Bioinspired Computing
Leveraging the Non-Linearity of Magnetic Nano-Oscillators

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Artificial Neural Networks Look Like the Brain, to Some Extent


But there are fundamental differences
What Is a Neuron?

Brain neuron

- regular spiking (RS)
- intrinsically bursting (IB)
- chattering (CH)
- fast spiking (FS)

ANN neuron

A=ReLU(z)

Non linearity is the only shared property
The simplification of neurons is actually a key of deep learning success

Are we missing an opportunity?
Non Linear Dynamical Devices Now Exist: Magnetic Nanooscillators

Nanoscale, fast (GHz), non-linear and easily measurable

magnetic tunnel junction

spin torque

CMOS-compatible

CoFeB
MgO
FeB

Current

Same structure as magnetic memories

Can we use them as neurons?

Bioinspired Computing Leveraging the Non-Linearity of Magnetic Nano-Oscillators

- Can We Use Coupled Dynamical Devices for Computation?

- Why Is It Working?

- Can We Use Concepts from AI with Nanooscillators?
First Idea: Use a Single Device to Implement an Assembly of Neurons

Mark D. Stiles talk

Spoken digit recognition through reservoir computing

Exploiting STNOs’ dynamics and non-linearity

New Work: Exploiting the Whole Physics of Magnetic Nanooscillators

Tunability

Ability to synchronize to AC signals

A. Slavin and V. Tiberkevich, IEEE TM 45, 1875 (2009)

W. H. Rippard et al., PRL. 95, 067203 (2005)
The Oscillators Ability to Mutually Interact Opens the Path to RF Communication between Neurons

Same frequency: strong synapse

Different frequencies: weak synapse
Vowels Classification with Spin-Torque Oscillator Neural Network

Inputs: vowels $f_A$ $f_B$

Magnetic Nano-Oscillators

Outputs: synchronized states

Hillebrands Michingan dataset
An Experimental Implementation

Response of the neural network without inputs

Spectral power density (µW/MHz)
Frequency (MHz)

I₁  I₂  I₃  I₄

M. Romera, P. Talatchian et al, arXiv:1711.02704
Impact of an RF Input

The inputs modify the oscillator responses: oscillator 4 is sync to source B.
We summarize all these measurements in a map where the different synchronization states have different colors.
For classification, all the points corresponding to one vowel should fall in a single synchronization region.

M. Romera, P. Talatchian et al, arXiv:1711.02704
We Train the Network by Tuning the Currents through the Oscillators

Following an online learning rule

Experimental set-up

Computer

(Learning algorithm)
M. Romera, P. Talatchian et al, arXiv:1711.02704
After 3 steps:

- Oscillator frequencies (MHz):
  - $f_A$ (MHz)
  - $f_B$ (MHz)

- DC currents in oscillators (mA):

- Recognition rate (%):
  - After 3 steps:

M. Romera, P. Talatchian et al, arXiv:1711.02704
M. Romera, P. Talatchian et al, arXiv:1711.02704
After 7 steps:

M. Romera, P. Talatchian et al, arXiv:1711.02704
After 12 steps:

- **Recognition Rate (%):**
  - 0 20 40 60 80
  - 0
  - 20
  - 40
  - 60
  - 80

- **DC Currents in Oscillators (mA):**
  - 0 20 40 60 80
  - 340
  - 350
  - 360
  - 370

- **Oscillator Frequencies (MHz):**
  - 0 20 40 60 80
  - 330
  - 340
  - 350
  - 360
  - 370

M. Romera, P. Talatchian et al, arXiv:1711.02704
M. Romera, P. Talatchian et al, arXiv:1711.02704
M. Romera, P. Talatchian et al, arXiv:1711.02704
After 21 steps:

Recognition rate (%)

DC currents in oscillators (mA)

Oscillator frequencies (MHz)

Number of training steps

M. Romera, P. Talatchian et al, arXiv:1711.02704
After 29 steps:

M. Romera, P. Talatchian et al, arXiv:1711.02704
After 35 steps:

M. Romera, P. Talatchian et al, arXiv:1711.02704
After 40 steps:

M. Romera, P. Talatchian et al, arXiv:1711.02704
After 44 steps:

M. Romera, P. Talatchian et al, arXiv:1711.02704
After 48 steps:

M. Romera, P. Talatchian et al, arXiv:1711.02704
After 86 steps:

M. Romera, P. Talatchian et al, arXiv:1711.02704
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Is Classifying Vowels a Hard Task?

• For benchmarking, we trained a conventional multilayer perceptron on the same dataset

M. Romera, P. Talatchian et al, arXiv:1711.02704
Our Experiments Achieves Higher Recognition Rates than Conventional ANNs with Same Number of Parameters

More physics helps!

M. Romera, P. Talatchian et al, arXiv:1711.02704
Why Is this Intriguing?

- Based on conventional EE thinking, our system should not really be working

- *Entirely analog*

- *Terrible device variability and phase noise*
What Is Important for Our System to Work?

Device Tunability

Device Coupling

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Is our Architecture Generic?

• Not everything can be learned with our architecture

Task
Synchronization pattern of 2 oscillators (green) should match red examples
Generalized Architecture

D. Vodenicarevic et al, J. Appl. Phys., 2018
• For the training (optimizing W), can we get at same time benefits of dynamical neurons + power of deep learning techniques?

• We tried a brute force approach
  – Take the differential equations of our system
  – Put them in a deep learning framework (Tensorflow by Google)
Benchmark on a Simple Machine Learning Task

Iris-setosa  Iris-versicolor  Iris-virginica

Works, but slow learning!

D. Vodenicarevic et al, J. Appl. Phys., 2018
Going Further

• The architecture scales (D. Vodenicarevic, Sci Rep 2017) but training it is difficult

• Future: Going toward multilayer architecture

• Work on coupling mechanisms and detection schemes

• Use on dynamical data
Perspectives: Deep Learning with Spintronic Nanodevice?
Conclusions

• Exploiting the dynamical behavior of nanoelectronics devices to perform complicated computation works!

• This form of computation is closer to how the brain uses its own devices

• Tunability of devices and their capability to synchronize and to couple to each other are critical

• Possibility to import AI concepts, but the most exciting prospects could come from designing the whole system from scratch
Thank you for your attention!