THE DREAMWEAVER'S ABACUS

Some experts think that a quantum computation could be plaited like a skein of string. And now they may have found the sorts of string they need, finds **Liesbeth Venema**.

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How much absurdity can you take? If you are a mathematician or a quantum physicist, the answer is probably quite a lot. Topologists, for example, regard a coffee mug and a doughnut as essentially one and the same: two different variations on a basic shape-with-a-hole-in-it theme. Quantum-computer enthusiasts are happy to deal with the idea of 'qubits' that can be ones and zeroes at the same time. Condensed-matter physicists have no problem with the idea that electrons can break up into 'quasiparticles' with fractional charges — a third that of one of the original electrons, say. And theorists are happy to accept that there are particles called anyons that live only in two dimensions and are part electric charge, part magnetic flux.

But there are limits. And when in 1997 Alexei Kitaev, now at the California Institute of Technology in Pasadena, published a preprint suggesting that the topological properties of quasiparticles, moving around each other and behaving as anyons, could be used as the basis for a new form of error-proof quantum computing[1], it seemed that he had gone beyond them.

"I laughed when I first read it," recalls Nick Bonesteel, a theoretical physicist at Florida State University in Tallahassee. And there may still be some people laughing today — but at least a few of them are doing so with excited anticipation. "Intellectually, the idea might seem far-out," admits mathematician Michael Freedman, currently based at the Microsoft research group called 'Station Q'. Station Q was founded in 2005 at the University of California, Santa Barbara, specifically to tackle this sort of topological quantum computing. "To understand it requires knowledge of the maths as well as condensed-matter physics, which may be off-putting at first." But gradually, the far-out came in.

The attraction of the proposal is that the quasiparticles singled out by Kitaev happen to turn up in one of the most intensively studied condensed-matter systems of the past few decades — a quantum Hall device. These are systems in which, under the right conditions, charge carriers are forced into 'current channels' governed by the rules of quantum mechanics.

In the early 2000s several theorists, including Bonesteel, began thinking seriously about ways to create qubits, the building blocks of quantum computing, in a quantum Hall device. Sankar Das Sarma, a theoretical physicist at the University of Maryland in College Park, teamed up with Freedman. "First we developed this crazy idea about manipulating quasiparticles with a microscope tip. Then we realized that the current paths in a quantum Hall device already move quasiparticles around," says Das Sarma. Their blueprint for a topological qubit, together with related proposals from other groups, was presented at a meeting on 'Emergent phenomena in quantum Hall systems' in Taos, New Mexico, in 2005. Moty Heiblum, an experimental physicist at the Weizmann Institute of Science in Rehovot, Israel, says that the meeting made him and his colleagues return to the lab. "Most of us had been feeling that the topic was already exhausted, but the meeting revived the field. For the first time, it was driven by theorists," he says.

Neither boson nor fermion

A very clear task was set out for the experimentalists; construct a quantum Hall device in which the right type of quasiparticle shows up. Quantum Hall devices are made from stacks of semiconductor put together using well-known microelectronics fabrication techniques so as to create a two-dimensional electron gas, or 2DEG, at the interface between two of the layers in the stack. When a magnetic field is applied perpendicularly to one of these electronic flatlands, current channels form along the edges of the sample in which a specific number of electrons can travel — this is the quantum Hall effect. Chill the 2DEG down further, and crank up the magnetic field, and the electrons' behaviour becomes stranger; they start to interact strongly with each other and, as a result, appear to break up into smaller pieces: these are the quasiparticles. They have no independent existence — you couldn't lift one out of a 2DEG and set it on its way — but within the 2DEG they really do act in a particle-like manner.

Still, they have peculiarities. Because they move in just two dimensions they do not follow the same quantum mechanical rules as real particles out in the three-dimensional world. Those particles come in two types: bosons, like the photon, and fermions, like the electron. These particles are something fundamentally different: anyons (see 'Braiding anyons').

Non-abelian abilities

Not any old anyon can work as a qubit, though. A qubit has to be able to exist in several states at once. That is what, in computational terms, lets them represent '0' and '1' at the same time, which is what gives a quantum computer its power; where classical computer bits are either '0' or '1', qubits can be various degrees of both — and thus, in effect, can carry out different versions of a computation in parallel. This powerful capability, also called 'superposition' can be exploited to design quantum computers that can tackle challenging tasks such as factoring large prime numbers to break codes, searching databases much larger than any yet built, and simulating complex processes in interesting materials such as high-temperature superconductors.

Superposition has already been demonstrated for some physical systems. Qubits with 'superposition' states can be based on trapped atoms and electrons; the sorts of quantum-logic operation that could lead to ultrafast factoring have been demonstrated on them. But this has happened only in very small circuits of four or fewer qubits. And it has become frustratingly clear how difficult it is to protect the fragile states of a qubit based on a trapped particle from the outside world. Even minute interactions with nearby surroundings can destroy them. And for each additional qubit in a circuit, many more calculation errors are introduced. "In theory it is possible, but the engineering problem to build a scalable quantum computer may be too big" says Das Sarma.

The topological nature of anyon-computing would get round the sensitivity problems, as long as the anyons were of the right sort. The key attribute is that the order in which a given set of interactions between anyons happens has to matter. That allows a given state to be a superposition of different histories — different ways of braiding the particles together. This 'order

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matters' criterion is expressed, mathematically, in terms of the structure of the group, which describes the interactions as being "non-abelian". If order didn't matter, they'd be abelian.

Whether a quasiparticle will behave as a non-abelian anyon or not depends on the details of the way that the fractional quantum Hall effect gets electrons in the 2DEG to interact. By slowly turning up the magnetic field, experimentalists can 'tune' a quantum Hall device into different regimes. The regime seen as the most likely breeding ground for the quasiparticles that can act as non-abelian anyons has been described before[2], but it is a delicate one, and has been hard to characterize or investigate.

One of the most salient features, and one of those that was hardest to discern, is that the quasiparticles appearing in this regime should have a quarter of the charge of an electron. The evenness of the fraction is in itself is a curiosity: so far, mainly odd fractions, such as a third, or a fifth of an electron, have been seen. But not any round number would do. Half-charge quasiparticles would not be non-abelian, and this has been a real worry to the field, as there seemed to be a possibility that quarter-charge particles would clump into half-charge ones, thus losing their non-abelian mojo.

Now such worries can be put to rest. In this issue of *Nature*, Moty Heiblum and his co-workers report[3] measuring fractional charges in quantum Hall devices by forming a narrow constriction of controllable width, called a point contact, in the middle of the 2DEG, making it look something like a flattened hour-glass (see inset picture opposite). Current injected at one end is carried in the form of quasiparticles along one edge of the 2DEG and through the central constriction. But if the constriction is thin enough, not all the quasiparticles can make it from one lobe to the other: some fail to get through the point contact and jump to the other edge of the lobe in which they started. The discrete movements of quasiparticles that are diverted in this way at the point contact cause fluctuations in the currents on both sides of the contact. Analysis of this reverberating 'shot' noise reveals the precise value of the quasiparticles' charge.

Because there are many other sources of noise that can mask the fluctuations, this kind of experiment demands an extremely clean and carefully constructed device. Merav Dolev, the graduate student on the project at the Weizmann Institute, had to balance many

Braiding anyons

In classical mechanics, if two identical particles are swapped around, the end state is identical to the initial state. In quantum mechanics things are more complex. When two electrons exchange places, the quantum mechanical wavefunction that describes them is shifted so that what used to be peaks in the function become troughs and vice versa. Exchanging a pair of photons also shifts the wavefunction, but by exactly one period so that the peaks and troughs stay in the same place. All other everyday particles behave either like electrons, if they are fermions, or like photons if they are bosons.

Anyons make things more complicated; it's a result of the fact that, being defined from the start as two dimensional, they are described by different statistical rules. When two anyons are swapped, the wavefunction that describes them shifts phases not by a whole period or half a period, but by some other fraction of a period. If a number of anyons swap places repeatedly, weaving around each other, the wavefunction undergoes a distinct series of phase shifts, depending on which was where, and when. It captures the braided trajectories of the anyons moving to and fro.

If anyons are swapped according to specific rules, the braided histories recorded in the wavefunction can be seen as steps in a computation. If the anyons are 'non abelian' (see main text) then one set of particles can have a whole range of different braids recorded in their combined wavefunction. And so the arrangement of the anyons — the topology of the system — becomes a quantum computation.

The attraction of this approach is that it is the overall shape — the topology of the braid — that matters, not the precise details of every movement that went into it. Topology is a robust quality; a doughnut is doughnut shaped even if it gets a bit squashed — or distorted into the shape of a mug. This insensitivity to detail makes a topological approach to quantum computing very attractive, and largely immune to error. **L. V.**

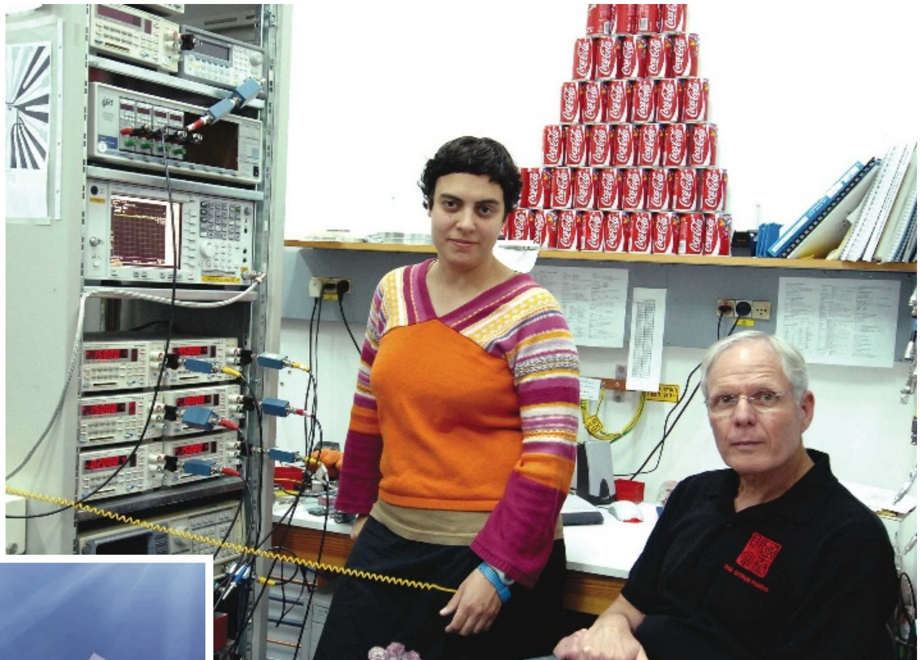
parameters during fabrication of the device which is about a millimetre in width and is made from a number of layers of gallium arsenide and aluminium gallium arsenide. The density of electrons in the 2DEG has to be very high — about three billion in a square millimetre — while the structure has to be so clean that electrons can move through the 2DEG for up to half a millimetre without hitting any sort of defect. And the 2DEG will inevitably be damaged in the process of putting down metallic wires to form the point contact, which means it has to start off even better than is needed.

2DEG or not 2DEG

But the effort has paid off. An enormous amount of shot noise recorded while the device was cooled down to 10 milliKelvin has provided solid evidence in favour of quarter-charge quasiparticles. Independent confirmation of the existence of quarter-charge particles in such a set-up comes from a team at Harvard, the Massachusetts Institute of Technology in Cambridge and Bell Laboratories in Murray Hill, New Jersey. These researchers used a similar device, but measured the conductance between the two current channels at the point contact, rather than the shot noise[4].

This is the news the field has been waiting for. "In all my talks on topological quantum computation I've said this is the one experiment that needed to be done first. And frankly I didn't expect it this soon," says Das Sarma. However, although experts regard the experiments as important and necessary, many also see them as insufficient in themselves. To really validate the idea of making a computer this way you need to show that the quarter-charge quasiparticles really do behave in a non-abelian way. This can be done by making the quasiparticles encircle an island of anyons, as a rudimentary anyon braid. To do this, at least two point contacts need to be constructed that can be shut tightly so that all quasiparticles can be made to jump from one side of the 2DEG to the other. The quantum properties of the braid that is formed by this weaving around of quasiparticles will show up in the measured current-voltage characteristics.

Building such a 'quasiparticle interferometer' is a challenge, given that making just one point contact in the required quantum Hall regime has proved difficult enough, but it is not a far-fetched ambition. Can we expect it this year? Dolev is cautious. "This field is just starting. In the next few months we will find out what the experimental difficulties are," she says. For example, the interferometer needs much more stable point contacts than were used in the system that first demonstrated the existence of quarter-charges.



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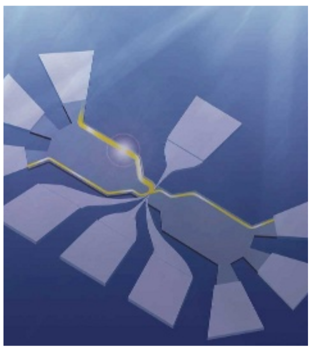

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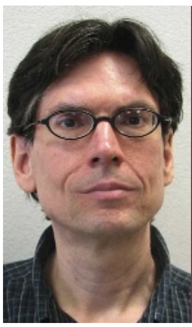
Merav Dolev (above left), Moty Heiblum and an artists impression of the quantum Hall device (left) in which they measured even fractional charges.

However, having identified a particular side-effect of the 2DEG fabrication process that produces instabilities in the point contacts, the group is already getting stabler devices. And if they don't succeed, competitors inspired by their work may. "Proving the non-abelian properties of [quarter charge] quasiparticles would be a hard experiment, but the work by Dolev *et al.* will certainly motivate people to try it," says Bonesteel.

"One of the most exciting aspects of this demonstration is that it shows the quality of devices is steadily improving," says Kirill Shtengel, a theoretical physicist at the University at California, Riverside. "With luck, we might see a non-abelian interferometer within a year."

There are many experimental challenges to be met before a topological qubit sees the light. But everyone agrees that the concept of topological quantum computation is so attractive that it is worth a try. Ady Stern, a theorist with the Weizmann group, explains; "Other quantum computing approaches have a head start, but the concept is amazingly beautiful and the one advantage — topological protection of quantum states — is huge." Shtengel agrees: "Other approaches have serious problems with scalability. Right now we are behind, but once we have a non-abelian quasiparticle interferometer, a topological qubit should soon follow." Getting those qubits to knit together as computations will require geometries a lot more complex than a flattened hour-glass. In the long run, it is possible that some more suitable system will be found for topological quantum computing — something perhaps a little more user, or developer, friendly than an ultra-clean and precisely designed quantum Hall device that needs to be cooled down to near-zero temperatures. Whether it will sound any less absurd to begin with, though, we will have to wait and see. ■



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