Domain wall trajectory determined by its fractional topological edge defects

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A domain wall (DW) in a ferromagnetic nanowire is composed of elementary topological bulk and edge defects with integer and fractional winding numbers, respectively, whose relative spatial arrangement determines the chirality of the DW. Here we show how we can understand and control the trajectory of DWs in magnetic branched networks, composed of connected nanowires, by considering their fractional elementary topological defects and how they interact with those innate to the network. We first develop a highly reliable mechanism for the injection of a DW of a given chirality into a nanowire and show that its chirality determines which branch the DW follows at a symmetric Y-shaped magnetic junction—the fundamental building block of the network. Using these concepts, we unravel the origin of the one-dimensional nature of magnetization reversal of connected artificial spin ice systems that have been observed in the form of Dirac strings.

The theory of topological defects has had a significant influence on the understanding of various physical phenomena ranging from superfluid helium-3 to liquid crystals1,2. We study the implications of this theory in finite in-plane magnetized systems, in the shape of soft ferromagnetic nanowires and their networks. Topological defects are general features in systems with broken symmetries such as head-to-head (HH) and tail-to-tail (TT) DWs (ref. 3) in these nanowires. The DWs themselves have rich internal structures that can be associated with elementary topological defects4. Understanding the influence of the structure of the DWs on their motion in response to magnetic fields and electric currents is critical for both fundamental5–8 and technological reasons9,10. Here we show first how the formation of the elementary topological defects can be manipulated to obtain DWs of a desired structure, and second how this can be used to control DW trajectory in an interconnected network of nanowires. Finally, using our understanding of the elementary topological defects, we show that we can explain the formation of one-dimensional (1D) Dirac strings commonly seen during the magnetization reversal of connected artificial spin ice systems11,12.

In thin nanowires with negligible intrinsic magnetic anisotropy, where the magnetization points in the plane of the nanowire, the competition between the exchange and magnetostatic energies leads to DWs of primarily two types13,14—vortex and transverse walls. In a vortex DW (Fig. 1a), the magnetization rotates by 360° around a vortex core that is magnetized perpendicular to the plane of the nanowire, with a positive or negative polarity14. In a transverse DW (Fig. 1b), the magnetization rotates by 180° perpendicular to the length and in the plane of the nanowire. Both vortex and transverse DWs can have either anticlockwise (ACW) or clockwise (CW) chiralities. We can use the concepts of winding numbers from the theory of topological defects to describe the magnetic texture of these different types of DW.

The magnetic texture surrounding a topological defect can be mapped onto the parameter space, θ, defined as the angle that the magnetization makes with an arbitrarily chosen axis (Fig. 1c), as detailed in Supplementary Information SI. For a bulk topological defect, its winding number, n, can then be defined15 as:

\[ n = \frac{1}{2\pi} \oint_{\partial \Omega} \nabla \theta \cdot d\mathbf{r} \]  

(1)

n takes integer values (±1) when Ω, described by the polar coordinate r(θ, φ), encompasses a bulk topological defect. For finite systems, boundary conditions play a significant role15. One way to incorporate the boundary conditions is by defining fractional topological defects that are confined to the boundaries of the magnetic structure under consideration, whose n can be calculated15 as:

\[ n = -\frac{1}{2\pi} \oint_{\partial \Omega} (\theta - \theta_r) \cdot d\mathbf{r} \]  

(2)

n takes fractional (±1/2) values where the integration is confined to a path along the edge of the nanowire, and where \( \theta_r \) is the angle of the local tangential direction along the boundary of the system.

One of the fundamental results of the topological theory of defects is conservation of the winding number of any physical system13,14 (even when smoothly deformed). This implies that the net topological winding number of the system given by the equation below is a conserved quantity4:

\[ n_{total} = \sum_i n_i + \sum_j n_j = 1 - g \]  

(3)

where g, defined as the genus, is the number of holes in the magnetic system. For instance, a nanodot has one bulk n = +1 defect in the centre and no edge topological defects (Fig. 1d), whereas a nanobar has two n = +1/2 defects at the end points as shown in Fig. 1e. Likewise, in a Y-shaped junction that forms the backbone of a branched network of nanowires, there are three n = +1/2 defects at the three tips (Fig. 1f). This implies that there will always be an n = −1/2 nodal defect at the junction so as to

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Figure 1 | Characterization of topological defects. 

(a, b) Chiral vortex (a) and transverse (b) HH DWs with their topological defects denoted. Grey arrows indicate bulk \( n = +1 \) topological defects. Polarity of the vortices is not shown. c, The winding number of any closed contour, \( \partial \Omega \), is calculated by measuring the total change in \( \theta \), as the contour boundary is traversed as described by the polar coordinate, \( r(\theta, \phi) \). d, A nanotip containing one bulk \( n = +1 \) topological defect in the centre and no edge topological defects. e, A nanotip containing two \( n = +1/2 \) defects at the end tips. f, A branched Y-shaped junction with three \( n = +1/2 \) defects at each of the tips, along with one \( n = -1/2 \) defect at one of the vertices. g, Schematic of the remnant state of a honeycomb network magnetically saturated in the \(-x\) direction showing positions of the \( n = -1/2 \) defects in each ring.

satisfy equation (3). Extending our understanding to an artificial spin ice system then leads to the realization that there are two \( n = -1/2 \) nodal defects per ring in the remnant state of a saturated honeycomb network (Fig. 1g).

One of the corollaries of equation (3) is that the winding number of a DW, \( n_{\text{total}}^{\text{DW}} \), must be zero, as the presence of a DW should not change \( n_{\text{total}} \). For instance, a vortex DW (Fig. 1a) is composed of a bulk defect in its centre and two \( n = -1/2 \) defects, one at each edge of the nanowire, giving \( n_{\text{total}}^{\text{DW}} = 0 \). A transverse DW (Fig. 1b), on the other hand, is composed of an \( n = +1/2 \) defect on one edge and an \( n = -1/2 \) defect on the other edge of the nanowire \( k \text{,}16 \), again with \( n_{\text{total}}^{\text{DW}} = 0 \). We note that the chirality of a DW is determined by the spatial arrangement of these defects. Now we consider the trajectory of DWs under the influence of a magnetic field\(^{17,18} \). When the magnetic field exceeds a critical value, namely the Walker breakdown field\(^{19} \), typically between 10 and 20 Oe (refs 20,21), the structure of the DW evolves as it moves. In particular, a vortex DW moves along a nanowire by switching its polarity back and forth (Supplementary Information SII), while preserving its chirality, whereas, a transverse DW moves along a nanowire by switching its chirality back and forth through a transient anti-vortex or a vortex DW (ref. 20). We will show that the motion of a DW in a branched network is intimately connected to its chirality. To do this we focus on vortex DWs because their chirality is robust under motion in a magnetic field. First we need to develop a reliable method for injecting vortex DWs of a given chirality into the network.

Controlling the chirality of injected DWs

We use local magnetic fields generated from current passed through an injection line to inject DWs into permalloy (Py) nanowires. Although this method has been widely used\(^{20,22,23} \), reliable chirality control has not yet been demonstrated. Figure 2a shows a scanning electron microscope (SEM) image of a typical device with two 500-nm-wide injection lines separated by 6 \( \mu \)m. The dimensions (300 nm wide, 20 nm thick) of the Py nanowire, under the injection lines, are carefully chosen to favour vortex (rather than transverse) DWs (ref. 12). We find that the placement of a notch at one edge of the nanowire under the injection line can be used to control the chirality of the injected DW (see Supplementary Information SIII for details). In the device of Fig. 2a (inset in orange), a 60-nm-deep triangular notch is strategically placed at the bottom edge of the nanowire, underneath the left injection line.

We first explore the dependence of the chirality of the injected DW on the local magnetic field strength using micromagnetic simulations. Let us consider the case when the nanowire’s magnetization is first set in the \(-x\) direction by a large magnetic field (500 Oe). Now the magnetic moments curl around the notch in the ACW direction, as shown in the micromagnetic simulation in Fig. 2b (ref. 24). It is the curvature of the magnetization that this notch engenders that favours a certain chirality of the injected DW. Applying a few-milliseconds-long electrical pulse of voltage amplitude \( V_{\text{inj}} \) along the injection line above a critical voltage, \( V_{\text{inj}}^c \), creates a local magnetic field, \( H \propto V_{\text{inj}} \), greater than the critical field, \( H^c \), required to reverse the magnetization beneath the injection line. Micromagnetic simulations show that this leads to the formation of HH and TT DWs, each with ACW chirality, through intermediate states (see Fig. 2c and Supplementary Movie S1) composed of an anti-vortex and two vortices. It is because the cores originate near the notch at the bottom edge of the nanowire at \( V_{\text{inj}}^c \propto H^c \) that the DWs possess ACW chirality.

We can controllably inject a DW of the opposite CW chirality by varying the strength of the injection field. As this field, that is \( V_{\text{inj}} \),...
Figure 2 | Creation of a vortex DW of a given chirality. a, SEM image of a typical 300-nm-wide Py nanowire with the contacts separated by 6 μm. The left (orange) inset shows a 60-nm injection notch underneath the left injection line at the bottom edge of the 20-nm-thick nanowire. The right (purple) inset shows a 60-nm-deep probe notch at the top edge of the nanowire 3 μm away from the left contact for DW pinning. H\textsubscript{inj} is applied along the x axis.

b, Micromagnetic simulation of a 200-nm-wide nanowire with a 60-nm-deep notch at the bottom edge showing the curvature of magnetization near the injection notch. c,d, Time-resolved micromagnetic simulations showing the DW injection process when 51 mA and 57 mA currents are passed through the injection line, respectively. At 51 mA (Supplementary Movie S1) the vortex cores of the DWs that survive (are indicated by their polarities) originate near the notch and have ACW chirality. At 57 mA (Supplementary Movie S2) the vortex cores of the DWs that survive (are indicated by their polarities) originate near the intersection of the injection line and the top edge of the nanowire and have CW chirality. e,f, Relative injection probability for the two chiralities for HH and TT DWs respectively as a function of V\textsubscript{inj}. For every V\textsubscript{inj}, 100 repetitive experiments of injecting a DW and determining its chirality were performed to build statistics. Below V\textsubscript{c} no injection takes place. Above V\textsubscript{c} ACW HH (CW TT) DWs get injected followed by CW HH (ACW TT) DWs above V\textsubscript{sw}. Increasing the voltage further stochastically injects DWs of both chiralities.

is monotonically increased, it leads to oscillatory buckling of the magnetization\textsuperscript{25} along the nanowire alternating between its bottom and top edges, with a periodicity of ~2 times the nanowire width. As a vortex created at the bottom edge is always ACW whereas a vortex created from the top edge is always CW (for magnetization initially along −x), this has a profound consequence that the chirality of the injected DW will oscillate with increasing V\textsubscript{inj}. Thus, increasing V\textsubscript{inj} above the switching voltage V\textsubscript{sw} > V\textsubscript{c} leads to the reliable injection of CW DWs (see Fig. 2d and Supplementary Movie S2; for details see Supplementary Information SIII–SIV). The results of these simulations agree well with our experimental results, as discussed below.

With a small global assisting field along the nanowire, H\textsubscript{inj} = 20 Oe, applied in tandem with the local magnetic field created by a voltage pulse through the left injection line, the two injected (HH and TT) DWs move away from the injection line: one gets annihilated at the left end tip of the nanowire and the other gets inserted to the right of the injection line into the
Figure 3 | Ascertaining the DW trajectory due to interplay of fractional topological defects. a, SEM image of a branched Y-shaped junction made from 20-nm-thick Py with input branch A and output branches B and C along with their injection contact lines. Each branch is 200 nm wide and 6 μm long intersecting at the Y-junction with θ = 60° between branches B and C. Hky is applied along the x axis. The left inset shows the 45-nm-deep notch at the bottom edge of the nanowire underneath the injection line A. The right insets show the probe notches in branches B and C. b, Micromagnetic simulation showing magnetization near the Y-junction with an n = −1/2 topological defect at the vertex VBC denoted by the purple dot. Vertices VAB (blue dot) and VAC (red dot) labelled as discussed in the text. c, d, Time-resolved micromagnetic simulations showing ACW DWs with both polarities go into branch C with (+) polarity (see Supplementary Movies S3,S4). e, f, Time-resolved micromagnetic simulations showing CW DWs with both polarities go into branch B with (−) polarity (see Supplementary Movies S5,S6). The results of the simulation are summarized in the truth table. Topological defects with their respective n indicated. All vortex cores have an n = +1 topological defect (not indicated) regardless of their polarity. In d, and f, the n = −1 defect in reality signifies two n = −1/2 defects along the edge on both sides of the vertex VBC, which form when the n = +1 defect gets created in the bulk.

main section of the nanowire. A second 60-nm-deep triangular probe notch is positioned at the top edge in the middle of the nanowire to trap the injected DW (Fig. 2a inset in purple). We can experimentally determine the chirality of the trapped DW by measuring its depinning field required to dislodge the DW from the notch26. Figure 2e shows the relative probability of the chirality of HH DWs injected as a function of V inj. Below V inj = 2.6 V, no DW is found in the nanowire. At V inj = 2.6 V, HH DWs of only ACW chirality are obtained. Above the switching voltage, V switch = 3.0 V, and for V inj < 5.0 V, the chirality of the injected HH DW is switched to CW. For V inj > 5.0 V, the chirality of the injected HH DW switches back to ACW, albeit with lower relative probability as injection becomes stochastic at high fields. TT DWs also show similar effect (Fig. 2f).
Controlling the trajectory of injected DWs

We exploit the DW chirality control to demonstrate that the trajectory of a DW in a branched network is determined by its chirality. We study the DW motion in the fundamental building block of a branched network, namely a Y-shaped magnetic structure, as shown in the SEM image in Fig. 3a. The structure is formed from 20-nm-thick Py with three branches A, B and C, each 200 nm wide and 6 μm long. The DW is injected from the injection line, which is positioned above a 45-nm-deep notch (Fig. 3a, left inset) in branch A. Branches B and C, angled at θ = 60° to each other, have 60-nm-deep probe notches that are used to trap the injected DW (right insets Fig. 3a).

We note that the initial state of the structure, even when fully magnetically saturated, has a single topological edge defect with n = −1/2 at the vertex $v_{BC}$ (see micromagnetic simulations in Fig. 3b and Supplementary Information S5). When a vortex DW is introduced, both of its fractional edge defects are constrained to move along their respective edges of the nanowire (Supplementary Information S1), one of them leading the n = +1 defect and the other lagging, depending on the DW chirality. As the DW moves closer to the junction, it will travel along either branch B or C depending on which edge has the leading n = −1/2 defect. Conservation of the total winding number implies that the vortex DW, after entering the bifurcation region, leaves its n = −1/2 defect that was behind the vortex core, on the outside vertex ($v_{AB}$ or $v_{AC}$ in Fig. 3b) of the junction, and picks up the n = −1/2 defect from the vertex $v_{BC}$ before going into the appropriate branch, determined by the n = −1/2 defect in front of the vortex core. Passage of the DW from the junction merely rearranges the location of the n = −1/2 defect from $v_{BC}$ to one of the other vertices as shown in the simulations in Fig. 3c–f and Supplementary Movies S3–S6. Hence, by controlling the chirality of the DW injected in branch A, the DW can be selected to enter one of the two branches B or C.

Interestingly, the DW should not only have the correct chirality but also should have the appropriate polarity so as to pass the branched junction. This is due to the gyrotropic force acting on the vortex core that pushes the ± polarity in the ±x direction, for a vortex core moving in the ±y direction. In cases where the chirality and the polarity are driven towards opposite branches (Fig. 3d, f and Supplementary Movies S4 and S6), the polarity switches before the DW goes into the branch selected by its chirality. Thus, regardless of its polarity an ACW HH DW travels from branch A to branch B, whereas a CW HH DW travels from branch A to branch B, as summarized in the table in Fig. 3.

Figure 4 shows the experimental verification of the chirality-dependent branch selection discussed above (for a device with θ = 45°). Probability maps as a function of $V_{ij}$ and of $H_{inj}$ for the DW traversing branch C ($P_C$) or branch B ($P_B$) are shown in Fig. 4a and Fig. 4b, respectively. As discussed earlier in Fig. 2, for $V_{ij} < V_{inj} < V_{ij}^{\text{sw}}$, an ACW chirality HH DW is injected that enters into branch C, whereas $V_{inj} > V_{ij}^{\text{sw}}$ injects a CW chirality HH DW, which traverses branch B. Increasing $V_{ij}$ further (by ~30%) injects predominantly ACW HH DWs, albeit with lower fidelity as the injection process becomes stochastic. To quantify the anti-correlation between $P_C$ and $P_B$ we define the sorting fidelity of the branched junction (Fig. 4c) as $F(\theta) = (P_C - P_B)/(P_C + P_B)$, whose value when $+1(-1)$ indicates that the DW traverses branch C(B) with 100% fidelity. A value of zero, on the other hand, means that the DWs travel either branch with equal probability. Events with no injection and when the DWs get trapped in the junction are discarded. Both $V_{ij}$ and $V_{ij}^{\text{sw}}$ decrease linearly with increasing $H_{inj}$ so that the total critical injection field, $H^*$, and the field needed for switching the chirality of the injected DW remain the same. Line cuts of the relative sorting probability into branch B and C for $H_{inj} = 50$ Oe are shown in Fig. 4d, which mimics what is observed in Fig. 2c, indicating that the trajectory of the DW is indeed controlled by its chirality.

The high fidelity reported here confirms that: the injection process is highly chirality-controlled owing to the presence of the injection notch, the vortex DWs do not switch their chirality as they traverse the junction even at fields much higher than the Walker breakdown field (at least up to 75 Oe for the dimensions of our nanowires) and, most importantly, the trajectory of the DW through the junction is determined by its chirality, that is, by its fractional topological edge defects.

Origin of 1D Dirac strings in connected artificial spin ice

This understanding can now be extended to more complex magnetic networks, for example, to explain the propagation of magnetic monopoles in connected kagome artificial spin ice lattices$^{37,38}$. In particular, we suggest that the formation of 1D Dirac strings under the application of magnetic field in artificial kagome lattices, rather than 2D domain growth that would be anticipated from Zeeman energy minimization, is a result of the chiral nature of the DWs that propagate along one of the two possible branches depending on their constituent fractional topological defects during the switching of individual links in the honeycomb network.
illustrate the formation of two possible types of Dirac string under magnetic field, which we define as staircase and armchair types, in an initially saturated honeycomb network. Their evolution can be understood in terms of their fractional topological defects as shown in Fig. 5 and detailed in the Supplementary Information SVI. We find that there are two distinct behaviours at the two inequivalent nodes a and b (Fig. 5a) in the hexagonal network, which depend on the location of the topological defect at the vertex of each node in the network relative to those of the DW. When the node’s $n = -1/2$ defect is on the same edge as the $n = -1/2$ defect of the vortex DW (Fig. 5b) these two fractional defects annihilate together with the bulk $n = +1$ defect of the vortex DW to leave behind the $n = -1/2$ defect on the opposing edge (Fig. 5c). The second behaviour is the chirality-dependent branch selection that takes place at nodes a and a’ whose $n = -1/2$ nodal defect is on neither edge common to those of the DW. The staircase (Fig. 5d–f) or armchair (Fig. 5d’–f’) Dirac string formation then depends on transverse DW or vortex DW propagation between nodes b to a’ respectively. In the transverse DW case, it is the $n = +1/2$ defect that determines its trajectory through a branched junction (Fig. 5d,e) rather than the leading $n = -1/2$ defect for the case of vortex DWs (Fig. 5d’,e’) and also discussed in Fig. 3).

Using the theory of topological defects, we have obtained a detailed microscopic understanding of DW trajectories in complex branched networks. Our understanding will allow for the formation of more complex chiral magnetic orders by controllably generating and propagating several domain walls of specific chiralities into artificial spin ice structures to form defined lattices of Dirac strings. These concepts along with our capability of chirality-controlled DW injection reported here can also be applied to build reliable DW-based logic devices, such as a chirality-controlled 2-bit demultiplexer, and denser racetrack memory devices that exploit the topological repulsion of adjacent HH and TT DWs of appropriate chiralities.
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A.P. and T.P. conceived and performed the experiments, and analysed the data. A.P. and T.P. did nanofabrication of the devices. A.P., T.P. and S.S.P.P. wrote the manuscript. S.S.P.P. supervised. All authors discussed the results and implications.

Additional information
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