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Magnetic skyrmions achieve weighted summations in a scalable structure

The particle-like behaviour of magnetic skyrmions is exploited to perform a fundamental neuromorphic computing operation: the weighted summation of synaptic signals. The use of skyrmions enables a compact and energy-efficient implementation that could pave the way for neuromorphic spintronic components that mimic the efficiency of biological systems.

This is a summary of:
da Câmara Santa Clara Gomes, T. et al. Neuromorphic weighted sums with magnetic skyrmions. *Nat. Electron*. https://doi.org/10.1038/s41928-024-01303-z (2025).

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The mission

A major challenge in the coming years will be to develop efficient, low-power devices to meet the exponential growth of digital technologies and demands. This issue has become even more pressing with the rise of generative artificial intelligence (AI), which is highly energy intensive, particularly during the training phase. In this context, neuromorphic computing, inspired by the highly efficient and compact architecture of the biological brain, emerges as a promising paradigm with the potential to enable more sustainable and accessible technological solutions. However, there are challenges that must be overcome to achieve this vision. For example, it will be necessary to develop nanoscale devices capable of performing fundamental computing operations with scalability, durability, high-speed processing and low-power electrical control. Nanoscale dynamical spintronic devices, which exploit both the spin and charge degrees of freedom of electrons, have the potential to meet these requirements[1].

The observation

In our study, we explored the properties of magnetic skyrmions — nanoscale, stable isolated magnetic textures — and used them to mimic the role of biological neurotransmitters in a neural network. Taking advantage of the particle-like behaviour of skyrmions[2], which makes them countable and hence summable, enabled us to perform a basic neuromorphic computing operation: the weighted summation of synaptic signals. To perform this operation, we designed a device comprising parallel tracks, which act as synapses, connected by transverse electrodes, which act as neurons (Fig. 1a). The tracks feature defined nucleation sites where a controlled number of skyrmions ($N_{\mathrm{Sk},i}$) can be generated, proportional to the input current pulses (J_i^{In}) and the synaptic weights (w_i) in each track (with i the index of the track). These skyrmions are then moved via current pulses to detection areas located at the intersections of the tracks and electrodes. The total skyrmion count ($\sum_i N_{\mathrm{Sk},i}$) is obtained by measuring the Hall voltage across the detection area (ΔV), enabling the implementation of the weighted sum operation $\Delta V \propto \sum_i w_i J_i^{\mathrm{In}}$.

We demonstrated the linear control of skyrmion injection into the track using current pulses, confirming the linear relation between the number of injected skyrmions and the input value: $N_{\mathrm{Sk},i} = w_i J_i^{\mathrm{In}}$. Additionally, we showed that w_i can be tuned by applying a low magnetic field, offering learning ability and adaptability. The device can be reset by applying a magnetic field that saturates the device magnetization, or by applying a current pulse of reversed polarity. We then produced a proof-of-concept device featuring two synapses and one neuron, which was made of high-resistance tantalum to minimize disturbances to the skyrmion motion. We found that the voltage measured at the end of the transverse electrode is linearly proportional to the total number of skyrmions nucleated in the two tracks as observed by Kerr microscopy (Fig. 1b), confirming that the summed skyrmion signals can be electrically detected.

Future directions

These developments highlight the potential of compact, energy-efficient neuromorphic architectures that use magnetic skyrmions to perform weighted sum operations at the nanoscale. Our device can be easily scaled by adding more tracks in parallel and increasing the number of transverse electrodes in a crossbar array configuration.

However, several challenges remain. The nucleation mechanism must be improved to increase the energy efficiency and ensure the seamless conversion of inputs to outputs in devices with multiple neural layers. Our current device relies on volatile weights induced by applied magnetic fields. A key future challenge is to achieve non-volatile synaptic weight control by permanently and reversibly tuning the properties of the tracks. The performance of the device could also be improved by enhancing the output signal, because the present detection method relies on the low-signal anomalous Hall effect (AHE).

The next steps will involve developing nucleation sites with oxide gates to enable voltage-gated skyrmion nucleation[3]. This approach could support low-energy skyrmion generation and directly convert voltage outputs into inputs for subsequent neural layers. Furthermore, magneto-ionic gates, in which ion motion can be reversibly controlled by the gate voltage, could enable non-volatile tuning of synaptic weights[4]. Finally, the use of magnetic tunnel junctions in the detection area could increase the signal readout through tunnel magnetoresistance (TMR)[5] and enable the direct integration of the required nonlinear activation function, allowing all neuromorphic computing operations to be performed locally.

Tristan da Câmara Santa Clara Gomes, Julie Grollier & Nicolas Reyren
Laboratoire Albert Fert, Palaiseau, France.

EXPERT OPINION

"An important problem for inference using neural network hardware is being able to multiply the output of different neurons of one layer with synaptic weights and then sum these products to determine the input to a neuron of the next layer. The authors show that this can be, in principle, implemented in a skyrmion racetrack." **Jayasimha Atulasimha, Virginia Commonwealth University, Richmond, VA, USA.**

FIGURE

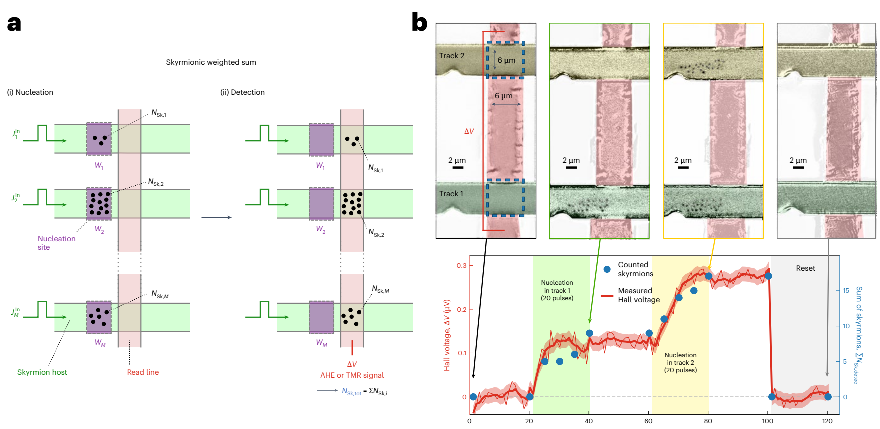

Fig. 1 | Skyrmionic weighted sum device. **a**, The scalable device structure featuring M parallel tracks (green) in which input currents J_i^{In} generate controlled skyrmion numbers $N_{\mathrm{Sk},i}$ at nucleation sites (purple) with synaptic weights w_i. These skyrmions are moved into detection zones at the intersection of the tracks and the transverse electrodes (red), where the cumulative number of skyrmions $\sum_i N_{\mathrm{Sk},i}$ can be electrically detected through an output voltage ΔV. **b**, Top, Kerr microscopy images of the device, showing the nucleation of skyrmions in the two tracks, before they are erased using a magnetic field. Bottom, the measured Hall voltage ΔV (thick (thin) red line is the smoothed (raw) data) accurately reflects the total number of skyrmions observed by Kerr microscopy $\sum N_{\mathrm{Sk,detec}}$ (blue circles). The shaded red region indicates the standard deviation of the initial and final 20 ΔV measurements. © 2025, da Câmara Santa Clara Gomes, T. et al.

BEHIND THE PAPER

In the Laboratoire Albert Fert, researchers explore various topics in condensed-matter physics. Along the same corridor, scientists working on the France 2030, PEPR SPIN CHIREX project study magnetic skyrmions (chiral nanostructures with the potential to revolutionize computing and memory), while others research neuromorphic computing in the Grenadyn project (funded by the European Research Council), which draws inspiration from physics and the brain to create ultra-low-power hardware for AI.

At the end of this corridor is the coffee room, which hosts numerous cake contests and has a well-used whiteboard. It was here that researchers began to connect the (magnetic) dots. They realized that skyrmions could serve as innovative vehicles for carrying brain-like signals in hardware neural networks. This insight sparked the current work and the SkyANN project (funded by the European Union), which aims to harness and multiplex different skyrmionic particles to enhance computing capabilities. **T.d.C.S.C.G., J.G. & N.R.**

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FROM THE EDITOR

"The electrical nucleation, motion and detection of magnetic skyrmions in heterostructure devices has been demonstrated, but using skyrmions to perform neural network operations remains challenging. Here, the authors generate a number of skyrmions proportional to an input with an efficiency given by a non-volatile weight. The team reports on a proof-of-concept two-input to one-output device that performs a weighted sum operation with skyrmions." **Katharina Zeissler, Associate Editor, *Nature Electronics*.**