PERSPECTIVES: FERROMAGNETISM

Vortex Cores—Smaller Than Small

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As a result of dipole-dipole interactions, the magnetization becomes circular in the vicinity of the center of an isolated Fe, Co, or Ni platelet (panel A, first figure). It cannot, however, remain circular down to the platelet center (**r** = 0) because of exchange interactions, which become dominant at short distances. The magnetization has to leave the plane (*1–3*), defining what is termed a magnetic vortex.

Some 20 years ago, it was inferred from low-angle electron diffraction that the region with out-of-plane magnetization should not exceed ~15 nm (*4*). On page 577 of this issue, Wachowiak *et al.* (*5*) use sophisticated spin-polarized scanning tunneling microscopy (SP-STM) to show that the radius of a vortex within an Fe island (a supported nanoplatelet) amounts to only 4 to 5 nm.

This is a striking result in at least three respects. First, the measured vortex width is comparable to the smallest flux line core sizes in high-temperature superconductors (*6–8*). Second, it is compatible with an almost analytical model of classical vortex lines in ferromagnets (*9*), as confirmed by numerical simulations (*3*). The pertinence of micromagnetics down to the nanometer scale is thus reinforced. Third, it confirms SP-STM as a low-noise spectroscopic imaging technique with unprecedented spatial resolution (*9*).

Swirling eddies in the wake of bridge piles, a draining bathtub, whirlpools, and hurricanes are familiar images of vortices. Yet vortices seem to elude an all-inclusive definition.

In hydrodynamics, the rotational of the flow velocity, $\omega = \nabla \times \mathbf{v}$, is a differential measure of the local rotation of the fluid particles and is therefore called "vorticity."

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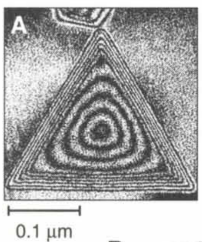
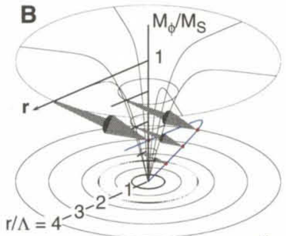
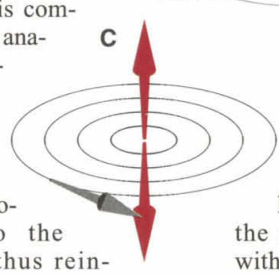
For a velocity vector field with a single nonzero tangential component (panel A, second figure) proportional to $1/r$, the vorticity is nil as long as $r \neq 0$. However, the circulation of the velocity along a closed path C that bounds a surface S is equal to the flux of ω through S. It follows that the vorticity is singular along the vortex line. The increasing shearing of the fluid with decreasing r will eventually become proscribed by viscosity: Close to the core of this swirling motion, the vorticity vanishes, resulting in a vortex tube (panel A, second figure) (*10*).

In quantum systems, the gradient of the phase of the wave function plays a role analogous to the velocity. The circulation of the velocity therefore becomes quantized; this is why a stirred Bose-Einstein condensate spreads its imposed vorticity into a vortex lattice (*11*, *12*). In high-temperature superconductors, the flux of the induction is quantized within each vortex line (*13*). The vector potential is equivalent to the hydrodynamic velocity, and the induction is equivalent to vorticity (panel B, second figure).

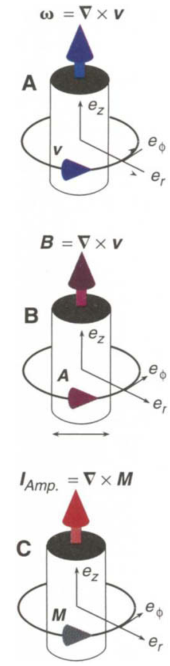






A magnetic vortex and a Bloch point. **(A)** Electron holography observation in a self-supported cobalt platelet. The inner fringes correspond to magnetic induction flow lines (*1*, *2*). **(B)** Tangential magnetization component versus distance to the core. **(C)** Schematic representation of a Bloch point.

If **M** or **B** is associated with the velocity field in a classical ferromagnet, then the vorticity corresponds to the equivalent Amperian current (panel C, second figure). The variation of the tangential magnetization component that gives rise to the vorticity may be decomposed into two regimes (panel B, first figure): a regime of linear increase with distance from the core (where the vorticity is constant), followed by a constant-value regime (where the circulation of **M** increases linearly with path radius). Hence, a vortex in a ferromagnet cannot be viewed as a "defect" of the magnetization distribution to be characterized by some invariant (here, the flux of the vorticity). Disappointing as this may be, the concept of magnetization circulation is probably sufficient to justify the vortex appellation for the tiny magnetization distribution observed in (*4*).



Vorticity versus "velocity." **(A)** ω versus **v** in a fluid. **(B)** Equivalent quantities for a flux (penetration) line in a high-temperature superconductor; **B** is the induction and **A** is the vector potential. **(C)** In a ferromagnet, the Amperian current is analogous to the vorticity for the circulating magnetization **M**. However, a vorticity thread may not be defined.

Consider now a vortex defined by its circulation and core magnetization. Construct a second vortex structure by reversing the sole core magnetization and combine the two structures such that their cores form a single straight line. The magnetization is everywhere continuous except in one point, called a Bloch point (panel C, first figure).

A Bloch point is a singularity of a three-dimensional magnetization vector field (*14*). Topology dictates that the reversal of the core magnetization of a vortex may occur either by sweeping the vortex out of the dot, followed by the nucleation of a fresh vortex configuration (*5*), or via Bloch point injection and punch-through (*15*). Indirect evidence for Bloch point injection exists (*16*). Real-time observations are, however, still lacking.

A Bloch point naturally links classical and quantum magnetism. After the experimental breakthrough of Wachowiak *et al.*, might it be the ultimate challenge in ferromagnet imaging?

References and Notes

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15. This means that a singularity of the magnetization distribution called a Bloch point is injected at one surface, travels to the opposite surface, and is finally expelled from the platelet.
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