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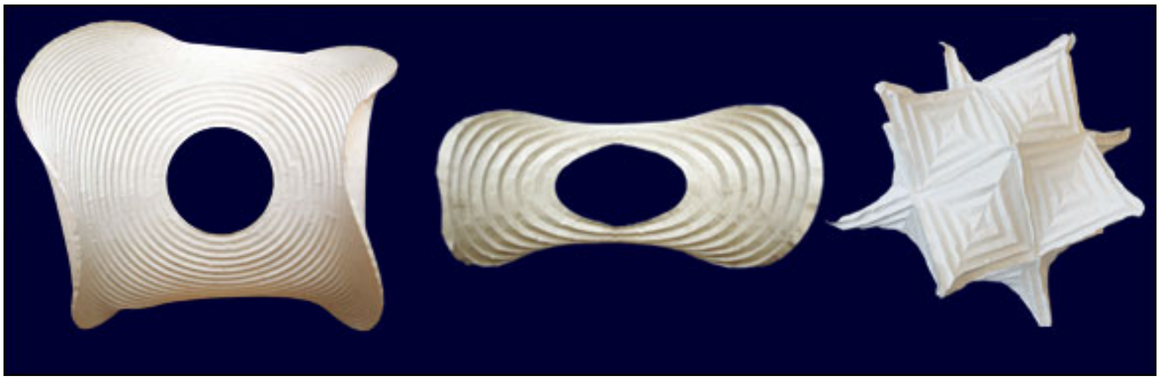
Origami as the Shape of Things to Come



By MARGARET WERTHEIM
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Correction Appended

CAMBRIDGE, Mass. - "Some people don't even think this exists," says Dr. Erik Demaine, turning in his hands an elaborately folded paper structure. The intricately pleated sail-like form swooshes gracefully in a compound curve and certainly looks real enough - if decidedly tricky to make.

Dr. Demaine, an assistant professor of computer science at the Massachusetts Institute of Technology, is the leading theoretician in the emerging field of origami mathematics, the formal study of what can be done with a folded sheet of paper. He believes the form he is holding is a hyperbolic parabaloid, a shape well known to mathematicians - or something very close to that - but he wants to be able to prove this conjecture. "It's not easy to do," he says.

Dr. Demaine is not a man to be easily defeated by a piece of paper. Over the past few years he has published a series of landmark results about the theory of folded structures, including solutions to the longstanding "single-cut" problem and the "carpenter's rule" problem. These days he is applying insights he has gleaned from his studies of wrinkling and crinkling and hinging to questions in architecture, robotics and molecular biology.

Origami may seem an unusual route to a prestigious university job, but most things about Dr. Demaine defy academic norms.

As a child, he and his father, Martin, a goldsmith and glass artist who home-schooled his son as a single parent, traveled around the United States, settling somewhere new every 6 to 12 months.

At 12 years old, after Erik had become intensely interested first in computer games, then in computer programming, and finally in mathematics, he persuaded the administrators of Dalhousie University in Halifax, Nova Scotia, to let him take classes in math and computer science. His father sat in as an auditor. Erik Demaine received his doctorate at 20 and at the same age became the youngest professor ever at M.I.T. In 2003 he was granted a MacArthur "genius" fellowship.

Today, at 23, he has published over 100 academic papers in fields as diverse as computational geometry, combinatorial game theory, data stuctures and graph theory. Along with his interest in folding, Dr. Demaine is also an expert in algorithms. He is also one of the computing world's major collaborators, with more than 140 co-authors so far.

"He loves working with other people," says Dr. Joseph O'Rourke, a mathematician and computer scientist at Smith College who has been collaborating with Erik Demaine since he was 16. "He has a very broad understanding of a whole range of topics and he often brings in ideas that at first seem off the wall but really help to enrich what you are doing."

Yet for all Dr. Demaine's smarts, the pleated form in front of him is not giving up its secrets easily. The perplexing question is whether its concertina-like structure can be derived by purely mathematical transformations of a flat sheet, or whether the sheet must be stretched in places to take on this complex shape.

As Dr. Demaine explains, stretching would warp the intrinsic flatness thereby destroying the underlying geometry. If that were the case then, mathematically speaking, it would not exist. "But if it doesn't exist mathematically then something else is going on and it would be nice to know what that is," he says, setting the model down on his desk.

The model is just one of a whole class of related structures. The hyperbolic parabaloid form has four sides, but in theory variations can be made with any number of sides. The complexity depends only on the patience of the folder.

Dr. Demaine's office is littered with these models, and a myriad other constructions made of paper, plastic, tubing and little wooden sticks. The room looks less like a professor's office than some kind of geometric playpen. On the windowsill is a collection of glass vases and sculptures made by Dr. Demaine and his father, who is now a researcher in his son's lab.

Aside from the mathematical value of the hyperbolic forms, Dr. Demaine is interested in them as potential architectural structures. At M.I.T. he has also taught courses in the school of architecture and imagines being able to computationally generate a scaffolding of these shapes over which a flexible skin could be draped.

"If we believe the edges are really straight, which we do, then you could 3-D print the skeleton and really build it," he said.

By his own admission, Dr. Demaine is primarily a theoretician. "I love the idea of timeless truths," he remarked over a sushi lunch in the cafeteria of M.I.T.'s Stata Center, the lavish new Frank Gehry building where Dr. Demaine has his office. But he is also deeply interested in relationships between disparate disciplines, particularly the sciences and the arts. In this respect his father has been a major influence.

Though Mr. Demaine trained as a glass artist, when his son developed a fascination for computing and mathematics he happily read the books and attended lectures with him. "I don't really think of them as such different activities," he said of this switch from art making to mathematical theorizing.
Today father and son have written 43 papers together. Meanwhile Mr. Demaine, who has just been appointed artist in residence in the computer science department, is also a technical instructor and artist in residence at the M.I.T. glass blowing workshop, where one of his students is his son.

Among the topics the two have researched together is the "single cut" problem, whose roots go back to ancient China and to magic tricks. Before Houdini became an escape artist he had a career as a magician and supposedly performed a trick in which he folded a piece of paper, then cut across the creases to "magically" create a five-pointed star. Other examples of single cut magic are sprinkled through historical literature. The question that arises is, What sorts of shapes can you make this way? In 1998 the two Demaines, working with Dr. Anna Lubiw at the University of Waterloo in Ontario, proved that you could effectively make any shape just with folding and a single cut - a star, a swan or a unicorn.

You can even create multiple shapes with a single snip of the scissors - 2 stars, 10 stars or 50 stars if you like. One set of shapes that can be produced this way is the letters of the alphabet.

And since Dr. Demaine's proof shows that you can get as many shapes as you want, "in theory you could produce the complete works of Shakespeare with a single cut," said Dr. Robert Lang, a former laser physicist and professional folder who is collaborating with Dr. Demaine on a major origami math project.

Understanding what you can do with paper is a two-dimensional problem, but Dr. Demaine also works with the one-dimensional analog or what are known as linkages. A linkage is a set of line segments hinged together like the classic carpenter's rule. Though it sounds simpler, Dr. Lang noted that the one-dimensional case is often much harder to understand and analyze than the two-dimensional case.

The major part of Dr. Demaine's doctoral thesis was a solution to the so-called "carpenter's rule problem," which asks a question about how linkages can be unfolded. Put simply: Imagine a carpenter's rule arranged on a table in a complicated pattern. Is it always possible to unfold the rule, or are there patterns that cannot be opened out, that are in what mathematicians call a "locked" state? Dr. Robert Connelly, a mathematician at Cornell who worked with Dr. Demaine on the solution, noted by phone that the problem was a good deal subtler than it initially sounded. At first mathematicians thought all linkages could be unfolded, but during the 1990's they discovered a number of very clever arrangements that looked impossible to unfold. "Many people thought a lot of these were locked," said Dr. Connelly.

But he and Dr. Demaine, along with Dr. Günter Rote of the Free University of Berlin, proved that all linkage arrangements could be unfolded. It turns out that the problem of folding and unfolding linkages is applicable to one of the major scientific questions of our time: how do proteins fold up? Proteins are made up of long strings of amino acids, and as the strings are produced inside a cell by the ribosome they fold up into complicated shapes.

It is this shape that largely determines the biochemical function of each protein. Molecular biologists and pharmaceutical companies are extremely interested in understanding how protein folding occurs, in part because they would like to design specialized proteins for use as drugs.

Recently Dr. Demaine has been working on the question of how protein folding occurs. "We think they fold by keeping their backbones as linkages," he said. He and Dr. O'Rourke, along with Dr. Stefan Langerman at the Free University of Brussels, have created a computer model of this process and will report their results soon in a paper for the journal Algorithmica. Dr. O'Rourke said their model proved that protein linkages could not become locked. If their main assumptions hold up, he said, this result could help pharmaceutical companies to radically speed up the time it takes to find useful proteins.

Ideally, molecular biologists would like to be able to predict from the chemical structure of a protein what shape it would fold into. "If you could predict that," said Dr. Demaine, "then you wouldn't have to do all the hard work of synthesizing and crystallizing the protein to find out what it does."

Dr. Demaine hope to solve the protein-folding problem completely. "I'm an optimist," he said. "I believe it can be done in my lifetime."

Monumental though this challenge is, he is pursuing other equally difficult goals. Recently he has begun to work on a branch of mathematics called graph theory, a sort of generalized version of linkages. Graph theory is known to be fiendishly difficult, but Dr. Demaine is confident he can make headway once he immerses himself in its arcane lore. In the meantime he has origami models to tame and his new hobby of glass blowing to practice.

In the M.I.T. glass lab, under the encouraging tutelage of his father, Dr. Demaine gently turned a piece of red-hot glass on the end of long metal blowpipe. He was making a small vase in a shape that he had recently learned to craft.

"We haven't found any mathematics in here yet," he said, before blowing into the pipe. "But I'm sure it exists." If anyone can find the formalisms in an amorphous molten blob it must surely be he.

Correction *Tuesday, Feb. 22, 2005An article in Science Times last Tuesday about Dr. Erik Demaine, an M.I.T. computer scientist who is a leading theoretician of origami mathematics, misidentified the director of the university's Glass Lab, where Dr. Demaine studies glass blowing. The director is Peter Houk. (Martin Demaine, Dr. Demaine's father, is a technical instructor and artist in residence there.)*