like Crystal Defects: From Quantum Computers to Biological Sensors. Lilian Childress et al. in *Physics Today,* Vol. 67, No. 10, pages 38–43; October 2014.

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The Diamond Age of Spintronics. David D. Awschalom, Ryan Epstein and Ronald Hanson; October 2007.

Quantum Computing with Ions. Christopher R. Monroe and David J. Wineland; August 2008.

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