Active Fluids Solve Icy “Six-Vertex” Model

Researchers demonstrate an active-fluid system whose behaviors map directly to predictions of the six-vertex model—an exactly solvable model that was originally developed to explain the behavior of ice.

By **Yi Peng**

Active fluids—collections of self-propelled agents such as bacteria, cells, or colloids—consume energy to move, flowing without being pushed [1]. These materials break the conventional rules of fluid dynamics, as they can flow spontaneously, switch direction without apparent cause, and organize into complex patterns with no external control. Active fluids were initially studied to understand the collective dynamics observed in biological systems. Now they offer a rich playground for exploring nonequilibrium physics. Yet, in the ever-expanding universe of active-fluid physics, it is rare to find an experimental system that maps precisely onto a mathematically exact model. Now Camille Jorge and Denis Bartolo from the University of Lyon, France, demonstrate that the flows of an active fluid confined in a two-dimensional square lattice of microchannels realize the six-vertex model from statistical mechanics—one of the earliest and most elegant examples of an exactly solvable model for interacting particles in a lattice [2]. This discovery is remarkable not just for the elegance of the mapping but also for what it reveals: a nonequilibrium fluid behaving exactly as predicted by a theoretical model devised to describe a completely different system (water ice with a disordered proton distribution). The finding could aid in the control and design of complex materials.

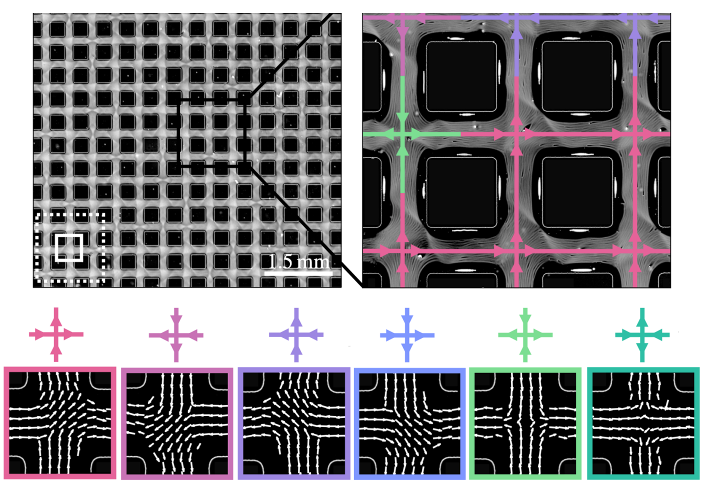
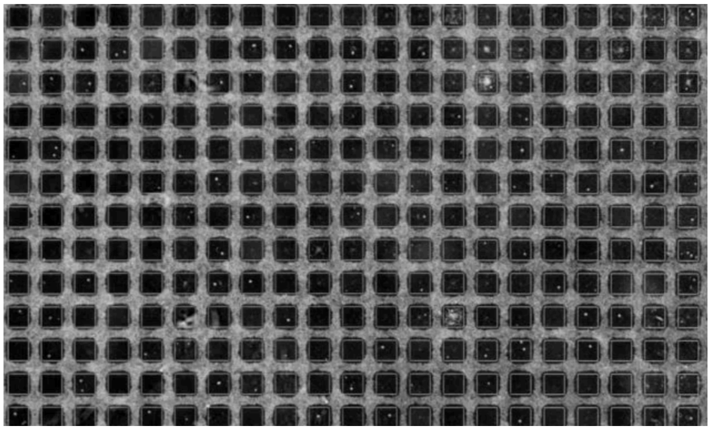


Figure 1: The flows of an active colloidal fluid confined in a two-dimensional square lattice of microchannels realize the six-vertex model from statistical mechanics. In this model each vertex of the square lattice enforces the “ice rule” in which the direction of flow of two channels point into and two channels point out of every node. There are six different flow configurations for this rule.
Credit: C. Jorge and D. Bartolo [2]

In unconfined environments, active fluids often exhibit chaotic and unpredictable motion, with swirls, jets, and spontaneous symmetry breaking that defy conventional control. To tame this complexity, researchers can turn to geometric confinement of the fluid, shaping the boundaries—whether through plates, posts, or junctions—with which the fluid interacts in order to manipulate local interactions among the fluid constituents and impose global order [1]. This approach has led to the manipulation of turbulent flow patterns [3] and revealed unexpected scaling laws [4], transforming active fluids into tunable platforms for exploring collective dynamics under constraint.

The six-vertex model, also known as the ice model, was



Video 1: The flows of an active colloidal fluid self-organize in a square lattice made of identical channels.
Credit: C. Jorge and D. Bartolo [**2**]

introduced in the 1930s to account for the peculiar entropy of frozen water [**5**]. Each vertex of the model's square lattice enforces the "ice rule": Two arrows must point into every node and two must point out of every node. Although the model failed to fully explain the behavior of ice, it became a cornerstone in the field of integrable systems and found application in magnetism, ferroelectrics, and quantum spin chains. Yet, for all its theoretical triumphs, the model remained abstract—until now.

At the core of the new experiment is a two-dimensional lattice of microchannels filled with colloidal rollers—micrometer-sized particles that, when subjected to an electric field, will roll along a surface. These particles spontaneously generate flow in the surrounding fluid, and when confined to a square network, the resulting currents at each junction obey local mass conservation: Two channels have currents that flow in and two have currents that flow out—just like the ice rule (Fig. **1**).

By introducing cylindrical posts at the junctions, Jorge and Bartolo were able to tweak the relative frequency of the flow patterns—which channels have currents that flow in, and which channels have currents that flow out—of a vertex, effectively tuning the statistical weights of the model and driving the system through a phase transition from a disordered to an ordered state. This transition mirrors the disordered-to-antiferroelectric ordering predicted by the six-vertex model's phase diagram. As the posts grew larger, they suppressed certain flow configurations and promoted others, causing the system to develop alternating flow patterns across the lattice. To understand what was happening, Jorge and Bartolo tracked so-called Lagrangian particle trajectories and reconstructed the entire flow network, showing that the ensemble of loops formed by the moving particles matched the predictions of another statistical model, the completely packed loop model, which is exactly equivalent to the six-vertex model.

The agreement between theory and experiment is unusually good. The loop size distributions, the fractal dimensions of the trajectories, and the spatial correlations between two points on a loop all match analytic predictions, including conformal-field-theory results. Large loops exhibit a fractal dimension of 7/4, characteristic of percolation, while smaller ones have a fractal dimension of 4/3, consistent with "self-avoiding" walks. Such quantitative alignment is rare in active fluids, where theoretical mapping often requires major approximations. Here, the experimental system is the model, transforming the active fluid into a solver for statistical mechanics problems. The agreement between theory and experiment also demonstrates that nonequilibrium systems can exactly mimic the behavior of equilibrium models, not just in spirit but in detail, and it offers a new tool for studying the six-vertex model—instead of simulating the six-vertex model computationally, researchers can now implement it physically, tuning parameters with microfluidic design rather than code.

This work also opens other avenues for theory and experiment. On the theoretical side, it invites extensions of the hydraulic rules and their mappings to statistical models in systems with higher coordination numbers or with three-dimensional geometries. On the experimental side, future studies could test whether similar hydraulic rules apply to other classes of active fluids and examine how far the mapping to statistical models can be pushed. Beyond geometry, intrinsic properties of the ambient medium—such as viscoelasticity—may fundamentally alter the hydraulic rules and lead to new emergent phenomena [**6**].

More broadly, this work will inspire physicists to rethink the role of geometry and activity in material design. Just as colloid systems became playgrounds for probing the microscopic dynamics of phase transitions [**7**], active fluids could serve as experimental platforms for classical and statistical field theories. The idea that one can "draw" a flow pattern by sculpting microchannel geometries—and have it follow exact theoretical predictions—is powerful. It also holds promise for disciplines far beyond soft matter, from microfluidic computing and robotics to developmental biology and the physics of living systems [**8**]. In a broader sense, this study reminds us that even the most abstract theories can find vivid manifestations in the physical world, if we look creatively enough.

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