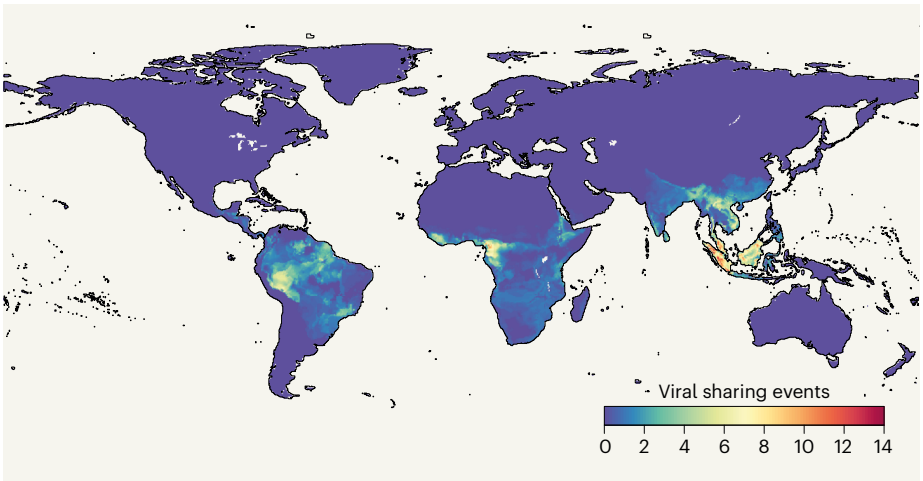

Figure 1 | Projected virus-sharing events between bats and primates. Carlson *et al.*[1] model how climate change will alter the geographical ranges of wild mammals. Altered geography can lead to new encounters between mammalian species, posing a risk that viruses will be transmitted between them for the first time. This heatmap indicates the regions in which new virus-sharing events between bats and primates are predicted to occur by 2070. The results are an average, taken from nine models of future climate change. (Figure adapted from Fig. 3d of ref. 1.)

has been less robustly investigated in work on the effects of a changing climate, and the literature shows a bias towards results that apply only to the most extreme warming scenarios. However, Carlson *et al.* present results across the full spectrum of possible climate (and land-use) futures, and at different time points, revealing interesting and subtle predictions regarding the possible timing of future changes. They suggest, for example, that climate-mitigation measures will not reduce the probability of increased virus sharing, but will influence the pace of sharing.

The scope of biological limitations explored is also ambitious. Stark results emerge when it is assumed that the geographical ranges of mammals depend only on climate factors, meaning that mammals could migrate to a suitable climate irrespective of distance or topology. However, this is probably biologically unrealistic (as the authors note): small flightless mammals, for instance, might not be able to jump continents if the climate becomes inhospitable. Carlson and colleagues' results are more modest when biological limits on species dispersion are considered.

The dispersal-limited models also underscore the importance of a particular mammalian order: bats could be a key driver of altered virus sharing under climate change (Fig. 1). The animals have long held the spotlight in the zoonoses theatre because of their ability (albeit contested[4]) to harbour and transmit emergent pathogens[5]. But Carlson *et al.* reveal another reason to focus on them. As winged mammals, bats might be particularly well positioned to respond to changing environmental conditions, by literally taking flight and migrating elsewhere.

Interestingly, this behaviour has already been recorded. Over the past century, the range of the black flying fox, or black fruit bat (*Pteropus alecto*), in Australia has moved southwards[6], most probably in response to climate change. This bat happens to harbour Hendra virus, which can infect horses and also people who have contact with infected horses[6,7]. Human-to-human transmission has not yet been recorded for Hendra virus, and this is one more biological hurdle that a virus must leap to be a real threat to people. Nevertheless, this is one small snapshot of the types of change predicted by Carlson and colleagues' work. Improved global surveillance will prove crucial for broadening the picture[8].

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Nanotechnology

A microscopic electric motor made of DNA

Henry Hess

The race is on to develop nanometre-scale motors for future tiny machines. The latest entry is a multi-component motor that self-assembles from DNA, harnesses Brownian motion to spin a rotor, and can wind up a molecular spring. **See p.492**

At the microscopic scale, thermal fluctuations drive the random motion of objects and spontaneous binding and unbinding events. However, microscopic motors are needed to accelerate and direct motion and to power assembly processes in micro- and nanotechnology. On page 492, Pumm *et al.*[1] describe a remarkable nanoscale system that serves this purpose: a rotary motor assembled from DNA structures, powered by electricity.

Electrical power is increasingly supplanting fossil fuels in a wide variety of applications, and electric motors are rapidly taking market share from their most widely used competitors — combustion engines and muscles. Electricity is also likely to be the preferred power source for generating mechanical work at the micro- and nanoscale, necessitating the development of high-performance electrical nanomotors. A milestone on this path was the construction of a nanoscale metal rotor spinning on a carbon nanotube axle[2], reported in 2003. The rotor was driven by the coordinated application of voltages to three electrodes.

In the two decades since then, DNA has emerged as a versatile material from which to construct nanoscale objects, and tremendous advances have been made in constructing ever larger and more complex structures from DNA in aqueous environments[3]. In 2006, the DNA origami technique — in which short, 'staple' strands of DNA fold a long DNA strand into complicated 2D or 3D structures — revolutionized the field, and is now a standard tool for

constructing nanoscale objects such as sheets, tubes and boxes[4]. Today, DNA origami structures are increasingly used as substructures of larger assemblies[5,6].

Pumm and colleagues take things further by reporting a rotary motor that self-assembles from three DNA origami structures: a pedestal, a platform and a rotor arm (Fig. 1). These parts are gigantic by molecular standards (the rotor is 550 nanometres long, for example), and the fact that they assemble correctly simply by diffusing around in solution is arguably as surprising as it would be to find that nuts and bolts thrown into a washing machine have threaded together during a wash cycle.

Importantly, the motor's operation relies on a 'Brownian ratchet' mechanism[7], in which random rotations of the rotor caused by thermal fluctuations are promoted in a desired direction of rotation, but blocked in the opposite direction. The idea of working with randomness, rather than trying to suppress it, is tremendously appealing to those aiming to engineer microscopic machines. In this case, the randomness of thermal fluctuations is overcome by the interaction of an applied, periodically changing electric field with the asymmetrical shape of the intrinsically charged motor. The precise mechanism by which the electric field acts on the rotor requires further study, however, because the field also produces other effects that could alter rotor movement – for example, it induces a flow of ions through the water around the device.

Often, when I read about a new nanomotor, my first thought is to question whether it can actually do mechanical work. The development of machines that produce predictable motion without doing work is still an achievement – in engineering history such machines proved invaluable, because they could be used as clocks for applications such as ocean navigation. Are Pumm and colleagues' devices capable of more than producing directed motion? Crucially, the authors demonstrate that their system can do work against a load by winding up a molecular spring, and that it therefore is unequivocally a motor.

My second thought is often about the efficiency of the nanomotor. Many artificial microscopic motors have energy efficiencies equivalent to a car consuming one million litres of petrol per 100 kilometres of travel, precluding their widespread application[8]. Pumm and colleagues derive an equation that can be used to roughly estimate the efficiency of their DNA origami motor, accounting for energy losses due to internal frictional drag. However, the biggest drain on efficiency is that the electrodes generating the electric field are placed millimetres apart around the device, a distance that is more than 1,000 times the rotor length. This is necessary to separate electrochemical reactions occurring at the electrodes from the motors, but it means that most of the electrical energy is lost on the way to the motor. Another breakthrough is needed to address this issue.

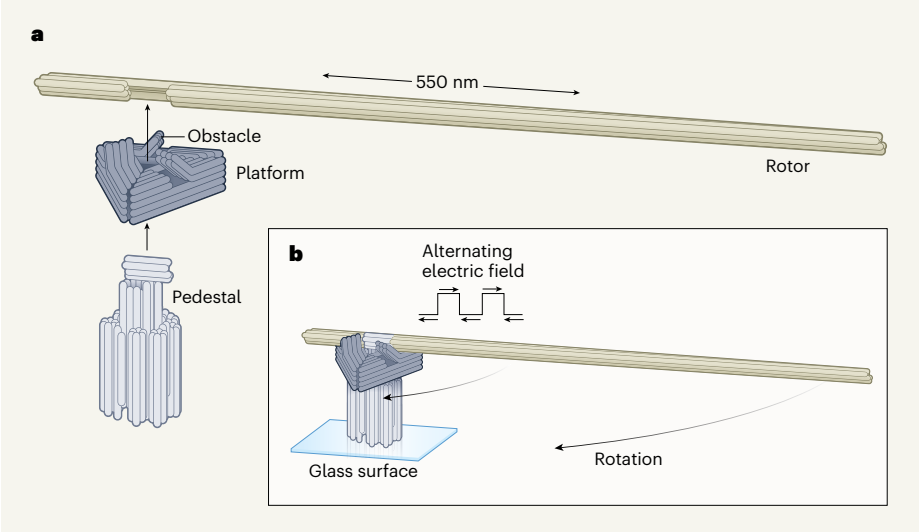

Figure 1 | The assembly and operation of a DNA nanomotor. Complex nanoscale structures can be assembled from DNA using the 'origami' technique, in which a long DNA strand is folded into a complex shape by dozens of short DNA strands acting as staples. Pumm *et al.*[1] report a nanomotor consisting of a pedestal, a platform and a rotor (**a**), all produced using the origami technique. These components self-assemble in solution to form the motor, which docks to a glass surface (**b**). Obstacles are incorporated on the edges of the platform to create a ratchet that promotes movement of the rotor in one direction. An alternating voltage applied to electrodes (not shown) on either side of the motor generate an electric field that spins the rotor.

I have previously argued[9] that vast numbers of tiny motors will be used in the future to power micro-robots and 'active' materials (which contain units that consume energy to produce motion or exert mechanical forces). Engineers are currently racing to achieve this vision by building motors using microfabrication techniques, biotechnology or organic chemistry, and choosing between electricity, light and fuels as the energy source. In the case of DNA devices, biotechnology can be used to manufacture motors in large numbers[10], and – as now shown by Pumm *et al.* – electricity can be used as the energy source for operation in water. By comparison, the electric motor[2] reported in 2003 was prepared using methods developed for fabricating semiconductor devices, and is operated in a vacuum to prevent the condensation of water on the exposed parts. The two motors are therefore complementary, and are likely to be used in different environments and applications, suggesting that there is room for more than one winner in this race.

"Crucially, the authors demonstrate that their system can do work against a load."

Pumm and colleagues' achievement is another step forward for DNA nanotechnology, demonstrating that DNA can be used to make a motor composed of multiple parts that have dimensions of up to several hundred nanometres, yet have precisely fabricated features at a much smaller scale, as are needed for the motor's operation. Furthermore, the authors have applied the hard-won theoretical understanding of Brownian ratchets to construct a new type of artificial nanoscale motor. More broadly, their findings show that we are getting closer to acquiring a mastery of molecular engineering, with the development of tools that can shape, move and assemble nanostructures whose functionalities rival those of the molecular machinery found in cells.

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