

QUANTUM COMPUTING

Against the odds of imperfection

For a 'real life' quantum computer, mere capability is not good enough. It also has to defy disturbances attempting to weaken its special powers. To succeed, the task has to be addressed on various levels.

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The technologies on which future quantum computers will be based is still an open question today. It is clear, however, that these devices will be composed of components that just cannot be perfect. But does this imply that the accuracy of quantum computations can only go so far? Consider, for example, a quantum computer made from semiconductor materials, one of the proposed platforms. Such a solution would bring along the marriage of two giants: the future potential of computational feats impossible to achieve in the classical world could be tapped using the enormous — and already existing — infrastructure of the semiconductor microchip industry. The task of practically unlimited replication of basic data structures and control units seems to be mainly of a technological nature. However, how to operate the resulting structure in the presence of inevitable imperfections is far less clear. Taylor and co-workers¹, reporting on page 177 of this issue, come forward with a proposal for how to tackle a whole host of problems that such a quantum computer based on semiconductor technology will have to face, and thus highlight a route to complete perfection.

The emergence of a perfect device constructed from imperfect components — as counterintuitive as it sounds — was already a concern in the early days of classical computers, when they were constructed out of notoriously unreliable vacuum tubes. This prompted John von Neumann to develop a theory of fault-tolerant classical computation². The theory was generalized fairly recently to the quantum setting, including elegant proofs that it is, in principle, possible to achieve quantum fault tolerance^{3,4} — in the sense that arbitrarily accurate quantum computation is achievable, provided that the initial errors are below a threshold value. Taylor *et al.*¹, however, lift quantum fault tolerance to a new level: rather than considering an abstract and idealized model, the authors focus on a very specific architecture, based on 'real' — and already realized⁵ — quantum bits (qubits) encoded into pairs of electrons localized

in nanosize structures of a semiconductor crystal, known as 'quantum dots'.

They consider in detail the many different sources of errors potentially afflicting their system, and devise a comprehensive strategy for suppressing these errors to a degree that fault-tolerant operation becomes possible. The proposed strategy is multilayered, and Taylor *et al.* reach deep into the bag of tricks available to the quantum-computer architect. Such a 'hybrid approach', combining strategies to avoid errors and — where this is not possible — to correct for them, has been advocated before⁶, but the feat accomplished by Taylor and colleagues is that they carefully mesh all these pieces of quantum armour together into one coherent strategy that seems to fit their particular architecture remarkably well.

The first layer of protection concerns the basic data-structure considered: the qubit, which consists of two electrons confined in the combined potential well of two quantum dots. Taking the spin into account, these electrons can be in any superposition of four different basis states. In the choice of their qubit — picking, from all possible states, one state to represent '1', and another to represent '0' — Taylor *et al.* ensured that no noise process could disturb the configuration. This involves, on the one hand, passive protection against processes that affect both electrons in the same manner (such as large-scale magnetic field fluctuations); the symmetry of the states makes it inherently impossible for such a trouble-maker to turn a 1 into a 0 or vice versa. On the other hand, to tame processes that act independently on each of the two electrons (in particular the respective magnetic fields created by the nuclei around each electron), active measures are needed: periodic exchange of the two electrons — accomplished by electrical control — usually results in cancelling these asymmetric effects.

But what about the remaining configurations that do not correspond to a superposition of a 0 or 1 state? Whenever such a 'leakage state' is realized, an error is inflicted on the calculation, and the quantum computer would eventually crash, if such errors were left uncorrected. Therefore, Taylor and co-workers had to guarantee that leakage states are virtually out of reach, and this is achieved by suitably manipulating the energy spectrum of the electrons using external magnetic fields.

This careful choice of the qubit and safeguarding it against deterioration, however, is not the end of the story. In order to perform calculations, the qubits have to be actively manipulated, by applying so-called quantum logic gates. These, for example, couple pairs of qubits in a manner that generates quantum entanglement. This capability, together with arbitrary logic gates on single qubits, in fact suffices to generate any arbitrary quantum computation⁷. Errors in the quantum logic gates are the equivalent of accidental discharges of vacuum tubes in von Neumann's computers. However, the quantum errors are far more subtle. For example, the nuclear magnetic fields mentioned above undergo slow variations and this gives rise to gating errors. To fight them, a trick known as composite pulses can be borrowed from nuclear magnetic resonance to reduce any kind of systematic error by several orders of magnitude.

The levels of defence against noise discussed so far endow the Taylor *et al.* proposal with significant resilience. The clincher is a final layer of protection: a hierarchical, self-similar superstructure of 'quantum error correcting codes'. A code is constructed by collecting a number of qubits together to form a new, logical qubit, somewhat akin to the manner in which two electrons are used to construct the logical 0 and 1. Quantum error correcting codes work a bit

like a quantum refrigerator: they cool the quantum computer by constantly coupling its qubits to fresh and 'cold' so-called ancilla qubits — qubits that do not contribute in the actual calculation, but serve as a 'dumpster' for accumulated errors that can be viewed as disorder or 'heat'. The self-similarity of the hierarchy of levels of error correction ensures that errors at all different levels of resolution are removed. Provided the errors at the highest level of resolution (the original qubits discussed above) are sufficiently small, there are important models within which it can be proved that quantum fault tolerance will then emerge: the quantum computer constructed from these imperfect components will operate perfectly^{3,4}. The set of defence levels, so carefully crafted in the proposal by Taylor and colleagues, are crucial in attaining this low initial error level. And it is this kind of careful hybrid approach that will probably prevail when large-scale quantum computers are eventually constructed.

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