QUANTUM SIMULATION

Probing information scrambling

Quantum information encoded in one of many interacting particles quickly becomes scrambled. A set of tools for tracking this process is on its way.

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Quantum information can never be entirely lost, but it can be exceedingly well hidden. In interacting systems of many particles, information encoded in a given particle can quickly become diluted among all the degrees of freedom like a drop of dye in the sea — each dye molecule soon to be found everywhere with equal probability. Understanding how quantum information spreads may have wide-ranging implications, from elucidating the information paradox in black holes[1,2] to imposing fundamental limits on transport properties of strongly correlated materials[3]. Writing in *Nature Physics*, Martin Gärttner and colleagues present a powerful set of tools for directly probing the 'scrambling' of quantum information in an experiment using laser-cooled ions[4].

Scrambling is intimately related to chaos[5], a concept that is tricky to define in the framework of quantum mechanics. Classically, a hallmark of chaos is the sensitivity to initial conditions. But, consider two slightly different quantum states of a system, $|\psi_1\rangle$ and $|\psi_2\rangle$, governed by a Hamiltonian H, and compare their time evolution under the Schrödinger equation. A one-line derivation reveals that the overlap $\langle\psi_2(t)|\psi_1(t)\rangle$ is a constant, so two states that are initially similar will remain similar for all time. What, then, does it mean for the Hamiltonian H to be chaotic?

Paraphrasing the famous analogy of chaos theory, how can the flap of a quantum butterfly's wing in Brazil trigger a tornado in Texas[6]? The answer is easiest to formulate in the Heisenberg picture of quantum mechanics, in which states are constant, but

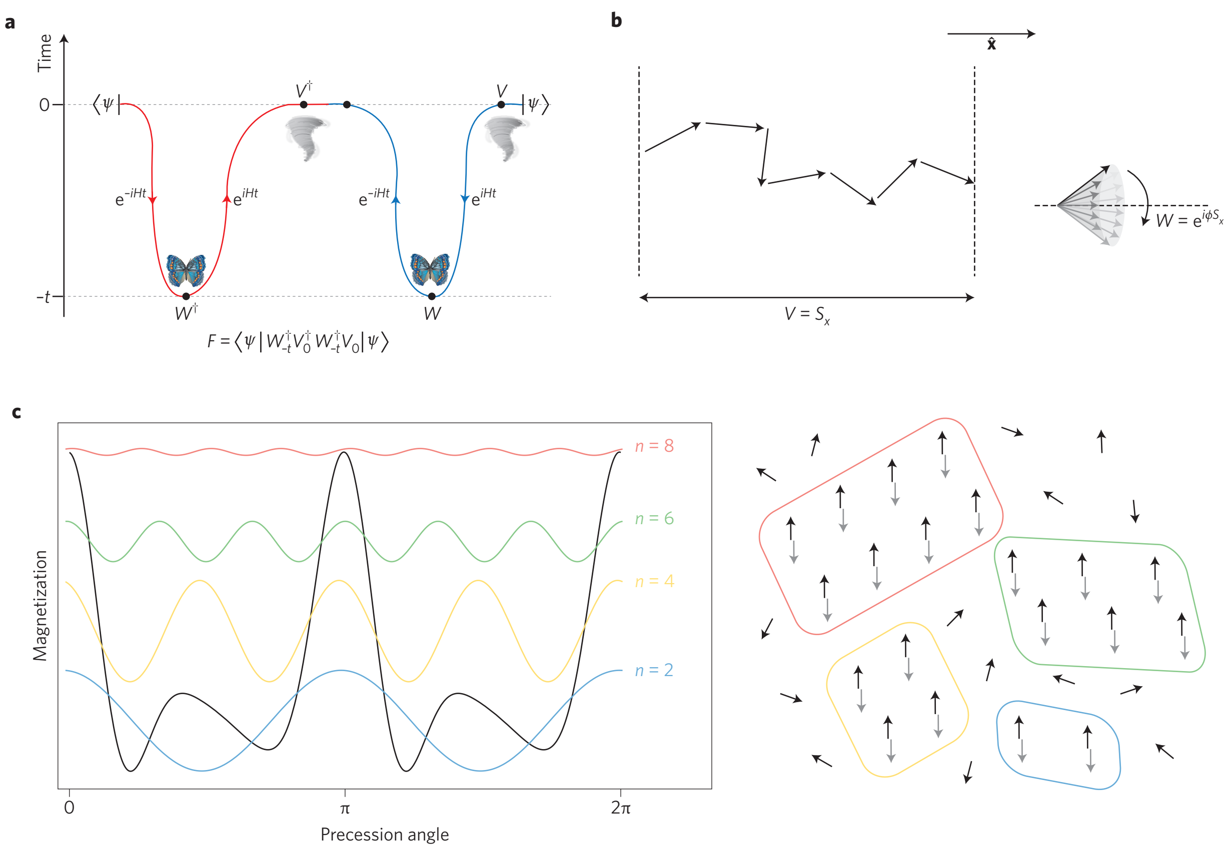

Figure 1 | Quantum mechanical butterfly effect. **a**, As the information encoded in a perturbation W is scrambled, the out-of-time-order correlation function $F = \langle\psi|W^\dagger_{-t}V^\dagger_0 W_{-t}V_0|\psi\rangle$ decays. F quantifies the overlap between states obtained by either first applying W, then letting the system evolve for a time t under the Hamiltonian H before measuring V (red); or first measuring V, then going back in time to apply W (blue). Operators $O_t = e^{iHt}O_t e^{-iHt}$ are represented in the Heisenberg picture. **b**, In the experiment, the perturbation W is a Larmor precession by an angle ϕ about the x axis, while the measurement V is of the magnetization along $\hat{\mathbf{x}}$. **c**, Multi-spin correlations are manifest in the Fourier decomposition (coloured curves) of the average magnetization (black curve).

operators evolve in time. A chaotic system is then one where an initially localized operator — say W, the wing that flaps in Brazil — rapidly extends its influence throughout Hilbert space, affecting the vorticity of the air in Texas. As a result, the operator for the vorticity V, initially commuting with W, no longer does so at later times. The more chaotic the system, the faster the commutator can grow.

The growth in the commutator is equivalent to the decay of a quantity called the out-of-time-order correlation function, which monitors the overlap between two states: one obtained by applying the operator W first, then letting the system evolve for some time before measuring V; and the other obtained by applying V first, then going back in time to apply W (Fig. 1a). Measuring this effect is a non-trivial endeavour, particularly because of the key step of going back in time. But it is possible in a well-controlled quantum system. After all, reversing the sign of time in the Schrödinger equation is equivalent to reversing the sign of the Hamiltonian — by changing repulsive interactions to attractive ones, for example.

It is physically impossible to change the sign of the Coulomb interaction in the trapped-ion experiment. Since the ions are positively charged, their interactions are always repulsive. However, abstracting away these experimental details, Gärttner and co-workers use a crystal of ions as a quantum simulator. Each ion has two internal states that can be viewed as the spin-up and spin-down states of a spin-1/2 particle. The spins can be made to interact by a laser field that converts spin excitations to phonons in the crystal and back again[7]. The resulting interactions can be ferromagnetic or antiferromagnetic, depending on the laser frequency[8]. Thus, in the quantum simulator, the researchers can switch the sign of interactions and thereby reverse the flow of time.

Analogous time-reversal schemes have a long history in nuclear magnetic resonance (NMR) experiments[9,10]. Gärttner and colleagues' work, together with recent related work on nuclear spins[11,12], rediscovers a decades-old NMR protocol and recognizes its significance for measuring out-of-time-order correlations. The protocol begins by initializing the quantum simulator in a spin-polarized state, then allowing the spins to interact for a time t. If the sign of interactions is immediately switched, the system evolves 'back in time' and thereby returns to the fully magnetized state. If, however, the researchers perturb the spins between the forwards and backwards time evolutions — by applying a field that induces a Larmor precession (Fig. 1b) — then the final magnetization is reduced. Algebraically, one can show that this reduction quantifies the failure of an initial magnetization measurement and the later Larmor precession to commute, due to the intervening interactions among the spins. Physically, Gärttner and colleagues interpret the decay in magnetization as indicative of scrambling.

Rather than simply accepting that information has been lost somewhere in the complex quantum system, the researchers find evidence of where it is going: into the quantum correlations between a growing number of spins[9]. They infer the emergence of multi-spin correlations from the dependence of the final magnetization on the Larmor precession angle (Fig. 1c). The dependence is necessarily periodic, as each spin is invariant under a 2π rotation. Theoretically, the period can be even n times shorter if groups of n spins are entangled by the interactions. Most generally, the magnetization is 2π-periodic, but not sinusoidal, and its higher harmonics signify correlations among multiple spins — as many as $n = 8$ within the hundred-ion simulator.

The measurement of scrambling performed by Gärttner *et al.* is a proof-of-principle demonstration. They simulated a model of globally interacting spins that is exactly solvable, restricted to a small Hilbert space, and not even chaotic: in principle, the information that appeared to be scrambled should periodically revive after long times. The benefit of this simple model is that it enables a detailed comparison between experiment and theory, which provides confidence that the quantum simulator can tackle more complex problems in future experiments. Achieving the same level of control in a chaotic system within an exponentially large Hilbert space may yet pose a challenge. Beyond lies the long-term prospect of engineering tabletop models for information scrambling in black holes, conjectured to be the most chaotic systems of all. ❐

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