Second International Workshop on Theoretical and Experimental Material Computing (TEMC 2020)

Prague, Czech Republic (virtual)
July 2021

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EPRSC SpInspired project EP/R032823/1 and the University of York, UK

The **Second International Workshop on Theoretical and Experimental Material Computing** (TEMC 2020; postponed from last year) is being held online, as a satellite workshop of the Artificial Life Conference (ALife 2021), Prague, Czech Republic (virtual) 19-23 July 2021.

Material computing exploits unconventional physical substrates and/or unconventional computational models to perform physical computation in a non-silicon and/or non-Turing paradigm. Such computations find a natural home in a variety of ALife applications, including unconventional and soft robotics.

TEMC 2020 encompasses a range of theoretical and experimental approaches to material computing. The aim of the workshop is to bring together researchers from a range of connected fields, to inform of latest findings, to engage across the disciplines, to transfer discoveries and concepts from one field to another, and to inspire new collaborations and new ideas.

Programme and Organising Committee

Susan Stepney
Matt Dale
Simon O'Keefe
Angelika Sebald
Martin Trefzer

Programme (Wed 21 July 2021)

9:00-9:20 BST (10:00-10:20 CEST)

Susan Stepney (chair)

Introduction and Welcome

9:20-10:20 BST (10:20-11:20 CEST)

Herbert Jaeger (keynote speaker)

Material Computing: From Fruits to Roots

10:20-11:00 BST (11:20-12:00 CEST)

Odd Rune Lykkebø.

Implementing Cellular Automata in Artificial Spin Ice

11:00-11:30 BST (12:00-12:30 CEST)

break

11:30-12:10 BST (12:30-13:10 CEST)

Kristine Heiney, Ola Huse Ramstad, Sidney Pontes-Filho, Tom Glover, Trym Lindell, Jørgen Jensen Farner1, Håkon Weydahl, Stefano Nichele..

Bridging the computational gap: From biological to artificial substrates

12:10-12:50 BST (13:10-13:50 CEST)

A.S. Goossens, M. A. T. Leiviska, A. Jaman, T. Banerjee.

Anisotropy and current control of magnetization in oxide devices for unconventional computing

12:50-13:30 BST (13:50-14:30 CEST)

Matt Dale.

Reservoir computing with magnetic films in the SpInspired project

13:30 BST (14:30 CEST)

Close

Material Computing: From Fruits to Roots

Herbert Jaeger

Faculty of Science and Engineering, University of Groningen, The Netherlands

In material (or physical or unconventional or…) computing we can already serve and relish a number of material demonstrations. These fruits are diverse and some are exotic, based on substrates as different as DNA sniplets, fungi, silicon nanobeams, or gold particle films; and they exploit very different physical phenomena, like energy minimization in collective systems, coupled mechanical oscillations, phase transitions, quantum state interactions, or reaction-diffusion processes. Looking at digital computing, we see that its long-lasting, prosperous development is safely rooted in unifying and abstract theory: automata theory and formal languages, Turing computability, Boolean and other symbolic logics. These theory branches are transparently interconnected and taught to computer science students worldwide always in the same canonical format. The unifying invariant across all these sub-theories is the concept of *discrete symbol structures*. In order to make material computing stand confidently side by side with digital computing, it has been observed that an *"over-reaching formalism ... may be desirable"* (Stepney and Hickinbotham, 2018). I will argue that it is not merely desirable but critically needed; and that it will not be a single formalism but a system of interconnected formalisms which only together give guidance for practical system engineering pipelines from nanoscale phenomena to physical system design to system interfacing to task specifications to societal impact assessment. I will propose a theory organigram, pinpointing which sub-theories would be needed to fill which roles in a future engineering science of material computing; and I will try to explain my intuitions about mathematical objects which could generalize discrete symbol structures, yielding the conceptual invariant to tie it all together.

Implementing Cellular Automata in Artificial Spin Ice

Odd Rune Lykkebø [1]

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Introduction

Artificial Spin Ices (ASI) are 2D lattices of nano-scale magnets, arranged such that they interact magnetically. Often these magnets are elongated, giving them anisotropy, expressed as a 'preferred' magnetization direction along their longest axis, much like an ordinary kitchen magnet. A common model for these magnets are as *spins*, having two distinct states or 'poles' and a per-spin threshold magnetization value deciding when it changes direction.

The magnetic interaction between two or more magnets lead to 'frustration', where the preferred direction of one magnet can be in opposition to its neighbors. Much like larger magnets they "want" to snap together "north to south". Since they are fixed in place in a lattice, they can never achieve this. Furthermore, the size of each nano-scale magnet is such that they are not individually able to remain in a magnetically stable position. However, as an ensemble they can form magnetic domains. An ASI thus has some dynamics without supplying an external energy source, however it is common to supply an external magnetic field to further "drive" the dynamics. Without this, the ASI will quickly freeze into some lower energy state.

By adjusting this external field, positions, angles and shapes of the magnets, many exotic behaviors can be observed using a synchrotron such as the Swiss Light Source to observe the state of each individual magnet. This is exciting from the perspective of material computation, where we are interested in exploiting exotic physical behavior for computation. To this end, a simulator called flatspin Jensen et al. (2020) focusing on large scale dipole interactions between nano-scale magnets have been developed.

Method

A cellular automata (CA) consists of a lattice of cells, each cell having a discrete state from a final set, and a set of transition rules that describe the next state of the cell, usually as a function of the state of the neighbors and the cells' own state. At first glance this maps well onto a regular lattice of locally interacting 2-state elements such as an ASI. The rule set giving the next state of a cell, given its own and neighbors' states, seems realizable by adjusting the shape and position of the magnets. However, once a subset of magnets have had some of the frustration removed by flipping their spin direction (similar to a CA state transition), they are in an energy minimum, and are rather reluctant to "go back up the hill", and return to a frustrated state without applying a strong external field, which can destroy structures (e.g. magnetic domains) that were formed during the relaxation process. Smaller, local fields that only affect the state of 1 magnet and its neighbors is a possible solution to this, but implementing this in a physical system is beyond our labs current capability.

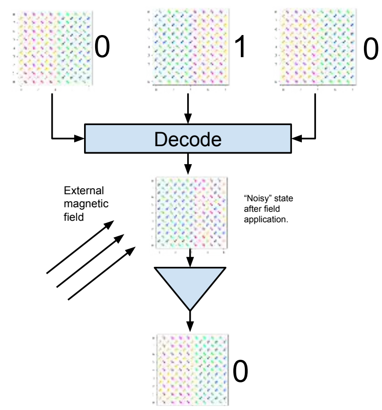

Figure 1: The neighbors in the grid of ASI decide the applied field protocol, one field per neighbor. The fields are applied sequentially to the "clean" state, leading to a "noisy" ASI. This is in turn amplified back to a "clean" state, ready for the next timestep in the CA evolution.

Furthermore, a synchrotron is a rather large instrument[1]. The time where we can fit such equipment in our pockets seem far away. In stead, we are forced to observe higher-level emergent behaviors. One such desktop-realizable observational method is the direction of the total sum of individual magnetic fields in the entire lattice of spins, which is

[1]The Swiss Light Source is 138m in diameter.

what I use in this abstract.

Mead (1990) argues for the use of amplification of analogue states, in order to remove noise from an analogue computing device. While the ASI is not exactly what Mead had in mind when he wrote about neuromorphic computing, we take with us the idea of amplification of noisy states. I filter, or amplify, the state of the lattice to a distinguishable and realizable state.

All the simulations were done using flatspin (Jensen et al. (2020)) without temperature. The cell is implemented by a vertically split 22x22 lattice, the left half being rotated 45 degrees and the right half 33 degrees, as shown in figure 1. The CA state-transition rules are implemented as a global external forcing field. I apply an angle ϕ_i and amplitude H_i, for all neighbor cells i. The so-called *field protocol* is thus a sequence of two fields applied sequentially in time; $(\phi_0, H_0), (\phi_1, H_1)$. Each field protocol corresponds to a CA rule set, and we sample 10000 of all possible combinations of field application angles and field amplitudes slightly below and above the switching threshold.

Each field is held while the lattice is *relaxed*, i.e. until all the are spins that can flip under the current forcing field have flipped. After the two fields in the field protocol have been applied, the total magnetic field direction of the system is calculated by summing the contribution from each spin. If it points more to the west than east, it is labeled 0, and if it points more to the east, it's a 1. Before the next field application, the state is amplified to the corresponding ASI state. For a "0", half of the lattice points east, and the other half points west. For a "1" the directions are opposite, as seen in Figure 1.

Results

Figure 2 shows all the rules that were discovered during the sampling, for alpha value 0.003, which means the magnets are rather strongly interacting. Rule 110 and its equivalents 124, 137 and 193 are all found. Interestingly, seen from a human perspective, class IV rules produce many complex magnetic domain interactions, and different rules show qualitatively different behaviors, i.e. 'mostly horizontal domains' and 'mostly vertical domains'.

Conclusion

Filtering and amplifying the resulting state after field applications resets the system back to a frustrated state, after the external fields have been applied. We are in a sense winding up the clockwork again to a specific time. This allows one to obtain more of the "interesting dynamics" that we use further. In some sense this is not too far from a partitioning function applied to a chaotic system as in Crutchfield (1994).

Secondly, in ASIs, there is a balance between the dipole dynamics and the external field. On one hand, one needs to supply some energy to the system to let its dipole dynamics "unfold", however if you push too hard, you risk losing emergent state. We have not yet succeeded in creating a "perpetual" ASI, in which the energy supplied by the system is perfectly balanced with the energy dissipated by releasing dipole frustration. Pushing too hard leads to loss of emergent patterns, pushing too little leads to a frozen ASI. Perhaps this could be achieved by exploring different geometries and field protocols using some stochastic search method.

ASIs do inhabit many "wants" in material computing, such as non-obvious emergent dynamics from nearest-neighbor interactions and per-element non-linearity. Its similarity to the more standard Ising model allows some theoretical grounding, which could potentially direct future research.

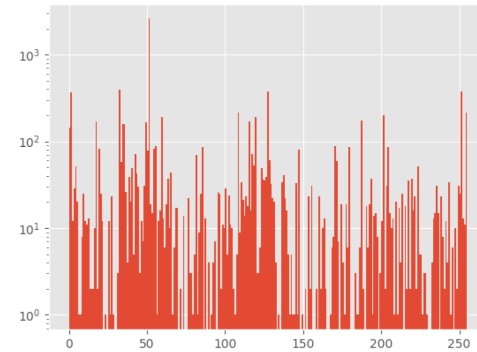

Figure 2: Distribution of found rules.

Acknowledgements

This work was funded in part by the Norwegian Research Council by the IKTPLUSS project SOCRATES (Grant no. 270961), and in part by the EU FET-Open RIA project SpinENGINE (Grant no. 861618). Simulations were executed on the NTNU EPIC compute clusterSjälander et al. (2019).

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Bridging the computational gap: From biological to artificial substrates

Kristine Heiney[1,2,*], Ola Huse Ramstad[1,3], Sidney Pontes-Filho[1,2], Tom Glover[1], Trym Lindell[1], Jørgen Jensen Farner[1], Håkon Weydahl[1] and Stefano Nichele[1,4]

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As digital computing technology advancements accelerate, we are approaching some major impasses in what we can achieve (Jaeger, 2020). We demand more and more computing capabilities from smaller and smaller devices, challenging our ability to miniaturize the necessary hardware, and the energy required, especially for methods like deep learning, is skyrocketing. These impasses have driven researchers to look to new methods of computation—to exploit nonlinear dynamics in physical systems in a new computing paradigm that would be more flexible, energy-efficient, and robust against component failure. Distributed models and hardware show great promise if we can construct them with the right properties to optimize their computing performance (Adamatzky, 2017; Stepney et al., 2018).

To this end, we aim to develop more powerful and efficient computing methods by translating findings from biological neurons to both unconventional computing models and physical substrates (Heiney et al., 2020). In this abstract, we will first present preliminary findings on the dynamical behavior of in vitro neuronal networks, followed by a general modeling framework developed to simulate dynamic systems. We then discuss how we will transfer our experimental findings on computationally beneficial neuronal behaviors to both simulated and physical computing systems.

To explore how biological neurons process information, we study the electrophysiological behavior of in vitro preparations of neuronal networks (Fig. 1a). Neurons in vitro spontaneously organize into networks through which they propagate electrical signals. Microelectrode arrays (MEAs) can be used to both record and evoke such signals. Using MEA electrophysiological data, we are exploring two facets of network behavior: the spiking dynamics through the lens of criticality and the network organization of the functional connectivity.

Criticality is a dynamic state in which many features associated with computation are optimized, such as dynamic range and the number of metastable states (Heiney et al., 2021). It is characterized by power-law scaling of patterns of activity termed neuronal avalanches, as defined in Fig. 1b; that is, most activations in the network will die out quickly, and few will set off large network-wide cascades. In our preliminary work, we have monitored the avalanche behavior of in vitro networks as they mature and observed that supercritical networks, which are characterized by high synchrony, can be brought closer to criticality by increasing inhibition (Fig. 1c) (Heiney et al., 2019).

Ongoing work involves evaluating the functional connectivity to determine what network structures support features beneficial to computation, including criticality. By utilizing the extracted functional and effective connectivity from in vitro data, we aim to quantify the computational capacity of the network as a liquid state machine and draw a comparative analysis between network stability and robustness.

With these targeted characteristics extracted from biological data, we can build models that show the types of features we observe in our in vitro systems. To that end, we are developing a general modeling framework based on TensorFlow called EvoDynamic[1] (Pontes-Filho et al., 2020a) that can evolve and simulate a range of model systems, such as cellular automata (CAs), random Boolean networks, echo state networks (ESNs), and liquid state machines (LSMs). Fig. 2 depicts the organization of the components of EvoDynamic. In early work using this framework (Pontes-Filho et al., 2020b), CAs, RBNs, and ESNs have been evolved to achieve power-law scaling of sequential cellular activations, in a manner analogous to neuronal avalanches, and the behavior of the evolved CA is shown in Fig. 3. Targeting such model characteristics will allow us to construct model systems that can be used as effective computational reservoirs.

As we pursue this modeling work, we will also use reservoir computing methods to evaluate the reservoir properties of both biological neurons and neuron models as well as CA models. The CA is a very reduced substrate when compared to biological or artificial neural networks, yet CAs are capable of generating very complex dynamics (Wolfram, 2002). Because of the simple nature of the CA, large portions of the rule space can be explored on established benchmarks, e.g., by exploring the property of memory on the 5-bit memory benchmark. We aim to asses how computational power may

[1]https://github.com/SocratesNFR/EvoDynamic

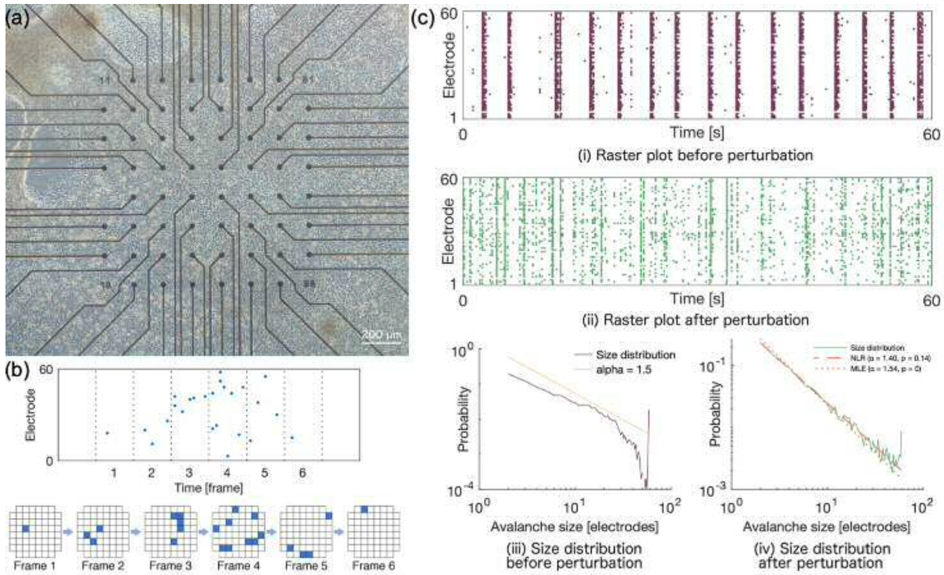

Figure 1: Biological inspiration for the development of novel computing methods. (a) Neurons plated atop an MEA (Heiney et al., 2019). (b) Definition of a neuronal avalanche: a sequence of active time frames bounded before and after by empty frames (Heiney et al., 2021). (c) Activity of the neurons in (a) before (purple) and after (green) perturbation to increase inhibition. Perturbation broke network synchrony and brought the avalanche size distribution closer to a power law (Heiney et al., 2019).

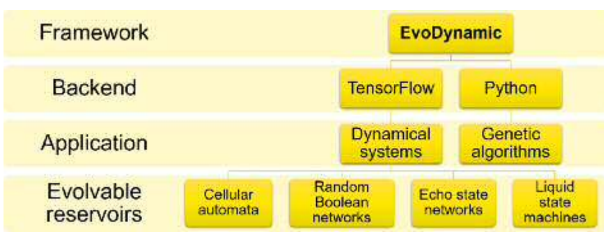

Figure 2: Main components of EvoDynamic framework.

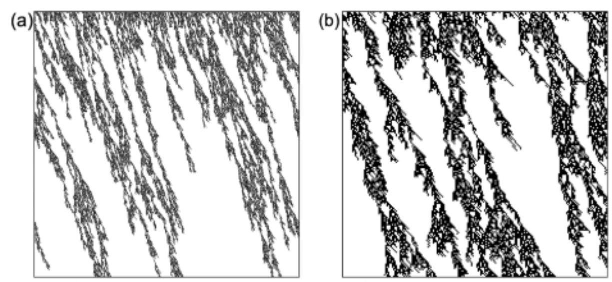

Figure 3: Example of a CA evolved to approach power-law scaling of sequential activations (Pontes-Filho et al., 2020b). (a) Full CA. (b) First 200 cells and 200 time steps.

be generalized among different complex systems and how they may differ. This will lay the foundations for combining different reservoir substrates into better-performing hybrid reservoirs with potential deep architectures.

In work led by our colleagues, we are also developing computational hardware based in two-dimensional arrays of coupled nanomagnets, known as artificial spin ice (ASI). Because the nanoscale dimensions of the nanomagnets in ASI confine their magnetization to a single domain, each can be viewed as a single bit that can take on one of two spin states. As demonstrated in modeling work by Jensen et al. (2018), square-lattice ASI can be made to show complex behavior by tuning the parameters of an external drive—that is, the amplitude and frequency of an externally applied magnetic field—to maximize the number of unique states visited by the system.

A great many modern approaches to computation have been inspired by biology, and when it comes to the brain, there is still much to learn. With our work, we approach questions of computation from a complex systems perspective, asking how we can identify features beneficial for computation and then engineer those features into distributed computing substrates. This research will lay the groundwork for developing novel computing hardware with greater power and flexibility than what can be achieved with the von Neumann architecture.

Acknowledgements

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Title of the abstract:

Anisotropy and current control of magnetization in oxide devices for unconventional computing

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Abstract:

For unconventional computing schemes, physical systems exhibiting stochasticity are being actively researched. At the forefront, are magnetic tunnel junction trilayer structures, that demonstrate stochastic magnetization switching employing approaches that go beyond driving current or applying an external magnetic field. Such devices require specific design and material consideration for their use as stochastic bits for example in probabilistic computing. Experimental proof of concept of probabilistic computing has been demonstrated with such magnetic tunnel junctions exhibiting different relaxation timescales. Current understanding of their physical mechanism that leads to such variations are limited and designs that will improve their thermal stability of such bits are being explored.

In this context, we have looked at different material systems that offer the possibility of substantial variation in the magnetization that can be controlled with simple device designs. The control is achieved by designs that relies on the interplay between the spin, charge and lattice degrees of freedom in perpendicular magnetized films in a solid state device using oxide ferromagnetic layers. We employ an approach that goes beyond those used in switching magnetic tunnel junctions and relies on spin orbit torque (SOT) when an in-plane current is applied to a magnetic element that is noncentrosymmetric or in magnetic heterostructures with broken space inversion symmetry and with sizable spin-orbit interaction.

Utilizing the crystal orientation, magnetic anisotropy in tailored $SrRuO_3$ (SRO) ferromagnetic layers, tuned to either exhibit a perfect or slightly tilted perpendicular magnetic anisotropy (PMA) are studied. The strong magnetocrystalline anisotropy in SRO not only allows for the design of a perpendicular magnetic anisotropy in such devices but enables the tailoring of easy axes at controlled tilt angles from the surface normal, for probabilistic as well as deterministic switching, with relative ease. We find significant differences in the magnetic anisotropy when thin films of SRO are grown on $SrTiO_3$ (STO) substrates with different crystalline directions. We investigate current induced magnetization modulation in such tailored SRO ferromagnetic layers with a material with strong spin-orbit coupling (Pt), exploiting the spin Hall effect. We find significant differences in the magnetic anisotropy between the SRO/STO heterostructures, as manifested in the first and second harmonic magnetoresistance measurements. Current-induced magnetization switching can be realized with spin-orbit torques (SOT), but for systems with perfect PMA this switching is probabilistic as a result of the high symmetry. Slight tilting of the PMA can break this symmetry and allow the realization of deterministic switching. Our findings in tailoring the anisotropy potentially opens avenues for probabilistic and deterministic current-induced magnetization switching , with substantial control in such solid state devices. The benefit of this approach lies in the simplicity of the

device design and in the scalability, compared to conventional PMA devices whose operation relies on a multitude of layers and with concerns on thermal stability when downsized.

In light of neuromorphic applications, this gives the possibility to integrate such layers in a tunnel junction acting as spintronics memristive devices, where the anisotropy controls the device functionality. With perfect perpendicular anisotropy, a device with probabilistic switching serves the role of an artificial neuron, whereas by tuning the easy axis to have a slight tilt, the switching can be deterministic and provide synaptic functionality.