Quantum information

Versatile neutral atoms take on quantum circuits

Hannah J. Williams

Neutral atoms are fast becoming prime candidates for use in quantum computers. Two studies involving multiple quantum bits show how this platform enables creative solutions for building quantum circuits. **See p.451 & p.457**

Many platforms for quantum computation are being explored. The most well developed use quantum bits (qubits) built from superconducting circuits[1,2] or ions trapped in electrostatic fields[3]. But such systems are difficult to scale up beyond tens of qubits, making the task of readying them for practical computation challenging. Platforms that use neutral atoms do not have this problem. Indeed, researchers have already succeeded in creating defect-free arrays of hundreds of neutral atoms[4,5], and have performed operations involving logic gates – the building blocks of quantum computers – with high fidelity using one and two qubits[6]. Now, Bluvstein *et al.*[7] (page 451) and Graham *et al.*[8] (page 457) show that neutral atoms can form multi-qubit quantum circuits – a key step towards realizing a practical, scalable quantum computer.

Neutral-atom platforms are based on cold atoms that are held in an array by means of individual traps created using laser light. The atoms can be manipulated by tightly focused laser beams (optical tweezers), to rearrange them into a desired geometry[9,10]. The separation between the atoms is typically micrometres, so an array containing hundreds of atoms can be less than 50 micrometres wide. The number of traps that can be created is limited only by the available laser power.

Unlike conventional bits, which can be in a state of only 0 or 1, qubits can be in a combination of the two, known as a superposition. A qubit remains in a given superposition for only a limited time, known as the coherence time. Bluvstein *et al.* and Graham *et al.* encoded their qubits in low-energy atomic states that are insensitive to magnetic fields, leading to long coherence times. Two or more qubits can then be entangled, meaning that the state of one qubit cannot be described independently of those of the others. This entanglement is a fundamental feature of quantum information. However, low-energy states interact very weakly with each other, making it difficult to create entangled states.

To overcome this problem, the researchers used highly excited (Rydberg) states to execute logic-gate operations. When an atom is in a Rydberg state, one of its electrons is excited to a high energy level and is physically far away from the positively charged nucleus. The separation creates a large dipole moment – like a tiny bar magnet – which has the effect of making two Rydberg atoms interact very strongly with one another. This means that gate operations can be performed rapidly. However, Rydberg states have very short lifetimes, typically hundreds of microseconds, which has limited the coherence time in previous experiments to only a few microseconds[11].

By using the Rydberg state as a conduit for creating entanglement between states with low energies, both groups were able to build laser-based gates that could perform rapid operations and achieve long coherence times. In particular, Bluvstein *et al.* used protocols that were developed in nuclear magnetic resonance studies[12] to extend the coherence time to a timescale of seconds. Quantum circuits, such as those reported in the latest studies, consist of a sequence of initializations, logic-gate operations and measurements on qubits. The large number of operations justifies the need for long coherence times. The gate operations entangle the qubits, creating virtual connections between them, analogous to the wires in an electronic circuit.

Bluvstein *et al.* entangled atoms that weren't adjacent in the array by using the optical tweezers to physically move the atoms between gate operations. First, they initialized the system with atoms in pairs. They then configured the gates to address each pair simultaneously, so that the pairs became entangled, before moving a subset of atoms to create the next pairings (Fig. 1a). The authors demonstrated that this architecture could be used to realize well-established quantum information states, including cluster and toric-code states. They then went further by using this shuffling of atoms to measure the degree of entanglement – a quantity known as the entanglement entropy – in a quantum simulation. They also measured the progression of entanglement entropy to explore the complex dynamics of quantum many-body

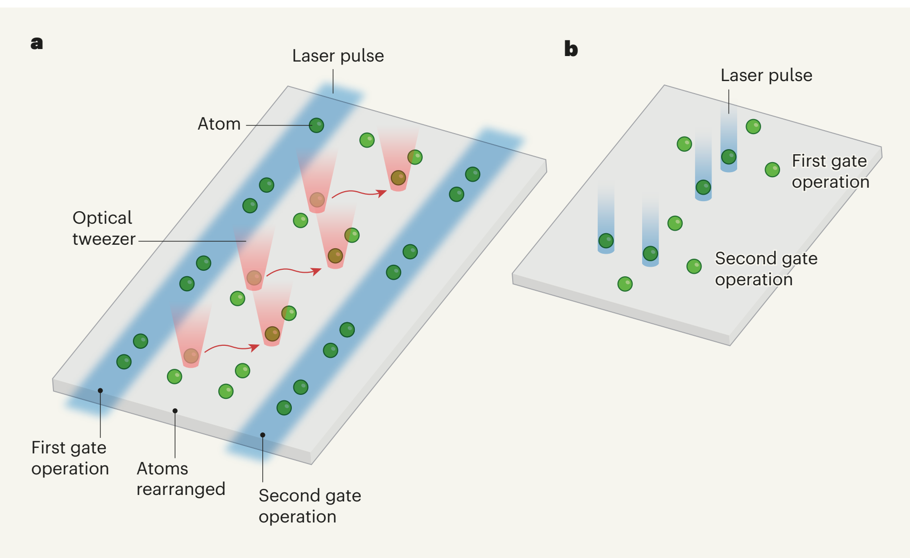

Figure 1 | Multiple quantum bit (qubit) circuits realized with neutral atoms. Two groups have shown that quantum circuits can be produced using neutral-atom qubits, by entangling multiple qubits so that the state of one qubit cannot be described independently of those of the others. In both studies, atoms were arranged in arrays, and operations involving logic gates – the building blocks of quantum computation – were performed by exciting the atoms with laser beams. **a**, Bluvstein *et al.*[7] arranged their atoms in pairs, and drove the gate by exciting the whole array with a laser pulse. Between operations, they moved a subset of atoms using tightly focused laser beams (optical tweezers). (Adapted from Fig. 1a of ref. 7.) **b**, Graham *et al.*[8] performed sequential gate operations on pairs of atoms by exciting the atoms individually with lasers. These studies each represent a large step towards achieving a powerful quantum-computing platform.

scars, which are special states that do not reach thermal equilibrium with their environment[13].

Graham *et al.* developed a complementary method for entangling multiple qubits. Instead of changing the positions of the atoms to entangle pairs of quantum states, the authors used tightly focused laser beams to drive the gates. This allowed them to keep the array static and to perform gate operations on specified pairs of atoms (Fig. 1b). They used this technique to prepare a system of up to six qubits in what is known as the Greenberger–Horne–Zeilinger state, or cat state, which many consider to be the gold-standard test for proving that a platform is capable of quantum computation.

The authors then demonstrated that they could calculate the molecular energy of a hydrogen molecule using a well-established quantum algorithm. Finally, they implemented a hybrid quantum–classical algorithm — the quantum approximate optimization algorithm — to solve the problem of how to maximize the number of edges that are cut when a graph (network) is divided in two. This is called the MaxCut problem, and it is 'NP-hard', which is the most complex class of problem in computer science.

A combination of the techniques presented by these two groups would lead to a robust and versatile platform for quantum computing. Because Bluvstein and colleagues' atom shuffling connects atoms that are not adjacent, their approach allows the creation of complicated quantum circuits, with the drawback that the time between gate operations is long. Graham and co-workers' platform enables sequential gates to be implemented very rapidly and allows independent, parallel gate operations, which makes larger circuits a possibility.

The next challenge for the field is to improve the gate fidelity, which describes the probability of correctly preparing the desired state. Although the gate fidelities reported are currently comparable to those of other platforms[14,15], they must still be increased to achieve the threshold for correcting the errors that arise naturally in any quantum computer.

The two groups' results represent a key step towards realizing a quantum computer using neutral atoms. The extension of the techniques demonstrated here to large numbers of atoms should, in theory, be straightforward. But scaling up to a practical quantum computer would require many improvements. The atoms would need to be cooled until they were almost at a standstill, and the shape of the laser pulses used would need to be optimized and the laser power increased. The prospect of realizing a quantum circuit using hundreds, or even thousands, of atoms therefore presents a tantalizing new goal — but one that now seems within reach.

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Migration

A lengthy look at climate and hominin evolution

Michael D. Petraglia

Climate effects on ecosystems shaped the evolution of our hominin relatives in the human family tree. A modelling study examines these habitat changes and the various ways in which they influenced hominin species. **See p.495**

Changes in terrestrial ecosystems are inextricably linked to the evolution of humans and that of our ancestors and relatives in the genus *Homo*. Timmermann *et al.*[1] show on page 495 how climatic shifts over the past two million years shaped hominin habitats, dispersal patterns and species diversity. The work addresses crucial questions about the evolution of *Homo*, including the evolution of our own species.

It has long been understood that large-scale shifts in the global climate correspond to changes in terrestrial ecosystems as a result of alterations in available habitats. Accordingly, researchers from a range of fields, including Earth science, palaeoanthropology and archaeology, have theorized that major habitat changes might have profoundly affected hominin populations by altering the availability of resources, and thereby influencing biological and behavioural pressures[2,3].

In investigations of habitat variability over millions of years, one of the most notable problems is that terrestrial records of habitat information — such as that obtained from sedimentary outcrops and palaeolake drill cores — are often limited in terms of the time frames of data available. Moreover, fieldwork to gather such records is geographically biased, with only partial coverage of the regions that hominins inhabited. Furthermore, the existing records demonstrate temporal, spatial and complex regional variation[4,5], supporting the view that researchers need to examine the full range of habitats in which hominins resided[6].

Timmermann and colleagues took a sophisticated modelling approach, examining the relationship between simulated predictions of ancient habitats and the presence of hominin-fossil localities and archaeological sites. The authors' habitat predictions for a location correspond to a time frame of 1,000 years for each piece of data, and are based on a range of climate variables, such as precipitation, temperature and net primary productivity (the generation of plant biomass). These predictions are mapped on a spatial scale corresponding to 1° of latitude by 1° of longitude. Timmermann *et al.* also compiled a comprehensive data set of hominin fossil and archaeological sites across Africa and Eurasia, comprising 3,245 data entries, with dated samples ranging from 2 million to 30,000 years ago.

The authors examined five hominin groups comprising six species — early African *Homo* (combining *Homo habilis* and *Homo ergaster*), Eurasian *Homo erectus*, *Homo heidelbergensis*, *Homo neanderthalensis* (Neanderthals) and *Homo sapiens*. Timmermann *et al.* note that certain groupings are contentious, such as that of *H. heidelbergensis*[7], and that species, such as the Neanderthals and *H. sapiens*, are better understood in comparison with the other hominin species. Among the limitations of this study is the exclusion of the hominins Denisovans, *Homo naledi*, *Homo floresiensis* and *Homo luzonensis*, owing to the small number of relevant fossils or fossil locations available. Also missing are newly proposed species, such as *Homo longi* and *Homo bodoensis*.