add features, only revisiting this assumption after further reflection or explicit prompting. Similarly, members of a university community might implicitly assume that the incoming president wants them to formulate new initiatives, not criticize existing ones.

What are the implications of Adams and colleagues' findings? There are many real-world consequences of failing to consider that situations can often be improved by removing rather than adding. For instance, when people feel dissatisfied with the decor of their home, they might address the situation by going on a spending spree and acquiring more furniture — even if it would be equally effective to get rid of a cluttering coffee table. Such a tendency might be particularly pronounced for resource-deprived consumers, who tend to be particularly focused on acquiring material goods[3]. This not only harms those consumers' financial situations, but also increases the strain on our environment. On a grander scale, the favouring of additive solutions by individual decision-makers might contribute to problematic societal phenomena, such as the increasing expansion of formal organizations[4] and the near-universal, but environmentally unsustainable, quest for economic growth[5].

Adams and colleagues' work points to a way of avoiding these pitfalls in the future — policymakers and organizational leaders could explicitly solicit and value proposals that reduce rather than add. For instance, the university president could specify that recommendations to remove committees or policies are both expected and appreciated. In addition, both individuals and institutions could take self-control measures to guard against the default tendency to add. Consumers could minimize their storage space to restrain their purchases, and organizations could specify sunset clauses that trigger the automatic shutdown of initiatives that fail to meet specific goals.

Of note, it is unlikely that a bias towards addition will always apply. In some situations, it should arguably be easier to generate subtractive changes, because those do not require imagining something that isn't already there. Indeed, when people imagine how a situation could have turned out differently, they are more likely to do so by undoing an action they've taken rather than by adding an action they failed to take[6]. Going forwards, it would be worth exploring when our readiness to imagine removing events extends to imagining removing features, thereby helping us to solve problems through subtraction.

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Quantum information

Quantum computer based on shuttling trapped ions

Winfried K. Hensinger

A microchip-based quantum computer has been built incorporating an architecture in which calculations are carried out by shuttling atomic ions. The device exhibits excellent performance and potential for scaling up. **See p.209**

Quantum computing based on trapped atomic ions has already proved itself to be a leading hardware platform for quantum information processing. Indeed, trapped ions have been used to realize quantum gates — the basic building blocks of a quantum computer — that have the smallest quantum-computation errors of any hardware platform[1,2]. The approach also stands out because it could allow practical machines to be built that do not require cooling to ultra-low (millikelvin) temperatures. However, there have been few comprehensive demonstrations of quantum-computing architectures capable of being scaled up to thousands of quantum bits (qubits). On page 209, Pino *et al.*[3] report the construction and operation of a prototype microchip-based, trapped-ion quantum computer that incorporates a promising architecture based on ion shuttling.

The concept of quantum computing relies on the strange phenomena of quantum physics, the counter-intuitive predictions of which Albert Einstein referred to as spooky. Quantum computers promise to perform calculations in hours or even minutes that might take millions of years to run on the fastest conventional supercomputer. Full-scale quantum computers containing millions of qubits would have transformative uses in nearly every industry, from simulating chemical reactions and helping to develop pharmaceuticals to disruptive

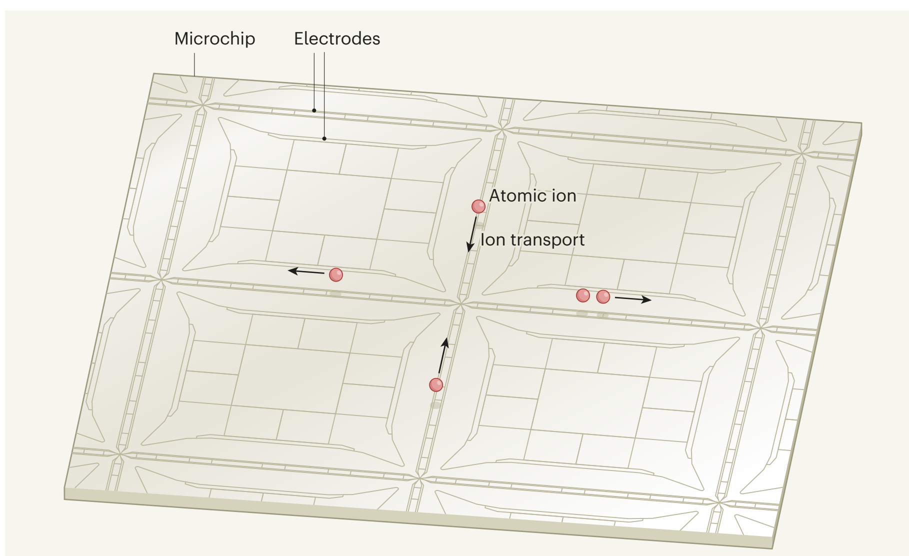

Figure 1 | Quantum-computing architecture based on ion shuttling. In a computing platform known as the quantum charge-coupled device (CCD) architecture, atomic ions hover above the surface of a microchip. These ions are transported along tracks by changing the voltages applied to electrodes (grey lines not in tracks) located on the chip's surface. Quantum computations consist of a sequence of such ion-transport operations interleaved with other operations called quantum gates (not shown). Pino *et al.*[3] built a quantum computer according to this quantum-CCD design.

applications in finance and machine learning. However, building such machines has been viewed as a holy grail of science because of the enormous difficulty involved.

The two most promising approaches to constructing practical quantum computers are based on superconducting circuits[4] and trapped ions. A distinct advantage of superconducting qubits is that they are fundamentally chip-based. However, their working principle relies on cooling to millikelvin temperatures. The maximum cooling power that can be achieved at such low temperatures is very small. This makes it difficult to cool large devices, making it challenging to scale up machines to sizes large enough to hold millions of qubits.

By contrast, trapped ions have delivered world records in reducing errors that occur in the operation of quantum gates used to carry out calculations[1,2], but many demonstrations have not been chip-based or have been accomplished with only 2–15 qubits. The next crucial step for trapped-ion quantum computing is the practical demonstration of architectures that enable scaling to thousands or even millions of qubits.

Pino and colleagues' paper describes the realization of a prototype microchip-based, trapped-ion quantum computer. In the reported architecture, which is somewhat reminiscent of the Pac-Man video game, ions hover above the surface of the microchip and are moved along tracks by the adjustment of voltages applied to electrodes located on the chip surface (Fig. 1). Because of its similarity to microchips known as charge-coupled device (CCD) arrays, this design has been termed the quantum-CCD architecture[5,6]. The authors' quantum computer is not the first realization of this design, but it is by far the most advanced implementation yet. A different trapped-ion architecture had already been demonstrated in an alternative microchip-based quantum computer, one in which laser beams manipulate the internal state of individual ions in a chain of trapped stationary ions[7].

Quantum computers are often characterized by how many qubits they can host. Without the ability to correct for unavoidable errors, the number of usable qubits is limited both by the magnitude of individual errors and by the accumulation of all the errors in the system. A parameter known as the quantum volume provides a measure of how many usable qubits a machine contains, based on the overall system performance. Pino *et al.* determined that their device has a quantum volume of 64, which means that it can do generalized computations using up to 6 qubits. In principle, a single quantum-computing module built according to the quantum-CCD design could hold hundreds or even thousands of usable qubits. Therefore, it should be possible to scale up this architecture to a million-qubit machine using a modular approach[8].

The authors also demonstrated a complete toolbox of features that make up the quantum-CCD architecture. These features include a full range of ion-transport operations, parallel operation zones and a mechanism called sympathetic cooling, whereby an ion that serves as a qubit is cooled by an ion of a different element to preserve the qubit's internal state, which carries the quantum information.

Pino and colleagues' work constitutes an impressive achievement, yet again illustrating the coming of age of trapped-ion quantum computing as a leading hardware platform. However, quantum computers that can tackle some of the most exciting real-world problems will need to host millions of qubits. Although trapped-ion technology is well suited for scaling up because it works at room temperature or requires only modest cooling, such scaling requires innovative ideas.

In the current paper, the execution of quantum gates is achieved using laser beams that need to be carefully aligned, posing a substantial engineering challenge when considering scaling to millions of qubits. Another highly promising approach is to use microwave technology that allows quantum gates to be implemented by applying voltages to the microchip[9]. Alternatively, the interaction of ions with the relevant laser beams could be facilitated using structures called waveguides in the microchip[10].

Undoubtedly, the field of trapped-ion quantum computing is undergoing a transition from demonstrating the fundamental physics needed for quantum computations to addressing the difficult engineering problems involved in realizing a working computer. The solutions to these problems will enable the construction of quantum computers that will have transformative effects across many industry sectors. Indeed, this process has already started with the creation of a blueprint on how to build quantum computers hosting millions or even billions of qubits[8]. We are at the beginning of a fantastic journey towards constructing machines that were previously thought to belong to the realm of science fiction.

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Condensed-matter physics

Heating freezes electrons in twisted bilayer graphene

Biao Lian

Electrons usually move more freely at higher temperatures. But they have now been observed to 'freeze' as the temperature rises, in a system consisting of two stacked, but slightly misaligned, graphene sheets. **See p.214 & p.220**

Particles in a substance randomly jiggle about more vigorously at higher temperatures, causing solids to melt into liquids above a critical temperature. In thermodynamics, higher temperatures favour the formation of states that have larger amounts of entropy, a measure of disorder. The liquid state of a substance typically has a larger entropy than has the solid state, because the movement of atoms is more disordered. However, an exception occurs for helium-3, which freezes into a solid as the temperature rises[1]. This behaviour is known as the Pomeranchuk effect, and occurs because solid ^{3}He has a larger entropy than does the liquid form — a phenomenon associated with the fluctuation of the spin (angular momentum) of ^{3}He atoms. Saito *et al.*[2] (page 220) and Rozen *et al.*[3] (page 214) now describe a similar effect in a graphene system, in which electrons are found to 'freeze' as the temperature increases.

The system in question consists of two stacked sheets of graphene — single layers of carbon atoms, in which the atoms form a hexagonal lattice. The top sheet is twisted out of alignment with the sheet below, yielding a