Quantum logic at a distance

A quantum gate is realized by optically coupling trapped atoms separated by 60 meters

By **David Hunger**

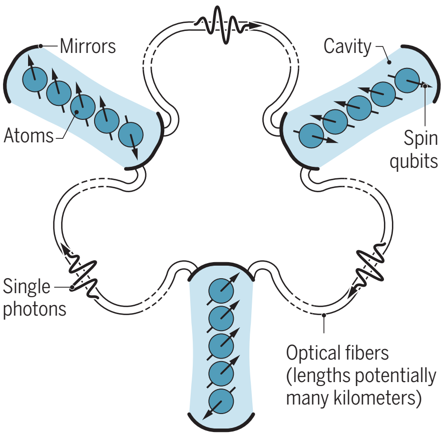
Quantum computers could revolutionize how specific computational problems are solved that remain untractable even for the world's best supercomputers. However, although the basic elements of a quantum computer realizing a register of qubits that preserve superposition states, controlling and reading out qubits individually, and performing quantum gates between them have been scaled to a few dozen qubits, millions are needed to attack problems such as integer factorization. One approach for scaling up quantum computers is to "divide and conquer" keep individual processing units smaller and connect many of them together. This approach leaves local processing nodes tractable but requires generation of entanglement and performance of quantum gates on qubits located at distant nodes to keep the advantages of quantum processing. On page 614 of this issue, Daiss *et al*. (*1*) made substantial progress toward this goal by performing quantum-logic operations on two distant qubits in an elementary network.

Entangling distant qubits in quantum networks can enable distributed computing and secure data transmission. Basic quantum networks have been demonstrated with a few different systems such as ultracold atoms (*2*), trapped ions (*3*), color centers in diamond (*4*), and superconducting qubits (*5*). By using schemes to improve the quality of initially imperfect entanglement, e.g., by so-called entanglement distillation (*6*), it should be possible to build noise-resilient, error-corrected quantum networks that perform better than their individual components (*7*). The additional benefits of improved qubit addressability, reduced cross-talk, and improved connectivity between arbitrary qubits controlled through the network connections suggest that a distributed quantum computer could outperform one large computing core.

Daiss *et al.* realized a quantum gate between two separated qubits in independent setups connected by a 60-m-long optical fiber. The qubits are implemented by internal spin states of two atoms that are trapped inside optical cavities. The qubits become connected when a single photon sent through the two setups is successively reflected from the two cavities and then detected (*8*). The presence of an atom strongly coupled to a cavity changes the reflection phase of the photon. A photon reflected off an empty resonant cavity undergoes a π phase shift. However, an atom strongly coupled to a cavity causes a frequency shift of the cavity resonance. This shift prevents photon entry upon reflection, and the reflected-photon phase remains unchanged. One qubit state of the atom, but not the other, couples strongly to the cavity, so one state does not change the photon reflection phase, and the other adds a π phase shift. An atom in a superposition state of its qubit levels will produce a corresponding superposition of the photon phase and create an atom-photon entangled state. When such an entangled photon is bounced off a second cavity and undergoes another atom-photon entangling operation with the second atom, a final state can be produced that corresponds to a NOT-gate operation.

Large-scale quantum circuits

Daiss *et al.* created quantum processors with single photons guided by optical fibers that were reflected successively by two atom–cavity devices. Scaling to multiple qubits could be achieved with large-scale photonic networks connecting optical cavities containing multiple atomic spin qubits.



The full scheme is actually more complicated and requires encoding through polarization states, a measurement of the resulting combined atom-atom state based on the photon polarization, and a conditional change of the first atom's state that depends on the measurement result. Daiss *et al.* realized a controlled-NOT gate with <15% deviation from the ideal gate performance. Together with the simpler single-qubit gates, this result represents a complete toolbox to implement any kind of quantum logic operation. The scheme is heralded, meaning that it produces a measurable signal when the gate operation is successful and becomes immune against photon loss as an error source.

At a first glance, the scheme requires surprisingly few resources only a single photon that is reflected successively by two atom-cavity devices. Indeed, strong atom-cavity coupling makes the scheme efficient as it increased the probability that the photon is reflected rather than lost through processes such as spontaneous emission. However, realizing such strongly coupled atom-cavity systems requires overcoming hurdles that include atom control, cavity performance, atomic coherence, and minimized photon loss. Also, the experiment was not yet operated with single photons but with attenuated laser pulses, which is easier to do but introduces errors caused by the presence of two-photon contributions and enforces low average photon numbers.

Although all of these issues limit the efficiency and fidelity of the gate demonstrated by Daiss *et al.*, none of them introduce fundamental limits and could be improved in the future. Thus, it should be possible to scale up the system (see the figure). For example, multiple atoms coupled to a single cavity could allow the reflection of a single photon to immediately produce an *N*-qubit Toffoli gate (*8*), an element of the Grover's search algorithm. Also, elegant ways for scaling multiple cavities in interferometer-type configurations have been proposed (*9*) in which a single photon can generate an entangling quantum gate between any selected qubits in a network. Although formidable challenges remain, it is intriguing to imagine the possibilities when distributed quantum computers form a quantum internet (*10*, *11*). ■

Physikalisches Institut, Institute for Quantum Materials
and Technologies, Karlsruhe Institute of Technology (KIT),
Wolfgang Gaede Strasse 1 76131 Karlsruhe, Germany.
Email: david.hunger@kit.edu

REFERENCES

1. S. Daiss *et al.*, *Science* **371**, 614 (2021).
2. S. Ritter *et al.*, *Nature* **484**, 195 (2012).
3. D. L. Moehring *et al.*, *Nature* **449**, 68 (2007).
4. P. C. Humphreys *et al.*, *Nature* **558**, 268 (2018).
5. N. Roch *et al.*, *Phys. Rev. Lett.* **112**, 170501 (2014).
6. N. Kalb *et al.*, *Science* **356**, 928 (2017).
7. N. H. Nickerson, J. F. Fitzsimons, S. C. Benjamin, *Phys. Rev. X* **4**, 041041 (2014).
8. L. M. Duan, B. Wang, H. J. Kimble, *Phys. Rev. A* **72**, 032333 (2005).
9. I. Cohen, K. Molmer, *Phys. Rev. A* **98**, 030302 (R) (2018).
10. H. J. Kimble, *Nature* **453**, 1023 (2008).
11. S. Wehner, D. Elkouss, R. Hanson, *Science* **362**, eaam9288 (2018).