conditions that allow episodic stormy outbursts is in itself a significant advance.

The authors' analysis also shows that the jet at 23° N remained robust throughout the storm disturbances. Using another numerical model, Sánchez-Lavega *et al.* tested various shapes of vertical shear below the clouds to reproduce the observed jet behaviour, and concluded that the jet stream's speed must increase with depth. This conclusion reaffirms an earlier result¹⁰ reached following studies of a very similar disturbance in 1990.

The disturbance in the 23° N jet marked the climax of a global upheaval on Jupiter, with changes in the colours of the visible clouds in several different latitude bands being seen throughout the 2007 observation season. This turmoil followed a very similar pattern to events in 1975 and 1990 (ref. 11). It is tempting to draw an analogy to a beating pulse — albeit an irregular one, and of unknown origin. It will be interesting to see whether a similar phenomenon returns sometime after 2020, following another break of a similar length. Saturn, too, has recurring giant convective outbursts¹²; both Jupiter and Saturn radiate more heat to space than they receive from the Sun, with cumulus convection transporting a great deal of heat vertically in their tropospheres. The pulsing nature of the giant storms on Jupiter and Saturn might even help us to understand how the heat flows from the deep interior to the surface on these planets.

A remarkable aspect of Sánchez-Lavega and colleagues' report¹ is the increasing part now being played by amateur astronomers in planetary observation campaigns. The almost continuous observational coverage by amateurs around the globe allowed the growth and motion of individual large-scale storm clouds to be followed for up to 45 days, while the Hubble telescope performed occasional tracking of fine-scale features for about 10 hours at a time. In recent years, inexpensive digital cameras and access to sophisticated image-processing techniques that correct for the blurring caused by Earth's atmosphere have enabled advanced amateurs with modest-sized telescopes to image planets with resolutions high enough to resolve many atmospheric phenomena (Fig. 1). This coverage from around the world nicely complements the more powerful, but less flexible capabilities of the large ground- and space-based telescopes. Undoubtedly, as the planetary physicians continue to probe deeper under the skin of their subjects, the dedicated amateur medic will be on hand to supply some of the diagnostic tools. ■

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4. Atkinson, D. H., Pollack, J. B. & Seiff, A. *Science* **272**, 842–843 (1996).
5. Seiff, A. *et al.* *Science* **272**, 844–845 (1996).
6. Rogers, J. H., Metting, H.-J. & Peach, D. *Icarus* **184**, 452–459 (2006).
7. Flasar, F. M. *et al.* *Nature* **427**, 132–135 (2004).
8. Simon, A. A. *Icarus* **141**, 29–39 (1999).

9. García-Melendo, E. & Sánchez-Lavega, A. *Icarus* **152**, 316–330 (2001).
10. García-Melendo, E. *et al.* *Icarus* **176**, 272–282 (2005).
11. Rogers, J. H. *The Giant Planet Jupiter* (Cambridge Univ. Press, 1995).
12. Sánchez-Lavega, A. *Chaos* **4**, 341–353 (1994).
13. www.christone.net/astro/jupiter

MATERIALS SCIENCE

Designer pores made easy

Michael J. Zaworotko

Imagine being able to tweak the properties of a compound simply by replacing a molecular 'cartridge' with a different one. Just such a capability has been developed in a new class of porous crystalline materials.

Porous materials are creating quite a stir among materials scientists because of their many possible uses, which range from gas storage to drug delivery. But before certain applications are possible, a simple way must be found of tweaking the properties of these molecular sponges. Reporting in the *Journal of the American Chemical Society*, Kawano *et al.*¹ describe just such a method. They have prepared a porous material consisting of two molecular components, one of which can be easily replaced, rather like changing the cartridge in a pen. This flexibility allows the absorption properties of the solid to be fine-tuned.

Metal–organic materials are porous compounds consisting of metals or metal clusters bound to organic molecules known as ligands. Research into these compounds has undergone two bursts of growth over the past couple of decades. The first occurred after the publication of a seminal paper² in 1990, which outlined

the design opportunities these compounds present for controlling the arrangements of atoms in solids. The second burst occurred in the late 1990s, when it became clear that such compounds combine unprecedented levels of porosity with properties such as magnetism, catalysis, polarity and luminescence^{3–5}. This makes them potentially useful for many applications, including for gas storage and separation, as chemical and biological sensors, and even for harvesting energy from light.

Metal–organic materials now deservedly lie at the forefront of advanced materials, offering a synergistic suite of features that gives them several advantages over other porous compounds. Their first useful property is ease of design. Most crystal structures are unpredictable, but those of metal–organic materials are controllable. They also have structural blueprints similar to those found in nature. For example, they can exist as 'zero-dimensional' nanostructures based on atomic polyhedra, rather like those

Figure 1 | Blueprints for form and function in porous solids. Metal–organic materials are porous crystalline solids, aspects of which are depicted in these paintings by M. C. Escher. **a**, *Cubic Space Division* (1952) shows a 'cubic net' framework. Some metal–organic materials adopt this structure, in which each cube is replaced with an appropriate molecular building-block. **b**, In *Symmetry E72 (Fish and Boats)* (1949), the spaces between the boats match the shape of the fish exactly. Similarly, metal–organic materials can be designed so that their pores fit exactly around specific target molecules — a prerequisite for molecular recognition.

1. Sánchez-Lavega, A. *et al.* *Nature* **451**, 437–440 (2008).
2. Limaye, S. S. *Icarus* **65**, 335–352 (1986).
3. Porco, C. C. *et al.* *Science* **299**, 1541–1547 (2003).

found in viruses or the carbon molecule buckminsterfullerene. Other metal–organic materials adopt two- and three-dimensional atomic frameworks that have topologies comparable to those of minerals^{6,7}. One such topology, known as the cubic net, inspired the Dutch artist M. C. Escher (Fig. 1a). Aesthetic qualities aside, the cubic net is a good example of the framework of a metal–organic material — a modular structure in which the dimensions of the pores are controlled by the size of its molecular building-blocks⁶.

The second desirable aspect of these materials is that a given topology can be constructed from very different molecular building-blocks — anything from simple metal ions to complex organic molecules. This means that a desired structural framework can be reproduced at different scales, and with diverse chemical or physical properties. For example, the cubic net can be constructed at an atomic scale from octahedral complexes of metal ions³, or at 10 to 30 times atomic scale from pseudo-octahedral nanostructures⁸. Furthermore, because these materials often self-assemble from existing molecular building-blocks, they can frequently be prepared in simple, single-step procedures.

Finally, the general properties of metal–organic materials set them apart from other porous materials: they are readily characterized, crystalline compounds with well-defined compositions and an unprecedented range of surface areas (as a result of their controllable pore and cavity sizes). Combined with the diverse range of specific properties that can be obtained by varying the molecular building-blocks, these compounds provide a platform of materials that can be adapted for many applications.

An exciting strategy for fine-tuning the properties of metal–organic materials would be to incorporate sites for molecular recognition into their pores, so creating systems that mimic molecular binding in nature. This general concept has also been illustrated by Escher (Fig. 1b). But building molecular recognition into these compounds requires chemical modification of their walls and cavities, to introduce groups that can bind to target molecules (by hydrogen bonding for example). This has, in fact, already been accomplished in a limited fashion using two approaches: pre-synthetic modification, in which chemical groups are incorporated into a molecular building-block before the metal–organic material is synthesized⁹, and post-synthetic modification, in which chemical reactions take place in the

Figure 2 | Modifying the binding properties of porous materials.

Kawano *et al.*¹ have made a porous material in which a framework of metal complexes (stick representation) traps bulky organic molecules known as triphenylenes (yellow). The resulting crystal structure forms two types of channel (indicated by the green and blue shaded areas) that can recognize and bind small molecules. Which molecules are trapped depends on the chemical groups attached to the triphenylenes. The recognition properties of the channels can be fine-tuned simply by replacing the triphenylenes with others that have different chemical groups attached.

pre-assembled compound^{10,11}. But these are not generally applicable strategies, because pre-synthetic modification of the molecular building-blocks can interfere with the reactions needed to form a metal–organic material, whereas post-synthetic modification often requires harsh reaction conditions that might damage the compound.

Kawano *et al.*¹ describe an innovative solution to this problem — they use interchangeable molecular ‘cartridges’ to modify the internal surfaces of the compounds. The authors prepared a porous system in which an organic ligand donates electrons to zinc iodide, forming so-called coordination bonds. The resulting network traps aromatic molecules (known as triphenylenes) via non-covalent interactions. This results in a three-dimensional compound held together by a synergistic combination of coordination bonds and non-covalent bonds, and which contains two types of nanopore (Fig. 2).

The triphenylenes can be thought of as molecular cartridges, because they can be replaced during synthesis with other triphenylenes that have different chemical groups attached. Because these molecules form some of the walls of the pores, the pores’ molecular-recognition properties depend on which

cartridge is present. More specifically, recognition depends on the chemical groups attached to the cartridges. So, for example, one of the triphenylenes used by the authors directs a phenol group — an OH group attached to a benzene ring — towards the interior of the pores; the resulting metal–organic material selectively adsorbs alcohol molecules such as propan-2-ol.

In effect, the authors have found a simple way of fine-tuning the hydrogen-bonding capabilities of their metal–organic material. This breakthrough is not just of scientific interest, as such compounds are serious candidates for membrane materials that will separate alcohols from mixtures of liquids. This property could be useful in biofuel production, for example, or in highly selective chemical sensors.

Kawano and colleagues’ discovery realizes long-held aspirations of many physicists. Almost 50 years ago, Richard Feynman had this to say¹²: “What would the properties of materials be if we could really arrange the atoms the way we want them? They would be very interesting to investigate theoretically. I can’t see exactly what would happen, but I can hardly doubt that when we have some control of the arrangement of things on a small scale we

will get an enormously greater range of possible properties that substances can have, and of different things that we can do.”

Feynman would undoubtedly have been thrilled at the possibilities opened up by the authors’ molecular cartridges.

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1. Kawano, M., Kawamichi, T., Haneda, T., Kojima, T. & Fujita, M. *J. Am. Chem. Soc.* **129**, 15418–15419 (2007).
2. Hoskins, B. F. & Robson, R. *J. Am. Chem. Soc.* **112**, 1546–1554 (1990).
3. Kitagawa, S., Kitaura, R. & Noro, S. *Angew. Chem. Int. Edn* **43**, 2334–2375 (2004).
4. Eddaoudi, M. *et al.* *Acc. Chem. Res.* **34**, 319–330 (2001).
5. Lin, X., Jia, J., Hubberstey, P., Schröder, M. & Champness, N. R. *CrystEngComm* **9**, 438–448 (2007).
6. Liu, Y., Kravtsov, V. Ch., Larsen, R. & Eddaoudi, M. *Chem. Commun.* **14**, 1488–1490 (2006).
7. Huang, X.-C., Lin, Y.-Y., Zhang, J.-P. & Chen, X.-M. *Angew. Chem. Int. Edn* **45**, 1557–1559 (2006).
8. Perry, J. J., Kravtsov, V. Ch., McManus, G. J. & Zaworotko, M. J. *J. Am. Chem. Soc.* **129**, 10076–10077 (2007).
9. Custelcean, R. & Gorbunova, M. G. *J. Am. Chem. Soc.* **127**, 16362–16363 (2005).
10. Wang, Z. & Cohen, S. M. *J. Am. Chem. Soc.* **129**, 12368–12369 (2007).
11. Mulfort, K. L. & Hupp, J. T. *J. Am. Chem. Soc.* **129**, 9604–9605 (2007).
12. Feynman, R. P. www.zyvex.com/nanotech/feynman.html