development that they studied, Fulde and colleagues show not only that TLR5-deficient animals develop an abnormal gut microbial community, but also that the presence of TLR5 in gut cells is sufficient to drive the community towards a more normal composition by limiting the presence of flagellated bacteria.

As with every major advance, questions remain. Determining the way in which different microbes associate and occupy niches in the gut in the presence or absence of TLR5 will require studies using mouse colonies in which the animals have a range of predefined, stable microbial compositions. This will allow researchers to discover how the presence or absence of microbial species affects the microbiota interaction with the host, and, by using a technique known as stable isotope tracing, to assess whether molecular crosstalk between microbial species affects the overall assembly of the microbiota.

Fulde and colleagues' work provides two key messages. First, it shows that TLR5 expression in early life can have a lasting effect on the composition of the intestinal microbial community. And second, it supports the emerging idea of sequential milestones during the mutually connected postnatal development of a host and its associated microbes. ■

Andrew J. Macpherson *and* **Stephanie C. Ganal-Vonarburg** *are in the University Clinic for Visceral Surgery and Medicine, Bern University Hospital, and in the Department for BioMedical Research, University of Bern, 3008 Bern, Switzerland.*
e-mails: andrew.macpherson@insel.ch; stephanie.ganal@dbmr.unibe.ch

1. Fulde, M. *et al. Nature* **560**, 489–493 (2018).
2. Dominguez-Bello, M. G. *et al. Proc. Natl Acad. Sci. USA* **107**, 11971–11975 (2010).
3. Yatsunenko, T. *et al. Nature* **486**, 222–227 (2012).
4. Macpherson, A. J., Gomez de Agüero, M. & Ganal-Vonarburg, S. C. *Nature Rev. Immunol.* **17**, 508–517 (2017).
5. Rogier, E. W. *et al. Proc. Natl Acad. Sci. USA* **111**, 3074–3079 (2014).
6. Koch, M. A. *et al. Cell* **165**, 827–841 (2016).
7. Gensollen, T., Iyer, S. S., Kasper, D. L. & Blumberg, R. S. *Science* **352**, 539–544 (2016).
8. Olszak, T. *et al. Science* **336**, 489–493 (2012).
9. Gomez de Agüero, M. *et al. Science* **351**, 1296–1302 (2016).
10. Vijay-Kumar, M. *et al. Science* **328**, 228–231 (2010).
11. Chassaing, B., Ley, R. E. & Gewirtz, A. T. *Gastroenterology* **147**, 1363–1377 (2014).
12. Carvalho, F. A. *et al. Cell Host Microbe* **12**, 139–152 (2012).
13. Ubeda, C. *et al. J. Exp. Med.* **209**, 1445–1456 (2012).

This article was published online on 8 August 2018.

QUANTUM PHYSICS

Programmable quantum simulation

A programmable array of superconducting quantum bits can simulate phase transitions in quantum systems, a step towards the study of exotic physics that is difficult or inefficient to model using ordinary computers. SEE LETTER P.456

MATTHIAS TROYER

In a 1981 lecture, the physicist Richard Feynman discussed the challenge of simulating quantum systems on conventional computers[1]. The memory required on such a computer to accurately store the state of a quantum system consisting of many particles increases exponentially with the number of particles. Feynman therefore proposed instead to build a quantum computer — a computer based on quantum-mechanical elements. Although large-scale quantum computers are yet to be developed, special-purpose quantum simulators for studying specific quantum models have been built[2,3]. These simulators have been based on technologies such as ultracold atomic gases[4], trapped ions[5] and superconducting circuits[6]. On page 456, King *et al.*[7] report a quantum simulator based on 1,800 superconducting quantum bits (qubits) that is programmable, adding another technology to our portfolio of quantum simulators.

The qubits used by King and colleagues are made from loops of superconducting niobium metal[8]. The loops are designed in such a way that, at low (millikelvin) temperatures, there are two energetically favourable states: one in which a persistent electric current circulates around the loop in an anticlockwise direction, and one in which such a current circulates in a clockwise direction. These states can be associated with the '0' and '1' of an ordinary (classical) bit. Because of a phenomenon known as quantum tunnelling, a loop can exist in both states at the same time, turning the classical bit into a qubit.

An anticlockwise current produces a magnetic field that threads up through the loop, whereas a clockwise current generates a magnetic field in the opposite direction. Intrinsic interactions between these fields lead to interactions between the qubits. The strength of the interaction between two qubits depends on the surrounding magnetic fields. The programmability of the authors' device comes from the fact that this magnetic environment can be changed by introducing additional magnetic fields through current-carrying loops adjacent to the qubits.

King and colleagues' device was originally designed to solve combinatorial optimization problems[8], in which a set of variables each have to be assigned a value of either '0' or '1' with the goal of minimizing a particular function of these variables. Such problems can occur when, for example, deciding which manufacturing task to assign to which factory, finding the shortest route through a series of cities, and deciding in which assets to invest. These tasks all belong to a class of difficult computational problem for which no efficient classical algorithm exists.

It was therefore hoped that a quantum optimizer could help, by making use of quantum tunnelling to more efficiently explore the range of possible variable assignments. Experiments on previous generations

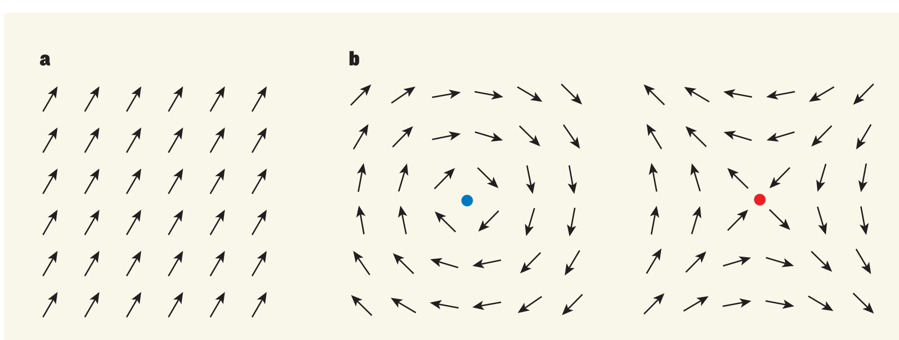

Figure 1 | Topological features in a quantum magnet. King *et al.*[7] report a quantum simulation of a particular model of a quantum magnet. In the model, the magnetic moments (arrows) of electrons can point in any direction on a plane. **a**, At zero kelvin, all of the moments point in the same direction. **b**, At non-zero temperatures, topological features can emerge. Such features include vortices (blue) and antivortices (red) — points around which moments rotate clockwise or anticlockwise, respectively, when traversing a closed loop around the point in a clockwise direction. (Adapted from Extended Data Fig. 1 of ref. 7.)

of the authors' device have demonstrated that quantum effects can be used to find solutions to optimization problems[8]. However, these devices were not shown to have advantages over classical algorithms for real-world optimization problems[9].

In the current paper, King *et al.* used their device not for optimization tasks, but for its more promising 'native' function of simulating quantum systems. In a model of a quantum magnet, the '0' and '1' states of a qubit in the device could correspond to the magnetic moment of a localized electron pointing up or down.

The authors simulated a particular quantum-magnet model in which competing interactions between magnetic moments give rise to a phase of matter that can be described by moments pointing in any direction on a plane. At zero kelvin, all of these moments are aligned (Fig. 1a). However, at non-zero temperatures, features known as topological defects emerge. Two such defects are vortices and antivortices — points around which moments rotate clockwise or anticlockwise, respectively, when circling the point in a clockwise direction (Fig. 1b).

At low temperatures, defects show up as tightly bound pairs of vortices and antivortices. As the temperature is increased, the system undergoes a phase transition in which these pairs of defects unbind to form isolated vortices and antivortices[10,11]. Work on this transition resulted in the 2016 Nobel Prize in Physics (see go.nature.com/2napzlx). The phenomenon has been observed in liquid-helium films[12], layered magnets[13] and ultracold atomic gases[14]. King *et al.* realized the transition in their quantum simulator, suggesting that such devices could be used to study this transition and others in a variety of models.

As interesting as the observed phase transition is, the main strength and impact of the paper is not in the specific model, but rather in the demonstration that reliable programmable quantum simulators that have more than 1,000 qubits can be built. Previous generations of King and colleagues' device had many defective qubits[8,9], but the current study required a perfect array of working qubits. This requirement was met thanks to improvements in the authors' fabrication technology over the past decade.

King and colleagues' observations are consistent with state-of-the-art classical simulations, showing that the results obtained by such quantum simulators can be trusted. This is an exciting development, as I have argued previously that the authors' device could have greater potential for quantum simulation than for optimization problems.

A limitation of the current device is that it can realize only what are known as stoquastic quantum models. These can be mapped to corresponding purely classical models and can, therefore, be simulated on classical computers. Although this mapping allows experiments to be compared to classical simulations, it limits the usefulness of the quantum simulator. To go beyond what is tractable on classical computers, two avenues of further development could be explored.

The first is to carry out quantum simulations of dynamical non-equilibrium effects, such as the propagation of excitations that occurs after the system of qubits is perturbed. Such effects are difficult to simulate classically, even in the case of stoquastic models. However, in contrast to quantum simulators built from dilute ultracold atomic gases or trapped ions, solid-state devices such as that made by the authors are subject to substantial environmental noise from lattice vibrations, and from electric-charge and magnetic-field fluctuations. This noise destroys the purely quantum evolution of the qubits. The design of qubits that have low sensitivity to noise will therefore be crucial for the study of quantum dynamics using solid-state quantum simulators.

The second direction for future development is to introduce other types of programmable interaction between the qubits that would realize non-stoquastic models for which no efficient classical simulators exist. Such models include those of frustrated quantum magnets, in which competing interactions give rise to unusual quantum phenomena, and to phases of matter that contain exotic types of excitation. A programmable quantum simulator for such models would open up entirely new approaches for studying complex quantum systems. ■

Matthias Troyer *is at Microsoft Quantum, Redmond, Washington 98052, USA, and the Institute of Theoretical Physics, ETH Zurich, Zurich, Switzerland.*
e-mail: mtroyer@microsoft.com

1. Feynman, R. P. *Int. J. Theor. Phys.* **21**, 467–488 (1982).
2. Cirac, J. I. & Zoller, P. *Nature Phys.* **8**, 264–266 (2012).
3. Georgescu, I. M., Ashhab, S. & Nori, F. *Rev. Mod. Phys.* **86**, 153–185 (2014).
4. Bloch, I., Dalibard, J. & Nascimbène, S. *Nature Phys.* **8**, 267–276 (2012).
5. Blatt, R. & Roos, C. F. *Nature Phys.* **8**, 277–284 (2012).
6. Houck, A. A., Türeci, H. E. & Koch, J. *Nature Phys.* **8**, 292–299 (2012).
7. King, A. D. *et al. Nature* **560**, 456–460 (2018).
8. Johnson, M. W. *et al. Nature* **473**, 194–198 (2011).
9. Rønnow, T. F. *et al. Science* **345**, 420–424 (2014).
10. Berezinskii, V. L. *Sov. Phys. J. Exp. Theor. Phys.* **32**, 493–500 (1970).
11. Kosterlitz, J. M. & Thouless D. J. *J. Phys. C Solid State Phys.* **6**, 1181–1203 (1973).
12. Bishop, D. J. & Reppy, J. D. *Phys. Rev. Lett.* **40**, 1727–1730 (1978).
13. Dürr, W. *et al. Phys. Rev. Lett.* **62**, 206–209 (1989).
14. Hadzibabic, Z., Krüger, P., Cheneau, M., Battelier, B. & Dalibard, J. *Nature* **441**, 1118–1121 (2006).

MEDICAL RESEARCH

Diet boosts cancer-drug effectiveness

A drug that slows cancer growth has been found to elevate the level of the hormone insulin. This insulin rise lessens the drug's effectiveness, but a diet that lowers insulin can increase the benefits of the therapy in mice. SEE LETTER P.499

MICHAEL POLLAK

Most studies of the causes of resistance to cancer treatment focus on the tumour itself. However, some resistance mechanisms might involve alterations in the host rather than the cancer. A particularly conspicuous gap in our knowledge concerns the possibility that dietary factors influence the outcome of some cancer treatments. This has been widely assumed not to be the case, but writing in *Nature*, Hopkins *et al.*[1] show that cancer drugs that inhibit the signalling protein PI3K are considerably more effective in mice if the animals are on a specific diet. The authors provide a plausible mechanism for why this is so.

A person with cancer might wonder whether their diet could affect their prognosis. A wide range of dietary recommendations are available, both on the Internet and from physicians and dieticians. Such advice is often conflicting. For example, a patient might read that extreme dietary calorie restriction helps to 'starve' a tumour in a clinically useful manner, but might also come across information suggesting that the opposite approach of maximizing calorie intake is beneficial, to avoid cancer-associated weight loss linked to later stages of the disease. Clinical data to support either of these approaches are not compelling. Physicians lack high-quality data on which to base dietary advice for people undergoing cancer treatment.

Hopkins and colleagues now provide evidence from mouse experiments that a diet that keeps levels of the hormone insulin low improves the effectiveness of cancer drugs that inhibit PI3K. There is great interest in trying to inhibit PI3K signalling in cancer cells, because mutations that cause