Snowflake's Riddle Yields To Probing Of Science
By JAMES GLEICK
New York Times (1857-Current file); Jan 6, 1987; ProQuest Historical Newspapers The New York Times (1851 - 2001)
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SCIENCE has conquered the snowflake problem.

In resolving two of nature's most poetic and maddening riddles — why are snowflakes symmetrical, and why are they all different — theoretical physicists have created a new body of mathematics for the laws that control the delicate branching growth of an unstable solidifying crystal.

Where traditionally snowflakes were left to weather experts and atmospheric scientists, now they have become part of a growing science of pattern formation that is drawing together theorists, computer modelers and engineers with practical problems ranging from metallurgy to flame propagation to oil recovery. The principles that govern ice crystals apply as well to metallic crystals, whose microscopic structure helps determine the strength of cast alloys.

Generations of snowflake-watchers sketched and catalogued the variegated patterns formed by airborne ice crystals: plates and columns, crystals and polycrystals, needles and dendrites. But snowflakes obey mathematical laws of surprising subtlety, and it has been impossible to predict precisely how fast a tip will grow, how narrow it will be or how often it will branch.

Snowflakes obey math laws of surprising subtlety.

"In the last two years, those problems have been solved," said Herbert Levine of the Schlumberger-Doll Research Center in Connecticut, one of the pioneers of pattern-formation research. The most recent breakthrough has provided a working mathematics for tying together the forces that stabilize the growing patterns and the forces that destabilize them.

By understanding the interplay of randomness and determinism, large-scale processes and microscopic processes, this new wing of physics has related a variety of subjects that were formerly treated separately.

"We've reached a very interesting point scientifically where we're starting to look at a whole bunch of older problems of pattern formation in nature, how complex formations emerge out of a generally featureless soup," said James S. Langer of the Institute for Theoretical Physics in Santa Barbara, Calif. "We finally seem to have a good idea of what controls these things."

A key to the new approach has been the availability of computers with which scientists could propose models, test them, make pictures of the results and then improve their models. Only recently, though, after more than five years of research by several groups, have computer simulations succeeded in realistically capturing the physics of crystal growth.

One problem is that such growth entails, as Dr. Langer says, "a highly nonlinear unstable free boundary problem," meaning that models need to track a complex, wiggly boundary that changes dynamically. "That's tough, trying to understand where this boundary is moving," he said. "If you guess wrong, the computer program just blows up on you."

Another problem has been deciding which of the many physical forces involved are important and which can safely be ignored. Most important, as scientists have long realized, is the diffusion of the heat released when

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Crystal Growth: Real and Programmed

A crystal tip or dendrite, top, magnified about 40 times and photographed in multiple exposure, becomes unstable as it grows downward, and subbranches bud from the sides. "Snowflakes" generated by computer reflect the variations of the real world. The computer uses a set of equations to model the physical conditions the flakes encounter. Slight changes in temperature or surface tension lead to very different patterns.

Solving the Snowflake Riddles

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water freezes.

When solidification proceeds from outside to inside, as in an ice tray, the boundary between solid and liquid generally remains stable and smooth, at a speed controlled by the ability of the walls to draw away the heat. But when a crystal solidifies outward from an initial seed — as a snowflake does, grabbing water molecules while it falls through the moist air — the process becomes unstable.

Any bit of boundary that gets out ahead of its neighbors gains an advantage in picking up new water molecules and therefore grows that much faster — the "lightning-rod effect." *Tips, or "dendrites," form,* moving rapidly outward and tending to give birth to subbranches.

This much has been known for years. But the physics of heat diffusion and unstable growth cannot completely explain the patterns scientists observe when they look at snowflakes under microscopes or grow them in the laboratory. Recently Dr. Langer's group in California and Dr. Levine's in Connecticut separately worked out a way to incorporate another process: surface tension.

Where diffusion creates instability, surface tension creates stability, preferring smooth boundaries like the wall of a soap bubble. It costs energy to make surfaces that are rough. And where diffusion is mainly a large-scale, macroscopic process, surface tension is strongest at the microscopic scales.

The competition between these forces makes for tricky mathematics, particularly since the equations must relate scales of millimeters to scales of molecules. Traditionally, physicists assumed that for practical purposes they could disregard the tiny surface-tension effects.

"That turned out to be just wrong," Dr. Levine said. "The breakthrough was showing that by throwing away this particular physical effect one was throwing away the right solution to the problem."

The reason is that the surface effects prove much more sensitive to the molecular crystal structure of a solidifying substance — in the case of ice, a natural hexagonal configuration. That gives ice a built-in preference for six directions of growth.

To their surprise, the physicists found that the delicate balancing act of stability and instability amplifies this microscopic preference, creating the magnificent lacework characteristic of snowflakes.

In effect, a snowflake records the history of all the changing weather conditions it has experienced. As a growing flake falls to earth, typically floating in the wind for an hour or more, the choices made by the branching tips at any instant depend sensitively on such things as the temperature, the humidity and the presence of impurities in the atmosphere.

The nature of turbulent air is such that any pair of snowflakes will follow very different paths, and enough combinations of patterns are possible to more than justify the folklore that all snowflakes are different. But why are all six arms of a snowflake alike?

"Lots of people have thought that there has to be some mechanical equivalent of somebody sitting at the center of the snowflake and telling all of them to do the same thing," Dr. Langer said.

But first of all, careful examination shows that snowflakes are not exactly symmetrical. And second, the six arms of one snowflake, less than a millimeter across, will have experienced nearly identical growing conditions — much closer than any two snowflakes experience, and close enough to explain their similarity.

In metallurgy, specialists seek a precise understanding of what controls the speed of crystal growth and the degree of irregularity because these, in turn, often control the tensile strength of an alloy after it solidifies.

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These scientists are also benefiting from the new style of using computer models to study such problems.

"There's a brand new interaction between technology and science, connected largely by the computer," Dr. Langer said. "People in industry say, 'We're dealing with more and more complex systems, and we're not going to do it by hunt-and-find any more — it's too tough."

Meanwhile, physics groups at Ecole Normale Superieure in Paris and California Institute of Technology in Pasadena are pursuing the new approach to pattern formation, and a physicist at Emory University in Atlanta, Fereydoon Family, has used the mathematics to create startlingly lifelike computer pictures of snowflakes.

One computer snowflake, an aggregation of 10,000 or more particles, requires about eight hours of high-speed calculation, and very slight changes in temperature or humidity produce vivid changes in the resulting patterns, Dr. Family said. He will present the results at the March meeting of the American Physical Society in New York.

Experimentalists, too, are pushing the science of pattern formation forward. Jerry P. Gollub, a physicist at Haverford College and the University of Pennsylvania, has conducted a series of experiments designed to shed light on the precise shape of the convoluted structures that appear behind the growing tip of a dendrite, a problem that continues to elude theorists.

Using a microscope and crystals of ammonium bromide, he has been able to resolve details as small as 500 angstroms, or 1/20th the width of a human hair. Most recently he has been able to characterize the irregularities within rows of these sprouting sidebranches.

In the back of their minds, many of these physicists nurse a belief that their work on pattern formation may apply to developmental biology as well. Some types of algae, for example, closely resemble patterns under investigation by physicists.

"There is a clear connection between this problem of stability and the early differentiation of certain organisms when they start from an egg and gradually acquire structure," Dr. Gollub said. "What we're really doing is pushing science in a new direction through a simultaneous development in mathematics and experiment.

"On the one hand snowflakes are important because there are lots of crystals in nature," he said, "but in the long run I think the most important aspect will be this general development of tools and ways of thinking. It is those things that are most likely to carry over into other areas of investigation."

From Snowflakes to Oilfields
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From Snowflakes to Oilfields

If you take a snowflake and remove the symmetry, you get patterns of special interest to engineers trying to squeeze oil from depleted fields.

In the process of secondary recovery, water is pumped into the ground to push out oil that will not flow under its own pressure. Unfortunately, engineers often find that the leading edge of the water becomes chaotic, breaking into bulbous "fingers" instead of pressing ahead with an effective smooth boundary.

Mathematicians are discovering that the same laws that govern the branching of crystals also explain why the interface between two substances grows unstably, creating a serious challenge for scientists who need to make predictions.

When the interface is the surface of a solid crystal of ice or metal, the outcome is determined by the six-way or four-way symmetry of interlocking molecules. But when one liquid flows through another, with no crystal to favor certain directions over others, the fingering becomes more random.

Nevertheless, to mathematicians modeling such processes, the likeness has become unmistakable.

"If you pick the right version of the oil recovery problem, you get things that look just like snowflakes and dendrites," said James Glimm of New York University's Courant Institute of the Mathematical Sciences. Finger-like formations occur in many other places, he said — in falling sheets of water that break into drops, for example, and in long plumes of salt water that float down into fresh water where rivers meet oceans.

In varying degrees, scientists have described all these processes as fractal, meaning that the irregularity tends to be measurably the same on large scales and small. To some extent, at least, fingering plays by the same rules whether in a desktop experiment or a giant oil field.

"Theoretical physics is changing," said Herbert Levine of Schlumberger Doll Research Center. "Twenty years ago people realized that there were very hard problems around involving systems with many degrees of freedom, many interacting parts, and people didn't know how to make much progress on those problems. But now everyone has computers, and that's one reason this field has blossomed. It's possible to use computers as experimental tools to see if they can reproduce the complex patterns that exist in nature."

So researchers continue to refine their models. Oil engineers try chemical additives to make water more viscous, reducing the degree of fingering. Experimenters put glass plates together and push different fluids through holes in them — and all these scientists are motivated by a sense that they are uncovering more evidence of a sort of unity in nature, certainly mathematical and still somewhat mysterious.

Source: J. D. Chen

Oil flowing into water, through hole at center, spreads in "fingers" with splitting tips.