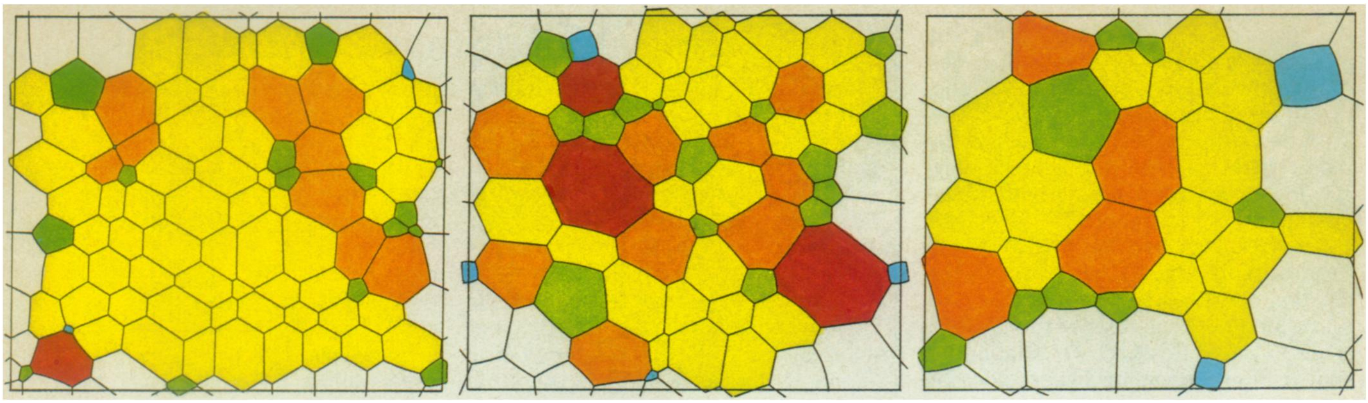


Frothy Physics

Scrutinizing the laws of suds

By FAYE FLAM

Take a close look at the suds in a bubble bath, the foam atop a mug of beer or the froth floating on an ocean wave. You'll notice that as the liquid partitions between the bubbles get thinner, the bubbles bunch up, squeezing into a network of polyhedra that fit together in a pattern suggesting crystals or cells. So striking is this similarity that metallurgists use soap froths as an analogy for metal crystals, and biologists compare them to living cells.

Scientists make froths easier to study by pressing them between transparent plates into two-dimensional jigsaws of polygons. They use these simplified systems to uncover rules and relationships governing the shapes and sizes of bubbles as they shift around over time. Through such studies, researchers are beginning to decipher the intricate dance performed by suds as they evolve toward a sort of balance between order and chaos.

In a state of perfect order, a two-dimensional froth would exist as an array of uniform, hexagonal bubbles arranged like a honeycomb. All mechanical forces would balance, and the froth would remain stable in that pattern. Scientists can create near-perfect froths by using a syringe to blow uniform bubbles into a soap film.

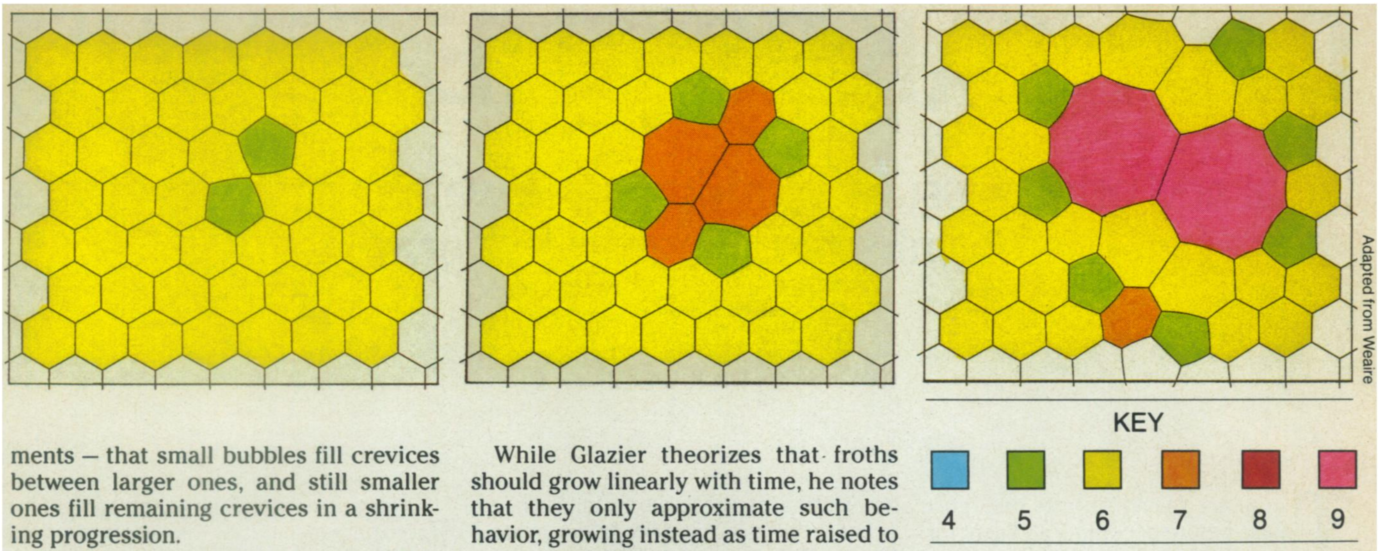
But small imperfections – the odd five- or seven-sided bubble – inevitably creep in, upsetting the balance and sending the system on a course toward randomness. Bubbles neighboring the imperfections begin to gain or lose sides, causing areas of disorder to spread like a cancer, says physicist James A. Glazier of the University of Chicago. Glazier's report in the March 13 Physical Review Letters, following up on work he described in the July 1, 1987 Physical Review, dispels some long-standing fallacies tied up in froths.

Glazier and other froth-watchers take their inspiration from former MIT metallurgist Cyril Stanley Smith, who pioneered the application of soap bubble models to metallurgy. In the 1950s, Smith demonstrated the usefulness of soap froths as analogies for metal crystals.

Smith was the first to observe soap froths squeezed between glass plates. In the two-dimensional arrays, he discovered relationships between edges, vertices and areas of the interconnected polygons. "The relationships describing froths are simple, beautiful equations," says Smith, now retired and living near Boston. He watched the way the froth pattern coarsened over time, and noted that the average of the areas enclosed in all the two-dimensional polygons increased in a linear relation to the time elapsed. These studies led him to discover the similarity between the way froth bubbles change shape as gas slowly diffuses from one bubble to another and the way metal crystals, or grains, change shape as heat expands them. Scientists agree that Smith's photographs of two-dimensional soap froths are indistinguishable from etched metal surfaces showing patterns of packed grains.

Smith's bubbling enthusiasm infected mathematician John Von Neumann, who in the 1950s formulated a law describing bubble coarsening. It's said that he devised his law while attending one of Smith's froth lectures. Basically, Von Neumann's law of bubble growth states that in a frothy world, the rich get richer and the poor get poorer. Bubbles with more than six sides grow larger in size, growing faster the more sides they have, while those with fewer than six sides shrink, the ones with fewest sides shrinking fastest and often disappearing altogether.

In the 1970s, David Aboav of Chorleywood, England, and Denis Weaire of Trinity College in Dublin, Ireland, took a closer look at Smith's soap froths. Working separately but using the same pictures Smith had taken more than 20 years earlier, they reached some conclusions that contradicted Smith's findings. Aboav and Weaire proposed in 1980 that the average area within the bubbles increases at a rate proportional to the *square* of the time elapsed, not proportional to time elapsed as Smith proposed. They also noted that, contrary to Smith's assertion, the froth grows continually more disordered. In 1984, Weaire proposed that froths take on fractal arrange-



Adapted from Weaire

Paint-by-numbers: On facing page, images from a computer simulation – with colors added to highlight the number of sides on each flattened bubble – depict three steps in the evolution of a natural soap froth. As individual bubbles gain or lose sides and grow, shrink or disappear, their average size increases in a process called coarsening. On this page, simulated suds start out in an orderly honeycomb pattern, but a subtle defect creeps in (far left), triggering a cancer-like spread of disorder.

ments – that small bubbles fill crevices between larger ones, and still smaller ones fill remaining crevices in a shrinking progression.

Over the last two years, however, Chicago's Glazier has made observations supporting Smith's original results and bursting the bubble of Aboav and Weaire's refutation.

Glazier blew his own bubbles in a film of "Dawn" brand dishwashing detergent, squeezing them between acrylic-plastic plates and highlighting them with a bit of dye. He put the slowly evolving array on an office photocopier to record how the 10,000 or more hand-counted bubbles changed over periods of days. Glazier initially filled his bubbles with air but later switched to helium, which makes a faster-evolving froth.

His soap photocopies show bubbles evolving in two stages. During the first stage, which Glazier calls the transient phase, the cancer-like spread of disordered areas progressively compounds the disorder of the whole system. This phase lasts several days with air-filled bubbles and about 10 hours with helium-filled ones.

During the second stage, called the scaling state, the disorder level remains constant. Although individual bubbles keep gaining or losing sides, growing, shrinking and disappearing, the total number of bubbles with a given number of sides stays the same. Three-sided bubbles, for instance, might keep disappearing but new ones form at the same rate. The scaling state lasts about 60 days in air bubbles and 10 days in helium bubbles.

In this state, observed Glazier, the average area enclosed by the bubbles grows in a roughly linear relation to time, not as time squared as Aboav and Weaire suggested. He also confirmed Von Neumann's law, showing that many-sided bubbles grow larger while few-sided ones shrink. As for Weaire's concept of fractal froths, Glazier concludes that bubbles take on interesting – but not fractal – patterns.

While Glazier theorizes that froths should grow linearly with time, he notes that they only approximate such behavior, growing instead as time raised to a power of 0.59. (Linear growth would correspond to a power of 1.) He proposes that the discrepancy creeps in because the plates enclosing the froths prevent them from expanding naturally. As the bubbles in a froth enlarge, the sum of their perimeters decreases while the total volume of liquid separating them remains fixed. Therefore, the artificially compressed bubble walls must start to thicken, perhaps slowing gas diffusion from one bubble to another, he says.

Glazier suggests that Aboav and Weaire probably went astray by examining photos of only the transient phase of bubble evolution, when disorder grows and the average bubble area does increase at different rates with respect to time, sometimes growing as time squared, as Aboav and Weaire concluded.

At the point when the scaling state begins, the system has reached an "equilibrium" level of disorder, says Glazier. He compares this level to the equilibrium position of a mechanical spring. When Glazier starts his system in a very ordered state, with mostly uniform hexagonal bubbles, disorder in the transient phase increases beyond the equilibrium level and then bounces back, becoming more ordered until it reaches the scaling state – like a compressed spring bouncing beyond, and then back to, its final resting length. If he starts the array closer to the disorder of the scaling state, the froth's disorder increases smoothly until it reaches this final state. Even an array that starts out disordered beyond the equilibrium point will gain order to achieve the scaling state, he says.

What is so special about the scaling state that causes the bubble-shape distribution to end up there no matter what its initial arrangement? "The system is trying to find a particular [level of] disorder, and the way it starts out might not be the right disorder," Glazier suggests.

According to physicist Nicolas Y. Rivier of Argonne (Ill.) National Laboratory, the "right" disorder might be comparable to the thermodynamic equilibrium of a gas. Rivier sees the scaling state as a "statistical equilibrium," meaning that shifts in individual parts of the system preserve its overall properties. Just as the overall temperature of a gas remains constant while some molecules move quickly and others move slowly, constantly colliding and changing speeds, individual bubbles can add or subtract sides while preserving the froth's constant overall distribution of five-, six- and eight-sided bubbles, he suggests.

Rivier characterizes the scaling state as one in which a specific brand of disorder, called entropy, reaches a maximum. The laws of thermodynamics predict that gases and other phases of matter progress toward a state of maximum entropy. Rivier describes maximum entropy as the state in which you can make the most rearrangements of individual items within a system. For example, if someone is about to toss four coins, there's only one way to achieve the unlikely outcome of all tails, making that a low-entropy outcome. On the other hand, six different combinations of coin sides are available to produce an even distribution of heads and tails, making this the highest-entropy outcome and the most

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laboratory division in Washington, D.C. But ultimately, he adds, the bureau would prefer to decentralize the monitoring of forensic DNA laboratories – much as the National Institutes of Health delegates many of its oversight responsibilities to Institutional Biosafety Committees at individual universities and research centers.

Issues of accuracy and regulation may prove particularly contentious because a single DNA test often consumes all of an available sample. Researchers disagree about the importance of this detail. If scientists perform the test accurately the first time, they note, then the autorad, unlike many other types of tests, remains as a permanent record and is available for corroborative inspection by any number of experts. In a sense, says Caskey, "you've not used up the DNA; you've immortalized it." Others, however, express frustration that the tests cannot be run from scratch a second time.

The quality-control debate touches upon questions of computer correction as well as human error. In basic research laboratories, scientists routinely use computer algorithms to "clean up" autorad records by digitally compensating for slightly variable migration rates in different parts of the gel. But when a slightly altered autorad might mean the difference between life imprisonment and walking free, these corrective techniques stir intense controversy. Some say that revealing the use of such techniques during a trial may inspire a jury – rightly or wrongly – to mistrust the data as a whole.

Indeed, one of the biggest unknowns in the debate about DNA forensics is just how big an impact the high-tech evidence will have on juries. Experience to date suggests that most people are easily swayed by the apparently incontrovertible—and not easily understood—nature of DNA evidence.

"With a [standard] fingerprint you can put it up on the wall, you can blow it up, follow the ridges—great, it matches," says Douglas P. Rutnick, an Albany, N.Y., public defender. However, he says, an average juror looking at an autorad doesn't know what it is. "I've looked at it, and I couldn't understand it for beans."

Ultimately, Rutnick suggests, it may be lawyers who have the most difficulty adjusting to this newest kind of evidence. Even Perry Mason might fail to see the flaws in a molecular biologist's testimony that restriction enzymes, polymorphisms and gel electrophoresis indicate a defendant's guilt.

"How do you cross examine [such a witness]?" asks Rutnick. "What do you do?"

He shakes his head.

"What you get is deadly. But I couldn't read [the autorad]. I couldn't at all." ☐

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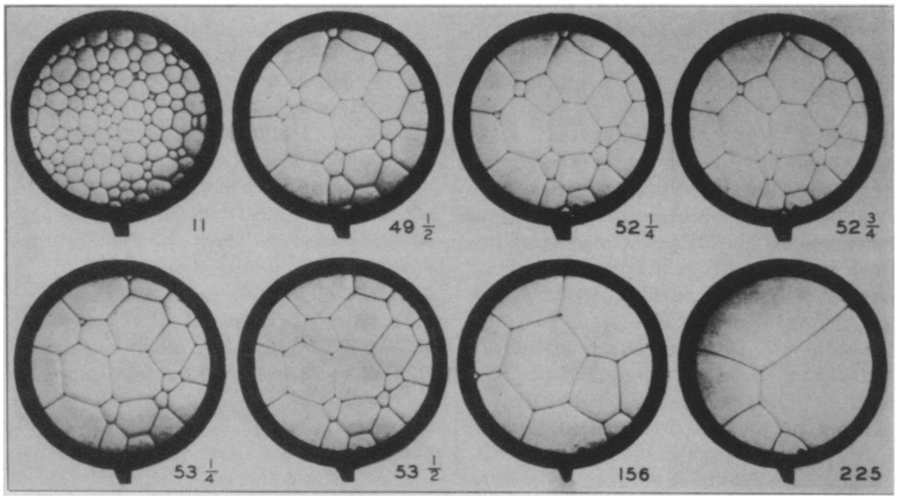
likely toss.

Rivier believes that a system in statistical equilibrium must obey a rule called the Aboav-Weaire law, which applies not only to froths but also to crystals and cells. This law relates the number of sides of each polygon to the number of sides of its nearest neighbors. Glazier likens the law to the tendency of electrical charges to hide or "shield" each other: Negative charges surround an extraneous positive charge in such a way that the positive one eludes detection from a distance. In a soap froth, the number of sides greater or fewer than six would correspond to a bubble's charge. For example, a seven-sided bubble is like a +1, while a four-sided one is like a −2. The Aboav-Weaire law, then, predicts the way in which few-sided bubbles will congregate around many-sided ones, and vice versa.



From *A Search for Structure* (Smith, © 1981 MIT)

Cyril Stanley Smith's original froth photos show how flattened bubbles grow and disappear over a period of 225 minutes.

Rivier thinks statistical equilibrium implies that the system also follows another rule, called Lewis' law, which predicts that the area enclosed within an individual two-dimensional bubble grows in a linear relation to the bubble's number of sides. F.T. Lewis formulated this law in 1928 while studying the skin of a cucumber. It seems to hold for biological cells but not as well for soap froths. Glazier observed that many-sided bubbles roughly follow Lewis' law, while fewer-sided ones deviate from it. Rivier says the deviation may stem from subtle differences between the physical properties of an actual network of bubbles and the theoretical ideal – just as real gases stray from ideal gas laws.

In his journal paper, Glazier highlights several ways in which froths stray from theoretical ideals. He says the real system contradicts the long-held assumption that all sides of the bubbles in a froth join in 120° vertices. Bubbles tend to bend their edges to accommodate the mechanically favored 120° joining angle, but according to Glazier, they don't always achieve that goal. He notes that earlier calculations, including Von Neumann's law, rest on the 120° angle assumption – but the bubbles don't seem to notice, violating the angle and following Von Neumann's law all the same.

Such bubble puzzles haven't kept researchers from grasping froth evolution well enough to simulate it on computers. Glazier is now working with Gary S. Grest of Exxon Research and Engineering in Clinton, N.J., to create computer froths that become disordered in much the same way as real ones. In the simulations, individual picture elements, or "pixels," on the borders between bubbles switch their allegiances to neighboring bubbles according to programmed-in physical laws. To an untrained eye, the computer froths appear indistinguishable from the real ones.

Natural froths, of course, come in a more complicated three-dimensional network. Nonetheless, Glazier says the two-dimensional rules may extend to the three-dimensional world, noting that cross sections of 3-D froths look like the squashed 2-D ones.

Real froths can be useful, too. Petroleum engineers use them to force oil from the ground, while brewers strive to achieve the perfect beer foam. Indeed, Glazier says the U.S. government has shown interest in using them for the unfrothy purpose of making hydrogen bombs. Yet the beauty of froth patterns alone would seem sufficient to entice scientists to investigate their filmy, ephemeral world. ☐

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