# Physics under the fold

There is a certain naivety in seeing physics solely as the study of the natural physical world — everything 'out there', as one might say. That's obviously a big part of physics, yet it's also true that the scope of physics inquiry keeps expanding as we learn more and, with new knowledge, create wholly new kinds of physical stuff that never existed before. Examples run from liquid crystals and high-temperature superconductors to plastics, carbon fibres and graphene. Technology continuously expands the dimensions of physics.

The latest frontier is the emerging world of metamaterials — material structures purposely designed with precise geometric modulations to give them unusual and often seemingly unphysical properties. These range from optical cloaks to waveguides with negative refractive index, and even structures for shielding buildings from earthquakes. It seems that almost any material property hitherto considered impossible may soon be realized by some clever metamaterial construction.

Curiously, some of these designs draw on ancient mathematical traditions, such as origami, which can give final forms a stiffness and structure that's quite alien to the initial sheet. Origami apparently originated in Japan in the sixth century, just after paper entered the country from China, although it might have existed in China before. The technique has delighted artists for centuries, but has gained scientific interest in the past few decades due to a profusion of new modern materials and possibilities for the precise fabrication of extremely intricate geometrical structures. The modern form of a sixth century technology may represent one of the most prominent engineering themes of the coming century, with applications on scales ranging from space, through architecture, and right down to the near-atomic level.

In 1970, Japanese astrophysicist Koryo Miura drew on his knowledge of origami in proposing a novel two-dimensional pattern of folds — now called the Miura-ori pattern — as a way to make an expandable array of solar cells for spacecraft. The delightful surprise of the periodic fold — easily produced in a sheet of paper, given some patience and practice — is that a large sheet will collapse entirely into a flat compact form through motion along just one degree of freedom (http://go.nature.com/2n6CHHP). The

> The modern form of a sixth century technology may be a prominent engineering theme of the coming century.

expanded size can be an order of magnitude larger in diameter than the compact form. What makes the Miura-ori pattern unusual in physics terms is that it has a negative Poisson ratio: expand it horizontally, and it also expands vertically, unlike most normal materials. As it turns out, nature has known and exploited this design many times — in insect wings, leaves and elsewhere.

Engineering use of Miura's fold is now becoming ubiquitous, running from things as simple as a foldable map up to a disc-like solar array, currently under development by NASA, which will have a diameter of about 25 m when expanded, but less than three when folded. Yet this fundamental pattern is also the basis of a world of further possible variations. For example, scattered defects — created by inverting the folds around a single Miura-ori cell — can increase the stiffness of a material, making it possible to tune material stiffness in a continuous and geometrically sensitive way. The basic Miura-ori fold has also been generalized to surfaces of arbitrary curvature, making applications possible in non-planar settings. This challenge is harder than it might sound, as a useful pattern must still retain the property of easy motion along one degree of freedom (L. Dudte *et al.*, *Nat. Mater.* **15,** 583–588; 2016).

But even these simple structures only begin to scratch the surface of the wider possibilities emerging from hierarchically organized structures that result when origami elements are combined. In recent work, for example, engineer Evgueni Filipov and colleagues (*Proc. Natl Acad. Sci. USA* **112,** 12321–12326; 2015) took the basic Miura-ori element as a building block, and systematically built prototypes of potentially useful engineering structures with impressive stability and strength.

Their idea was to first create a linear sheet of Miura-ori cells — a series of identical cells linked together, making a long, narrow, undulating dome. Next, imagine making the mirror image of this — an undulating trough. Placing the dome on top of the trough, and gluing the two together, gives a three-dimensional tube with outer surfaces that have Miura-ori structure. The point of this, the researchers show, is increased stiffness, while the expandability of the sheet is preserved. Whereas the linear dome-like sheet is itself easily bent or distorted, lacking strength, the tube structure has considerably more resistance to deformation, although it still possesses two distinct and relatively easy geometric bending modes.

In other words, putting two Miura-ori sheets together creates a stiffer element by eliminating certain deformation modes — or, more correctly, making the energy involved in exciting them significantly higher. Going further, Filipov and colleagues then showed that pairs of these Miura-ori tubes can be placed alongside one another and connected in a zipper fashion, after displacing one periodic structure slightly relative to the other. This kind of assembly, they found, significantly increases the rigidity of all remaining deformation modes, leaving just one still free — the one corresponding to the natural extension of the Miura-ori pattern for useful deployment. Technically, an eigenvalue analysis reveals a large gap in the eigenvalue spectrum, such that patterns of deformation other than the linear extension used for deployment are up to two orders of magnitude stiffer. From this stage, it is then a simple step to construct still more general shapes — sheets built from many zippered tubes, for example — which have great stiffness and yet can still easily be deployed through extension, even by forces applied at just one point in the structure.

In this way, the simple Miura-ori cell becomes a building block for a potentially limitless range of structures in two or three dimensions. Filipov and colleagues also showed how variations of the Miura-ori cell add controlled curvature into structures while still engaging natural forces of tension, compression and shear to create rigidity and strength.

Much remains to be learned, especially about techniques for creating structures of this kind from real-world materials, or even engineering their self-assembly, particularly on the molecular or microscopic scale. After 15 centuries, though, origami as a technology looks to be finally coming into its own. ❐

MARK BUCHANAN