QUANTUM CONTROL

Through the quantum chicane

In quantum control there is an inherent tension between high fidelity requirements and the need for speed to avoid decoherence. A direct comparison of quantum control protocols at these two extremes indicates where the sweet spot may lie.

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When one considers applications of quantum information science such as quantum computing, quantum communication and quantum metrology, it's hard not to think automatically of quantum decoherence as the main problem to overcome. But this is not the only challenge that quantum information technology faces. Indeed, there are now many instances of quantum systems in which decoherence has been understood and tamed to a remarkable extent[1]. Although decoherence will never be irrelevant, these advances place the spotlight squarely on achieving commensurate and stable precision in the control and measurement of such quantum systems. Now, as they report in *Nature Physics*[2], Mark Bason and his colleagues compare super-fast and super-adiabatic quantum control protocols using Bose–Einstein condensates in an optical trap. They find that a super-adiabatic protocol[3], with fidelity greater than 0.99 in some instances, is not only highly robust against system variations, but is also remarkably quick.

Perhaps the best-known application of quantum control is quantum computing. Here one requires not just precise control, but also high stability against parameter variations over a large number of individual quantum bits (qubits) and repeated quantum gate operations. Without a clear strategy to mitigate both environmental and control errors there would be no possibility of large-scale quantum computing, only relatively error-prone quantum simulation machines. Quantum error correction makes fault-tolerant quantum computation feasible, but it does this at a price. The introduction of massive redundancy increases the number of qubits and extra gate operations, and hence the opportunities for errors to occur grows as well. Effective protection of the encoded quantum information will only work if the error rate is well below a critical threshold. These thresholds are usually very stringent. Estimates for the threshold error probability range from 10^{-4} to 10^{-2}, depending on the error correction scheme and the assumptions about the qubit array.

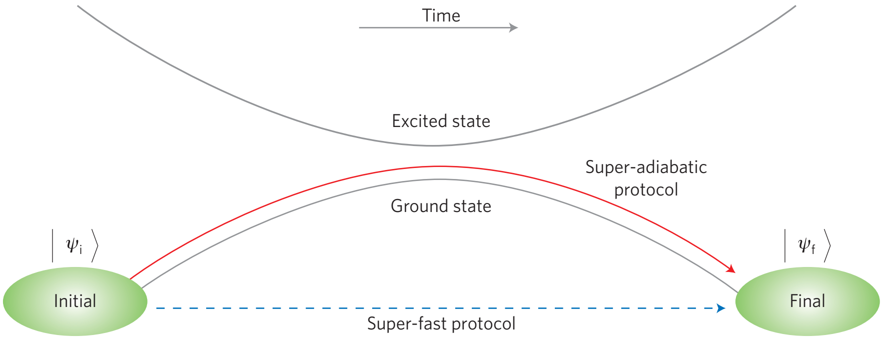

Figure 1 | Super-adiabatic versus super-fast quantum control. This simplified diagram shows the evolution of the adiabatic levels as a function of the time over which the parameters of the system are varied, and also shows the super-adiabatic control protocol that necessarily has to slow down through this 'chicane' to closely follow the ground state.

Although in some systems decoherence might be minimized to this extent, how can one reliably achieve such levels of precision and stability in quantum control? There is an inherent trade-off at play. As there will always be decoherence (we cannot totally isolate our qubits from the rest of the Universe), quantum control needs to be fast with respect to the typical decoherence time. At the same time we need to ensure that the quantum control protocol itself does not produce significant error. Furthermore, because we typically need to perform quantum control many times over, the protocol needs to be extremely stable against parameter fluctuations in the underlying physical system. Whereas speed and fidelity can already be matched in some cases to better than 99% (ref. 4), what of parameter robustness? It takes a lot of effort to characterize a quantum operation to know which control pulses to apply to produce a certain outcome.

For any quantum technology the lessons are clear: whereas decoherence can be engineered from the outset to a certain extent, quantum control must be precise, durable and, wherever possible, fast. Bason *et al.* investigated the limits of these aspects of quantum control in a series of experiments using Bose–Einstein condensates in optical lattices in which they realized an effective controlled two-level system with the familiar anticrossing physics. They measured the speed and fidelity of various protocols that took the system between given starting and final states. At the fast end of quantum control, they used a time-minimal ('super-fast') composite-pulse protocol and tested it against the usual linear adiabatic control scheme of Landau and Zener, as well as a more recent locally adiabatic protocol proposed by Roland and Cerf[5]. In a race to achieve a fidelity of 0.9, the composite-pulse protocol, by construction, won out, and indeed approached the quantum speed-limit bound. Interestingly, in this physical system the Roland–Cerf protocol reached the fidelity goal within a time only twice that of the time-optimal case, portending interesting things to come.

At the opposite end of the spectrum of control, the authors constructed and tested super-adiabatic protocols, which are engineered to counter non-adiabatic transitions so that the system followed the ground state as closely as possible, achieving nearly perfect adiabaticity (Fig. 1). Indeed, using this approach they achieve fidelities around 0.99, consistent with the precision and stability limitations of their physical system. Whereas one expects such a tailored adiabatic protocol to be accurate, the next obvious test is robustness. The authors deliberately varied their control parameters from the protocol design values (such as the total protocol time and state coupling). Remarkably, the super-adiabatic protocol maintained a fidelity around 0.99 even under parameter variations of up to 100%. The final surprise comes in the time cost of the super-adiabatic protocol — it's actually not that much slower than the time-minimal composite-pulse protocol, yet has the combined advantages of high fidelity and parameter robustness.

It will be interesting to see where these new protocols find their utility, and whether the same properties are retained in other physical systems and for multiple qubit gates. In quantum computing it remains to be seen if these control protocols satisfy the time-critical decoherence requirements in the various physical platforms; however, there are schemes that are specifically tailored to adiabatic control where the entire system is evolved to a new ground state[6], and even hybrid schemes relying on adiabatic quantum gates[7]. No doubt these super-adiabatic protocols will prove useful in other applications in quantum information technology where precise and reliable quantum control is required. ❐

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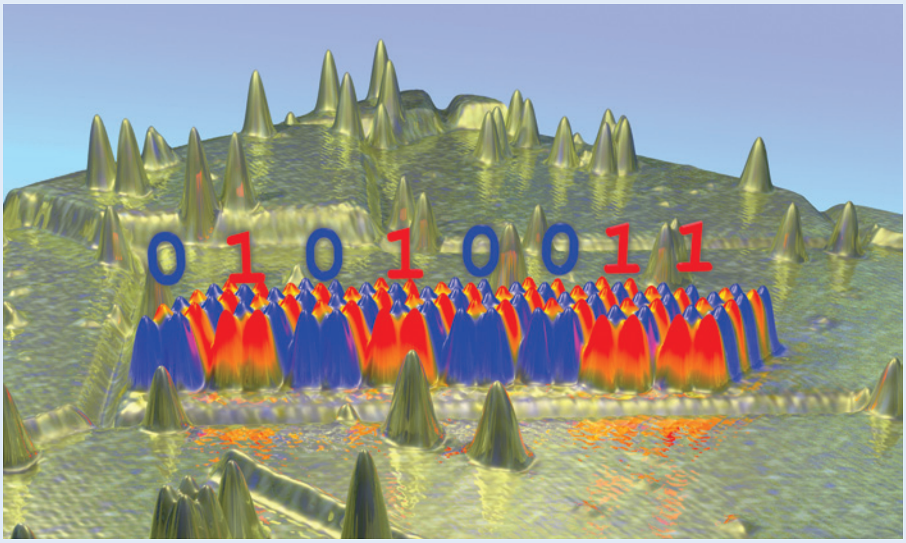
INFORMATION STORAGE

Dense bytes from antiferromagnetic bits

Using magnetism to record information was first demonstrated publicly at the Paris Exposition of 1900. Since the 1960s, it has been the dominant form of digital information storage. In all this time, the magnetic characteristic of the medium in which information is stored has remained the same — it has always been ferromagnetic. But ferromagnetism isn't the only kind of magnetism. Now Sebastian Loth and colleagues have demonstrated that it is also possible to store information in an antiferromagnetic medium (*Science* **335,** 196–199; 2012). And their results suggest that the number of bits stored per square inch of antiferromagnetic material could be much greater than is currently possible in ferromagnetic materials.

Two ways of improving the storage capacity of magnetic media are to reduce the volume of material needed to reliably record a single bit of information and to reduce the spacing between bits. Individual magnetic bits composed of isolated islands of just a few dozen ferromagnetic atoms have already been demonstrated (*Appl. Phys. Lett.* **96,** 102505; 2010). Reducing the spacing between ferromagnetic bits, however, is more challenging because of the effect that the magnetic fields of neighbouring islands can have on each other.

In contrast, the anti-aligned magnetic moments of antiferromagnetic materials result in no net magnetic moment. Consequently, the distance between antiferromagnetic islands can be drastically reduced without fear of the information stored on one island affecting that of neighbouring islands. The drawback, however, is that antiferromagnetic bits are more difficult to switch, and even more difficult to read, than ferromagnetic bits.



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The magnetic storage structures studied by Loth *et al.* consist of linear arrays of iron atoms deposited one at a time onto a copper nitride surface using a scanning tunnelling microscope (STM). The interaction of the iron atoms with the substrate and with each other causes the axis of their spins to align parallel to the array and causes their directions to alternate antiferromagnetically. The authors find that it takes just eight atoms for the two distinct antiferromagnetic states of such a chain to become stable. They show that they can induce this state to switch by applying a voltage above a certain threshold to the atom at the end of a chain with a magnetized STM tip. And they can determine which state it is in by simply measuring the below-threshold current through the tip.

To demonstrate the information density that might be achievable by such a technique, the authors deposited eight antiferromagnetic chains side by side and stored a byte (eight bits) of information in just 96 irons atoms (pictured). This is much fewer than the hundreds of millions of ferromagnetic atoms needed to store the same information on a conventional hard disk.

The study was carried out at a temperature of 5 K, but the authors expect that increasing the lengths of the chains to 200 atoms could make them stable at room temperature. The need to use a STM to fabricate, write and read these chains means that they are a long way from commercial storage applications, but it does prove the principle that magnetic storage doesn't have to be ferromagnetic.

ED GERSTNER