THERMODYNAMICS

Engines and demons

Brownian motion in a feedback-controlled optical trap provides a minimal experimental realization of a Szilárd engine, confirming fluctuation theorems and demonstrating the importance of spontaneous symmetry breaking in small thermodynamic systems.

Jörn Dunkel

Thermodynamics and information are intrinsically linked[1]. The laws of thermodynamics impose stringent bounds on the information transfer in physical, chemical and biological systems, thereby determining not only practical but also fundamental mathematical limits on the efficiency of classical and quantum computers[2]. Conversely, information must be included in the thermodynamic equations to avoid logical dilemmas. The most famous illustration of this profound connection is embodied by Maxwell's demon[3], an intelligent operator seemingly capable of violating the second law of thermodynamics — that is if one does not properly account for the entropy of information acquired and stored by the operator. Maxwell's demon and its relatives[3] have long been banished to the realm of thought experiments, but recent advances in experimental trapping and tracking techniques have now made it possible to test the underlying concepts from thermodynamics and information theory. Writing in *Nature Physics*, Édgar Roldán and colleagues[4] describe experiments where a Brownian colloid — a macroscopic particle pushed about through collisions with a fluid of atoms or molecules — in feedback-controlled optical traps is used to realize a minimal version of a Maxwell-type demon.

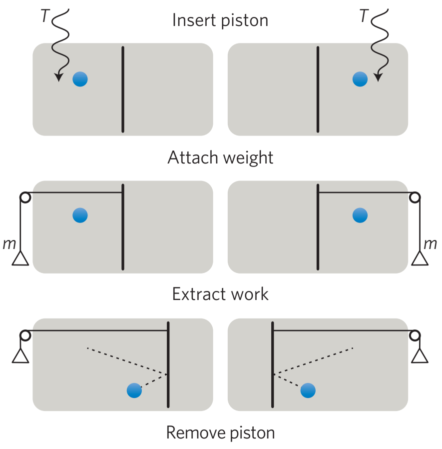

Figure 1 | Schematic of the Szilárd feedback cycle. A particle, coupled to a heat bath at temperature T, moves inside a container divided into two halves by a piston inserted by an intelligent operator ('demon'). The particle may be in either the left or right half of the container (top). The demon attaches a weight m to the left or right side of the piston depending on the location of the particle (middle). The particle's collisions with the piston are used to extract work from the system (bottom). Roldán *et al.*[4] have now created an experimental realization of such an engine and have probed the effect of symmetry breaking on the system's entropy production. Figure reproduced from ref. 11, © 1996 EPL.

The feedback protocol implemented by Roldán *et al.*[4] emulates an entropy-reducing thermal cycle originally proposed in 1929 by Leó Szilárd[5]. Szilárd, arguably one of the most remarkable physicists and inventors[6] of the past century, considered a hypothetical scenario in which an intelligent being operates a heat engine consisting of just a single particle in a closed container (Fig. 1). The cycle he proposed assumes that the particle is coupled to an infinite heat bath at constant temperature T and that the container can be divided into two initially equally sized compartments by a removable piston. Depending on the particle's position, the operator attaches a weight m to either the left or the right side of the piston. Once the piston has been pushed a certain distance by the particle, it is removed by the operator and reinserted at its original position. In principle, this process can be repeated an infinite number of times, with the particle continuously extracting energy from the heat bath and converting it into usable work. Szilárd reasoned that, in order for the system to be consistent with the second law of thermodynamics, the operator would have to create thermodynamic information entropy with a magnitude of at least $S = k_B \ln 2$, where k_B is the Boltzmann constant, during each measurement of the particle's position. Around thirty years later, an essentially analogous conclusion was reached by Rolf Landauer[1], who argued that the erasure of physical information is a dissipative process producing an average amount of heat not smaller than $k_B T \ln 2$ for each bit deleted. This lower bound was confirmed in recent experiments by Bérut *et al.*[7], who studied Brownian motion in a tunable bi-stable optical trap — a paradigmatic model system for classical memory erasure.

Roldán and colleagues[4] extend the work of Bérut *et al.*[7] by investigating how spontaneous symmetry breaking — induced by the spatio-temporal modulation of an external effective potential — affects the Brownian dynamics of a micrometre-sized colloid in a water bath at fixed temperature. To realize a sufficiently adjustable potential, the authors superimpose an electrostatic field on two optical traps. By varying the distance between the traps, the resulting effective potential can be changed continuously from a single-well to a double-well configuration. The superimposed electrostatic field, which couples to the surface charge of the colloid, biases the probability of finding the particle in either of the two potential wells.

To emulate Szilárd's engine, Roldán *et al.*[4] identify and implement a conditional sequence of changes in the potential parameters that leads to a negative mean entropy-production over the course of a full cycle. Their protocol starts with driving the potential from the single-well to a double-well configuration (isothermal expansion), forcing the Brownian particle to choose one of the two wells. During this 'symmetry breaking' step, the electrostatic field is held at a constant value, selected so that the colloid is nearly twice as likely to be found in one of the wells. Once the expansion has completed, the electrostatic field strength is increased to a large positive (or negative) value to ensure that there is a high probability that the particle stays in the same well during the subsequent compression step. In contrast with conventional naive thermodynamic processes, this crucial feedback step relies on information about the particle's position — just as the coupling of the weight in Szilárd's original cycle. Following the feedback step, the traps are driven back to the original single-well configuration (isothermal compression) while keeping the electrostatic field constant. The cycle is completed by adiabatically resetting the electrostatic field to its initial value.

The mean entropy production of the process is determined by relating the observed particle trajectories to statistical averages of the thermodynamic state variables through a suitably adapted canonical fluctuation theorem[8], similar to those used to characterize the folding energetics in DNA-pulling experiments[9,10]. Such an explicit averaging procedure is necessary because the one-particle system operates far from the thermodynamic limit, which means that the values of thermodynamic observables fluctuate substantially from cycle to cycle. The authors find that their process is indeed capable of extracting work from the thermal bath at a rate that is consistent with theoretically predicted lower bounds on the mean entropy-reduction.

At this point, it may be appropriate to add a brief technical remark that, in similar form, also applies to DNA-pulling experiments[9,10]. Owing to frequent collisions of the trapped colloid with the surrounding water molecules, the experimental set-up of Roldán *et al.*[4] is a realization of a canonical ensemble. Thus, in principle, there is always a small probability that the Brownian particle might spontaneously cross the potential barrier. In this sense, the isothermal expansion step in their experiments does not achieve strict symmetry breaking. Fortunately, however, as with all real-world implementations of thermodynamic cycles, changes to the parameters in the experiment occur in a finite time. Roldán and colleagues[4] verify that the mean time for the colloid to pass through the potential barrier (about one week) is much larger than the typical cycle time (less than one minute). This suggests that ergodicity is almost surely violated in their case, as the Brownian particle does not have the time to explore the full configuration space.

Regarding past and future applications of fluctuation theorems to complex processes, it is reassuring that the well-controlled experimental system of Roldán *et al.*[4] produces results that are consistent with theoretically predicted entropy bounds. It is worth noting that their study also suggests that memory erasure[7] can be interpreted as the restoration of a broken symmetry. Therefore, these new experiments not only provide guidance for the design of intelligent thermodynamic cycles but also elucidate the intimate connection between information, symmetry and thermodynamics. ❐

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FRICTION

Let it slip

Friction involves a complex set of phenomena spanning a large range of length scales, but experiments assessing the evolution of the slip-front between two dry sliding bodies now reveal that slip can be reasonably well described by linear fracture mechanics theory.

Robert W. Carpick and Roland Bennewitz

How do things slip? Scientists, from Leonardo da Vinci[1] to Pierre-Gilles de Gennes[2], have pondered friction and slip, but the difficulty in observing and measuring the behaviour hidden at the interface between contacting materials remains a vexing challenge. Yet the stakes are high as friction has costly and sometimes even life-threatening consequences: predicting earthquakes around geological faults (Fig. 1) and the optimal seismic design of buildings requires knowledge of frictional slip dynamics across multiple length scales. Moreover, frictional behaviour can determine the efficiency and reliability of sliding mechanical elements in systems ranging from wind turbines to deployable satellite components, and friction determines function in natural systems, from climbing geckos to the health and strength of hips and knees.

As they report in *Nature*, Ilya Svetlizky and Jay Fineberg[3] reveal how frictional slip is closely related to fracture. They address two key issues that are particularly relevant to sliding in dry conditions: measuring the local deformation and dynamics of the moving front of a buried sliding interface, and subsequently, whether one can use the simple and well-developed theory of linear elastic fracture mechanics to model the results. Up to certain limits, they find remarkable agreement between the theory (developed for shear-loaded cracks in an otherwise uniform single material) and the experiments (involving two distinct blocks in contact sliding relative to one another).

For two materials in contact such as the block-on-a-plane system examined by the authors, an applied shear force initially causes no relative motion, just a slight deformation of the two materials. However, as the applied force is increased, slip eventually occurs. In many dry systems (that is, systems with no lubricant), slip does not occur all at once but rather by the propagation of a pulse that originates at the back-end of the block, causing a crack to appear at the interface. As the leading edge of the pulse moves forward, the slipped region grows — the crack extends — until the entire block has moved forward. The challenge is to determine the