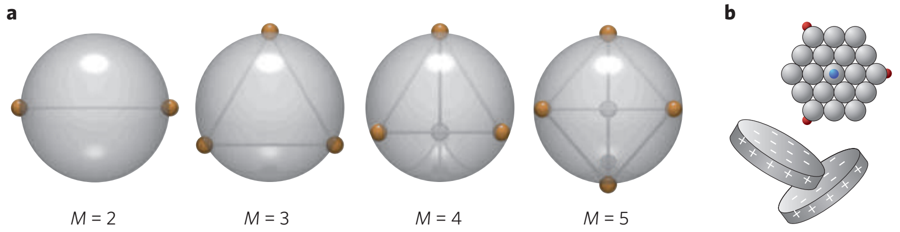

Figure 2 | Models of patchy colloids. **a**, Models with M attractive patches equidistantly located on the surface of a sphere[1]. **b**, Patchy disk model for Laponite as studied by Ruzicka and colleagues[6]. The patches on the disk represent charges, three positive (red) at the rim and two negative (blue), one at the centre of each disk face. Positive and negative charges induce a directional face–rim attraction, and electrostatic repulsions limit the number of bonds per disk. Panel **a** reproduced with permission from ref. 1, © 2006 APS.

a similar model was used in ref. 9, but those authors apparently looked at lower volume fractions.) Notwithstanding the approximations in the model, the topology of the phase diagram resulting from the simulations is qualitatively consistent with the experiments. Similarly, the time evolution of the static structure factors from simulation and experiments agree.

All in all, Laponite suspensions are found to undergo a classical gas–liquid phase separation in which the liquid can either be an empty liquid or an equilibrium gel. It is important to note that empty liquids are not actually observed, but that their existence is inferred from the global scenario. In fact, an equilibrium gel can be interpreted as an arrested empty liquid: both are network structures subject to continuous rearrangements driven by thermal fluctuations. In the case of the gel, however, bonds are stronger and rearrangements therefore are significantly (in fact drastically) less frequent. At higher Laponite concentrations the authors observe a Wigner glass[6] — a glass of clusters interacting with repulsive electrostatic interactions (Fig. 1) — but this is probably not the thermodynamically stable structure at these higher densities; which structure this is remains an open question.

The work by Ruzicka *et al.*[6] shines light on the remarkable properties of clay, which finds applications in areas as diverse as slide analysis, oil drilling and the production of ceramics[7]. But what is more exciting, if colloids with sticky patches can be synthesized in a systematic way, is that we expect new structures with amazing properties to be found. In biological systems, for instance, intricate structures such as spherical and cylindrical virus capsids are thought to arise in large part because of sticky (for example hydrophobic) patches on the protein molecules that make up these structures. Empty liquids and equilibrium gels thus represent a wonderful sneak preview of what can be expected from patchy colloidal particles. ❐

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References

1. Bianchi, E., Largo, J., Tartaglia, P., Zaccarelli, E. & Sciortino, F. *Phys. Rev. Lett.* **97,** 168301 (2006).
2. Glotzer, S. C. & Solomon, M. J. *Nature Mater.* **6,** 557–562 (2007).
3. Hermans, T. M. *et al. Nature Nanotech.* **4,** 721–726 (2009).
4. Pawar, A. B. & Kretzschmar, I. *Langmuir* **24,** 355–358 (2008).
5. Hong, L., Cacciuto, A., Luijten, E. & Granick, S. *Langmuir* **24,** 621–625 (2008).
6. Ruzicka, B. *et al. Nature Mater.* **10,** 56–60 (2011).
7. van Olphen, H. *Prog. Colloid Polym. Sci.* **61,** 46–53 (1976).
8. Lu, P. J. *et al. Nature* **453,** 499–503 (2008).
9. Kutter, S., Hansen, J-P., Sprik, M. & Boek, E. *J. Chem. Phys.* **112,** 311-322 (2000).

ORGANIC ELECTRONICS

Harvesting randomness

The practical use of electronic ratchets has long been hampered by low output powers and cryogenic operating temperatures. A pentacene-based organic ratchet can now drive electronic circuitry at room temperature.

Peter Hänggi

Humans have always dreamt of machines that perpetually perform useful work from random fluctuations, such as those in ambient thermal noise. However, the second law of thermodynamics forbids the realization of such devices — it is indeed impossible to obtain useful work from a system held at fixed temperature without driving it out of thermodynamic equilibrium. Although single, rare events can extract energy from a system at equilibrium — in what may seem a violation of the second law — the extraction of net work on average (that is, over a period of time larger than the duration of a single event) is ruled out. This constraint is closely related to the concept of a Maxwell demon[1,2], which was originally introduced to pick a hole in the second law. To overcome the limitations of the second law, it is necessary to drive a system out of thermodynamic equilibrium.

At the microscale, where thermally driven random forces can dominate interparticle interactions, it has recently become possible to build out-of-equilibrium, bio-inspired nanomachines that perform work by harvesting environmental randomness[3]. Such machines are known as Brownian motors[3], among which electronic ratchets[4,5] are prominent examples. Ratchet devices are set-ups composed of periodically arranged units with inherent asymmetry, and can be driven by unbiased, time-dependent, random or deterministic forces. Electronic ratchets have so far been limited by the need for cryogenic operating temperatures, and by low output voltages and currents[4,5]. Thus they have been of limited practical use. In *Nature Materials*, Martijn Kemerink and collaborators[6] report an ingeniously designed organic electronic ratchet that operates up to radiofrequencies at room temperature and delivers an unexpectedly high output performance, sufficient to power a simple logic circuit.

As in a self-winding wristwatch, which works especially well on a gesticulating wearer, the working principle of any ratchet device is based on the clever combination of asymmetry and an external, unbiased force that drives the system out of equilibrium. The device by Kemerink and colleagues mimics a flashing ratchet (Fig. 1a), in which the repeated on–off switching of a sawtooth-like potential rectifies the jittery thermal motion of charge carriers to yield directed charge transport in the absence of a source–drain voltage[3,7]. Its main building block is an organic transistor, in which a thin film of pentacene is contacted by Ti–Au source and drain electrodes, and mounted on top of a dielectric ($\mathrm{SiO_2}$) layer and a silicon back gate. A number of periodically arranged — but unevenly spaced — interdigitated finger electrodes, which are embedded in the dielectric layer, implement the required asymmetry (Fig. 1b). When a sinusoidally varying potential is applied to the electrodes, the device is driven out of equilibrium and a directed current is induced.

Surprisingly, the authors find large, directed net charge currents, of up to about 0.3 μA, for a device with an even number of electrodes. Such currents are three orders of magnitude larger than those obtained in previous electronic ratchet devices[4,5], thus vastly exceeding the current state of the art. This enhancement is achieved by a design in which interaction-induced drift motion dominates diffusion-limited motion. Somewhat smaller directed net currents are obtained when an odd number of electrodes are used, as indicated with the additional, right-hand-side electrode (AF1) in Fig. 1b. Such a ratchet design contains an additional symmetry breaking, namely that of the spatial periodicity of the arrangement composed of blue–red paired ratchet electrodes and the source–drain contacts. The breaking of this symmetry drastically alters the observed ratchet behaviour and leads to intriguing net current reversals as a function of the applied electrode modulation frequency[6]. Moreover, Kemerink and colleagues discuss the application of the ratchet as a direct-current power source and as a charge pump with an efficiency of up to 13%. Because the current direction can be controlled and even reversed, such efficient charge pumping may be used for the cooling of lab-on-chip architectures. Kemerink and co-authors further demonstrate the potential of the electronic ratchet as a building block for logic circuits in a pentacene-based inverter that is driven by the ratchet's output power. An advantage here is that the power used to drive logic circuitry is generated intrinsically as a result of the ratchet's current–drain voltage characteristics, in a regime in which charges move opposite to the applied source–drain bias.

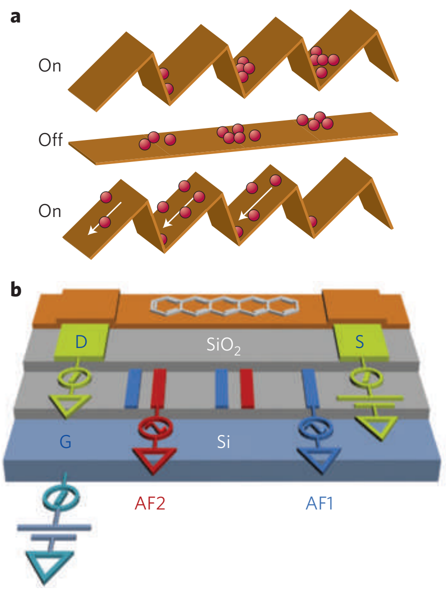

Figure 1 | The flashing ratchet concept. **a**, By repeatedly switching a sawtooth-like potential on and off, particles subjected to Brownian motion are on average transported in a specific direction (towards the left in the picture). This is so because the shape of the potential is asymmetric; in the off-state, the diffusion length to the crest that appears on the left-hand side in the subsequent on-state is on average effectively shorter than the diffusion length to the neighbouring right-hand crest[3,7]. **b**, The flashing ratchet realized by Kemerink and co-authors[6] consists of an organic (pentacene) semiconductor placed between source (S) and drain (D) contacts (G, gate). The sawtooth-like ratchet potential is induced by applying periodically varying voltages to all the underlying electrodes of type AF1 (blue bars) and AF2 (red bars), which are asymmetrically spaced along the channel. Electrodes of the same colour are electrically interconnected (not depicted).

From a physics point of view, however, an important question remains to be answered: what is the origin of the large directed current in these organic ratchet devices? Kemerink and collaborators give one plausible answer: they argue that charge–charge repulsion leads to the drastic enhancement in rectified current[6]. They support this conclusion with model calculations, which indicate that the applied voltage potentials induce asymmetric charge distributions in the organic semiconductor, leading to internal electric fields and effective drift-dominated directed transport. This mechanism is distinct from diffusion-controlled transport, which would be expected when charge–charge interactions are absent. However, when an oscillating, sawtooth potential is applied across the whole device, a sizable ratchet current emerges even in the absence of charge–charge interactions, with the latter becoming suppressed on inclusion of particle–particle interactions (see the Supplementary Information of ref. 6). This finding shows that the interplay between an interaction-mediated drift mechanism and the diffusion-mediated ratchet mechanism emerging from a single-particle picture leaves plenty of room for future theoretical and experimental studies aimed at optimizing these organic electronic ratchets. Notably, the present ratchet set-up is not the only one in which interaction affects the overall performance. For example, similar collective effects are found in type-II superconducting ratchets, which operate at much lower temperatures and with lower performance levels[3,8]. Because the physical origin of particle–particle interactions in these superconducting ratchets is distinctly different from the Coulomb interaction present in the set-up of Kemerink and colleagues[6], it would be interesting to investigate what type of interaction enables maximal current or power output.

Kemerink and co-workers have paved the way for interesting generalizations and applications of all-electronic ratchet circuitry. A future challenge would be to improve the functionality of these ratchets by aiming at even larger values for the net directed current and charge, either by optimizing device architectures and parameters or by fabricating devices with multiple, stacked ratchet electrodes. It is also tempting to consider whether the use of hybrid structures or different materials, or even the combination of different rectification mechanisms, could further optimize the performance towards an all-ratchet-based modus operandi for the rectification of transport and for charge separation at room temperature. In any case, ratchet physics will certainly offer many more surprises and unforeseen applications. ❐

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References

1. Maxwell, J. C. *Theory of Heat* (Longmans, Green and Co., 1871).
2. Leff, H. S. & Rex, A. F. *Maxwell's Demon: Entropy, Information, Computing* (Hilger, 1990).
3. Hänggi, P. & Marchesoni, F. *Rev. Mod. Phys.* **81,** 387–442 (2009).
4. Linke, H. *et al. Science* **286,** 2314–2317 (1999).
5. Kharpai, V. S., Ludwig, S., Kotthaus, J. P., Tranitz, H. P. & Wegscheider, W. *Phys. Rev. Lett.* **97,** 176803 (2006).
6. Roeling, E. M. *et al. Nature Mater.* **10,** 51–55 (2011).
7. Astumian, R. D. & Hänggi, P. *Physics Today* **55,** 33–39 (2002).
8. Villegas, J. E. *et al. Science* **302,** 1188–1191 (2003).