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Design links quantum bits

By Eric Smalley, Technology Research News

Much of today's effort to build quantum computers, which would use the attributes of atoms and subatomic particles to carry out blazingly fast computations, is focused on finding the best way to make quantum bits, or qubits, the basic building blocks needed to represent and process information using the quirks of quantum physics.

But getting quantum computing off the ground also means connecting thousands of qubits in much the same way transistors are wired together in ordinary computer chips.

Researchers at the Institute of Physical and Chemical Research (Riken) in Japan have moved a step toward making these connections with a design that calls for qubits made from tiny loops on superconducting material. The researchers have worked out a way to connect the loops so that they can efficiently carry out all the basic logic operations a quantum computer needs, according to Franco Nori, head of the digital materials laboratory at Riken and an associate professor of physics at the University of Michigan.

The payoff could be enormous; quantum computers have the potential to solve problems like cracking secret codes and searching large databases that are beyond the reach of the most powerful classical computer possible.

The loops provide access to the properties of subatomic particles because electrons pair up when they flow through a superconductor, and billions of electron pairs can be merged into a single entity that behaves as one giant subatomic particle in superconducting loops that have one or more small breaks, or Josephson junctions.

When one or two of the loops are connected to a reservoir of electron pairs, the number of pairs in the reservoir can be reliably changed by exactly one pair, which changes the reservoir's charge in a measurable way.

The two charge states can represent the 1s and 0s of computing. And because the electron pairs behave as one subatomic particle that follows the weird laws of quantum physics, the reservoir can be in both states at once. This characteristic is the basis of quantum computing's potential power.

The loops can be mass-produced using standard chipmaking processes, but linking the qubits requires more than simply wiring them together. The quantum states produced by the loops are fragile, and linking them also requires the presence of a carefully tuned magnetic field.

Other designs for building quantum computers from superconductor loops include ways to link neighboring qubits, but can only pair distant qubits in a bucket-brigade fashion through intervening qubits, which slows computing, said Nori. "A scalable quantum computer needs to couple any selected pairs of qubits, [whether they are] neighboring or far away," he said.

Time is of the essence in quantum computing because the quantum states that are used to store and manipulate information last for only fractions of a second, and the computers need to perform thousands of operations before the qubits decohere, or break down.

The Riken researchers' design can be likened to a series of water tanks connected by pipes that contain valves that can open a flow between any two tanks. The tanks represent qubits and the pipes the superconducting circuits between them.

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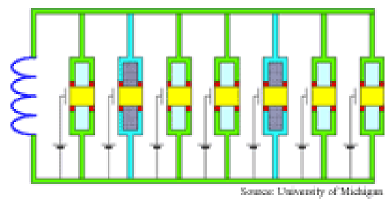

This diagram shows seven quantum bits. Each qubit consists of an electric charge reservoir (yellow box), super-conducting electrodes (green or blue forks), and tiny electrical barriers, or Josephson junctions (red dots). A tuned magnetic field opens and closes the flow of electricity between qubits, allowing researchers to link any two in the set.

Opening the correct valves by applying a magnetic field sends an electric current flowing between specific qubits, which makes it possible to link the qubits in the bizarre quantum state of entanglement.

When a subatomic particle or atom is isolated from the environment, it enters into superposition, meaning it is in some mixture of all possible states. Like a top, a particle can spin in one of two directions, but in superposition the particle spins in some mixture of both directions at the same time.

When two or more particles in superposition come into contact with each other, they can become entangled, meaning one or more of their properties, like spin or polarization, become locked together. This is a useful property for computing: if a pair of entangled photons have linked polarizations, when one of the photons is knocked out of superposition and becomes vertically polarized, the other photon leaves superposition at the same instant and also becomes vertically polarized, regardless of the distance between them.

Entanglement is key to quantum computing's potential speed: it will allow a computer to check every possible answer to a problem with one series of operations across a group of entangled particles rather than having to check each possible answer one by one.

The researchers' design provides an efficient way of implementing two key quantum logic circuits, or gates: CNOT and conditional phase shift. Each gate uses two qubits. In a CNOT gate, one of the qubits is a control bit and the other is a target bit. If the control bit is 1, the target bit changes -- either from 0 to 1 or 1 to 0. If the control bit is zero, the target bit does not change. The operation entangles the two qubits. A conditional phase shift synchronizes two qubits.

These two types of gates, together with gates made from single qubits, form the basic logic of quantum computing, said Nori. "All quantum computing operations can be decomposed into these gates and the basic one-bit gates," he said. One-bit gates change the state of a single qubit to, for example, reverse the spin of an electron to change it from a 1 to a 0.

Existing schemes to build quantum computers from superconducting loops require several two-qubit operations rather than just one to make up CNOT and conditional phase shift gates, said Nori. Because two-qubit operations are time-consuming, it is important to use as few as possible in order to get the most out of the limited lifetimes of the quantum states, he said.

A CNOT gate that requires only a single two-bit operation is a distinct advantage, said Jens Siewert, a staff member of the Institute for Theoretical Physics at the University of Regensburg in Germany.

The researchers' work is an engineering rather than a conceptual contribution, said Yuriy Makhlin, a staff member of the Institute for Theoretical Physics at the University of Karlsruhe in Germany. When techniques for manipulating two or three qubits become well-established, it will be important to build circuits with larger numbers of qubits and to optimize their design, he said. "Already at this stage one has to plan ahead."

There's a long way go before researchers can build practical quantum computers, which will have thousands of qubits, said Nori. "The first step is to make good working qubits, then the next step is to couple two, and then three," he said. Performing logic operations with the qubits and reading the results are also difficult problems, he added.

The researchers next steps are to improve the circuit designs to gain more reliable and less disruptive readout of the qubits, and to extend the amount of time information stored by qubit lasts before it decoheres, said Nori. "There are many steps involved in designing and building a quantum computer," he said. "Our group is aiming at identifying and working on key steps; the work is scheduled to last a decade or longer."

There is broad agreement in the research community that it could take two decades or longer to develop practical quantum computers. "The PCs we are using now on our desks are quite different from the first computing machines of the 1930s and 1940s," said Nori. "It took over half a century to get to our PCs. It might also take decades for this new type of computing to become widespread," he said.

Nori's research colleagues were J. Q. You of Riken and Jaw-Shen Tsai of Riken and NEC Research. They published the research in the November 4, 2002 issue of the journal Physical Review Letters. The research was funded by the National Security Agency (NSA) Advanced Research and Development Activity (ARDA), the Air Force Office of Scientific Research (AFOSR), the National Science Foundation (NSF), and Riken.

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