QUANTUM COMPUTING

A bit chilly

Leonard J. Schulman

A quantum computer needs a constant supply of 'qubits' in a known state. A nuclear magnetic resonance experiment that cools qubits by pumping entropy into a heat bath is a step closer to that goal.

On page 470 of this issue, Baugh *et al.*[1] demonstrate progress on one item in a long list of requirements for a functional quantum computer[2,3] — ensuring a continuous supply of the basic carriers of quantum information (quantum bits, or qubits) in known states. The experiment was small-scale, involving just three qubits and slight cooling to prepare them, but it potentially shows the way to preparing larger numbers of qubits in well-defined states.

The possibility that quantum-mechanical effects might be used to speed up computation was little expected and long overlooked. The origin of the possible advantage lies in a strange feature of quantum theory: whereas the state of a classical system with N members can be specified by a number of parameters that are linear with regard to N, a quantum system needs a number that is exponential in N.

In 1982, Richard Feynman noted that this discrepancy has implications for computing[4]: on the one hand, a seemingly unavoidable exponential deceleration in classical simulations of quantum systems; and on the other, potentially exponential accelerations on quantum computational devices. A quantum algorithm that was demonstrably faster than its classical counterparts[5] was developed in 1993; one year later, a quantum algorithm was found that could crack the RSA cryptosystem, the leading method for encrypting and authenticating communications[6].

More than a decade on, RSA is still used to protect electronic commerce. How can this be? It turns out, simply, that quantum computers are very hard to build. What is required is a highly controllable, many-qubit device that can be maintained in complex quantum states over long periods of time. Such a device is too extraordinarily fragile to exist under normal circumstances — which is why no one has ever seen Schrödinger's infamous cat, dead or alive. A successful quantum computer needs no cat; but it must, like the cat, embody the predictions of quantum theory at a scale of size and complexity at which that theory has not yet been verified.

Baugh and colleagues' advance[1] comes in a rather more modest system, and exploits one of the better-explored methods for supplying and controlling qubits — nuclear magnetic resonance, or NMR. In this approach, each qubit corresponds to the two possible states of the spin of a nucleus — up and down. The first difficulty in using an NMR quantum computer is putting each qubit in a known state (initialization). The usual approach to doing this is to apply a strong magnetic field, the effect of which is to make the spin-up state a higher-energy, excited state, and spin-down a lower-energy, ground state. This causes a preponderance of ground over excited states. The process extracts entropy from the system, and so can be thought of as a form of cooling.

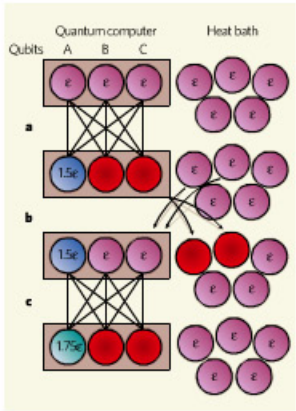

Figure 1 | Draining the heat bath. The heat-bath algorithmic cooling used by Baugh and colleagues' to prepare a quantum bit in a cooled state. **a**, After initial preparation, the three qubits of the quantum computer and many more in an ambient heat bath have a uniform bias ϵ to their lower-energy ground state. The overall bias of the three-qubit system can be shown[7,8] to be the summed bias of all three qubits divided by two (1.5ϵ). One of the qubits (A) can be cooled by making it inherit the higher bias of the three-qubit system. The excess entropy is taken up by the other two qubits (B, C). **b**, These qubits B and C can be swapped for qubits with the original bias from the heat bath. **c**, In a future step, the procedure from **a** could then be repeated, with qubit A inheriting the new overall system bias (1.75ϵ). A limit of 2ϵ is approached after many steps.

However, the effect of this direct cooling is small: the 'bias' of a qubit (the excess probability of its being in the ground state over the excited state) is increased from 0 to a mere 1×10^{-5}. Although such an increase is good enough for the scientific and medical applications of NMR imaging, a general-purpose quantum-computing algorithm requires much better initialization[7] — it needs so-called 'ancilla' qubits whose state is almost definite (having a bias close to 1). For useful computations, hundreds of these ancillas (at least) are required: direct cooling is, in short, an inadequate entropy pump.

The above difficulty is particular to NMR-based qubit applications, but a second difficulty is universal to all methods: a supply of ancillas is needed not only at the start, but also throughout any long computation. During a computation, the environment will occasionally interact with the device and cause coding errors. Fault-tolerance mechanisms that can prevent these errors from spoiling the computation do exist, but require additional ancillas.

The potential resolution to the difficulties of initialization and ancilla supply is algorithmic as much as it is physical. Qubits biased by just 10^{-5} towards their ground states may be thought of as highly disordered, or 'hot' (yet not infinitely hot — that would be zero bias, with total disorder between ground and excited states). A refrigeration process can be used to transfer entropy among a collection of qubits, cooling some while warming others. Eventually, the coldest qubits (those with the highest probability of being in the ground state, with a bias near 1) will be ready to be used in a computation. Such a refrigerator works at the level of individual qubit states and so can be regarded, and designed, as a computational algorithm.

A basic algorithmic cooling step was described by John von Neumann in 1956, albeit for a different purpose — reliable classical computation[8]. He calculated that if each of three bits has bias ϵ towards the 'right' answer to some question, then the bias of the system

as a whole (the 'majority vote') is given by approximately 1.5ϵ — so the bias of the whole system is greater than that of any individual qubit. The majority function can be computed 'reversibly' by a permutation of the eight possible sequences of the three bits (000, 001, ..., 111) such that one of the bits inherits the higher bias of the whole system and so is colder than it was before. The other two bits then pick up the excess entropy (Fig. 1a).

Closed-system experiments implementing this bias amplification have been performed previously using NMR[9,10], but the need for continuous ancilla resupply precludes a closed-system solution on a large scale. Instead, entropy must be pumped out of the computation qubits into an ambient heat bath[11], an approach known as heat-bath algorithmic cooling (Fig. 1b). What Baugh *et al.*[1] have achieved is an experimental demonstration of such a procedure. They take three hot qubits from a heat bath, put them in three computation nuclei, and then amplify the bias of one of these by a factor of 1.48 — remarkably close to the theoretically predicted performance of 1.5.

This is a significant first step along what will surely be a long experimental journey, leading, it is to be hoped, to heat-bath algorithmic cooling that can reach far lower temperatures on many more qubits. It may also be possible, even in the short term, to test a crucial aspect of open-system cooling: the use of continuous entropy pumping to achieve temperatures lower than those possible in a closed-system device. Specifically, in a closed three-qubit system, bias cannot be amplified by more than a factor of 1.5, whereas in an open system, a limit of 2 can be approached[12] by repeatedly recomputing the majority after exchanging the two 'used' (high-entropy) qubits for fresh ones from the heat bath (Fig. 1c). The modest gap between these two limits is a precursor of a much larger separation in many-qubit devices: a three-qubit open-system experiment exceeding an amplification of 1.5 will therefore be a notable milestone. ■

Leonard J. Schulman is at the California Institute of Technology, 1200 East California Boulevard, MC 256-80, Pasadena, California 91125, USA.
e-mail: schulman@caltech.edu

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CELL BIOLOGY

Silenced RNA on the move

Ralf Dahm and Michael Kiebler

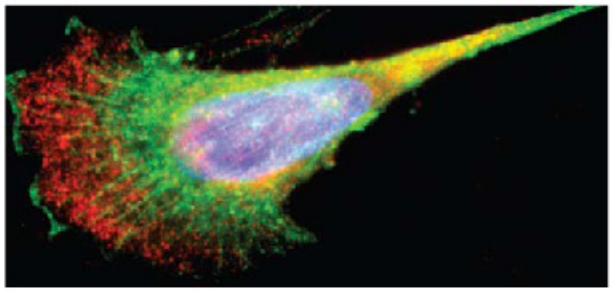
Proteins are often produced at their site of action, but the RNAs from which they are made must be kept inactive until they reach the right spot. It seems this 'silencing' of RNA is linked to its transport around the cell.

Almost all cells possess 'compartments' that enable them to separate different biological tasks. Neurons, for example, have dendrites that receive input from other cells, axon hillocks that integrate the information, and axons that transmit signals to other neurons. A key mechanism that cells use to create this functional subdivision is the localization of specific messenger RNAs (mRNAs) to distinct cellular domains[1], which allows the cells to fine-tune gene expression in both space and time. But for mRNA localization to divide up a cell effectively, synthesis of the encoded protein must be repressed until the mRNA arrives at its site of action[2], otherwise the protein will be made and begin to act all along the journey[3]. This strongly implies that there must be a tight coupling between RNA transport and repression of protein translation. In this issue, Hüttelmaier *et al.* (page 512)[4] provide the first evidence of a direct link between the two processes.

The authors studied the localization of β-actin mRNA in migrating cells. During their journey, cells extend protrusions in front of them to explore their path. These projections are generated by actin proteins polymerizing into long filaments that push the cell's membrane outwards. The β-actin mRNA is transported to the leading edge, so that the huge amounts of actin required for filament growth can be produced quickly and locally to establish cellular asymmetry (or polarity). Fibroblast cells, which proliferate around wounds and move inwards to fill in the lesion crater, are a classic example of migration (Fig. 1). This migration behaviour can be conveniently exploited in cell culture to dissect the molecular mechanisms underlying the polarization and directed migration of cells.

Previous work from the same laboratory[5] identified a short nucleotide sequence (the 'zipcode element') that is necessary and sufficient to move β-actin mRNA to the protrusions of fibroblasts and other migrating cells including neuroblastoma cells. The protein ZBP1 binds to the zipcode sequence, and is essential for this localization in fibroblasts and for the formation of dendritic filopodia, the precursors of synapses (the contact points between neurons)[5]. Now, Hüttelmaier *et al.*[4] demonstrate that ZBP1 also represses the translation of β-actin mRNA, both *in vitro* and in intact neuroblastoma cells. Moreover, neuroblastoma cells lacking functional ZBP1 do not repress the translation of β-actin. However, when ZBP1 is reintroduced into these cells, translation is again repressed. Together, these experiments show that RNA transport and translational regulation are more intimately linked than previously anticipated.

But what occurs to switch the mRNA from the translational 'off' state that prevails during transport to the 'on' state once the RNA–protein complex reaches its destination? A close inspection of the ZBP1 sequence revealed a potential SH3-binding motif. Such motifs can serve as docking sites for the non-receptor tyrosine kinase Src — an enzyme that adds phosphate groups to other proteins. Hüttelmaier *et al.* show that Src does indeed phosphorylate ZBP1 (on tyrosine 396) *in vivo*, and that the phosphorylation makes ZBP1 much less able to bind to β-actin mRNA *in vitro*. Similar mechanisms regulate the



A. WELLS

Figure 1 | A migrating fibroblast cell. β-actin mRNA (red) localizes to the fibroblast's leading edge. β-actin protein is shown as green, and the nucleus is stained blue.