New Frontiers in Quantum Information With Atoms and Ions

Both the precision control of trapped-ion systems and very large samples of cold neutral atoms are opening important new possibilities for quantum computation and simulation.

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The success story of quantum optics during the past 10 years is largely based on progress in gaining control of systems at the single-quantum level while suppressing unwanted interactions with the environment, which cause decoherence. Those achievements, illustrated by storage and laser cooling of single trapped ions and atoms and by the manipulation of single photons in cavity quantum electrodynamics, have opened a new field: the engineering of interesting and useful quantum states. In the meantime, the frontier has moved toward building larger composite systems of a few atoms and photons while still maintaining complete quantum control of the individual particles. The new physics to be studied in these systems is based on entangled states and ranges from a fundamental point of testing quantum mechanics for larger and larger systems to possible new applications such as quantum information processing and precision measurements.[1,2]

The past few years have seen extraordinary progress in experimental atomic, molecular, and optical (AMO) physics. Two highlights of those developments are laser-cooled trapped ions[3–8] and cold atoms in optical lattices.[9–11] These two examples also illustrate the different perspectives and strengths of AMO systems. Systems of a few trapped ions have demonstrated quantum-entanglement engineering with high fidelity (that is, low error rate) in the laboratory, and these systems are well on their way toward scalable quantum computing (see box 1), with no fundamental obstacles in sight—at least from our current understanding. Neutral atoms can be loaded from a Bose–Einstein condensate (BEC) into an optical lattice via a quantum phase transition and can provide a huge number of qubits that can be entangled in massively parallel operations. Such a system holds the promise of a quantum simulator (see box 2) that may offer insight into other fields of physics, such as condensed matter physics.

Although we focus on these two AMO systems in this article, other AMO and condensed matter systems that have been proposed for implementing a quantum computer[2] have also experienced very remarkable progress during recent years. Those systems include single photons, nuclear spins of donor atoms in doped silicon, superconducting Josephson junctions in both the charge- and flux-quantization regimes, semiconductor quantum dots, nuclear magnetic resonance samples, and electrons floating on liquid helium. Some of the ideas we review here will likely apply to these systems if they ultimately succeed as quantum computers.

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Cold trapped ions

Right after Peter Shor's discovery in 1994 of a factoring algorithm for quantum computers[1] (see PHYSICS TODAY, October 1995, page 24), trapped ions interacting with laser light were identified as one of the most promising candidates to build a small-scale quantum computer.[3] The reason is that, for many years, the technology to control and manipulate single (or few) ions had been very strongly developed for ultrahigh-precision spectroscopy and atomic clocks.[12] In particular, ions can be trapped and cooled in such a way that they remain practically frozen in a specific region of space; their internal states can be precisely manipulated using lasers and can be measured with practically 100% efficiency; and they interact with each other very strongly due to the Coulomb repulsion, yet they can, at the same time, be decoupled from the environment very efficiently.

Ions stored and laser-cooled in an electromagnetic trap (see figure 1) can be described in terms of a set of external and internal degrees of freedom. The external degrees of freedom are closely related to the center-of-mass motion of each ion; the internal, related to the motion of electrons within each ion and to the presence of electronic and nuclear spins, are responsible for the existence of a discrete energy-level structure in each ion. Each qubit can be stored in two of the internal levels, typically denoted by $|0\rangle$ and $|1\rangle$. These levels have to be very long-lived and suffer no decoherence, so that they are not disturbed during the computation. That condition can be achieved, for example, by choosing them as ground hyperfine or metastable Zeeman levels, where spontaneous emission is practically absent.

To start a computation, one can prepare all the qubits in state $|0\rangle$ by using optical-pumping techniques: Whenever an ion is in a state other than $|0\rangle$ it absorbs a photon and then decays; the process repeats until each ion decays into $|0\rangle$. After the computation, one can read out the state of the ions by performing measurements based on the so-called quantum jumps technique.[12] The idea is to illuminate the ions with a laser light of appropriate frequency and polarization so that an ion absorbs photons—and subsequently reemits them—only if it is in state $|1\rangle$. Detected fluorescence thus indicates that the ion was in state $|1\rangle$; absence of fluorescence indicates state $|0\rangle$.

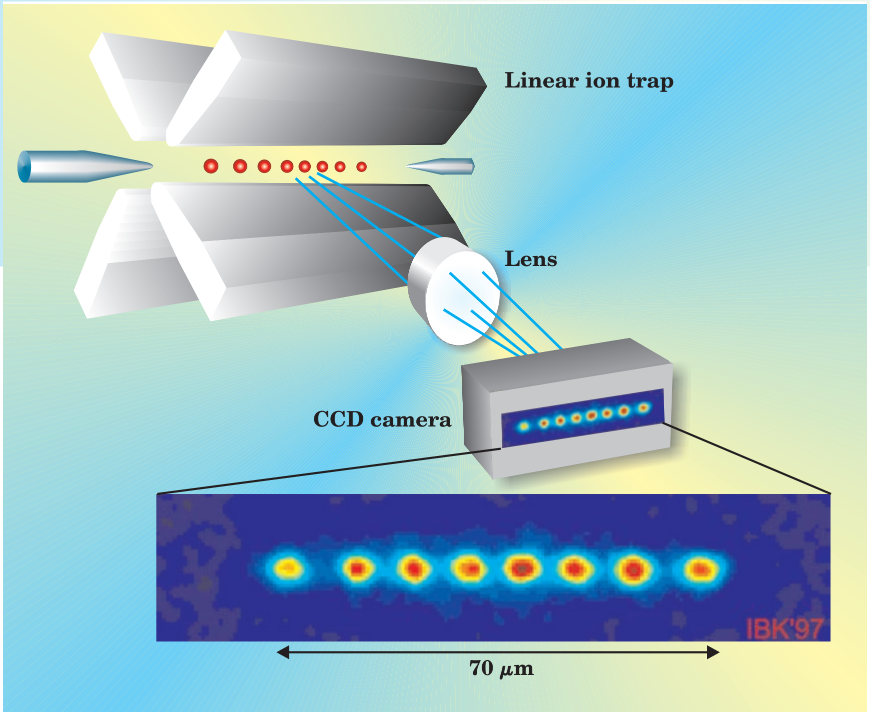


Figure 1. Trapped ions hold significant promise for implementing a scalable quantum computer. This schematic shows a string of ions in a linear trap and a CCD image of ions trapped in an actual experiment. (Courtesy of R. Blatt, University of Innsbruck).

The computation itself requires the implementation of single-qubit and particular two-qubit gates, as described in box 1. Single-qubit gates can be carried out on each ion independently by coupling the internal states $|0\rangle$ and $|1\rangle$ with a laser (or two lasers, in a Raman configuration). By adjusting the frequency and intensity of the laser, one can carry out general single-qubit gates.

For two-qubit gates, controlled interactions are always required. In the case of trapped ions, the interaction is provided by the Coulomb repulsion.[3] This force, however, does not depend on the internal states and thus is not sufficient on its own to produce the gate. But if a laser is used to couple the internal state of the ions to the external states, which are in turn affected by the Coulomb force, one can produce the desired effect in the internal levels of the ions (see box 1). Another interpretation of the way in which this gate proceeds is to note that the motional states are collective: If one ion is moved, then the others will move. The laser thus couples the internal state of each ion to the common motional state, and another laser interaction can then couple the internal and external modes back. That the laser couples the internal and external degrees of freedom of the ions is a simple consequence of the fact that each time an ion absorbs or emits a photon, not only does the internal state change, but so does the motional state due to the photon recoil.

The specific way in which the two-qubit gate was implemented in our proposal[3] required that the ions be at zero temperature and that they be singly addressed by the laser beam without affecting the other ions. In recent years, various ingenious ways of simplifying those requirements have been proposed by various groups, in particular Klaus Mølmer and Anders Sørensen, Gerard Milburn, and Martin Plenio and collaborators.[2,12]

The experimental verification of these implementation ideas started in 1995 with a proof-of-principle experiment that realized a two-qubit quantum gate.[6] There, the two qubits were not stored in the internal states of two different ions but, rather, in the internal and external states of a single ion: The states $|0\rangle$ and $|1\rangle$ for the second qubit were the states with zero and one phonon in the ion's motion. The main difficulties at that time were to cool more than one ion to the ground state and to address the ions individually. After achieving laser cooling of several ions to very low temperatures and using the gates proposed by Mølmer and Sørensen, gates that do not require zero temperature or individual addressing of the ions with lasers, scientists at NIST, led by David Wineland and Christopher Monroe, were able to implement quantum gates with two and four ions. In particular, they were, for the first time, able to entangle massive particles in a controlled way and even to produce a highly entangled state, the so-called Greenberger-Horne-Zeilinger or GHZ state $|0, 0, 0, 0\rangle + |1, 1, 1, 1\rangle$. Later, scientists in Innsbruck, led by Rainer Blatt, were able to entangle two qubits by individually addressing them with laser beams.

Scaling up ion systems

At the end of the past century, the performance of quantum gates was limited by the fact that, during the two-qubit gates, the ions' interaction with the environment produced undesired decoherence. Their motion coupled to some uncontrolled electric fields, which gave rise to heating by absorption of phonons. Such a coupling had an important effect during the two-qubit gate operation

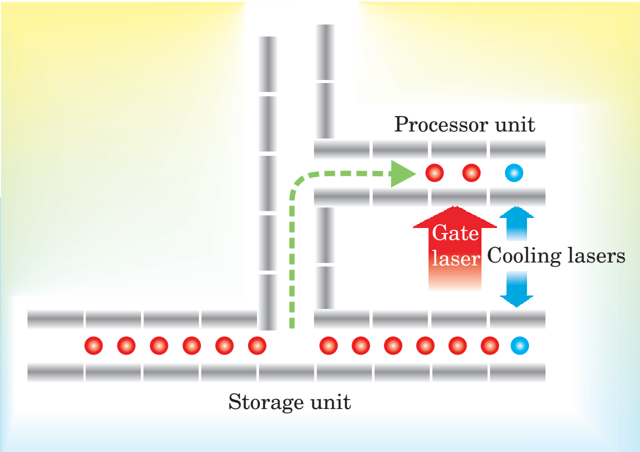


Figure 2. Scalable scheme for quantum computing with trapped ions. The ions' internal states serve as quantum memory. To perform one- or two-qubit gate operations, qubit ions (red circles) are moved from the storage area to a processing area; once the gate operations are completed, the ions are moved back. Heating due to transport of the qubit ions can be sympathetically removed with laser-cooled ions of a different species (blue circles). (Adapted from ref. 4.)

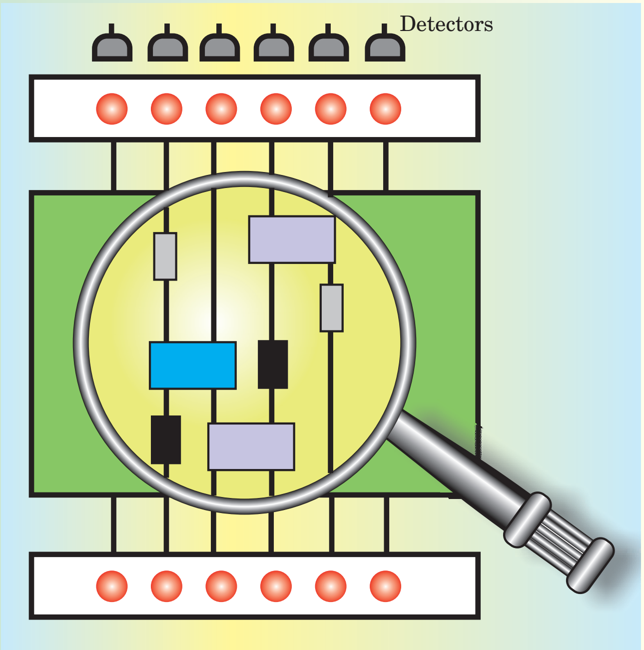
Box 1: Quantum Computing With Atoms and Ions

The basic element of quantum computing is the qubit, that is, a two-level or spin-½ system. The qubit states are typically denoted $|0\rangle$ and $|1\rangle$. A string of N qubits provides a quantum register. The general quantum state of the register is an entangled superposition

$$|\Psi\rangle = \sum_{\{x_i=0,1\}} c_{x_{N-1}x_{N-2}\dots x_0}\,|x_{N-1}x_{N-2}\dots x_0\rangle$$

in the 2^N-dimensional product Hilbert space of the qubits.

The figure illustrates the three steps of a quantum computation. The initial step of a typical computation is the preparation of the state $|0,0,\dots,0\rangle$ (lower circles in the figure). Quantum computing corresponds to unitary operations $\hat{U}$ on the state of the quantum register: $|\Psi\rangle \to \hat{U}|\Psi\rangle$. These unitary operations $\hat{U}$ can be decomposed into a sequence of single- and two-qubit quantum gates (center of figure). The last step is a readout of the final state of the qubits (upper circles).



A single-qubit gate corresponds to the general rotation of the spin-½ system representing the qubit, while a two-qubit gate is a nontrivial entanglement operation of a pair of qubits. Two important two-qubit gates are the controlled-NOT $|x_1\rangle|x_2\rangle \to |x_1\rangle|x_1 \oplus x_2\rangle$, where $\oplus$ denotes addition modulo 2, and the phase gate $|x_1\rangle|x_2\rangle \to (-1)^{x_1x_2}|x_1\rangle|x_2\rangle$.

The most difficult part to implement in a quantum computer based on atoms and ions is the two-qubit gate. For the case of ions, the gate implementation can be explained schematically as follows:

$$\begin{aligned}|\varepsilon_1\rangle_i \otimes |\varepsilon_2\rangle_j \otimes |\Psi\rangle &\to |\varepsilon_1'\rangle_i \otimes |\varepsilon_2'\rangle_j \otimes |\Psi'_{\varepsilon_1,\varepsilon_2}\rangle\\ &\to -(-1)^{\varepsilon_1\varepsilon_2}|\varepsilon_1'\rangle_i \otimes |\varepsilon_2'\rangle_j \otimes |\Psi'_{\varepsilon_1,\varepsilon_2}\rangle\\ &\to -(-1)^{\varepsilon_1\varepsilon_2}|\varepsilon_1\rangle_i \otimes |\varepsilon_2\rangle_j |\Psi\rangle.\end{aligned}$$

Here, $|\varepsilon\rangle_{i,j}$ with $\varepsilon = 0$ or 1 denotes the internal states of ions i and j on which the gate is applied, and $|\Psi\rangle$ denotes the motional state, which describes the external degrees of freedom. In the first step, a laser couples the internal and external states of the ions. After the states evolve due to the Coulomb interaction, another laser transfers the results back to the internal states. The motional state $|\Psi\rangle$ is unchanged at the end of the process. For two adjacent atoms in an optical lattice, the two-qubit gate that is applied after moving the lattices (see figure 4) is $|\varepsilon_1\rangle_j|\varepsilon_2\rangle_{j+1} \to e^{i\phi\varepsilon_1(1-\varepsilon_2)}|\varepsilon_1\rangle_j|\varepsilon_2\rangle_{j+1}$. These two-qubit gates for ions and neutral atoms are equivalent to the controlled-NOT gate: By applying appropriate single-qubit gates right before and after the two-qubit gate, one obtains the action of the controlled-NOT.

During a quantum computation, entangled states, which cannot be written as a product of single-particle wavefunctions, may be produced. Thus, whereas the capability of producing entangled states is necessary for building a quantum computer, the converse is not necessarily true. One may be able to create certain entangled states but still not be able to implement the required one- and two-qubit gates.

because, at some point, the internal state of the qubits was transferred to the motional state. Thus if the external motion is modified by interaction with the environment, it will affect the states of the qubits.

These problems have been largely overcome with improved trap designs: The electric fields are now controlled better either by using larger traps or by separating where the ions are trapped from where they are manipulated, which avoids surface contamination in the region where the quantum gate operations are performed. Several milestones have since been achieved in the NIST and Innsbruck laboratories. For example, a two-qubit gate with a fidelity $F = 0.97$ was implemented at NIST last year.[7] (The fidelity is directly related to the error E in the gate, $E = 1 - F$.) The main limitation was related to the small spontaneous-emission rate (which can be strongly decreased by using other types of ions or more sophisticated techniques to implement the gates). In Innsbruck, a two-qubit gate was performed using individual addressing.[8] In addition, the Innsbruck group implemented, with a single ion, the Deutsch–Jozsa algorithm, one of the first—albeit artificial—algorithms to show that a quantum computer would be more powerful than a classical one.[1]

The main obstacle nowadays to scaling up the current schemes is the increasing difficulty of dealing with larger numbers of ions. As the number of ions in the trap is increased, it becomes harder both to cool the ions and to affect only the desired ions with the laser; unintended coupling to others spoils the computation. About three years ago, new proposals to overcome this obstacle emerged.[4,5] Wineland and colleagues proposed to separate the region where the ions are stored from the one in which the gates take place (see figure 2).[4] To perform a gate operation, the qubit ion or ions are moved from the storage region to the gate region. That process does not disturb the ions' internal state because the Coulomb interaction used to move them is independent of the internal states unless the motion and internal states are coupled with a laser. In the processor region, the ions are driven by lasers to perform the gate operation and then are moved back to the storage region. The additional heating due to the motion can be transferred to a cooled ion of a different species in the same potential well; the resulting sympathetic cooling of the qubit ions will not disturb their internal states. Preliminary experiments at NIST have successfully demonstrated all the basic elements of this proposal. In view of those ex-

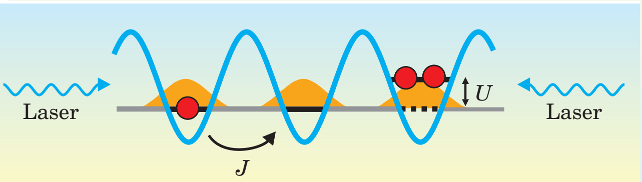


Figure 3. Cold atoms in an optical lattice can be described by a Hubbard model. An off-resonant standing light wave generates a periodic intensity pattern (blue) that is seen by the atoms as a periodic potential—that is, an optical lattice. The periodicity of the potential gives rise to a series of Bloch bands for the atomic motion. At low temperature, the atoms will only occupy the lowest Bloch band. Atoms (red) can move from site to site via tunneling, described by the hopping parameters J in the Hubbard Hamiltonian on this page. Atoms on the same lattice site will repel each other due to collisional interactions, resulting in an on-site interaction energy U in the Hamiltonian. The wavefunction of an atom in one of the potential wells is shown in orange.

periments, the two of us see at present no fundamental obstacle to achieving scalable quantum computation in these systems.

In the near future, we anticipate crucial experimental progress with trapped ions. Very likely, proof-of-principle experiments demonstrating teleportation, quantum error correction, and other intriguing properties of quantum mechanics will take place with three to six ions. When the technology admits 30 ions (using the scalable proposals), a new avenue of experiments will open up: Experimenters will be able to start performing computations competitive with those of the most powerful classical computers that we have nowadays (see box 2). Whether it is possible to scale the present setups up to several hundred thousand ions remains an open question. Such a scale is necessary for factoring 200-digit numbers—the most spectacular application of a quantum computer—and requires sophisticated fault-tolerant error-correction techniques (see PHYSICS TODAY, June 1999, page 24). No fundamental obstacle to achieving that goal seems to exist, although success depends on developing the appropriate technologies. Trapped ions are currently the only system for which this strong statement can be made.

Cold atoms in optical lattices

Bose–Einstein condensates provide a source of a large number of ultracold atoms. Due to the weak interactions, all atoms in a condensate occupy the single-particle ground state of the trapping potential, and the condensate is in a product state of the individual ground-state wavefunctions. Such a collection of atoms can be harnessed for quantum information processing by loading the atoms into an optical lattice.[9] The result is an array of many identifiable qubits that can be entangled in a massively parallel operation.[10,13] This scenario has recently been realized in the laboratory in a series of remarkable experiments.[11]

Generated by standing-wave laser fields, optical lattices are periodic arrays of microtraps for cold atoms. Due to the low temperatures, atoms loaded in an optical lattice will, like electrons in a crystal lattice, only occupy the lowest energy (Bloch) band. The physics of these atoms can be understood in terms of a Hubbard model with Hamiltonian[9]

$$H = -\sum_{\langle i,j\rangle} J_{ij} b_i^\dagger b_j + \frac{1}{2} U \sum_i b_i^\dagger b_i^\dagger b_i b_i,$$

with b_i and $b_i^\dagger$ bosonic annihilation and creation operators for atoms at each lattice site i. The parameters J_{ij} are hopping matrix elements that connect two lattice sites via tunneling, and U is the on-site interaction of atoms resulting from the collisional interactions (see figure 3). The distinguishing feature of this system is the time-dependent control of the hopping matrix elements J_{ij} (which correspond to the kinetic energy) and on-site interaction U (the potential energy) through the intensity of the lattice laser.

Increasing the intensity deepens the lattice potential and suppresses the hopping; at the same time, it increases the atomic density at each lattice site and thus the on-site interaction. Increasing the intensity will, therefore, decrease the ratio of kinetic to potential energy, J_{ij}/U, and the system will eventually become strongly interacting. In the case of bosonic atoms, the system will undergo a quantum phase transition from the condensate's superfluid state, with long-range coherence, to a Mott insulator state, which has no long-range order.[9] In the Mott insulator regime, loading exactly one atom per lattice site can be achieved, an arrangement that provides a *very* large number of identifiable atoms whose internal hyperfine or spin states can serve as qubits.

Entanglement of these atomic qubits is obtained by combining the collisional interactions with a spin-dependent optical lattice.[10] Here, with appropriate choice of atomic states and laser configurations, the qubit states $|0\rangle$ and $|1\rangle$ see different lattice potentials. Atoms can thus be moved according to the state of the qubit. In particular, one can collide two atoms "by hand," as illustrated in figure 4, so that the wavefunction component with the first atom in $|1\rangle$ and the second atom in $|0\rangle$ will pick up a collisional phase ϕ that entangles the atoms. For two adjacent atoms,

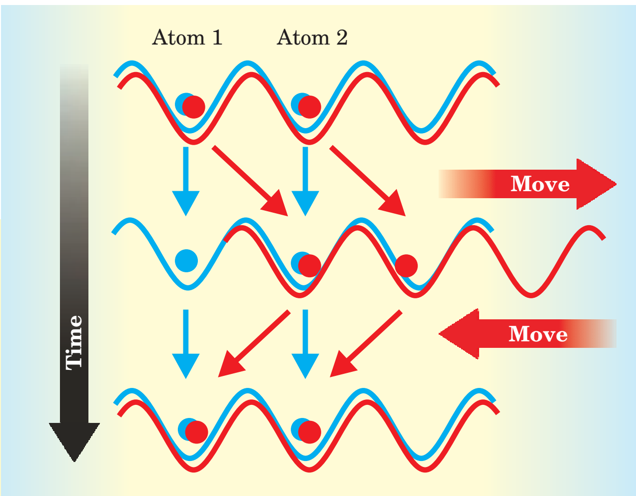


Figure 4. Controlled collisions can be used to entangle two atoms in an optical lattice. Each atom can be in a superposition of internal states $|0\rangle$ (blue circles) and $|1\rangle$ (red circles). The states can be coupled to movable state-dependent optical lattices (red and blue lattices) to entangle two atoms. If one lattice is shifted over one period, the overlapping states of differing atoms can pick up a phase factor, which entangles the two atoms.[10,11] This scheme underlies the quantum simulator in the optical lattice.

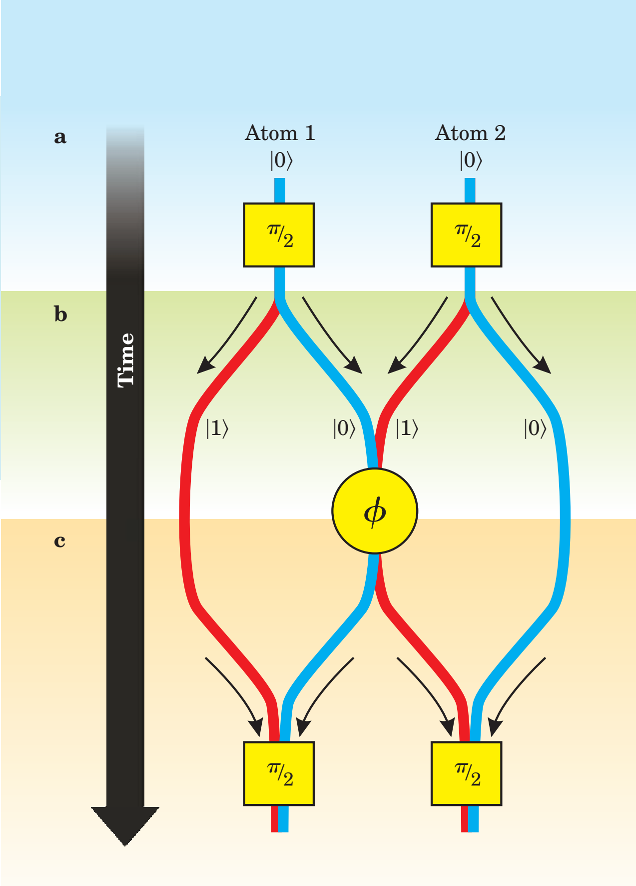


Figure 5. Ramsey experiment with two atoms colliding in a lattice to generate a Bell state.[10,11] Time evolution is from top to bottom. **(a)** The two-atom system is initially prepared in the product state $|0\rangle|0\rangle$. A $\pi/2$ pulse generates the (unnormalized) superposition state $(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$. **(b)** A coherent collision provides a conditional phase shift ϕ if the first atom is in state $|0\rangle$ and the second is in state $|1\rangle$. The wavefunction thus becomes $|0\rangle|0\rangle + e^{i\phi}|0\rangle|1\rangle + |1\rangle|0\rangle + |1\rangle|1\rangle$. **(c)** A final $\pi/2$ pulse closes the Ramsey interferometer and yields the state $(1 - e^{i\phi})|\mathrm{Bell}\rangle + (1 + e^{i\phi})|1\rangle|1\rangle$, which for $\phi = \pi$ is the Bell-like entangled state $|0\rangle(|0\rangle - |1\rangle) + |1\rangle(|0\rangle + |1\rangle)$. (Adapted from ref. 11.)

this physical process realizes the two-qubit gate required for quantum computation (see box 1).

This collisional process may allow one to entangle many atoms in an optical lattice. Consider, for the sake of simplicity, the case of two atoms initially prepared in an equal superposition of the two internal states. After applying the gate, one obtains a maximally entangled state $|0, 1\rangle + |1, 0\rangle$ (a so-called Bell state). This state can be detected by using the Ramsey technique (see figure 5). In a lattice loaded with many atoms, a single movement can entangle all qubits in parallel. For three atoms, this operation can produce the GHZ state $|0, 0, 0\rangle + |1, 1, 1\rangle$; for two-dimensional lattices, it allows the generation of a so-called cluster state.[14] Once produced, a cluster state can be used to perform quantum computations by making measurements only of the individual qubits; no further two-qubit gates are required.

These ideas have been implemented in a series of remarkable experiments. The Mott-insulator quantum phase transition was first observed by the group of Immanuel Bloch and Theodor Hänsch (University of Munich and the Max Planck Institute for Quantum Optics in Garching),[11] and later by the groups of William Phillips (NIST Gaithersburg), Tilman Esslinger (ETH Zürich), and Daniel Heinzen (University of Texas at Austin). In the experiments, on the order of 100 000 atoms were loaded into an optical lattice from a BEC. The Mott insulator transition was observed in the smearing out of the interference pattern formed by the atoms when they were released from the trap and allowed to expand (see PHYSICS TODAY, March 2002, page 18), and was also observed in the excitation spectra of the ensembles. The disappearance of the interference pattern can be attributed to having basically one atom in each lattice site; therefore, long-range correlations (which give rise to the interference) disappear. Additionally, in a seminal experiment, the Munich group has recently realized the two-qubit collisional gate.[11]

For the moment, the main experimental limitation is that there is not exactly one atom per lattice site. Such defects arise from the finite temperature of the experiments and from the background harmonic potential that exists on top of the lattice potential. As a consequence, the state that is generated in practice after the collisional process will also have some defects. Characterizing the entanglement of such a state is a current research topic. The problem of defects may be overcome by increasing the initial density to start with more atoms per site. A single atom from each site can then be adiabatically transferred into a different internal state that is trapped in a separate lattice potential.[15] Another current obstacle is the slow collision process: During the gate operation, other processes, such as spontaneous emission, can spoil it. The gate, however, can be sped up by modifying the scattering properties to increase the value of U. Presently, several experimental groups are investigating ways of making the process faster.

Putting cold atoms to work

The parallelism inherent in the lattice movements makes atoms in optical lattices ideal candidates for a quantum simulator—as first proposed by Richard Feynman—for bosonic, fermionic, and spin many-body systems. Such a system could allow simulation of various types and strengths of particle interactions, and one-, two-, or three-dimensional lattice configurations in a regime of many atoms, a regime clearly inaccessible to any classical computer. By a stroboscopic switching of laser pulses and lattice movements combined with collisional interactions, one can implement sequences of one- and two-qubit operations to simulate the time-evolution operator of a many-body system[16] (see box 2). For translationally invariant systems, there is no need to address individual lattice sites because all the atoms are exposed to the same kind of interactions at the same time, which makes the requirements quite realistic in light of present experimental developments. In addition, Hubbard Hamiltonians with interactions controlled by lasers can be realized directly with cold bosonic or fermionic atoms in optical lattices. Cold-atom "analog" quantum simulation provides a direct way of studying properties of strongly correlated systems and in the future may develop into a novel tool of condensed matter physics.

New designs of arrays of microtraps—based, for example, on nano-optics or magnetic microtraps—may be one way to allow individual addressing of atomic qubits and entanglement operations. In those systems, magnetic or optical fields independently control each site, in contrast to the optical lattices in which the same lasers con-

Box 2. Quantum Simulations

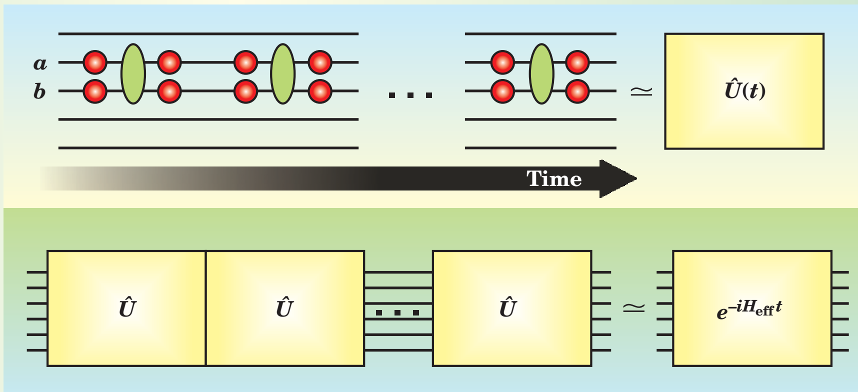
Let us consider a quantum system composed of N qubits all initially in state $|0\rangle$. We apply a two-qubit gate to the first and second qubit, another one to the second and the third, and so on. After we have performed $N-1$ such gates, we measure the state of the last qubit. How can we determine, within a prescribed precision (say 1%), the probabilities of obtaining $|0\rangle$ and $|1\rangle$ in that measurement?

One way to determine the probabilities using a classical computer is to simulate the whole process. We take a vector with 2^N components and multiply it by a $2^N \times 2^N$ matrix every time we simulate the action of a gate. At the end, we can use the standard rules of quantum mechanics to calculate the desired probabilities. But as soon as N is on the order of 30, we will not be able to store the vector and the matrices in any existing computer. Moreover, the time required to simulate the action of the gates increases exponentially with the number of qubits.

With a quantum computer, in contrast, the computation will need to be repeated several (on the order of 100) times to get the desired precision, but each computation requires only $N-1$ gates. Thus, the quantum computer itself is much more efficient for simulating quantum systems, a conclusion already reached by Richard Feynman in 1982.[1,16] Of course, this particular example is artificial and not related to a real problem. However, there exist physical systems that cannot be simulated with classical computers but for which a quantum computer could offer important insights into some physical phenomena not yet understood.[16] One could use a quantum computer to simulate spin systems or Hubbard models, for example, and extract information about open questions in condensed matter physics. Another possibility is to use an "analog" quantum computer (in the spirit of a classical analog computer) to do the job: One could choose a system that is described by the same Hamiltonian that one wants to simulate but that can be very well controlled and measured.

The figure illustrates how a quantum simulator would function. As shown in the top panel, the time-evolution operator for a single time step, $\hat{U}(t)$, can be built up from a sequence of single-qubit (red) and two-qubit (green) gates, here operating on qubits a and b. The effective time-evolution operator of the system being simulated, $\exp(-iH_{\text{eff}}t)$ where H_{eff} is the system's effective Hamiltonian, is built up from a sequence of operators $\hat{U}(t)$, as shown in the bottom panel.

To simulate a system of 30–50 qubits, error correction may not be needed if the error per gate is relatively small (say around 10%), but still larger than the one required for fault-tolerant quantum computation (about 0.01%). In any case, under certain conditions, the errors produced during the simulation may have effects similar to being at finite temperature; thus the result may still be useful to understand physical processes.



trol all the lattice sites. The ideas for implementing quantum gates with atoms in optical lattices can be easily extended to these systems, and we expect that they will soon be implemented experimentally. The main advantage of these systems is that once they are operating correctly, they can be scaled up relatively easily.

For the near future, we expect that atoms in optical lattices will be used to simulate a variety of other physical systems, such as interacting fermions in 2D using different lattice geometries. We also expect important progress toward loading single neutral atoms in different types of potentials (optical, magnetic, and so on), and performing quantum gates with a few of these systems. Such developments would allow the creation of few-atom entangled states that may be used to observe violations of Bell inequalities or interesting phenomena like teleportation or error correction. Unlike the case of trapped ions, it is difficult at the moment to predict if scalable quantum computation will be possible with neutral atoms in optical lattices using the present experimental setups. In any case, due to the high parallelism of these systems, we can clearly foresee that they will allow one to obtain deep insight into condensed matter physics via quantum simulations.

The progress continues

Although both trapped-ion and neutral-atom systems can be manipulated and controlled, they possess their own strengths and weaknesses. On the one hand, single or very few trapped ions can already be completely and individually controlled in the lab. The physics of trapped ions is very well understood by now. They are thus particularly suited to implementing quantum computations, which require complete and individual control of each of the qubits (as well as the ability to perform two-qubit gates). We foresee no fundamental obstacle to building a scalable quantum computer, although technical development may, of course, impose severe restrictions on the time scale in which a scalable quantum computer is achieved. On the other hand, neutral atoms in optical lattices can be very naturally manipulated in parallel (without individual addressing) because they are all exposed to the same lasers at the same time. Thus, they seem to be ideal candidates for studying a variety of physical phenomena by exploiting this parallelism to simulate other physical systems. Such quantum simulation may turn out to be the first real application of quantum information processing.

Other quantum optical systems have also experienced remarkable progress during the past several years and may prove equally important in the context of quantum information. For example, the groups of Jeff Kimble at Caltech, Michael Chapman at the Georgia Institute of Technology, Blatt at Innsbruck, and Gerd Rempe at Munich have trapped single atoms and ions inside cavities and let them interact with the cavity field, which can be used to generate single or entangled photons and to build quantum repeaters for quantum communication. Atoms have been trapped in several kinds of optical and magnetic traps and have been moved very precisely to different locations in space. The groups of Mikhail Lukin, Ronald Walsworth, Lene Hau (all at Harvard University), Eugene Polzik (University of Aarhus), and Kimble have taken initial steps toward demonstrating the storage and subsequent readout of quantum states of light with atomic ensembles and toward establishing entanglement of distant ensembles of laser fields. Such developments have the ultimate goal of building a quantum repeater for long-distance quantum communications.[17]

The past two years have witnessed spectacular progress in quantum information processing with quantum optical systems. Whether such progress—or the progress in solid-state systems—will eventually lead to the construction of a useful quantum computer is still an open question. What is already clear is that the complete control and manipulation of quantum systems will teach us many things about quantum mechanics and will eventually allow us to investigate the complicated properties of quantum many-body systems.

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