# Taking the measure of water's whirl

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# Taking the measure of water's whirl

With a 3D printer, a laser, and a few drops of dye, researchers have revealed hidden topologies of fluid vortices.

A tornado won't just swirl you around, it will pick you up. It has what fluid dynamicists call helicity—its flow field twists simultaneously around and along a vortex line like a corkscrew. When Cambridge University mathematician Keith Moffatt introduced the term in the late 1960s, he saw it as a convenient way to quantify the topological nature of hydrodynamic flows: Helicity is defined locally as the dot product of velocity and vorticity; but when integrated over an entire volume, it describes the extent to which long, thin flow structures, termed filaments, wrap around one another.[1]

Helicity has proven valuable for understanding real-world flows. It can help predict the evolution of cyclonic storms, has been conjectured to underlie planetary and stellar dynamos, and is thought to factor into the emergence and evolution of turbulence. But it was never clear that volume-integrated helicity was something that one could actually measure in an experiment. Seemingly, that would require mapping a three-dimensional flow at length scales small enough to capture the tiniest swirls and eddies—a practical impossibility.

Now a University of Chicago team led by William Irvine has found that at least for some flow geometries, a flow's helicity can be inferred entirely from measurements along and around the constituent vortex lines.[2] The team tested the approach by measuring the helicity of pairs of interacting vortices in water—a proof of concept that may pave the way to studies of more complex systems, including turbulent flows.

"This is the first time anyone has measured helicity in a real fluid," comments De Witt Sumners, an applied mathematician at Florida State University. "It's a crack in the facade of our ignorance about turbulence."

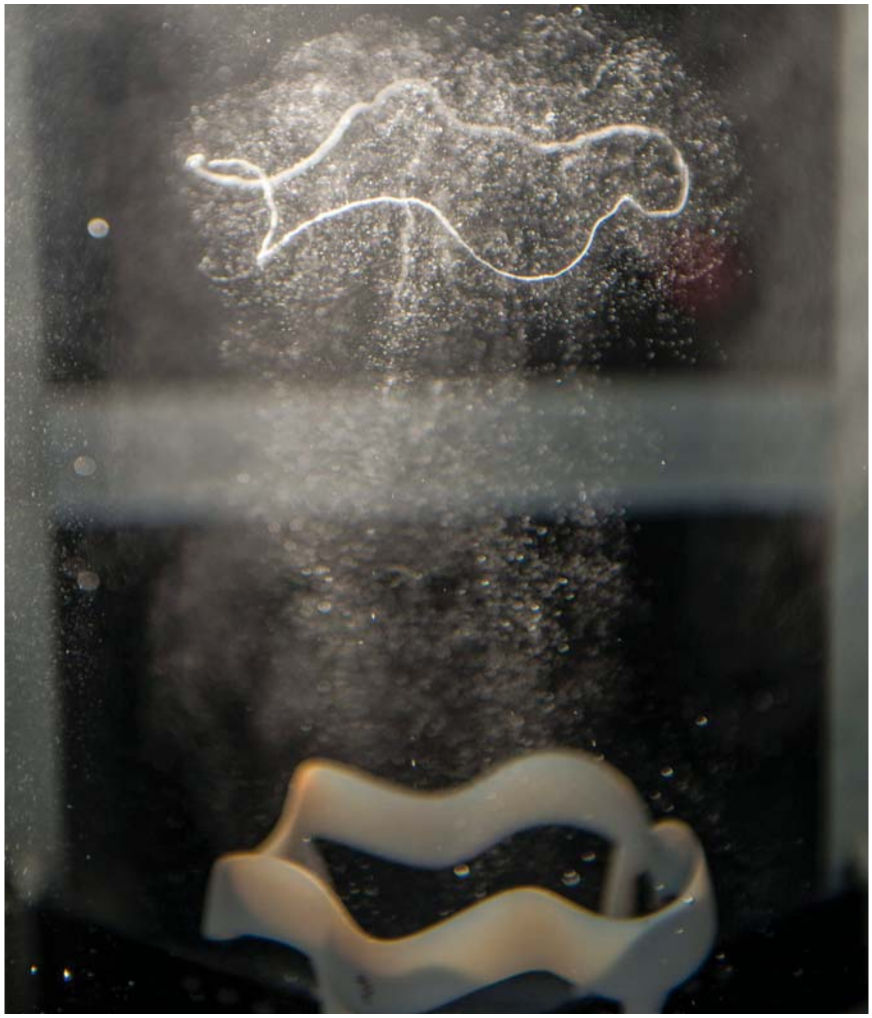

**FIGURE 1. A VORTEX RING** (top) was generated by the swift downward acceleration of a ring-shaped hydrofoil (bottom), roughly 10 cm in diameter, in a tank of water. The coils in the vortex ring are indicative of a topological property known as helicity. (Image courtesy of William Irvine.)

## Link, writhe, and twist

It's possible to show theoretically that helicity is a conserved property of ideal, inviscid flows. No matter how erratic or turbulent the flow, the topology of the filaments remains fixed. Superfluids approximate that ideal, but real fluids—water, air, and essentially every other fluid we encounter in our daily lives—are subject to viscous dissipation. A longstanding question is whether those fluids, too, can conserve helicity.

The equations that govern viscous flows are too complex to admit an analytical answer to that question, so Irvine turned instead to experiments. About five years ago, he and his postdoc Dustin Kleckner discovered they could generate vortex rings—miniature tornadoes whose centerlines join up at both ends to form loops—by swiftly accelerating ring-shaped hydrofoils in water. Using bespoke, 3D-printed hydrofoils, they could create vortex rings that were coiled (see figure 1), knotted, or even interlocking.[3] (For more on knotted and interlocking vortices, see PHYSICS TODAY, March 2010, page 18.)

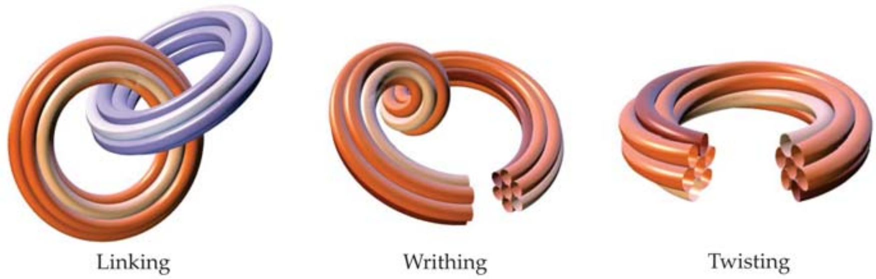


**FIGURE 2. HELICITY** describes how long, thin flow structures known as filaments (orange and purple) wrap around one another. In vortex rings, those filaments bundle in tubes, and helicity can therefore take three forms: Pairs of tubes can interlock (linking), a single tube can coil around on itself (writhing), and individual filaments can wind around the tube's centerline (twisting). The writhing and twisting forms are interconvertible but can't be converted to linking without breaking and reconnecting filaments. (Adapted from ref. 1.)

A vortex ring's flow structure can be understood as comprising a tube of filaments bundled like fibers in a rope. (See the article by Renzo Ricca and Mitchell Berger, PHYSICS TODAY, December 1996, page 28.) It follows that there are three ways filaments can wrap around one another to generate helicity, illustrated in figure 2: Two tubes can interlock (known as linking); a single tube can coil around on itself (writhing); and the individual filaments can wind around the tube's centerline (twisting). The linking form is topologically distinct from the others—it can't be converted to writhing or twisting without breaking and reforming filaments. Writhing and twisting are topologically interchangeable but physically distinct. In a purely writhing flow, neighboring filaments all run parallel to one another. In a twisting flow, they point in slightly different directions, which gives rise to viscous dissipation.

Irvine and his collaborators figured they could measure the helicity associated with a vortex ring by independently measuring its linking, writhing, and twisting. They had already developed a method to image vortex tubes using tiny air bubbles, which, due to their low density, tend to congregate near the centerline of a whirling vortex. And a coarse visualization of the tube is all that's needed to calculate linking and writhing. But as figure 2 implies, to directly measure twist, one needs to know the structure not only of the tube but of the individual filaments. After repeatedly trying and failing to unlock that structure, Irvine and his team came to a realization: They didn't actually need to measure twist to measure helicity.

Extending theoretical work done at Harvard University by Mitchell Berger and George Field,[4] Irvine and his colleagues showed that the topological constraints on flows around thin vortex tubes are such that total helicity—link, writhe, twist, and all—can be inferred from just the circulation around the tube and the velocity along the tube's centerline. The researchers could measure the circulation by watching how plastic microparticles embedded in the flow moved when they encountered a vortex ring. To measure the velocity of the flow along the tube's centerline, however, they needed a more precise technique.

Irvine's graduate student Martin Scheeler discovered such a technique when one day he happened to label a hydrofoil with a red marker instead of the usual black. The ink was swept up by a vortex ring, where it fluoresced under the light from the team's imaging lasers. That gave the researchers the idea to line the tips of all their hydrofoils with dots of fluorescent dye: The dye drops embed themselves along the vortex centerline, where their trajectories can be precisely captured with high-speed laser tomography. With that final puzzle piece, the team had all it needed to measure helicity. And because linking and writhing could still be computed independently, subtracting those quantities from the total helicity gives the twist.

"It's quite surprising that it works," says Irvine, whose group worked with Harvard postdoc Wim van Rees to validate the approach against numerical simulations. And even then, Irvine adds, "It took a lot of trial and error to come up with reliable, reproducible measurements—to make sure the dye was going where it was supposed to. It was painstaking work."

## A leap forward

Irvine and his coworkers tested the technique on a classic flow known as leapfrogging vortices, in which two copropagating vortex rings take turns passing through one another. Flow interactions cause the leading ring to decelerate and expand while the trailing ring contracts and accelerates, until the trailer becomes the leader.

Irvine and company put a new wrinkle on that textbook scenario: They endowed one of the vortex rings with writhe by generating it with a coiled hydrofoil. The second ring, a near-perfect circle, was helicity free. The coiled ring's helicity held steady as the ring expanded and contracted during the roughly second-long experiment, but the form of that helicity oscillated between writhing and twisting. Akin to the periodic stretching and releasing of a telephone cord, the behavior suggests one way that complex flows transfer energy between length scales.

For Irvine, the possibility to engineer vortices of known helicity and orchestrate the interactions between them is cause for optimism. "This puts us a step closer to being able to generate turbulent states with controlled amounts of helicity," Irvine says. "We're already working on that, but it will probably be some years before we have definitive results."

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