The future of computing -- carbon nanotubes and superconductors to replace the silicon chip

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The future of computing is under the spotlight at the Institute of Physics' Condensed Matter and Materials Physics conference at the Royal Holloway College of the University of London on 26-28 March.

The silicon chip, which has supplied several decades' worth of remarkable increases in computing power and speed, looks unlikely to be capable of sustaining this pace for more than another decade – in fact, in a plenary talk at the conference, Suman Datta of Pennsylvania State University, USA, gives the conventional silicon chip no longer than four years left to run.

As silicon computer circuitry gets ever smaller in the quest to pack more components into smaller areas on a chip, eventually the miniaturized electronic devices are undermined by fundamental physical limits. They start to become leaky, making them incapable of holding onto digital information. So if the steady increases in computing capability that we have come to take for granted are to continue, some new technology will have to take over from silicon.

Replacing the chip with carbon nanotubes

At the conference, researchers at Leeds University in the UK will report an important step towards one prospective replacement. Carbon nanotubes, discovered in 1991, are tubes of pure carbon just a few nanometres wide – about the width of a typical protein molecule, and tens of thousands of times thinner than a human hair. Because they conduct electricity, they have been proposed as ready-made molecular-scale wires for making electronic circuitry.

Some nanotubes behave as semiconductors, like silicon; others carry electric currents like metal wires. Already, fundamental elements of computer circuits such as transistors have been made from individual carbon nanotubes.

But the problem is arranging nanotubes into circuit patterns. One particular difficulty is that they are typically made as mixtures of metallic and semiconducting tubes, whereas just one type or the other is needed for a specific component. These electrical properties depend on the precise arrangement of carbon atoms in the nanotube, but that's hard to determine for single tubes.

Bryan Hickey and his coworkers at Leeds have now developed a technique that will reveal an individual nanotube's structure (and thus its electrical properties), and then allow it to be placed in a position on a surface with an accuracy of about 100 nanometres, a fraction of the width of a human blood cell. The nanotubes are grown on a perforated ceramic grid, and tubes lying across the holes are examined in an electron microscope to deduce their atomic structures. Then the researchers use two needle-fine tips like tweezers to pick up a single tube under the microscope and put back down on another surface.

Chris Allen, one of the Leeds teams, says, "With this technique we can make carbon nanotube devices of a complexity that is not achievable by most other means."

Boosting computer power with superconductors

Two further talks at the meeting will describe an even more dramatic way to overcome the limitations of silicon computers. Hans Mooij of the Delft University of Technology in the Netherlands and Raymond Simmons of the National Institute of Standards and Technology in Boulder, Colorado, USA, will claim that superconductors – materials that conduct electricity with zero electrical resistance – can harness the power of quantum physics to boost computer power tremendously.

So-called quantum computers have become one of the hottest items in physics over the past decade. They attempt to improve on the power of silicon not by making components smaller but by exploiting the counterintuitive principles of quantum mechanics, the theory generally used to understand how objects behave at the scale of atoms and subatomic particles.

Objects governed by quantum theory can be in several different states at once, like a light switch being simultaneously 'on' and 'off'. These 'superposition' states don't correspond to anything familiar from our everyday world, but countless experiments have proved that they can exist so long as the quantum objects are not disturbed by, for example, making a measurement on them.

In a quantum computer, the equivalent of 'bits' that hold binary information as 1's and 0's in today's computers will be quantum bits or qubits, which can also exist as superpositions of 1's and 0's. This massively increases the amount of information that can be encoded in a quantum computer's memory. The catch is that superpositions are extremely delicate and hard to maintain, especially in memories containing large numbers of qubits that interact with one another.

Various candidates for making qubits are being explored, such as magnetically trapped atoms or nanometre-scale blobs of semiconductors. But it has long been recognized that loops of superconducting material can also be placed in quantum superposition states, and thus act as qubits. Here the quantum states may correspond to an electric current circulating round the ring in one direction or the other. (In superconductors this circulation can continue more or less indefinitely without petering out, because there is no electrical resistance.)

At the conference, Simmonds will describe the first demonstration of information being transmitted between two such superconducting qubits. This shows that elements of this kind can act as a quantum-computing memory and a "bus" for qubits to communicate with one another, an essential requirement of any working computer.

The two superconducting loops are made from thin wires of aluminium laid down on a slice of sapphire and cooled to less than 0.1 degrees of absolute zero to make them superconducting. They sit just a millimetre apart, but are connected by a meandering waveguide 7 mm long – a kind of light channel, like an optical fibre, but for microwaves. The superposition state of one qubit can be transferred into a microwave electrical vibration of the waveguide, like plucking a guitar string. This microwave "photon" of energy recording the first qubit's state can then be controllably transferred to the other qubit – crucially, without destroying these delicate quantum states.

Mooij was part of a group that first demonstrated in 2000 that such superconducting loops can be placed in quantum superposition states. He will describe the progress that he and others have made since then, both in making practical quantum devices and in using them to explore fundamental aspects of quantum mechanics, such as whether and how the 'quantum weirdness' of superpositions can survive when the objects concerned get much larger than atoms.

Mooij says that one of the biggest challenges in making quantum computers this way is to progress from two to three qubits that communicate with each other. He says that the particular approach he and his colleagues have been developing has the advantage that, if this can be achieved, scaling up further won't be too difficult.

Mooij says, "With our qubit, once we have three set up we can move on to twenty or fifty."

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