50 Years Ago

With the increasing use of irrigation in horticulture and agriculture and the developing interest in the effects of evapotranspiration, it is frequently necessary to locate the level of a shallow water-table. This can be done inexpensively and effectively, using a small-diameter observation well and an electric probe … Twelve observation wells and a probe … have been satisfactorily used by me, in soils ranging from fine clay to coarse gravel, for a period of eighteen months, in connexion with investigations of the water-table in the Thames flood-plain. It is almost certain, however, that, if necessary, these instruments would give trouble-free service for a much longer period.
From *Nature* 16 June 1962

100 Years Ago

A Reuter message from New York reports that a steamer arrived at Seward (Alaska) on Sunday covered with volcanic dust from an eruption at Katmai, in the Aleutian Islands. It is stated by those on board that a steady stream of volcanic fragments and ash followed a terrific explosion, spreading over the countryside. The sun was obscured. Although the vessel was seventy miles distant, at four o'clock on Thursday afternoon complete darkness set in and ash fell in a thick layer on the decks. It is estimated that volcanic ash covers three hundred square miles of fertile country. According to a telegram from Seattle (Washington State) the volcanic disturbance is rendering wireless telegraphic communication with Kadiak, Rospberry, and Afognac, three of the most important islands of south-western Alaska, impossible.
From *Nature* 13 June 1912

one would normally be expected. They come in discrete, localized units and move as if they are particles.

Those two classic examples are good illustrations of noteworthy peculiarities of quasiparticles. Phonons, although they arise from the correlated motion of atomic nuclei, are particle-like objects that in no way resemble atomic nuclei. Holes, despite their origin in the correlated motion of electrons, have very different properties from electrons; indeed, they have the opposite electric charge. Quasiparticles transcend the elementary units from which they are built. They are emergent objects, embodying recognizable — that is, reproducible and long-lived — organizations of energy within structured materials.

Different materials can support different kinds of quasiparticles. Of course, each material's quasiparticles depend on the structure of the material and exist only within that material. Modern physicists can exploit their broad understanding of matter to design materials whose quasiparticles will have interesting or useful properties. Transistors, the building blocks of modern electronics, are an outstanding, but by no means singular, success story. They orchestrate the motion of electrons and holes to amplify and switch electronic signals.

Majorana modes add a striking new variation to the quasiparticle theme[7]. Appearing as solutions to equations of a type invented[8] by Ettore Majorana in 1937, Majorana modes represent forms of excitation predicted — and now observed — to be available to a few very special and specific kinds of quasiparticles. They were discovered as mathematical possibilities within quantum field theory[9], and were also found in theoretical models of possible exotic superconductors and of a particular form of the quantum Hall effect[10], which occurs in two-dimensional electron systems held at low temperatures and subjected to strong magnetic fields.

In a brilliant paper, Alexei Kitaev then showed[2] how Majorana modes could arise at the ends of superconducting wires. His reasoning was (relatively) simple and transparent, and is at the heart of most subsequent proposals for the realization of Majorana modes — including those that underlie the experiments of Mourik *et al.* and of other researchers[11,12] who have also reported evidence of the phenomenon in different but related systems.

To become acquainted with Majorana modes, it may be helpful to draw on their analogy to a more familiar property possessed by many particles and quasiparticles — their spin. For example, an electron at a given position can be in either of two states, with spin 'up' or 'down'. Spin provides new dynamic options for particles that have it; that is, the possibility of spin-dependent interactions, including interactions that change the spin's direction. Majorana modes generate, for quasiparticles that support them, a kind of emergent spin. It is convenient to have a word for the concept 'quasiparticle that supports Majorana modes', and I have suggested[13] 'mode-icule'. To describe the quantum state of a mode-icule, we must specify a two-component wavefunction, just as we do for a (spin-ful) electron.

Building on previous theoretical designs[14,15] for detecting Majorana modes, Mourik *et al.*[1] studied the electrical properties of indium antimonide nanowires lying atop a substrate made of a conventional superconducting material. Indium antimonide is a semiconductor that displays a strong quantum interaction called spin–orbit coupling: the motion of the electrons in the material is strongly coupled to their spin. Interaction with the substrate's electrons induces superconductivity in the wire's electrons as well, through a phenomenon known as the proximity effect. Mourik *et al.* observed that, in such a hybrid semiconductor–superconductor device, electrons can tunnel into and out of the wire with no change in energy, at an energy independent of applied voltage. This shows, quite directly, that there are unusual quantum states, associated with the ends of the wire, which have the properties predicted for Majorana 'spins'. The sensitivity of the strength of this tunnelling to the magnitude and direction of applied magnetic fields also matches theoretical expectations for the states associated with Majorana modes.

The analogy of Majorana modes to spin proves inadequate when we come to describe systems of several identical mode-icules. Crucially, the emergent 'Majorana' states attached to separate mode-icules, unlike ordinary spins, are not entirely independent. On the contrary, those emergent states are, unavoidably, highly entangled. As a result, the quantum state of $2n$ mode-icules is described by a 2^n-dimensional wavefunction, whereas $2n$ independent spins would require 2^{2n} dimensions[16]. This constraint arises because mode-icules are entities called non-Abelian anyons[17], and so have unconventional quantum statistics — as opposed to fermions (such as electrons) or bosons (such as photons).

The wavefunction's dimensionality, although drastically reduced by entanglement, remains exponentially large in n. Interchange of mode-icules is accompanied by the complicated, but perfectly predictable, evolution of their wavefunctions in a complex mathematical region known as Hilbert space. This evolution of wavefunctions in Hilbert space embodies the elegant principles of Clifford algebra[7,18].

Theorists have developed ingenious and ambitious proposals for exploiting mode-icules, with their controllable entanglement, to enable quantum computation[3,4]. Until recently, their visions have been, at best, loosely tethered to laboratory reality. To do useful computations, we will need to create many mode-icules, and to develop the ability to move their 'spins' around one another.