# Study outlines basic rules for construction with a type of origami

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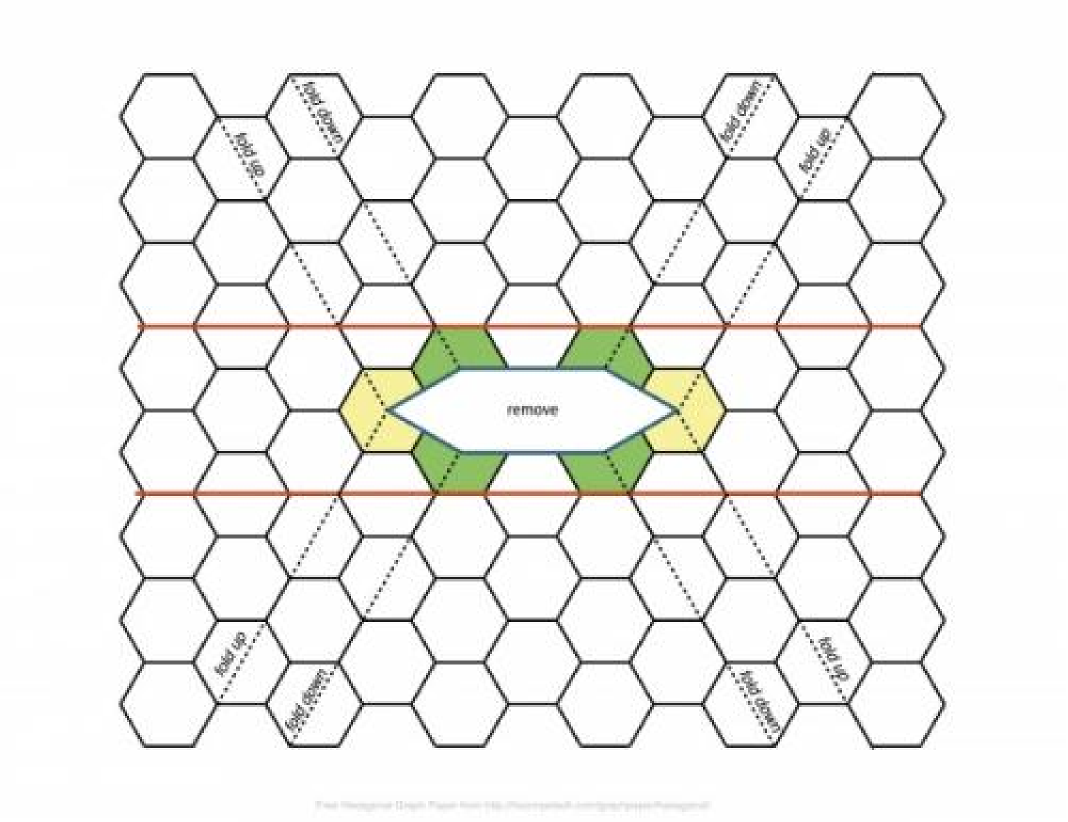

Try it yourself: With a cut and a few folds, this structure could serve as a shelter or a microfluidic channel. Because the researchers' rules keep the hexagons in proportion once the cuts and folds are made, the technique can be applied broadly across length scales and material types. Credit: University of Pennsylvania

Origami is capable of turning a simple sheet of paper into a pretty paper crane, but the principles behind the paper-folding art can also be applied to making a microfluidic device for a blood test, or for storing a satellite's solar panel in a rocket's cargo bay.

A team of University of Pennsylvania researchers is turning kirigami, a related art form that allows the paper to be cut, into a technique that can be applied equally to structures on those vastly divergent length scales.

In a new study, the researchers lay out the rules for folding and cutting a hexagonal lattice into a wide variety of useful three-dimensional shapes. Because these rules ensure the proportions of the hexagons remain intact after the cuts and folds are made, the rules apply to starting materials of any size. This enables materials to be selected based on their relevance to the ultimate application, whether it is in nanotechnology, architecture or aerospace.

The study was conducted by Toen Castle, a postdoctoral researcher in the School of Arts & Science's Department of Physics and Astronomy; Shu Yang, a professor in the School of Engineering and Applied Science's Department of Materials Science and Engineering; and professor Randall Kamien, also of the Department of Physics and Astronomy. Also contributing to the study were undergraduate Xingting Gong and postdoctoral researcher Daniel Sussman, members of Kamien's research group; graduate student Euiyeon Jung, a member of Yang's group; and postdoctoral researcher Yigil Cho, who works in both groups.

It was published in the journal *Physical Review Letters*.

"If you see a fancy piece of origami," Kamien said, "it can have arbitrarily small folds. We want to make something much simpler. If there are standards for the size of folds and cuts, we can make the math apply to any length scale. We can make channels, gates, steps and other

3-D shapes without needing to know anything about the size of the sheet and then combine those building blocks into even more complex shapes."

A hexagonal lattice may seem like an odd choice for a starting point, but the pattern has advantages over a seemingly simpler tessellation, such as one made from squares.

"The connected centers of the hexagons make triangles," Castle said, "so, if you start with a hexagonal lattice, you get the triangles for free. It's like two lattices in one, whereas if you start with squares, you only get squares."

"Plus," Yang said, "it's easier to fill a space with a hexagonal lattice and move from 2-D to 3-D. That's why you see it in nature, in things like honeycombs."

Starting from a flat hexagonal grid on a sheet of paper, the researchers outlined the fundamental cuts and folds that allow the resulting shape to keep the same proportions of the initial lattice, even if some of the material is removed. This is a critical quality for making the transition from paper to materials that might be used in real-world applications.

"You can think of the sheet of paper as a template for a mesh of rods that you can lay on top of it," Castle said. "Alternatively, you can think of the paper as the membrane that attaches to a scaffolding. Both concepts are in the theory from the start; it's just a question of whether you want to build the rods or the material between them."

Having a set of rules that draws on fundamental mathematical principles means the kirigami approach can be applied equally across length scales, and with almost any material.

"The rules we lay out," Kamien said, "tell you how you make the cuts so you only have to fold on straight lines, and so that, when you fold them together, the rods remain the same length and the centers remain the same distance apart. You may have to bend [or put hinges on] some of the rods to make the folds, but you don't have to be able to stretch them. That also means the whole structure remains rigid when you're done folding."

"This means it's just a matter of picking the materials with the properties you want for your application," Yang said. "We can go from nanoscale materials like graphene to materials you would make clothing out of to materials you would see in a space station or satellite."

The rules also guarantee that "modules," basic shapes like channels that can direct the flow of fluids, can be combined into more complex ones. For example, iterating those folds and cuts can produce a ratcheting interface that can lock itself into place at different points. This structural feature could change the volume of a channel or even serve as an actuator for a robot.

Kirigami is particularly attractive for nanoscale applications, where the simplest, most space-efficient shapes are necessary, and self-folding materials would circumvent some of the fabrication challenges inherent in working at such small scales.

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