given time must be roughly L^4 (destinations times stops en route). This represents blood volume, which based on empirical observations should be proportional to an organism's mass. The rest of the argument is reminiscent of Rubner's. The total metabolic rate is proportional to sites served (L^3, or $M^{3/4}$), which makes the specific metabolic rate proportional to $M^{-1/4}$, in agreement with Kleiber's law. The argument can also be adjusted to two-dimensional river networks, where it predicts cube-root scaling, in agreement with experimental observations.

Some experts say the simplicity of Banavar's model is a big plus. "I'd be happier if it were this way than the fractal model," says William Calder, a biologist at the University of Arizona, Tucson. But it must be interpreted with care, adds West: For example, a "site" cannot be an individual cell, because this would imply that the proliferation of cells could not keep pace with increasing organism size.

Banavar was not the only researcher trying to simplify the New Mexico team's model. West and his colleagues also felt that there had to be a broader argument that could apply to plants, animals, and even one-celled organisms lacking a vascular system. With that in mind, they scrapped the physics of fluid flow. In their latest *Science* paper, the team makes a case for a quarter-power law based mostly on geometry, particularly the hierarchical nature of circulatory networks. "We traded in the dynamics for the statement that hierarchy gives rise to a power law," West says. They argue that an organism's "internal area"—the total area of its capillary walls—fills up space so efficiently that it, in effect, adds a third dimension. The "internal volume" of all the vessels feeding the capillaries adds an extra dimension as well, scaling as the fourth power of internal length. The distinction between internal and external lengths, areas, and volumes is crucial, West says. "You really have to think in terms of two separate scales—the length of the superficial you and the real you, which is made up of networks."

The new argument by West's team poses its share of head-scratchers: If the internal length of an animal's circulatory system increases less rapidly ($M^{1/4}$) than the external length ($M^{1/3}$), what happens when it becomes too short to reach the skin? The answer, Dodds believes, may be a delicate balancing act: "I would argue that there are different scales in different parts of the animal"—that is, not one internal length scale but several. In the end, simplicity may have its limits. "The final theory will not be as simple as Banavar's but may be around the level of what West has done," Dodds says. "What I am sure of is that they will both be very controversial."

—DANA MACKENZIE

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FLUID DYNAMICS

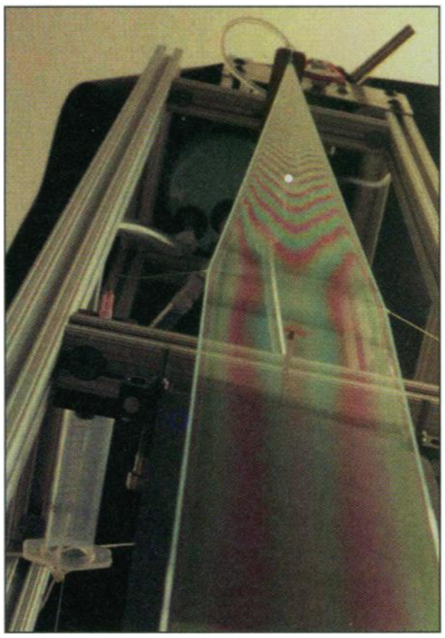
Soap Films Reveal Whirling Worlds of Turbulence

New techniques for studying "soap film tunnels" are giving researchers a glimpse into the surprising world of two-dimensional turbulence

Blowing a killer soap bubble takes a steady hand and a still day, as any child knows. But creating the kinds of soap films that thrill physicists goes far beyond child's play. Their high-tech films, clinging to a pair of wires hung a few centimeters apart, flow toward the floor and stream past strategically placed obstacles that stir roiling patterns in their wakes. The patterns, resembling swirls of smoke, are shedding new light on the intricate physics of turbulence in two dimensions (2D). "Soap films are a brilliant way to produce 2D turbulence," says fluid dynamicist Patrick Tabeling of the Ecole Normale Superieure in Paris. "They are a major contribution."

Two-dimensional dances with whorls, scientists believe, arise in nature when moving liquids or gases are confined to flat or curved surfaces. Cyclones and other large-scale wind flows in the atmospheres of planets fit this bill, says physicist Walter Goldburg of the University of Pittsburgh. These vortices are hundreds of kilometers across but just a few kilometers thick, so their motions are essentially 2D, Goldburg says. Plasmas corralled by magnetic fields in space or in fusion reactors, and ocean currents pinned in a narrow horizontal layer by sharp changes in temperature or salinity, may also be examples of 2D turbulence.

At first glance, some of the swirling 2D patterns in these systems look like cross sections of 3D vortices, the more familiar brand of turbulence generated, for example, behind a jet's wings. However, radically different principles of physics govern the two types of turbulence, says physicist Robert Ecke of Los Alamos National Laboratory in New Mexico. And although physicists have plenty of theoretical models and computer simulations of 2D turbulence, testing these models and theories in the lab has proven difficult. A turbulent flow initially confined to a 2D sheet likes nothing better than to unfold into three dimensions, as researchers trying to study 2D phenomena in wind and water tunnels discovered early on. But now, 2D turbulence is beginning to reveal its secrets, such as how its vortices evolve and suddenly swap energy, thanks largely to new techniques for studying "soap film tunnels."

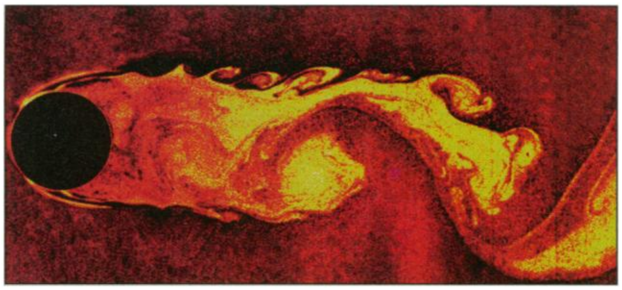


Physics in 2D. A 2-meter-long soap film streams downward between two wires in this apparatus designed by Maarten Rutgers.

CREDIT: BRENT DANIEL AND MAARTEN RUTGERS, THE OHIO STATE UNIVERSITY

The soap films build upon work in 1986 by French physicist Yves Couder, who dragged objects through stationary films to watch how turbulent patterns decayed to stillness. A few years later, a team led by fluid dynamicist Mory Gharib, then at the University of California, San Diego, pioneered a moving film that could be replenished continuously—a key advance that mimics flows in nature.

Today, in a system devised by Goldburg and Xiao-lun Wu at Pittsburgh and refined by physicist Maarten Rutgers of The Ohio State University in Columbus, nozzles spray dilute dish soap continuously onto a pair of vertical wires. Cords draw the wires apart, stretching the soap into a rectangular patch of film that flows at speeds of a few meters per second. In the middle of the patch, the forces of gravity and air drag balance out so that the film reaches a steady "terminal velocity," like a skydiver with outstretched limbs. The film, a sandwich of soap molecules and water, is sev-



Soapy swirls. A cylinder in a rapidly flowing soap film sheds a "vortex street" in its wake. Similar 2D turbulence may occur in the atmosphere and the oceans.

eral micrometers thick in the center and lasts for hours as pumps return the fluid to the nozzles at the top. Small cylinders inserted in the flow create vortices that look like mushrooms, spiral galaxies, and other graceful forms. These shapes are highlighted by microscopic spheres of titanium dioxide or polystyrene in the film, which catch the light of probe lasers or stroboscopic lamps.

This system let Rutgers probe one of the key differences between 2D and 3D turbulence. In a 3D fluid, swirls can intensify in a process called "vortex stretching," in which particles go faster and faster as they plunge toward the throat of the vortex. This happens to water gurgling down a drain or winds sucked into a tornado: The conservation of angular momentum amplifies motions as the whirling tube gets stretched thinner. However, this stretching and amplification can't happen in a 2D fluid, because the swirling particles are confined to a plane. Instead, according to theories proposed in the 1960s by physicists George Batchelor and Robert Kraichnan, some vortices should merge into progressively larger ones, a process called the inverse energy cascade. At the same time, smaller swirls should stretch and fold into the seething fluid like candy on a taffy puller—an effect known as the forward enstrophy cascade.

To test these predictions, Rutgers placed two vertical combs of cylinders along the edges of his soap film flow to generate constant trains of interacting vortices as the film streamed past. He saw evidence for both processes. If the vortices exceeded a certain size, they merged into larger whorls. However, smaller vortices sheared and vanished, like thin ribbons of cream in a mug of coffee. "This was a key theoretical prediction, but [the two energy cascades] had never been observed simultaneously," says Rutgers, whose findings appeared last September in *Physical Review Letters*.

Ongoing work by Rutgers and by Goldburg and Wu suggests that 2D turbulence doesn't always conform to theory, however. Theory predicts that 2D vortices should grow and dissipate gradually, because they cannot interact as chaotically as they do in 3D. Instead, says Goldburg, "we are finding that 2D flows can depart violently from the mean in rare bursts"—a hallmark of turbulence called "intermittency" that scientists had assumed was the sole province of the 3D world. The 3D phenomenon is familiar to airline passengers as "violent excursions"—unexpected jolts that leave your stomach in the lurch. In 2D flows, the excursions appear as occasional spiky transfers of energy among vortices.

Some experts wonder whether the soap film results are too squeaky clean. "The experiments are very nicely done, but they are not an exact analogy [to 2D turbulence] by a long shot," says fluid mechanician John Lumley of Cornell University in Ithaca, New York. The main problem, he says, is that the films vary in thickness by up to 30%. Such bulges could be compressed or squished, especially in a fast-moving film, he says. To Lumley, that invalidates the assumption that the turbulence traces a purely planar flow, because compression introduces a 3D component of motion to the film. Experimentalists acknowledge that the bulges are a concern. But in a report last August in *Physical Review Letters*, Ecke and two colleagues described a study of a tilted film that flows more slowly than the vertical ones. They found that the behavior of their film, bumps and all, hewed closely to predictions for an ideal 2D sheet.

Even so, Lumley wonders about the real-world relevance of soap films. "There is one important case where turbulence in nature is approximately 2D, and that is in the atmosphere on large scales," he says. "Beyond that, my feeling is that almost all turbulence in the universe is three-dimensional." Such views, however, shouldn't burst the bubbles of soap film researchers, says fluid dynamicist Katepalli Sreenivasan of Yale University in New Haven, Connecticut. "Finally, after 30 years, we see a convergence of theory, simulation, and experiment," he says. "Anything that cleans up our understanding of one area of turbulence is most valuable."

—ROBERT IRION

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SCIENCE EDUCATION

Reinventing the Science Master's Degree

The Sloan Foundation is backing an experiment at five universities to offer science undergrads an alternative to the Ph.D.

Meet Jarrell Pair, science professional. Fresh out of grad school, Pair is spending the next few months in Santiago de Compostela, Spain, creating a virtual driving tour of the 1200-year-old city's narrow cobblestone byways and bustling cafe-lined plazas. When the project is finished, people will be able to sit in a fake car surrounded by movie screens and take a virtual spin through Santiago, "experiencing all the sights and sounds of being in the actual city," Pair says. The exhibit, part of the Santiago 2000 celebration, will also tour computer graphics conferences in Europe, serving as a showcase, Pair says, for luring high-tech companies to the Santiago region.

Sim city. With a new master's under his belt, Jarrell Pair is helping design a virtual tour of Santiago, Spain.

Pair didn't have to tough out a Ph.D. for graduate training in his specialty, human-computer interaction. Instead, the 26-year-old with eclectic interests—he earned bachelor's degrees in computer engineering and international affairs, and certificates in music, drama, and film—last year completed a professional master of science degree at the Georgia Institute of Technology in Atlanta. The university is one of five in an experimental program, funded by the Alfred P. Sloan Foundation in New York, to test the academic waters by of-

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