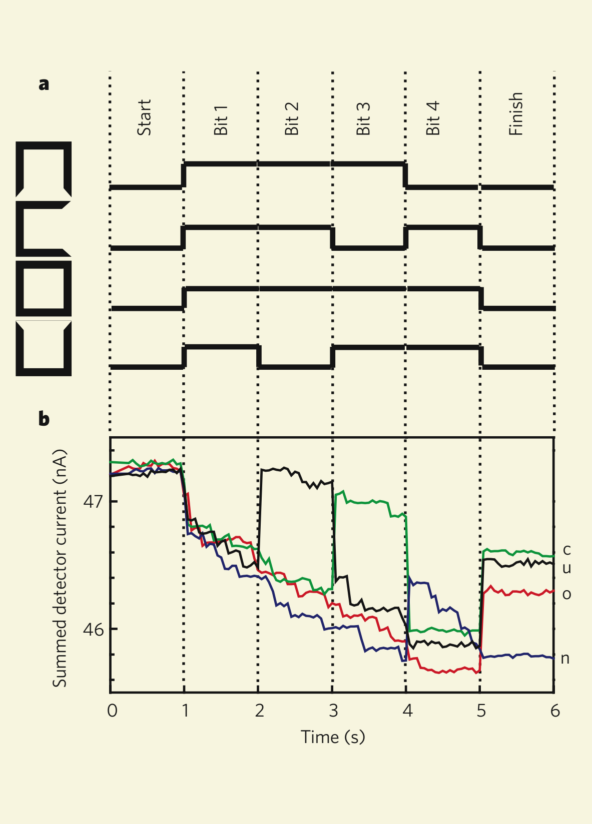

Figure 2 | Comparing letters. **a**, Images of the letters n, c, o and u can be translated into sequences of four bits (working clockwise from the left of each letter). **b**, Nishiguchi *et al.*[4] test their pattern-matching processor by sequentially feeding in the source image bits encoding n, and comparing them in turn with reference bit strings for n, c, o and u. The first bit in each reference sequence is 1, so the technique cannot distinguish between them — the detected current falls similarly for each. But as subsequent image and reference bits differ, the currents registered for those reference images increase — until after all four bits, the 'winning' reference image, n, is clearly marked by its low detector-current signal. The individual steps in the current record correspond to the tunnelling of individual electrons into the processor; the sharp steps in output current at the transitions between bits occur because the D-FET picks up changes in T-FET source and gate voltage. (Figure adapted from ref. 1.)

fast, and the current passing through the D-FET decreases rapidly. To recognize a pattern of bits such as that in an image — a series of 0s and 1s — a second unit is required that responds similarly when $i = r = 0$. This can be done simply by setting the T-FET source and gate voltages on the second unit to represent the logical inverses of whatever the input and reference bits are on the first unit. The output currents from both D-FETs are then added together. The result is the equivalent of an exclusive NOR logic gate: it flags up through a sharp drop in current whenever the input and reference bits match up (whatever the values of those bits are), but does not respond when they differ.

The authors demonstrate the principle of pattern matching using the circuit by feeding it sequentially with four bits representing an image of the letter n, and comparing it with four four-bit reference sequences encoding the letters n, c, o and u (Fig. 2a). The total error was found in each case by summing the number of electrons collected in the two T-FETs, as deduced from the drop in summed D-FET current. When the reference coding for n was used, the current drop was by far the greatest (Fig. 2b).

Nishiguchi and colleagues' advance is opportune for two reasons. First, it comes at a time when computing is moving away from single processors towards many processors operating in parallel. 'Cloud' computing, which uses very many parallel processors, is what allows search engines such as Google to provide rapid answers to our web enquiries, and now even many laptop computers contain chips that have two or more processors, or 'cores'. In this multi-processor environment, it is increasingly likely that we would wish to add special circuits dedicated to a single purpose, such as the fundamental task of pattern recognition.

Second, we are now recognizing that entirely new chip architectures and new approaches to computation are needed to continue the rapid growth in computing power to which we have become accustomed[1–3]. To that end, the semiconductor industry has developed a set of goals[3] for research aimed at producing truly nanoscale switches with low power requirements that work at room temperature. Nishiguchi and colleagues' circuit is a meaningful step in this direction: it uses silicon-on-insulator circuits that are compatible with conventional silicon technology, it works at room temperature, and it can respond to the stimulus of just a single electron.

In its present form, this work[4] represents just a proof of principle. But extended to a system that can handle many bits, such single-electron circuits that exploit stochastic quantum-mechanical effects to produce low-power devices could be an important part of a brave new electronic future. ■

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QUANTUM INFORMATION

Stopping the rot

Philip C. E. Stamp

Uncontrollable outside influences undermine the whole enterprise of quantum computing. Nailing down the sources of this 'decoherence' in a solid-state system is a step towards solving the problem.

In the quest for a quantum computer, no obstacle is more formidable than decoherence — the 'collapse' of an information-encoding quantum wavefunction when it couples to its surroundings. We pressingly need to understand what causes it, how it works and how to get rid of it. Bertaina *et al.* (page 203 of this issue)[1] have passed a milestone on that road. They report the first observation of Rabi oscillations, a signature of coherent spin dynamics, in a magnetic molecule of a kind envisaged as the basic physical carrier of a 'qubit' of quantum information in a quantum computer. Perhaps more importantly, they have also succeeded in pinpointing the sources of decoherence in their system, and so taken the first step towards eliminating them.

Magnetic molecules come in all shapes and sizes, and have spins with values ranging from 1/2 , the smallest that quantum theory allows, to more than 30. Their great advantage for making qubits is that all molecules of a species are the same, and have a structure governed purely by quantum mechanics. The authors focus on the vanadium $\mathrm{V}_{15}^{\mathrm{IV}}$ molecule, which, at just over a nanometre in diameter, is small-to-middling in size. It has an interesting spin structure, in which 15 vanadium ions, each with a net electronic spin of 1/2, couple strongly into three groups of five.

Because of the way spins add as vector quantities (direction, as well as magnitude, counts), the whole molecule can have an overall spin of 1/2 or 3/2, depending on how the individual electron spins line up. These low-energy spin states are very widely separated from the many higher-energy states. The spin-1/2 state in particular, which has two energy levels corresponding to molecular spin 'up' and molecular spin 'down', is a natural candidate for a two-state qubit.

But it's here that interactions with the environment — decoherence — become a problem. Decoherence was long thought to be a relatively simple process. A popular view was to model the environment as a 'bath' of oscillators that are not localized, but extend throughout space[2]. Decoherence was the result of transitions in the bath caused by its interactions with the central quantum system of interest. The results of experiments on simple quantum-optical systems[3] and on superconductors[4] agreed with this picture.

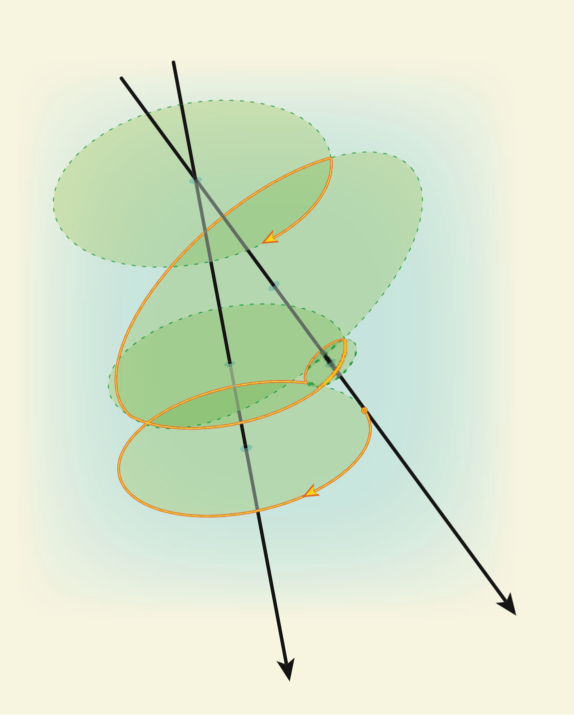

Figure 1 | Descent into decoherence. **In Bertaina and colleagues' experiment[1], a spin qubit flipping between its up and down quantum states (a Rabi oscillation) also flips the field acting on nearby nuclear spins between two orientations. The nuclear spins try to precess in this qubit field, but each time it suddenly changes they must begin anew. Thus, the path they follow is conditional on the specific trajectory of the qubit — the two are quantum-mechanically entangled, which leads to the decoherence of the qubit.**

But there were also good reasons to suppose that the oscillator-bath picture should not work in describing low-temperature decoherence in most solid-state systems, in which decoherence is mostly caused by the influence of entities in the local, rather than the extended, environment[5]. These might be nuclear spins, found almost everywhere, or else one of the many defects (some charged), dislocations and spin impurities found in anything but a perfect crystal. All these objects hop or flip quantum mechanically between a few different states, so that they act as a reservoir of quantum states known as a spin bath. A spin bath often causes little dissipation of energy, but can cause quite devastating decoherence by its interactions with the central quantum system.

Bertaina *et al.*[1] were able to spot Rabi oscillations between the low-energy qubit states of their vanadium molecule — the first time the phenomenon had been seen in a molecular magnet, and clinching proof that a degree of coherence is present in the system. But the authors were also able to work out what was causing decoherence, as manifested in the decay of the Rabi oscillation. They found that the prime source was the 15 vanadium nuclear spins in each molecule, with a rather smaller contribution from hydrogen nuclei (protons) also present in the structure. The experimental decoherence rate differed by only a few per cent from that expected theoretically for spin-bath decoherence in this system[5,6].

This result indicates that the decoherence mechanism is as follows. Each time the spin state of the qubit flips from up to down, it also flips the field on the vanadium nuclear spins. But because both other internal and externally applied fields are present, this nuclear flip is not through fully 180°. The nuclear spins attempt to realign with the field, but because the field is constantly jumping, they end up precessing in a complicated way that depends on the motion of the qubit. Quantum mechanically, this means that the dynamics of the nuclear spin bath are entangled with the qubit dynamics — decoherence has occurred, even though no energy has dissipated from the qubit into the nuclear spin bath[2] (Fig. 1). This is a remarkable finding, because the magnetic moments resulting from the nuclear spin are thousands of times smaller than those associated with the electronic spin of the qubit; and yet, like David overcoming Goliath, they prove the stronger party.

As far as other possible sources of decoherence are concerned, Bertaina *et al.* calculated the contribution of lattice vibrations (phonons) and found it to be more than a hundred times weaker than the nuclear-spin contribution. This is because the phonon frequency is much higher than that of the qubit's Rabi oscillation, so that the phonons smoothly follow the qubit dynamics, rather than destroying it. Dipolar interactions between separate vanadium molecules are potentially more dangerous than any other decoherence source, because they are effective over long ranges[7,8]; but the authors were able to suppress these effects simply by spacing the vanadium molecules far apart in a solvent.

What are the implications of these results for future work? Certainly, the prospects for using magnetic molecules as qubits are good. If one can get rid of nuclear spins — perhaps using systems with only zero-spin nuclei, prepared by isotopic purification — then the intrinsic decoherence time is about 100 microseconds for a two-level system with an energy separation of around 10 gigahertz. That should be enough to permit a quantum computer to work, given sufficiently weak dipolar interactions[7].

The nature of spin-bath decoherence has now been addressed experimentally in both molecular magnets[1] and rare-earth metals[9,10], and Rabi oscillations have been seen in both[1,9]. Such systems would thus seem to have a clear edge over a rival system posited as a viable basis for a qubit — electron transitions in the semiconductor structures known as quantum dots. In quantum dots, roughly a million nuclear spins can couple to each qubit (although ingenious methods have been proposed to deal with these[11]). Similarly, the magnetic-molecule qubits are superior to superconducting qubits, which are so large that they inevitably harbour many defects.

But before we get carried away by these latest achievements, two urgent 'architectural' problems must be solved. The first is that, in a real quantum computer, one might not have the option of keeping the qubits very far apart — so a way must be found to arrange the qubits and their interactions to suppress errors arising from dipolar interactions. The second is that the small size of the qubits means that reading out the quantum state of a large number of them, as well as controlling individual qubits externally, has so far defeated our experimental guile. But there is no fundamental reason why these problems cannot be solved. With advances such as that of Bertaina and colleagues[1], there would seem to be good grounds for optimism for the future of spin-based quantum computation. ■

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