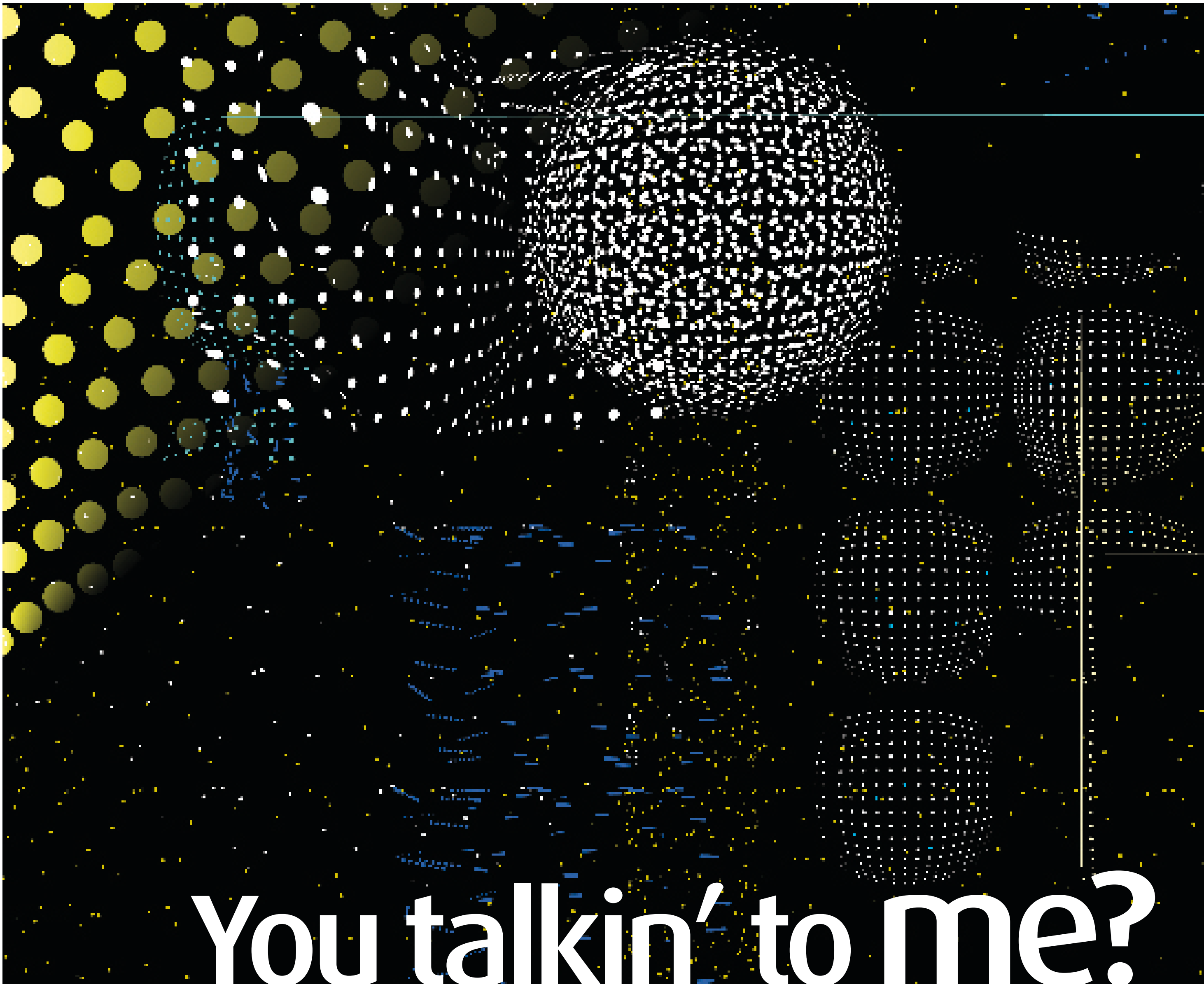


You talkin' to me?

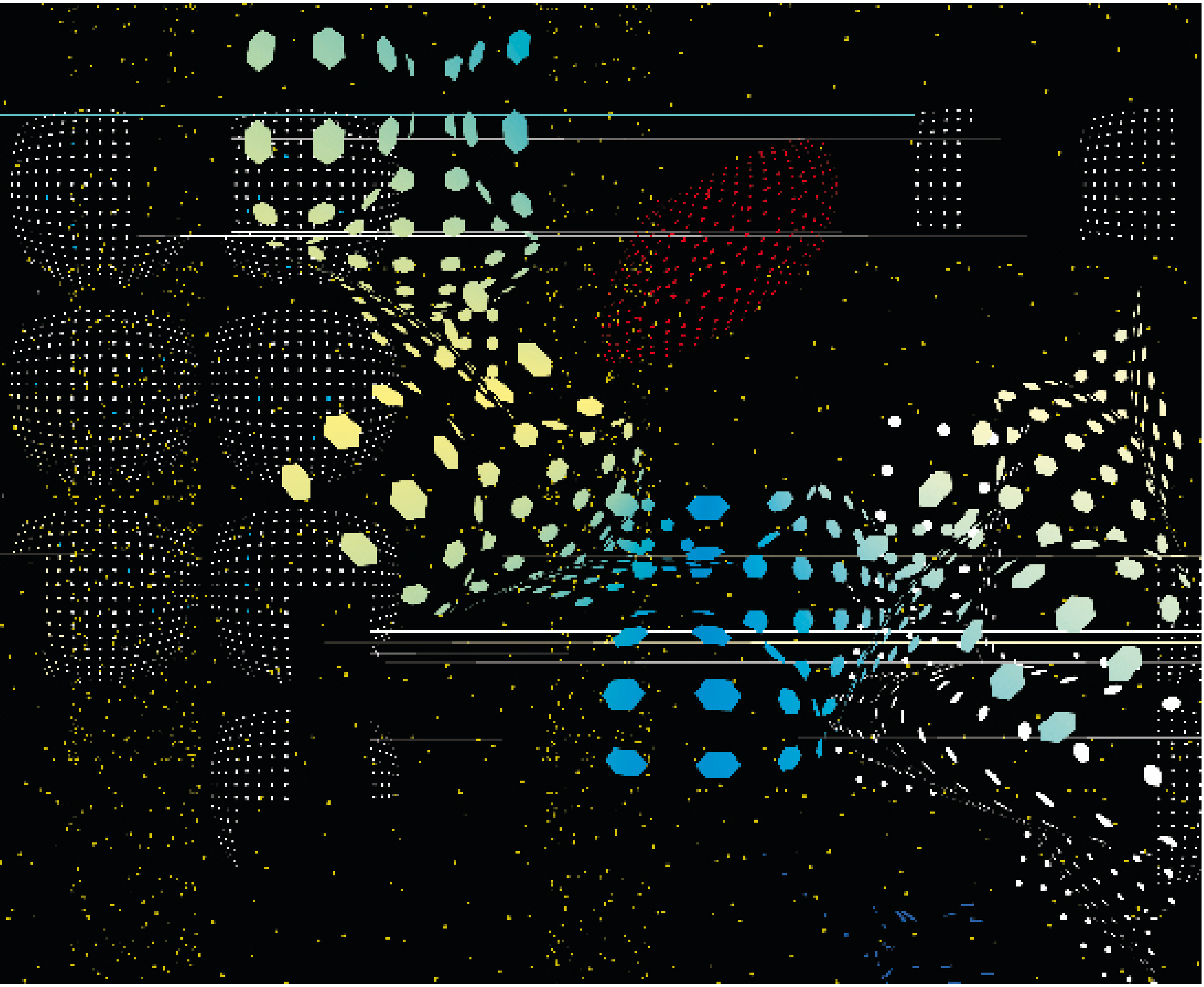
Photons are notoriously antisocial, but if you can get them to chat, they turn into

ANDREW GREENTREE is playing tricks with light. In a lab at the University of Melbourne, Australia, he's trying to do something to photons that no one has done before: trap them in cages and make them talk to each other. Unlike particles of matter such as electrons, photons are notoriously unsociable. They pass like ships in the night, even going straight through one another, and they don't even notice. If they could be made to interact, however, they might be compelled to form a peculiar new kind of quantum material, one made of light.

OK, it wouldn't be a material in the everyday sense of the word, like a solid you could touch, but it could behave like one in some important ways. What gives materials their properties is the way atoms interact, and the more we know about this, the more we can do with them. In a similar way, photons interacting in a quantum material could give us insights into how real materials with quantum properties work. For example, no one yet knows exactly why so-called high-temperature superconductors can make electricity flow with no resistance at all.

Why is all this important? For one thing, we might be witnessing the birth of a materials revolution for making new kinds of computers. Materials made of light could be used to model and then build optical circuits that store and process information faster and more efficiently than anything around at the moment. They may even offer a route towards a practical quantum computer, something that exists only in theory as yet, but would be able to perform calculations millions of times faster than a supercomputer.

So far, photon materials exist only in theory too, but the findings of Greentree's team and others have got physicists buzzing with anticipation. In the past few months, three groups have developed models independently showing that such photon materials should be feasible to build and test



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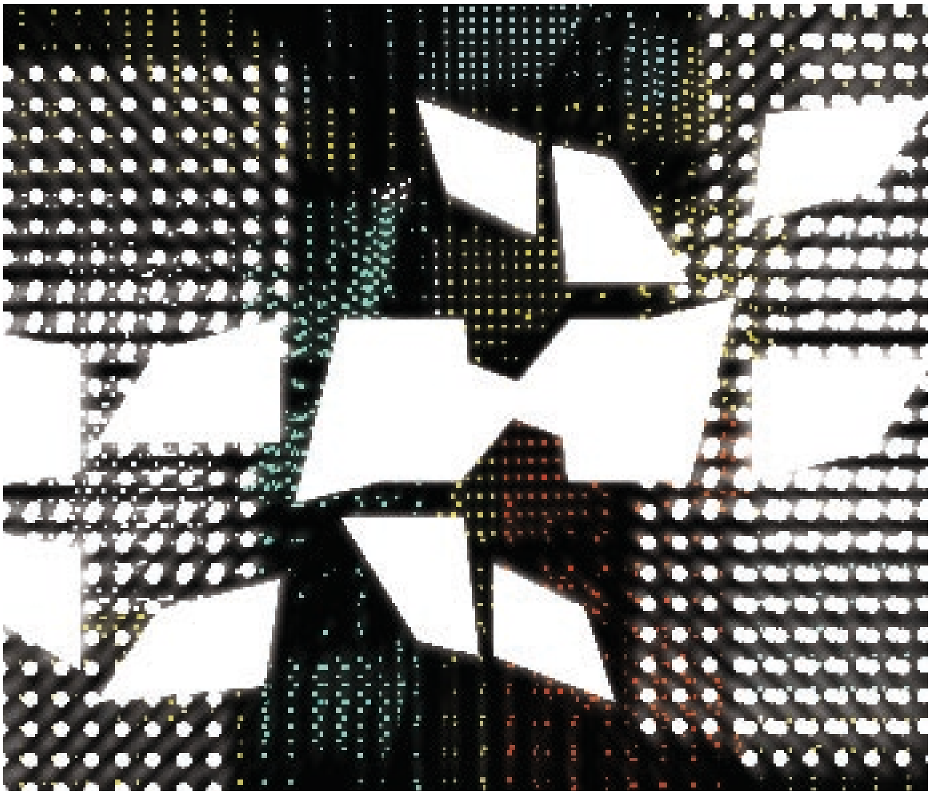
a material made of light. **Mark Buchanan** investigates

within a few years. "The excitement really comes from our ability to make what are essentially new forms of matter," says Charles Tahan of the University of Cambridge, one of Greentree's collaborators.

The idea that light can be manipulated to produce material-like behaviour is not entirely new. In recent years, for instance, researchers have experimented with so-called optical lattices, using these devices to model the quantum behaviour of materials. Optical lattices use criss-crossing laser beams to trap and control atoms, which can be kept rigidly in position as if they were in a crystal, or allowed to move and interact freely as if in a gas. Because of technical constraints, however, researchers can't study these gizmos down to the level of individual particles. Greentree and the others hope to remedy that by building complementary gadgets in which photons act upon each other in more easily measurable ways – and that's the key to the proposed photon materials.

Most of the time, it's a good thing photons don't interact the way atoms and electrons do; it's the reason we can see. Light reflecting off a mirror never backs up in a traffic jam, and two crossing flashlight beams never fight with one another. In the air and other ordinary materials, photons just don't talk to each other. "To make that happen you need to do something special," says Greentree.

Ideas for doing just that have circulated for a decade. In 1997, Ataç Imamoglu at the University of California, Santa Barbara, proposed that a special kind of box or "cavity" could be made to absorb one, and only one, photon. That photon would change the resonant properties of the cavity, preventing it from absorbing further photons, a process called photon blockade. Any photon that enters the system would effectively repel all others. "Put one in," says Dimitris Angelikas of the University of Cambridge, "and the second one will bounce back." ▶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In 2005, Jeff Kimble and colleagues at the California Institute of Technology in Pasadena showed a practical way to do this (*Nature*, vol 436, p 87). They built a small cavity between two mirrors, 80 micrometres across, in which only photons of a particular wavelength could exist. To this cavity they added a supercooled caesium atom and showed in experiments that if the cavity-atom complex absorbed one photon, it could no longer absorb another, because it wasn't in a resonant state to be able to attract light anymore.

This striking result spurred three research teams led by Angelikas, Greentree and Martin Plenio of Imperial College London to develop the idea further and design full-blown quantum materials out of photons. The approach, says Angelikas, was to get "light to talk to light through matter", and to do so in such a way that many photons could be made to interact at the same time (www.arxiv.org/quant-ph/0606159).

What each group envisions begins with a photonic crystal – a structure that can channel photons rather like the way an irrigation system controls the flow of water across fields. Made of glass, plastic or diamond, the crystal allows only photons with certain wavelengths to flow inside it. The right geometric pattern of holes drilled into the material using an ion beam can create natural cavities where photons can sit, surrounded by regions where they cannot.

Each cavity then needs something that will produce a photon blockade. Greentree's team proposed adding an atom with exactly two energy levels, the difference tuned to match the energy of photons trapped by the cavity (*Nature Physics*, vol 2, p 856). The result: an array of atom-containing cavities, each capable of taking up one and only one photon. Add photons to the cavities and they will interact with their nearest neighbours by effectively repulsing one another. "You end up with something that looks like a classic material system," says Greentree, "but made out of light."

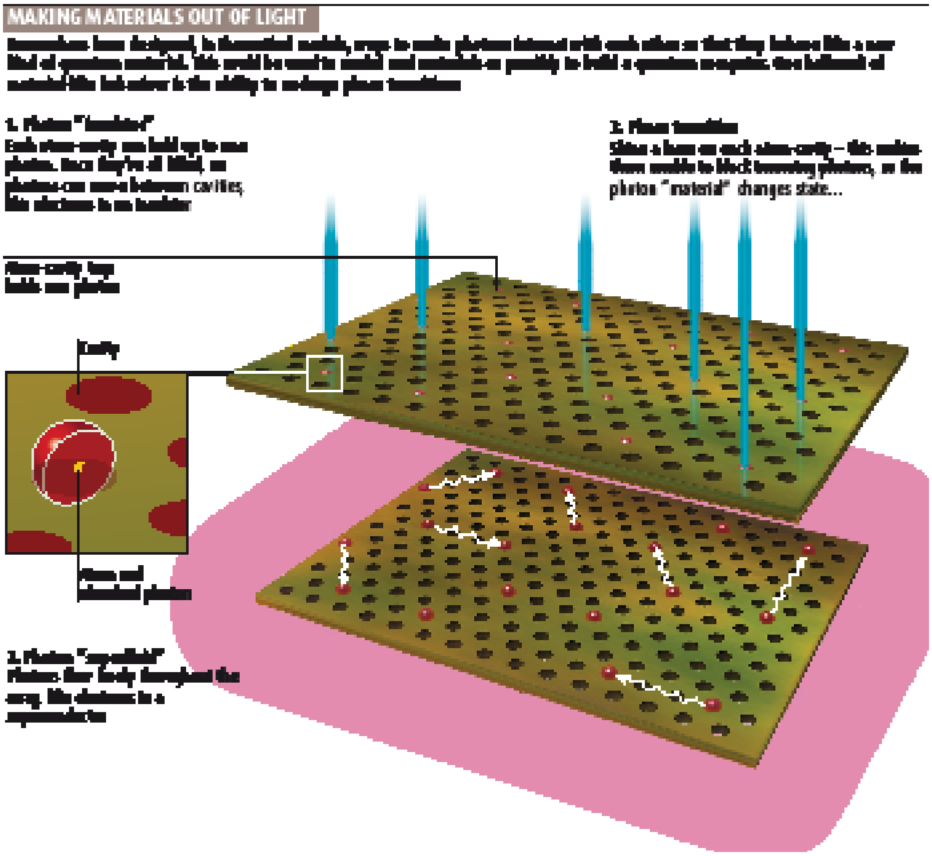
"You end up with something that looks like a classic material, but made of light"

How exactly? In models, the photon materials show behaviours every bit as rich as those of real materials. One of the hallmarks of any material is the ability to change its state - liquid water freezing into solid ice, for example - a process known as a phase transition. All three research groups have shown that their proposed photon systems would undergo the quantum equivalent of a phase transition, from a so-called "Mott insulating" state, with a photon contained in each cavity unable to move, to a strikingly different "superfluid" state, in which each photon flows without resistance over the entire array, like an electron in a superconductor.

This effect really proves the principle. "It's been an open question for a long time as to whether you could ever see a quantum phase transition for light," says Angelikas. The answer, it seems, is a resounding yes. The transition could be triggered by changing the energy levels of the two-level atoms so that the atom-cavity systems no longer produce photon blockade. That could be induced in a fraction of a second by shining a laser onto each cavity simultaneously.

Plenio's team reckon that each cavity could contain not one but an ensemble of atoms, and have shown that photon blockade can be realised by driving the atoms with laser light (*Nature Physics*, vol 2, p 849). Each group has confirmed in calculations that the behaviour of any photon in the array is intimately linked to the behaviour of others, as is the case with particles that make up liquids, solids and other states of matter. "The interactions are so strong in such systems," says Gerard Milburn of the University of Queensland, Australia, "that thinking in terms of the bits, the particles, that make them up can be misleading. You need an effective theory for the system as a whole."

"This is really elegant work," says Pieter



Computing by light

The ability to make photons interact could make less traditional schemes for quantum computing more practical. In 2001, Robert Raussendorf and Hans Briegel of the Ludwig Maximilian University in Munich, Germany, proposed that quantum computing might be more easily realised by packing all the quantum links or "entanglements" into one initial step. They showed theoretically that if a number of quantum particles were set up in a highly entangled state known as a cluster state, then any quantum computation could be carried out by making a sequence of simple measurements on the individual particles.

Researchers have since created experimental cluster states involving up to four photons, and have recently proposed ideas for scaling up the process using photons to entangle stationary quantum bits, or qubits (*New Scientist*, 25 March 2006, p 42). Carrying out useful calculations will require more complex cluster states, though, and that's tough.

Michael Hartmann at Imperial College London suggests that his team's proposed quantum material, in which the interactions between photons in an array of optical cavities can be adjusted quite flexibly, might help. Using such a model, researchers could specifically design the photon interactions to create large numbers of entangled qubits. "This should make it more straightforward," Hartmann says.

Kok at the University of Oxford. "It will be fascinating if they can show it experimentally." In that case physicists will have a totally new tool to help them understand a range of weird quantum effects. Richard Feynman first suggested in 1981 that simulations of quantum systems such as photons and electrons could best be carried out with other quantum systems – you should simulate like with like. With a "quantum simulator" made of interacting photons, researchers might gain clues into the baffling nature of high-temperature superconductors and other exotic materials in which strong quantum interactions play a dominant role.

Researchers suspect, for instance, that the bizarre behaviour of such materials might have something to do with what goes on when a system is close to the boundary of a quantum phase transition, such as the Mott insulator-to-superfluid transition. At such a boundary, fluctuations in the microscopic organisation of a material become unnaturally large and seem to dominate the system's properties (*New Scientist*, 28 January 2006, p 40). However, at the moment researchers have few techniques for probing the fine details of this state in real materials. "We haven't yet cracked the basic rules," says Jan Zaanen of Leiden University in the Netherlands. "There's a great demand for well-controlled experimental models of these systems. This light stuff might work."

What's more, a quantum simulator could be an important step towards the fabled quantum computer (see "Computing by light", left). That's because these simulators can be thought of as rudimentary computers which carry out calculations in strictly quantum terms.

But how to actually build them? Greentree's team propose that an alternative and promising way to construct photon materials would be to use not two-level atoms in the cavities, but defects in the crystal lattice of thin sheets of diamond. These defects – created where a nitrogen atom replaces a carbon atom – can bind an electron and act like simple atoms with two energy levels. A cavity system of this sort would naturally have many quantum bits, or qubits, that could be exploited to do computations.

Greentree and his colleagues have started working on this idea. They believe they can build the right kinds of devices within a few years, thanks in part to existing fabrication techniques. "We've never made something this complicated," Greentree admits, "but it is like things being made in silicon already. We certainly think it should be feasible."

The end result could be a quantum computer made of diamond. If not, however, Greentree and the others won't be too upset. "There are so many potential pitfalls on the way to quantum computing," he says, "that I hesitate to make any predictions. This is a great toy to let us understand new physics. We can combine things in new ways and see brand new effects, hopefully ones never seen before." ●

Mark Buchanan's book *Small World: Uncovering nature's hidden networks* is published by Weidenfeld and Nicolson