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Three-dimensional nanomagnetism

Amalio Fernández-Pacheco1, Robert Streubel2, Olivier Fruchart3, Riccardo Hertel4, Peter Fischer2,5 & Russell P. Cowburn1

Magnetic nanostructures are being developed for use in many aspects of our daily life, spanning areas such as data storage, sensing and biomedicine. Whereas patterned nanomagnets are traditionally two-dimensional planar structures, recent work is expanding nanomagnetism into three dimensions; a move triggered by the advance of unconventional synthesis methods and the discovery of new magnetic effects. In three-dimensional nanomagnets more complex magnetic configurations become possible, many with unprecedented properties. Here we review the creation of these structures and their implications for the emergence of new physics, the development of instrumentation and computational methods, and exploitation in numerous applications.

Nanomagnetism, the scientific field dedicated to the study of nanoscale magnetic objects, has undergone an explosion of activity over the last few decades, driven by fascinating discoveries such as the interaction of magnetization with spin currents (the area of spintronics)1,2 and a wide range of real-world applications3–7. For example, since both the storage and sensing parts of hard disk drives use nanomagnetic structures, the development of nanomagnetism has been a key factor in the vast recent improvements in computer performance and the development of cloud computing. With the exception of some self-assembled systems8,9, nanomagnetism has been mostly confined to two dimensions. In two-dimensional (2D) patterned planar single- or multi-layered magnetic structures, the thickness is of the order of some characteristic magnetic length-scale. This simple geometry leads to monodomain magnetic states in the vertical direction, restricting functionality to the substrate plane (Fig. 1b). In these cases, complex and useful magnetic behaviour is nevertheless possible by exploiting interfacial effects between layers.

The maturity now reached in this field10, together with the need for low energy technologies with new functionalities11 and the advent of advanced chemical and self-assembly synthesis techniques capable of growing non-planar nano-objects, make the expansion of nanomagnetism into three dimensions possible (Fig. 1a). In this new paradigm, spin configurations and capabilities extend not only in the plane but also into the vertical direction, and more complex, hierarchical systems leading to new effects can be designed. In this article, we review the state-of-the-art of three-dimensional (3D) nanomagnetism: the new physics associated with different types of 3D magnetic nanostructures, the most promising synthesis and

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Magnetic multi-layered element with perpendicular anisotropy. Nanostrip with protrusions for DW trapping. Bi-layered magnet with AF coupling due to indirect exchange via an interlayer (not shown for clarity).

...additional degrees of freedom in 3D nanomagnets leads to the emergence of new physical phenomena, which may find applications in multiple areas. Examples of 3D nanomagnets, from left to right: magnetic sphere with vortex configuration. Magnetic thin film element with a skyrmion. Symmetry breaking is caused by bulk or interfacial Dzyaloshinskii-Moriya interaction. Möbius strip with perpendicular magnetization; a DW is present in the ground state due to the object’s topology. Cylindrical NW with modulated diameter, with different magnetic configurations depending on the diameter. Antiferromagnetic (AF) superlattice (interlayers not shown for clarity) with a wide soliton in the middle. Examples of 2D nanomagnets, from left to right: Single-domain magnet. Magnetic multi-layered element with perpendicular anisotropy. Nanostrip with protrusions for DW trapping. Bi-layered magnet with AF coupling due to indirect exchange via an interlayer (not shown for clarity).

Figure 1 | Towards three-dimensional nanomagnetism. Schematic view comparing some examples of geometries and magnetic configurations (indicated by blue arrows) for (a) 3D and (b) 2D nanomagnetism. The dependence of the magnetization $M$ on spatial coordinates (black arrows) is indicated for both cases. New synthesis, characterization and computational methods have the potential to make the leap to 3D. The combination of more complex magnetic states and additional degrees of freedom in 3D nanomagnets leads to the emergence of new physical phenomena, which may find applications in multiple areas. (a) Examples of 3D nanomagnets, from left to right: magnetic sphere with vortex configuration. Magnetic thin film element with a skyrmion. Symmetry breaking is caused by bulk or interfacial Dzyaloshinskii-Moriya interaction. Möbius strip with perpendicular magnetization; a DW is present in the ground state due to the object’s topology. Cylindrical NW with modulated diameter, with different magnetic configurations depending on the diameter. Antiferromagnetic (AF) superlattice (interlayers not shown for clarity) with a wide soliton in the middle. (b) Examples of 2D nanomagnets, from left to right: Single-domain magnet. Magnetic multi-layered element with perpendicular anisotropy. Nanostrip with protrusions for DW trapping. Bi-layered magnet with AF coupling due to indirect exchange via an interlayer (not shown for clarity).

characterization techniques available to create (Box 1) and probe (Box 2 and Box 3) these systems, and the latest advances in computational methods for their modelling (Box 4). We also highlight some of the major challenges still associated with these studies, and the great potential of this field to impact areas such as sensing, data storage, nanoelectronics, the Internet-of-Things and medical biology.

Emerging physics of 3D nanomagnetism

New types of domain walls. The extension of 2D nanostructures into the 3D world brings with it the emergence of unconventional spin textures, where novel physical effects comprising geometry, topology and chirality are involved. A paradigmatic example regards domain walls (DWs) in magnetic nanowires (NWs). NWs are subject to extensive investigation in nanomagnetism because of their potential use as DW conduits for memory and sensing applications. Considering in detail NWs formed by soft magnetic materials, magnetization tends to be aligned parallel to their long direction, due to shape anisotropy. In this case, DWs are of either head-to-head or tail-to-tail type, holding a magnetostatic charge $2SM_z$ (with $S$ the NW section and $M_z$ the spontaneous magnetization of the material), irrespective of the spin texture within the wall. This gives rise to magnetostatic energy, such that competition with exchange determines a complex panorama of DW types, in a manner depending on dimensionality and strip size. The size is compared with the characteristic dipolar exchange length $\lambda_d = (2A/\mu_0M_s^2)^{1/2}$ (ref. 15), where $A$ is the exchange stiffness of the material. We first describe their static features, before highlighting some peculiar aspects of their dynamics.

2D NWs (from now on denoted nanostrips to distinguish them from their 3D counterparts) have been widely studied in theory, simulation and experiments, because of their ease of fabrication and integration into devices. These are patterned with standard top-down lithography methods from thin films, having widths much larger than $\lambda_d$ and thicknesses comparable or not much larger than a few times this length. Thus, any significant variation of magnetization across thickness is prohibitive expensive energetically, such that magnetization textures can be faithfully described by a 2D field of a 3D magnetization vector $M(x,y,z)$. For those nanostrips with moderate widths, significant variation of magnetization across the nanostrip would also be energetically unfavourable. Therefore, such DWs may be described using a 1D model by $M(y)$, where magnetization in the core of the wall is aligned transverse to the strip long axis; this is the so-called transverse DW (TDW, see Fig. 2a). Obviously, the transverse component imparts additional dipolar energy due to the edge charges that are created. For sufficiently wider strips, this energy can be reduced by the emergence of a different type of magnetic boundary, the vortex DW (VDW): here, magnetization becomes more parallel to the strip edge by curling around a vortex with core perpendicular to its surface (Fig. 2a). These two types of DWs share a large metastability region in the phase space, consisting of thickness ($t$) versus width ($w$), around an iso-energy line, determined by simulations as $t \approx 61.\lambda_d^2$.

To extend this already well understood phase diagram (see dashed region in Fig. 2b) to an arbitrary cross-section, the thickness of a nanostrip can be progressively increased towards a NW of square cross-section. DWs initially transverse and vortex in nature end up in magnetization textures with a tube of magnetization going through the wire along a transverse direction, $x$ and $z$ respectively. Remarkably, these two types of walls, characterized now by a full 3D magnetization field $M(x,y,z)$, are identical upon rotation by $\pi/2$ around the wire axis. For large lateral wire dimensions, they display simultaneously transverse and vortex characteristics. They may, therefore, be denoted transverse-vortex domain walls (TVDWs)\textsuperscript{15}, whereas the denotation of either transverse or vortex is sufficient in nanostrips (or $\pi/2$-rotated: very narrow and thick NWs), where one of these features is largely dominant (Fig. 2a). Being able to transform from one to the other using only continuous transformations from the flat nanostrips reveals that they share the same topology. This topological equivalence remains valid for any NW cross-sectional shape, for instance either square or circular.

Until now in our discussion, 3D NWs were considered as if the 2D DW magnetization was simply extruded along the third direction. However, considering 3D NWs from the start allows for the emergence of novel spin textures. The DWs so far described display two areas where magnetization is perpendicular to the wire surface: the entry and outlet points of the vortex core.
Since magnetization pointing perpendicular to a surface implies an increase in magnetostatic energy, DW configurations with a more efficient magnetic flux closure (that is, with magnetization mostly parallel to the wire surface at any point) should be expected. Such a texture is possible for cylindrical symmetry, leading to a curling of the magnetization parallel to the wire axis. For a solid cylindrical NW, and with these boundary conditions, the continuity of a vector field of uniform magnitude becomes impossible. Hence, there must exist one point where \( M \) cancels, that is, a local singularity where ferromagnetism is quenched. This very peculiar object, called a Bloch point, was theorised decades ago, based on similar external boundary conditions in bubble media. It refers to a micromagnetic object of zero thickness (0D); it is the counterpart of Bloch walls as 2D objects and is impossible. Hence, there must exist one point where the continuity of a vector field of uniform magnitude becomes impossible. This very peculiar object, called a Bloch point, was theorised decades ago, based on similar external boundary conditions in bubble media.

**Three main routes for synthesizing 3D nanomagnets.** (a) A buckyball made by two-photon optical lithography, with cobalt sputtered on top. Reprinted with permission from ref. 125. Copyright (2015) by the American Physical Society. (b) Cylindrical NWs electrodeposited from a CoSO\(_4\) electrolyte on alumina templates (see inset). Reproduced from ref. 136 with the permission of AIP Publishing. (c) A nano-spiral created by 3D nano-printing using Co\(_2\)(CO)\(_8\). Adapted from ref. 154, Nature Publishing Group.

The above description of DWs in NWs illustrates characteristics of 3D spin textures displayed by other non-planar nanomagnetic objects. For instance, nanotubes (NTs) exhibit a rather similar phenomenology, with just qualitative differences of the iso-energy lines, and notably with the absence of the Bloch points seen in the case of DWs with an axial vortex. The ends of elongated objects are also worthy of consideration, as they constitute the loci of nucleation for magnetization reversal. With the same physics (magnetostatics versus exchange) at play, these loci display end states called ‘C’ or curling, which may be viewed as a fraction of a TDW or BPDW, respectively.

Additionally, unlike planar surfaces, curved surfaces lack space inversion symmetry. This can be the source of remarkable effects.
Magnetic characterization techniques at the nanoscale have been mostly developed for and are suitable to probe planar systems. Their extension to the study of 3D nanomagnets, presenting complex vectorial spin textures and geometries is far from trivial, and requires new methodologies and multi-technique approaches. In particular, magnetometry techniques able to probe single planar nanostructures has been an essential factor for the progress of nanomagnetism in recent years. These studies have been extended to 3D for the simplest geometries, such as NWs and NTs, following an intermediate micromanipulation step, which places them flat at a particular position on a substrate. Using this approach, the switching field angular dependence of cylindrical NWs has been measured, to determine the mechanism behind magnetization reversal. This has been done by detecting the emanating magnetic flux using nano-SQUID and their magneto-optical response using Kerr effect. Analogously, dynamic-cantilever magnetometry has been employed in nano-NWs and NTs glued at the edge of a cantilever, detecting the frequency shift of oscillation caused by the magnetic torque under external fields. Switching probability measurements also allow a method to probe the thermally activated nature of the switching process. For the advance of the area, new magnetometry methods for measurements of as grown 3D suspended nanostructures, which do not require such complicated micromanipulation intermediate steps are desired. This has been recently reported using magneto-optical Kerr effect, where the switching fields of 100 nm-diameter, several μm-long cobalt NWs grown tilted with respect to the substrate were measured. The NW angle creates a projection on the substrate of the order of the laser diameter (5 μm), making the magneto-optical signal measurable.

A traditional way to probe magnetism in relatively large volumes consists of using neutron scattering techniques. To address this phenomenon of curvature-induced DMI, a 3D theory has recently been proposed, consisting of reducing the existing exchange interaction into scalar Heisenberg exchange and thereby give rise to the Spin-Cherenkov Effect. For instance, polarized neutron reflectivity has been used to determine the magnetic state of superlattices during soliton propagation, and small-angle scattering has revealed the formation of skyrmion lattices in non-centrosymmetric bulk crystals. Recently developed neutron tomography methods enable the vectorial reconstruction of magnetic domains with resolution of ~100 μm. In the case of spatially localized 3D objects, magnetic arrays such as wires and nanoparticles can be investigated in a small-angle scattering geometry. However, the analysis soon reaches its limits when many parameters contribute to the recorded signal, such as distributions, imperfect texturing or correlations. A powerful approach consists of probing a highly ordered array of textured objects, where the scattering pattern can be analysed in a similar way as crystallography makes use of the reciprocal space, to extract detailed information of the structure of the lattice cell.

Magnetometry measurements on 3D cylindrical NWs. In (a), the wire is placed on top of a nano-SQUID using a micromanipulator. Scale bar, 1 μm. Reprinted with permission from ref. 162. Copyright (1996) by the American Physical Society. In (b), the magnetic switching of free-standing NWs forming 45° with the substrate plane is detected using spatially resolved magneto-optical Kerr effect. Additional sources of noise result from the mechanical motion via vibrations and coupling with the external field, and the large amount of diffusive scattering produced by a non-planar surface. Figure taken from ref. 154, Nature Publishing Group.

For instance, micromagnetic simulations have shown that the surface curvature in cylindrical NTs and NWs can give rise to a chiral symmetry breaking that results in different properties, depending on the rotation sense of the magnetization. This effect resembles the Dzyaloshinskii–Moriya interaction (DMI). To address this phenomenon of curvature-induced DMI, a 3D theory has recently been proposed, consisting of reducing magnetostatic effects to an effective anisotropy. Under this assumption, curvature and torsion in NWs and shells split up the existing exchange interaction into scalar Heisenberg exchange and two effective magnetic interactions, namely curvature-induced effective anisotropy (magnetization patternning) and curvature-induced effective DMI (chirality selection). Systematic studies of magnetic NTs have proven the existence of an exchange energy that manifests as an effective easy-axis anisotropy along the tube axis, which induce a gap in the dispersion relation of magnonic spin excitations in NTs. Remarkably, the strength of the curvature-induced chiral effects could be tuned mechanically by bending flexible magnetic nanomembranes, thereby providing a new method to manipulate magnetic properties at the nanoscale.

Dynamic effects. Dynamic magnetic properties may also differ significantly between 2D and 3D nanomagnets, as recently demonstrated in the case of DW propagation and NWs. The dynamic motion of DWs in NWs is of paramount importance for their exploitation in applications. This has led to a large amount of works in nanostrips in the last years, where a complex scenario including several regimes of DW propagation, can be observed. In particular, DWs under external fields usually become unstable when propagating above a critical speed, an effect called Walker breakdown. This effect originates from a torque exerted by the driving field on the DW. If this torque is sufficiently strong, the wall magnetic structure changes significantly in a periodic fashion, causing the motion to become oscillatory, as described by the Landau–Lifshitz–Gilbert equation. Recent studies using micromagnetic simulations carried out in cylindrical NWs and NTs, reveal that DWs with an axial vortex configuration can propagate smoothly at very high speed (~1 km s⁻¹) when driven by an external magnetic field, overcoming the Walker breakdown. Axial VDWs in NTs and NWs can surpass this limit due to the radial component of the magnetization, caused by magnetostatic field distributions. This stability against the Walker breakdown in NTs and cylindrical NWs, described by micromagnetics, can also be understood in the context of the aforementioned chiral break of symmetry due to the surface curvature. The effective dynamic-DMI counteracts this torque and thereby preserves the magnetic structure of the DW, even at large fields. Since this is a chiral effect, only one of the two possible vortex configurations of the DW is stabilised. These ultra-stable DWs can even reach the phase velocity of spin waves and thereby give rise to the Spin-Cherenkov Effect (Fig. 2c,d). This effect describes the spontaneous emission of spin waves
BOX 3 | MAGNETIC MICROSCOPY IN 3D.

Imaging 3D magnetic textures requires techniques with nanoscale spatial resolution, quantitative information and sensitivity to the vector character of the spin. Transmission electron microscopies (TEM) and X-ray microscopies (XM) are currently the techniques most suitable for these studies. Magnetic lateral spatial resolution ranges from tens of nm for XM, down to sub-10 nm for TEM. Recent advances in Lorentz lens aberration corrections have enabled magnetic imaging at zero field down to 0.5 nm (ref. 174). XM has some other advantages, such as the straightforward application of electromagnetic fields, and the possibility to perform time-resolved experiments exploiting the temporal structure of pulsed X-ray sources.

TEM and XM are sensitive to either the projection of the magnetic induction vector \( \mathbf{B} \) onto the plane perpendicular to the electron path (TEM), or to the component of the magnetization \( \mathbf{M} \) along the photon direction (XM). The standard methodology to investigate 3D magnetic textures thus consists of comparing the information of a 2D projection for a given angle, with the one obtained by micromagnetic simulations. For instance, the magnetic configuration of a skyrmion lattice in FeCoSi and FeGe thin films has been determined using Lorentz TEM\(^{175,176}\). Using off-axis Electron Holography, multi-layered NWs reveal different magnetic configurations depending on their microstructure and composition\(^{174}\). Also, remanent states of Ni cylindrical NWs\(^{223}\) and multi-layered Co/Ni NWs\(^{177}\) give experimental evidence of some of the types of DWs discussed in the main text.

The increasing demand on 3D imaging techniques is leading to novel concepts that go beyond the aforementioned approach, by extending nano-tomography of scalar quantities\(^{178}\) to magnetic investigations. By rotating the stage along an axis and acquiring 2D projections of \( \mathbf{B} \) at several angles, both chirality and core orientation of vortices in magnetic disks have been determined\(^{179}\), and the magnetic structure of NWs and nano-spirals has been imaged\(^{180-182}\). Whereas in special symmetries full vector-field tomographic reconstructions of \( \mathbf{B} \) is feasible by one simple projection\(^{183}\), in general projection series need to be recorded while rotating the sample about at least two axes. This has been applied to reconstruct the vectorial magnetic configuration of Permalloy squares\(^{184}\) and of magnetic vortices in two stacked disks\(^{185}\).

In the realm of XMs, new 3D imaging methodologies have been reported so far for transmission-X-ray photoemission electron microscopy (XPEEM)\(^{128,186}\), ptychography\(^{125}\) and magnetic X-ray tomography (MXT)\(^{187}\). In XPEEM, the 3D magnetic configuration of core-shell NWs has been visualized, by collecting both secondary photoelectrons emanating from the NW surface (conventional XPEEM) and from the substrate (XMCD shadow contrast)\(^{186}\). This same method has been employed to prove the existence of Bloch point DWs\(^{44}\) and to image magnetization reversal processes in buried layers of magnetic nanomembranes\(^{188}\). First demonstrations of MXT vectorial tomography have been recently obtained for 3D nanomembranes\(^{187}\) and films with canted magnetization\(^{189}\).

Magnetic vectorial tomography using electron and X-ray methods. (a) Reconstructed 3D magnetic vectorial potential (red arrows) of a Permalloy square using Lorentz electron microscopy. Reprinted with permission from ref. 184. Copyright (2010) by the American Physical Society. (b) Perspective SEM view of a standing rolled-up nickel nanomembrane overlaid with XMCD shadow contrasts recorded at various projection angles from the planar substrate using XPEEM. Scale bar, 5 \( \mu \text{m} \). Adapted from ref. 187, Nature Publishing Group.

3D spin textures. 3D magnetic spin textures with non-trivial topological charges (vortices, skyrmions and chiral bubbles) possess an exceptional stability under external perturbations against transitions into trivial states, for example, to collinear magnetization. Enhanced stability, particle-like properties and high susceptibility to electric, spin and heat currents, and magnonic excitations have put these chiral structures into the spotlight of fundamental sciences, as well as application-oriented research. A paradigmatic 3D spin texture is the magnetic vortex with its nanometric core magnetization (Fig. 3a). Experimentally observed for the first time almost two decades ago\(^{41}\), it is typically present in patterned thin films formed by soft magnetic materials. The spin structure is defined by both in-plane magnetic circulation and out-of-plane core polarity, with the core expanding laterally \( \sim 10 \text{ nm} \)\(^{42}\), as set by \( A_4 \). This strong confinement has allowed the quantification of pinning site potentials in thin films by probing Barkhausen noise\(^{43}\), generate nano- and micro-oscillators with tuneable frequency\(^{44}\) and design of magnetic vortex memories\(^{45}\).

While the chirality of vortices (defined as the product of circulation and core polarity) and other objects such as Bloch points is intrinsically degenerate in common 2D nanomagnets, 3D geometries with inherent new types of interactions can break this symmetry. As mentioned above, this is the case of 3D curved nanomagnets, which reveal a chirality selection due to curvature-driven DMI\(^{46}\). Similarly, heterostructures formed by ultrathin magnetic thin films and heavy-element materials with large spin–orbit coupling, result in interfacial antisymmetric spin couplings due to spin-polarized scattering from conduction electrons in the heavy-element layer. This antisymmetric
Micromagnetic simulations, rooted in a rigorous implementation of the fundamental equations of the theory of nanomagnetism, describe the spatial and temporal evolution of the continuous vector field of the magnetization and of the magnetostatic field, and can incorporate spin-torque effects. This powerful computational framework has provided a deep understanding of experimental observations and promoted research toward new effects.

The experimental realization of 3D magnetic nanostructures necessitates micromagnetic investigations at a large scale. Progress in computer hardware and code development has made it possible to simulate micron-sized samples with an ordinary desktop computer. Owing to enhanced numerical methods and massively parallel computations, the upper limit in size is no longer a critical issue. Similarly, memory limits, which used to be hit easily several years ago, no longer represent a serious concern. Today, micromagnetic modelling requires high-performance computing for other reasons, such as the simulation of large arrays of interacting nanomagnets or hybrid atomistic-continuum simulations. Programmable Graphical Processing Units (GPUs) represent an impressively powerful approach to high-performance computing for these purposes. In the past years, GPU-based personal supercomputing has outpaced the use of traditional large-scale supercomputing facilities, since they are inexpensive and require much less energy. As a result, post-processing, visualization and storage of huge amounts of simulated data have emerged as new challenges.

Another important point is which of the two possible branches, either finite difference methods (FDM) or finite element methods (FEM), are employed. FEM can model arbitrary shapes with high accuracy, making it more suitable for simulating complex 3D shapes, especially if curved surfaces are involved. On the other hand, FDM generally has higher speed for calculating magnetization dynamics and is easier to use and implement. In the past, the regular grid required by FDM (allowing for the use of Fast-Fourier Transform methods for the calculation of magnetostatic fields) allowed for shorter computational times and lower memory requirements. However, current matrix compression schemes employed now by FEM have largely removed these differences. Still, owing to the regular discretization grid of the FDM, the time integration of the Landau–Lifshitz–Gilbert is generally less critical than in FEM, which allows for larger time steps and thus faster integration.

Although micromagnetic simulations studies of 3D structures have proven to be generally very reliable, the continuum theory behind these algorithms ceases to be valid in certain cases. Strongly inhomogeneous magnetic structures, laser-induced magnetization dynamics, and sample sizes approaching the atomic limit call for extensions to the standard approach. In such cases, atomistic magnetic models can be introduced. These models may either replace a micromagnetic code, or complement it in the form of a hybrid model where atomistic magnetic moments are coupled to a surrounding continuum.

Multiscale micromagnetic and atomistic models. The magnetic sphere combines both models to simulate the structure and dynamics of Bloch points. The central blue and outer orange areas correspond to the space where either a purely atomistic or a purely micromagnetic model is used to calculate the exchange interaction between spins, with the green area in between as the interface between both. Reprinted with permission from ref. 39.

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skyrmion lattice that exists for temperatures up to 30 K and magnetic fields up to 9 T. The stabilization of skyrmions at room temperature has been achieved by increasing the film thickness of the transition metal, providing interlayer exchange interaction, and engineering asymmetric multilayer stacks with distinct heavy-element films for additive IDMI at top and bottom interfaces of the magnetic layer. The corresponding skyrmion core/bubble size at room temperature is on the order of 10–100 nm, and hence 10–100 times larger than those in Fe/Ir(111).

Owing to their small size, highly non-collinear spin texture and topological protection, they can act as localized mobile data for spintronic applications. To write, read and delete these skyrmions/chiral bubbles, several mechanisms have been proposed and some demonstrated. These include spin-transfer/spin–orbit torque via spin-polarized current, magnons, spin Hall effect and electric field-driven magnetoelectric coupling. The potentially low pinning and small scattering cross-section of skyrmions originating from their texture and motion of solitons can be distinguished, as schematically shown in Fig. 3d.

Vertical data motion using magnetic solitons. The extension of magnetic data mobility to the vertical direction has been recently realised by means of magnetic solitons in AF superlattices; this opens a new route to 3D magnetic random access memory devices with out-of-plane functionality. The term soliton refers here to a (topological) kink in a discrete chain of spins, and is equivalent to an AF wall. The idea is analogous to the one employed in Nano-Magnetic Logic, but instead of using soliton motion in dipolar-coupled nanomagnets positioned on the substrate plane, solitons are moved perpendicularly to the substrate plane in magnetic superlattices, where the coupling between magnetic thin films is provided by non-magnetic spacers via AF RKKY interactions. The system can be represented in its simple form by a 1D chain of spins (Fig. 3d), following a macrospin approximation, where layer thickness, anisotropy and surface coupling energies rule the physics of the system. Depending on the ratio between RKKY coupling and anisotropy fields, three regimes regarding magnetic texture and motion of solitons can be distinguished, as schematically shown in Fig. 3d.

For high RKKY couplings, solitons are wide, comprising a large number of layers, with those spins forming the soliton deviating a great amount from the anisotropy direction. In systems with very high coupling/anisotropy ratios, the rotation results in helical spin structures. For soliton nucleation, the surface-spin flop transition can be exploited, and reliable unidirectional propagation can be achieved by creating asymmetric superlattices, where thickness and anisotropy of a gate edge layer is tuned differently from the others. Following this approach, asynchronous motion under external magnetic fields using gates formed by single and highly coupled multiple layers has been
achieved. As RKKY coupling decreases, becoming comparable to anisotropy, solitons get narrower, acquiring a well-defined magnetic moment. Interestingly, macrospin and micromagnetic simulations predict how in this case, external rotating magnetic fields can couple to the soliton magnetic configuration, resulting in synchronous propagation with the field, where the direction of motion is defined by the soliton chirality and sense of rotation of the field. This could be exploited to create bi-directional multi-bit vertical shift registers.

Moreover, in spite of losing their chirality, synchronous motion is also possible for sharp solitons (when anisotropy becomes much larger than coupling). This has been realised under external oscillating magnetic fields, in Ising systems with strong perpendicular magnetic anisotropy, where the intrinsic layer coercivity \(H_u\) substitutes \(H_{an}\) as relevant parameter for operation. By carefully engineering the thickness of the layers and the exchange coupling between them, it is possible to break inversion symmetry, which induces a unidirectional ratchet action. Figure 3e shows schematically the structure of a ratchet superlattice, where layer thickness and interlayer RKKY coupling oscillate periodically between two possible values. Such a scheme makes possible the synchronous propagation of a soliton with perpendicular oscillating magnetic field. Remarkably, and following this approach, a unidirectional soliton shift register with vertical functionality equivalent to \(\sim 20\) transistors has been achieved within a thickness of \(2\) nm (ref. 68). Simple logic operations involving soliton–soliton annihilation have been realised as well. Analogous ratchet schemes are possible; for example, a similar behaviour has been achieved by designing a superlattice with same thickness for all magnetic layers, and a combination of AF and ferromagnetic interlayer couplings.

The aforementioned results refer to studies in extended films. Future studies are expected in laterally patterned nanostructures, to investigate the effect of rotating fields and dipolar interactions on the domain formation and soliton operation. The use of different mechanisms for propagation, such as spin-transfer torque, microwave excitations or all optical switching, are also anticipated. Additionally, a new energy storage concept based on the continuous injection of solitons via the rotation of one edge spin in a cork-screw fashion, has been recently proposed.

Future applications of 3D nanomagnetism

**Sensing and actuation.** The use of 3D nanomagnets for sensing and actuation applications has a huge potential in many scientific and technological areas. Some of the novel functionalities foreseen in the field of 3D magnetic nano-sensing are the substantial increase in surface-to-volume ratio with respect to planar systems, their capability to probe vectorial fields, an ad hoc geometrical design to match a sensed structure, and the exploitation of mechanical and thermal effects present in suspended structures which may couple to their magnetic response.

In particular, 3D magnetic nanomembranes (forming part of the large family of emerging flexible devices, for example, electronics displays and solar cells) which are transforming rigid electronics into light and shapeable elements, have already proven to bear great universal potential as flexible magnetic sensors.
Remarkably, their magnetic sensitivity, harnessing giant magnetoresistance or giant magnetoimpedance, is similar (or in some cases more than one order of magnitude larger\textsuperscript{76}) to devices produced on Si wafers, even after demanding manipulations\textsuperscript{4,77}. This is due to the continuity of the magnetization along their closed surface, that is, due to their topology\textsuperscript{78}. These features have stimulated desire for their application in industry as precise and flexible positioning control of magnetic bearings in electric motors\textsuperscript{79}, and as printable sensing paste for simple but versatile magnetic switches (for example, electric postcards\textsuperscript{80}). Further potential applications in life sciences and diagnostics include light, mobile and affordable devices with great spatial localization so as to facilitate magnetoencephalography\textsuperscript{76} for early stage disease detection.

Additionally, 3D nanomagnets could be incorporated as sensors in a new generation of scanning probe microscopy methods for advanced imaging and spectroscopy. In fact, high aspect-ratio NWs have already been employed as ultra-sharp MFM tips, improving magnetic resolution down to 10 nm\textsuperscript{81} and overcoming limitations of standard triangular tips in probing 3D nanostructures\textsuperscript{82}. Furthermore, nano-spheres grown on top of cantilevers have been exploited to perform ferro-magnetic-resonant force microscopy, measuring magnetization dynamics with high spatial resolution\textsuperscript{83}. The development of new tip designs incorporating new geometries and materials can exploit high-order resonant cantilever modes to measure field gradient components along several directions in space\textsuperscript{84}. This and other approaches\textsuperscript{85} could make possible the realization of scanning probe vectorial microscopy: mapping the three components of stray fields emanating from a magnetic system at nanoscale resolution.

Moreover, 3D nanostructures often make very good actuators: their larger volume compared to planar 2D structures increases the torque and force generated by electromagnetic fields and strain. They are often free to deform reversibly, with interest for the NEMS industry, nanoelectronics, sensing, robotics and studies in the quantum regime\textsuperscript{86–90}. In the case of 3D nanomagnets, additionally to standard electrical driving methods, remote magnetic actuation is possible via external magnetic fields\textsuperscript{91}. This can be exploited to create nanomotors in fluids, where chiral helical structures\textsuperscript{92} or Janus particles\textsuperscript{93} have been controllably moved under rotating and oscillating magnetic fields, respectively. We foresee future works exploiting dipolar interactions, integrating different magnetic materials and more complex geometries, incorporating optical and electrical readout methods, and further integration into biological environments.

In particular, 3D nano- and micro-scale mechanical actuators are a key part of the tool-kit of mechano-biology\textsuperscript{94,95}, an emerging field which tries to understand the role of cell and tissue mechanics in diseases. Single 3D magnetic nanostructures subjected to laboratory-scale magnetic fields can generate tens of nanonewton of force locally and controllably to cells. This is sufficient to probe the phenotype of cells\textsuperscript{96}, mechanically induce differentiation of bone stem cells\textsuperscript{97}, burst payload-carrying neural stem cells\textsuperscript{98} and destroy cancer cells\textsuperscript{99}. Additionally, mammals use motile cilia (flagella-like microtubules) beating together to sweep objects through organs (such as removing dirt from the lungs or transporting eggs through female Fallopian tubes). Magnetic NWs could perhaps form artificial cilia\textsuperscript{100}, transporting reagents through on-chip microfluidic channels.

Towards data storage and the Internet-of-Things. 3D magnetic nanostructures could form the basis of a new storage class of non-volatile memories, in which multiple data bits are stored magnetically above a single electronic memory cell on an integrated circuit. This is sustained by the impressive progress on ‘magnetic data mobility’ in the last few years, in which physical effects such as spin-transfer torque\textsuperscript{101,102} allow digital information to be propagated through nanomagnets via magnetic entities such as DWs, skyrmions or solitons. The realization of 3D magnetic memories could be implemented using perhaps the original racetrack architecture\textsuperscript{103}. Alternatively, existing magnetic random access memory technology could be enhanced by increasing the number of data storing magnetic layers in the stack, such that each cell can store a data word instead of a data bit\textsuperscript{104}. In both of these cases, digital shift-register action is an essential ingredient\textsuperscript{68}, allowing data bits in magnetic form to be sequentially pumped into the nanomagnet during writing and then pumped back out during reading. Also, a recent trend in microelectronics is to create 2.5-dimensional devices\textsuperscript{105} by stacking multiple thin substrates on top of each other in a single package, with wire interconnects running between layers. Magnetic NWs could use these ideas to enable 2.5-dimensional spintronic devices (that is, chips which use both electronic and magnetic components), allowing chip designers to connect electronic parts using electrical wires and magnetic parts using magnetic NWs.

Magnetic interconnect is a particularly interesting idea because it can host both magnetic DWs\textsuperscript{106} and magnetic spin waves\textsuperscript{107}. The former would carry digital information in a very compact form but at low speed, while the latter would offer long-range...
transmission. Intriguingly, the magnetic hysteresis and non-linearity present in many magnetic NWs mean that the interconnect is potentially also a memory element and a logic gate\(^ \text{108} \), opening up new computing architectures in which the traditional boundaries between memory, logic and interconnect are eliminated. Such chips could even go beyond conventional Boolean logic and implement neuromorphic computing architectures\(^ \text{109} \) in which 3D networks of magnetic NWs mimic the neurons and synapses in living brains.

However, significant challenges still remain before such applications become reality. In particular, modern microelectronics makes great use of precision interfaces between materials; many of the growth techniques used for 3D structures do not currently offer sufficient purity and control to engineer interfaces with single atomic layer precision. Also, while planar microchips successfully integrate and connect \( 10^8 \) transistors on a single chip, complex interconnectivity in 3D is still to be developed. A human brain may connect up to \( 10^4 \) synapses to each neuron\(^ \text{110} \); there are currently no known 3D fabrication techniques able to achieve this.

The integrated circuits of the future will increasingly incorporate a wider range of technologies onto a single die to form full systems (Fig. 4). The inclusion of physical sensors and energy harvesters into the menu of devices available to designers is particularly important for the Internet-of-Things. 3D magnetic nanostructures may find a role in both of these, where large surface areas, the ability to easily strain, and the possibility of sustaining temperature differentials are often important and difficult to achieve in 2D planar geometries. Recent advances in spin caloritronics\(^ \text{111} \) and multiferroic materials\(^ \text{312} \) will provide the necessary interconversion between the electronic, magnetic and thermal worlds.

**References**

1. Editorial. Memory with a spin. Nat. Nanotechnol. 10, 185–185 (2015).
2. Hoffmann, A. & Bader, S. D. Opportunities at the frontiers of spintronics. Phys. Rev. Appl. 4, 047001 (2015).
3. McCray, W. P. How spintronics went from the lab to the iPod. Nat. Nanotechnol. 4, 2–4 (2009).
4. Melzer, M. et al. Imperceptible magnetoelectronics. Nat. Commun. 6, 6080 (2015).
5. Makarov, D., Melzer, M., Karnasuenko, D. & Schmidt, O. G. Shapeable magnetoelectronics. Appl. Phys. Rev. 3, 011101 (2016).
6. Koh, I. & Josephson, L. Magnetic nanoparticle sensors. Sensors 9, 8130–8145 (2009).
7. Chen, R., Romero, G., Christiansen, M. G., Mohr, A. & Anikeeva, P. Wireless magnetothermal deep brain stimulation. Science 347, 1477–1480 (2015).
8. Faure, B. et al. 2D to 3D crossover of the magnetic properties in ordered arrays of iron oxide nanocrystals. Nanoscale 5, 953–960 (2013).
9. Sun, H. et al. Self-organized honeycomb structures of Mn\(_2\) single-molecule magnets. J. Phys. Chem. B 113, 14674–14680 (2009).
10. Stamps, R. L. et al. The 2014 magnetism roadmap. J. Phys. D Appl. Phys. 47, 333001 (2014).
11. Waldrop, M. M. The chips are down for Moore’s law. Nature 530, 144–147 (2016).
12. Parkin, S. & Yang, S.-H. Memory on the racetrack. Nat. Nanotechnol. 10, 195–198 (2015).
13. Matthies, R., Gläsle, S., Diegel, M. & Hübner, U. Concepts and steps for the realization of a new domain wall based giant magnetoresistance nanowire device: From the available 24 multiturn counter to a 2\(^ \text{12} \) turn counter. J. Appl. Phys. 111, 113920 (2012).
14. Hricak, G., Dean, J. & Allwood, D. A. Nanowire spintronics for storage class memories and logic. Philos. Trans. A Math. Phys. Eng. Sci. 369, 3214–3228 (2011).
15. Jamet, S., Rougemaille, N., Toussaint, J. C. & Fruchart, O. in Magnetic nano- and microwires: design, synthesis, properties and applications (ed. Vazquez, M.) 783–811 (Woodhead, 2015).
16. McMichael, R. D., Eicke, J., Donahue, M. J. & Porter, D. G. Domain wall traps for low-field switching of submicron elements. J. Appl. Phys. 87, 7058–7060 (2000).
17. Arrott, A., Heinrich, B. & Aharoni, A. Point singularities and magnetization reversal in ideally soft ferromagnetic cylinders. IEEE Trans. Magn. 15, 1228–1235 (1979).
This paper demonstrates imaging of the internal structure of domain walls in cylindrical nanowires.

Da Col, S. et al. Observation of Bloch-point domain walls in cylindrical magnetic nanowires. Phys. Rev. B 89, 184045 (2014).

This article reports experimental proof of the existence of Bloch-point domain walls in cylindrical nanowires.

Landeros, P. et al. Reversal modes in magnetic nanotubes. Appl. Phys. Lett. 90, 102501 (2007).

Hertel, R. Curvature-induced magnetochirality. Spin 3, 1340009 (2013).

This work presents a theoretical discussion of magnetochiral effects induced by surface curvature in ferromagnetic systems.

Gaididei, Y., Kravchuk, V. P. & Sheka, D. D. Curvature effects in thin magnetic shells. Phys. Rev. Lett. 112, 257203 (2014).

Sheka, D. D. et al. Curvature effects in statics and dynamics of low-dimensional magnetism. J. Phys. A: Math. Theor. 48, 125202 (2015).

Landeros, P. & Núñez, A. S. Domain wall motion on magnetic nanotubes. J. Appl. Phys. 108, 033917 (2010).

González, A. L., Landeros, P. & Núñez, A. S. Spin wave spectrum of magnetic nanotubes. J. Magn. Magn. Mater. 322, 330–335 (2010).

Streubel, R. et al. Magnetism in curved geometries. J. Phys. D Appl. Phys. 49, 363001 (2016).

A comprehensive topical review of 3D curved magnetic geometries.

Ryu, K.-S., Thomas, L., Yang, S.-H. & Parkin, S. Chiral spin torque at magnetic domain walls. Nat. Nanotechnol. 8, 527–533 (2013).

This article provides an elucidation of the mechanisms behind chiral spin torques in nanostrips made of ultra-thin films.

Ettmayr, S., Bohn, S. M., Martin, E. & Beach, G. S. D. Current-driven dynamics of chiral ferromagnetic domain walls. Nat. Mater. 12, 611–616 (2013).

This article demonstrates chiral spin torque in Neel-type domain walls in nanostrips.

Miron, I. M. et al. Fast current-induced domain-wall motion controlled by the Rashba effect. Nat. Mater. 10, 419–423 (2011).

Schrory, N. L. & Walker, R. L. The motion of 180° domain walls in uniform dc magnetic fields. J. Appl. Phys. 45, 5406–5421 (1974).

Yan, M., Andreas, C., Káoky, A., García-Sánchez, F. & Hertel, R. Fast domain wall dynamics in magnetic nanotubes: suppression of Walker breakdown and Cheremkov-like spin wave emission. Appl. Phys. Lett. 99, 122505 (2011).

This numerical study predicts the Spin-Cherenkov effect in nanotubes.

Yan, M., Andreas, C., Káoky, A., García-Sánchez, F. & Hertel, R. Chiral symmetry breaking and pair-creation mediated Walker breakdown in magnetic nanotubes. Appl. Phys. Lett. 100, 252401 (2012).

Hertel, R. Ultrafast domain wall dynamics in magnetic nanotubes and nanowires. J. Phys. Condens. Matter 28, 483002 (2016).

Andreas, C., Káoky, A. & Hertel, R. Multiscale and multimodel simulation of Bloch-point dynamics. Phys. Rev. B 89, 134403 (2014).

An application of multiscale modelling for the study of 3D spin textures.

Hertel, R. & Andreas, C. In Magnetic Nano- and Microwires. Design, Synthesis, Properties and Applications (ed. Vazquez, M.) 653–677 (Woodhead, 2015).

This paper describes the experimental observation of vortices in dots.

Wachowiak, A. et al. Direct observation of internal spin structure of magnetic vortex cores. Science 298, 577–580 (2002).

Miron, I. M. et al. Quasiparticle magnetization and control of the barkhausen effect. Science 339, 1051–1054 (2013).

Streubel, R., Fischer, P., Kopte, M., Schmidt, O. G. & Markarov, D. Magnetization dynamics of imprinted non-collinear spin textures. Appl. Phys. Lett. 107, 112406 (2015).

Zhu, J.-G., Zheng, Y. & Prinz, G. A. Ultrahigh density vertical magnetic conjugative recursive random access memory (invited). J. Appl. Phys. 87, 6668 (2000).

Plypovskyi, O. V. et al. Coupling of chiralities in spin and physical spaces: the mobius ring as a case study. Phys. Rev. Lett. 114, 197204 (2015).

Zhang, S., Levy, P. & Fort, A. Mechanisms of spin-polarized current-driven magnetization switching. Phys. Rev. Lett. 88, 236601 (2002).

Burgess, J. A. J. et al. Chiral magnetic order at surfaces driven by inversion asymmetry. Nature 447, 190–193 (2007).

Dupé, B. et al. Tailoring magnetic skyrmions in ultra-thin transition metal films. Nat. Commun. 5, 101–103 (2014).

Nembach, H. T., Shaw, J. M., Weiler, M., Jué, E. & Silva, T. J. Linear relation between Heisenberg exchange and interfacial Dzyaloshinski–Moriya interaction in metal films. Nat. Phys. 11, 825–829 (2015).

Chen, G. et al. Tailoring the chirality of magnetic domain walls by interface engineering. Nat. Commun. 4, 2671 (2013).

Wiedenmann, R. et al. Nanoscale magnetic skyrmions in metallic films and multilayers: a new twist for spintronics. Nat. Rev. Mater. 1, 16044 (2016).

Reichhardt, C. et al. Writing and deleting single magnetic skyrmions. Science 341, 636–639 (2013).

Woo, S. et al. Observation of room-temperature magnetic skyrmions and their current-driven dynamics in ultrathin magnetic ferromagnets. Nat. Mater. 15, 501–506 (2016).

This work reports the creation of skyrmions at room temperature, driven by current pulses in magnetic racetracks.

Jiang, W. et al. Blowing magnetic skyrmion bubbles. Science 349, 283–286 (2015).

This article demonstrates injection and motion of skyrmionic bubbles at room temperature.

Hanneken, C. et al. Electrical detection of magnetic skyrmions by tunneling non-collinear magnetoresistance. Nat. Nanotechnol. 10, 1039–1042 (2015).

Seki, S., Yu, X. Z., Ishiwata, S. & Tokura, Y. Observation of skyrmions in a multiferroic material. Science 336, 198–201 (2012).

Hsu, P.-J. et al. Electric field driven switching of individual magnetic skyrmions. Nat. Nanotechnol. 12, 123–126 (2017).

Reichhardt, C. & Reichhardt, J. C. Noise Fluctuations and drive dependence of the skyrmion Hall effect in disordered systems. New J. Phys. 18, 095005 (2016).

Barker, J. & Tretiakov, O. A. Static and dynamical properties of antiferromagnetic skyrmions in the presence of applied current and temperature. Phys. Rev. Lett. 116, 147203 (2016).

Cowburn, R. P. Room temperature magnetic quantum cellular automata. Science 287, 1466–1468 (2000).

This paper shows transport of magnetic information in isolated dots for nanomagnetic logic applications.

Niemier, M. T. et al. Nanomagnet logic: progress toward system-level integration. J. Phys. Condens. Matter 23, 493302 (2011).

Vredenendaal, E. Y. & Altwein, D. Topologically protected magnetic helix for spin-tunneling non-collinear magnetoresistance. Phys. Rev. Lett. 112, 017206 (2014).

te Velthuis, S., Jiang, J., Bader, S. & Felcher, G. Spin flop transition in a finite antiferromagnetic superlattice: evaluation of the magnetic structure. Phys. Rev. Lett. 89, 127203 (2002).

Fernández-Pacheco, A. et al. Controllable nucleation and propagation of topological magnetic solitons in CoFeB/Ru ferrimagnetic superlattices. Phys. Rev. B Condens. Matter Phys. 86, 104422 (2012).

Fernández-Pacheco, A. et al. Magnetic state of multilayered synthetic antiferromagnets during soliton nucleation and propagation for vertical data transfer. Adv. Mater. Interfaces 3, 160097 (2016).

Petit, D., Mansell, R., Fernández-Pacheco, A., Lee, J. H. & Cowburn, R. P. in VLSI: Circuits for Emerging Applications (ed. Wojcicki, T.) Ch. 12 (CRC Press, 2014).

Lavrijsen, R. et al. Magnetic ratchet for three-dimensional spintronic memory and logic. Nature 493, 647–650 (2013).

This paper presents the development of soliton-based vertical shift registers.

Lavrijsen, R. et al. Multi-bit operations in vertical spintronic shift registers. Science 287, 104422 (2010).

Mansell, R. et al. A robust soliton ratcheting using combined antiferromagnetic and ferromagnetic interlayer couplings. Appl. Phys. Lett. 106, 092404 (2015).

Lee, J. H. et al. Soliton propagation in micron-sized magnetic ratchet elements. Appl. Phys. Lett. 104, 232404 (2014).

Lee, J.-H. et al. Domain imaging during soliton propagation in a 3D magnetic nanowire. New J. Phys. 18, 113036 (2016).

Lambert, C.-H. et al. All spin-based applications. Adv. Mater. 27, 6582–6589 (2015).
This paper reports the 3D nano-printing of ferromagnetic nanostructures with purities above 90%.

This work demonstrates the magnetic-optical detection of magnetic nanowires in a 3D configuration.

This paper demonstrates three-dimensional magnetic vectorial tomography using electron microscopy.

This work demonstrates three-dimensional magnetic vectorial tomography using X-ray microscopy.

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Author contributions
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Additional information
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