**Toward Control of Large-Scale Quantum Computing**
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for some fitness variation in a field experiment in Lille, France.

Changing climates may require rapid adaptation. Adaptation based on selection on new mutations (species-wide or regionally limited selective sweeps) can be slowed down by the lack of suitable mutations, whereas selection on existing low- or intermediate frequency variants can be faster. Only selection on new mutations leaves a footprint of long tracks of correlated variants around the selected sites. Fournier *et al*. did not find such a signal, and conclude that selection has mostly been on existing variation. In contrast, Hancock *et al*. did identify this signal of selection on new mutations. These different findings remain to be explained. Recent genome-wide resequencing studies have shown that such selection on new mutations has been common in *Drosophila* (*13*) but not in the human lineage (*14*).

In addition to selection on individual loci, phenotypic data suggest that selection on quantitative traits is also important for local adaptation. Suitable methods need to be developed for finding the signals of this kind of selection in the genome (*15*).

Perhaps surprisingly, none of the top "climate adaptation" SNPs identified in (*1*) were close to the intensively studied flowering-time genes *FRI* and *FLC* (*9*). The role of these loci in governing fitness variation merits further study.

SNP-based studies cannot be used to examine all polymorphisms. The effects of the polymorphisms related to climate are only detected if they are correlated with the SNPs that were genotyped. As the *Arabidopsis* resequencing project (*16*) advances, these problems will be avoided. Improving genomic resources will also allow genome-wide studies of species with very strong signals of local adaptation.

**References and Notes**

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PHYSICS

# Toward Control of Large-Scale Quantum Computing

Basic quantum computing elements are combined to improve quantum simulations and to create a quantum version of a central processing unit.

**David P. DiVincenzo**

During the past decade, a wide array of physical systems—atoms, semiconductors, and superconductors—have been used in experiments to create the basic components of quantum-information processing. Precision control over elementary quantum two-state systems (qubits) is now well advanced, and it is now possible to ask how a complete, functioning quantum computer with many qubits would really work. In this issue, two very different steps in this direction have been taken. On page 61, Mariantoni *et al*. (*1*) examine how the basic architectural elements of a stored-program computer, as articulated originally by von Neumann, can be achieved in the quantum setting. On page 57, Lanyon *et al*. (*2*) explore how a quantum computer can be programmed. Although the physical qubits used in each study are extremely different, both attack a device-independent question of system functionality.

A vision of the possible approaches to programming a quantum computer has emerged only very tentatively in the past decade. Quantum computers will unquestionably be able someday to solve arithmetic problems that are so difficult that they are intractable for digital computing, most notably finding the prime number factors of large numbers. However, the scale of these problems in their interesting form (that is, exceeding what supercomputers could do), and the high precision of operation needed to solve them, points toward a machine containing millions of qubits.

Such large machines are many years away, so attention has focused in the near term on other problems, more directly connected to quantum physics, for which much smaller machines can be programmed to solve problems. Lanyon *et al*. present results on "digital quantum simulation," as distinct from the less powerful technique of "analog quantum simulation." The analog approach implies a direct emulation of the system to be simulated; the quantum processor is tailored to have, up to a scale, the same intra- and interqubit forces (i.e., described theoretically by the same type of Hamiltonian function) as the simulated system.

In the digital approach, the qubit Hamiltonian is fixed to be one of two (or several) optimized forms. The simulated Hamiltonian is approximated by switching rapidly between these qubit Hamiltonians, so that the average effect is correct. Parallel parking provides a good analogy of the enhanced capability of this machine. An analog simulation that emulates moving forward and backward to park on the right can do only that operation. Digital simulation implies programmability; the car can also be parked to the left with a modified application of the same basic actions. Lanyon *et al*. used up to six qubits in an ion trap, with only one type of physical coupling between them mediated by quanta of collective ion vibrations. By successive alternation of interactions, they simulated the dynamical creation of entangled quantum states in small magnetic clusters with a variety of spin interactions.

Mariantoni *et al*. attacked the very different problem of machine architecture. The superconducting device toolkit has grown in recent years to include qubits of a wide variety of constructions and characteristics, and a quantum version of computer "busses" (a classical bus transfers data between computer components; quantum busses can be created from harmonic quantum systems based on superconducting electrical resonators). Can these devices be combined to take

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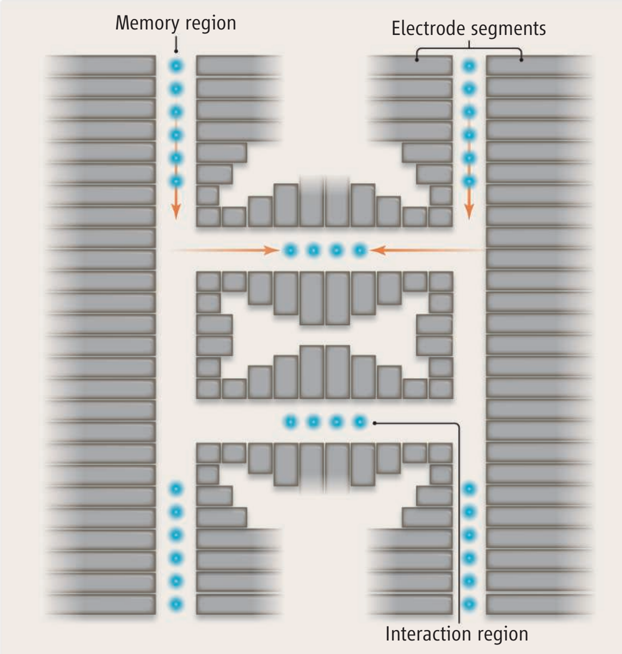


**Harnessing ion-trap qubits.** The ideas explored in Mariantoni *et al.*—creating the elements of a quantum computing architecture using superconducting circuit elements—have been previously articulated (*4*) for qubits like the ones used by Lanyon *et al.* based on trapped ions. In this vision of a quantum computer, arrays of radio-frequency electrodes trap ions. These ions (blue circles) can be moved from a memory region to an interaction region (the central processor) by changing the operating voltages on the electrodes (shown as gray bars). Slow progress has been made in realizing this vision. [Adapted from (*4*)]

advantage of their individual strengths in a processing system?

Mariantoni *et al*. used, without modification, a two-qubit structure used in previous studies (*3*) but created a new architectural interpretation of its parts. The two qubits were coupled via a resonator in such a way as to allow for rapid application of quantum operations; this is the quantum central processing unit, or quCPU, of the structure. Each qubit was also coupled separately to another resonator that was good at receiving and retaining information received from the qubits to form a quantum random-access memory element, or quRAM. The superconducting devices contained other microscopic two-level systems suitable for dumping information from the qubits so they could be reset. These systems function as reset registers, although they were not designed for that purpose. Mariantoni *et al.* used these basic circuit elements to demonstrate three-qubit operations using retrieved and re-stored data.

There is not, and there should not be, any reason that architecture is the exclusive domain of superconducting structures or that programming for digital simulation is confined to ion systems. These very basic computer engineering problems should be solvable independent of the hardware platform. Indeed, the roles have been reversed in previous studies; Mariantoni *et al.*'s hardware was previously used to demonstrate a crude quantum algorithm (*3*), and a vision for a scaled-up ion-trap quantum processor was already proposed several years ago (*4*) (see the figure). In this proposal, there is a central processor area, "cooling ions," which perform the resetting function, and side traps with a shuttling system for storing quantum information. Slow progress has been made in the experimental realization of this vision (*5*).

Before much more progress is made on these design problems, basic device metrics must be developed both in the atomic and the solid-state areas. Such metrics will evaluate coherence (how long quantum states survive) and fidelity of quantum operations (how well quantum states are being prepared and measured). Improved designs that attain an order of magnitude greater coherence times for superconducting qubits (*6*) must be adopted, and the technical limits imposed by laser intensity fluctuations in the ion system must be overcome. Only then will we start seeing quantum processors of respectable complexity and power.

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GEOCHEMISTRY

# Diamond Window into the Lower Mantle

**Ben Harte**

Tiny inclusions in diamonds reveal subduction of oceanic crust to depths of at least 700 km.

Nature's secrets are often well hidden, but painstaking investigation of minute quantities of material may unravel complex histories of mineral formation and provide major insights into Earth's evolution. On page 54 of this issue, Walter *et al.* (*1*) illustrate this point by revealing the extent of the subduction of oceanic crust into Earth's interior. They found that natural diamonds, carried to the surface by kimberlite volcanoes 92 to 95 million years ago in Juina (Brazil), contained minute (0.015 to 0.040 mm long) inclusions composed of several minerals such as nepheline, Na-kalsilite, and MgFe-spinel. These minerals are expected to form at depths of less than 200 km. However, careful investigation showed that these minerals had formed by the breakdown of other minerals known to form only at very high pressures and depths in excess of 700 km.

The principal rock compositions expected in Earth's mantle are those of basic and ultrabasic rocks. Many diamonds contain inclusions of minerals (e.g., olivine, pyroxene, garnet) formed in such rock compositions at depths of less than 200 km in continental lithosphere; but, rarely, distinct groups of other minerals are found that formed at much greater depths. The Juina kimberlite province in Brazil has been prominent in yielding such deep diamonds, including a suite indicating minerals expected in ultrabasic rocks at lower-mantle depths (>660 km). These ultrabasic inclusions are thought to have formed in slabs of oceanic

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