direction and heading estimate in EPG neurons; this connection was maintained for minutes, even after the authors uncoupled the stimulus position from the fly's turns. But dampening ExR2 neurons decreased the strength of the coupling – showing that this cell type is necessary for generating an accurate heading representation based on a visual landmark.

The role of dopamine in reinforcement learning is long established. But now, Fisher *et al.* propose that the molecule also controls learning rate in unsupervised learning; in this case, a behavioural variable (the rate of turning) signals, through dopamine release, to compress the flood of incoming sensory information, allowing only the most useful to be selected. The authors point out that when a fly walks in a straight line, its visual information is limited, so a mental model built on such partial data is likely to be incorrect. This means that coupling the update rate in the compass with turning is not only efficient – similar to updating only those pixels that differ between frames when streaming a video – but also avoids the risk of overfitting to incomplete information.

Several questions remain, including how exactly dopamine changes synaptic connection strength. For example, does this occur only through changes in the number of neurotransmitter receptors, or do other structural changes also contribute to learning? It is unclear how general the when-to-learn signal is. The arthropod navigation centre is widely conserved in evolution, but locomotion strategies are diverse: how do circuits adapt to these differences? In mammals, the same task is performed by a functionally analogous, but structurally distinct, system that might use other motor signals and molecules to create its own learning logic. The mammalian navigation system not only stores spatial maps, but can also represent more-abstract cognitive spaces[5,6]. How does the brain find an appropriate when-to-learn signal for these maps? Answers could inspire the design of artificial-learning systems that can select task-relevant data on a moment-to-moment basis.

**István Taisz & Gregory S. X. E. Jefferis** are in the Division of Neurobiology, MRC Laboratory of Molecular Biology, Cambridge CB2 0QH, UK.
e-mails: itaisz@mrc-lmb.cam.ac.uk; jefferis@mrc-lmb.cam.ac.uk

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# Driven quantum bits push computational limit

## Tomaž Prosen

An exercise in benchmarking a quantum computer reveals that the processor can go beyond the 'integrability' limit, at which dynamical systems no longer have explicit solutions, and standard mathematical techniques struggle. **See p.240**

The old adage that three is a crowd is an apt introduction to the concept of integrability. For example, the celestial mechanics of a star and a planet are said to be integrable. In simple terms, this means that the behaviour of this two-body system can be fully characterized by fewer variables than we have at our disposal: enough of its physical observables remain unchanged for long enough to enable a robust description. But add a third body into the mix (or multiple extra bodies) and this integrability disappears. On page 240, Morvan *et al.*[1] describe how they simulated a model for many-body quantum dynamics in a system of 24 quantum bits (qubits) that are periodically driven to interact with each other. In doing so, the researchers have shown that it is possible to push the limits of integrability.

Integrability applies to phenomena as diverse as the spinning of a top and the propagation of waves in shallow water. It is universally characterized by robust, indestructible excitations that persist for arbitrarily long periods. Such excitations are usually referred to as solitons or quasiparticles, but they can also take the form of stable, bound states that comprise more than one quasiparticle. A system with a large number of components (a many-body system) is said to be integrable if it has an equally large number of physical observables that do not change with time[2,3].

Another physical principle, ergodicity, stipulates that large systems find equilibrium by changing states for long enough to eventually sample all possible states. Integrable systems have unchanging observables, and are therefore not ergodic. For this reason, integrable systems preserve a memory of their initial conditions, and this memory grows with their size. A pioneering example of this phenomenon was demonstrated in an experiment that used ultracold atoms to mimic a Newton's cradle – the
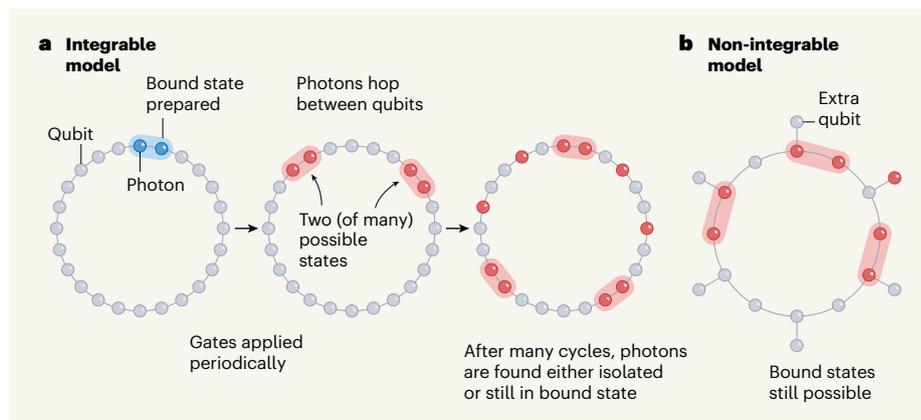


**Figure 1 | Driving interactions in a ring of quantum bits.** Morvan *et al.*[1] benchmarked a quantum processor with a model that is 'integrable', in that its physical observables permit a robust mathematical description. **a**, The authors prepared a ring of 24 quantum bits (qubits) with a string of 2 or more photons, known as a bound state. They then drove the system by periodically applying a quantum logic gate to all adjacent pairs of qubits in the ring, allowing the photons to move between qubits. With each cycle, single photons hopped around the ring, but so did bound states, as previously predicted for this model[7]. **b**, Morvan *et al.* then implemented a 'non-integrable' model by adding an extra qubit to every other qubit in a smaller system. After many cycles, they found that the bound states persisted for longer than expected. These states should decay to equilibrium quickly in systems that are not integrable, suggesting that quantum processors can push the limits of integrability.

swinging-ball toy beloved by physics teachers and chief executives alike[4].

Many models for integrable systems have been proposed so far, and such models provide an excellent means of benchmarking quantum computers. However, these descriptions are usually independent of time, and quantum processors are better suited to simulations of periodic dynamics that run in discrete steps. An integrable model for periodically driven, many-body discrete quantum dynamics, known as the XXZ circuit, was proposed four years ago[5,6], and was shown to have stable quasiparticles that can form bound states[7] — a surprising result for a system in which the dynamics are driven such that the system never reaches equilibrium. The model thus provides an ideal benchmark for a quantum computer.

Morvan *et al.* performed a quantum simulation of an XXZ circuit comprising a ring of 24 qubits. These could interact with each other through superconducting currents, in which charge carriers flow without any resistance, and were able to host trapped photons (light particles). The authors first prepared the system with a string of photons, and then drove it by periodically applying a quantum logic gate to all adjacent pairs of qubits in the ring, allowing the photons to move between qubits (Fig. 1a). Single photons hopped around the ring, but so did strings of photons, and the authors clearly demonstrated that these bound states could involve up to five photons.

The experiment is extremely versatile, because the driving is implemented with a robust type of gate known as an fSim gate, which can be applied rapidly and with high fidelity. Morvan and colleagues' implementation involved the original two-parameter XXZ circuit[6] with a third parameter that they used to mimic an external magnetic field.

The XXZ circuit is the driven analogue of a well-established model for magnetism in a one-dimensional system (the XXZ model) that can be obtained from the XXZ circuit by supposing that the frequency of the driving is infinite. In the XXZ model, the excitations are bound states of magnons, which themselves are excitations of the intrinsic angular momenta of electrons in a material[8]. The corresponding relationship between the velocity and momentum of quasiparticles in the (driven) XXZ circuit has previously been predicted[7], and Morvan *et al.* corroborated this by directly observing the velocity of stable bound states associated with a one-dimensional chain of photons. This measurement complements a less-direct observation of the same relation in a solid-state system using neutron-scattering experiments[9].

Each qubit in Morvan and co-workers' experiment has a remarkably long coherence time, which is the duration for which a qubit can remain in a given quantum-mechanical state. However, the experiment is not without

difficulties. The main challenge seems to be that the photons can 'leak' out of the system during the many cycles over which the qubits maintain coherence. The ideal XXZ circuit does not allow this: the total number of excitations (and thus photons) must remain constant. The authors fixed this problem by selecting only qubit sequences for which the number of excitations was conserved.

Beyond benchmarking with the XXZ model, Morvan and colleagues' work contains the conceptually intriguing, albeit speculative, suggestion that a quantum processor can probe the limits of integrability; these are inaccessible to standard classical computation when the system size is large. The bound states of photons are expected to be stable in integrable systems, and to decay quickly to equilibrium in systems that are not integrable. So the authors measured the decay of bound states for a situation in which the system should not be integrable.

They implemented this in a rather unorthodox fashion — specifically, by attaching an extra qubit to every other qubit in the ring, using an fSim gate (Fig. 1b). They found that the decay of the fraction of photons in bound states was surprisingly slow. Instead of decaying quickly, the bound states survived for up to 40 experimental cycles with a probability that was close to one, even when the ring qubits were coupled to the extra qubits as strongly as they were to each other.

In my view, this is potentially the most remarkable result of the paper, and it invites further in-depth analytical, conceptual and simulation studies of the problem. It is possible that this phenomenon shares similarities

with the non-ergodic behaviour of another non-integrable periodic XXZ model, which was previously revealed in classical simulations[10]. There are also hints that it could be explained by some (quantum) form of the Kolmogorov–Arnold–Moser theorem, which quantifies the stability of classical integrable systems when they are subjected to perturbations[11]. Regardless of the underlying mechanism, Morvan and colleagues' result is a tantalizing example of what can currently be achieved with quantum processors.

**Tomaž Prosen** is in the Department of Physics, University of Ljubljana, SI-1000 Ljubljana, Slovenia.
e-mail: tomaz.prosen@fmf.uni-lj.si

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## Alzheimer's disease

# Swollen axons impair neuronal circuits

## Inma Cobos & Jorge J. Palop

**Abnormal protein aggregates are a hallmark of Alzheimer's disease. It emerges that these plaques cause swellings in neuronal projections called axons that prevent proper circuit function. See p.328**

Alzheimer's disease is characterized by the abnormal accumulation of two misfolded proteins — amyloid-β, which forms structures called plaques outside cells, and tau inside cells. However, the effect of these aggregates on neuronal and network functions has been difficult to assess. The highly aggregated amyloid-β that makes up the core of plaques is surrounded by areas in which the synaptic connections between neurons have been

lost[1,2], and by neuronal projections called axons that have abnormal swellings, known as dystrophic neurites. Are these dystrophic neurites inert, or do they drive disease progression? On page 328, Yuan *et al.*[3] outline evidence suggesting that dystrophic neurites impair neuronal-circuit function, and provide mechanistic insights into this process.

The authors used high-resolution, time-lapse imaging to study single axons with