Research Matters
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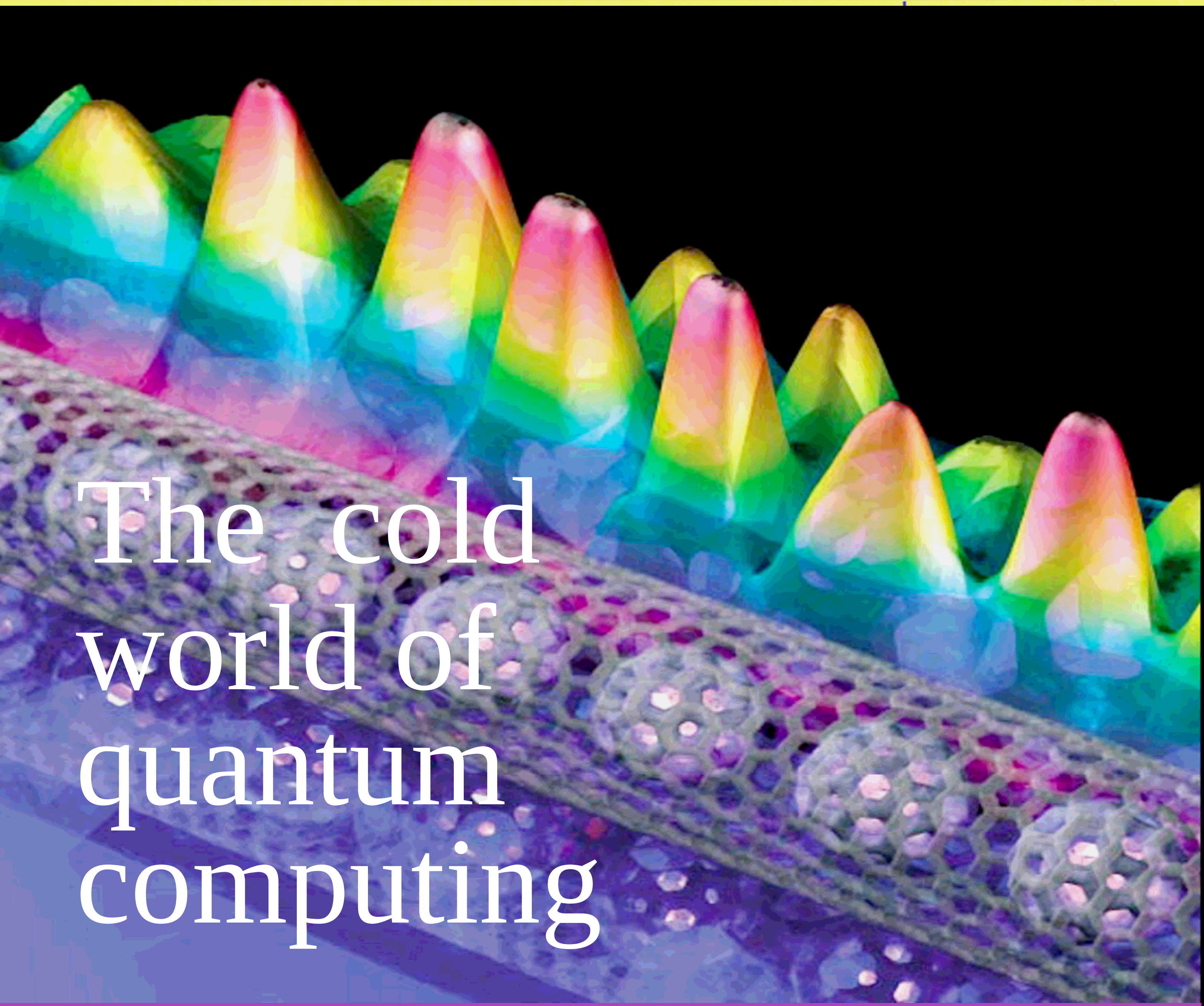


The cold world of quantum computing

The world’s most powerful supercomputer, the Earth Simulator, has a peak performance of 40 tera-flops (one Tflop equals a trillion floating-point arithmetic operations per second). Although the majority of PC users may find this much processing power hard to comprehend, systems such as these may, in future, be made obsolete by a totally different approach. Quantum computing offers not only much faster computers but also a whole new way of processing information.

Quantum bits

In a classical computer, the basic unit of information is the ‘bit’, which can exist in one of two possible states, e.g., yes/no (or 0/1, as used in binary language). Quantum computers make use of quantum bits (qubits), which can exist in a superposition of both states, e.g. a mixture of both 0 and 1 simultaneously. Qubits are also subject to quantum entanglement. When two or more qubits are entangled, they behave as one system, so that the state of one qubit depends directly on the state of the others. Entanglement has the consequence that the potential processing power of a quantum information system increases exponentially with the number of qubits, rather than linearly in a classical system.

Although the principles behind quantum computing have been established and small model systems constructed, it still remains a considerable task to scale these up to practical, working computers. This is certainly worth doing, however, as it would enable certain types of computation that are currently, if not impossible using classical computers, then certainly impractical within a sensible timescale. A raft of potential applications includes bioinformatics, molecular modelling, codebreaking and encryption. Quantum computers could also be used as simulators to solve quantum mechanics problems.

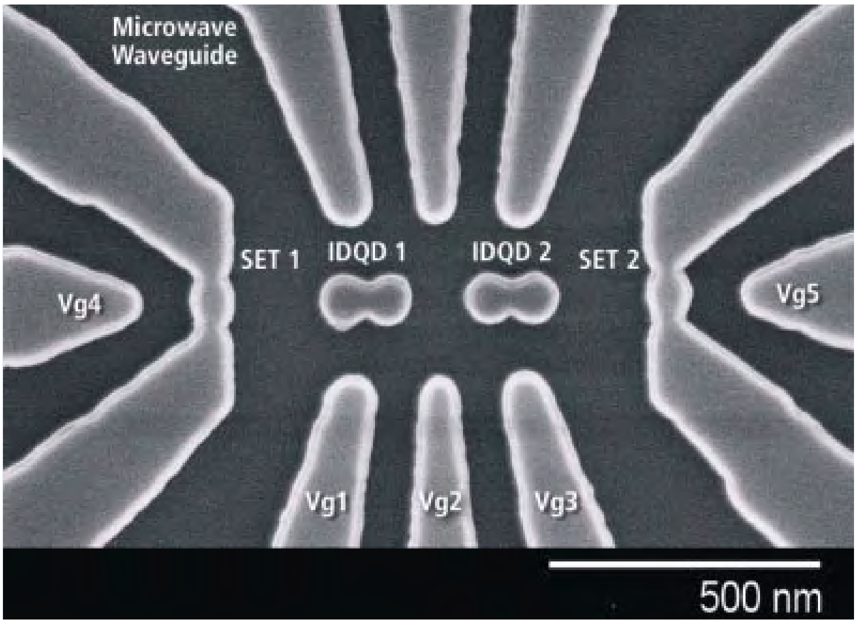
From theory to practice

A new project, run jointly by Oxford Instruments Superconductivity, Hitachi, Oxford and Cambridge Universities and Rutherford Laboratories aims to build a custom platform for the development of qubit technology. Hitachi Europe works in close collaboration with the Microelectronics Research Centre (MRC, part of the Cavendish Laboratory at Cambridge University) with the MRC specialising in construction of the components, and the Hitachi laboratory experts in testing them. Hitachi were also the first to demonstrate single electron memory cells and logic, work which has helped to form the basis of subsequent quantum computing research. The laboratory is currently investigating solid state systems, using materials including silicon, gallium arsenide and carbon nanotubes.

Creating the right environment for quantum computing

There are several challenges to be met before a practical quantum computer can be built, with some of the current issues being:

- Algorithm development – there are currently only two suitable algorithms available (although some have already been described for error correction). There is little point in being able to construct the necessary hardware if no software exists that can fully take advantage of the power offered by quantum systems.
- Maintaining quantum entanglement – the link between qubits needs to be maintained for long enough to carry out calculations.
- Hardware architecture – the structure used needs to be able to produce uniform qubits and to enable the user to manipulate them without interfering with conditions needed for quantum information processing.



A scanning electron micrograph of two silicon qubits integrated with gates and electrometers, made by electron-beam lithography. Courtesy of Emir Emiroglu, Cambridge University.

A very cold answer

Cryogenics may provide a means of achieving a working quantum computer using ultra-low temperatures to preserve quantum coherence and remove any thermal processes that could interfere with computations. Systems will probably have to be tested at mK temperatures, with 4.2 Kelvin or lower needed for the first operational computers.

Superconducting magnets will also form an essential part of the computer, as electron spin can form the basis of the qubit. Magnets of up to 18 Tesla may be needed to control electron behaviour, e.g. trajectory and spin orientation. Factors such as magnet field homogeneity, strength and stability will all be essential in ensuring these can be controlled effectively.

A quantum computing platform will most likely include a dilution refrigerator and a superconducting magnet, together with custom-built electronics working at between 50 mK and 4.2 K. These electronics will act as the control and measurement interface between the computer (working at mK temperatures) and the operator interface (working at room temp). One of the major challenges here will be to block out heat leak and electromagnetic interference from wires extending from the room temperature interface into the computer itself. Additionally, the researchers will need to know what the system's initial entanglement states are, preserve this known entanglement, and also know what processes are taking place during computation.

Conclusions

Although quantum computers are currently in the early stages of development, small model systems have already been demonstrated and the potential power and number of applications remains huge. Indeed, many more applications may become apparent once larger working models have been built and more algorithms have been tested. Although the origins of this discipline are in highly specialised theoretical physics, the potential applications may have a dramatic impact on everyone from physicists to pharmaceutical chemists.

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