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 deformation of the material around the crack tip as it races along the interface at accelerating speed.

Measuring deformation is typically achieved using strain sensors that change their electrical resistance when stretched or compressed. However, these strain sensors are clumsy on the scale of a crack tip and, moreover, they need to be attached to a fixed position. Svetlizky and Fineberg addressed this problem using the innovative and elegant approach[3] of converting high recording bandwidth into high spatial resolution. Strain was recorded one million times per second by fixed strain gauges and the local crack propagation velocity was measured by a high-speed camera. Combining these data enables reconstruction of the strain around the crack tip by transforming to the local crack-tip reference frame.

The authors compared the reconstructed strain pattern with predictions from the theory of linear elastic fracture mechanics. The theory makes quantitative predictions about the relationship between the strain emanating from a crack tip and external stresses — such as overall tension or, in this case, shear — applied to the body. Assuming that the material behaves in a linear elastic isotropic manner, the most significant prediction is that strain increases inversely with the square root of the distance from the crack tip, reaching a singularity at the crack tip itself for the ideal case of an infinitely sharp crack. The authors found strikingly detailed agreement between the theory and their experimental results. Intriguingly, they point out that their method could lend itself to measuring the strain state of earthquake fronts through fast strain measurements with simple devices placed near geological faults.

Svetlizky and Fineberg observe the limits of agreement between linear elastic fracture mechanics theory and their experimental findings when the crack speed approaches the Rayleigh velocity (the speed of sound on a surface, which is the upper limit of the crack speed). Interestingly, close to the Rayleigh velocity, a sort of relativistic effect takes place. According to the special theory of relativity, nothing can move faster than the speed of light, and we know that strange effects — such as the Lorentz length contraction — occur when bodies approach this speed. In the linear theory of elasticity, no deformation can move faster than the speed of sound. Correspondingly, length scales, such as the characteristic length of a zone of weakened cohesion preceding a crack tip, contract as the tip's velocity approaches the speed of Rayleigh waves — crack-propagation scientists refer to this as a 'Lorentz-like contraction'. The experiments performed by Svetlizky and Fineberg[3] give direct access to these contracting lengths and thus enable the testing of new models for fast shear-cracks.


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Figure 1 | San Andreas Fault, California, USA. Major geological faults occur where tectonic plates slide past one another, generating seismic activity and sometimes resulting in large earthquakes. It is difficult to experimentally study *in situ* exactly what happens at the frictional interface between two such sliding bodies. However, Svetlizky and Fineberg[3] now show how friction can be examined in the lab by monitoring the spatio-temporal evolution of strain fields associated with a propagating crack.

The progress made by Svetlizky and Fineberg has the potential to significantly impact on the modelling of friction, a difficult problem as the different length scales involved — ranging from molecular interactions at the interface to the deformation of individual contacts to the long-range elastic correlation between contacts — require multi-scale descriptions[4]. The experimental proof of the onset of sliding following classical shear-crack dynamics is a breakthrough as it establishes connections between these different regimes. Not only are analytical solutions available for the long-range coupling of contacts through stress and strain, the theory of classical shear-cracks also provides values (such as the characteristic length-scale of interface weakening and the interfacial strength) that can now be compared with results from microscopic models of the problem. Svetlizky and Fineberg's work offers exciting prospects for using linear fracture mechanics to broaden our understanding of friction and sliding. ❐

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