Building smart materials with flexible building blocks

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→Material properties are largely governed by the atoms and molecules out of which the materials are made. In contrast, *metamaterials* are artificial materials, which, owing to their carefully designed architecture, can exhibit properties not found in nature. Over the past few years, scientists from widely different fields have started to develop metamaterials that can manage and channel light, heat, deformations and mechanical vibrations in unprecedented ways. Examples include thermal, mechanical and optical cloaking (think of Harry Potter's 'invisibility cloak'), optical super-resolution, one-way propagation of light or mechanical signals, and surprising mechanical responses. The list of the exciting new properties keeps on growing and metamaterials now start to offer possibilities for society and industry that were unconceivable not so long ago.

Periodic vs. non-periodic

When compressed in one direction, ordinary materials expand laterally. However, metamaterials made of a two-dimensional (2D) square pattern of pores can shrink laterally. In most situations that have been studied to date, the metamaterials' architecture consists of a single building block, repeatedly stacked in space, similar to a crystalline lattice. Creating a material that shows unusual mechanical responses is greatly simplified by the use of such periodic architectures. However, with the advent of 3D printing, it is now possible and even becomes relatively easy to produce arbitrarily complex 3D shapes that are non-periodic. It has thus become possible to create materials with arbitrarily complex properties. The key challenge is now to find out which structure to fabricate and how to design new functionalities.

Flexible building blocks

Inspired by the striking mechanical effect described above and its apparent simplicity, at least in 2D, we wondered how to extend it to 3D non-periodic materials. A first step was to design a cubic building block that preferably forms a flat or elongated shape (see Fig. A). A 3D periodic stacking of many of such flexible building blocks then results in a new material with an easy mode of deformation, which has the desired effect: the material folds in laterally when compressed (Fig. B).

A 3D puzzle

Such a 3D strategy reproduces the mechanism previously observed in 2D, yet introduces a completely new flavour. As opposed to 2D, the 3D building blocks have an orientation. In the previously described case, the blocks were all stacked parallel, but in principle they can also be stacked with different orientations. Obtaining compatible deformations in a stacking of multiple such units turns out to be a particularly tortuous combinatorial problem. One indeed has to ensure that all the local protrusions and dents of each unit cell fit in 3D (Fig. C) to design a cube with no internal frustration, where all the building blocks can flex in harmony.

Mechanical spin-ice

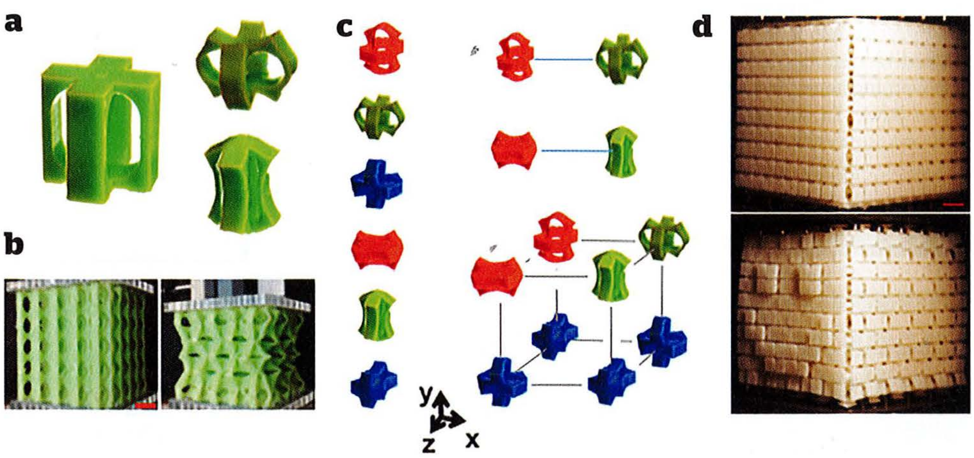
Progress can be made by reducing the puzzle to its essence and representing the inwards and outwards deformations by spins, just as in a spin-ice. Even with that simplification, solving the problem in its full complexity amounts to solving the notoriously impossible 3D Ising model. Fortunately, we realised that since the building blocks have mirror symmetries (Fig.C), our mechanical spin-ice problem was tractable. Using advanced mathematical analysis, we were able to solve it and, in particular, count the number of possible configurations, where all the spins fit together. We found that the number of possibilities is astronomical: for a 14 x 14 x 14 stacking, the number of possible cubes is equal to 30625852190216495511364347343665021261262812628299779541749100810 !

Designing functionality

Along the way, we also uncovered principles to orient the building blocks in order to rationally design cubes with a fully programmable texture at the surface of the cube. In order to materialise this concept, we 3D-printed a cube, which when non-deformed has flat surfaces, and when compressed reveals a carefully designed smiley (Fig. D)! Although our study is fundamental in nature, there may be applications on the horizon. The principles we uncovered could be generalised; programmable textures obtained in this way could be of use to tune interfacial phenomena such as friction, wetting or adhesion. Finally, this type of programmable shape changers could be ideal for prostheses or wearable technology. Ω

→ Reference

C. Coulais et al., Combinatorial Design of Textured Mechanical Metamaterials. *Nature* 535, 529-532 (2016), http://dx.doi.org/10.1038/nature18960



↙ Figure

A. Cubic flexible building block in its undeformed and deformed states.
B. Silicon rubber metacube consisting of 5x5x5 building blocks undeformed (left) and under uniaxial compression (right). Scale bar is 1 cm.
C. (left) Deformed building blocks in their three possible orientations, depicted in red (x), green (y) and blue (z). (middle to right) Sketch of 2x1x1 (top and middle) and 2x2x2 (bottom) complex stackings of differently orientated, deformed building blocks.
D. 3D-printed 10x10x10 mechanical metamaterial. This cube is made of 10x10x10 building blocks where the outside blocks have been decorated with square pedestals to clearly visualise surface deformations. (top) Undeformed state. (bottom) Deformed state revealing the programmed smiley texture. Scale bar is 2 cm.