Nonlinear Dynamics, Psychology, and Life Sciences, Vol. 15, No. 1, pp. 129-136.

The Art and Science of Foam Bubbles

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Abstract: *Art and science become inevitably intertwined in our appreciation of nature's forms. This concept is demonstrated by the creative team responsible for the 2011 cover images of Nonlinear Dynamics, Psychology, and Life Sciences. Denis Weaire, Stefan Hutzler, Wiebke Drenckhan form a leading international collaboration with photographers Tim Durham and Michael Boran that explores the physics of bubble patterns. The images they generate capture and manipulate the striking aesthetic impact of foam bubbles. Furthermore, the foams exhibit a balance between simplicity and intricacy that symbolizes many of the complex systems that permeate nature and society.*

Key Words: fractal, art, foam, aesthetics

Galileo Galilei's famous declaration, "Nature's great book is written in mathematical symbols", suggests that the key to unlocking nature's secrets lies in the underlying science. Quantifying the geometric parameters behind nature's patterns often provides the critical step in discovering the 'how' and 'why' of their formation. Intriguingly, it might also serve as the springboard for explaining their aesthetic value. The Bauhaus movement declared that the functionality of an object generates an inherent aesthetic quality. Similarly, we might be drawn to nature's patterns because they are a direct manifestation of the natural laws that dictate our lives. In this way, art and science become inevitably intertwined in our appreciation of nature's forms.

This concept is demonstrated by the creative team responsible for the 2011 cover images of *Nonlinear Dynamics, Psychology, and Life Sciences*. Denis Weaire, Stefan Hutzler (both at the School of Physics, Trinity College, Dublin, Ireland) and Wiebke Drenckhan (at the Laboratoire de Physique des Solides, University Paris-Sud) form a leading international collaboration that explores the physics of bubble patterns. They collaborate with Dublin photographers Tim Durham and Michael Boran. The images they generate capture and manipulate the striking aesthetic impact of foam bubbles. Furthermore, the foams exhibit a balance between simplicity and intricacy that symbolizes many of the complex systems that permeate nature and society.

Much like an epic abstract painting, the structure shown in Fig. 1 seems

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to celebrate the essence of artistic composition. All of the components of the image appear to mesh together well. If we adopt the 'Bauhausian' view of aesthetics, this visual appeal should derive from the processes that form the foam and dictate its functional properties. So, what rules drive bubble formation?

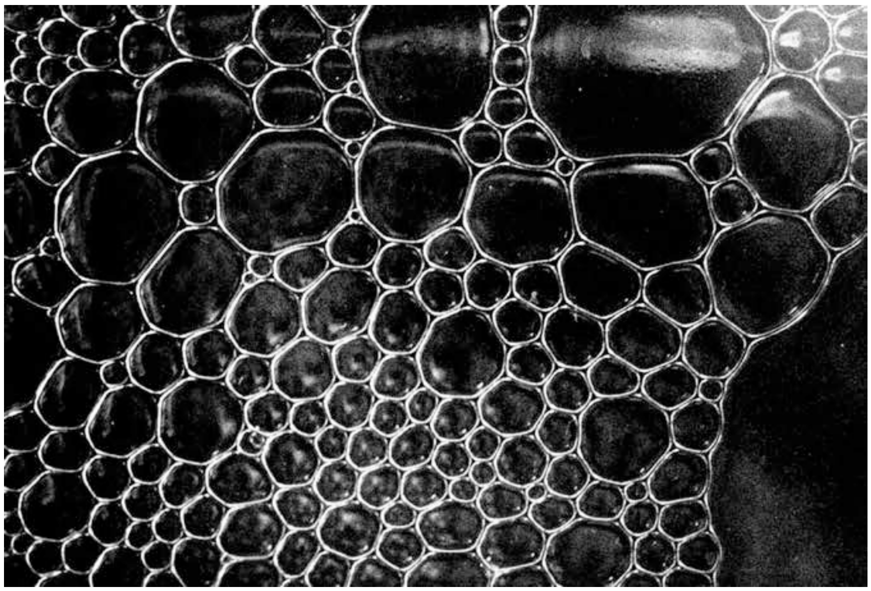

Fig. 1. Photograph of a bubble foam taken by Taylor.

Soap bubbles serve as the perfect illustration of physical objects striving to minimize their surface area. For example, the beautiful simplicity of a spherical soap bubble occurs because this is the optimal shape for enclosing a given volume of air within a surface with a minimal area. Whereas this fundamental fact has been known for several centuries, the science becomes more challenging as the number of bubbles increases. Consequently, foams consisting of many bubbles feature more intricate shapes compared to the simple spheres of isolated bubbles.

In 1993, Weaire employed computer simulations to determine the optimal bubble shapes for foams. The search for the pattern that most efficiently packs bubbles into foam is known as the "Kelvin problem" (Weaire, 1997). This label derives from the physicist Lord Kelvin, who was the first to focus on this challenge back in 1887. Weaire's simulations revealed an intriguing three-dimensional geometry now named after him and his student Robert Phelan. The Weaire–Phelan structure has become well-known within the physics community because it finally improved on Kelvin's long-standing guess at the optimal bubble shape.

However, the Weaire–Phelan structure has since become etched into the public's memory for reasons well beyond its unique packing properties. In 2008, its fame spread into the field of architecture and its distinctive form appeared on TV screens across the globe when the structure served as the inspiration for the aquatic centre at the Olympics in Beijing, China. The foam pattern of the so-called Water Cube is shaped by more than 22,000 steel beams (Trinity College Dublin, 2008).

As with many great artistic creations, the journey that led to the transformation of a 19th-century scientific challenge into modern architecture was precarious. Weaire notes that he was not even searching for a solution to the Kelvin challenge but was "playing around on the fringes" of the problem, investigating other scientific aspects of foam structures. But when he found that he had surpassed Kelvin's foam structure, "It was a bit like a hole in one in golf" he remembers. Similarly, the principal designer of the Water Cube, Tristram Carfrae, recalled in the New York Times during the Olympics (Fountain, 2008): "I knew nothing of this area [foam physics] at all. But from an architectural perspective we were very keen to end up with a building that had some connection with water." This led him to foams and finally to the Weaire–Phelan structure.

Despite the visual balance conveyed by foam structures, the building blocks of the patterns are surprisingly intricate. The basic building block (the unit cell) of the Weaire–Phelan foam consists of two bubbles with twelve faces and six bubbles with fourteen faces (Aste & Weaire, 2008). Carfrae's design took a diagonal section through the Weaire-Phelan structure, as if cutting through a block of foam at a 60-degree angle. "That's what gives it its random appearance," Weaire notes. "Only if you look carefully do you see that it's a repeating pattern" (Fountain, 2008). Shapes of varying size cram together into a pattern that appears to be disordered – but only superficially. The underlying structure follows the clean geometric order required by nature's rules of foam formation.

This subtle interplay of shapes across a range of size scales is a common feature of many of the more intriguing bubble patterns. Figure 2 shows an equally striking geometry, but one where the multi-scale characteristic is induced by very different means. This image, generated by Drenckhan and her student, Antje van der Net, is a computer simulation that shows the view obtained by looking through multiple layers of bubbles (van der Net, Drenckhan, Weaire, & Hutzler, 2005). All of the bubbles in this simulation are in fact identical in size. The apparent repetition of bubbles at different size scales is caused by the overlapping layers of bubbles. As the viewer peers into the foam, the nearer layers provide the larger bubbles, through which the viewer sees the bubbles from more distant layers, which appear smaller.

This optical illusion emphasizes the degree to which artistic input is being used to 'sculpt' the remarkable visual properties of foams. In this case, the multi-scale intricacy was induced by the act of observation rather than any intrinsic distribution of bubble sizes. However, the image of Fig. 2 raises an obvious question: for foams that are composed from multiple sizes of bubbles, how does the size distribution impact the visual appearance of the overall structure? Figure 3 shows a sketch of a pattern in which circular components are crammed together using an Apollonian packing strategy developed in the 16^{th} Century (Aste & Weaire, 2008). Increasingly small circles are packed into the gaps that inevitably form between the larger circles. This repetition is similar to that used by Sierpinski in 1915 to build his well-known fractal pattern from repeating triangular components.

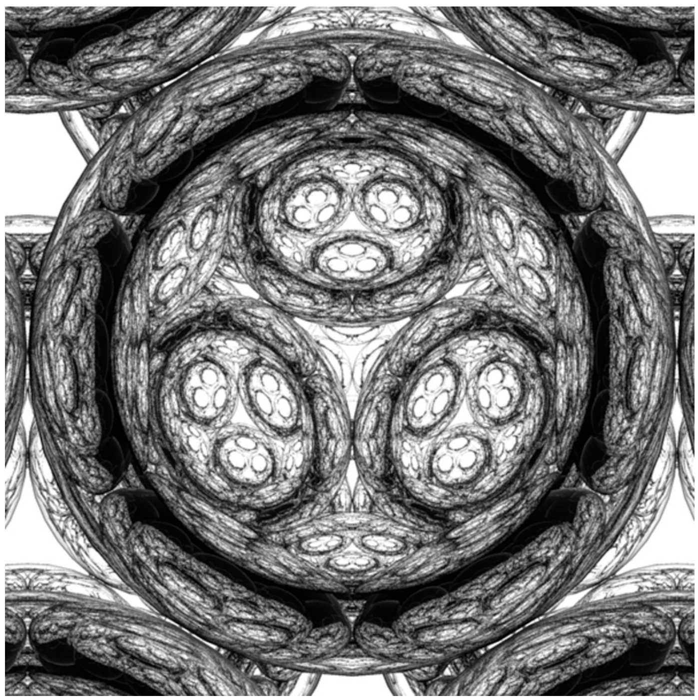

Fig. 2. A simulated image by Drenckhan and van der Net, in which the repeating patterns are created by viewing through multiple layers of bubbles.

Figure 3b shows a sketch of the first proposed fractal foam, created by Weaire in 1983 when he modified Apollonian packing by replacing the circular components with bubbles (Weaire & Kermode, 1983; Weaire & Rivier, 2009). The scaling properties of this foam are described by a fractal dimension, D, of 1.3 (Manna & Hermann, 1991). The fractal dimension serves as a measure of the relative contributions of the coarse and fine components in a fractal pattern. Measured on the scale of $1 < D < 2$, a higher D indicates an increase in the ratio of fine-scale bubbles to coarse-scale bubbles. Previous research has shown that people find fractal patterns in the range $1.3 < D < 1.5$ to be aesthetically pleasing

(Taylor et al, 2005) and that these patterns reduce the physiological stress of the observer (Taylor, 2006). Significantly, Weaire's fractal foam lies within this aesthetic scaling regime.

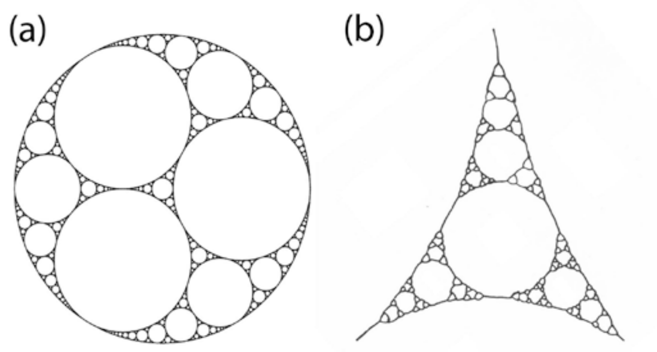

Fig. 3. Apollonian packing (left) and a fractal foam (right). The fractal image is based on the image published in Weaire and Kermode (1983).

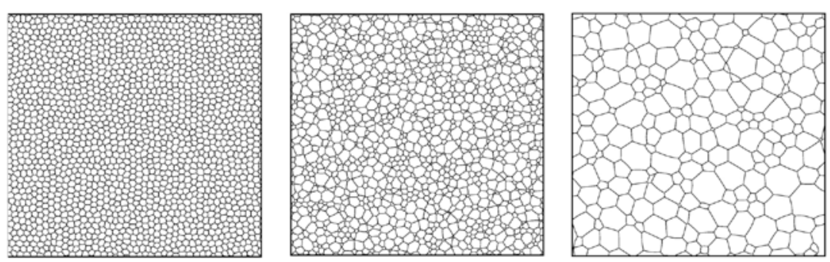

Fig. 4. Simulations by Drenckhan of the evolution of a foam as a function of time.

Whereas the sketches of Fig. 3 show exact fractals (ones in which the patterns at different size scales repeat exactly), most of nature's fractals are statistical (ones in which the patterns don't repeat exactly but their statistical qualities are scale-invariant). Figure 4 shows computer simulations generated by Drenckhan that demonstrate how foam evolves with time. The foam gets 'coarser' such that the spread in different bubble sizes increases. This causes the foam to evolve from a rather uniform and monotonous pattern into one that takes on the visual characteristics of a statistical fractal. Although the magnification range (i.e. the ratio between the largest and smallest bubble sizes) is limited, a preliminary fractal analysis performed by Ben Wright and myself at the University of Oregon reveals the decrease of *D* with time shown in Fig. 5 (Taylor & Wright, 2010). The aesthetically pleasing foams are characterized by *D* values of 1.3. This value is similar to the exact fractal foam discussed above and again lies in the aesthetically pleasing scaling regime.

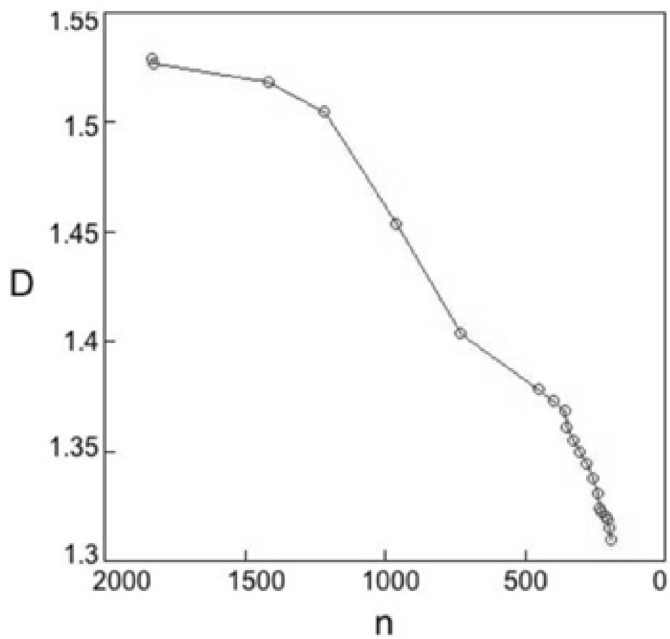

Fig. 5. A plot of *D* versus the number of bubbles *n* in the simulated foam of Fig. 4. Note that the number of bubbles in the foam decreases with time: the data points on the left of the graph therefore correspond to earlier in the coarsening process, while data on the right corresponds to later times.

These preliminary results signal the growing interest in the artistic importance of foams, and the associated study of human response to their aesthetic qualities. However, it is worth stressing that the interaction between the physics of foam formation and its artistic appeal is far from new. Going back to Lord Kelvin's era, fellow physicist C. V. Boys's book (Boys, 1890) influenced many of his contemporaries in the arts. It is therefore not surprising to find that the research of Weaire, Hutzler and Drenckhan is directly inspiring today's artists.

Their recent exhibition "Bubble: Don't Burst it", at Trinity College's Science Gallery in 2009, was designed to trigger the visitor's imagination and the exploration of the interconnection between the science and art of bubbles. As Hutzler explains (Hutzler, 2009): "The idea was that we show different aspects of the science of soap bubbles and foams, and that people come and play with it. It's an exhibition where you get your hands, not dirty, but you get them clean!"

The scientific investigations of Weaire, Hutzler and Drenckhan overlap with the work of photographers Tim Durham and Michael Boran. Reflecting on their experience, Durham notes: "One of the things I like about photography is that it gives me an excuse to go exploring – visually and mentally." Boran echoes these thoughts by celebrating the rich subject matter presented by foams: "There's a huge variation of bubbles. As I worked with them I realized that you have different shapes, structures, colors …"

Hutzler, in particular, is interested in the variations of colors and employs imaginative techniques to emphasize their characteristics: "We want to transform these colors into sounds. The colors indicate the thickness of the soap films. When you blow a bubble, the liquid drains out of the bubble due to gravity. Therefore, the thickness of the bubble changes with time and so do the colors". An apparatus called the "soaper-sonic" then converts the bubble colors into the musical notes so that Hutzler's audience can listen to the bubbles sing!

This strategy of using bubbles as performance art also builds on a long history. The art of creating bubbles for visual entertainment is at least 400 years old. For example, 17th century Flemish paintings show children blowing bubbles with clay pipes. More recently, in 1984, New York architect David Stein invented a giant bubble generator called the Bubble Thing. This apparatus features a large open-and-closable loop of fabric which, when dipped in a bucket of soap solution, can create large soap bubbles. Using similar techniques, it is possible to blow spheres over 14 feet in diameter and tube-shaped bubbles that are up to 114 feet long!

Many of today's soap bubble performances combine artistic achievement with entertainment. Sometimes the bubbles envelope objects or even humans during shows. Bubble artists create bubbles that form cubes, tetrahedra and other shapes. To add to the visual experience, the bubbles are sometimes filled with smoke, vapor or helium and combined with laser lights and even fire: soap bubbles can be filled with a flammable gas such as natural gas and then ignited. In all of the excitement and artistic intrigue that surround such events, it is easy to forget one crucial fact: none of this would be possible without a scientific understanding of how bubbles behave.

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