New Opportunities in Physics-based Computing: Magnonics, Spintronics, Photonics and Beyond

853. WE-Heraeus-Seminar

26 Apr - 30 Apr 2026
at the Physikzentrum, Bad Honnef, Germany

The WE-Heraeus Foundation supports research and education in science, especially in physics.
The Foundation is Germany's most important private institution funding physics.

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 853. WE-Heraeus-Seminar:

Physics-based computing explores alternatives to traditional transistor-based electronics, leveraging nonlinear phenomena in various physical domains to solve real-world problems.

This approach extends the concept of analog computing, offering potential for sustainable, energy-efficient solutions in information and communication technologies. The demand for machine learning has surged, driven by advancements like ChatGPT, but the energy cost of digital, transistor-based computing remains high, particularly in large-scale data centers. In contrast, physics-based computing, such as physical reservoir computing, harnesses nonlinear dynamics in systems like magnetic skyrmions, photons, and spin waves to enable more efficient data classification, pattern recognition, and time series predictions. By operating in the nonlinear regime, these physical systems convert input signals into measurable outputs, offering a promising route to edge computing applications in fields like medical diagnostics, autonomous mobility, and smart energy grids. The strength of physical computing lies in its ability to process complex data with minimal energy consumption, without relying on traditional deep learning algorithms. Magnonics, spintronics, and photonics are key fields in this emerging area, offering systems that can serve as powerful, interconnected computational reservoirs. Spintronics, harnessing the electrons' spin, enables the design of energy-efficient neural networks, while magnonics and photonics provide high-frequency platforms for wave-based computing. The integration of these fields, alongside other platforms such as superconductors, presents new opportunities for developing complex, scalable computing systems that can meet the growing demands of machine learning while advancing sustainable technologies.

Scientific Organizers:

Dr. Katrin Schultheiss	Helmholtz-Zentrum, Dresden-Rossendorf, Germany E-Mail: k.schultheiss@hzdr.de
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Introduction

Administrative Organization:

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Registration:

Martina Albert (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, April 26, 2026

17:00 – 21:00	Registration	
18:30 – 21:00	*BUFFET SUPPER*	

Monday, April 27, 2026

08:00	*BREAKFAST*	
09:00 – 09:45	Scientific organizers	**Opening, Welcome and Intro film team and Intro WEH**
09:45 – 10:30	Damien Querlioz	**Taming and exploiting the physics of memristors**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Karin Everschor-Sitte	**Unconventional computing with excitations**
11:45 – 12:30	Hidekazu Kurebayashi	**Dynamical stability of magnetisation and its potential use for probabilistic computing**
12:30	*LUNCH*	

Program

Monday, April 27, 2026

14:30 – 15:15	Emilie Jué	**Superconducting self-training neural network with nanosecond learning**
15:15 – 16:00	Daniel Brunner	**In-situ training and scaling laws for computing with physical substrates**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Klaus Knobloch	**AI/ML emerging compute paradigms & next gen architectures**
17:15 – 18:00	Tobias Hula	**Innovation: Scientific Fascination vs. Industrial Reality?**
18:30	*DINNER*	
20:00	**Poster session and Discussion**	

Program

Tuesday, April 28, 2026

08:00	*BREAKFAST*	
09:00 – 09:45	Erik Folven	**Memory and directionality in a magnetic metamaterial**
09:45 – 10:30	Tom Hayward	**Go Hard(ware network) or go home: Networking spintronic metamaterials for neuromorphic computation**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Claas Abert	**Inverse micromagnetics for the design and characterization of magnonic and spintronic devices**
11:45 – 12:30	György Csaba	**Nonlinear waves and oscillators for computing**
12:30 – 12:40	**Conference photo**	
12:40	*LUNCH*	

Program

Tuesday, April 28, 2026

14:30 – 15:15	Amel Kolli Victor Gonzalez
15:15 – 16:00	Akash Kumar Mohamed Menshawy
16:00 – 16:30	*COFFEE BREAK*
16:30 – 17:15	**Poster Flash**
17:15 – 18:00	**Poster session**
18:30	*DINNER*
20:00	**Poster session and Discussion**

Program

Wednesday, April 29 2026

08:00	*BREAKFAST*	
09:00 – 09:45	Kathy Lüdge	**Reservoir Computing with Dynamical Systems in Optics and Electronics**
09:45 – 10:30	Bert Koopmans	**Applications of magnetization switching by light – Towards spintronic-photonic integration**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Na Lei	**Magnetics and ferroelectrics based physical reservoir computing for energy-efficient time-series and multimodal artificial intelligence**
11:45 – 12:30	Juliane Heim Gijs Simons	
12:30	*LUNCH*	
14:30 – 15:15	Serge Massar	**Machine Learning with Equilibrium Propagation.**
15:15 – 16:00	Philippe Talatchian	**On-chip Training of Stochastic Multilayer Spintronic Neural Networks**
16:00 – 16:30	*COFFEE BREAK*	

Program

Wednesday, April 29, 2026

16:30 – 17:15	Ursula Ebels Yuean Zhou	
17:15 – 18:00	**Poster Session**	
18:30	*HERAEUS DINNER at the Physikzentrum* *(cold and warm buffet, with complimentary drinks)*	
20:00	**Poster session and Discussion**	

Thursday, April 30, 2026

08:00	*BREAKFAST*	
09:00 – 09:45	Susan Stepney	**New models of computation to support novel physics-based computing devices**
09:45 – 10:30	Jack Gartside	**Learning nonlinear heterogeneity in physical Kolmogorov-Arnold networks**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Ryosho Nakane	**Reservoir computing performance via nonlinearity-induced spin waves**
11:45 – 12:30	Christopher Heins	**Magnetic vortices as a platform for magnonic pattern recognition and self-induced floquet dynamics**
12.30 – 12.45	Scientific organizers	**Closing and awards**
12:45	*LUNCH*	

End of seminar and departure

Posters

Posters

Donatella Albano	**Controlling magnetic skyrmion Brownian motion through Focused-Ion-Beam patterning**
Erwan Aubouin	**Development of a hybrid CMOS-spintronic crossbar architecture for small networks of interconnected spintorque nano-oscillators: application to Ising machines**
Anja Bartelmei	**Delay-embedding in spatio-temporal optical reservoir computing**
Simone Bonino	**Spatial Reservoir Computing Based on Spin–Orbit Torque Driven Skyrmion Motion**
Finn Marten Boyer	**Exploring Reinforcement Learning for Particle Transport in the Presence of Inhomogeneities**
Arthur Courberand	**Study of coupled spiking magnetic tunnel junctions**
Connor Devitt	**Advances in YIG-on-GGG Spin-Wave Fabrication**
Thibaut Devolder	**Self-induced Floquet states via three-wave processes in synthetic antiferromagnets**
Jack Griffiths	**Diffusion-Based Surrogate Models for Optimising and Inverse Design of Physical Computing Systems**
Maximilian Hofschen	**Small-Form-Factor Peripheral Circuitry for Hybrid Magnonic Systems**
Andrey Iljin	**All-optical switching in liquid crystals through order parameter modulation**
Loukas Kokkinos	**Floquet states modulation in spin-torque oscillators for unconventional computing**
Kilian Leutner	**Skyrmion devices for physics-based non-conventional computing**
Yung Cheng Li	**Magnetic dynamics in isotropic ferromagnetic insulator**

Posters

Baojia Liu	**Toward Cascaded Spin–Acoustic Neuromorphic Hardware: Integrated Synaptic and Neuronal Functions in SAW–SOT Devices**
Atreya Majumdar	**Physical Reservoir Computing with Ferroelectric Oxides**
Maryam Massouras	**Real-time characterization of vortex core reversal under nonlinear gyrotropic motion**
Levente Maucha	**Spin-wave holography for neuromorphic computing**
Tobias Mohr	**Machine Learning-Based Spin Structure Detection in Engineered X/CoFeB/MgO Multilayers**
David Navas	**Spinwave modes in synthetic antiferromagnetic nanodots**
Adam Papp	**Scalable spin-wave neural networks**
Gauthier Philippe	**Hysteretic excitation of self-induced Floquet magnons in vortex-state magnetic tunnel junctions**
Igor Polonskiy	**Reinforcement**
Sina Ranjbar	**From Concepts to Scalable Spintronic Devices for Emerging Technologies**
Thomas Winkler	**Multi-Value Probabilistic Computing with Current-controlled Skyrmion Diffusion**
Zeling Xiong	**Predicting the future with magnons**
Tomoki Yamagami	**Sign-dependent autocorrelation benefits in time-series-based decision making**
Zhibo Zhao	**Voltage-Modulated Interaction-Driven Dynamics in Macrospin Networks for Low-Power Neuromorphic Computing**

Abstracts of Lectures

(in alphabetical order)

Inverse micromagnetics for the design and characterization of magnonic and spintronic devices

C. Abert

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Designing magnonic and spintronic devices with targeted functionalities is challenging due to the complex nonlinear dynamics of magnetic systems. We present an inverse micromagnetic framework built on the open-source libraries NeuralMag and magnum.np [1] that combines differentiable micromagnetic solvers with gradient-based optimization. Automatic differentiation through the Landau–Lifshitz–Gilbert equation, paired with adjoint-state methods, enables memory-efficient computation of design sensitivities with respect to device geometry and material parameters.

We demonstrate this through the topology optimization of a magnonic spin-wave demultiplexer. A level-set function parameterized by radial basis functions defines the device geometry and is evolved via gradient descent. The optimizer discovers non-trivial hole patterns in a thin-film waveguide that route spin waves of different frequencies to separate output channels [2].

Closing the loop between design and fabrication requires accurate characterization of magnetic states in realized devices. The same framework enables magnetization reconstruction from indirect measurements by combining differentiable forward models with micromagnetic energy regularization. Applied to nitrogen-vacancy magnetometry of $\mathrm{Fe_3GaTe_2}$, it recovers chiral spin textures including Néel skyrmions [3], and extends to 3D X-ray magnetic circular dichroism tomography for full vector magnetization mapping [4].

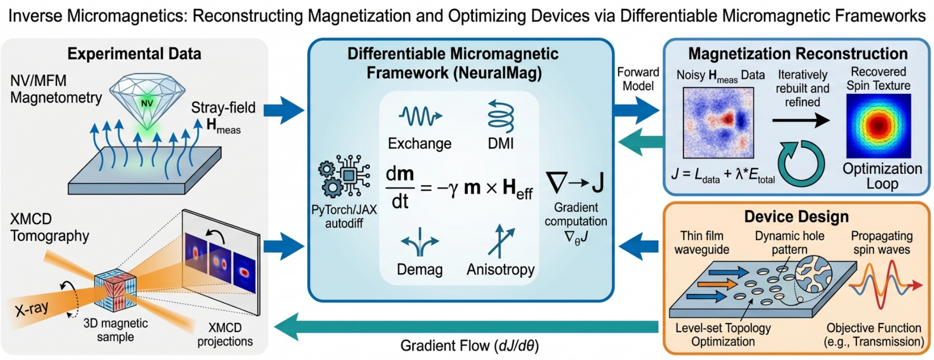

Figure 1. Inverse micromagnetics: experimental data and design targets are processed through a differentiable solver for magnetization reconstruction and device optimization.

[1] C. Abert et al., npj Comput. Mater. **11**, 193 (2025). [2] A. A. Voronov et al., npj Spintronics **3**, 19 (2025).

[3] A. Setescak et al., arXiv:2602.17180 (2026). [4] A. Setescak et al., in preparation (2026).

In-situ training and scaling laws for computing with physical substrates

D. Brunner

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Besançon, France.

Neural network concepts revolutionize computing by solving challenges previously thought to be reserved to the abstract intelligence of humans. For maximal efficiency, the largest fraction of a NN's hardware should be dedicated to the core computational task, and in this context, we demonstrated a high-dimensional semiconductor laser that implements a scalable photonic NN fully in parallel and with minimal support by a classical digital computer. The NN comprising ~5.000 neurons is end-to-end trained via an in-situ setting , achieving >96% MNIST test accuracy without any pre or post processing. Finally we identify the scaling laws between computing performance and physical system's dimensionality for the first time.

Nonlinear waves and oscillators for computing

Gyorgy Csaba[1], Tamas Rudner[1], Adam Papp[1], Maucha Levente[1], Markus Becherer[2]

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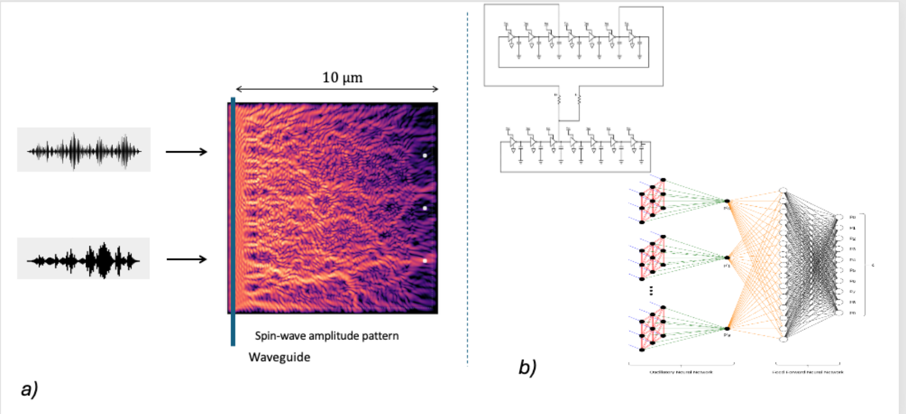
Analog computing is based on the idea of solving computational problems using an analogous physical system—that is, by letting the laws of physics perform the computation. Regardless of the hardware platform, the main challenge is to design the physical system so that it carries out useful computations. In this work, we focus on the methodology of training physical systems.



a) Nonlinear spin waves doing classification [1] and a hierarchical, b) oscillator-based system analog computing system for this purpose [2].

One physical system we demonstrate is based on spin waves in magnetic materials. Spin waves provide rich oscillatory dynamics without the need for dissipative current flow. I will show how nonlinear waves in a material substrate can be trained perform analog, neuromorphic computation using gradient-based learning on a digital twin.

Analog circuits may be used in a similar fashion. Ring oscillators are simple electrical circuits that are easy to realize in hardware. When coupled together, they can synchronize into collective oscillatory states and implement neural-network-like functions. I will present examples of dynamic neural computation based on ring oscillators.

[1] Papp, Ádám, Wolfgang Porod, and Gyorgy Csaba. "Nanoscale neural network using non-linear spin-wave interference." *Nature communications* 12, no. 1 (2021): 6422.

[2] Rudner, Tamas, Wolfgang Porod, and Gyorgy Csaba. "Design of oscillatory neural networks by machine learning." *Frontiers in Neuroscience* 18 (2024): 1307525.

A hardware implementation of an Ising-spin system based on the stochastic phase dynamics of spintorque nano-oscillators

Abderrazak Hakam[a], Chloé Chopin[a], Erwan Aubouin[a, b], Leandro Martins[a], Simon de Wergifosse[c], Clément De Barbarin[a], Nicolas Mollard[a], Eyub Yildiz[a], Louis Hutin[b], Franck Badets[b], Luana Benetti[d], Alex Jenkins[d], Ricardo Ferreira[d], Liliana Buda-Prejbeanu[a], Flavio Abreu Araujo[c], Philippe Talatchian[a], Ursula Ebels[a*]

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Ising machines (IMs) are physics-inspired computing platforms that can efficiently solve combinatorial optimization problems. IMs emulate a coupled network of binary-valued spins s_i, whose energy minimization naturally leads to solutions of COPs, encoded in the spin-coupling interactions J_{ij}. To determine the solution state, one can either use deterministic annealing schemes [1,2] or thermal noise to stochastically explore the spin state configurations. The latter is explored here using the stochastic phase dynamics of a system of coupled spin-torque nano-oscillators (STNOs), whose phases are binarized via synchronization to a microwave signal at frequencies f_S two-times their natural frequency $f_S=2f_{STNO}$ [3].

Experimental and simulation results are presented for the implementation of a spatial and programmable N-spin stochastic IM using vortex-based STNOs operating at frequencies around 200-300 MHz. Thermal noise induces stochastic transitions between binarized phase states that are perfectly equiprobable [3]. By adding an external microwave signal at $f_S/2$ of varying amplitude and phase, the phase-state probability can be biased in a controlled manner between both values such that the STNO represents a tuneable stochastic binary neuron. Replacing the external microwave signal at $f_S/2$ by a second STNO, with tuneable coupling strength and sign, two STNOs can mutually influence their stochastic phase dynamics. By leveraging these results, we built an electrical platform implementing a 5x5 cross-point architecture to couple up to N=5 vortex-based STNOs synchronized at twice their natural frequencies. We demonstrate that phase states of highest probability correspond to the lowest energy levels of the corresponding Ising-spin Hamiltonian.

[1] D. I. Albertsson et al., Appl. Phys. Lett. **118**, 112404 (2018).

[2] A. Litvinenko et al., Commun Phys, **6**, 227 (2023).

[3] N.-T. Phan et al., Phys. Rev. Applied **21**, 034063 (2024).

Unconventional computing with excitations

K. Everschor-Sitte[1]

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The rapid expansion of artificial intelligence has led to unprecedented computational demands, with power consumption emerging as a key bottleneck of current hardware architectures. Physics-based computing offers a promising route beyond this limitation by exploiting the intrinsic physical dynamics of materials to process information directly in matter [1,2]. In this context, functional magnetic materials [3-5] are particularly attractive, as their nonlinear and hysteretic responses naturally provide the complex dynamics required for unconventional computing paradigms [6] such as reservoir computing [7-11] or swarm-based computing [12]. Our work highlights how the interplay between material properties and algorithmic approaches can be used to explore novel computing architectures, representing initial steps toward the broader vision of intelligent matter.

References

[1] G. Finocchio, …, KES, et al., Nano Futures 8, 012001 (2024)
[2] KES, A. Majumdar, K. Wolk, D. Meier, Nat. Rev. Phys. 6, 455 (2024)
[3] H. Kurebayashi, G. Finocchio, KES, et al., Nat. Rev. Phys. (2026)
[4] G. Finocchio, M. Di Ventra, K.Y. Camsari, KES, P. K. Amiri, Z. Zeng, JMMM **521**, 167506 (2021)
[5] J. Grollier, D. Querlioz, K.Y. Camsari, KES, S. Fukami, M.D. Stiles, Nat. Elect. **3**, 360 (2020)
[6] O. Lee, R. Msiska, M. A. Brems, M. Kläui, H. Kurebayashi, KES, Appl. Phys. Lett. 122, 260501 (2023)
[7] H. Youel, D. Prestwood, O. Lee, T. Wei, K. D. Stenning, J. C. Gartside, W. R. Branford, KES, H. Kurebayashi, arXiv:2410.18356 (2024)
[8] R. Msiska, J. Love, J. Mulkers, J. Leliaert, KES, Adv. Intell. Syst. 5, 2200388 (2023)
[9] D. Pinna, G. Bourianoff and KES, Phys. Rev. Appl. **14**, 054020 (2020)
[10] G. Bourianoff, D. Pinna, M. Sitte and KES, AIP Adv. **8**, 055602 (2018)
[11] D. Prychynenko, M. Sitte, et al, KES, Phys. Rev. Appl. **9**, 014034 (2018)
[12] A. Pignedoli, A. Majumdar, KES, arXiv:2601.22874 (2026)

Memory and directionality in a magnetic metamaterial

<u>E. Folven</u>1

1 Dept. Electronic Systems, NTNU, 7491 Trondheim, Norway

Artificial spin ice (ASI) systems with their rich behavior and potential for fundamental physics exploration, have long intrigued the research community. More recently, their potential use as substrates for energy-efficient information processing, such as physical reservoir computing, has gained considerable attention. Here, I will discuss our recent efforts to establish how collective emergent phenomena in ASI systems can support essential reservoir computing properties.

A physical reservoir to be used for computing should support certain properties. It should be nonlinear, have rich dynamics, be high dimensional and display so-called fading memory. Several of these properties are inherent to ASI systems. However, the linear, state-to-state memory, as quantified by the memory capacity measure, seems to be somewhat challenging. This property should not be confused with non-volatility, the ability to retain a state without constant input, but is rather the systems ability to “remember” past inputs.

In our research group, we have recently made a targeted effort to overcome the limited memory capacity of ASI systems. We have found that introducing directed connections within such networks is crucial for improving memory performance [1], and we have demonstrated two different approaches to achieving such directionality in these 2D arrays of nanomagnets. In this talk, I will discuss how specific domain textures in a pinwheel ASI can exhibit glider-like behavior, propagating through the array while preserving their initial shape [2] (Fig.1a). I will also show how lattice geometries can be tailored to inherently support directed domain motion (Fig.1b). We believe that these results represent important steps toward unlocking the full memory potential of physical ASI reservoirs.

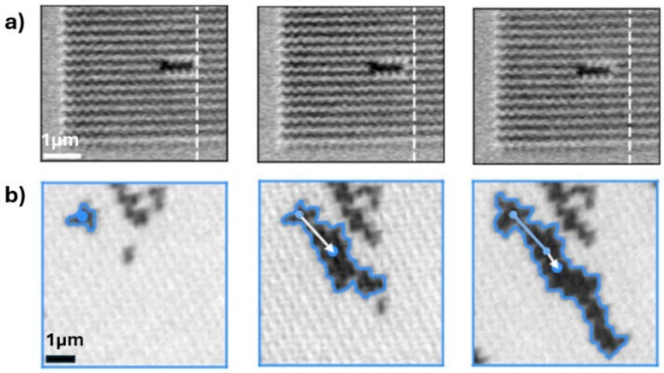

Figure 1:(a) MFM image of propagating 'snake'-glider and (b) XPEEM image of a ferromagnetic domain showing directed growth.

[1] T. Aven, J.H. Jensen, Gunnar Tufte. Proc. of the 2024 Artificial Life Conference (2024)
[2] A. Penty, , J.H. Jensen, I. Breivik et al. Nature Communications 16, 7500 (2025)

Title: Learning Nonlinear Heterogeneity in Physical Kolmogorov-Arnold Networks

Speaker Dr. Jack C. Gartside

Abstract: Physical neural networks typically train linear synaptic weights while treating device nonlinearities as fixed. We show the opposite - by training the synaptic nonlinearity itself, we yield markedly higher task performance per physical resource than conventional linear weight-based networks, and demonstrate that network topologies transferring learning to diverse synaptic transfer functions are well matched to exploit tuneable nonlinear physical dynamics for learning.

We realise this physically in silicon-on-insulator on-chip devices operating at room temperature, 0.1-1 microampere currents, and 2 MHz speeds with no observed degradation over 10^13 measurements and months-long timescales. However, the benefits of harnessing heterogenous nonlinear dynamics, and designing network architectures and physical devices tailored to exploiting them, is relevant across a broad and growing range of systems, from nonlinear lasing-based photonics, spintronics, and more.

We demonstrate higher performance than linear weight based networks across diverse tasks, with markedly higher performance-parameter scaling - requiring up to two orders of magnitude fewer parameters or devices than linear weight approaches. These results establish programmable heterogenous physical nonlinearity as a promising computational primitive for compact and efficient learning systems, ripe for deeper development.

Taglietti, Fabiana, et al. & Jack C. Gartside "Learning Nonlinear Heterogeneity in Physical Kolmogorov-Arnold Networks." arXiv preprint arXiv:2601.15340 (2026).

Liu, Ziming, et al. "Kan: Kolmogorov-arnold networks." arXiv preprint arXiv:2404.19756 (2024).

Bio:

Jack C. Gartside is a Lecturer/PI at Imperial College London, Physics, and leads the Neuromorphic Metamaterials group.

Research interests include nanomagnetism, nonlinear nanophotonics, nonlinear SOI devices, development of neuromorphic computing architectures and algorithms, magnonics & optical magnetic switching. Jack is an ERC grantee & Royal Academy of Engineering Research Fellow.

Let the Physics Do the Math: Spintronic Oscillators as Physical Combinatorial Solvers

Victor H. Gonzalez[1,2], Artem Litvinenko[2,3], Akash Kumar[2,4], Roman Khymyn[2], Johan Åkerman[2,4]

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[2]Department of Physics, University of Gothenburg, Sweden
[3]Department of Physics, Oakland University, Rochester, USA
[4]Center for Science and Innovation in Spintronics, Tohoku University, Sendai, Japan

Combinatorial optimization problems lie at the heart of many modern applications, from logistics and circuit design to finance and materials science, yet conventional von Neumann architectures remain fundamentally ill-suited to tackling NP-hard instances at scale due to the separation of memory and processing units. In this talk, we report our findings on spintronic Ising machines: energy-efficient, room-temperature hardware solvers that exploit the intrinsic nonlinear dynamics of magnetic systems to minimize an embedded Ising Hamiltonian (*1*). We focus on two complementary paradigms: spatially-resolved architectures based on spin Hall nano-oscillators (SHNOs) and time-multiplexed architectures based on spin waves in yttrium iron garnet (YIG) delay lines. In the spatially-resolved case, nanoconstriction-based SHNO arrays provide tunable Kuramoto-like phase oscillators whose pairwise coupling can be engineered via propagating spin waves and controlled through voltage-controlled magnetic anisotropy (*2*), enabling reconfigurable Ising lattices with local, hardware-level programmability. In the time-multiplexed case, we discuss a delay-line spin-wave Ising machine (*3*), supported by a delayed-oscillator model that clarifies the role of circuit nonlinearities and guides the design of scalable, densely connected networks. Taken together, these results highlight spintronic oscillators as a promising platform for next-generation unconventional computing accelerators, bridging fundamental spin-wave and magnetization dynamics with practical Ising machines capable of addressing real-world optimization tasks.

References

1. V. H. González, A. Litvinenko, A. Kumar, R. Khymyn, J. Åkerman, *Curr. Opin. Solid State Mater. Sci.* **31**, 101173, ISSN: 1359-0286 (2024).

2. A. Kumar *et al.*, *Nat. Phys.* **21**, 245–252, ISSN: 1745-2481 (Feb. 2025).

3. A. Litvinenko *et al.*, *Commun. Phys.* **6**, 227 (2023).

Go Hard(ware network) or Go Home:
Networking Spintronic Metamaterials for Neuromorphic Computation

T.J. Hayward[1]

[1]School of Chemical, Materials and Biological Engineering, University of Sheffield UK

Spintronic devices offer a promising route toward neuromorphic computing due to their inherent non-volatility, rich nonlinear and transient dynamics, and compatibility with conventional CMOS technologies. Current proposals for spintronic neural hardware typically fall into one of two camps. At one extreme are physical neural networks (PNNs), which attempt to reproduce the architecture of software multilayer perceptrons (MLPs) using large arrays of nominally identical synaptic and neuronal devices. At the other are physical reservoir computing (PRC) approaches, which treat complex spintronic systems as monolithic dynamical substrates that project inputs into high-dimensional spaces where simple linear readouts perform classification or regression. However, neither approach is without limitations. PNNs require the fabrication and interconnection of huge numbers of devices, a challenge when working with novel technologies. PRC is more easily implemented but lacks the expressivity of the massively parameterized networks used for state-of-the-art applications.

In this talk, we illustrate alternatives to this false dichotomy, showing how networking modest numbers of complex spintronic systems can produce powerful computational architectures. Building on our research into the computational properties of magnetic metamaterials [1,2], we show that their computational capabilities are significantly enhanced when multiple devices are connected into modestly sized networks. We first present a machine-learning approach for constructing noise-aware, differentiable transient models of these devices, and demonstrate how this enables the connectivity of dynamic device networks to be trained to tackle challenging time-domain problems such as neuroprosthetic gesture recognition [3]. We then present new theoretical and experimental results showing how the spin–orbit torque ferromagnetic resonance spectra of these materials can act as powerful basis functions for physical Kolmogorov–Arnold Networks (KANs) [4]. This recently introduced neural network paradigm replaces the simple linear synaptic weights of MLPs with trainable nonlinear functions, offering substantial advantages in parameter efficiency and interpretability. Collectively, these results illustrate how networking spintronic devices can provide a scalable and expressive route toward physical neuromorphic computing.

[1] I.T. Vidamour *et. al.* Communications Physics **6**, 230 (2023).

[2] R.W. Dawidek *et. al.* Advanced Functional Materials **31**, 2008389 (2021).

[3] I.T. Vidamour *et. al.* Nature Communications **16**, 9192 (2025).

[4] Z. Liu *et. al.* arXiv preprint arXiv:2404.19756. (2024)

Quantifying Information Transport in a Nonlinear Optical System

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Nonlinear optical systems are increasingly considered for computation [1]. Yet, for such systems, the question of computational relevance cannot be reduced to task-wise performance alone. Rather, it is necessary to ask which input-output mappings are physically accessible at all, how large the mapping space is under given operating conditions, and by which measurable quantities their effective complexity may be estimated. The present work addresses these questions for a fiber-based nonlinear optical system with programmable spectral phase encoding.

A programmable spectral filter encodes information in the phase of narrow bands of a femtosecond pulse. After propagation through a nonlinear fiber, the output spectra are recorded for many phase realizations [2]. For each encoding condition, the measured spectra define wavelength-resolved response functions (Fig.1) of the applied phase, which we interpret as experimentally realized input-output mappings.

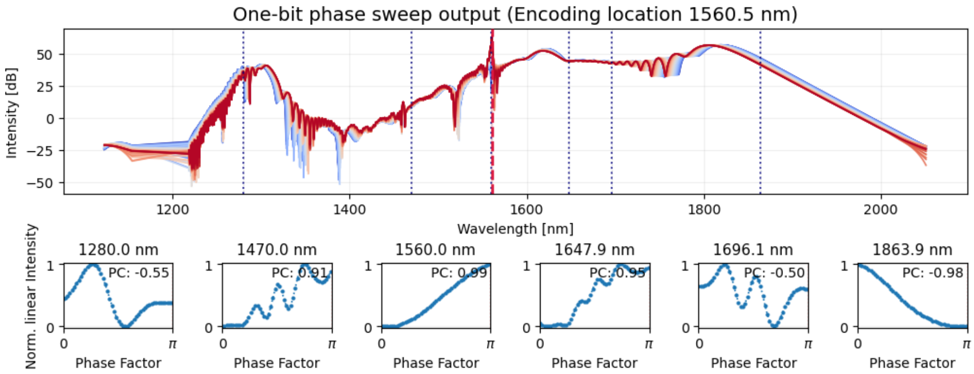

Figure 1: Wavelength-resolved response functions to a Single-bit Phase Sweep

Our aim is to estimate the effective size of the accessible mapping space. To this end, we analyze statistical dependencies between encoded spectral regions and output wavelengths using mutual information, correlation measures [3], and local sensitivity measured through the phase-dependent evolution of distances between neighboring spectral responses [4]. Furthermore, the response functions are approximated by polynomial models of increasing degree. The minimal polynomial degree required to reproduce a response within a prescribed error tolerance is used as a model-dependent proxy for its functional complexity.

Within the explored parameter range, the system remains predominantly stable but shows increasing wavelength-dependent sensitivity and fit complexity with growing optical nonlinearity. This suggests that nonlinear spectral broadening enlarges the accessible mapping repertoire and may enhance functional capacity in optical computing systems.

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Magnetic Vortices as a Platform for Magnonic Pattern Recognition and Self-Induced Floquet Dynamics

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Magnetic vortices are prototypical examples of topological textures in magnetism, characterized by a rich magnon spectrum as well as the eigenresonance of the vortex texture itself: the gyration of its core. These two types of excitations are usually well separated in frequency. This frequency separation provides a unique opportunity to study the interaction between collective spin-wave excitations and the time-periodic modulation of the magnetic ground state, while simultaneously offering a versatile substrate for unconventional computing architectures.

The intrinsic nonlinear interactions between vortex eigenmodes can be harnessed for physical reservoir computing [1]. This paradigm uses the inherent nonlinearity of physical systems to map input signals into a higher-dimensional space, rendering different patterns linearly separable, offering distinct advantages in speed, energy efficiency, and hardware simplicity. By exploiting nonlinear interactions between eigenmodes directly in reciprocal space, temporal information processing and pattern recognition become possible without requiring information transport in real space.

Combining these high-frequency eigenmodes with a time-periodic modulation of the spin texture, induced by coherent gyration of the vortex core, further enriches the dynamical complexity [2]. In this driven regime, Floquet magnon bands emerge as regular magnon modes hybridize with the temporal lattice. These excitations are distinct from both the static magnon spectrum and the vortex core resonance, representing new quasiparticles unique to driven magnetic systems.

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Innovation: Scientific Fascination vs. Industrial Reality?

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When exploring new computing paradigms, the key realization is that CMOS is no longer a design choice - it is a boundary condition imposed by six decades of technological and economic optimization.

Over the past 60 years, CMOS has evolved from a simple planar geometry into one of the most complex engineered systems. Modern front-end-of-line (FEOL) processing involves hundreds of tightly interdependent steps, co-optimized to achieve statistical stability, long-term reliability, and cost efficiency at the smallest physical scales. This degree of optimization transforms the transistor from a tunable device into a stabilized outcome of coupled physics and process control. As a consequence, even conceptually minor changes in device physics propagate into large penalties in variability, qualification effort, modeling complexity, and manufacturing cost.

From an industry perspective, this makes disruptive replacement of the CMOS transistor in high-volume manufacturing highly challenging. Instead, innovation predominantly enters through Value-Added Solutions (VAS) – including e.g. RF devices, high-voltage components, embedded non-volatile memories, photonics, cryogenic electronics, and heterogeneous integration - which deliberately preserve the optimized CMOS FEOL while introducing new physical functionality at higher abstraction levels.

Looking ahead, progress in computing will increasingly arise from combining new physics with mature CMOS platforms rather than replacing them. VAS emerges as the key interface between scientific innovation and industrial reality: it is the primary mechanism by which new computing concepts can scale, qualify, and deliver impact without destabilizing the transistor core.

The talk will provide an overview of how modern semiconductor foundries operate, illustrating the highly integrated process flows, organizational structures, and economic constraints that govern high-volume CMOS manufacturing, and will outline how VAS-based innovation can be systematically introduced into these processes.

Superconducting self-training neural network with nanosecond learning

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Superconducting electronics is a compelling technology for designing neuromorphic computing systems [1]. The technology uses the natural spiking behavior of the Josephson junctions (JJ) to transmit voltage spikes over long distances with near-zero loss. In this work, we propose a new superconducting synapse developed at NIST and demonstrate its integration in a self-learning neural network.

The artificial synapse is implemented using a SQUID-based circuit with a flux-storage loop for the synaptic weight [2]. The synapse is designed to be bipolar, meaning that the weights can be either positive or negative, enabling the implementation of a more efficient learning algorithm. Using SPICE simulations, we demonstrate that the synaptic circuit can be tuned with digital single-flux quantum pulses. We then integrate the SQUID-based artificial synapses into a small-scale self-training neural network architecture using SPICE simulations [2]. The network follows reinforcement learning rules that update local weights internally with a learning cycle of 1 ns. This property allows the network to learn new functions by changing the target output for a given set of inputs without needing any external adjustments. Finally, we present our work in progress to transition from simulation to experiment and build a superconducting self-training neural network in hardware.

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AI/ML emerging compute paradigms & next gen architectures

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The race towards the next big AI/ML application continues and even accelerates. Latest breakthroughs in generative AI and the wide application of such are driving the need for exponentially bigger models and faster data-center compute hardware. At the same time there is still the urgent need for true positive business cases. The focus in the recent past was on training with an exponentially increase in data but in order to create positive business cases soft- and hardware for efficient inference in data-centers is desperately needed. Power consumption for training was and is already plain crazy, but for inference of useful applications it is even more needed to set a limit here. The latest developments with Nvidia partnering with Groq, OpenAI with cerebras and many more new data-center inference platforms are a consequence of this. One central focus for all of these approaches is power efficiency and low-latency with near memory access, mixed precision and local compute in a mesh of processing elements and memories.

The talk discusses the key issue of memory access as well as local compute and provides a view on how current analogue and event based AI/ML hardware architectures are approaching this. The different emerging concepts are compared from system perspective, scaling, locality in time and space as well as abstraction.

The targets for such emerging concepts are set high and higher, almost on a daily bases and with unprecedent speed. To reach a competitve benchmark over classical approaches, emerging concepts needs to have a clear focus not only on device level but application and system perspective.

Complexity Analysis of FMR Driven Chaotic Magnetization Dynamics in a Nanodisk

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We investigate chaotic magnetization dynamics driven by nonlinear ferromagnetic resonance (FMR) in out-of-plane magnetized BiYIG nanodisks, where uniaxial anisotropy nearly compensates for shape anisotropy (Fig. 1a). Driving this system with a single microwave frequency triggers a self-modulation instability, which destabilizes the uniform mode due to nonlinear interactions between spin-wave modes [1]. This nonlinear coupling unfolds on a measurable, low-dimensional manifold and generates chaotic oscillations.

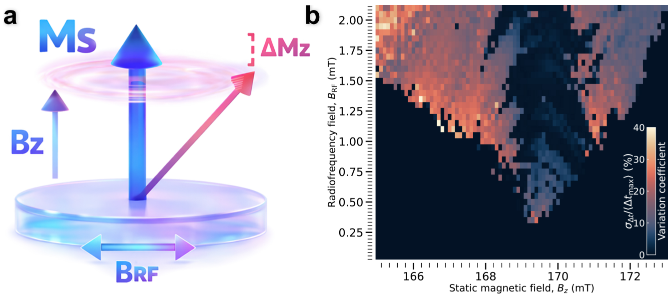

Figure 1: **a.** Schematic of the BiYIG nanodisk driven by an in-plane 5 GHz microwave field under an out-of-plane static bias. **b.** Dynamical phase diagram in the (B_z, B_{RF}) control space. The color scale shows the normalized standard deviation of peak-to-peak time intervals ($\sigma_{\Delta t}/\langle \Delta t_{\text{max}} \rangle$) of the M_z component, distinguishing periodic orbits (dark) from complex aperiodic states (bright).

By combining micromagnetic simulations and nonlinear time series analysis across the control parameter space (Fig. 1b), we map the topological transitions from stable periodic orbits to strange attractors. Extracting the full Lyapunov spectrum uncovers multiple positive exponents, revealing that the system intrinsically generates hyperchaos. This exponential phase-space divergence characterizes the unpredictable yet deterministic nature of the state, for a high rate of entropy generation. To ensure a reliable source for TRNG, raw signals undergo N-derivative processing stages before being subjected to the NIST Randomness Test Suite [2]. The streams successfully passed the standard statistical tests, establishing magnetic nanodisks as highly controllable, low-power physical substrates for unconventional computing and secure communications. This complex dynamic could be directly harnessed in CoFeB-based magnetic tunnel junctions, which would enable integrated nanoscale TRNG.

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Applications of magnetization switching by light – Towards spintronic-photonic integration

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Novel schemes for controlling the ferromagnetic state at femtosecond time scales by pulsed laser excitation have received great interest. By driving systems into the strongly non-equilibrium regime, it has been shown possible to switch the magnetization by single laser pulses – so-called all-optical switching (AOS). Based on this phenomenon, a new class of hybrid spintronic-photonic devices is envisioned [1], in which data is copied between photonic and magnetic (spintronic) domain without any intermediate electronic steps, leading to ultrafast and highly energy-efficient IT solutions.

After a brief introduction on the underlying physical concepts, progress on scientific issues that are considered key for realizing the envisioned technology will be discussed. Recent results include current-induced domain wall motion in Pt/Co/Gd-based conduits that display efficient AOS in combination with high domain-wall velocities [2], as well as first proof-of-concept demonstrations of on-chip AOS as realized in a Si_3N_4 photonic integrated circuit [3], and on-chip magneto-optical reading of small magnetic elements structured on top of InP photonic waveguides [4]. Future steps to reduce the device footprint and increase data densities, e.g. using near-field plasmonic approaches [5], will discussed. When time permits, recent work on deterministic optical creation and annihilation of skyrmions will be briefly addressed as another example of spintronic-photonic integration.

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Spin-wave mediated mutual synchronization and phase tuning of spin Hall nano-oscillators

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Generation and manipulation of propagating spin waves (PSWs) in magnetic multilayer systems have opened new frontiers for magnonics and spin-wave-based computing [1]. The precise control of frequency and phase of PSWs in nanoscopic CMOS compatible systems is of high importance for emerging applications such as reservoir computing and Ising machines [1,2,3]. Recently, spin-orbit torques have been shown to drive PSW auto-oscillations in perpendicular magnetic anisotropy (PMA)-based nano-constriction spin Hall nano-oscillators (SHNOs) [2]. Due to their long-range propagation, the mutual synchronization of SHNO, previously demonstrated in 1D chains [4] and 2D arrays [5], can also benefit from these PSWs.

In this work [6], we report spin-wave mediated variable-phase mutual synchronization in nano-constriction SHNOs, enabling both in-phase and anti-phase synchronization of their individual auto-oscillatory modes, Fig. 1a. Using W/CoFeB/MgO trilayers with PMA, SW auto-oscillations were observed and characterized via electrical measurements and phase-resolved micro-focused Brillouin light scattering (µ-BLS) microscopy. Electrical power spectral density measurements on W/CoFeB/MgO samples (Fig. 1b) with 500 nm spacing reveal distinct synchronization regimes, including constructive (in-phase) and destructive (anti-phase) interference patterns. These patterns (denoted as regions II and III) can be further controlled through the applied magnetic field and direct current. In contrast, in-plane magnetized W/NiFe systems (Fig. 1c) showed no phase control due to the absence of PSWs. Phase-resolved µ-BLS confirms both in-phase and out-of-phase states, providing conclusive evidence of long-range SW coupling. Micromagnetic simulations corroborate the experimental results and highlight the role of SW dispersion in phase tuning. Additionally, voltage-controlled magnetic anisotropy (VCMA) is proposed for localized phase control, offering a scalable mechanism for phase-tunable SHNO arrays. These findings hold significant promise for SW-based Ising machines, neuromorphic computing, and reconfigurable logic devices [1,3,6].

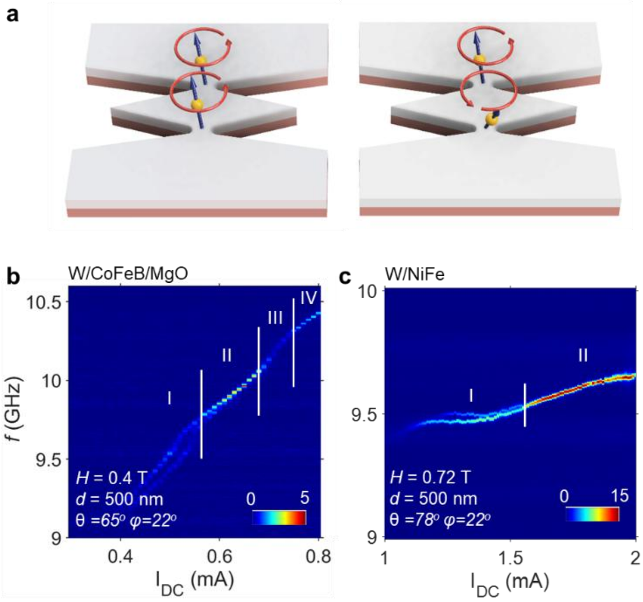

Figure 1. (a) Schematic of in-phase and out-of-phase mutual synchronization between two SHNOs. Power spectral density as a function of applied current (IDC) for two mutually synchronized SHNOs fabricated using (b) PMA based W/CoFeB/MgO thin films and (c) in-plane magnetized W/NiFe thin films.

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Dynamical stability of magnetisation and its potential use for probabilistic computing

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Spin-transfer torques (STTs) enable electrical control of magnetisation and underpin many nanoscale spintronic devices. Unlike typical external forces that modify a conservative potential to excite nonequilibrium dynamics, STTs control dissipative forces and destabilise the equilibrium magnetisation by counteracting magnetic relaxation. In this work, we maximise the STT efficiency by using dedicated CoFeB thin films with minimised magnetic anisotropy. As a result, we achieve low-current dynamical stabilisation of the magnetisation in a direction opposite to an applied magnetic field, realising a spintronic analogue of the Kapitza pendulum (Figs. a-c) [1]. I will present experimental signature of the dynamical stability including ferromagnetic resonance experiments presented in Fig. d and our analysis developed. This system with full electric control of magnetic relaxation offers sampling of the entire Bloch sphere as shown in Figs. e-g. The resulting continuous, stochastic magnetisation state provides a natural resource for probabilistic computation and neuromorphic architectures [2].

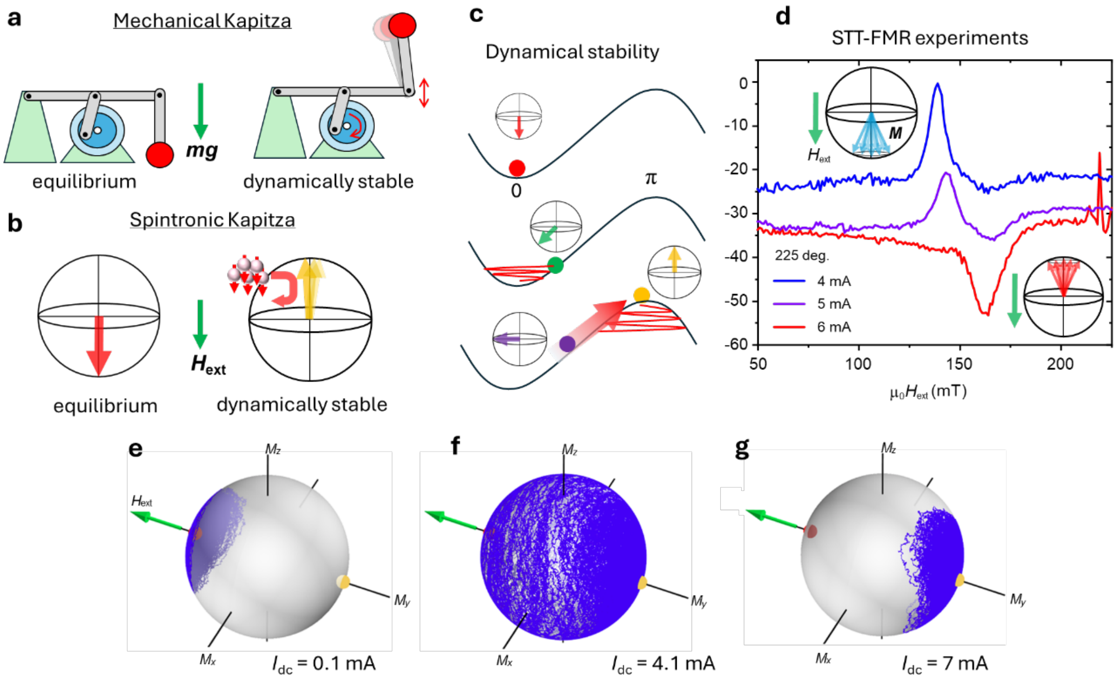

Figure caption: **a-b**, Schematic of mechanical and spintronic Kapitza pendulums. **c.** Magnetic energy diagram and dynamical stability. **d.** spin-torque ferromagnetic resonance experiments with dc currents. **e-f.** Simulated magnetic state distributions with different STT drive strengths.

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Magnetics and Ferroelectrics based Physical Reservoir Computing for Energy-Efficient Time-Series and Multimodal Artificial Intelligence

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Abstract:

Physical reservoir computing (PRC) is a brain-inspired method that uses the natural properties of materials, like memory and nonlinearity, to efficiently solve time-based problems. It significantly reduces power and hardware needs compared to traditional AI. We're developing two PRC systems demonstrating this capability.

One system uses electric field control magnetic skyrmion states as PRC, enabling a rich, nonlinear response for time-series data. It achieved 99.3% accuracy in waveform recognition and predicted chaotic signals with low error (0.2) [1]. Adding parallel reservoirs further reduce the prediction error from 0.5 to 0.23, showing temporal and spatial co-multiplexing boost performance without increasing power [2].

The second system, featuring PZT (a ferroelectric material), focuses on multimodal recognition for spoken digits, handwriting, and typed words. It showed strong individual accuracies (e.g., 91.3% for images, 90.3% for words) and a remarkable 98.0% when combining all three input types. This system remains reliable even with missing or noisy data.

Leveraging magnetic and ferroelectric materials, these two systems demonstrate significant potential for creating intelligent, energy-efficient computing units. Their intrinsic low power consumption, derived from materials naturally processing signals, positions them as ideal candidates for advancing AI.

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Reservoir Computing with Dynamical Systems in Optics and Electronics

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Time-multiplexed reservoir computing (RC) allows to utilize the dynamical response of physical systems to a given input in time. This sequential analog computing approach, with only one linear regression step for training, is specifically suited for time series forecasting and a large variety of physical system can be used. Lasers with optical self-feedback exhibit complex emission dynamics and are one example for photonic RC where only one single physical node is needed [1,2]. By tuning the feedback parameters, the dynamic response of the laser is changed (Fig.1a), which is important to optimize the performance on a given task (Fig.1b,c show prediction performances on two tasks that are optimal at different operation points).

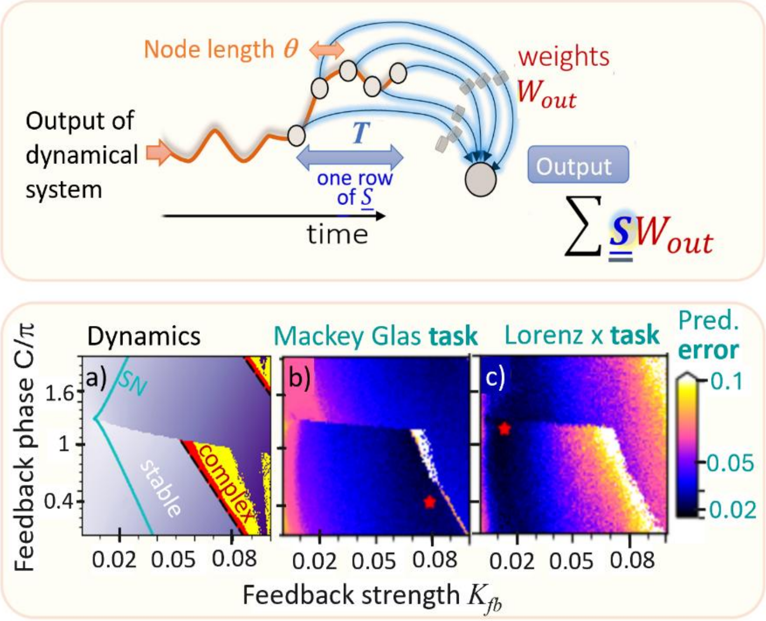

Figure 1: Top: Readout scheme for time-multiplexed RC with dynamical systems where the response in time is sampled and written into the state matrix $\boldsymbol{S}$ *at a rate of* $1/\theta$*, data is injected at a rate of* $1/T$ *with* $T=N\theta$ *and linear regression yields* W_{out}*.*

Bottom: Prediction performance (NRMSE) for a laser with self-feedback showing (a) dynamic response without input and (b,c) performance in the feedback-parameter plane for two different prediction tasks [2].

System response time and task requirements critically influence optimal RC conditions. By investigating different dynamical systems, i.e. Quantum-dot laser systems as photonic examples, Josephson junctions as superconducting devices capable of reproducing key neuronal traits, and spiking resonant tunneling diodes that operate in the electronic domain, we outline how to best utilize the intrinsic dynamics. Key findings are that a clear understanding of the *bifurcation structure* of the physical RC system is crucial to simplify hyper parameter searches; *data input schemes* significantly change the performance of the physical RC system by altering perturbation direction and nonlinearity; and *memory properties* of the RC can be augmented via external delay lines to adjust the RC to new tasks without changing the setup.

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Machine Learning with Equilibrium Propagation.

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In 2017, Scellier and Bengio introduced Equilibrium Propagation, a machine learning algorithm in which the stationary state of a dynamical system performs the computation. A simple illustrative example involves a network of masses coupled by nonlinear springs. Learning is implemented by tuning the spring constants in such a way that the ground state of the network implements the desired input-output map. I will present the basic principles of the Equilibrium Propagation algorithm and discuss several recent extensions. These include quantum systems, finite temperature systems, the extension to time-dependent Lagrangian dynamics, and the case of nonreciprocal forces. These developments broaden the applicability of Equilibrium Propagation, making new connections between machine learning, quantum mechanics, statistical physics, and dynamical systems theory.

Wireless programming of weights by broadcasting in frequency-selective spintronic neural networks

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In-memory computing removes the need for data transfer between memory and processing units, but programming such memories in dense arrays remains challenging. The reliance on selector transistors or individual access lines in crossbar architectures, as well as spintronic and photonic networks, increases circuit complexity thus limiting scalability.

Here, we propose remote programming of spintronic synapses using a broadcast radiofrequency (RF) signal, removing the need for individual access. We program the polarity (up or down) of vortex-based magnetic tunnel junctions (MTJs) with a resonant oscillating signal [1]. We connect 11 MTJs of different frequencies (200 to 700 MHz) in series into a synaptic chain. Leveraging the frequency selectivity of the programming, we inject the programming RF signals into a single metallic strip-line capacitively coupled to the chain. Thus, we demonstrate the individual programming of the 11 MTJs.

Then, we assemble two synaptic chains of 11 MTJs into a neural network to perform classification. We send inputs as RF signals, using frequency multiplexing as shown by Ross et al [2], through the metallic strip line of each chain. We demonstrate that we can reconfigure the network to perform two different classification tasks: 8×8 images of handwritten digits 0 and 1 with 94.9% accuracy, and RF signatures from two types of drones with 97.3% accuracy.

By removing the need for individual physical access, this approach provides a scalable route toward ultra-fast, compact neuromorphic hardware capable of on-the-fly reconfiguration.

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Reservoir computing performance via nonlinearity-induced spin waves

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The central concept of reservoir computing (RC) is that high-dimensional spatiotemporal responses generated by an information reservoir enable the construction of a concise machine-learning framework in conjunction with a linear learner endowed with adjustable weights. The role of a reservoir is to nonlinearly transfer a series of input data into a high-dimensional temporal output vector under fading memory influence. This is common for software-based echo-state networks and hardware-based physical reservoirs. On the other hand, in the case of physical reservoir, it is necessary to convert dimensionless data with discrete time steps to physical quantities with continuous time, and vice versa, twice in the entire computational system, which introduces significant complexities in finding specifications for physical dynamics. The demonstrations of physical RC so far have gradually clarified that nonlinear phenomena driven by a time-step duration less than the relaxation of the physical dynamics is a key to successful computing, however, methods for their tuning and quantitative analysis on the relationship between physical phenomena and computational capacities have not been established, posing a common challenge across the field.

A continuous magnetic insulator film is regarded as an excitable-media reservoir since spin waves in response to serial input stimulus create a spatiotemporal magnetization distribution that eventually disappears. In other words, a spin-wave-based reservoir is essentially “information reservoir” and thereby has great potential for high-performance reservoir computing. Furthermore, for long-term practical applications, utilizing fatigue-tolerant properties such as electron-spin-related quantities is highly desirable. Thus, the collective dynamics of magnetization offers an inherent advantage over other memristive reservoirs in terms of robustness and reliability.

So far, we have proposed a spin-wave-based RC device using a continuous ferrimagnetic $Y_3Fe_5O_{12}$ (YIG) film with a thickness of 320 nm and numerically demonstrated its high computing capabilities. An advantage of physics-based simulation enables to detect the spatiotemporal magnetization distribution driven by one input electrode, using 120 output electrodes regularly arranged on the YIG surface with 12 μm × 12 μm in area. When the dynamics is suitably controlled by stripe magnetic domains and the input signal expression, such as the amplitude and time duration for a discrete time step, our device achieves high computational performance comparable to state-of-the-art values using bulk optical RC systems, in various RC tasks from fundamental to application-oriented ones, e.g., temporal XOR tasks, 10th-order nonlinear autoregressive mean average (NARMA-10) prediction tasks. Nonlinear phenomena in the output signals under the various input conditions were characterized by discrete Fourier transformation (DFT) to find that excessive strengths of nonlinear phenomena degrade computational performance.

More recently, we have experimentally studied spin-wave-based RC using a 3-μm-thick YIG film with 10 coplanar antennas on the surface, where two regimes were explored: one input antenna with 9 output antennas and two input antennas with 8 output antennas. Owing to practical constraints of the total antenna number, the virtual node method was applied to increase the dimension of the reservoir output vector up to 360. Using the DFT signals calculated from all the output signals, linear and nonlinear phenomena relevant to spin-wave propagations were characterized. As in the case of physics-based simulation, excessive strengths of nonlinear phenomena were found to degrade computational performance. In basic benchmark tasks, delay tasks and temporal exclusive XOR tasks, a trade-off between linear and nonlinear computational capacities was clearly shown, indicating that moderate nonlinear phenomena are crucial to realize high computational performance.

The presentation will provide a detailed analysis of the interplay between physical dynamics and computational performance, offering insights into the tuning of nonlinearity in spin-wave reservoirs.

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Taming and Exploiting the Physics of Memristors

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Memristors (or oxide-based RRAM) are a promising substrate for analog in-memory computing, where crossbar arrays implement matrix-vector multiplication directly through Ohm's and Kirchhoff's laws. This tight device-algorithm match has enabled convincing large-scale inference demonstrations, but it also exposes a core challenge: memristors are difficult to program precisely. Variability and stochastic filament dynamics typically require iterative program-and-verify loops, with penalties in latency, energy, and endurance. I will argue that a route to robust systems is to embrace, rather than fight, device physics. First, I will show how memristor variability can become a computational resource in Bayesian neural networks (BNNs), where synapses are probability distributions instead of fixed weights. I will discuss strategies to cope with the device-level coupling between mean weight and uncertainty, and illustrate the approach with prototype BNN demonstrations, including arrhythmia identification [1].

I will then address the next grand challenge: on-chip learning. I will present an approach that exploits an underused operating regime of standard filamentary HfOx/Ti stacks: sub-1 V reset-only updates, where repeated pulses progressively erode an existing filament. Combined with forward-only training, this enables array-scale learning (up to 8,064 devices) with 89.6% accuracy on an ImageNet-resolution transfer task, ~460× lower update energy than program-and-verify, and accuracy retention for at least one month [2]. Finally, I will place these results in a broader HfO2 co-design vision: ferroelectric HfO2 as an ultra-low-energy, high-endurance short-term substrate for accumulating updates (despite destructive read), paired with memristive HfO2 for stable long-term storage, suggesting a workflow from short- to long-term memory [3].

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Monolithic spintronic-photonic integration for optical control of on-chip magnetic memory

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Spintronic memory offers non-volatile data storage by encoding information in magnetic materials. Integrating such concepts within photonic integrated circuits (PICs) provides additional functionality to the photonic platform, while avoiding energy-intensive electrical–optical conversion steps when information is transported optically. In addition, optical control of spintronic devices offers an option to bypass the spin-precessional dynamics that limit conventional magnetic writing schemes, as well as the constraints associated with charge-based transport readout. Recent advances at the intersection of photonics and spintronics have therefore opened new opportunities for hybrid magneto-photonic memory devices capable of ultrafast all-optical switching (AOS) [1] of magnetization on femtosecond timescales and all-optical readout (AOR) of magnetic states via the magneto-optical Kerr effect (MOKE) [2,3].

Here, we focus on the integration of spintronic elements into PICs to realize stable on-chip all-optical toggle switching and to enhance AOR using plasmonic nanoantennas for efficient, contactless detection with sub-diffraction-limited spatial resolution. In particular, we address the deterministic verification of ~100 nm magnetic domain patterns in Pt/Co heterostructures patterned via Ga^+-ion irradiation. We further discuss the implementation of proof-of-concept on-chip AOS and AOR on silicon nitride (TriPleX) and indium phosphide (IMOS) photonic platforms, respectively.

This monolithic integration establishes universal building blocks for direct optical control and readout of magnetic domains without intermediate electrical conversion, thereby reducing energy dissipation and enabling faster operation. Moreover, combining AOS and AOR with current-induced domain-wall motion offers a pathway toward optically driven racetrack memory, in which ultrafast optical writing and contactless optical readout are seamlessly coupled. Such an approach provides a promising framework for next-generation, fully integrated on-chip magnetic memory with low energy consumption and ultrafast performance.

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New Models of Computation to support Novel Physics-based Computing Devices

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Novel physical devices offer intriguing new possibilities for new forms of computation. However, such novel devices are often exploited through conventional models of computation, such as Boolean logic, reservoir computing, and the like. Using such conventional models with unconventional devices may result in those devices not being exploited to their full, novel potential.

Here I discuss our methodology for devising new models of computation based on the physical capabilities of novel devices and materials. This approach is based on the Abstraction/Representation Theory definition of when a physical system *computes*, rather than is merely behaving as a material device (Horsman et al, 2014). This theory provides the framework for defining a "top down" method, for designing a substrate that conforms to a computational model (Stepney, 2024), and a "bottom up" method, for defining a model of computation and associated Domain Specific programming Language based on a given device and/or material.

I describe the bottom-up method in the context of our ARIA-funded project LoCoMo (Lossy Computational Models). We are using this approach to define a computational model suitable for exploiting lossy photonic systems that implement boson sampling and some forms of machine learning.

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On-chip Training of Stochastic Multilayer Spintronic Neural Networks

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Developing energy-efficient AI systems requires the integration of on-chip learning within physical neural networks. Stochastic spintronic neurons, particularly coupled superparamagnetic tunnel junctions (SMTJs)[1,2], provide a promising hardware platform due to their thermally induced stochastic magnetization fluctuations, which inherently emulate binary stochastic neurons at the nanoscale. In this work, we present the first experimental demonstration of a binary classification task performed using a network of SMTJs. Our approach leverages the intrinsic stochasticity of SMTJs to process binary inputs and produce classification outcomes. The network architecture is designed to exploit the probabilistic switching behavior of SMTJs.To facilitate network learning, we implement a local rule inspired by Equilibrium Propagation [3-4], allowing us to avoid the energy-intensive data shuffling typically required in neural network training. By interfacing SMTJ arrays with electronic control circuits, we demonstrate the network's ability to learn and classify binary patterns in real time. Our experimental results showcase the robust performance of SMTJ-based networks in performing binary classification tasks, highlighting the potential of spintronic neurons for implementing on-chip learning in hardware-based neural networks. This advancement paves the way for scalable, low-power neuromorphic and Ising-based systems capable of real-time processing and training.

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Multi-value probabilistic computing using current-controlled, AC-field-enhanced skyrmion diffusion

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Magnetic skyrmions are topologically stabilized spin textures with enhanced stability and rich dynamical behavior. Their intrinsic stochasticity and controllable diffusion make them attractive building blocks for unconventional computing paradigms, including stochastic computing, Brownian reservoir computing [1], and probabilistic computing [2]. In realistic devices, the pinning sites can be harnessed as a tunable resource for computation, in which both the metastable states and the transitions between them can be tuned reliably.

Here we investigate thermally activated hopping of a single skyrmion between voltage-tunable pinning sites and quantify the confined dynamics using Markov State Models [3]. Voltage control reshapes the stationary distribution, enabling a multistate probabilistic computing platform. As a proof of concept, we realize an invertible OR gate. With the output clamped, the system samples the set of input states compatible with that output, demonstrating inverted computation in a voltage-programmable energy landscape.

We then mitigate the mobility limitation caused by pinning by applying oscillating out-of-plane (OOP) magnetic fields [4] to enhance transitions in confinement. The diffusion constant increases by more than one order of magnitude and exhibits a pronounced maximum at a specific driving frequency. We attribute this resonance-like response to stochastic resonance from the interplay between thermal noise and periodic OOP excitation; micromagnetic simulations qualitatively reproduce the resonance peak. Together, these results show that voltage-programmable landscapes enable multi-value probabilistic logic, while OOP driving provides an effective handle to enhance skyrmion transitions for faster skyrmion-based computing.

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Abstracts of Posters

(in alphabetical order)

Controlling magnetic skyrmions Brownian motion through Focused Ion Beam patterning

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In Beyond-CMOS device research, magnetic skyrmions, particle-like topological spin textures, received great attention due to their nano-size, high stability and low power manipulation, which makes them potential carriers for logic and memory devices. This work revolves around the study of magnetic skyrmions Brownian motion, an intrinsic feature of skyrmions that could be harnessed in unconventional computing paradigms. The study of skyrmions moving with Brownian motion is carried on sputtered *W/CoFeB/MgO/Ta* thin films, irradiated with Gallium ions [1].

The regulated disorder systematically introduced by ions improves skyrmions' diffusivity. Indeed, analyzing the Mean Square Displacement of skyrmions trajectories, it resulted that pinning forces, which trap skyrmions at defects, are reduced with higher amounts of implanted ions. Controlling the diffusivity of skyrmions through irradiation is a reliable way to make use of random fluctuations in a room-temperature system, and with a technology that is highly compatible with existing CMOS technologies.

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Development of a hybrid CMOS-spintronic crossbar architecture for small networks of interconnected spintorque nano-oscillators: application to Ising machines

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Spintorque nano-oscillators (STNO) are nano-scale microwave devices that are promising for physics based computing applications. These applications require coupling of STNOs into a network of interconnected devices of variable coupling strength. For STNOs, two types of coupling schemes can be envisaged: direct electrical coupling or coupling via a field line antenna, see Fig. 1a, that is nanofabricated on top of the STNO device. The latter scheme has the advantage of being able to decouple the input signals for driving the STNO auto-oscillations from the coupling signals coming from other STNO devices. Consequently it allows read-out of the individual STNO responses, and for the specific case considered here the STNO phase. We have recently developed such an experimental setup using a PCB-based coupling matrix, see Fig. 1b,c, to couple up to five STNOs through variable resistances R_{ij} that allow control of the mutual coupling between all pairs of STNOs i and j (i, j = 1…5). Here, the microwave voltage output of a given STNO i is fed, via the variable resistance R_{ij} into the fieldline antenna of STNO device j. If needed, besides the variable resistance other microwave components can be inserted into the coupling path, such as amplifiers or phase shifters. This setup is used to demonstrate a hardware implementation of an Ising machine, based on synchronized and mutually coupled STNOs [1]. Ising machines (IMs) are physics-inspired computing platforms that can efficiently solve combinatorial optimization problems (COP). Energy minimization of a coupled network of binary-valued Ising spins s_i, naturally leads to solutions of COPs, encoded in the spin-coupling interactions J_{ij}. An alternative scheme uses the stochastic phase dynamics of synchronized and coupled STNOs [2] to infer the lowest energy states from the maxima of the resolved probability distribution.

The developed experimental setup, using a PCB coupling matrix, is a first step to validate this type of physics-based computing with STNOs. However, for practical applications, the tunable coupling matrix as well as all associated electronic circuitry needed for the input (DC biasing circuit, microwave signal for synchronisation) and output (phase readout) should be co-integrated on a single chip with the STNO devices. For this we have designed and fabricated a crossbar coupling matrix, see Fig. 1d, where variable resistances are realized through transistors. Besides realization of a CMOS circuitry, it is necessary to characterize the microwave transfer function of all components and parts of the setup, to insure proper transmission of microwave signals. Here we will present first results obtained for the PCB-based and CMOS-based coupling matrix and discuss the different issues for the full implementation. This realization represents a significant step towards a full hybrid CMOS-spintronic computing system based on STNOs, that can also be exploited also to study the collective dynamics of a coupled STNO network.

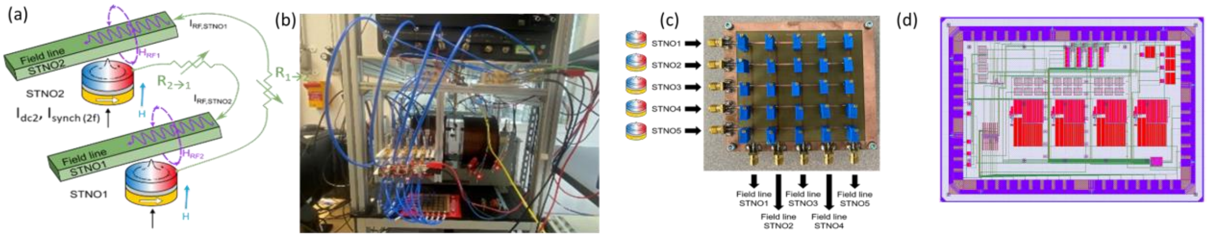

Fig. 1: (a) Schematic showing the mutual coupling of two STNOs via a fieldline, (b) experimental setup for the Ising machine where the coupling can be realized by a PCB or CMOS cross bar coupling matrix, (c) PCB crossbar coupling matrix, (d) layout of the developed hybrid CMOS-spintronics based coupling matrix.

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Delay-embedding in spatio-temporal optical reservoir computing

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Optical data processing has many advantages. In addition to processing speed, parallelism and energy efficiency, it offers several possibilities for implementing new computing paradigms. One of these is brain-inspired reservoir computing. The backbone of this computational method is a sparsely connected recurrent neural network, the reservoir, which maps (sequential) inputs into a high-dimensional state space and then outputs data to predict e.g. time series. In contrast to other machine learning methods, the output weights are trained only. We present an optical implementation of a reservoir computing model based on a free-space laser imaging system [1]. The setup employs a spatial light modulator (SLM) as optical input device which, in combination with two polarizers, enables nonlinear processing of the reservoir state vectors. Owing to its full-HD resolution, the SLM provides sufficient pixel density to process large datasets in parallel without requiring dimensionality reduction. Within this framework, we systematically investigate how the arrangement of data on the SLM influences the prediction performance of the system. By simultaneously encoding the current input and the reservoir states from the previous prediction step on the same SLM frame, we implement a recursive image within a single optical pass. This parallel processing creates a cascading short-term memory, effectively realizing a delay embedding that enhances the network's memory capacity and improves predictive performance over a broad parameter range. The resulting multi-level representation of past time steps is particularly well suited for forecasting chaotic time series. The key hyperparameters are the size of the input array and the number of implemented delays. To evaluate the capabilities of our approach, we investigate the performance of the system on time series data obtained from the 1d Kuramoto-Sivashinsky equation..

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Spatial Reservoir Computing

Based on Spin–Orbit Torque Driven Skyrmion Motion

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Skyrmions are nanoscale, topologically protected magnetic textures whose stability, nonlinear dynamics, and particle-like behavior make them promising candidates for neuromorphic computing.

Our goal is to exploit spin-orbit torque driven skyrmion motion [1] as a physical substrate for spatial reservoir computing.

The proposed approach implements a physical reservoir using magnetic textures hosted in patterned spintronic devices. In spatial reservoir computing, computation is performed by a high-dimensional, nonlinear physical system, while only a simple readout layer is trained. This avoids the high training costs of recurrent connections typical of recurrent neural networks. Physical reservoirs must exhibit nonlinearity, short-term memory, stability, and high dimensionality, those properties are naturally present in skyrmion-based systems.

The studied sample consists of a Ta/FeCoB/TaOx multilayer where skyrmions and meander domains can be stabilized. The device is patterned into multiple tracks with different shapes and widths, creating gradients in current density. When electrical currents are applied, skyrmions exhibit nonlinear velocity responses and hysteretic behavior, providing both nonlinearity and memory [2]. Magneto-optical Kerr effect microscopy is used to monitor the magnetic textures and evaluate the dynamic response of the system.

High dimensionality is achieved through spatial multiplexing: different regions along the tracks experience distinct current density regimes. By sampling multiple areas of the MOKE images, the system exploits a range of nonlinear skyrmion dynamics, increasing the number of effective neuron channels.

The reservoir is tested on simple classification tasks such as distinguishing sine-wave from square-wave input signals. Only the output weights are trained using linear regression. Using random sequences of sine and square waves, the system achieves classification accuracies of up to 85%. Further improvements are expected by increasing the effective dimensionality through enhanced image analysis.

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Exploring Reinforcement Learning for Particle Transport in the Presence of Inhomogeneities

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Classical transport theories typically assume homogeneous media, yet real materials often exhibit inhomogeneities that limit the applicability of such models [1]. In particular, standard approaches like renormalization may fail when particles encounter defects whose characteristic energy scales are comparable to or larger than their kinetic energies. We investigate reinforcement learning as a data-driven framework for optimizing particle transport in strongly inhomogeneous environments [2]. Our work indicates the potential of reinforcement-learning-based approaches for particle dynamics in more realistic and complex systems.

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Study of coupled spiking magnetic tunnel junctions

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Magnetic tunnel junctions (MTJs) exhibit various types of dynamic properties that can be exploited to design new computational approaches. One promising opportunity concerns spiking neural networks, a computational approach inspired by the human brain, where information is encoded and transmitted by discrete electrical pulses between neurons. For artificial intelligence-based applications, these structures are more suitable than the classical von Neumann architecture, offering potential gains in terms of performance and energy consumption [1].

For this purpose, we have demonstrated that a single junction comprising two perpendicularly magnetized free layers, due to mutual internal coupling between the active layers, can produce resistance spikes reminiscent of biological neurons [2]. These spikes can vary in frequency and width depending on the operation point (e.g., injected current, applied magnetic field), and therefore change when several spiking MTJs are connected electrically. Magnetic tunnel junctions are already relevant candidates for true random number generation [3] and Ising machine implementations [4], demonstrating their inherent advantages such as high speed, low power consumption, stochastic behavior, and CMOS compatibility.

In our work, we characterized the windmill regime of a single MTJ using field-current phase diagrams and applied this knowledge to simulate coupled junctions. The results obtained with two identical junctions already reveal key information about their mutual interaction: the resistance state of one junction alters the current distribution, which can either suppress or trigger spiking in the other. By choosing an appropriate operating point, this effect can be controlled. Future work will generalize the approach to non-identical junctions, larger arrays, and different coupling topologies (parallel or series), ultimately aiming to provide tunable coupling for spiking neural network applications.

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Advances in YIG-on-GGG Spin-Wave Fabrication

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Yttrium-Iron-Garnet (YIG) is a key material for emerging spin-wave (SW) based computing due to its exceptionally low damping and long propagation distances [1], [2]. The highest reported SW resonator quality factors (Q-factors), indicative of SW waveguide losses, are achieved with thin-film single-crystal YIG grown on lattice matched Gadolinium-Gallium-Garnet (GGG) substrates via liquid-phase epitaxy (LPE). However, microfabrication techniques are limited and less mature than those used by silicon-based CMOS logic. In particular, through-vias are not possible with conventional top-side metal lift-off processes used to form SW transducers in the YIG-on-GGG (YoG) platform. To scale SW computing beyond individual gates and simple logic operations, robust signal routing techniques must be developed to transport microwave signals across the chip between each SW logic gate.

In this work, we present recent advances in microfabrication techniques for the YoG material platform [3]–[5]. We demonstrate high-aspect ratio etching of $3\,\mu\mathrm{m}$-thick LPE YIG with feature widths and spacings down to $1.4\,\mu\mathrm{m}$ enabling precise SW dispersion control. Furthermore, we realize through-GGG-vias enabling microwave signal routing on both sides of the chip with low-loss patterned electroplated gold. Using these processes, we showcase edge-coupled SW filters [5], high-performance SW resonators with Q-factors exceeding 2600, and SW ladder filters [3], [4]. These microfabrication advances establish a platform for wafer-scale nonlinear SW computing enabled by low-loss resonators, dispersion engineering, and robust microwave signal routing.

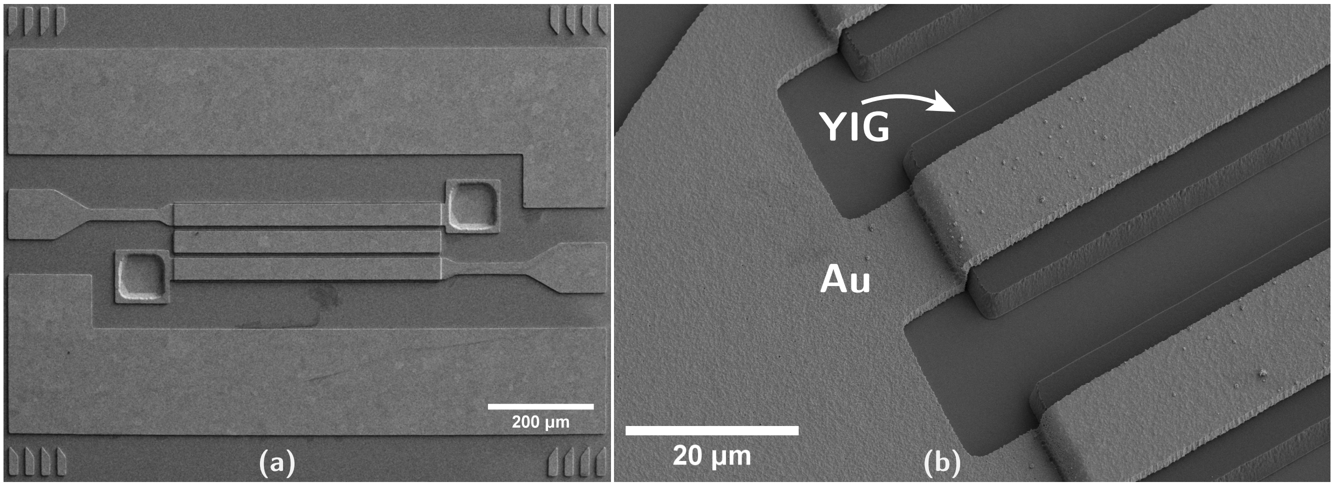

Fig. 1: **(a)** SEM of an edge-coupled spin-wave filter consisting of three $3\,\mu\mathrm{m}$-thick YIG resonators separated by $1.39\,\mu\mathrm{m}$ gaps. Electroplated gold transducers conformally over top of the etched YIG excite the spin-waves. Two through-GGG-vias connect the topside transducers to a ground plane on the backside of the chip. **(b)** SEM of an array of $20\,\mu\mathrm{m}$-wide YIG cavities separated by $10\,\mu\mathrm{m}$ with $1.5\,\mu\mathrm{m}$ thick patterned Au transducers.

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Self-induced Floquet states via three-wave processes in synthetic antiferromagnets

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We present a mechanism for self-induced Floquet states involving acoustic and optical modes in synthetic antiferromagnets. By driving optical modes off-resonantly with radiofrequency fields in the canted antiferromagnetic state, limit cycles arising from the predator-prey dynamics of the acoustic and optical mode populations can appear. The cyclic growth and decay of these mode populations induce a time-periodic modulation of the canted state, which subsequently generates Floquet states. These states appear as a rich frequency comb in the power spectrum of magnetization oscillations.

Diffusion-Based Surrogate Models for Optimising and Inverse Design of Physical Computing Systems

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Designing a physical computing substrate for a physical reservoir computer [1] means finding device parameters, such as geometry, material properties, drive conditions, etc., that maximise computational performance. This requires either exhaustive physical measurement or a numerical simulation—the latter demanding knowledge of governing equations that is often unavailable. We demonstrate that diffusion models [2,3]—a class of deep generative model—can be trained on observed device response data alone to learn system dynamics and serve as differentiable surrogates for the physical substrate. Conditioned on physical parameters, these surrogates accurately reproduce deterministic, stochastic and chaotic dynamics. The models are also differentiable with respect to these physical parameters, so device optimisation reduces to experimental data collection followed by gradient descent through the learnt model. We validate this on the stochastic, damped, driven Duffing oscillator, recovering the periodic forcing amplitude from an ensemble of trajectories with a mean absolute percentage error of 5.74% ± 3.9%, with 95% of the 100 total trials below 12.3% error. We further apply the framework to model spintronic nanoring reservoir computing devices [4], and to optimise hyperparameters to find the best configurations from experimental observations. For any physical substrate where parameters can be controlled and trajectories measured, this framework offers a practical route to systematic, data-driven optimisation without repeated physical experimentation or knowledge of the underlying dynamics.

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Small-Form-Factor Peripheral Circuitry for Hybrid Magnonic Systems

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Countless different magnonic devices with diverse applications have been proposed and demonstrated in recent years. However, these demonstrations typically rely on large, expensive measurement equipment, such as vector network analyzers, spectrum analyzers, or instruments that use the magneto-optical Kerr effect. All mentioned read-out techniques are not feasible for integration into real-world applications. This work proposes multiple peripheral radio-frequency circuits for hybrid magnonic systems that can replace expensive measurement equipment in both lab-scale experiments and stand-alone demonstrators. Using diode-based power detection as a core feature, amplitude-encoded information can be digitized, enabling the integration of magnonic devices into traditional charge-based systems. The suggested technology utilizes printed circuit boards, which are widely available and scalable at low cost. As shown in Figure 1, the highlighted small-form-factor design embeds a magnonic device into the peripheral system using bond wires. Thus, this work enables the exploitation of magnonic device capabilities in hybrid systems through a cost-effective, small-form-factor, and scalable methodology. Hence, the technology catalyzes advanced spin-wave-based neuromorphic and analog computing, as well as low-power signal processing at the gigahertz regime.

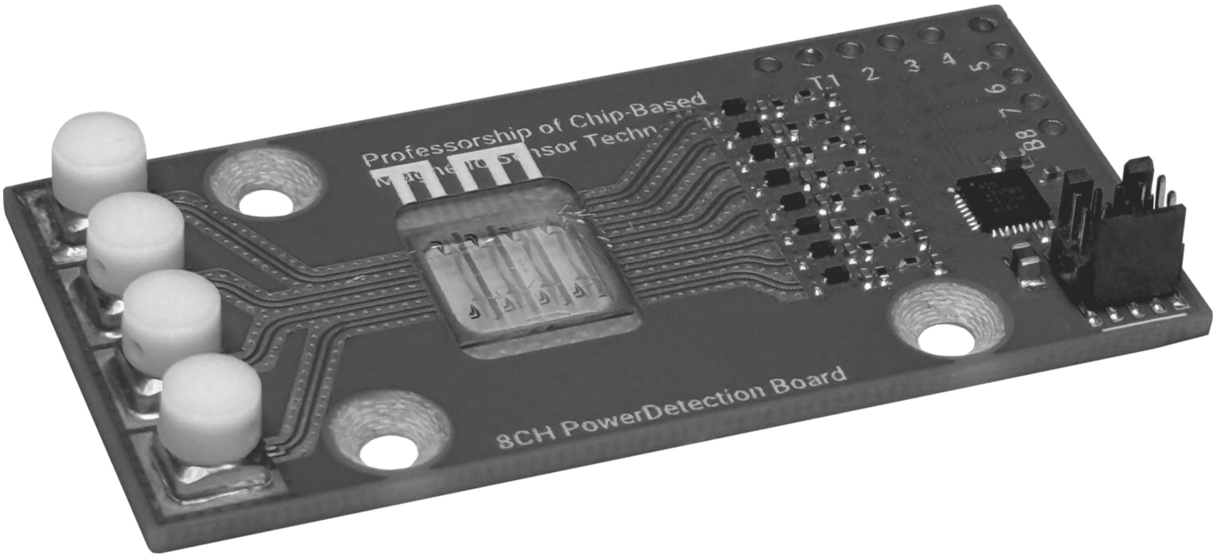

Figure 1: 8-Channel Power Detection Board with a spin-wave device implanted in the middle. On the left, four connectors allow for radio-frequency input signals, and on the right, eight parallel power detectors feed the analog-to-digital converter in the bottom right corner. The board is connected to a microcontroller through the connector on the bottom right to read out the digitalized data. Mechanically, it measures 6cm by 3cm.

All-optical switching in liquid crystals through order parameter modulation

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Demands for comprehensive and extensive computing have been steadily increasing recently at an ever greater pace, even besides the AI bubble, for such routines as machine learning in many an application. Common opinion suggests the next generation of communication and information technologies to be all-optical, i.e. data transmission, processing and storage will be handled with light. That requires light-controlled photo-responsive media, in other words, systems revealing nonlinear optical properties.

Nowadays, liquid crystals (LC) seem omnipresent in display systems; the vast majority of modern optoelectronic and photonic LC-applications employ the realignment of the LC director to control the effective birefringence and manipulate the flows of light benefiting from large birefringence and easy response to external fields influence.

Intrinsic elasticity of LC medium, however, makes the nonlinear optical response associated with reorientation of the optical axis to be quite slow and substantially nonlocal, effectively decreasing the real resolution, obstructing, thus, the optical information processing whilst a strict one-to-one correspondence between the light intensity and refractive index modulation is required.

Photo-induced changes of the LC order parameter taking place at much shorter temporal and size scales provide a superior alternative to the light-induced LC director reorientation. The phenomenological model of Light-Induced Order Modification (LIOM) is presented that accounts for the modulation of the refractive indices emerging due to the photo-induced changes of the LC order parameter. This extremely fast as for LC systems nonlinear optical mechanism was successfully employed to explain the experimentally observed large optical nonlinearities [1].

The LIOM-type processes do not depend on the cell thickness and furnishes really fine resolution. It encompasses a widest range of wavelengths and, since the optical read-out is spectrally independent from the pumping, could be employed for fast control of waves, besides optical, in the IR range, THz and beyond.

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Floquet states modulation in spin-torque oscillators for unconventional computing

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Floquet states arise in periodically-driven systems and represent time-periodic solutions analogous to Bloch states in crystals. For example, time-periodic driving of quantum materials has proven to be useful for inducing nonequilibrium topological phenomena. Recently, it has been shown that vortex gyration in thin-film disks can also give rise to magnon Floquet states [1,2]. These states evolve from the scattering of linear eigenmodes with the core gyration, resulting in rich spectra featuring frequency combs with a strong dependence on the azimuthal number m.

In this work, we discuss Floquet modes in spin-torque vortex oscillators in which the background magnetization state is nonuniform. In addition to a regular vortex state, we also focus on a rotating C-state [3] magnetization which can be likened to vortex gyration but with a virtual core outside the disk. We perform a numerical study on permalloy disks of various sizes using the open source micromagnetic code MuMax3 [4].

In a vortex free layer, Floquet modes can be generated as desrcibed in [1,2]. Our main focus is to exploit the properties of the oscillator in order to control and tune the Floquet frequency combs. We show that by applying a current through our oscillator, we can damp or anti-damp the core gyration through spin-transfer torque, resulting in variation of the Floquet comb's spacing frequency and peak amplitude, which we can then exploit for reservoir computing applications [5].

We further show that the rotating C-state also exhibits Floquet modes. These modes emerge from modulation of the linear eigenmodes of the frozen C-state, and recover cylindrical symmetry through time periodic rotation of the C-state, leading to similar dispersion relations as the ones of a gyrating vortex. These findings hold potential for unconventional computing applications. For example, by using an operating regime near the transition between vortex and C-state in spin-torque oscillators, it might be possible to alternate between two sets of Floquet states.

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Skyrmion devices for physics-based non-conventional computing

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Spintronics exploits the additional degree of freedom of electron spin, giving rise to nonlinear emergent dynamics that can be harnessed for computing beyond von Neumann architectures. Magnetic skyrmions are topologically stabilized spin structures that provide a suitable platform for implementing such concepts.

One example is the realization of confined skyrmion counter-sensors [1]. A mechanical rotation around an axis is converted into individually nucleated skyrmions. This is achieved by exploiting skyrmion dynamics in confined geometries, enabling non-volatile information storage that requires no electrical power for sensing and storage, but only for electrical readout [2].

Such a skyrmion ensemble forms a high-dimensional state space with intrinsic memory, providing a direct interface to neuromorphic computing. Thermally activated skyrmion dynamics further extends this functionality: Brownian diffusion in low-pinning multilayers enables stochastic reshuffling and probabilistic processing [3]. Geometrically confined skyrmions have been demonstrated as reservoirs capable of implementing nonlinearly separable logic at ultra-low current densities by exploiting the energy landscape of skyrmion devices [4]. Time-multiplexed skyrmion reservoirs further enable real-time gesture recognition without conventional AI-based recognition, relying instead on purely hardware-based processing [5].

Skyrmion-based devices can serve both as sensors and for reservoir and neuromorphic computing, enabling compact, low-power systems that integrate sensing and computation. This establishes skyrmion devices as key building blocks for unified spintronic hardware platforms for physics-based computing.

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Magnetic dynamics in isotropic ferromagnetic insulator

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Spin-wave (magnons) in magnetic materials form a key branch of spintronics. It enables transport information via pure spin angular momentum without charge current, offering a pathway toward low-Joule-heating, energy-efficient devices. On the other hand, their intrinsically nonlinear dynamics such as multi-magnon scattering and dynamically stabilized states [1], facilitating magnonics as a promising platform for wave-based computing [2]. A key requirement for spin-wave computing is the tunability of the frequency and phase of propagating waves within the magnetic medium [3]. Approaches such spin torque introduce damping or antidamping torque into magnetic materials which helps compensate or enhance damping [4], serveing as additional tuning knob.

In this work, we demonstrated rich magnetization dynamics in in super low magnetic anisotropic yttrium iron garnet (YIG) thin films. In transport measurement, magnetization signal is detected through spin pumping and inverse spin Hall effect [2]. At the same time, to induce dynamically stable states of magnetization, direct current is applied to generate spin orbit torque with spin Hall effect to reach nonlinear regime. On the other hand, We also propose utilize iontronics to locally manipulate magnetic anisotropy. Electric-field-driven ion migration enables magnetic control without external magnetic field [5], which provides potential of nonvolatile approach controlling spin wave dynamics in the magnonic device. Our study advance understanding of the evolution of dynamical stability in spin-wave systems in electric-field tuned magnetic materials and the potential of integrating magnonics with iontronics in energy-efficient wave-based analog computing application.

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Toward Cascaded Spin–Acoustic Neuromorphic Hardware: Integrated Synaptic and Neuronal Functions in SAW–SOT Devices

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Physics-based computing exploits nonlinear dynamics and wave-mediated signal processing beyond conventional transistor logic. We report an integrated spin-acoustic neuromorphic platform based on SAW and SOT in $LiNbO_3$/Ta-MgO-CoFeB-Ta devices. The same hardware supports multimodal synaptic and neuronal functions: coexisting electromagnetic and acoustic pathways generate volatile short-term plasticity, SOT-driven domain evolution provides nonvolatile multilevel long-term plasticity, and SAW acts as a global modulatory channel for heterosynaptic tuning with improved update linearity and symmetry. In the neuronal regime, SAW-induced contraction of SOT-switched domains is observed optically and electrically, enabling a physically realized leaky process; combined with SOT-driven integration and reverse-pulse reset, this yields leaky integrate-and-fire behavior. We further demonstrate a preliminary three-synapse-to-one-neuron cascade, defining a scalable route toward field-minimized, fully cascaded wave-assisted spintronic networks for temporal neuromorphic and reservoir-inspired computing.

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Physical Reservoir Computing with Ferroelectric Oxides

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Physical reservoir computing exploits nonlinear dynamics, fading memory, and intrinsic material complexity to solve time-series pattern recognition tasks [1]. Magnetic and ferroelectric materials hosting complex textures have recently emerged as promising platforms, offering fast dynamics, energy-efficient operation, and scalable architectures for processing time-dependent signals [2]. Here, we demonstrate that the photocurrent dynamics of the ferroelectric semiconductor ErMnO$_3$ can be harnessed for real-time time-series classification. Moreover, the relaxation time of the photocurrent is tunable, enabling the capture of diverse temporal features and thereby enhancing performance. Altogether, these results highlight the potential of ferroelectric oxides as scalable, energy-efficient platforms for real-time physical reservoir computing.

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Real-time characterization of vortex core reversal under nonlinear gyrotropic motion

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The core of a magnetic vortex plays an important role in vortex dynamics [1] through deformation [2] and switching polarity when undergoing large-amplitude gyration. Probing real-time dynamics remains an experimental challenge and stroboscopic event-averaged views [3] miss the potential chaotic behavior arising from reversals. This work investigates the vortex dynamics of thin film ferromagnetic disks embedded in magnetic tunnel junctions with single-shot measurements. The junction voltage oscillates at the drive frequency displaying abrupt drops of amplitude and phase jumps at high enough powers of rf field. Micromagnetic simulations [4] confirm that these signatures correspond to aperiodic core reversals. From the amplitude and phase of the demodulated voltage traces, we reconstruct the vortex core position and polarity. We find that core reversals are followed by three distinct waveform patterns. The first is a fast-growth cycle associated with negative phase jump followed by a rise of amplitude within a few gyrations. The second is a slow-growth cycle with a small positive phase jump that is gradually restored to the drive phase over several gyrations. The last one is an extinction case with two phase jumps that sum up to -2π, strongly damping the gyration up to the disk center then being restored within few gyrations. We will demonstrate that the switching of polarity and thus the vortex chirality occur at specific angular position despite the system's rotational symmetry and the aperiodicity of the dynamics. Finally, we will show that the sequences of waveform patterns generate a symbolic dynamics whose entropy suggests that vortex-based systems are promising nanoscale sources of entropy for information processing [5].

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Spin-wave holography for neuromorphic computing

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Various physical phenomena have been investigated to develop hardware capable of performing neuromorphic computations more efficiently than conventional CMOS-based devices. One prominent approach is wave-interference-based computing, among which spin-wave (magnonic) systems are considered particularly promising [1-2]. In this work, we utilize a well-known concept from optics, holographic pattern recognition, and present a theoretical comparison between magnonic systems governed by the Landau–Lifshitz–Gilbert (LLG) equation and optical systems described by the scalar wave equation.

We analyze the holographic phenomenon for forward volume magnetostatic spin waves and directly compare their behavior to optical holography. We investigate how information is encoded in the amplitude and phase of propagating wave fronts and how interference enables similarity-based pattern recognition. We show that holographic similarity recognition naturally implements associative memory functionality but exhibits limited separability in conventional classification tasks.

To address this limitation, we introduce a machine-learning-based design framework for holographic structures that surpasses traditional design strategies. Through gradient based optimization, the system learns class-level similarity features, enhancing its classification performance while preserving its associative capabilities.

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Machine Learning-Based Spin Structure Detection in Engineered X/CoFeB/MgO Multilayers

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Magnetic skyrmions are nanoscale topological spin structures with intrinsic stability and non-volatility, making them promising candidates for future information processing and neuromorphic computing architectures. Reliable detection of their position, shape, and dynamics in experimental imaging data is a key requirement for both device operation and fundamental studies. However, magneto-optical Kerr microscopy (MOKE) measurements in engineered multilayer systems such as X/CoFeB/MgO (X = Ir, W, Ta) are often affected by noise, low contrast, and optical artifacts, which limit the applicability of conventional image processing approaches.

In this work, we present a machine learning-based framework for robust spin structure detection in such systems. Building on convolutional neural networks for image segmentation, we develop an enhanced architecture incorporating attention gates (AGs) to selectively focus on relevant magnetic features while suppressing background artifacts [1,2]. The proposed Attention U-Net model enables accurate identification of skyrmion position, size, and shape across varying imaging conditions.

The network is trained and validated on an experimental dataset, allowing for systematic evaluation of its generalization capabilities. Our results demonstrate that attention-based models improve detection accuracy and reliability compared to conventional methods. The approach provides an efficient and scalable tool for preprocessing magnetic microscopy data and can be extended to other spin structures and imaging techniques.

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Spinwave modes in synthetic antiferromagnetic nanodots

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The study of antiferromagnets has recently attracted a lot of attention due to many factors such as their abundance, robustness to the influence of external fields, and ultrafast dynamics in THz range. However, the main problem is the manipulation of magnetization dynamics which in intrinsic antiferromagnets cannot be done by external fields. In this sense, synthetic antiferromagnets SAFs (two antiferromagnetically coupled ferromagnetic layers) offer a possibility to easy manipulation via traditional means. Nanopattering of SAFs in forms of dots of different shapes constitutes an additional possibility to control magnetization dynamics. In this work, we have modeled the high-frequency magnetization dynamics in dots of SAFs. The chosen material was Ni80Fe20 and the two layers were considered with non-equivalent thicknesses. We evaluated ferromagnetic resonance frequencies as a function of external magnetic in-plane field. At high fields SAFs have a ferromagnetic-like state and only one FMR mode is excited. Nanostructuring leads to the appearance of additional edge modes due to the influence of magnetostatic fields. At low applied magnetic fields, the system is in the AFM-like state and while the thin film possesses two resonance modes, the nanodot presents many confined modes with different symmetries. We have analyzed the modes profile, and the spectra were compared with an analytical model based on 2 coupled magnetic moments. Then, SAFs show interesting features such as reduced net magnetic moment by minimizing the dipolar interactions, and a rich high-frequency spectrum that can be engineered through dot geometry, layer thicknesses, dot sizes and interlayer coupling strength. Such a configuration could be an interesting approach for applications in neuromorphic computing [1].

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Scalable spin-wave neural networks

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Scalability is one of the major limitations of spin-wave devices for computing applications. Conversion into and out of the spin-wave domain is by far the most expensive part of the computation line with spin waves, which defies the ultra-low power promise of spin-wave devices. To circumvent this issue, the complexity of the computation within the spin-wave domain must be maximized, and the number of outputs limited. Neural networks (and in general, classification tasks) are a good fit for these limitations [1], as the output of the network is typically compact and low precision.

To keep the internal complexity scalable, energy losses must be compensated, and signals have to be reconditioned without reading out into digital/electric signals. Parametric pumping is a promising, but not trivial solution for this problem. In this contribution we present an alternative approach, where instead of amplification of the spin-wave signal, an off-resonant nonlinear excitation [2] is used at the connections of the perceptron layers. The excitation amplitude is set to below-threshold level, so no spin waves are generated in an empty magnetic medium. However, if there is an incoming spin-wave signal from the previous layer, nonlinear excitation is triggered and a high-amplitude, nonlinear spin wave is generated with an amplitude that is only slightly dependent from the incoming signal level (Fig. 1). If there is insufficient signal level arriving on the nonlinear excitation antenna, then no new spin-waves are generated. This operation resembles a CMOS buffer, or an activation function in neural networks. This way of spin-wave reconditioning/nonlinear amplification can be very efficient, because a single line can drive many independent channels between device blocks, and the spin-wave radiation resistance will add up to high levels to match the impedance of the driving circuit, thus maximizing efficiency. We present simulation results and preliminary measurements of proof-of-concept devices.

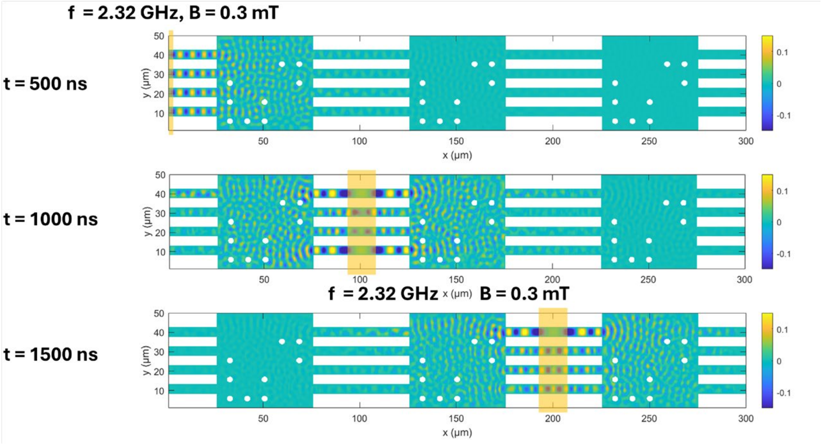

Figure.7¡.Simulation.of.spin_wave.scatterer.blocks.with.nonlinear.interconnects¡

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Field-tunable self-induced Floquet magnons in a magnetic vortex

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Magnetic vortices in ferromagnetic nanostructures host a low-frequency gyrotropic mode and higher-frequency spin-wave modes that can strongly interact under microwave excitation. In the nonlinear regime, this interaction leads to self-induced Floquet magnons, appearing as frequency combs with sidebands spaced by the vortex gyration frequency [1]. Theory predicts that feedback between Floquet magnons and vortex-core motion can produce multiple stable steady states under identical driving conditions, resulting in hysteretic and history-dependent Floquet spectra [2].

Here we experimentally demonstrate such behavior using vortex-state magnetic tunnel junctions. Microwave spectroscopy reveals the emergence of Floquet frequency combs above a threshold excitation power, accompanied by a sharp increase in the vortex-core gyration radius. Power sweeps show clear hysteresis, with Floquet sidebands persisting to lower powers when the drive is reduced, indicating bistability between a centered vortex state without Floquet response and a large-amplitude gyration state sustaining a frequency comb.

We further show that this bistability can be controlled by displacing the vortex core with an in-plane magnetic field prior to microwave excitation. Under identical drive conditions, magnetically displaced initial states exhibit Floquet sidebands at lower power and over broader frequency ranges than centered states. Measurements of the gyrotropic mode confirm that the vortex-core equilibrium position sets the steady-state gyration radius and the instability threshold.

These results are explained by a nonlinear model in which vortex gyration and Floquet magnons mutually interact wich each other, giving rise to multiple stable gyration radii. Our work establishes the vortex-core position as an internal control parameter for Floquet magnon generation and demonstrates history-dependent control of Floquet spectra in magnetic nanostructures.

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Reinforcement Learning for Balancing the Cart-Pole

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Balancing a pole on a moving cart by applying lateral forces is a standard benchmark problem in reinforcement learning. Deep Q-Networks [1], which integrate reinforcement learning with neural networks, have been highly effective in solving this problem. Training the multiple hidden layers of Deep Q-Networks, however, is computationally expensive and thereby energy-demanding. Replacing these hidden layers with an Echo State Network reduces training costs while maintaining performance [2].

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From Concepts to Scalable Spintronic Devices for Emerging Technologies

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Spintronics is a key research field that investigates the influence of electron spin on the functionality of electronic devices. This presentation addresses the challenges and opportunities associated with transferring spintronic concepts from fundamental research to next-generation computing technologies. We present results of our research group's ongoing projects conducted in a state-of-the-art CMOS cleanroom facility (see Figure 1). Our work encompasses not only the development of optimized material stacks, but also device fabrication, integration, and characterization, covering technologies such as tunnel magnetoresistance (TMR) sensors, spin-transfer and spin–orbit torque magnetoresistive random-access memory (STT/SOT-MRAM), and racetrack memory devices. We will also discuss advanced array-level characterization methodologies that were developed to provide reliable and high-performance memory technologies for automotive applications [1]. Emerging concepts such as cryogenic spintronic memory devices and neuromorphic computing architectures [2] are also addressed to highlight their importance for future computing technologies. This contribution emphasizes the need to support the transfer of academic fundamental research into large-scale industrial implementation through discussions of specific methods and strategies. By leveraging the capabilities of a CMOS-compatible cleanroom environment, we aim to support the transition of spintronic devices from laboratory-scale demonstrations toward scalable and industry-relevant implementations.

Figure 1: 300mm wafer-level PVD tool for MTJ stack deposition.

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Multi-Value Probabilistic Computing with Current-controlled Skyrmion Diffusion

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Magnetic systems are highly promising for implementing probabilistic computing paradigms because of their fitting energy scales and pronounced nonlinearity. While conventional binary probabilistic computing has been achieved, the more advantageous multi-value probabilistic computing (MPC) has remained a challenge. Here, we report the successful realization of MPC by harnessing the thermally activated diffusion of magnetic skyrmions through a non-flat energy landscape defined by a discrete number of pinning sites. The time-averaged spatial distribution of diffusing skyrmions directly realizes a discrete probability distribution, which is tunable by current-induced spin-orbit torques and can be quantified by non-perturbative electrical measurements. Even a simple implementation with global tuning allows us to demonstrate the softmax computation - a core function in artificial intelligence. Moreover, we demonstrate invertible logic without the need to create a network of probabilistic devices, offering significant scalability advantages. Our proof of concept can be extended to multiple skyrmions and can accommodate multiple locally tunable inputs and outputs using magnetic tunnel junctions. This potentially enables the representation of highly complex distribution functions. Further, the stack recipe can, in principle, be adjusted to host skyrmions with length and time scales in the nanometer/nanosecond regime.

Predicting the Future with Magnons

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The Mackey-Glass time series data describes how the density of mature circulating cells change over time using time delayed differential equations [1]. This is a standard problem to test the performance of physical reservoirs. Here, we used different magnon-scattering reservoirs to carry out such a time series prediction task. By connecting several reservoirs together, we increase the reservoir depth which yielded very accurate long-time future prediction.

The original data at discrete time steps was converted to frequencies in a range suitable to address magnons in NiFe microstructures. The magnon response is measured using time-resolved Brillouin light scattering spectroscopy (BLS). For the analysis, a time-integrated magnon spectrum is extracted for each time step of the Mackey-Glass series. Then a simple linear regression $Y(t + t') = w(Y) + c$ was used to complete the prediction of t' steps into the future. We tested the system's performance by predicting up to 200 future time steps instead of only a few specific values commonly done in literature.

The task was carried out using five different geometries for the magnon-scattering reservoir, all excited by omega-shaped microwave antennas. The input microwave signal was all kept the same so results from different devices can be combined to increase the reservoir depth. In general, deeper reservoirs lead to more accurate prediction. As shown in Fig. 1, the prediction using our magnon-scattering reservoir (BLS in blue) is highly accurate and even follows small changes in the actual data (plotted in grey). Due to the memory and nonlinear interactions of magnons, the original Mackey-Glass data is converted to a higher-dimensional output given by the magnon spectrum. The BLS data then allows us to use a simple linear regression to complete this chaotic time series prediction.

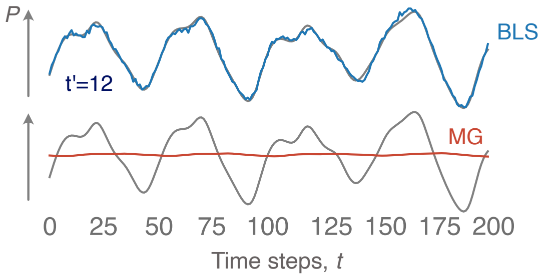

Figure 1. Prediction of 12 steps into the future for 200 data points. The actual MG values are shown in grey. The prediction using magnon-scattering reservoir is marked as BLS shown in blue and follows the true data very well. The comparison only using Mackey-Glass original data is marked as MG in red and fails to predict the actual value.

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Sign-dependent autocorrelation benefits in time-series-based decision making

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Laser-chaos-based decision makers have emerged as a promising physical approach to solving multi-armed bandit problems using tug-of-war algorithms, leveraging chaotic time series produced by semiconductor lasers and enabling gigahertz-scale decision making. Prior experiments have reported that sampling the chaotic signal at points where its autocorrelation is negative leads to higher decision-making accuracy. Nevertheless, a comprehensive theoretical explanation for why this strategy improves performance has yet to be fully established. In this presentation, we investigate a simplified decision-making model for the two-armed bandit problem, in which the original time series is reduced to a stochastic binary Markov chain. Through numerical simulations, we observe that either positive or negative autocorrelation can enhance decision-making accuracy, depending on the environment. In addition, we present a mathematical statement indicating that, under a particular environmental condition, decision-making accuracy becomes independent of the autocorrelation.

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Voltage-Triggered Emergent Dynamics in a Magnetic Neuron Network

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Emergent dynamics arises from local interactions among large population of simple elements, underpinning energy-efficient computation in the brain [1]. Arrays of non-interacting nanomagnets are widely used in magnetic storage, where dipole-dipole interactions are considered detrimental. Here, by embracing this physical interaction, we present a wafer-scale, self-assembled magnetic neural network composed of billions of $SmCo_5$ nanomagnets, where emergent dynamics can be triggered by electrochemical potentials of only ~1 V. The network combines three key ingredients: (1) voltage-responsive nanomagnets, which can be toggled between stable memory state and dynamic update regime, enabled by unprecedented nearly 1000-fold change of coercivity; (2) autonomous flipping of nanomagnet's state driven entirely by local dipolar interaction; and (3) self-assembled, disordered network architecture producing spin frustration and complex Ising-like energy landscape. At the network level, the system evolves under the Ising-type Hamiltonian, with asynchronous spin-state updates governed entirely by local interactions. Upon voltage stimulation, we observed a rich spectrum of emergent behaviors, including spontaneous self-demagnetization, large-scale reconfiguration of magnetic state, and convergence into stable state. These dynamics exhibit stochastic spin flipping and power-law evolution dictated by energy minimization, paralleling behaviors seen in spin-glass systems and energy-based models. Our work introduces a new class of physical substrate in which emergent dynamics —driven by native interactions and triggered by biologically-relevant inputs—opens a playground for implementing scalable, energy-efficient neuromorphic computing grounded in physical principles.

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