fields to provide the energy required to overcome the energy barriers and change their microstate, leading to an effective thermodynamics[9].

By careful tuning of the parameters in the Hamiltonian, Farhan *et al.* have reduced the energy barriers in their system to the extent that slow — on the timescale of tens of seconds — magnetization dynamics, driven by thermal fluctuations, take place. This was done by reducing the thickness of their magnetic nanoislands to just 3 nm — only about ten atomic diameters. Then, using advanced, synchrotron-based, magnetic microscopy, they were able to observe those dynamics in real time.

Their observations can be described remarkably well in terms of a simple model in which the direction of magnetization of each element defines the position of the system's configuration on one edge of a hypercube. Carefully following the observed dynamics in the experimental system then permits them to map out the route through this hypercubic energy landscape that offers the lowest energy barriers. Doing so reveals the key role of interaction between elements. There are coupled cascades of reversals of individual elements: as one of them flips its magnetization direction, the energy barriers for its neighbours are reduced, allowing them to also quickly reverse their magnetic moments like a series of dominoes falling.

Finally, by preparing artificial-spin-ice systems of different sizes, Farhan *et al.* have been able to discriminate between the dynamics of those elements around the edge of the array, and those inside it. Elements in the interior of the array have frustrated interactions with their neighbours, meaning that they cannot simultaneously satisfy their pairwise interactions with all of them. As a result, their energy barriers to magnetic reversal are particularly low, and they flip their magnetization direction rapidly as they try to seek a low-energy, equilibrated state. All of this rich behaviour is reproduced in a Monte Carlo computer simulation.

The implications of this work are significant. At a fundamental level, these artificial spin-ice systems provide an excellent laboratory for studying the crossover between equilibrium and non-equilibrium statistical mechanics, and the way that these systems explore their phase space and energy landscape. Extending the work to the application of driving forces — magnetic fields, for instance — will bring fresh insight into the way that energy, entropy and information can be driven through such systems. Interpreting that insight in terms of complex-network theory could then lead to its widespread applicability in many areas — both in commercial settings, such as describing a financial or logistical network, and in solving societal problems, for instance in active traffic management to reduce congestion and hence pollution.

Moreover, there could be many possible applications of these systems in the future. One way of viewing the magnetic behaviour of such systems is to consider excitations above the ground state as quasiparticles that possess magnetic monopole properties[8,10]. The unjamming of the motion of these monopoles by thermal fluctuations opens up the possibility of using currents of magnetic charge to transmit information in an array: so-called magnetricity[11]. Moreover, arrays of nanomagnets strongly resemble proposed, but not yet commercialized, technologies such as bit-patterned media[12], where resistance to thermal fluctuations is critical, and magnetic quantum cellular automata[13,14], where control of switching and coupling is vital. Neural networks can also be modelled in terms of frustrated magnetic systems[15], and thermalized artificial spin-ice systems offer the prospect of building neuromorphic information-processing systems in hardware, rather than relying on software emulation. ❐

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LASERS

Amplified by randomness

Usually a laser consists of a light-amplifying medium nested between two mirrors. A mirrorless laser that operates by forcing the light to take a long, random path through the gain medium has now been demonstrated.

Vladan Vuletic

A conventional laser is a device with two mirrors that emits a bright, directional beam of light through one of the mirrors. Lasers with no mirrors and no preferred direction of emission can be envisaged, and have even been observed to occur naturally in outer space and in planetary atmospheres[1,2]. For instance, stellar gases are known to emit surprisingly strong radiation on certain molecular spectral lines[1], and an intense source of infrared radiation on Mars has been attributed to mirrorless laser operation[2]. Writing in *Nature Physics*, Quentin Baudouin and colleagues report the first laboratory implementation of this type of 'random laser' — originally proposed by Vladilen Letokhov almost half a century ago[3] — using laser-cooled atoms[4].

The function of the mirrors in a typical laser is to increase the path length of the light inside the gain medium, and thus to reach an amplification that overcomes the losses due to the output coupling of the light. How is it then possible to do away with the mirrors? The key is to add light scatterers to the gain medium, so the light cannot escape by travelling along a straight path. Repeated

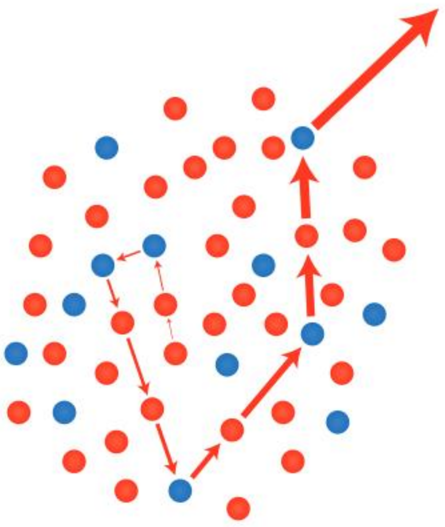

Figure 1 | A random laser consists of a gas of two types of atom: One amplifies the light (red), and the other (blue) merely scatters the light in a random direction. The scattering substantially increases the path length before the light leaves the medium. This results in larger optical gain (indicated by the increasing size of the red arrows), so the lasing threshold can be reached. Laser light is emitted in all directions.

scattering means that light can only leave the gain medium by a much longer, random diffusive route (Fig. 1). This substantially increases the optical amplification, which can bring the laser above threshold.

To realize a random laser with controllable parameters in a laboratory setting, Bauduoin *et al.*[4] use an ensemble of up to 10^{11} laser-cooled rubidium atoms at temperatures of 50 μK. They prepare the cold gas by optical excitation in a non-thermal state, where more atoms reside in one of two stable ground states than in the other. The gas is then illuminated with a laser that excites atoms in the more populated state. This corresponds to optical gain, where light can be generated and amplified as the atoms make the transition from the more populated towards the less populated state. However, for the given ensemble size and atom number, the optical gain for the light traversing the atom cloud on a straight path is too small for the system to reach the lasing threshold. To increase the optical path length inside the gain medium, Bauduoin *et al.* added randomly distributed atoms in a third state. These atoms scatter the generated light, forcing it to travel through the medium on a much longer diffusive path, whose length increases with the density of scatterers (Fig. 1). This system can reach the lasing threshold if the number of scatterers in a given volume is sufficiently large.

As the random laser has no preferred direction of emission, and the light is therefore emitted uniformly on average, it is not immediately obvious how to detect the onset of the lasing action in the device. Bauduoin *et al.* chose to measure the light emitted by the ensemble as a function of the laser frequency near the scattering resonance, which is equivalent to changing the density of scatterers. For low atomic density, corresponding to low optical gain, they observe no dependence of the light emission on laser frequency around the scattering resonance. However, as the density of atoms increases, a peak in the total light emission on the scattering resonance develops. This dependence of the collective light emission on the light frequency near the scattering resonance — equivalent to a dependence on the density of scatterers — is interpreted as a strong signature of random lasing.

In the future, other characteristic properties of lasers should be tested. For instance, the quantum properties of light — such as the correlations between successively detected photons — are different for laser light and for the more classical light emitted by a cloud of atoms below the lasing threshold. This transition could be probed directly. Furthermore, the theoretical model may be refined further to provide quantitative agreement with the data, and a more detailed insight into the lasing process. The experimental set-up used by Bauduoin *et al.* has a variety of control parameters, opening up exciting prospects for studying this intriguing type of laser. This will provide new insight into stellar and planetary sources of laser-like operation — without the need to invoke little green men holding up mirrors. ❐

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MAGNETIC MONOPOLES

Entropy lost

Low-temperature experiments on spin ice indicate that entropy plateaus at a value close to that estimated for water ice — a result at odds with the third law of thermodynamics. New measurements below 500 mK are consistent with the idea that spin ice finds a way to lose this residual entropy.

Nic Shannon

In many ways, life gets simpler as things get colder. Atoms slow down, magnetic ions order and entropy slowly leaks away until, at absolute zero, none remains. But the spin-ice materials $Ho_2Ti_2O_7$ and $Dy_2Ti_2O_7$ seem to buck this trend — neither system has ever been seen to order at any temperature. Instead, at the lowest temperatures measured, each magnetic ion retains a finite residual entropy, close to the $s \approx k_B/2\ln(3/2)$ predicted for water ice[1]. Now, writing in *Nature Physics*, David Pomaranski and co-authors describe new experiments on $Dy_2Ti_2O_7$, which bring us one step closer to solving this mystery[2].

Our understanding of spin ice takes its cue from another remarkable substance: water. Chemical bonding in water ice fails to select a unique ground state. Instead, proton configurations are governed by the 'ice rules'[3], which can be satisfied by an exponentially large number of different states[4], giving rise to a finite residual entropy. Exactly the same considerations arise in $Ho_2Ti_2O_7$ and $Dy_2Ti_2O_7$, where strong magnetic anisotropy and ferromagnetic nearest-