types and activate many biochemical pathways, such as acetylcholine receptors in muscle cells, T- and B-cell receptors that regulate immune responses, integrin receptor clustering that affects cell motility, as well as other apoptosis 'death receptors'. There are many cellular functions, however, that will not be able to be controlled this way. However, in light of these findings — and in spite of the drawbacks — nanomagnetic actuation technology has been brought significantly closer to clinical application. ❐

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References
1. Cho, M. H. *et al. Nature Mater.* **11,** 1038–1043 (2012).
2. Pankhurst, Q. A., Thanh, N. K. T., Jones, S. & Dobson, J. *J. Phys D* **42,** 224001 (2009).
3. Brazel, C. S. *Pharma. Res.* **26,** 644–656 (2009).
4. Kim, D-H. *et al. Nature Mater.* **9,** 165–171 (2010).
5. Dobson, J. *Nature Nanotech.* **3,** 139–143 (2008).
6. Dobson, J., Cartmell, S. H., Keramane, A. & El Haj, A. J. *IEEE Trans. NanoBioSci.* **5,** 173–177 (2006).
7. Kanczler, J. M. *et al. Tissue Eng.* **16,** 3241–3250 (2010).
8. Mannix, R. J. *et al. Nature Nanotech.* **3,** 36–40 (2008).
9. Creixelle, M., Bohorquez, A. C., Torres-Lugo, M. & Rinaldi, C. *ACS Nano* **5,** 7124–7129 (2011).
10. Huang, H. *et al. Nature Nanotech.* **5,** 602–606 (2010).

ARTIFICIAL MOTORS

Peptide-powered boats

The release and self-assembly of peptides from metal–organic frameworks creates surface tension differences that can fuel the cruising motion of the framework, and a microscale 'boat' wrapped around a framework particle, at the air/liquid interface.

Laurent Courbin and Franck Artzner

Initiating fluids into self-propelled motion, that is, without using an external force, is a topic that has intrigued scientists for many years. Self-propulsion requires spatial asymmetry to direct the motion, and an energy supply to sustain it. In the case of liquid drops on solid surfaces, the asymmetry can be provided by a suitable design of the surface topography[1,2], or by the use of reactive droplets interacting chemically with the substrate to generate surface tension gradients[3,4]. Such gradients lead to fluid motion as they result in an imbalance of the surface forces acting on the opposite sides of a drop. Temperature gradients can also generate such a driving force; for example, the motion of a drop heated asymmetrically using a light source[5]. These flows driven by surface tension gradients, which can even make a drop move up an inclined plane[6], are generally referred to as Marangoni flows[7].

Now, writing in *Nature Materials*, Matsui and co-workers[8] elegantly exploit Marangoni effects, which are also responsible for the 'wine tears' phenomenon seen when swirling a glass of wine, for the design of biomimetic motors. By combining the ordered, porous structure of metal–organic frameworks (MOFs) with the self-assembling nature of peptides, they create a chemical motor that converts chemical energy into long-lasting translational motion. The motor can even be inserted into millimetre-sized vehicles that resemble self-cruising 'boats' in a Petri dish 'boating lake'.

More generally, chemical motors have already been shown to take advantage of Marangoni effects to displace a liquid drop on solid surfaces[6] or to move objects at an air/liquid interface[9,10]. Thermal gradients or the release of molecules behind a moving carrier produce surface tension gradients that can trigger the motion of objects in the direction of large surface tensions. Increasing the autonomy of such motors remains a challenge. So far, their autonomy has been limited by the stocking efficiency of molecules and, in the case of air–liquid systems, by interfaces becoming saturated too quickly with the released molecules. Overcoming these obstacles requires the development of carriers capable of precise and controlled release of surface-active molecules. The chemical motor designed by Matsui and colleagues addresses some of these issues by using a highly ordered MOF as an energy-storing cell, or fuel tank, which stores fuel molecules (peptides) inside the nanoscale pores of its coordinated framework.

To generate large surface-tension-gradients that favour strong Marangoni effects, Matsui and colleagues have cleverly chosen a low-molecular-weight peptide, diphenylalanine (DPA) that exhibits robust self-assembling properties in a variety of solvents[11] and has a strong amphiphilic nature. As a consequence of the peptides' amphiphilicity, these molecules can significantly lower air/liquid surface tension. By depositing the MOF on an aqueous solution containing a ligand ethylenediaminetetraacetic acid (EDTA) that removes the metal ions from the framework, they show that the MOF can behave like a motor capable of producing a significant amount of kinetic energy per unit mass of fuel. Indeed, the energy produced is more than twice that obtained in previously reported gel motor systems[10]. The impact on the long-lasting motion is impressive and the millimetre-sized engine can cruise autonomously for more than ten minutes at high speeds, typically of the order of several centimetres per second.

More impressive than the autonomy characteristics of this chemical motor, the real breakthrough of this work lies in the two-step mechanism through which the chemical energy is converted into mechanical energy (Fig. 1). The first step is the release of peptides (that is, the fuel) from the carrier by gentle dissolution of the MOF matrix on addition of EDTA, which forces the peptides to dissolve in the water. Because the hydrophobic peptides have a lower state of energy at the air/liquid interface, the molecules quickly go to the surface, where they self-assemble, which significantly lowers the surface tension at the rear of the MOF as it is moving. The direction of motion is controlled by the direction of the initial impulsion of peptides released from the MOF.

Interestingly, during the second step, it is shown that the peptides' lowest state of energy at the air/liquid interface does not result in the formation of a self-assembled monolayer but instead of small crystalline

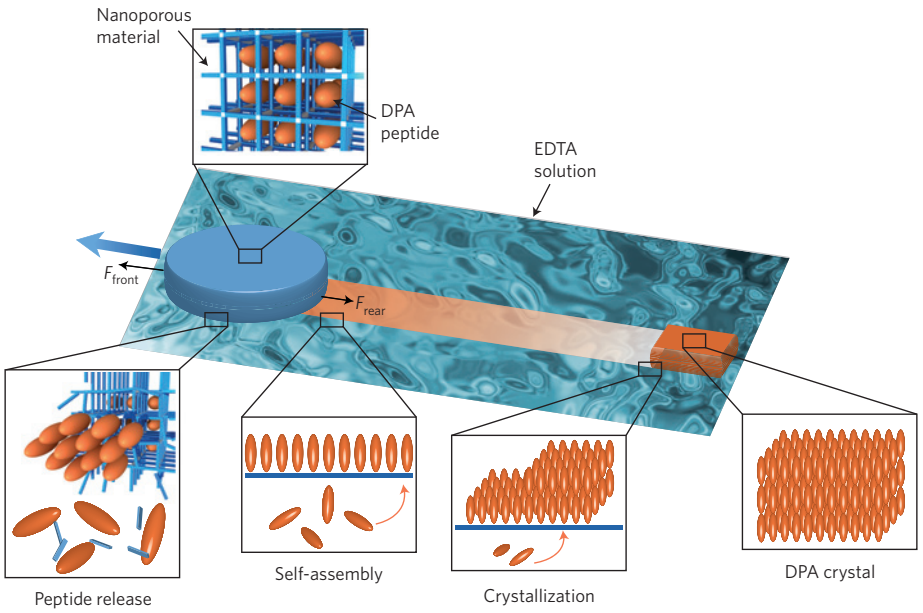

Figure 1 | A schematic showing the cruising ability of a metal–organic framework (MOF) particle with encapsulated DPA peptide on the surface of an EDTA solution[8]. Following deposition on the EDTA solution, the MOF partially decomposes and releases the peptides trapped within. The peptides self-assemble at the air/liquid interface, which induces an imbalance of the surface forces acting on the MOF. The MOF experiences a net force, F_{front}–F_{rear}, which powers its translational motion in the direction indicated by the blue arrow. The self-assembled peptides eventually form crystalline structures that help to increase the surface tension far from the MOF engine and ensure its long-lasting motion.

structures (Fig. 1). Such reorganization at the interface reduces the peptides' surface concentration and quickly increases the surface tension far from the MOF. A steady surface-tension-gradient is thus maintained between the front and the rear of the MOF, which sustains the motion as long as fuel is still present in the tank. Both steps, occurring concurrently, are important for the observed long-lasting motion: First, the peptide release causes a surface tension drop at the rear of the boat triggering motion, and second, the generation of crystalline structures increases the surface tension far from the boat, which prevents the interface from becoming saturated with peptides too quickly. The front of the boat 'sees' an unsaturated interface — a region of almost pure water — and keeps on cruising because of the sustained surface tension gradient.

It remains to be seen whether the lifetime of the chemical motor described by Matsui and co-workers could be enhanced. A larger fuel tank or new configurations that would prevent the inevitable destruction of the engine could help. In any case, this contribution should promote interesting developments in biochemistry, in particular for the fabrication of motors mimicking bacteria. ❐

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References

1. Linke, H. *et al. Phys. Rev. Lett.* **96,** 154502 (2006).
2. Lagubeau, G., Le Merrer, M., Clanet, C. & Quéré, D. *Nature Phys.* **7,** 395–398 (2011).
3. Sumino, Y., Magome, N., Hamada, T. & Yoshikawa, K. *Phys. Rev. Lett.* **94,** 068301 (2005).
4. Dos Santos, F. D. & Ondarçuhu, T. *Phys. Rev. Lett.* **75,** 2972–2975 (1995).
5. Nagy, P. T. & Neitzel, G. P. *Phys. Fluids* **20,** 101703 (2008).
6. Chaudhury, M. K. & Whitesides, G. M. *Science* **256,** 1539–1541 (1992).
7. Marangoni, C. *Ann. Phys.* **219,** 337–354 (1871).
8. Ikezoe, Y., Washino, G., Uemura, T., Kitagawa, S. & Matsui, H. *Nature Mater.* **11,** 1081–1085 (2012).
9. Nakata, S. & Murakami, M. *Langmuir* **26,** 2414–2417 (2010).
10. Gong, J. P., Matsumoto, S., Uchida, M., Isogai, N. & Osada, Y. *J. Phys. Chem.* **100,** 11092–11097 (1996).
11. Reches, M. & Gazit, E. *Science* **300,** 625–627 (2003).

COLLOIDAL SELF-ASSEMBLY

Superparticles get complex

The assembly of hundreds of thousands of semiconductor nanorods into nearly spherical or needle-like colloidal superparticles made of highly ordered supercrystalline domains can be explained by simple thermodynamic and kinetic principles.

Uri Banin and Amit Sitt

One of the aspirations of nanocrystal chemistry is to develop processes for the synthesis of functional structures at the meso- or microscales from basic building blocks in a bottom-up manner. Clearly, the structure, shape and functionality of the obtained structures result from the shape of the building blocks, and from the interactions between them (mostly of electrostatic or van der Waals nature) and with the environment (solvophilic versus solvophobic interactions). However, controlling such interactions — in particular when they are anisotropic — and the conditions at which self-assembly takes place, has proved to be difficult. Writing in *Science*, Charles Cao and colleagues demonstrate impressive control over the formation of colloidal superparticles[1] — in particular, double-domed cylinders each hundreds of nanometres in size, and micrometre-sized needle-like particles — assembled from hundreds to hundreds of thousands of colloidal CdSe–CdS semiconductor nanorods[2,3] arranged into well-defined supercrystalline domains.