of flight. Insects need change only by several percent the relative timing of wing rotation in order to alter substantially the magnitude and direction of forces on the wings, and thus to effect maneuvers. A general conclusion from this and other physical studies of flapping airfoils (*7*, *8*) is that unsteady aerodynamic forces are profoundly sensitive to the kinematic details of wing motion.

Wings of many insects are highly flexible about deformational axes largely determined by an often cross-connected network of hollow veins (*9*). Many tiny insects also express fringing hairs about the perimeter of the wing that likely enhance torsional and bending abilities. Use of flexible wing models in the robotic fly apparatus, however, only marginally altered forces during symmetrical wing flapping (*4*). Instead, the aerodynamic effects of wing flexibility may be most evident during maneuvers when these bilaterally paired locomotor appendages are activated asymmetrically. Much aeronautical attention has recently been focused on the construction of miniature flying machines, also known as microair vehicles. Can humans emulate technologically the elegance of a hovering hummingbird or the miniaturized maneuverability of a fruit fly? Wing flexibility, opposite wing interference, and the use of four rather than two wings (as characterizes the highly maneuverable dragonflies) (*10*) all potentially influence the magnitude of such unsteady force-producing mechanisms as rotational circulation and wake capture. Given this informative demonstration of the "robotic fly" for low–Reynolds number aerodynamics, the skies are now clear for functional evaluation of the wonderfully numerous evolutionary variants in insect design.

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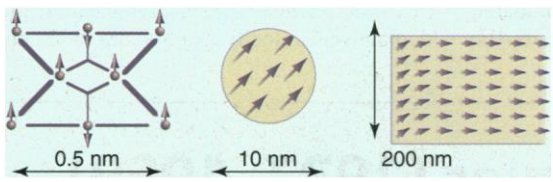
PERSPECTIVES: MAGNETISM

Small Is Beautiful

André Thiaville and Jacques Miltat

Much effort is currently being devoted to the study of magnetic samples with at least two dimensions smaller than a micrometer (*1*–*3*). Many different approaches have been applied to the fabrication of such small magnetic entities, such as ultrahigh vacuum growth on carefully prepared surfaces, electrochemical growth on patterned substrates, and chemistry in nanosized vesicles. The motivation for this research is fundamental as well as applied. Fabrication and characterization tools can now achieve system sizes that allow testing and refinement of theoretical models. It is also important to understand the effects of reduced dimensions on future magnetic recording media.



All lined up. Three systems representing magnetism in reduced dimensions: **(left)** the high-spin complex Fe8, in which only the iron atoms and their oxygen bridges have been drawn, **(middle)** a single-domain magnetic nanoparticle, and **(right)** the edge of a soft element of nickel with a thickness of 30 nm.

Bulk magnetism is conventionally described by a hysteresis cycle, a map of magnetization versus field. Any point inside the cycle is accessible through a suitable field path. This macroscopic behavior results from many individual events that involve the creation and motion of magnetic domain walls or magnetization rotation. When the sample volume is reduced, the number of degrees of freedom also goes down. Classical micromagnetism theory has shown that each degree of freedom extends over a distance similar to the domain wall width. If a sample is smaller in all directions than the size equivalent to one degree of freedom, it falls into a single-domain state: All spins are now coupled (see figure, middle panel). This sample is described by just one magnetization direction, and only a finite number of orientations are allowed at each field, such that the hysteresis cycle becomes almost empty. The first virtue of reducing the sample size is thus simplification.

The drawback is that, until recently, no one could see or measure the magnetic properties of such a single small object. However, recent years have seen the emergence of several techniques—magnetic force microscopy, microscopic superconducting quantum interference devices (microSQUID), and Lorentz force microscopy—that are sensitive enough to detect a single magnetic object of say 10 nm in diameter. In a recent paper, Majetich and Jin (*3*) show that Lorentz microscopy can be used to determine the magnetization direction in nanoparticles as small as 5 nm. MicroSQUID can now measure moments down to 10^4 Bohr magnetons (the moment of a 6-nm iron sphere) (*4*), and developments are under way to improve that figure. Another property specific to nanometric scales is magnetotransport, as an electron keeps its spin orientation over the so-called diffusion length, which can reach tens of nanometers. Giant magnetoresistance and tunnel magnetoresistance are sensitive to the relative magnetization orientation of an electrode with respect to that of the counter electrode. This may enable direct read access to magnetic information (*5*). Moreover, tunneling spectroscopy can probe individual magnetization levels (*6*). Finally, magnetotransport might be the integrating link between the worlds of semiconductors and magnetism, with magnetism supplying the additional spin degree of freedom. Altogether, this palette of investigation tools has confirmed fundamental concepts such as single-domain states, superparamagnetism, and spin polarized tunneling. But new questions have also emerged. For example, nanoparticles of antiferro- or ferrimagnetic materials are prone to develop new magnetic orderings (*7*).

One very fundamental issue is the possible manifestation of a "macroscopic" quantum behavior of the magnetization in these small magnetic objects. Calculations suggest that quantum tunneling through an anisotropy barrier could become dominant over magnetic switching through thermally activated quantum tunneling below ~1 K. Last year, this effect was finally convincingly demonstrated in BaFeTiCo ferrite nanoparticles 10 to 20 nm in diameter below 0.3 K (*8*). A recent experiment (*1*) was performed on still smaller objects, namely high-spin molecular clusters (see figure, left). The well-known Mn_{12} and

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Fe_8 complexes have a total spin $S = 10$. Below a few kelvin, thermal fluctuations cannot overcome the anisotropy barrier on the scale of hours, and quantum physics sets in. Rather than by rotation, magnetization variation proceeds by transitions across the discrete energy levels approximately described by the magnetic quantum number M. In a spectacular manifestation of quantum tunneling, the tunnel splitting between $M = -S$ and $S - n$ (where n is an integer between 0 and S) oscillates as a function of the applied magnetic field, as a result of interference of two tunneling paths connecting the two quantum levels. Moreover, the oscillation phase depended on the parity of n, providing solid proof for a quantum mechanic effect.

Magnetic structures slightly larger than the single domain case are most likely to be used in applications in the near future. Claude Chappert proposed calling such structures that are not single domain but have a limited number of degrees of freedom "coherent spin structures." The entire structure of these samples can be computed with micromagnetic theory and compared with experiments. One example is the prospective basic element for magnetic random access memory (MRAM) (*5*), a rectangle several hundreds of nanometers in lateral size and a few nanometers thick. The material is magnetically soft (no anisotropy) so that the magnetization lies in the element plane, oriented along the long edge with some deviation at the ends (see figure, right panel). An IBM team recently measured the switching of such an element with nanosecond time resolution by magnetotransport measurements (*9*). Comparison was made with the predictions of the Landau-Lifshitz-Gilbert equation, which describes the evolution of the local magnetization and contains a relaxation or damping term. Many mechanisms contribute to this damping, such as magnon excitation and intrinsic damping for asymmetric ions. The Gilbert damping parameter α is therefore often adjusted to experimental values. With some care, it can be extracted from the ferromagnetic resonance (FMR) linewidth, but the bulk FMR value is lower than that extracted from experiments involving an inhomogeneous magnetic structure. For example, Ono *et al.* (*2*) recently measured the domain wall velocity in a 500 nm by 20 nm NiFe wire and extracted $\alpha = 0.6$, which is rather large. Hopefully, structures with reduced dimensions will help us to understand damping better by restricting the available loss channels. Industry also requires that damping be controlled, because MRAM elements should reverse as fast as possible with no overshoot.

All these experiments on high-spin molecules, nanoparticles, or small elements such as wires, are concerned with magnetization relaxation or damping. The many different approaches to magnetism—classical and quantum, continuous and discrete—can guide each other to understand and use magnetism at dimensions that have only recently become accessible to experiments.

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RETROSPECTIVE

Rolf Landauer (1927–1999)

Charles Bennett

Rolf Landauer, noted for his contributions to the theory of electrical conductivity, mesoscopic phenomena, and the physics of information, died of brain cancer on 27 April at age 72.

Born into a German Jewish family in Stuttgart in 1927, he emigrated to the U.S. during the 1930s, received his Ph.D. from Harvard in 1950, and began working for IBM in 1952. During his long career at IBM, he was awarded the American Physical Society's Buckley Prize and the Institute of Electrical and Electronics Engineers' Edison Medal and was elected to the U.S. National Academies of Sciences and Engineering, to the American Academy of Arts and Sciences, and to the European Academy of Science.

Rolf Landauer's work on electrical transport theory has found important applications in almost all areas of mesoscopic physics. In a pioneering paper in 1957 and subsequent contributions, he arrived at a simple and elegant formulation for electrical conductance in terms of scattering. His observation that elastic scattering does not break the coherence of quantum mechanical wave functions led to the idea of normal persistent currents. The Landauer approach now stands along with the Kubo formula as one of the most powerful ways to understand conduction.

During the 1960s, as director of IBM Research's Solid State Sciences Division, Rolf Landauer oversaw the development of the injection laser and promoted large-scale integration, before returning to full-time research in 1969.

Landauer did more than anyone else to establish the physics of information processing as a serious subject for scientific inquiry. This achievement grew out of his deep conviction that "information is physical." He had little use for purely mathematical ideas that could not be given an operational meaning or physical embodiment. This passion led him to pursue the thermodynamics of information and to eventually overturn the long-held belief that each elementary information-processing act requires an expenditure of work at least as great as the mean thermal energy. In his landmark 1961 and subsequent papers, Landauer established that this is true only for operations like erasure that cannot be undone, whereas other operations have no intrinsic, irreducible thermodynamic cost. This discovery led to the theory of reversible computers and communication channels, as well as our modern understanding of Maxwell's Demon, whose obedience to the Second Law of Thermodynamics is enforced by what is now called Landauer's principle, the thermodynamic cost of forgetting.

Landauer was critical of portraying each new physical phenomenon as "tomorrow's revolutionary computer technology." Recently, he doubted whether quantum computers could ever be made stable enough for their promised advantages to materialize. Advocates of quantum computation responded with ingenious error correction, eventually earning his grudging respect.

But he was no simplistic opponent of scientific fashion. Recently, he contrasted the narrowness of many recent sessions on quantum mechanical entanglement, with the diversity of the first conference seriously addressing the fundamental physics of computation, held at MIT in 1981: "The narrowing represents real progress; we now understand more about what counts." But, at the same time, the narrowing strengthens fashionability in science. A carefully selected group reinforces its existing values, and declares to science journalists that their stuff is what really counts. I hope that quantum information can receive the attention it deserves, without eclipsing [...] other questions."

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