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A building of bubbles

The swim center for the Olympics, which looks like it formed out of froth, was designed using the mathematics of foam.

BY [JULIE REHMEYER](#)
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The National Aquatics Center in Beijing, newly built for the Olympics, is a glowing cube of bubbles. The walls, roof and ceiling of the “Water Cube” are covered — indeed, made from — enormous bubbles that seem to have drifted into place randomly, as if floating on the surface of a pool.

But of course, those bubbles hardly skittered there of their own free will. Creating this frothy confection took a lot of steel, a lot of manpower, and not least, a lot of fancy mathematics.

The motivating idea for the building was that it would express the spirit of water. Its designers first thought of liquid water, vapor, or ice, but finally settled on foam. The bubbles, they decided, really would be bubbles: pillows made of a transparent plastic called ethylene tetrafluoroethylene (or ETFE) filled with air, attached to a steel framework outlining the edge of each bubble.

A basic challenge was that they wanted the foam to look random and organic. But for the engineering to be practical, it had to have some underlying order. So Tristram Carfrae, an engineer at Arup, the Australian engineering firm on the project, looked into the mathematics of foam.

The trail led all the way back to an idea from the 1880s. The physicist Lord Kelvin decided that the ether, the mysterious substance then believed to fill the universe and transmit light waves, must consist of foam.

George Darwin (Charles’ son) declared the idea “utterly frothy,” but Kelvin was undeterred. He set out to understand the shape that ether-foam must have. The fundamental thing keeping bubbles together, he realized, is surface tension, which tends to pull bubbles into a shape with the least surface area for the volume. That’s why a single bubble forms a sphere. The same principle determines the complicated shapes bubbles form when they are packed together.

He also figured that the individual bubbles in the ether were probably all of the same (very small) size. So the structure of the ether-foam would be one with equal cell size and minimal surface area. But what bubble shape created those properties?

It turned out that Kelvin was asking a hard question indeed — so much so that it’s still unsolved and has been dubbed the “Kelvin problem.” But Kelvin didn’t know that, and he set to work in the most straightforward way possible: he started blowing bubbles with soapy water. Before long, his experimentation paid off with a candidate shape he dubbed the “tetrakaidcahedra.” It’s a modified octahedron, with each sharp point sliced off and the edges and faces slightly curved. Kelvin guessed, but couldn’t prove, that by packing these shapes together, he had created the foam with least surface area for a particular bubble size — and hence, perhaps, found the structure of the ether.

He was wrong about the ether — not because it wasn’t foam, but because it didn’t exist at all. But when Carfrae read about this, he figured it was just what he needed to solve his engineering problem: a systematic way to build foam.

Carfrae created a large block of Kelvin’s foam on a computer and tried slicing it up, cutting at various angles to produce a flat surface he could use for his walls. The result, however, didn’t look right. When he cut at some angles, the bubbles were too regular. Other angles produced too many rectangular bubbles, which just didn’t look real.

Kelvin’s work did not solve Carfrae’s problem. Kelvin’s work did inspire an entire branch of mathematics that Carfrae could mine for ideas. Mathematicians were stuck on the small fact that Kelvin hadn’t *proven* his structure was the single best. Could some other foam structure be lurking out there with even lower surface area?

It took more than a century, but finally two physicists, Denis Weaire and Robert Phelan of Trinity College in Dublin, realized that Nature herself had been performing experiments to answer Kelvin’s question. A whole family of natural chemicals called clathrates form lattice structures with many of the properties a good foam shape should have. By examining Nature’s repertoire of clathrates, Weaire and Phelan spotted a shape for foam that beat Kelvin’s.

Unlike Kelvin’s structure, the Weaire-Phelan foam was built from two different shapes. One was a slightly curved dodecahedron and the other was a 14-sided shape with two opposite hexagonal faces and 12 pentagonal faces. Despite the different shapes, Weaire made sure all the bubbles had the same volume. The resulting surface area was a whopping 0.3 percent less than that of Kelvin’s foam.

Weaire and Phelan are convinced that their solution is the best one, but, just like Kelvin, they haven’t been able to prove it. Weaire says that at this point, a proof would be extraordinarily difficult. “I’m not holding my breath.”

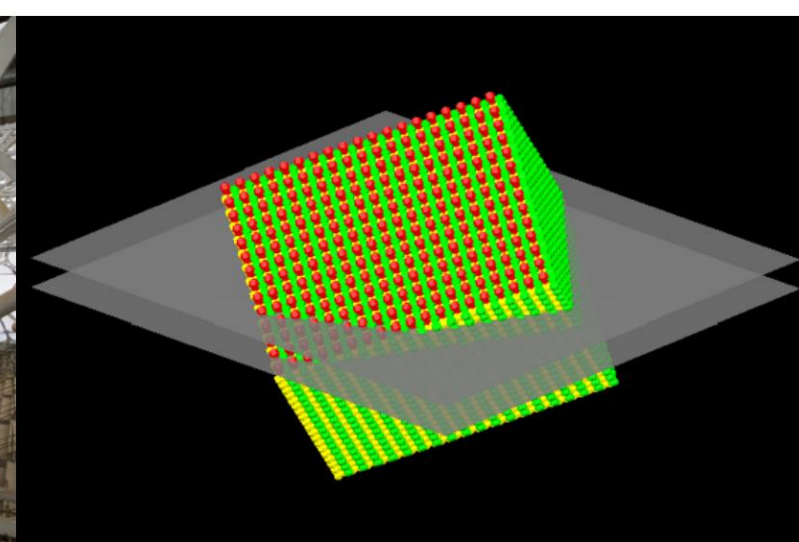
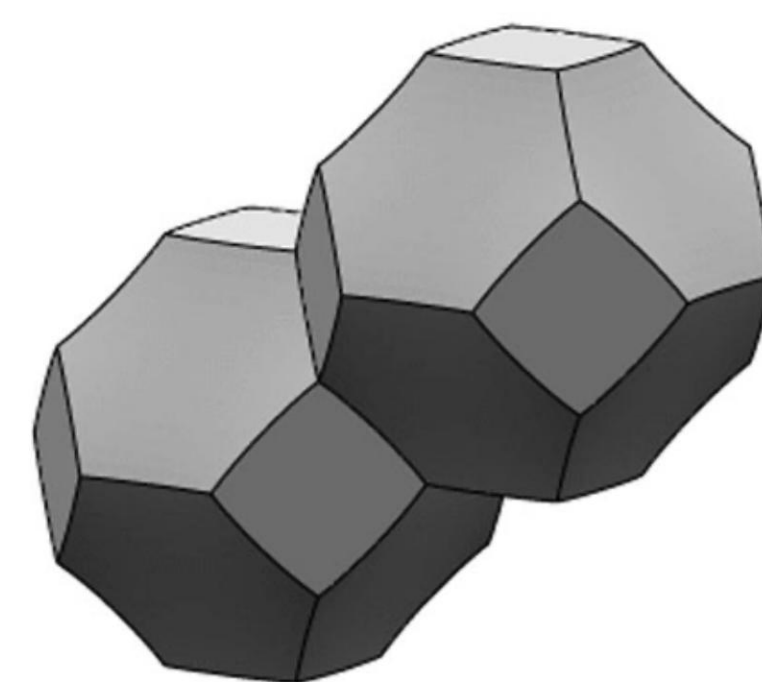
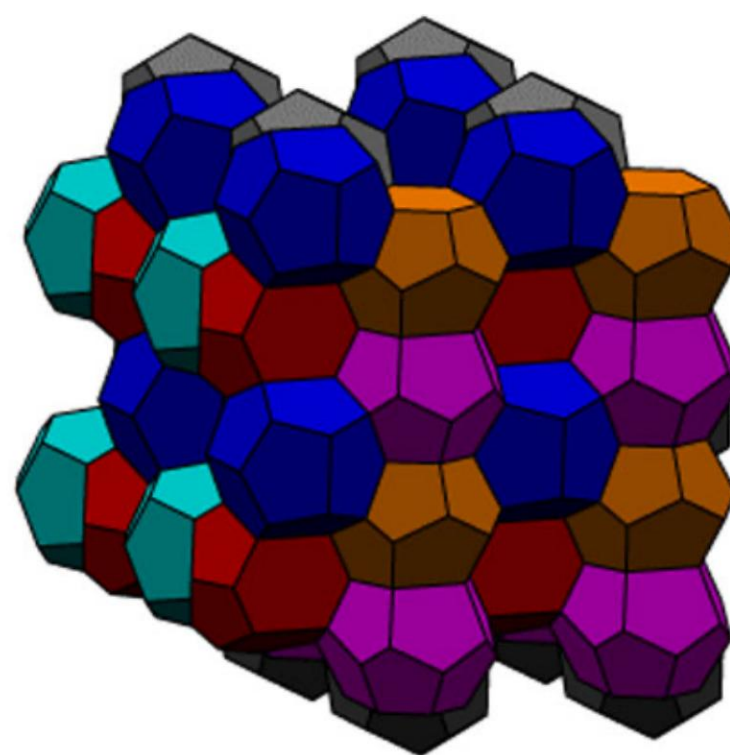
Carfrae didn’t need a proof, though. He just needed the foam. He tried his same slicing method using the Weaire-Phelan foam. This time, by cutting at an angle of about 111 degrees, he found a pattern that looked entirely natural. In fact, the pattern actually repeated in ways that were very hard for the eye to detect. That repetition was key, because it meant the building would be far easier to construct.

The Weaire-Phelan foam provided not just a pretty surface for the walls, but the building’s very structure. Imagine an enormous block of the foam, with steel beams outlining the edge of each bubble. Now carve out the center to form a building with 12-foot-thick walls and 24-foot thick ceilings. This is the weight-bearing structure of the Water Cube.

The result is so strong, the engineers say, that the entire building could be turned on its side without collapsing. Furthermore, the remarkable effect is that they’ve designed a building without triangles. Ordinarily, buildings rely on triangles to provide stiffness, since a triangle is the only two-dimensional shape that can’t be deformed without changing the length of its sides. The engineers say that this lack of triangles will make the building more flexible and hence more able to withstand earthquakes.

To form the outside of the walls and ceiling, the designers placed ETFE pillows in the polygonal openings created by the steel beams. This created the three-dimensional, bubbly surface they were looking for. They did the same thing for the interior walls. The empty chamber between the interior and exterior walls provides solar heating and cooling.

Weaire learned of the building only after the design was complete, and he visited the building during construction. He has two words to describe it: “It’s spectacular.”



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