The magnetic landscape

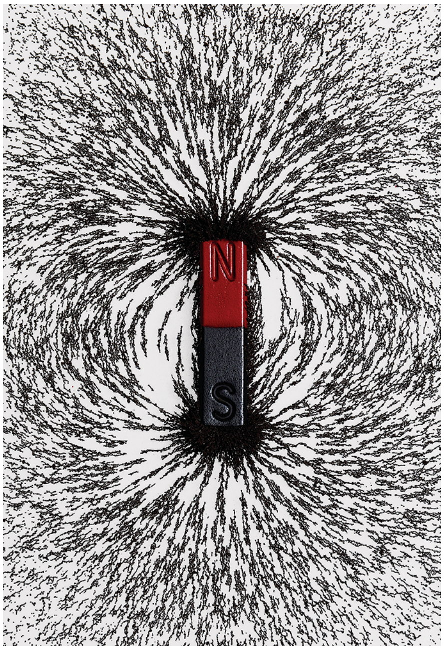
Synergy between materials and methods is helping to address open questions in magnetism and superconductivity.

The magnetic periodic table is lackluster. Only some elements, a handful of 3*d* transition metals, order magnetically at room temperature[1]. Things become more interesting when we synthesize multinary compounds out of 3*d* or 4*f* elements, which enable the formation of a range of magnetically ordered systems. The control of their magnetic properties, for example by electrical current or chemical doping, forms the basis of inquiries into diverse fields from spintronics to high-temperature superconductivity and critical phase transitions[2].

Magnetic order is switched on when the symmetric Heisenberg magnetic exchange interactions dominate the tendency towards thermal disorder, and these interactions strongly depend on the bonding geometry. In fact, different magnetically ordered ground states such as ferromagnetism or antiferromagnetism can appear if the bonding angles are changed. Magnetic ordering further depends on lattice symmetry. The breaking of inversion symmetry allows for an antisymmetric Dzyaloshinskii–Moriya (DM) interaction that enables spiral-like magnetic structures. As such, the ground states of magnetic materials are not only dependent on the constituent atoms, but also sensitive to the geometry of the lattice.

Advances in the synthesis of magnetic materials, spanning thin films grown by epitaxy to crystals grown in image furnaces, offers new opportunities to modify the underlying lattice. Equally as important is the development of sensitive tools to probe the magnetic order and its fluctuations, from wave and particle probes to magnetotransport and magnetometry. In this issue of *Nature Materials* we bring together several research articles and a Comment that draw from a wide range of materials and methods to drive forward inquiry into magnetism and its many sub-fields, which are of both fundamental and applied interest.

The DM interaction allows for the formation of topologically protected magnetic objects on the length scale of tens of nanometres, known as skyrmions, which are promising for future information technologies. Two independent research teams led by researchers from the UK and Germany show in this issue that the DM interaction can extend through many layers of atoms. Both investigations utilized synthetic antiferromagnetic films prepared by sputtering, where the sign of the exchange interaction can be tuned by the thickness of the non-magnetic spacer layer. These teams turned to the magneto-optical Kerr effect, where the polarization of reflected light depends sensitively on the magnetic state of the material, to tease out the details of this interaction. While the DM interaction in these works is of interfacial origin, Teruo Ono and colleagues consider how a DM interaction can be realized in a bulk material. They utilize a similar synthetic and analytic toolset to prepare an amorphous ferrimagnetic material with a chemical composition gradient that induces inversion symmetry breaking throughout the sample and leads to a bulk DM interaction. As noted in a related News & Views, these long-range and bulk DM magnetic interactions could be utilized in the design of functional magnetic devices.



Iron filings following the magnetic field lines of a bar magnet. Credit: Alchemy/Alamy Stock Photo

The established framework of magnetic exchange interactions may not be enough to explain d^0 magnetism occurring in certain oxides that do not contain *d*-electrons. In these materials, evidence for high-temperature magnetic ordering in the absence of magnetic cations with *d*- or *f*-electrons has defied explanation for quite some time. In a Comment, Michael Coey outlines two hypotheses to explain d^0 magnetism, both based on electrons associated with oxygen vacancies. One hypothesis is high-temperature spin ferromagnetism in a narrow defect-related conduction band; the other is collective orbital paramagnetism in response to zero-point fluctuations of the electromagnetic field. He highlights a few examples of such d^0 magnetism and charts a way forward, emphasizing the necessity to study tunable uncontaminated samples over diverse length scales under controlled conditions, and suggesting that advanced magneto-optical probes may again provide insight here. At the same time, he calls for more complete electronic structure calculations that include defects, adsorbates and spin–orbit coupling to distinguish between these two hypotheses.

High-temperature superconductivity — characterized by the expulsion of magnetic fields and the zero resistance flow of current — based on copper oxides or iron pnictides emerges when long-range magnetic order is suppressed. However, short-range magnetic fluctuations persist and the superconducting pairing mechanism is thought to rely on these magnetic fluctuations. In an Article, the nematicity of such magnetic fluctuations in the iron chalcogenide superconductor FeSe is addressed. This work utilized powerful international neutron user facilities to study a mosaic of detwinned single crystals grown by chemical-vapour transport. The elucidation of the anisotropy of the low-energy spin fluctuations in FeSe above and below the superconducting transition temperature feeds into theories on the role of electronic correlations for high-temperature superconductivity, of interest for many everyday applications.

The conditions under which long- and short-range magnetic order arises, the interactions governing its occurrence, how to control its orientation and domains, and the knock-on consequences of magnetic interactions are key questions for condensed matter physicists. Addressing these questions requires ever more finely tuned materials and probes. We thoroughly look forward to covering new developments in magnetism in future issues of *Nature Materials*. ❐

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References

1. Quarterman, P. et al. *Nat. Commun.* **9**, 2058 (2018).
2. Collins, M. F. *Magnetic Critical Scattering* (Oxford Univ. Press, 1989).