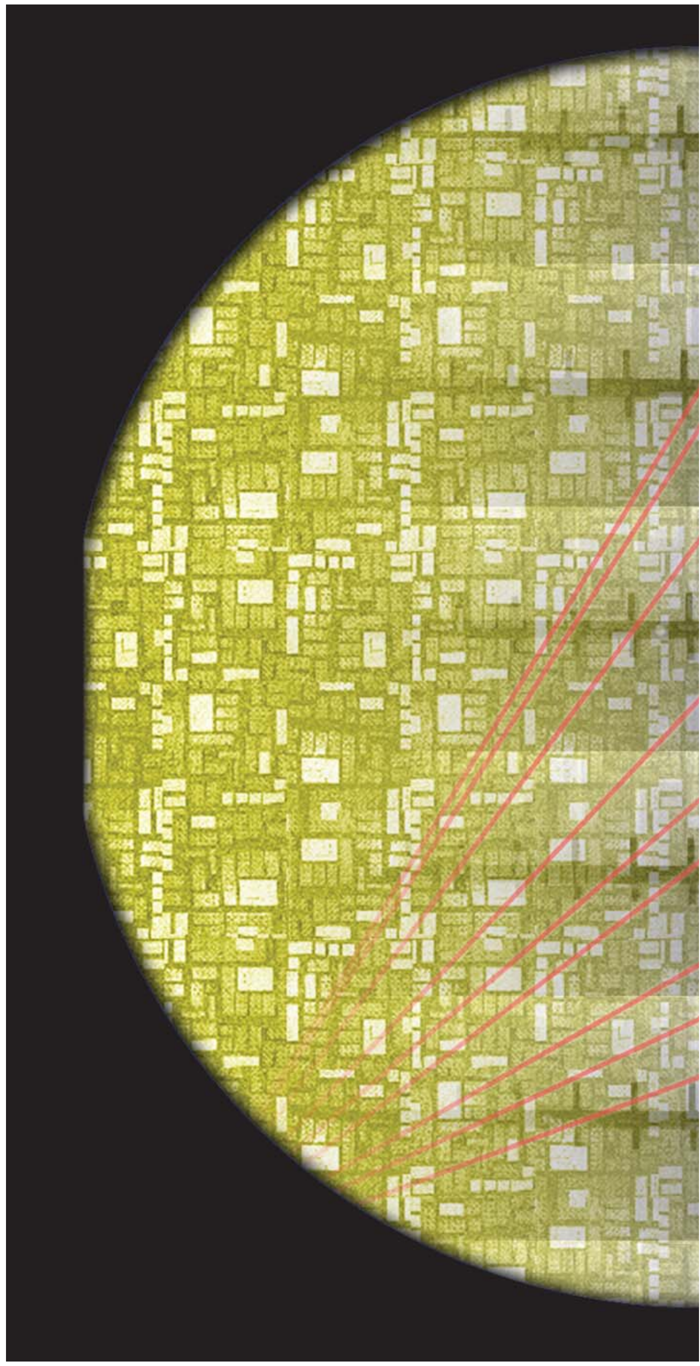
Remapping the quantum frontier



A full-scale universal quantum computer may still be a long way off, but the quest for this goal is opening up new areas of science and producing useful applications and techniques along the way. **Christopher Monroe** and **Mikhail Lukin** reveal a few of the most exciting developments

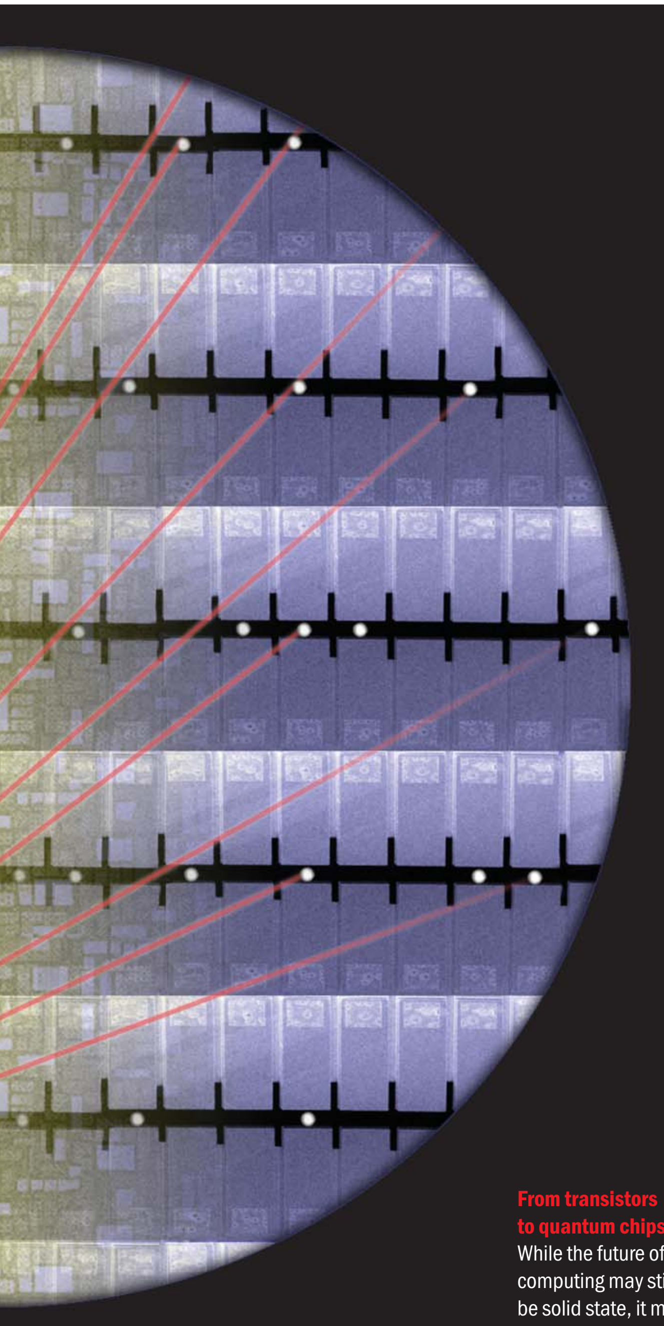
Christopher Monroe is with the physics department at the University of Maryland and the Joint Quantum Institute at the University of Maryland and the National Institute of Standards and Technology, US, and **Mikhail Lukin** is with the physics department at Harvard University, US, e-mail monroe@umd.edu

In 1994 the mathematician Peter Shor, then working at AT&T Bell Laboratories in the US, applied quantum mechanics to an age-old problem in number theory and made a remarkable discovery. He showed that a computer that operates on and processes quantum systems could factor large integers exponentially faster than a conventional computer. This result attracted a lot of attention because the difficulty of factoring large numbers is what ensures the security of modern cryptography schemes – even the best conventional computer would take several thousand years to factor a number with more than about 150 digits. Shor's quantum factoring algorithm could, in principle, break such encryption standards – a possibility that led to an explosion of interest in quantum information science. Until then it was a field that had largely been a mere curiosity, despite notable contributions from the likes of Richard Feynman and David Deutsch.

There followed a decade of intense effort aimed at building practical quantum information systems, with leading theorists and experimentalists across different fields of physical science and mathematics coming together to tackle this challenge. The result was major progress towards understanding and realizing simple quantum information systems composed of a few quantum bits (qubits). Qubits, which form the basic building blocks of quantum processors (see box on page 35), are physical systems that can be in one of two possible states – for example a particle that is spin up or spin down – or in a superposition of both. Near complete control has been achieved over qubits represented by a variety of different physical systems, thereby enabling demonstrations of simple quantum computations.

A full-scale quantum computer that can implement Shor's visionary algorithm, however, is still a distant dream. A major problem is that it is hard to sufficiently isolate a complex quantum system from its environment. The larger and more complex the system, the more likely it is that interactions with the environment will cause it to lose its quantum character, or "coherence". Addressing the challenge of decoherence requires new approaches that combine ideas and techniques from different disciplines within physics, chemistry, engineering, mathematics and computer science.

As a result, a new area of quantum science and engineering is emerging – one that is already producing useful quantum technologies that fall outside of the narrow goal of realizing a universal quantum computer. These include microchips in which individual quantum systems can be isolated and used to encode information in electrical charges, currents and spins. We are



M Madsen, Wabash College

From transistors to quantum chips
While the future of computing may still be solid state, it may look quite different.

At a Glance: The quantum frontier

- Since the mid-1990s researchers have been taking the first steps towards a universal quantum computer capable of tasks, such as factoring large numbers, that are believed to be impossible with conventional computers
- While this goal is still a long way off, the research effort has led to the development of many other useful quantum technologies
- These include long-distance quantum communication systems, quantum simulators that promise to solve the riddle of high-temperature superconductivity, and quantum networks that use several different kinds of physical system to store and process quantum information
- In particular, researchers are turning to solid-state manufacturing as a route to large-scale quantum systems, and have developed several types of quantum chips

also seeing quantum networks that can pass quantum information between widely different physical systems, as well as quantum simulators that could, strange as it may sound, solve some of the most vexing problems in condensed-matter physics.

Going solid state

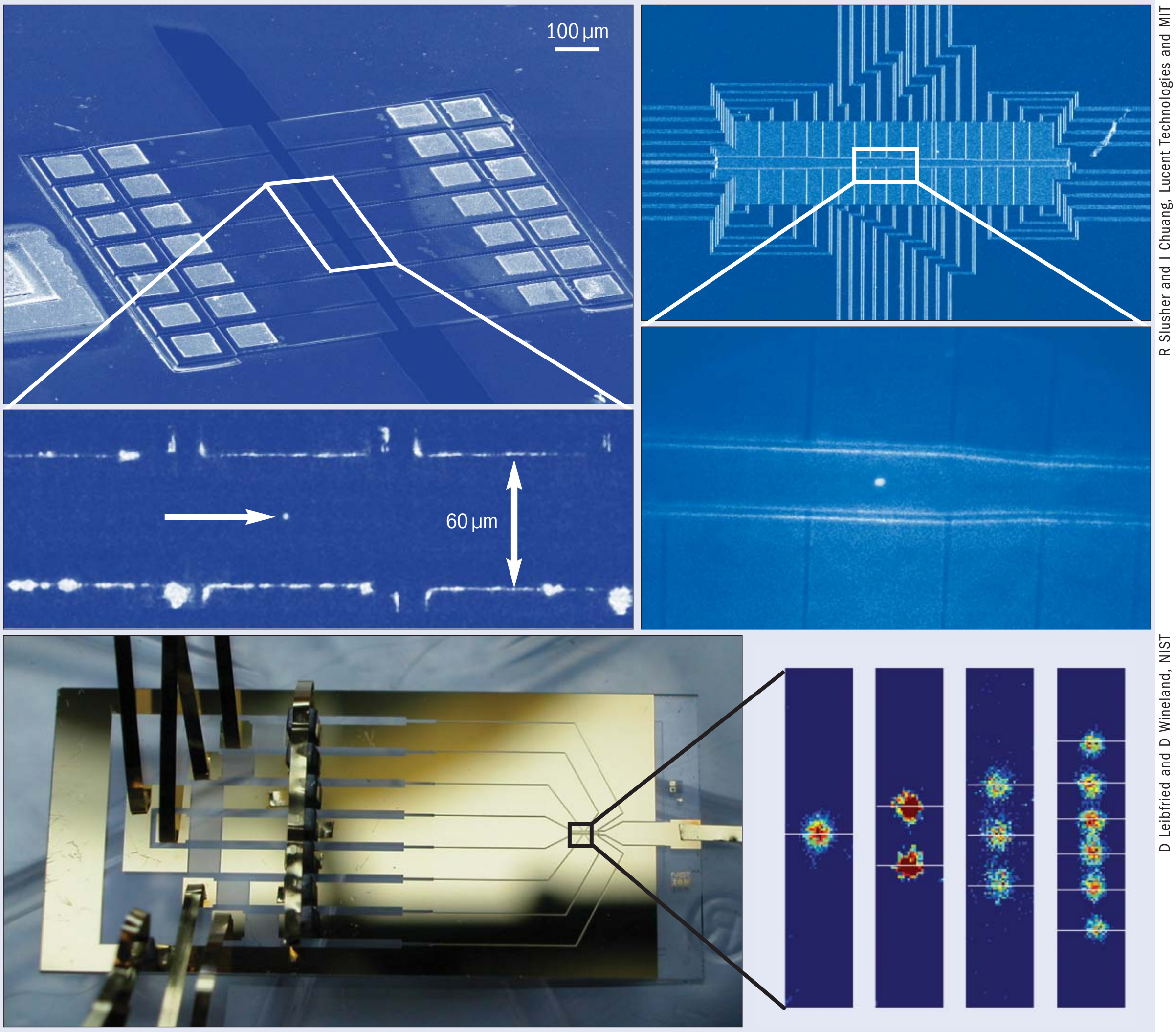
Much of the early work in controlling individual quantum systems was done using atom and ion traps, in which individual atoms or ions are confined by electromagnetic fields in vacuum chambers and brought to rest in free space using laser beams. Thanks to pioneering theoretical work by Peter Zoller and Ignacio Cirac at the University of Innsbruck in Austria, by the late 1990s we knew how to use ion traps to build all the necessary elements of a quantum computer. Indeed, researchers can now manipulate about a half dozen or so qubits of this type, culminating with the recent work by Rainer Blatt and co-workers at Innsbruck who were able to produce quantum gates with high fidelity. However, it has proved difficult to achieve full quantum control of hundreds or thousands of atomic qubits using conventional technology.

Instead, researchers are turning to semiconductor-processing techniques to fabricate the large-scale electrode structures necessary for the reliable control of these numbers of atoms. In the last few years groups led by David Wineland at the National Institute of Standards and Technology (NIST), Richard Slusher at Lucent Technologies and the Georgia Institute of Technology, and Matthew Blain at Sandia National Laboratories, as well as one of the current authors (CM), have developed semiconductor-chip traps in which lots of ions can be suspended. We expect to eventually be able to scale up such systems to accommodate hundreds or thousands of qubits (figure 1). The ultimate physical limits for semiconductor-chip traps are, however, far from clear. The problem is that as these devices are made smaller, the solid-state environment begins to encroach on the atomic qubits, thus causing decoherence. Exploring this nano-scale interface between isolated, trapped atomic and molecular systems and mesoscopic solid-state devices is a new and intriguing field.

In addition to steady progress with well-isolated quantum systems such as trapped ions, we are also now seeing major advances in our ability to control quantum states in a wide variety of solid-state systems (figure 2). The isolation and control usually associated with simple atomic systems can now be achieved on microchips similar to those at the heart of the conventional computer industry, thus providing several new approaches to the realization of quantum computers.

For example, research groups led by Yasunobu Nakamura at NEC in Japan, Denis Vion at the CEA-Saclay in France and Hans Mooij at the University of Delft in the Netherlands, as well as Rob Schoelkopf, Michelle Devoret and Steve Girvin at Yale University and John Martinis at the University of California at Santa Barbara, have achieved unprecedented control over the quantum states of individual Cooper pairs of electrons – the carriers of superconducting current – that are localized on micrometre-sized objects. When cooled to cryogenic temperatures, single Cooper pairs make excellent qubits. By combining advances in superconducting technologies and mesoscopic physics

1 Solid-state ion traps



Current ion-trap technology, which involves lasers and vacuum chambers, can only cope with a few qubits at a time, thus making it unsuitable as a basis for a full-scale quantum computer. As a result, researchers are turning to semiconductor-manufacturing techniques to construct solid-state ion traps. In such traps hundreds of ions can be suspended by electromagnetic fields in cavities within a semiconductor chip. Researchers have etched such a trap from a gallium-arsenide/aluminium–gallium-arsenide heterostructure (top left), the inset to which shows a single trapped cadmium ion fluorescing. Other approaches include a gold-on-quartz planar trap, shown holding small arrays of magnesium ions (bottom left); and a silicon surface trap, shown holding a single strontium ion (top right).

with materials science and quantum control techniques borrowed from nuclear magnetic resonance (NMR), researchers have achieved long coherence times and reliable quantum manipulation in these systems.

Groups led by Charles Marcus and Amir Yacoby at Harvard and by Leo Kouwenhoven and Lieven Vandersypen at Delft have also been able to coherently manipulate and measure the spins of single electrons in quantum dots – isolated islands of semiconductor – using micron-sized electrical detectors. They exploited the Pauli exclusion principle, which gives rise to an effective spin–spin interaction between electrons, while NMR-like techniques – such as "spin echo" – were used to decouple the electron spins from background nuclear spins in the semiconductor, thus tempering a major source of decoherence in these systems. Similar techniques that use laser control are also being developed by Atac Imamoglu at ETH Zurich, Duncan Steel and Dan Gammon at the University of Michigan and the Naval Research Laboratory in Washington, DC, David Awschalom at Santa Barbara and Gerhard Abstreiter at the Technical University of Munich.

Meanwhile, optical techniques from atomic physics – such as optical spin polarization and spin-selective fluorescence detection – are allowing individual spins to be manipulated in a host of other, atom-like, solid-state systems, including the so-called nitrogen vacancy (NV) in diamond. The NV is a localized impurity in which a nitrogen atom is substituted for a carbon atom next to a missing carbon atom in the diamond lattice. This impurity behaves like an artificial atom and has non-zero electronic spin in its ground state, much like the hydrogen atom.

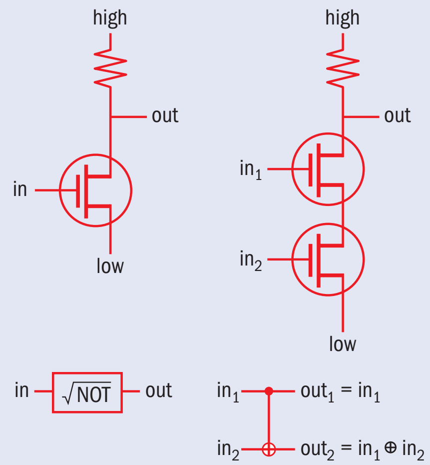
By using optical techniques borrowed from single-molecule spectroscopy to isolate single NV centres within the diamond lattice, Jörg Wrachtrup at the University of Stuttgart, Awschalom at Santa Barbara, and one of the current authors (ML) and their colleagues

Quantum bits and quantum gates

The fundamental unit of classical information is the binary digit (bit), which can take a value of either 0 or 1. Each bit is represented by a physical system, such as the on/off states of a mechanical switch or the high/low voltage level at the output of a transistor. Multiple classical bits can be manipulated and processed using logic gates built from transistors – for example the classical NOT gate (top left) is formed by a single transistor. When the voltage at the gate input is low (0), the transistor does not conduct and the output is high (1); but when the gate voltage is high (1), the transistor conducts and the output is low (0).

The classical NAND (NOT-AND) logic gate (top right), on the other hand, operates on two input bits (00, 01, 10 or 11) and produces a single output bit. The output is 0 if the input is 11, and 1 for any other input. This gate is "universal" in the sense that an arbitrary classical logic network of many bits can be built from a sequence of NAND gates, and it is also irreversible, as a low (0) output could result from any of the three inputs 00, 01 or 10.

Quantum bits (qubits), as well as being able to take the values of 0 or 1, can be in a superposition of both states, which is denoted by [0]+[1] (the brackets signify a quantum state



[0] → [0]+[1]
[1] → [0]−[1]

[0][0] → [0][0]
[0][1] → [0][1]
[1][0] → [1][1]
[1][1] → [1][0]

and the plus sign indicates a quantum superposition). Qubits are nothing more than quantum two-level systems such as the state of polarization of a single photon or two internal (electronic or spin) states in an atom. Unlike their classical counterparts, qubits can only remain in a coherent state when left unobserved and unperturbed by the environment – in other words, information must be prevented from leaking from the qubit system to the environment.

As with their classical counterparts, qubits can be processed and manipulated by logic gates. However, all quantum logic gates are reversible, since coherent quantum evolution (the Schrödinger wave equation) is itself reversible. There are families of universal quantum logic gates that can be used to construct an arbitrary quantum state from a collection of qubits. Examples of quantum gates are the quantum "square-root-of-not" gate (bottom left), which puts a single qubit into a superposition state, and the two-qubit controlled-NOT gate (bottom right), which flips the second qubit conditionally on the state of the first qubit.

The controlled-NOT gate is particularly interesting, as it is a fundamental gate for the generation of quantum entanglement. For instance, if the first input is in the superposition state [0]+[1] and the second qubit is in state [0], then the resulting entangled quantum superposition is written as [0][0]+[1][1]. Quantum gate circuits are typically depicted as a series of a parallel rails, with each rail representing a qubit as it evolves in time from left to right.

have been able to manipulate individual electronic and even nuclear spins while maintaining excellent coherence even at room temperature. (Usually at these temperatures uncontrolled couplings to thermal excitations in the solid destroy all quantum behaviour.) Other avenues being explored as potential solid-state qubit candidates range from single spins in both silicon and carbon nanotubes and buckyballs, to topological degrees of freedom associated with quantum Hall systems, which are 2D electron systems at low temperature.

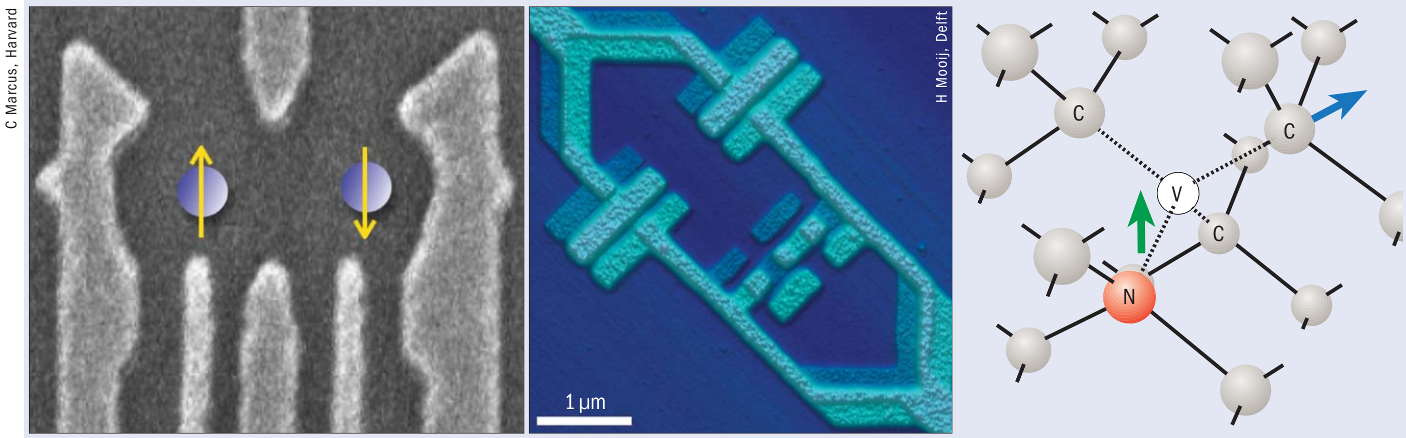
Simulating superconductivity

Despite these successes, the ability to perform universal quantum computations with hundreds or thousands of qubits for applications such as Shor's algorithm is still several years away. But this has not prevented scientists from putting current technology to good use. There is currently a lot of interest in applying quantum computation to a class of physics problems that are much simpler than Shor's algorithm yet are still extremely difficult to tackle using conventional computers. Indeed, Feynman's original interest in quantum computing was motivated by the difficulty of solving the Schrödinger equation, which describes how the quantum state of a physical system changes in time, for interacting quantum many-body systems. Since the dimension of the Hilbert space associated with N spin-1/2 particles scales exponentially with N, an exact simulation of such a system would have to keep track of the dynamical evolution of an exponentially large number of probability amplitudes, which becomes impossible even for a modest system of 100 spins.

Feynman suggested that a controllable quantum system (the quantum computer) could emulate the behaviour of a second quantum system (the target system), thereby obtaining the required answer via a quantum simulation. An arbitrary quantum simulator is, of course, no different from a full-scale quantum computer, but certain useful quantum simulations are possible with a reduced set of quantum logic gates that is currently available in the lab. For example, we may want to know the ground state of a particular homogeneous system, such as an array of mutually coupled identical spins, or measure simple correlations between different parts of the system. Such questions are relevant to understanding condensed-matter systems in which strong interactions between particles play a key role. Their answers could lead to a better understanding of materials such as high-temperature superconductors.

These materials were discovered more than 20 years ago but we still do not understand how they lose their electrical resistance when cooled below a certain temperature. Even the simplest model that has been proposed for describing these materials – the so-called Hubbard model, which describes the hopping of repulsive fermions (particles with 1/2-integer spin) between the nodes of a periodic crystal – does not allow for reliable analytical or numerical analysis. The Heisenberg spin model, which deals with complex magnetic interactions between periodic arrays of spins, is also intractable. Despite being at the core of theoretical many-body physics for many years, even using these models to determine the ground state of a set of interacting spins can be, in some cases, an exponentially

2 Solid-state implementations of qubits



Qubits can be represented by any two-state physical system, and researchers have recently made major advances in controlling quantum states in solid-state systems. Qubits have been realized by the spin states of individual electrons confined in isolated islands of semiconductor known as quantum dots (left); micrometre-sized loops of superconducting metal, through which current must flow either clockwise or anticlockwise when an external magnetic flux is applied (middle); and the electronic spins (green arrow) of a nitrogen impurity adjacent to a vacancy in a diamond lattice and the individual nuclear spins (blue arrow) of carbon-13 atoms (right).

hard problem. In both cases the difficulty stems from the exponential growth of the number of distinct quantum states that must be considered.

To address this challenge, several groups are now trying to simulate Heisenberg spin chains and Hubbard models with cold atoms and ions (figure 3). One way to simulate Hubbard models is to use an optical lattice – an egg-box-like periodic intensity pattern formed when two or more laser beams interfere. Ultracold bosonic or fermionic atoms can be placed at the intensity extrema to create what is effectively an artificial atomic crystal. Optical-lattice systems are natural candidates for the simulation of Hubbard models because the atoms in such lattices can slowly hop between different lattice sites and the strong interactions that take place between atoms can be adjusted "by hand".

In 2003 Immanuel Bloch, Theodor Hänsch and co-workers at the University of Munich and the Max Planck Institute for Quantum Optics (MPQ) demonstrated how atoms in an optical lattice arrange themselves so that there is no more than one atom per site to form a so-called Mott insulator – a material that, according to conventional band theory, should conduct but is actually an insulator. Following that pioneering achievement, Bloch's group at the University of Mainz, as well as Trey Porto and Bill Phillips at the Joint Quantum Institute (JQI) at the University of Maryland and NIST, Tilman Esslinger at ETH Zurich and Wolfgang Ketterle at the Massachusetts Institute of Technology, have used these techniques to explore in detail a bosonic version of the Hubbard model.

In addition, in a crystal of laser-cooled trapped ions certain arrangements of laser beams can result in a "spin-dependent force" on the ions. This force indirectly couples the spins to each other via their collective motion, and when these interactions are applied to a whole collection of qubits, they allow the simulation of Heisenberg-like interactions. So far such trapped-ion systems only consist of a few atoms, but this system has the advantage of exhibiting extremely long coherence times while each and every spin can be measured with near 100% efficiency, thereby allowing experimentalists to detect arbitrary correlations between spins. These systems enable researchers to carry out controlled studies of complex many-body phenomena, which should lead to a better understanding of the quantum phases of strongly correlated condensed matter.

Interacting quantum systems, such as spins described by the Heisenberg model, generally involve entanglement. Indeed, many researchers are trying to understand the entanglement properties of strongly correlated systems so that they can be used for quantum information processing. Remarkably, however, these efforts might also yield more efficient ways to do classical simulations of certain strongly correlated states. As shown by recent theoretical work by Ignacio Cirac's group at MPQ, certain strongly correlated systems can be described by special classes of entangled states. This effectively allows researchers to reduce the relevant computational overhead and greatly speed up classical simulations of such phenomena.

Mixing it up

Cold atoms and ions are well suited to simulating strongly interacting condensed-matter systems, but they are not ideal for other quantum applications. Indeed, in general qubits based on different physical systems are each best suited for different tasks. Photons, for example, are fast and robust carriers of quantum states encoded in, say, their polarization state, thus making them a good medium by which to transmit quantum information. However, these attributes also mean that they are difficult to localize and store. Nuclear spins, on the other hand, make excellent quantum memory since they interact with their environment only via their tiny magnetic fields; but for the very same reason they are usually hard to access. Quantum bits encoded in states with different electrical charges have the advantage that they can be manipulated and measured very rapidly, even at sub-micron dimensions, with techniques that are similar to those currently used in conventional, classical circuits. But, as a rule, the charges make short-lived qubits since they are strongly coupled to their local electrical environment.

When it comes to building practical quantum information systems, therefore, we would like to be able to combine the advantages of various different qubit systems. One example of such a hybrid approach involves a so-called quantum network, in which quantum states are stored and manipulated in matter qubits and, when desired, mapped into photons for long-distance transmission. The key challenge in making such a network is developing techniques for coherently transferring quantum states carried by photons into atoms and vice versa.

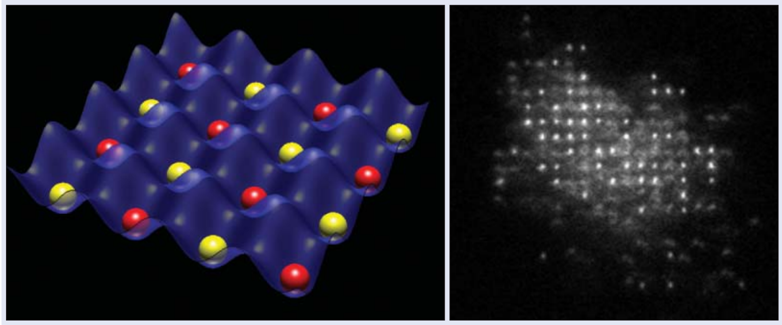
This atom–photon interface was investigated in the 1990s in pioneering work on cavity quantum electrodynamics (QED) by Serge Haroche at the ENS in Paris, Herbert Walther at the MPQ and Jeff Kimble at the California Institute of Technology (Caltech) in the US. The researchers created strong quantum interactions between strongly coupled single atoms and single photons, which allowed quantum bits to be morphed from matter to light. In these early experiments photons stored in low-loss optical cavities, in which they were kept bouncing between mirrors, were coupled to atoms held either in optical cavities or in cryogenically cooled microwave cavities. While major advances are still being made in controlling quantum states of light and atoms using these systems at Caltech, the ENS and in Gerhard Rempe's laboratory at the MPQ, similar control has also recently been achieved using many other systems.

Research groups led by Jelena Vukovic and Yoshi Yamamoto at Stanford, Imamoglu at the ETH and Jonathan Finley in Munich, for example, have recently achieved quantum control over the interaction between quantum dots and single optical photons in semiconductor cavities. Similar techniques have been used by researchers led by one of us (ML) and Hongkun Park at Harvard to couple individual solid-state emitters to individual quanta of current (known as surface plasmons) propagating along nano-sized metallic wires. These systems enable the efficient generation of indistinguishable single photons and make it possible to build single-photon switches, in which one photon can control the propagation of another. Such switches can be used to build completely new types of all-optical transistors operating at the single-quantum level.

This work, which was carried out by the quantum-optics community, inspired Schoelkopf, Devoret and Girvin at Yale to develop the field of "circuit QED", in which single superconducting qubits are coupled to a single quantum of oscillating voltage in superconducting stripline resonators microfabricated on a chip (see figure 4). Such a system allows researchers to efficiently read-out the state of the superconducting qubit and to coherently couple remote qubits via single microwave quanta. Recently the team has reported fascinating progress for the non-local coupling of superconducting quantum bits using this technique.

Many other ways of quantum mechanically coupling dissimilar qubit systems are also being explored, including the coupling of photonic and matter qubits to individual phonons in nano-mechanical resonators. This may eventually allow the quantum manipulation of mechanical motion, at which point systems of this kind could be used to test fundamental physics theories as well as to transport quantum information mechanically. Likewise, approaches involving different kinds of matter qubits are being actively investigated, such as combining isolated polar molecules or trapped ions with solid-state quantum bits. Most of this research is at a very early stage, but the key idea of combining the best of all worlds – the pristine memory of isolated spins, fast electrical control and photon-mediated long-range coupling – continues to drive exciting experimental progress in this area.

3 Quantum simulators



The small-scale quantum computers currently available, although no good for applications such as Shor's algorithm for factoring large numbers, can be used to simulate poorly understood condensed-matter systems such as high-temperature superconductors, for which our best models are too complicated to analyse with a conventional computer. One way to simulate these materials is to use an optical lattice – an egg-box-like periodic intensity pattern formed when two or more laser beams interfere (left). Ultracold bosonic or fermionic atoms can be placed at the intensity minima to create what is effectively an artificial atomic crystal. On the right is an image of individual atoms in partially filled lattice.

New architectures

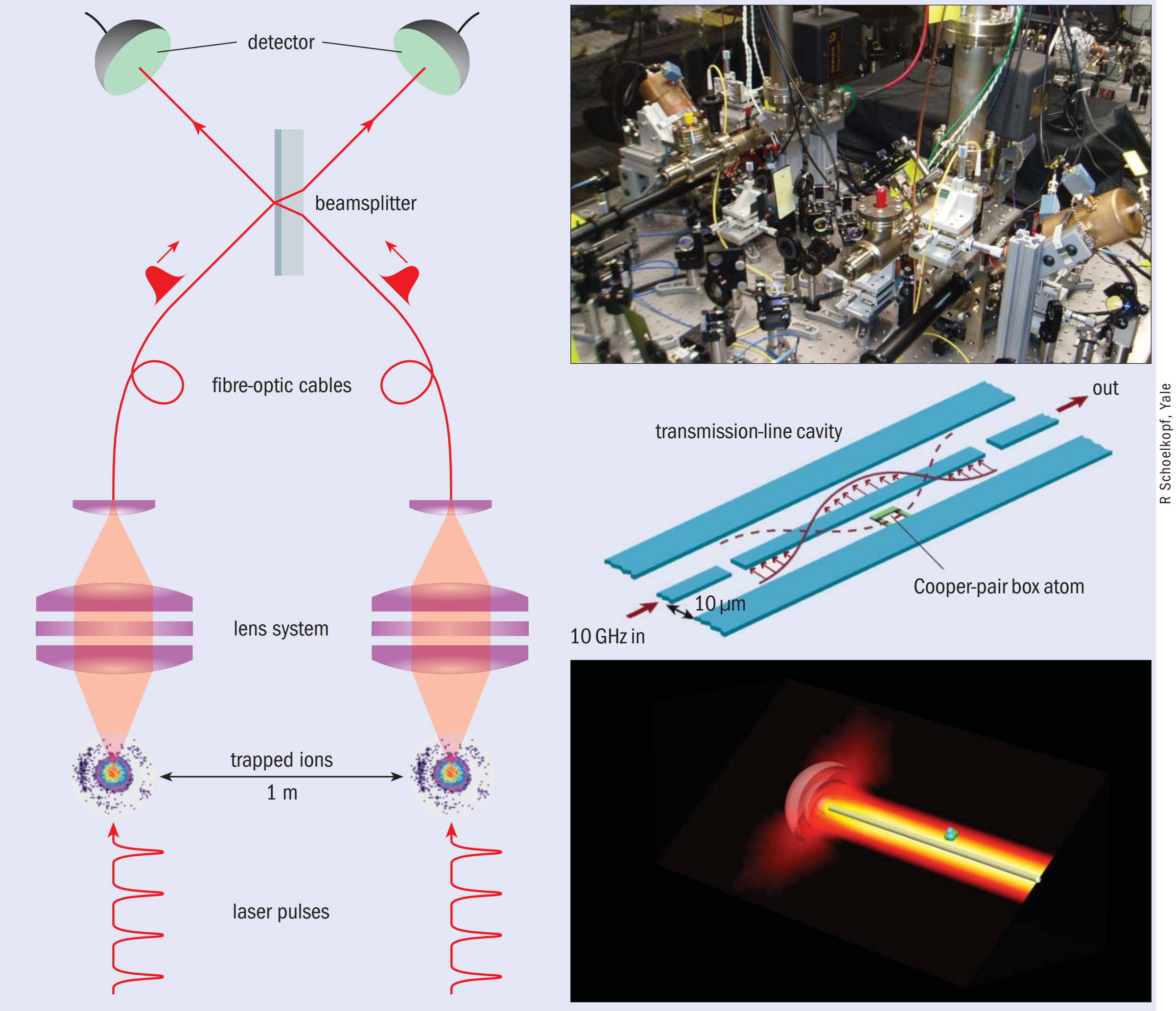
These developments are inspiring novel models and architectures for quantum information processing based on the global properties of quantum systems such as topology. An example of a "topological" quantum system is a strongly correlated quantum system that is exhibiting "frustration", which occurs in spin systems when various spin configurations compete for the lowest energy configuration. Frustrated quantum systems often have many different ground states, where the individual spins are entangled in a very complicated way. Such ground states can display highly nonlocal correlations that depend on the system's topology.

Researchers are currently trying to make and control such topological quantum systems. In particular, Alexei Kitaev at Caltech, Michael Freedman at Microsoft and Sankar Das Darma at the JQI have shown that such systems may enable "topological quantum computing". Since topological order depends only on the global properties of a system, quantum information can be encoded in such systems with remarkable resistance to most common local errors. Motivated by these ideas, researchers are now trying to identify topological degrees of freedom in natural systems such as the 2D fractional quantum Hall systems that can be obtained in very pure semiconductor samples at low temperature and specific magnetic field values. They are also investigating the emergence of such topological degrees of freedom in optical lattices and trapped-ion crystals.

Hybrid networks also open up completely new av-

A quantum network is a hybrid approach that would store and manipulate quantum states in matter qubits and map them into photons for long-distance transmission

4 Hybrid quantum systems



R Schoelkopf, Yale

In general, qubits based on different physical systems are each best suited for different tasks, so many researchers are working on hybrid quantum networks that link together two or more different types of qubit. For example, trapped ions have been shown to exhibit extremely long coherence times and near-perfect read-out, so they make great quantum memories. A photon, on the other hand, is a nearly ideal quantum communication channel, since it can travel along great distances very quickly, often without significant loss of coherence. These properties can be used to entangle two remote ions (left and top right). Each ion is first entangled with an emitted photon, which is collected by a system of lenses and directed to a 50:50 beamsplitter. Due to quantum interference, only if the two photons are in opposite quantum states will they be simultaneously detected at both output ports of the beamsplitter. This "double-click" of the detectors heralds the entanglement of the two ions, which can be used for more advanced quantum-information applications. Another example of a quantum network involves superconducting charge qubits in the form of single Cooper pairs interacting with a microwave transmission line (right middle), which allows the interconversion of matter and photonic quantum information, while a quantum dot on the surface of a nanowire can interact with propagating optical plasmonic modes on the surface of the conducting wire (right bottom).

enues for realizing large-scale quantum information systems. One such avenue currently being investigated involves making a quantum measurement on a pair of photons entangled with remote quantum "nodes", which allows those nodes to be entangled with each other. Each node can consist of a few locally coupled qubits, and the remote entanglement of several nodes can be used to wire them into a single large-scale quantum system. This concept, known as "probabilistic entanglement", was first demonstrated in 2004 by Anton Zeilinger at the University of Vienna and Nicolas Gisin at the University of Geneva in experiments involving two pairs of entangled photons. In such a scheme there is a very small probability of successful entanglement but the photon-detection events can fully guarantee that the proper entanglement was achieved. In other words, when the quantum measurement succeeds, you can be certain that the desired entanglement was created. This technique forms the basis for quantum computation using linear optics, which was proposed by Manny Knill and Raymond LaFlamme at the Los Alamos National Laboratory in the US and Gerard Milburn at the University of Queensland in Australia in 2002, and has since been used by several groups to run small quantum algorithms with multi-photon entangled states.

The probabilistic approach becomes much more powerful when used to entangle qubits represented by systems that have long-lived quantum memories, such as cold ions or nuclear spins in solids, since the memory allows one to wait until very good entanglement has been achieved. Indeed, such systems hold promise for realizing scalable quantum computers, with one of us (CM) at the JQI and Luming Duan at the University of Michigan recently taking the first step in this direction by demonstrating the entanglement of two atomic ion qubits a metre apart (figure 4). The ability to perform high-quality local operations within small quantum registers composed of ions make this system particularly attractive for these applications.

Similar techniques are now being explored for "wiring up" other quantum systems, ranging from NV centres to quantum dots, in which long-term memory is available and photons can be efficiently collected with integrated optical microcavities and nanophotonic systems. These techniques may also allow researchers to extend the range of quantum communication to long-distances (see box right). Such new approaches may someday yield a much-needed breakthrough for the realization of large-scale quantum computers.

Branching out

Despite the many recent advances in research, we are still a long way from a general-purpose quantum computer that would be able to tackle useful problems such as factoring a 1000-digit number. However, the field of quantum information science is flourishing well beyond this single application. Atomic systems such as single atoms and photons are now accompanied by quantum-condensed matter systems. Many research groups are trying to send qubits reliably over long distances, and new approaches to quantum architectures are beginning to emerge. Quantum properties of strongly correlated materials are being simulated by ultracold atoms and small "Schrödinger's cat states" involving quantum superpositions of macroscopically distinguishable states are being created and manipulated by using isolated microwave photons and atomic ions.

Several practical applications for these techniques are now starting to emerge. The entanglement of two different species of ions at NIST, for example, has been crucial to the demonstration of a new atomic clock with unprecedented accuracy, with researchers there having also recently succeeded in building chip-scale atomic clocks that will have a variety of practical uses in Global Positioning System devices and for network synchronization. Meanwhile, spin qubits in diamond have been used by researchers at Harvard and Stuttgart to demonstrate a nano-scale magnetic sensor that offers an unprecedented combination of sensitivity and spatial resolution. This device is now being exploited for unique applications in biomedical and materials science. A commercial system for quantum key distribution was even used last year to ensure the secure transmission of votes in recent national elections in Switzerland.

It is interesting to compare quantum information technology with the development of conventional electronic computers in the 1940s. The theoretical groundwork laid down by Alan Turing and Claude Shannon eventually led to the information revolution of the late 20th century. But things were not so clear early on, as Herman Goldstine, who worked on ENIAC, one of the first American electronic computers, pointed out: "The electronics people said there were too many vacuum tubes and it would never run. The mathematics people said there were no problems complex enough that computers were needed."

Today it is similarly tempting to view quantum computing as having limited applications and hardware that is extremely difficult to control and maintain. But it is likely that this view will be just as short-sighted. Recent progress is propelling quantum science in directions that are extending the domain of quantum mechanics from simple atomic, molecular and optical systems to more complex systems in condensed matter. Indeed, the most lasting impact of the recent developments may be an impetus for questioning and perhaps better understanding complex quantum behaviour at the interfaces of different areas of physical sciences and engineering.

Going the distance

The quest for a quantum computer has also led to breakthroughs in communications technology. For several years now it has been possible to transmit secure messages via quantum cryptography over short distances using single photons propagating in optical fibres. But the problem is that photons are easily blocked by optical fibres, which limits the range of direct quantum-communication techniques. Indeed, the probability of retrieving a photon from an optical fibre decreases exponentially with increasing distance, thereby making transmission impractical for distances larger than 100 km.

The photon losses in quantum channels can be overcome, however, and long-distance quantum cryptography made possible, by using a specially designed "quantum repeater" protocol. Originally proposed by theorists at the University of Innsbruck, this approach uses intermediate quantum nodes, each of which contains a small quantum computer that can store photon states for long periods of time and perform a few quantum operations. Such a system creates entanglement over long distances by building a backbone of entangled pairs between closely spaced nodes and then connecting them to one other. Quantum operations are always subject to errors, but by incorporating a quantum error-correction technique known as entanglement purification at each step, one can create long-distance, high-quality entangled pairs. Since the build-up of entanglement at each segment is a gradual process, often requiring multiple attempts, the long-term memory at each repeater node is essential for successful operation of the entire system.

Ideally, quantum repeaters would be realized using hybrid quantum systems that combine different types of qubit. In 2001, for example, researchers at Innsbruck and Harvard showed that in principle a quantum repeater could work by simply scattering light off ensembles of matter qubits, which would efficiently couple the quantum memories associated with an ensemble of atoms to quantum states of light. A number of groups are now trying to build quantum-repeater elements using such remote ensembles, while other researchers have been inspired to investigate the possibility of using systems such as trapped ions, NV centres and quantum dots where long-lived memory is available, for this application.

More about: The quantum frontier

Special issue 2008 Quantum coherence *Nature* **453** 1003–1049

M Aspelmeyer and A Zeilinger A quantum renaissance *Physics World* July pp22–28

J I Cirac and P Zoller 2004 New frontiers in quantum information with atoms and ions *Physics Today* March pp38–44

S Das Sarma, M Freedman and C Nayak 2006 Topological quantum computation *Physics Today* July pp32–38

M Greiner and S Fölling 2008 Condensed matter physics: optical lattices *Nature* **453** 736–738

C Monroe 2002 Quantum information processing with atoms and photons *Nature* **416** 238–246