benefit plant communities and aid ecological processes regulated by such plants, including shoreline protection. The authors conducted their study in salt marshes at Elkhorn Slough, one of California's largest remaining coastal wetlands. At this site, intense land development, excess nutrient input (eutrophication) and sea-level rise has caused coastal erosion, and more than 60% of the marsh area found in 1870 has either been lost or converted into other habitat types[6].

Over the past 40 years, the number of sea otters (*Enhydra lutris*) – a top predator that was once hunted to near extinction – has gradually increased in the area, from a few individuals in the 1980s to more than 100 identified animals by the late 2000s, as the authors note. Hughes and colleagues were inspired by previous findings from their team indicating considerable effects from sea otter recovery on food webs in nearby seagrass beds[7]. Sea otters (Fig. 1) need to consume an amount of food equivalent to more than 20% of their body mass per day in these cold estuarine waters[8], and their diet includes the commonplace striped shore crab *Pachygrapsus crassipes*. The authors hypothesized that, in tidal marsh creeks where otters had become abundant, their intense predation of these crabs should reduce crab burrowing and feeding on roots of the dominant marsh plant, pickleweed (*Salicornia pacifica*). This plant is an effective 'ecosystem engineer' that stabilizes shorelines. Therefore, sea otter recovery should have triggered a trophic cascade that mitigates salt-marsh erosion, similar to the proposed effect of wolves on the landscape in Yellowstone.

To test their hypothesis, the authors combined four approaches, each of which could have been a study in its own right. First, Hughes and colleagues used time-series data partly extracted from aerial and satellite imagery from the 1930s to the present day. They combined these data with advanced statistical modelling to assess the influence of sea otter abundance on tidal creek widening (a measure of creek-bank erosion). The model output suggested that, despite a sustained increase in factors known to cause erosion of the shorelines (such as eutrophication or sea-level rise), marsh erosion instead abated alongside the recovery of the sea otters.

The second, and in my view major, feat was to experimentally test the effect of otters on the ecosystem at this site. This was done by excluding otters from fenced plots measuring 1 × 2 metres and comparing these exclosures with unfenced controls in five tidal creeks over the course of an impressive timespan of three years. This type of field experiment is usually run for just a couple of months because of the regular need for maintenance and the risk of damage to the exclosures – a period that can be too short to capture effects that build up over time.

The authors' results indicate that sea otter predation strongly suppressed crab numbers and crab burrowing, which increased pickleweed root biomass and soil density; factors known to reduce the risk of erosion on creek banks. The authors also demonstrate that common side effects of exclosures, such as shading or the alteration of water flow, did not affect their results. Consequently, this proves that the otters have an effect on coastal plants and soil stability through a trophic cascade.

For the other two approaches, the authors used field surveys covering both time (comparing the periods before and after the otter population increased) and space (across 13 creeks) to scale up their experimental results. This involved more than three years of daily observations of sea otter foraging and diet composition by trained observers. As predicted, otter-predation rates on crabs rose over time with increasing otter abundances, whereas marsh-creek erosion decreased. Compared with creeks that had the highest predation rates, creeks with the lowest measured predation rates had more than twice as many crabs, half the amount of plant-root biomass and three times faster marsh-erosion rates – data that again support the trophic-cascade hypothesis.

Hughes and colleagues' study is notable for at least three reasons. First, it experimentally confirms the theory that abundant top predators can strongly influence both ecosystem structure and processes. This adds to a large body of work showing that predation, similar to factors such as nutrients and temperature, matters for ecosystem functioning[9]. Second, the powerful combination of methods used raises the bar on the evidence needed to support claims of strong effects of organisms on ecosystem functioning in the wild. Finally, the findings should intensify discussions on the role of conservation of large animals to help mitigate the environmental effects of stressors such as eutrophication and global warming[10]. This is especially important in times of rapid climate change and increasing calls to again limit coastal top-predator populations as a way to reduce conflicts between wildlife and fisheries[11].

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1. Hairston, N. G., Smith, F. E. & Slobodkin, L. B. *Am. Nat.* **94**, 421–425 (1960).
2. Hughes, B. B. *et al. Nature* **626**, 111–118 (2024).
3. Eriksson, B. K., Bergström, U., Govers, L. L. & Eklöf, J. S. in *Reference Module in Earth Systems and Environmental Sciences* https://doi.org/10.1016/B978-0-323-90798-9.00006-8 (Elsevier, 2023).
4. Ripple, W. J., Larsen, E. J., Renkin, R. A. & Smith, D. W. *Biol. Conserv*. **102**, 227–234 (2001).
5. Beschta, R. L. & Ripple, W. J. *Ecohydrology* **12**, e2048 (2019).
6. Van Dyke, E. & Wasson, K. *Estuaries* **28**, 173–189 (2005).
7. Hughes, B. B. *et al. Proc. Natl Acad. Sci. USA* **110**, 15313–15318 (2013).
8. Costa, P. *Physiol. Zool*. **55**, 35–44 (1982).
9. Koske, A. K. et al. *Integr. Comp. Biol.* **51**, 644–646 (2011).
10. Malhi, Y. *et al. Curr. Biol.* **32**, R181–R196 (2022).
11. Tixier, P. *et al. Fish Fish*. **22**, 31–53 (2021).

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Quantum information

Mobile atoms power up logical qubits

Barbara M. Terhal

Small groups of mobile neutral atoms have been manipulated with extraordinary control to form 'logical' quantum bits. These qubits can perform quantum computations more reliably than can individual atoms. **See p.58**

Over the past 20 years, scientists have been developing ways of using neutral atoms for quantum computing[1]. On page 58, Bluvstein *et al.*[2] demonstrate how far these methods have come: the authors' efficient optical techniques enabled them to control tens to hundreds of atoms in parallel, maintaining the quantum state of the atoms, and allowing them to execute logical operations on an unprecedented scale.

Bluvstein and colleagues' quantum-computing platform uses lasers to trap atoms in arrays that are hundreds of micrometres wide. Two of the possible energy levels of the electrons in each atom form a quantum bit (qubit). Before any computation can begin, a cloud containing millions of extremely cold atoms is loaded into the optical array, and atoms are removed and reshuffled until they are positioned in an organized grid.

The authors first subdivide the grid into three zones (Fig. 1). One section is designated a storage zone, in which each qubit could hold its state for at least one second, or in which states of single qubits could be altered selectively or collectively. The second is an interacting zone, in which atoms could interact with their neighbours and become 'entangled', meaning that the state of one qubit depends on that of its neighbour. Finally, the authors specify a read-out zone, in which the state of all qubits could be measured in parallel in less than a millisecond.

What is crucial and impressive about this approach is that the atoms can be shifted from one zone to the other with exquisite control: a whole row of atoms can be quickly moved sideways, and then upwards or downwards, essentially without any change to the qubits' states. The platform is also extremely efficient at executing basic qubit operations simultaneously. For example, a single laser pulse lasting just 300 nanoseconds, and illuminating all the atoms in the entangling zone, can be used to make each qubit interact with its neighbour – and not with all the other atoms in the zone.

Any quantum-computing platform is ultimately useless if operations on qubits cannot be performed with high accuracy and low error. Bluvstein *et al.* showed that basic operations, such as the one that entangles two neighbouring qubits, can be executed with an error rate of 0.5% or less. This rate is on a par with numbers achieved for other qubit platforms, such as those using superconducting qubits and trapped ions. However, error rates certainly need to be reduced much more to realize a truly 'fault-tolerant' quantum computer.

One process for minimizing these error rates is known as quantum error correction, and the idea is to use redundancy: a set of many physical qubits (in this case, atoms) is used to make another type of quantum bit, known as a logical qubit. The error rates of logical qubits can be impressively lower than those of the underlying physical qubits because the physical qubits are repeatedly monitored for errors, and the errors that are found can be corrected. And this is where the neutral-atom platform shines: as Bluvstein *et al.* showed, neutral atoms can be controlled in an efficient way to perform computation on logical qubits on a larger scale than has been achieved with other platforms.

Quantum error correction comes at a price, because the redundancy implies an overhead in the number of qubits required, and fault-tolerant operations on logical qubits can incur a further cost in terms of the time spent monitoring errors. One approach to error correction is known as the surface code, which involves representing a logical qubit by physical qubits that are arranged in a 2D array. This method has been implemented using superconducting qubits[3], but such qubits are typically not mobile, which exacerbates the cost associated with needing many qubits.

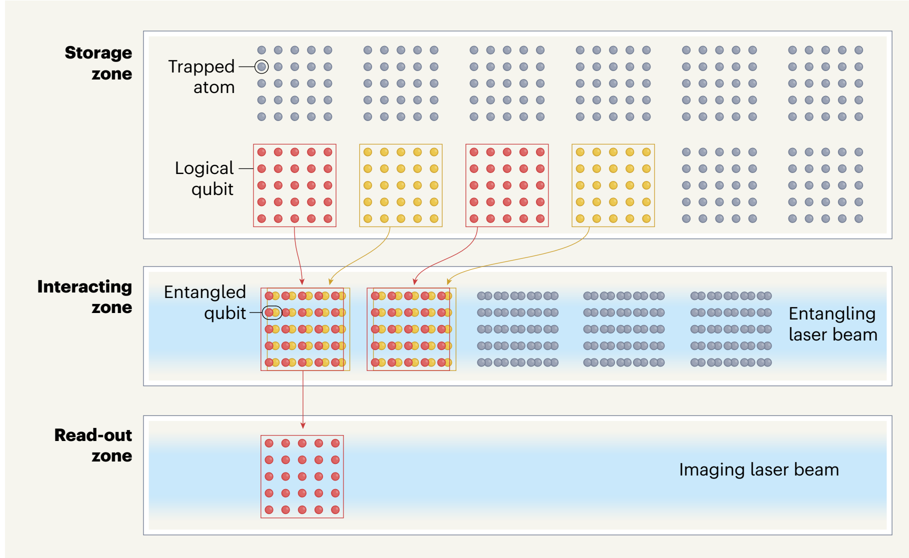

Figure 1 | An efficient way of using neutral atoms for quantum logic operations. Bluvstein *et al.*[2] devised a method for simultaneously manipulating atoms that form quantum bits (qubits), and are grouped into structures called logical qubits (red and yellow), with which the authors performed a quantum computation. The atoms were trapped using lasers (not shown) in a grid that was subdivided into three zones – a storage zone, an interacting zone and a read-out zone – and the atoms could be rapidly shifted between zones. A laser beam illuminating the entire interacting zone was used to perform parallel operations that 'entangled' each atom with its neighbour, such that the state of one qubit depended on that of the other. A second laser was used to image atoms that had been moved to the read-out zone, providing a quantum measurement that determined each qubit's state. (Adapted from Fig. 1a of ref. 1.)

Bluvstein and colleagues' ability to move their qubits quickly and easily offers the opportunity to go beyond the limitations of 2D connectivity. Indeed, the authors performed logical operations for various small quantum-error-correcting codes in an extremely efficient manner. Whereas previous experiments[4–7] on superconducting or trapped-ion qubits involved operations on one to three logical qubits, Bluvstein *et al.* played, for example, with 40 logical qubits, each comprising 7 atoms. They also showed that a single logical operation was more reliably executed using a surface code involving a large array than when using a smaller array, demonstrating that, when it comes to quantum error correction, bigger is better.

The authors then showed that hundreds of two- and three-qubit logical operations could be executed using 48 logical qubits, each of which was represented by 8 atoms. To execute these logical operations efficiently, it was essential for Bluvstein *et al.* to use patterns of interactions between individual atoms that go beyond nearest-neighbour interactions in two dimensions, hence requiring mobile atoms. The goal of the quantum computation was to demonstrate quantum advantage: the time it takes a quantum computer to perform a quantum computation increases slowly with the number of qubits, whereas the time taken for a classical computer to carry out an equivalent computation explodes with the number of qubits[3]. The computation executed with the logical qubits achieved an accuracy that surpassed anything attainable without quantum error correction.

One disadvantage of working with neutral atoms is that a quantum measurement is destructive: in future experiments, atoms will need to be continuously resupplied throughout the course of lengthy error-monitoring measurements that stabilize a logical qubit. By contrast, superconducting qubits are measured non-destructively and can be used again immediately. For this reason, Bluvstein and colleagues' results fall short of showing that logical qubits comprising more atoms can be sustained for longer than can those with fewer atoms, which has been achieved with superconducting qubits[4], albeit for a smaller surface code than the one Bluvstein *et al.* studied. Another challenge is that qubits can 'leak' to other electronic states during two-qubit operations, although ideas for how to convert such qubit leakage into benefits for quantum error correction have already been proposed[8].

What is exciting is that there is still plenty of room for growth. Bluvstein *et al.* are already looking ahead to future experiments comprising 10,000 atoms, further reducing measurement and operation times, saving on laser power and enabling atoms to be loaded into the grid continuously. Implementations of quantum error correction could also be improved: newly developed codes[9,10] with higher efficiency and thus a smaller qubit overhead could further enhance quantum computing with Bluvstein and colleagues' impressive platform.

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1. Jaksch, D. *et al. Phys. Rev. Lett.* **85**, 2208 (2000).
2. Bluvstein, D. *et al. Nature* **626**, 58–65 (2024).
3. Arute, F. *et al. Nature* **574**, 505–510 (2019).
4. Google Quantum AI. *Nature* **614**, 676–681 (2023).
5. Postler, L. *et al. Nature* **605**, 675–680 (2022).
6. Honciuc Menendez, D., Ray, A. & Vasmer, M. Preprint at https://arxiv.org/abs/2309.08663 (2023).
7. Wang, Y. *et al.* Preprint at https://arxiv.org/abs/2309.09893 (2023).
8. Wu, Y., Kolkowitz, S., Puri, S. & Thompson, J. D. *Nature Commun.* **13**, 4657 (2022).
9. Xu, Q. *et al.* Preprint at https://arxiv.org/abs/2308.08648 (2023).
10. Bravyi, S. *et al.* Preprint at https://arxiv.org/abs/2308.07915 (2023).

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Engineering

Flexible fibres take fabrics into the information age

Xiaoting Jia & Alex Parrott

A technique for embedding fibres with semiconductor devices produces defect-free strands that are hundreds of metres long. Garments woven with these threads offer a tantalizing glimpse of the wearable electronics of the future. **See p.72**

Imagine a washable hat that can help a blind person to sense changes in traffic lights, or a dress that can act as a tour guide as its wearer moves through a museum. These technologies can be realized using smart flexible fibres equipped with semiconductor devices that detect and process signals, and the performance of such fibres has advanced rapidly over the past few years[1–8]. However, existing fabrication methods can produce threads with fractured, defective semiconductor cores. On page 72, Wang *et al.*[9] report an innovative approach in which tiny semiconductor components are fed into a fibre-pulling machine, resulting in continuous high-performance flexible fibres that can sense, communicate and interact with each other.

Humans have been using fibres since the Stone Age[10], but attempts to expand their functionality beyond simple thermal insulation are much more modern. One of the challenges associated with incorporating semiconductor devices into fibres involves wearability: the fibres must be flexible and twistable, so that they can be woven; washable, for repeated use; and breathable, so that they can be worn comfortably. Many researchers have prioritized these features by creating smart fibre devices made from amorphous semiconductor materials. However, incorporating conventional silicon-based semiconductors is expected to lead to superior electronic properties and performances[2].

An alternative approach involves generating a glass-clad fibre with a silicon core, but this technique, known as the molten-core method, often leads to fibres that fracture easily and contain defects. Wang *et al.* overcame this problem by first performing a detailed mechanical analysis of the fabrication process to identify the sources of stress that induce fracture. The molten-core method begins with a semiconductor wire made of silicon or germanium being inserted inside a glass tube (Fig. 1). Both materials are heated to at least 1,000 °C until they are soft enough to be pulled into a thin strand, which is then cooled.

Wang *et al.* identified stress formation in two stages: the point at which the core solidifies; and the subsequent phase, in which the fibre is cooled. Specifically, they found that mismatches in the viscous behaviour of glass and the melting point of the wire induced stresses in the core, as did differences in the thermal-expansion rates of the materials. The authors showed that both problems could be alleviated by choosing the right combination of materials: silicon cores worked well with cladding made from ultra-tough silica glass, whereas germanium cores performed better when clad in aluminosilicate glass.

The resulting fibres are fracture-free and of high quality, but the glass cladding compromises their applicability. For this reason, the cooled fibres are immersed in hydrofluoric acid to remove the outer layer of glass, leaving behind the semiconductor core. This core is then fed into a polymer tube together with electrically conductive wires. The whole structure is heated again, and pulled into a flexible fibre that can be hundreds of metres long. The resulting fibre takes the form of a p–n junction, which is the basic building block of modern electronics and can convert light signals into electrical currents. The process is reminiscent of making spun sugar — if the sugar were embedded with tiny, controllable, electronic components.

Wang *et al.* showed that their fibres could be used to make several devices. In one example, the authors knitted fibres into a hat that could be used to sense signals from traffic lights. The signal received by the hat was sent to a mobile phone, which then buzzed when the lights turned red or green. In another case, the fibre was woven into a sweater that served as a light-fidelity (Li-Fi) device, a technology that transmits data at light frequencies instead of the radio frequencies used by wireless networks such as 5G. The sweater detected image signals that were encoded as light pulses, and then a second device decoded these signals to

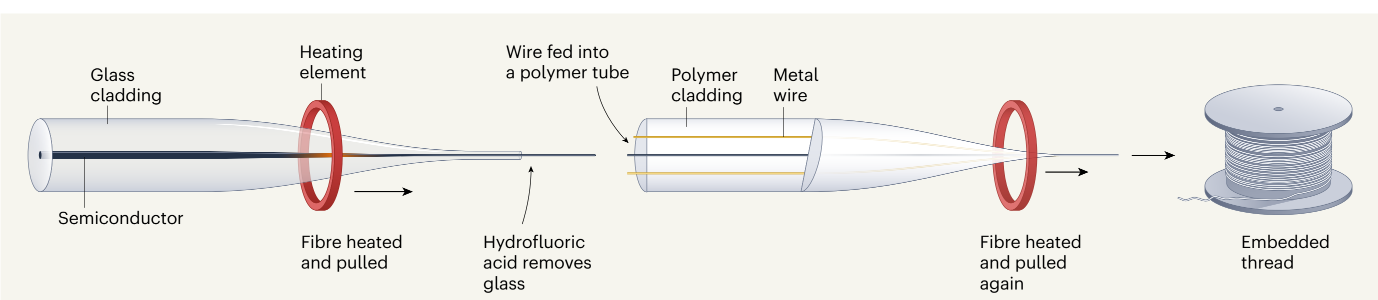

Figure 1 | A method for fabricating digitized fibres. Wang *et al.*[9] devised a way of embedding fibres with semiconductor materials to create long, flexible threads. A semiconductor wire is inserted inside a glass tube and both materials are heated until they are soft enough to be pulled into a thin strand, which is then cooled. Hydrofluoric acid is used to remove the glass. The wire is then fed into a polymer tube together with metal wires. The structure is heated again, and pulled into a flexible thread that can be hundreds of metres long, and can be woven into fabrics that detect and process signals.