a shock. This caused a return of their fear only in response to the orange square, confirming that the memory-editing effect of the reconsolidation–extinction procedure was specific to the reactivated memory.

Finally, to investigate the longevity of the effect, the authors brought a sample of their volunteers back to the lab one year later, and gave them a reminder shock. Remarkably, those who had received extinction training within 10 minutes of the reminder trial the year before continued to be immune to the shock. Taken together, Schiller and colleagues' results thus show that updating windows exist in humans, that the effects of extinction training during this window are stimulus-specific, and that the effects last for an extended period not commonly observed for other experiments in this field.

Schiller *et al.* studied healthy volunteers, but an exciting possibility is that their findings might be useful for the treatment of anxiety disorders such as PTSD. Current therapies involve extinction-based exposure to memory cues, but because extinction training is less effective in PTSD[7], pharmacological methods are being explored to augment fear extinction[8], or to block fear reconsolidation[9,10]. The obvious advantage of Schiller and colleagues' reconsolidation–extinction method is that no drugs are required, only a modification of the timing of standard exposure therapy.

There are, however, several issues that need to be carefully examined with regard to the potential clinical efficacy of this approach[2]. The aversive stimulus used in the study was a mild electric shock, which might have quite distinct effects from the kind of life-threatening events that lead to PTSD. Furthermore, it is not clear whether Schiller and colleagues' method would be effective for modifying fear memories acquired months or years before extinction training, rather than in the 24-hour period of their experiments. Finally, PTSD is a complex disorder that involves symptoms such as avoidance of traumatic reminders, emotional numbing, nightmares, flashbacks and sleep disturbances. The extent to which all these symptoms depend on aversive associations that are susceptible to editing remains to be determined. Nevertheless, Schiller and colleagues' findings are an exciting development that paves the way for mechanistic studies, in both rodents and humans, to discover how memory retrieval prepares fear circuits for updating by extinction training. ■

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QUANTUM PHYSICS

Trapped ion set to quiver

Christof Wunderlich

The peculiar ultra-fast trembling motion of a free electron — the Zitterbewegung predicted by Erwin Schrödinger in 1930 when he scrutinized the Dirac equation — has been simulated using a single trapped ion.

In seeking to investigate the properties of a particular system, natural scientists often encounter situations in which the difficulty in accessing and tuning the system of interest experimentally prevents such investigation being made. An effective, and widely used, remedy for these unfortunate instances is the numerical simulation of the system's properties and behaviour on a computer. However, in many cases, faithful digital replication of the system is not possible because of limitations in computing power and memory. These limitations become prohibitive for systems governed by the laws of quantum mechanics, not least for many-body quantum systems, because the range of possible system states grows exponentially with the number of system constituents.

In such cases, new insight may be provided by a quantum simulation, which simulates a quantum system using a different, experimentally accessible and controllable quantum system. On page 68 of this issue, Gerritsma *et al.*[1] report their use of a single atomic ion trapped in an electrodynamic cage to simulate a free particle (for instance, an electron) in an extremely fast quivering motion superimposed on a slow drift — the Zitterbewegung, as it is known, which was first predicted by Erwin Schrödinger in 1930 but has so far not been directly accessible to experiments.

In the late 1920s, Paul Dirac succeeded in devising an equation — the Dirac equation — that married two descriptions of the physical world, each of which had already revolutionized our view of it: quantum mechanics and special relativity. This equation describes the quantum-mechanical behaviour of half-integer-spin particles, taking into account the fundamental principles of special relativity — for example, that the speed of light in a vacuum is the ultimate speed limit at which information can be transferred across distances in the Universe.

Non-relativistic quantum mechanics predicts phenomena that are difficult to reconcile with our classical perception of the world. For example, quantum-mechanical superposition states, in which a particle simultaneously occupies separate regions of space, are hard to envisage, but cleverly designed wave-interference experiments reveal that such unexpected behaviour is possible. Adding special relativity to the mix results in even more perplexing phenomena. In interpreting the solutions of his relativistic quantum-mechanical equation, Dirac postulated the existence of an anti-particle to the electron — the positron. Although initially seen as a daring prediction, positrons were observed shortly thereafter, and today are routinely used for medical imaging.

Other predictions of the Dirac equation have remained elusive, particularly Schrödinger's Zitterbewegung, which arises from the interference of particle states that are interpreted to have positive and negative energies. This is a prediction of the Dirac equation that describes a 'free' particle — that is, one that is not subject to external forces and yet changes its velocity, in blatant conflict with Isaac Newton's second law of motion in classical mechanics.

The 'art' of a quantum simulation lies in the faithful reproduction of the Hamiltonian (a mathematical entity from which the system's static and dynamic properties can be derived) of the quantum system we want to learn about using a system we can experiment with[2–4]. The experiment performed by Gerritsma *et al.*[1] was designed such that each quantity appearing in the Hamiltonian of a trapped ion mirrors a quantity in the Hamiltonian of a free relativistic quantum particle (a free Dirac particle, for instance an electron). Two of the ion's internal energy states represent positive- and negative-energy states of a free Dirac particle; and the position and momentum of the trapped ion simulate the position and momentum of the free Dirac particle. To reproduce the (one-dimensional) Dirac Hamiltonian, the authors irradiate the ion with laser light, which allows the ion's motion in one dimension to be coupled to the two internal energy states.

By adjusting the intensity and frequency of the laser, Gerritsma and colleagues could vary at will the effective mass of the simulated free Dirac particle and the effective speed of light, which appears in the Dirac equation and constrains the particle's motion. They first observed the Zitterbewegung for an ion with zero average momentum, the internal states of which would be in a superposition (corresponding to the superposition of the positive- and negative-energy states of a free Dirac particle) with equal relative strengths. The frequency of this quasi-periodic motion extends from about 10 kHz to 80 kHz — a range that was accessible in the authors' experiments.

Next, the researchers created another superposition state of positive- and negative-energy states, but one in which these two components moved in opposite directions. They observed that the Zitterbewegung disappears as soon as these parts leave the space they had initially jointly occupied. Furthermore, they showed that a pure negative-energy state results in no Zitterbewegung. These results, obtained by controlling the ion's initial state, confirm that it is indeed the interference between positive- and negative-energy states that gives rise to the Zitterbewegung. When the authors changed the particle's effective mass and kept its momentum constant, both in the non-relativistic limit (large effective mass) and in the highly relativistic case (small effective mass), the Zitterbewegung disappeared, whereas this quivering motion was clearly present in the regime in between.

The measurement of the ion's average position as it evolves in time requires exacting experimental control, because it needs to be carried out with a precision of a few nanometres to be able to resolve the Zitterbewegung. Gerritsma *et al.* achieve this precision by mapping, using a sequence of laser pulses, the ion's motion onto its internal states, which can in turn be measured through the detection of scattered laser light.

Gerritsma and colleagues' experiment[1] not only demonstrates a much-sought-after effect in a real system, but also marks important progress in bringing quantum simulations closer to yielding new insight even in scientific fields that lie beyond the realm of quantum-information science. Trapped ions[5], neutral atoms[6], superfluids[7] or optical fields[8] may be used to further our understanding of relativistic quantum mechanics and astrophysical processes. Furthermore, simulating many-body physical phenomena with neutral atoms may help in deciphering hitherto unsolved problems in condensed-matter physics — for instance, the nature of high-temperature superconductivity[4,9]. Similarly, internal states of a collection of trapped ions can be made to interact as particle spins do, with the interaction strength designed by the experimenter[10]. Thus, trapped ions could be used to investigate phenomena such as quantum magnetism[11,12]. Finally, coupled cavity arrays in the solid state, although still in their infancy in terms of experimental work, offer promise for quantum simulations[13,14].

Although quantum-information research progresses in unforeseen, and sometimes spectacular, steps, building a universal quantum computer — one that would be able to simulate other quantum systems and thus solve problems that are intractable on a classical computer — still poses formidable challenges. Specialized quantum simulations, such as that performed by Gerritsma and colleagues[1], promise to be a versatile and, at the same time, more amenable scientific tool. ■

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VIROLOGY

Bornavirus enters the genome

Cédric Feschotte

A survey of mammalian genomes has unexpectedly unearthed DNA derived from bornaviruses, leading to speculation about the role of these viruses in causing mutations with evolutionary and medical consequences.

Some people might find it disquieting that a hefty 8% of human genetic material originates not from our vertebrate ancestors but from viruses. The assimilation of viral sequences into the host genome is a process referred to as endogenization. It occurs when viral DNA integrates into a chromosome of reproductive germline cells and is subsequently passed from parent to offspring. Until now, retroviruses were the only viruses known to generate such endogenous copies in vertebrates. But on page 84 of this issue, Horie *et al.*[1] report that non-retroviral viruses called bornaviruses have been endogenized repeatedly during mammalian evolution. The finding unveils bornaviruses as a potential cause of mutation and also as an unforeseen source of genomic innovation (Fig. 1).

Borna disease virus (BDV) owes its name to the town of Borna, Germany, the site of a dreadful virus epidemic that decimated a regiment of cavalry horses in 1885. However, it is only recently that BDV has been characterized genetically: it belongs to the order Mononegavirales, and is a negative-sense RNA virus (in which the single-stranded RNA genome has the opposite sequence to messenger RNA). BDV infects a range of birds and mammals, including humans, and is unique among RNA viruses in that it naturally infects only neurons, establishing a persistent infection in its host's brain. In addition, the entire life cycle of BDV takes place in the nucleus of the infected cells, and does not require chromosomal integration[2]. This intimate association of BDV with the cell nucleus prompted Horie *et al.* to investigate whether bornaviruses may have left behind a record of past infection in the form of endogenous elements.

Horie *et al.* searched the 234 currently available eukaryotic genomes for sequences that are similar to that of BDV, and unearthed a plethora of endogenous Borna-like N (EBLN) elements in diverse mammals. The sequences of these elements resemble the nucleoprotein (*N*) gene of BDV, which encodes a structural protein involved in packaging the viral RNA into a nucleocapsid[2]. The authors show[1] that bornavirus endogenization has occurred in multiple mammalian lineages and at different times, ranging from more than 40 million years ago in anthropoid primates to less than 10 million years ago in squirrels. These molecular fossils add to the growing evidence[3–6] for the long-term coevolution of RNA viruses and their mammalian hosts.

All instances of endogenization described by Horie *et al.*[1] correspond to the *N* gene, and although most EBLN sequences are fragmentary and seem to be non-functional (they have decayed into pseudogenes), surprisingly, two EBLNs in the human genome are annotated as protein-coding genes. They retain long open reading frames (sequences that seem to encode proteins) and are transcribed from