extend into the cytoplasm of red blood cells, it is unclear how chaperone proteins in the host cell might be recruited to cargo exiting PTEX.

Garten *et al.*[4] investigated EXP2 using *in vitro* experiments, and report that it has another role in addition to its function in PTEX. Previous experiments using electrophysiological techniques have shown that a channel exists in the vacuolar membrane of parasite-infected red blood cells through which nutrients such as amino acids and sugars can pass[10], but the identity of this channel has been a mystery. In electrophysiological studies, Garten and colleagues demonstrated a direct relationship between the level of expression of EXP2 and the frequency of detection of the mysterious channel. When the authors generated a version of EXP2 that had a truncated C-terminal domain, which is located in the vacuole and is not required for protein export, this altered the voltage-response properties of the nutrient channel, leading the authors to conclude that EXP2 is indeed the elusive nutrient channel.

That EXP2 might have a role separate from its function in PTEX is consistent with evidence that EXP2's gene-expression profile differs from that of the other PTEX components[5]. Moreover, the authors found that most EXP2 is not present in a complex with PTEX. Although EXP2 is essential for parasite survival[11,12], the contribution of the EXP2 nutrient channel to parasite growth remains unknown. The channel could be characterized in detail if EXP2 was incorporated into lipid bilayers for *in vitro* experiments.

The studies by Ho, Garten and their respective colleagues offer a close look at how major *P. falciparum* proteins function. Interestingly, EXP2 is evolutionarily conserved among vacuolar-dwelling parasites called apicomplexans[1]. Perhaps the nutrient-transiting capacity of EXP2 was adapted by *P. falciparum* to generate a protein-conducting channel that evolved through the recruitment of other proteins such as HSP101 and PTEX150. EXP2 and PTEX are expressed throughout the life cycle of *P. falciparum*, so drugs that target them might be highly effective at tackling malaria. These new insights into the interactions between the components of PTEX offer exciting possibilities for the development of peptides or small molecules that might block the function of this complex. ■

Tania F. de Koning-Ward *is in the School of Medicine, Deakin University, Geelong, Victoria 3216, Australia.*
e-mail: tania.dekoning-ward@deakin.edu.au

1. de Koning-Ward, T. F. *et al. Nature Rev. Microbiol.* **14**, 494–507 (2016).
2. Ho, C.-M. *et al. Nature* **561**, 70–75 (2018).
3. de Koning-Ward, T. F. *et al. Nature* **459**, 945–949 (2009).
4. Garten, M. *et al. Nature Microbiol.* http://doi.org/10.1038/s41564-018-0222-7 (2018).
5. Bullen, H. E. *et al. J. Biol. Chem.* **287**, 7871–7884 (2012).
6. Johnson, D. *et al. Parasitology* **109**, 1–9 (1994).
7. Elsworth, B. *et al. Nature* **511**, 587–591 (2014).
8. Beck, J. R., Muralidharan, V., Oksman, A. & Goldberg, D. E. *Nature* **511**, 592–595 (2014).
9. Hakamada, K., Watanabe, H., Kawano, R., Noguchi, K. & Yohda, M. *Biochem. Biophys. Res. Commun.* **482**, 700–705 (2017).
10. Desai, S. A., Krogstad, D. J. & McCleskey, E. W. *Nature* **362**, 643–646 (1993).
11. Matthews, K. *et al. Mol. Microbiol.* **89**, 1167–1186 (2013).
12. Matz, J. M., Matuschewski, K. & Kooij, T. W. A. *Mol. Biochem. Parasitol.* **191**, 44–52 (2013).

This article was published online on 27 August 2018.

QUANTUM PHYSICS

Designer atom arrays for quantum computing

A key step in the development of quantum computers that use neutral atoms as quantum bits is the assembly of tailored 3D arrays of atoms. Two laser-based approaches have now been reported to do this. **See Letters p.79 & p.83**

NATHAN LUNDBLAD

Quantum computers and simulators are of enormous interest because of their potential to shed light on mysteries of physics that are difficult to model using conventional computers. Some physical platforms used in realizing quantum-computing protocols — including trapped ions and several solid-state systems based on superconductors — have received increased attention in the past year. But in this issue, two groups report technical breakthroughs that will aid the development of another platform: trapped neutral atoms. Barredo *et al.*[1] (page 79) report their use of precision optical-engineering methods to sort atoms into arbitrary 3D patterns, whereas Kumar *et al.*[2] (page 83) construct cubic lattices by revisiting a fanciful thought experiment known as Maxwell's demon. The ability to organize neutral atoms exactly into planned 3D arrays will be valuable for the development of neutral-atom quantum computers that use a large number of quantum bits (qubits).

Arrays of isolated neutral atoms have long shown promise for quantum computing because neutral-atom qubits are extremely well isolated from environmental noise and are highly controllable, and also because such systems can be scaled up to large numbers of qubits[3,4]. Given that controlled interactions between atoms are needed to perform quantum-computing operations, neutral-atom quantum computers will need qubits to be precisely arranged in a specified pattern. However,

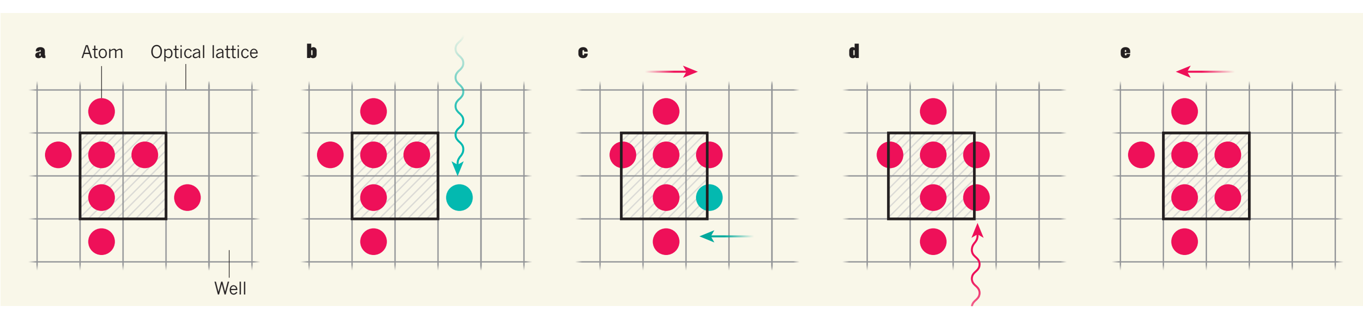

Figure 1 | A protocol for arranging neutral atoms in cubic optical lattices. Kumar *et al.*[2] report a method for arranging ultracold, neutral caesium atoms in defined patterns in a cubic, 3D optical lattice — a series of laser-generated potential-energy wells in which atoms can be confined. Only one layer of atoms is shown, for simplicity. **a**, The atoms start off in random positions and in the same electronic state (state A, red). The shaded square indicates a target region that is to be filled with atoms. **b**, A combination of lasers and microwaves (wavy arrow) flips the state of one atom into a different state (state B, turquoise). **c**, A lattice shift is induced that moves the lattice and all atoms in state A half a step to the right and those in state B half a step to the left. **d**, The atom in state B is flipped back to state A. **e**, A reverse lattice shift moves the lattice and all atoms in state A half a step to the left, so that the square region is now filled with atoms.

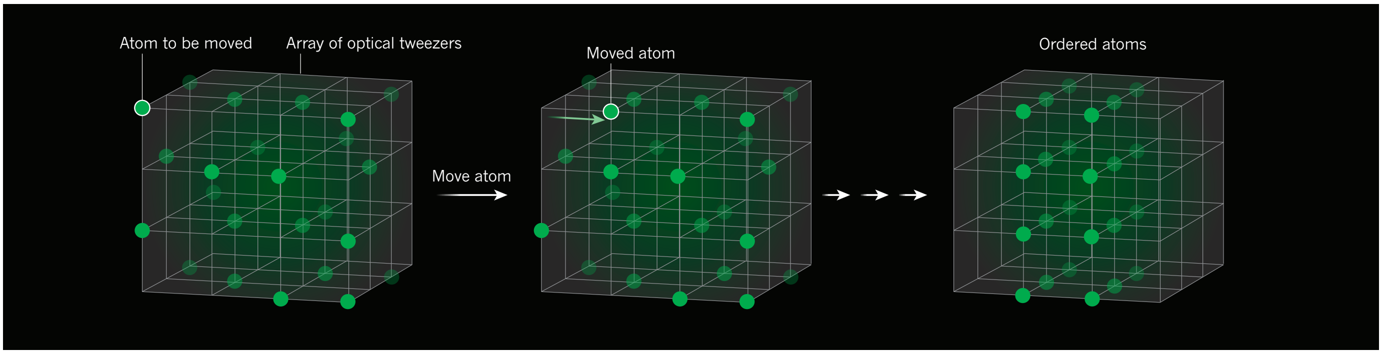

Figure 2 | A protocol for arranging neutral atoms in arbitrary 3D patterns. Optical tweezers are laser-generated optical traps that can capture atoms. Barredo *et al.*[1] formed 3D arrays of optical tweezers in arbitrary patterns (each vertex of the array represents an optical tweezer), and part-filled them with ultracold rubidium atoms, which initially reside at random positions. The authors then used a movable optical tweezer (not shown) to grab atoms at 'incorrect' positions and deposit them at desired positions, to produce precise arrangements of atoms.

developing methods for sorting atoms into patterns has proved challenging. Neutral-atom qubits require ultracold temperatures and extremely high vacuums to function, and therefore require complicated apparatus; ordering them into arrays using optical techniques adds an extra level of practical complexity. Progress has been made in arranging neutral atoms in one and two dimensions[5–8], but 3D stacking will become essential as the number of qubits used approaches the hundreds, or to construct arrangements that have topologies not achievable in two dimensions.

Kumar *et al.* have extended their previously reported approach[9] to assemble cold clouds of caesium atoms into a 3D lattice. The method begins with a randomly populated optical lattice: a trap formed from the interference patterns of counter-propagating lasers, in which atoms can be confined much like eggs in cartons. After imaging and recording the random locations of atoms in the lattice, the authors implement a sorting protocol that involves intricately controlling the polarizations of the lattice lasers, while using additional 'addressing' lasers and microwaves to position any given atom within a 5 × 5 × 5 array of lattice sites (Fig. 1). In this way, up to 50 neutral atoms can be precisely ordered into an array that is suitable for use in a quantum computer.

Kumar *et al.* frame their sorting and preparation protocol in terms of Maxwell's demon. This thought experiment was proposed by James Clerk Maxwell in 1867, and explores the nature of entropy, a measure of disorder. Maxwell postulated that a reversible sorting mechanism (a sentient demon, although a non-sentient process would also work) could partition gas molecules into two sub-volumes. But this sorting process would lower the entropy of the gas in apparent violation of the second law of thermodynamics, which states that the entropy of any isolated system can only increase. How can this conundrum be explained? The answer turns out to be that the act of sorting inevitably increases the entropy of the Universe. Because the dominant entropy in Kumar and colleagues' experiments is associated with the physical arrangement of the atoms, their work is a realization of an omniscient Maxwell's demon, summoned to organize the initial arrangement of a qubit array.

Meanwhile, Barredo *et al.* extend their previously reported method[10] for 2D atom sorting to three dimensions. Their approach to disorder and sorting is different from Kumar and colleagues' method, but just as effective. They use a holographic technique whereby a laser beam is reflected off a spatial light modulator and then focused to form traps known as optical tweezers. In this way, they generate arrays of traps in arbitrary configurations that can be loaded with up to 72 cold rubidium atoms. To remove disorder and build the desired atomic configuration, the authors use a separate, movable optical tweezer to pluck atoms from 'wrong' traps and either move them to correct sites or discard them (Fig. 2). This allows them to build qubit arrays in standard grid patterns, in topologies such as a Möbius strip, and even in the shape of the Eiffel Tower (see Fig. 2 of the paper[1]).

Barredo and colleagues go on to engineer an interaction between two qubits in a sorted array. To do this, they excite the atoms into 'Rydberg' states, which produce atomic electrical dipoles that allow the qubits to sense each other through dipole–dipole interactions. By contrast, atoms in their ground states have vanishingly small dipole–dipole interactions. Rydberg interactions have previously been used to enable quantum-logic operations carried out by small systems of neutral-atom qubits[3,4], and could form the basis of both the current groups' future efforts to develop quantum computers.

The two papers report similar milestones for the assembly of neutral-atom quantum computers, with Barredo and colleagues also reporting a working two-qubit interaction. However, the atoms in Barredo and colleagues' system are not as cold as they could be, which means that the entropy remaining in their arrays is substantially greater than in Kumar and colleagues' system. The resulting micrometre-scale motion of the atoms within the traps could limit the performance of future devices based on this system — a restriction that does not apply to Kumar and co-workers' apparatus. But Barredo and colleagues' approach does allow qubit arrays of any spatial design to be made, whereas Kumar and co-workers' apparatus generates only a cubic lattice. These differences might not be important for near-term quantum-computing goals, however. It remains to be seen whether quantum entanglement (a phenomenon that produces stronger correlations between particles than those permitted by classical physics, and which fuels quantum-computing algorithms) can be created for such large numbers of working qubits.

Both papers report technical tours de force, and showcase how far neutral-atom systems have come in terms of stability, reproducibility and technical sophistication. The next step is probably to generate quantum entanglement between arbitrary pairs of atoms in sorted arrays. It will also be interesting to see which exotic quantum states can be simulated using these qubit arrays, especially if some of those states cannot be modelled using existing computational approaches[11]. Finally, it will be exciting to see whether the potential advantages of neutral atoms will now begin to pay dividends in the race to develop a working quantum computer. ■

Nathan Lundblad *is in the Department of Physics and Astronomy, Bates College, Lewiston, Maine 04240, USA.*
e-mail: nlundbla@bates.edu

1. Barredo, D., Lienhard, V., de Léséleuc, S., Lahaye, T. & Browaeys, A. *Nature* **561**, 79–82 (2018).
2. Kumar, A., Wu, T.-Y., Giraldo Mejia, F. & Weiss, D. S. *Nature* **561**, 83–87 (2018).
3. Weiss, D. S. & Saffman, M. *Phys. Today* **70**, 44–50 (2017).
4. Saffman, M. *J. Phys. B* **49**, 202001 (2016).
5. Endres, M. *et al. Science* **354**, 1024–1027 (2016).
6. Robens, C. *et al. Phys. Rev. Lett.* **118**, 065302 (2017).
7. Lester, B. J., Luick, N., Kaufman, A. M., Reynolds, C. M. & Regal, C. A. *Phys. Rev. Lett.* **115**, 073003 (2015).
8. Sturm, M. R., Schlosser, M., Walser, R. & Birkl, G. *Phys. Rev. A* **95**, 063625 (2017).
9. Wang, Y., Kumar, A., Wu, T.-Y. & Weiss, D. S. *Science* **352**, 1562–1565 (2016).
10. Barredo, D., de Léséleuc, S., Lienhard, V., Lahaye, T. & Browaeys, A. *Science* **354**, 1021–1023 (2016).
11. Gross, C. & Bloch, I. *Science* **357**, 995–1001 (2017).