Quantum Bits

Assembling a quantum computer

By IVARS PETERSON

"I call it the Oxford flu," Rolf Landauer declared at a recent workshop on physics and computation. "In a large audience like this, there are always a few carriers of the new epidemic, and I want to give you a vaccination."

This was Landauer's way of injecting a dose of reality into a heady brew of theory and speculation about the prospects of constructing a quantum computer. A fellow at the IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y., Landauer has long served up antidotes to the unbridled euphoria and unwarranted optimism that often accompany visions of future technologies.

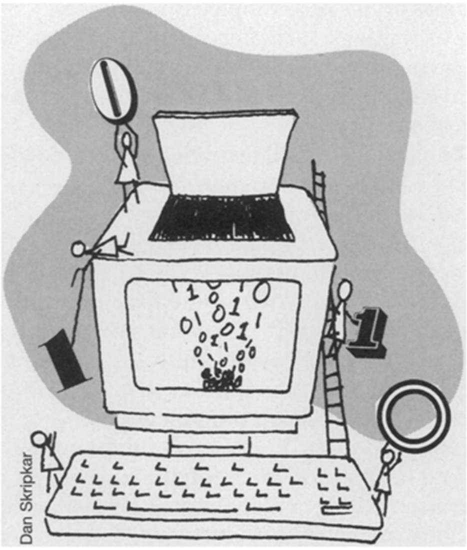
"We have to be honest about the problems in new, adventurous proposals," Landauer insists. The possibility of moving toward quantum mechanical procedures for information processing is beset with difficulties, he says.

The current outbreak can be traced back to 1981, when the late Richard P. Feynman noted that physicists always seem to run into computational problems when they try to simulate a system in which quantum mechanics plays a dominant role. The necessary calculations — involving the behavior of atoms, electrons, or photons — invariably require huge amounts of time on a conventional computer. Feynman suggested that a computer based on some sort of quantum logic might circumvent the problem.

In 1985, David Deutsch of the University of Oxford in England provided the first theoretical description of how a quantum computer might work. Deutsch and a number of collaborators gradually refined these ideas, and they established that a quantum computer could perform certain logical operations that a conventional computer cannot.

Researchers also began looking into the feasibility of actually constructing such a device. These efforts received a boost last year when mathematician Peter W. Shor of AT&T Bell Laboratories in Murray Hill, N.J., made the startling discovery that, in principle, quantum computation can greatly speed the factoring of whole numbers (SN: 5/14/94, p.308).

Building a quantum computer became more than just another step in the miniaturization of computer circuitry to achieve higher computational speeds and greater energy efficiency. Such a computer could also offer special advantages for solving certain mathematical problems encountered in cryptography and other important applications.


Dan Skripkar

The challenge of making this vision more than the stuff of dreams proved irresistible to many, even as they contemplated the immense practical problems involved in such a venture. Although formidable difficulties are to be expected, "there is hope at the end of the tunnel that quantum computers may one day become a reality," says Gilles Brassard of the University of Montreal in Quebec.

Both the promise of this potentially revolutionary technology and the significant obstacles in its way were addressed at a number of meetings that took place during the past year, including the physics and computation workshop held last November in Dallas.

The theory of quantum mechanics provides a remarkably complete, accurate description of the behavior of atoms, electrons, photons, and other entities on a microscopic scale. Nonetheless, in the everyday world, one doesn't often need to think about this small-scale behavior. For instance, a knowledge of quantum mechanics isn't really necessary for designing, manufacturing, or using a screwdriver — even though the hardness and toughness of its metal tip depend on quantum mechanical interactions.

Similarly, it isn't necessary to go back to the fundamental theory, as expressed by the Schrödinger equation, to understand enough about how a conventional transistor works to use it appropriately. Simple models involving the motion of electrons and "holes" are adequate for determining its overall behavior.

Ordinary, or classical, computers rely on vast arrays of miniature transistors, arranged into logical units called gates, to perform their calculations. They typically use the presence or absence of certain amounts of electrical charge to represent the 1s and 0s of a computer's binary code. Each individual bit must be either a 0 or a 1, and quantum mechanics doesn't enter into the computations themselves.

In contrast, quantum computation invokes quantum mechanics in a far more explicit manner. Encoded using two different energy levels of a particle, each bit in a quantum computer can exist as a combination of the two possible particle states. The 1 and 0 states are said to be entangled. It is only when the particle is observed — detected by some instrument — that it settles into one or the other of the two states.

One can program a conventional computer to select — according to the laws of probability — one of several possible computational paths to arrive at an answer. In any specific instance of the calculation, only one of the potential paths is taken, and the choices not made have no influence on the calculation's outcome.

In contrast, "what makes quantum computation so powerful — and mysterious — is that all potential computational paths are taken simultaneously in a single piece of hardware, in accord with the superposition principle of quantum mechanics," Brassard says. All the possible paths interfere with one another in much the same way that overlapping waves of water can cancel or reinforce each other. Such quantum interference, or superposition, adds a logical element that's missing from classical computation.

The trick is to program the computer so that the computational paths that yield undesirable results cancel each other out, whereas the "good" computational paths reinforce each other, Brassard says.

To turn a quantum system into a computer, however, one must be able to program it, verify that the computation has been completed, and extract the results of the calculation.

Researchers have looked at several candidate systems. One approach involves the use of electrons, atoms, or ions trapped inside webs of magnetic and electric fields, intersecting laser beams, or cages of atoms. Exposing such a confined particle to a pulse of laser light of precisely the right wavelength and duration can readily kick it into an excited energy state; a second laser pulse can restore it to its ground state.

By applying the proper sequence of pulses, one can presumably place an array of these particles into any desired pattern of states, including superpositions of the excited and ground states.

Seth Lloyd of the Massachusetts Institute of Technology has proposed assembling a quantum computer out of organometallic polymers — long, one-dimensional molecules made up of short, repeating sequences of atoms. In such a polymer, the possible energy states of any given atom are determined in part by its interactions with neighboring atoms.

Using laser pulses of specific frequencies, it's possible to send signals down the polymer chain in a manner analogous to electrons flowing down a wire. Moreover, because atoms at the two ends of a polymer chain have neighbors on only one side, they have unique energy states. Subjecting the polymer to light at one of these energies affects only the ends. Thus, these states can be used to load information onto a chain or to pull it off.

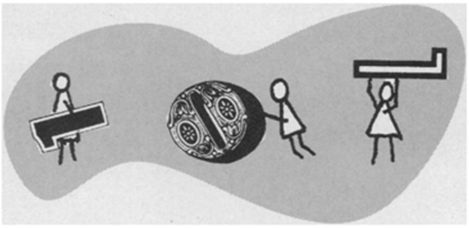
The same procedure could work in a crystal, which is made up of three-dimensional repeating units. In this case, shining light of different frequencies onto the crystal would excite different types of vibrations of the crystal's atoms. Each mode of vibration would correspond to information being stored in a particular way. Additional laser pulses would allow one to process this information.

David P. DiVincenzo and John Smolin of IBM have suggested an alternative approach based on creating quantum logic gates, perhaps out of arrays of nuclear spins or ions in traps. These quantum systems have the advantage of being long-lasting. Relatively isolated, the particles remain in a given energy state for lengthy periods.

One can imagine "programming" an array of atomic nuclei (spinning either clockwise or counterclockwise) using the needle tip of an atomic force microscope. The atomic nucleus at the tip has a particular spin, and bringing this tip near nuclei on a surface can "read" or even alter their spins.

"I'm not picking an atom off the surface and moving it around," DiVincenzo says. "I'm simply reading off a logical state and transporting [this state] elsewhere, which is really what we need to get quantum-coherent computation."

"Using repetitive motions of the tip, you could eventually write out any desired logic circuit," he adds.



Maintaining the delicate superposition of states that makes quantum computation potentially so powerful is no simple matter. A quantum computer must operate in pristine isolation, undisturbed by even a single stray photon, electron, or atom. Any such defect destroys a quantum interference pattern, much as protruding rocks disorder ripples moving across the surface of a pond.

It's hard to imagine any real physical system meeting the standards of perfection required for quantum computation. "No machinery is perfect," Landauer notes.

He points out that in a real material, the presence of structural defects and the "noise" of atomic vibrations would readily swamp a quantum computation. Small errors would accumulate, causing the computation to wander off track. A computation could even turn around and end up going backward. Such a quantum computer would be prone to producing lots of random and irrelevant signals.

That's much less of a problem in a conventional computer because the circuitry is designed to boost signals, representing 1s and 0s, back to their intended values at every stage of a computation. "It is this feature — the stability of the 1 and 0 states — that ensures the success of the digital computer," Landauer says. No such direct intervention to correct errors or restore signals is possible in a quantum computer without affecting the computation itself.

Researchers have suggested several ways to overcome this deficiency. One is to keep the computations extremely short, thus reducing the chances of an error. Another is to store redundant copies of the information in an ensemble of quantum computers, do the same calculation on all the machines, then take the answer that comes up most often as the true result.

André Berthiaume of the University of Montreal, Oxford's Deutsch, and their colleagues are trying to work out a purely quantum mechanical form of error correction for use in a quantum computer. "Like the classical methods, it utilizes redundancy, but it does not depend on measuring intermediate results of the computation," the researchers say.

However, in its current form, this particular theoretical scheme appears extremely inefficient, nearly wiping out any advantages quantum computation may have over classical computation. And it isn't at all obvious how one would go about implementing such a strategy in hardware.

At present, researchers interested in the practical aspects of quantum computing are focusing on constructing and operating a single quantum logic gate. Such an arrangement of components performs a particular logical operation. For example, a certain type of gate may switch a 1 to a 0 and vice versa, and another type could take two bits and make the result 0 if both bits are the same and 1 if they are different.

It may be possible to construct such gates from rows of ions held in a magnetic trap or single atoms passing through a microwave cavity. "I wouldn't be surprised if somebody actually demonstrates some kind of quantum logical gate in the next year or two," says Paul S. Julienne of the National Institute of Standards and Technology in Gaithersburg, Md.

But that's a long way from a practical computer, which must have millions of gates.

Landauer's efforts to vaccinate researchers against the Oxford flu have had some effect. "Exposure to Landauer has made me very cautious about making any predictions," DiVincenzo admits. "But I think we're going to make a lot of progress in the next few years, and from there, we'll see how it goes."

"I'm telling the IBM management not to worry about it for the next 10 years," he adds. "I think that's a safe statement."

Meanwhile, researchers are enjoying the chance to explore some new possibilities for manipulating atoms, electrons, and photons in decidedly quantum mechanical realms. "Quantum computation casts a unique light on some aspects of quantum mechanics that are worth pursuing, and it may in fact lead to some new insights," says William G. Unruh of the University of British Columbia in Vancouver.

"Even if one can't do a full-blown quantum calculation, let alone factor a large number, I think one will end up with some very interesting physics coming out of the effort," Lloyd says. "We may be able to create weird states of matter that exhibit unusual properties."

"Quantum computing is not some sort of disease that one has to get over," Unruh remarks. "Rather, I would say that the practical problems standing in the way of implementing quantum computers are diseases that someone must try to cure to actually achieve the promise of this exciting field. If we don't recognize them, think about them, and worry about them, the problems won't get solved." □