Hardware implementation of neural network algorithms, based on machine learning and neuroscience models, using spintronics

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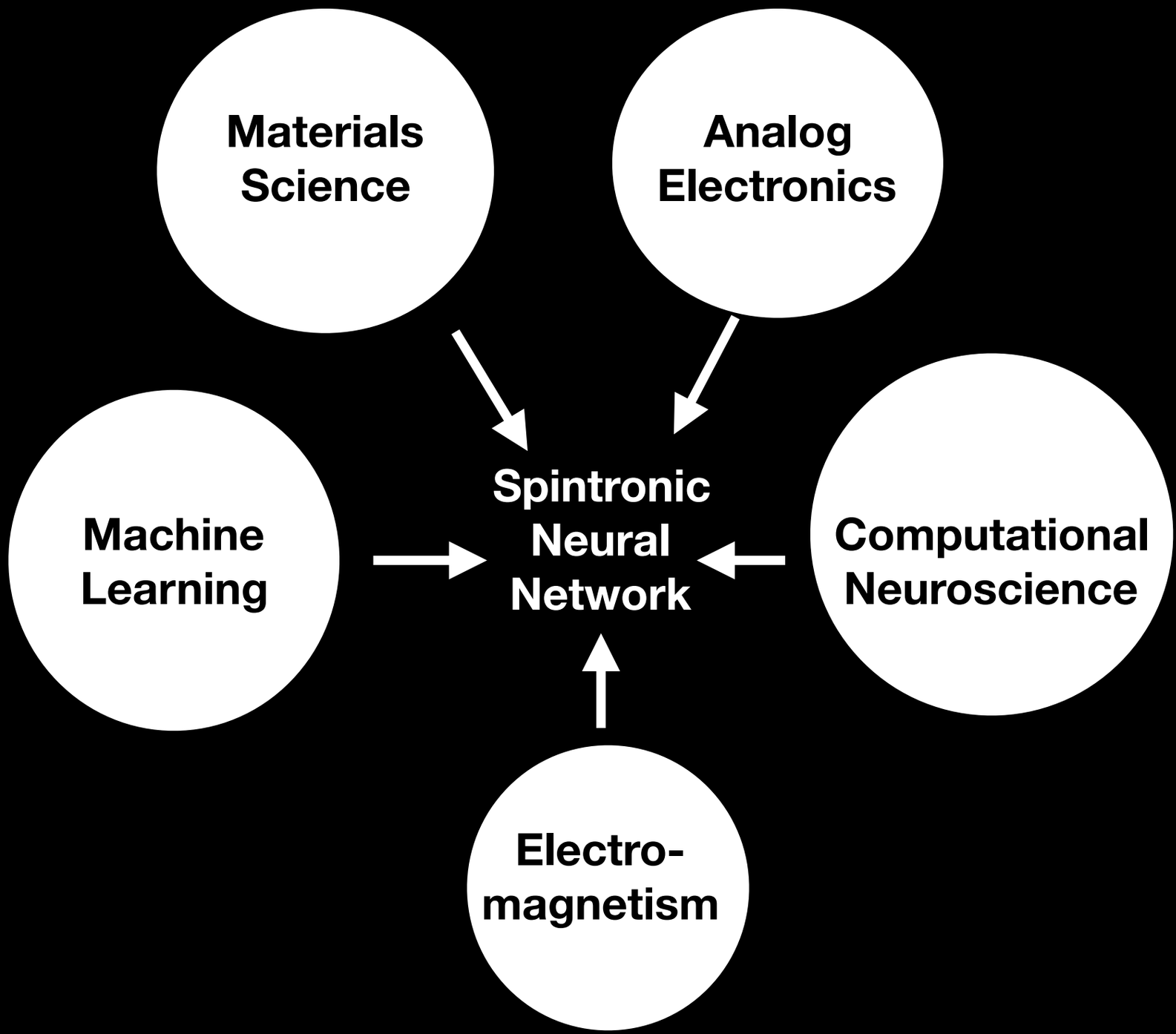
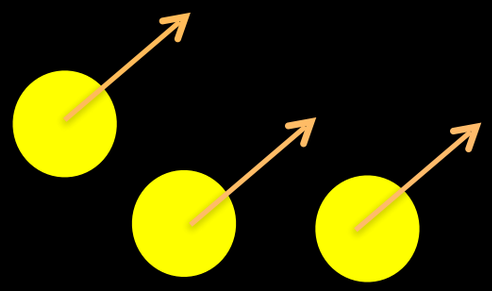
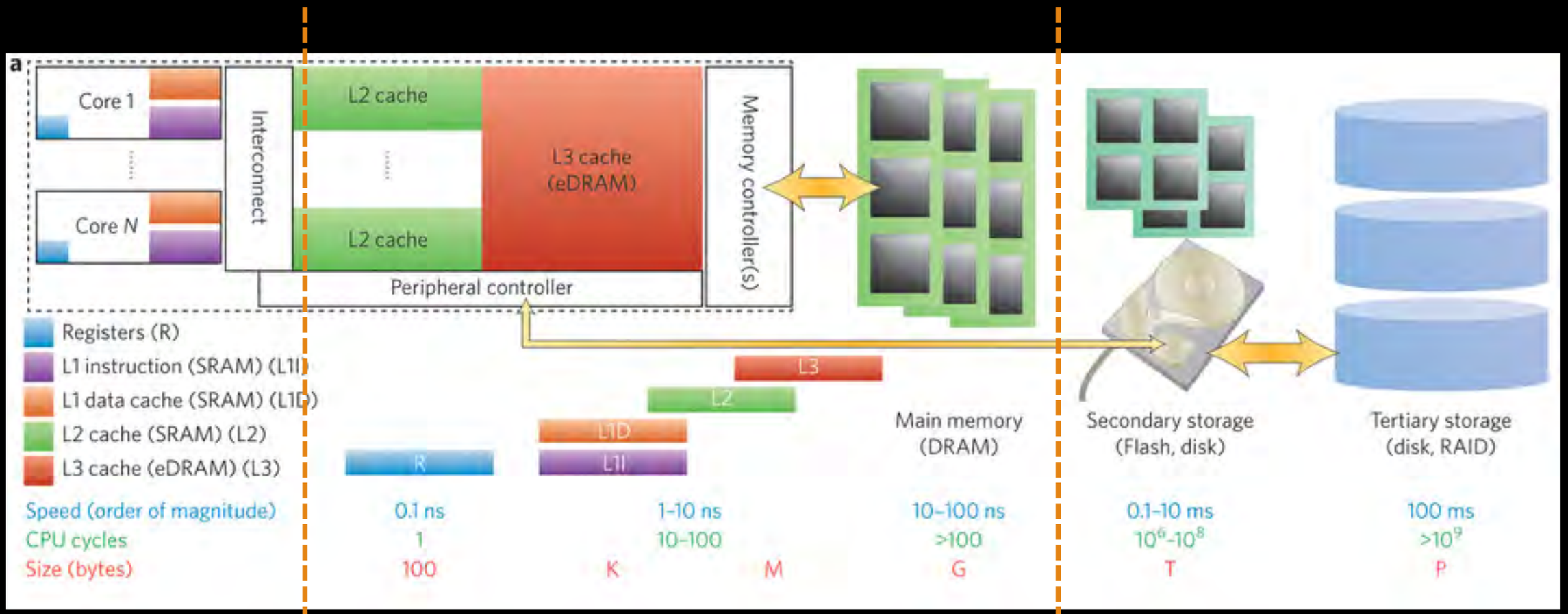


Memory-Computing hierarchy of modern computers and role of Spintronics



Electronics using magnetic moment or spin of electrons is called spintronics.



Computing (spin FET, nanomagnetic logic)

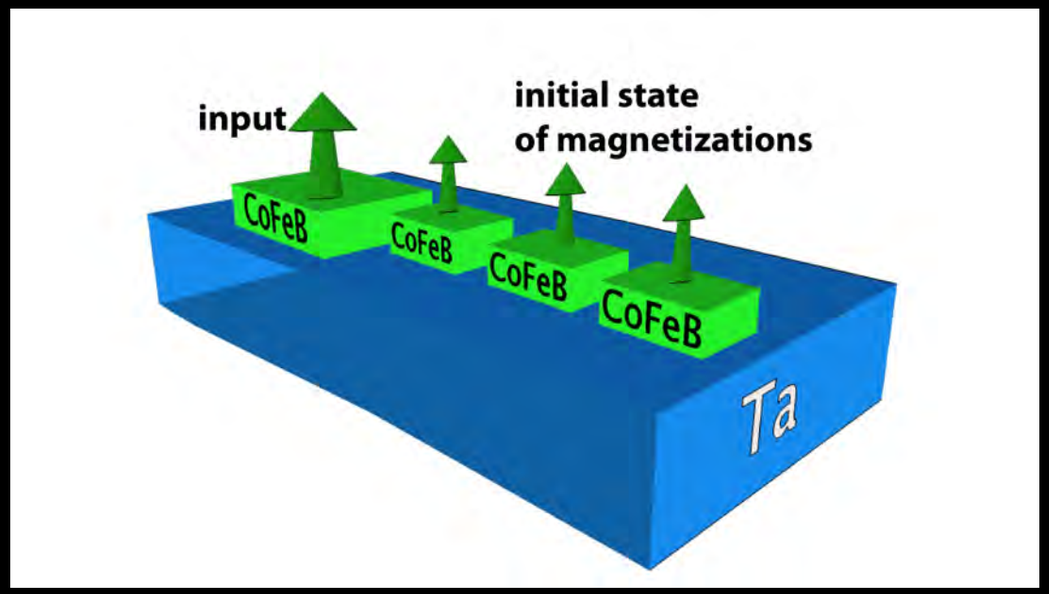
Memory (SpinTransferTorqueMagneticRAM, domain wall racetrack memory)

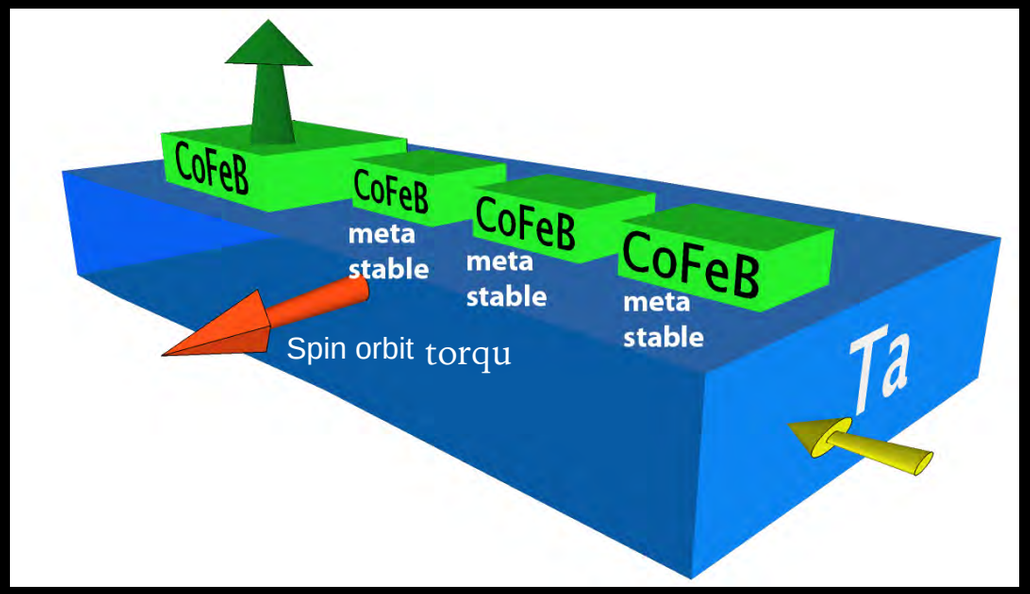
Magnetic hard disk widely used

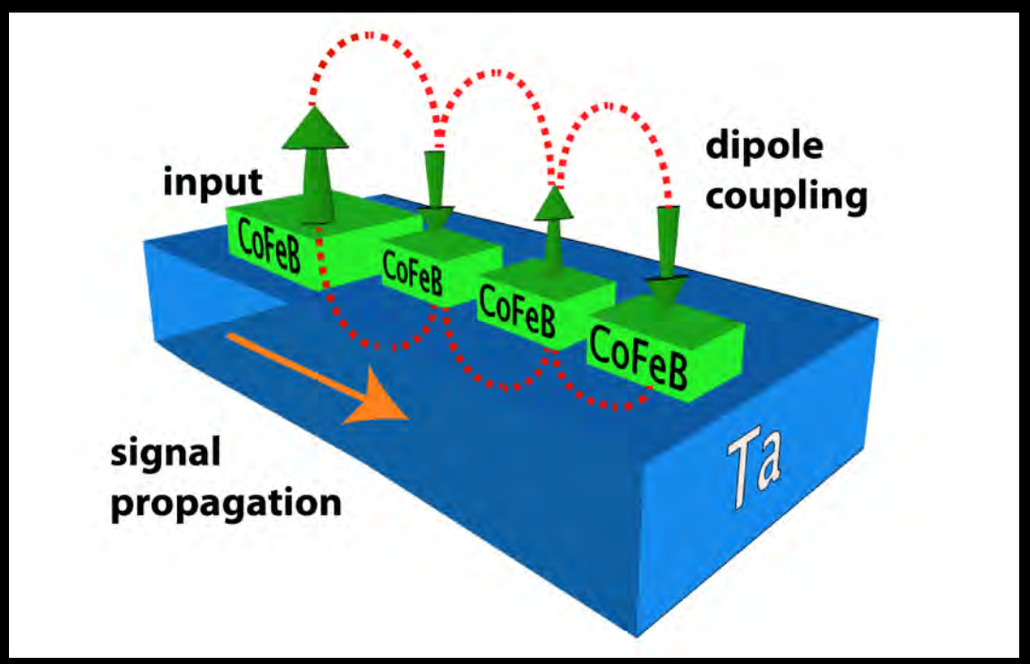
Wong, P.H.S. *et al. Nature Nano.* 10 (2015)

Doctoral research

Spin orbit torque driven nanomagnetic logic (experiment)







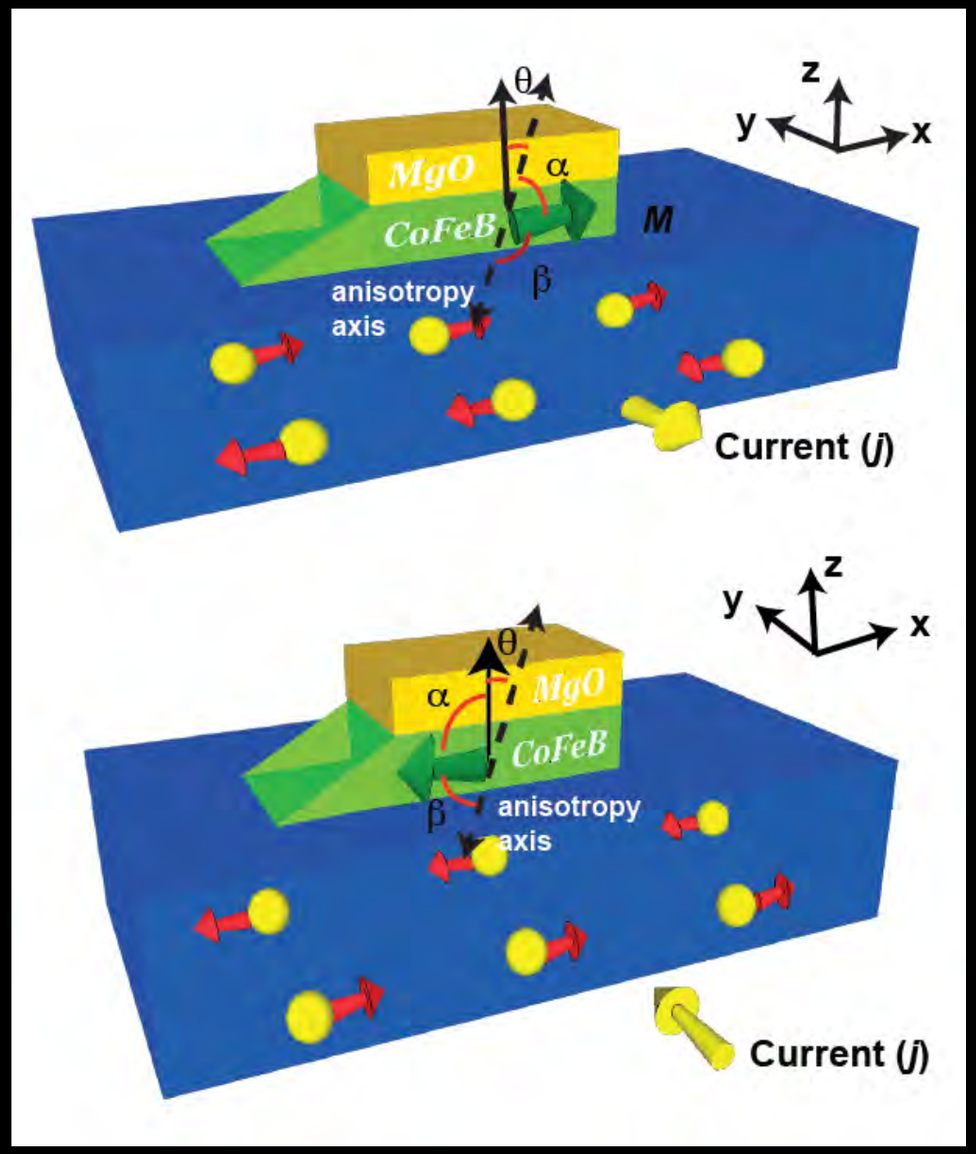
Three 500 by 500 nm magnetic dots with a microns sized input dot separated by 30 nm each. Dipole coupling determines the final state- chain of inverters.

Current needed for clocking is 2mA, While that in Oersted field clocking is ~700 mA.

Bhowmik, D. *et al*. Nature Nanotechnology **9** (2014)

Magnetic switching is too slow for logic.

Spin orbit torque driven magnetic switching for memory (simulation)



We engineer a tilt in the structure of the ferromagnet to cause deterministic switching in it by current.

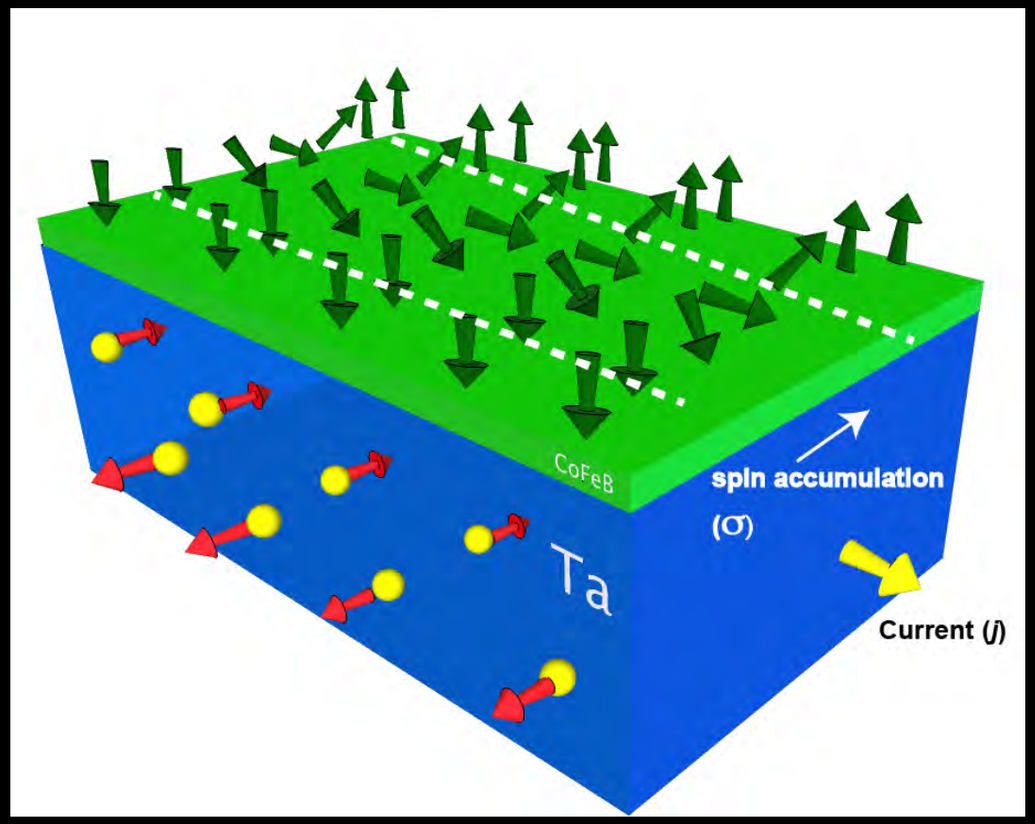
Direction of magnetization M driven by spin orbit torque	Direction of final Magnetization M
+x	+z
-x	-z

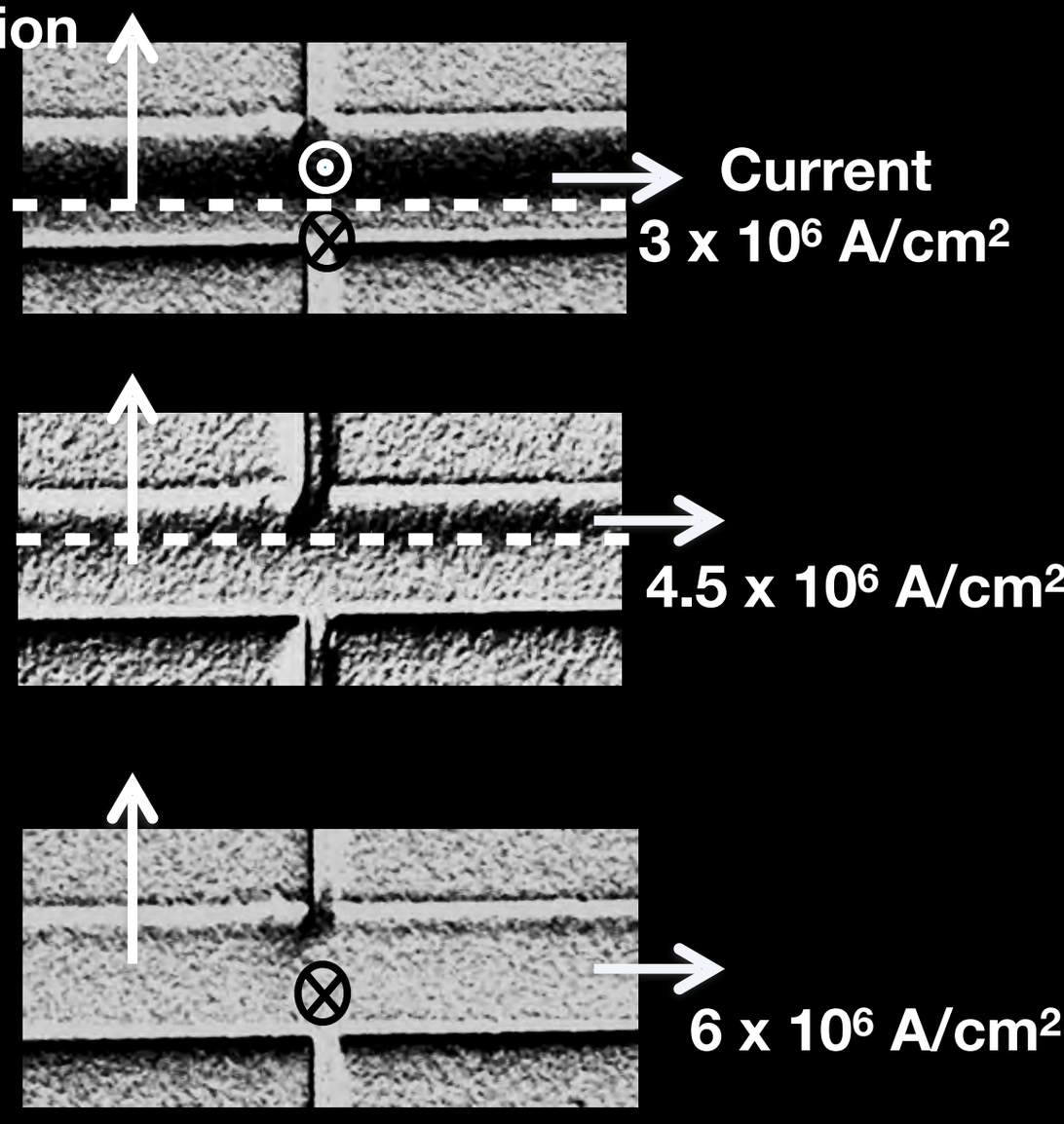
L. You, O.J. Lee, D. Bhowmik *et al.* Proceedings of National Academy of Sciences 112(33) 2015

Spin Transfer Torque Magnetic Random Access Memory already being commercially made

Doctoral research

Spin orbit torque driven domain wall motion (simulation and experiment)





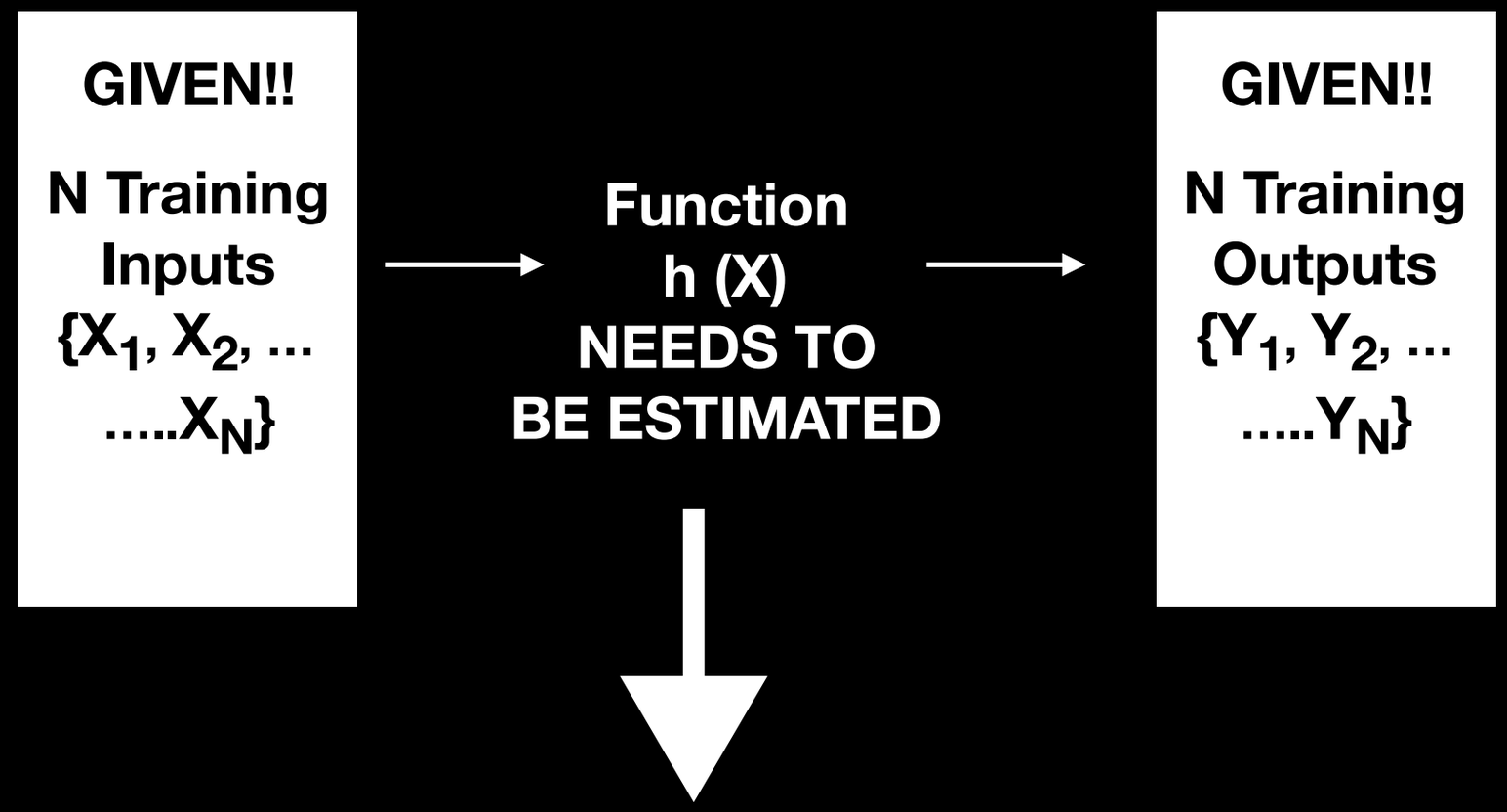
D. Bhowmik et al. Scientific Reports 5, 11823 (2015)

Multiple electrically controlled magnetic states can be obtained with different conductances- functional memristive behaviour.

Can this device be used for new kind of computing that combines memory and logic?
-Theme of my ongoing research

Theme of my research as faculty

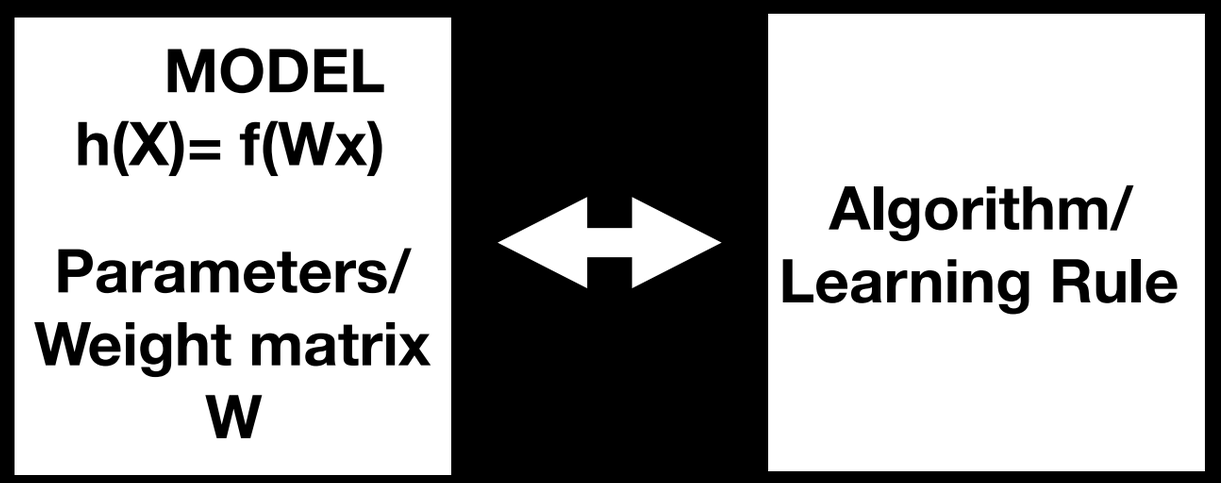
Neural Network Algorithms have memory- computing intertwined



Wx calculation: computing

f(Wx) calculation: computing

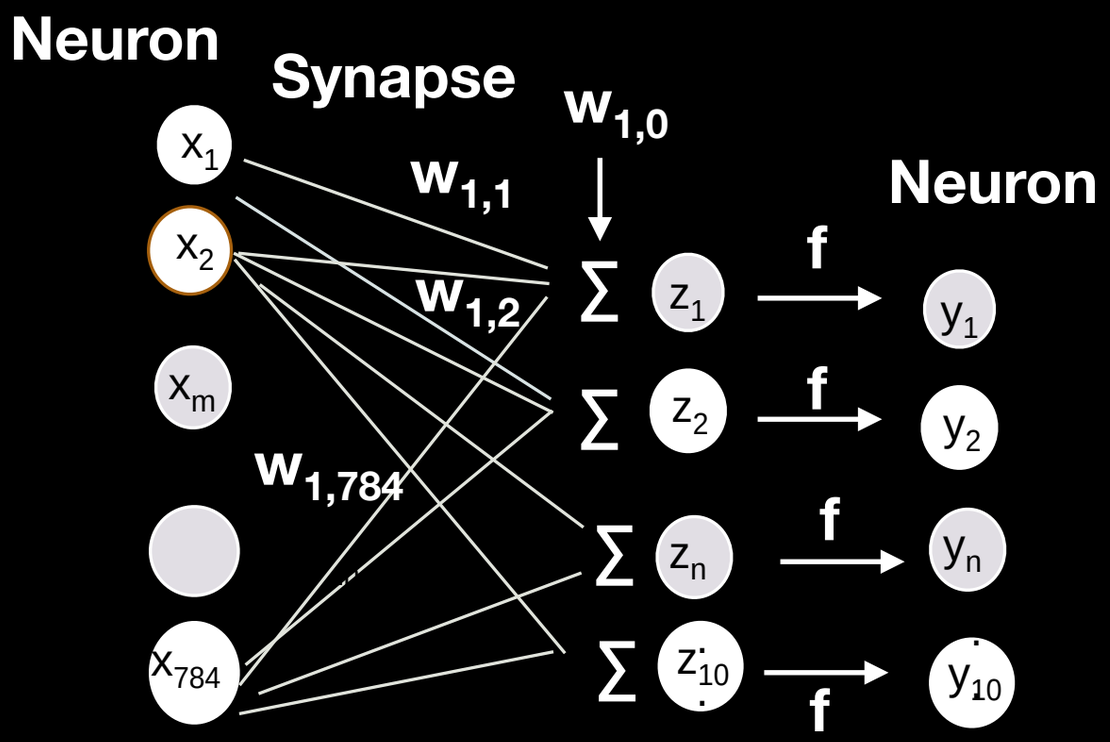
Storing W: memory

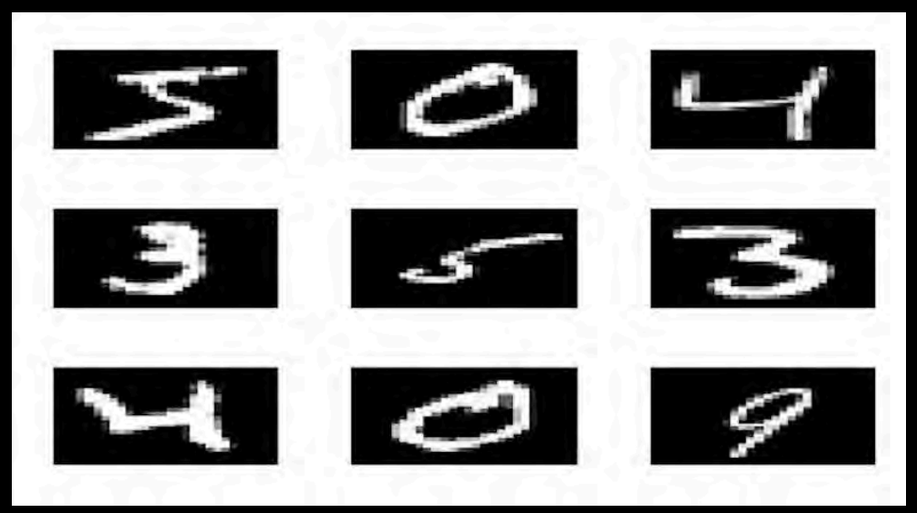


computing

Theme of my research as faculty

Fully Connected Neural Network (FCNN)





28 by 28 pixel images from MNIST dataset

Forward computation:

$$y_n = f(z_n) = \frac{2}{1+e^{-\lambda z_n}} - 1;$$
$$z_n = w_{n,1}x_1 + w_{n,2}x_2 + ...w_{n,784}x_{784} + w_{n,0}$$
$$= (\Sigma_{m=1}^{m=784} w_{n,m}x_m) + w_{n,0}$$

Stochastic Gradient Descent (SGD) learning rule :

$$\epsilon_n = \frac{1}{2}(Y_n - y_n)^2$$

$$w_{n,m}^{i+1} = w_{n,m}^{i} - \Delta w_{n,m}$$
$$= w_{n,m}^{i} - \eta \frac{\partial \epsilon_n}{\partial w_{n,m}}$$

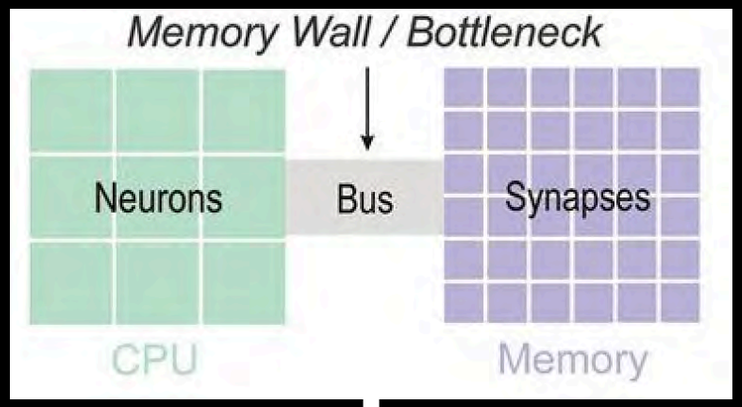
applied over every training example, multiple times.

η **: learning rate**

Theme of my research as faculty

Solving FCNN on different computer architectures

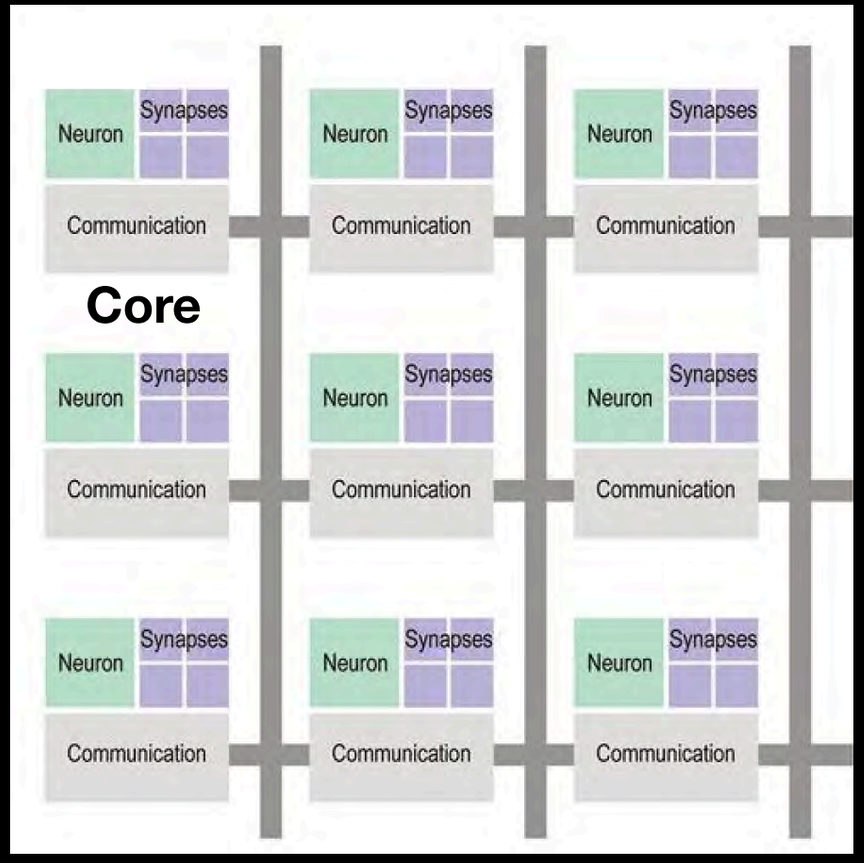
Traditional computer architecture: von-Neumann

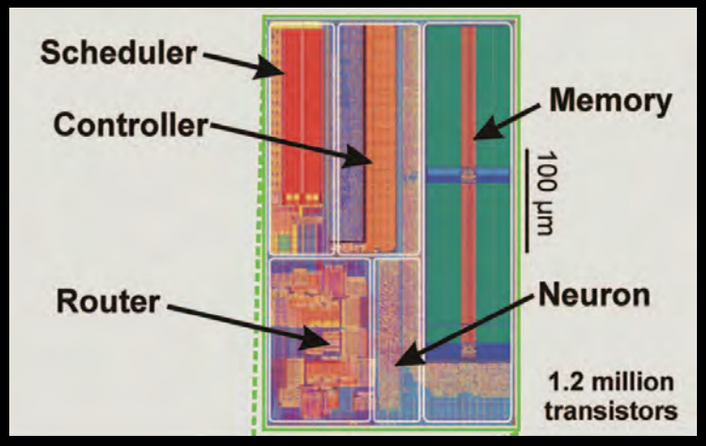


Memory and computing are completely separate

Inside each core

Digital Hardware Neural Network: IBM True North chip

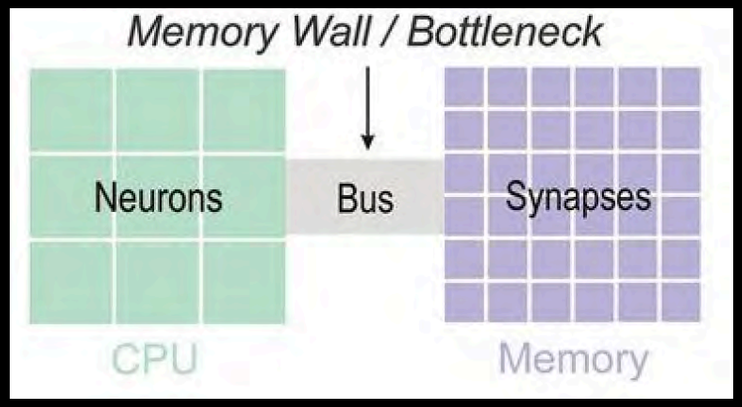




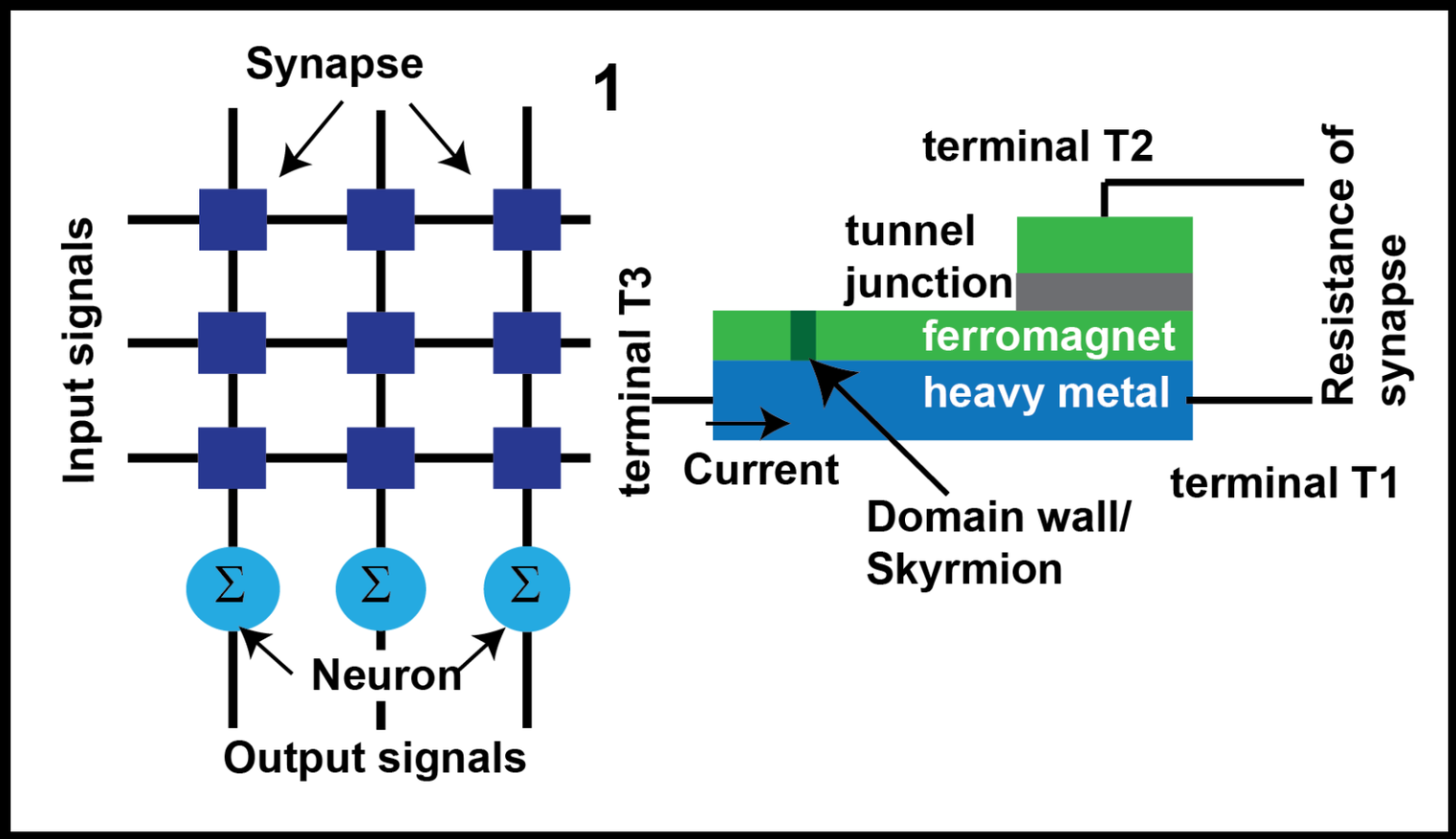
Memory and computing are separate inside each core, but more intertwined overall.

Theme of my research as faculty

Solving FCNN on different computer architectures



Memory and computing are completely separate



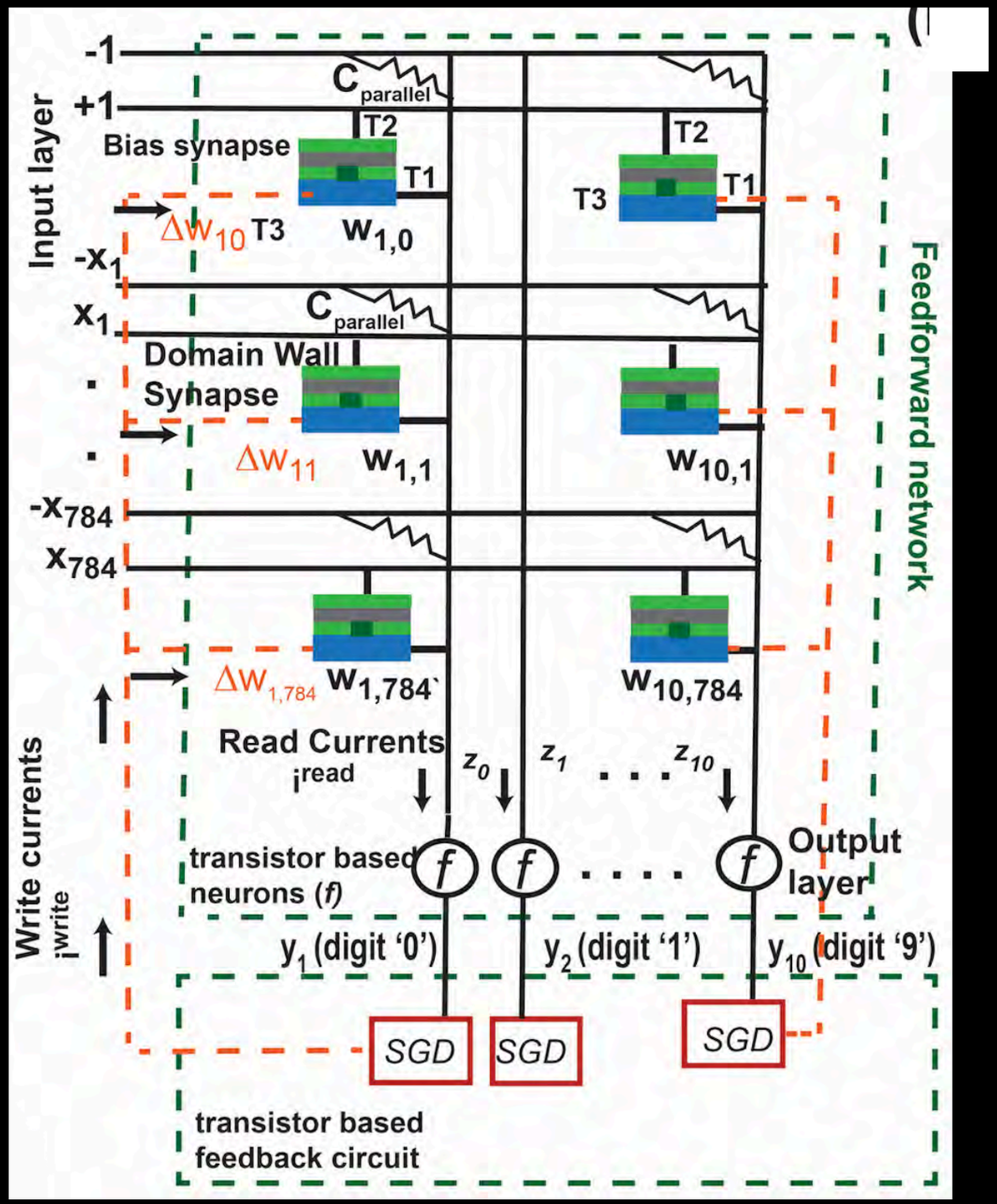
Analog Hardware Neural Network: Spintronic Synapse

Memory and computing are completely intertwined.

Grollier, J. Proceedings of the IEEE Vol. 104, 10 (2016)
Sengupta, A. Applied Physics Reviews 4, 041105 (2017)

Results from our research group

Simulation of spintronic hardware based Fully Connected Neural Network (FCNN)



Spintronic synapses in cross-bar:

$$z_n = w_{n,1}x_1 + w_{n,2}x_2 + ...w_{n,784}x_{784} + w_{n,0}$$
$$= (\sum_{m=1}^{m=784} w_{n,m}x_m) + w_{n,0}$$

w is adjusted at every iteration by write current

Transistor based neuron:

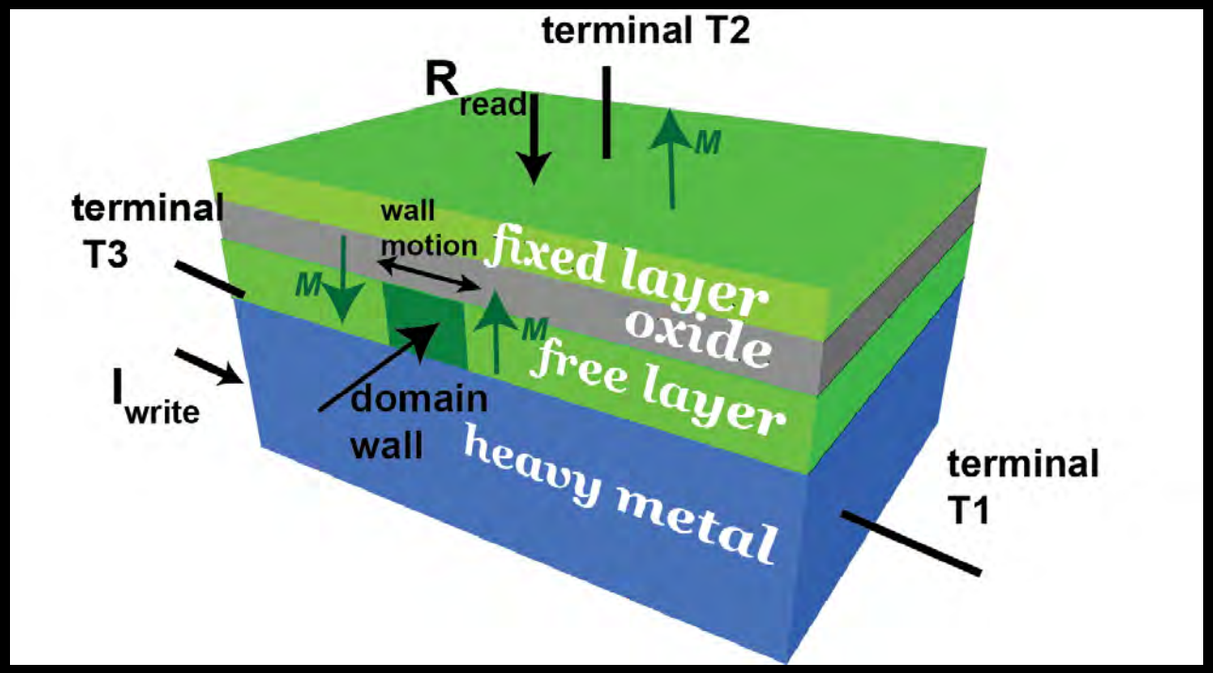
$$y_n = f(z_n) = \frac{2}{1 + e^{-\lambda z_n}} - 1$$

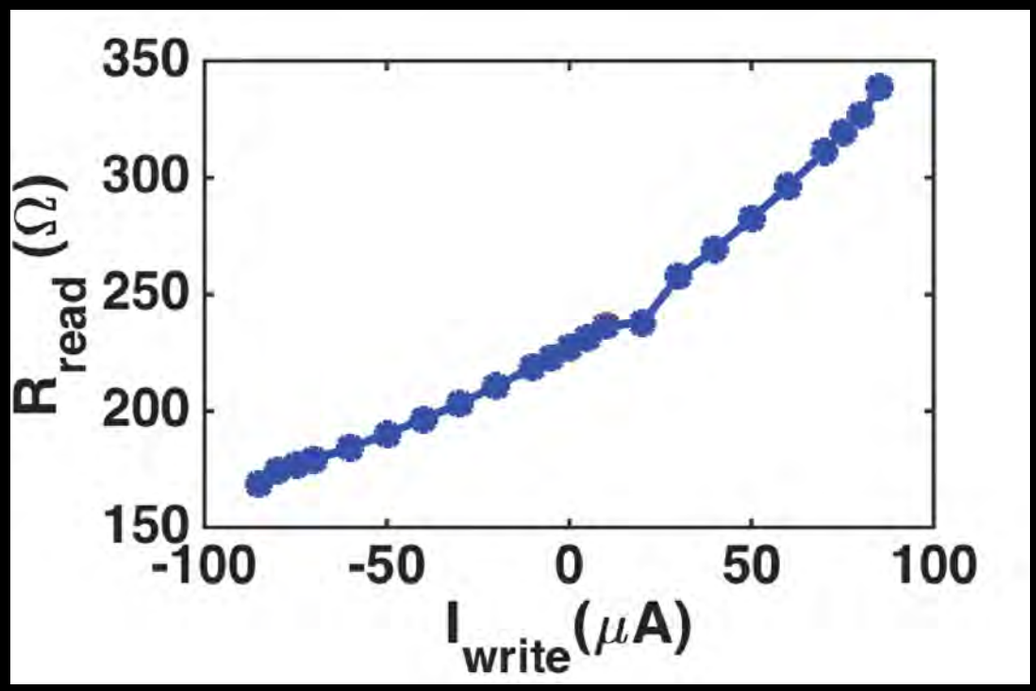
Transistor based SGD circuit:

$$w_{n,m}^{i+1} = w_{n,m}^{i} - \Delta w_{n,m}$$
$$= w_{n,m}^{i} - \eta \frac{\partial \epsilon_n}{\partial w_{n,m}}$$

Results from our research group

Micromagnetic simulation of domain wall synapse





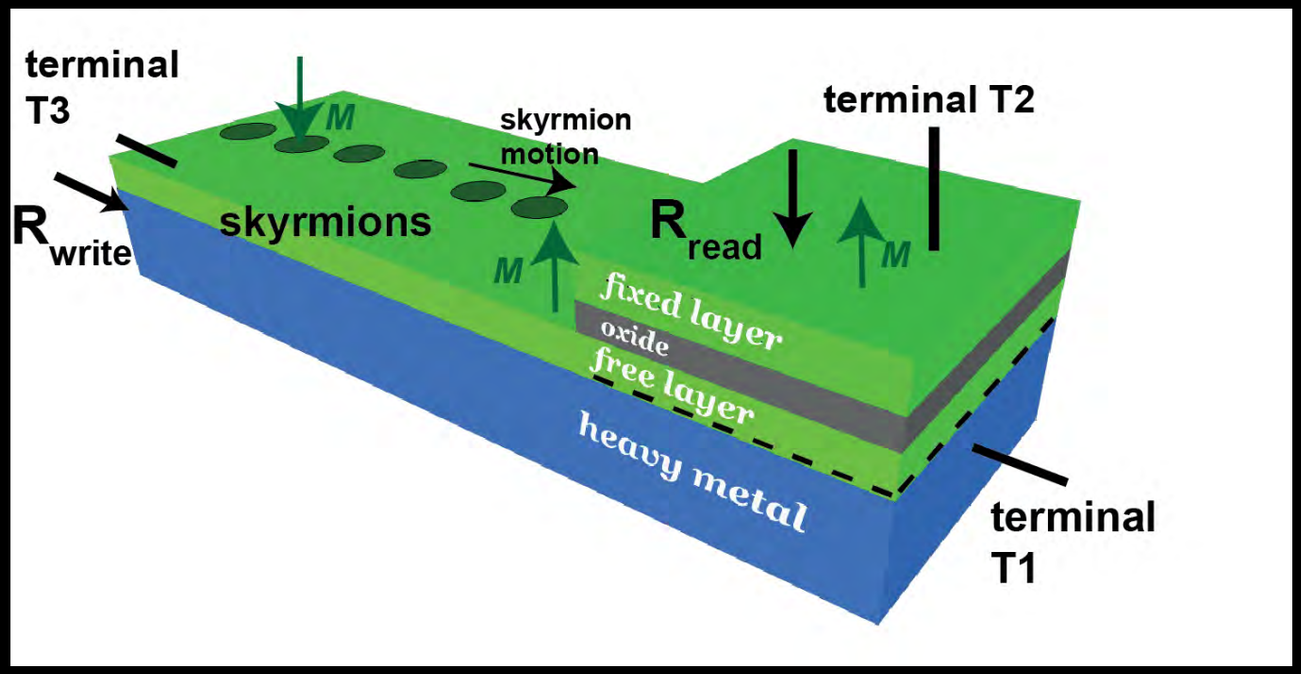
Multiple current controlled conductance states which are non-volatile: Essential for synapse

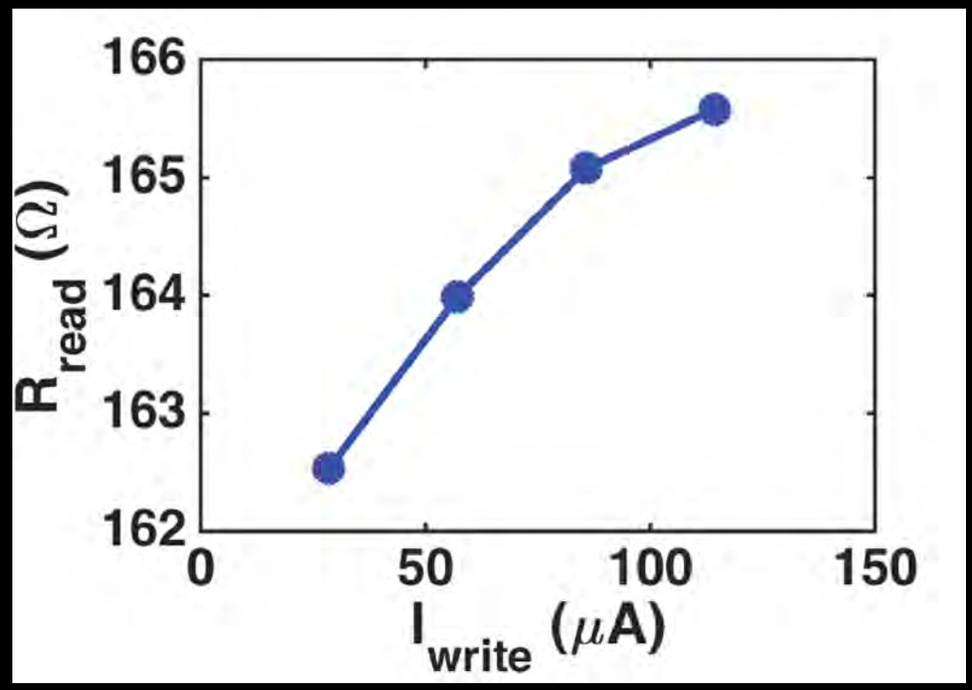
simulated domain wall synapse device, proposed by Sengupta *et al. (2016)* on micromagnetic simulation package mumax

U. Saxena et al. IEEE Transactions on Magnetics, vol. 44, no. 11 (2018).

Results from our research group

Micromagnetic simulation of skyrmion synapse





Multiple current controlled conductance states which are non-volatile: Essential for synapse

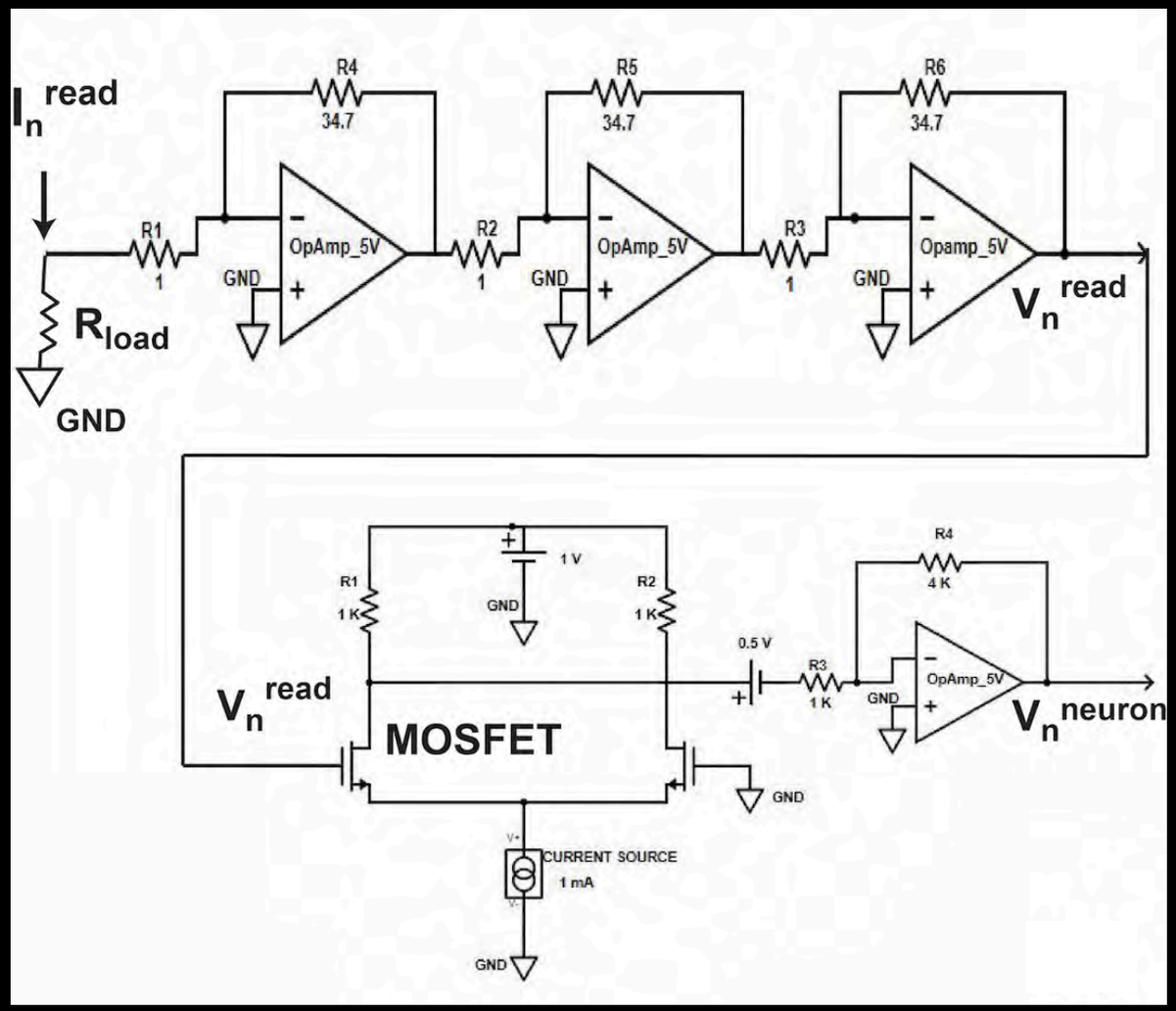
proposed and simulated skyrmionic synapse on micromagnetic simulation package mumax.

showed that it consumes lower energy than domain wall synapse if operated with low current.

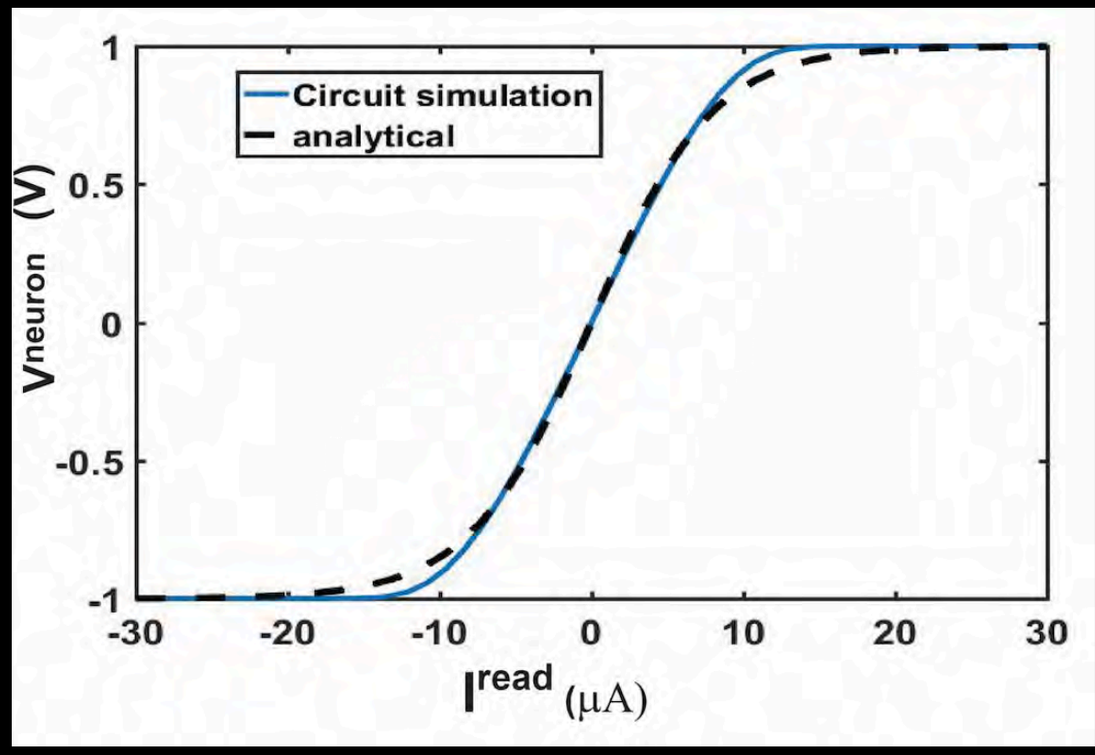
U. Saxena et al. IEEE Transactions on Magnetics, vol. 44, no. 11 (2018).

Results from our research group

Transistor based Neuron circuit



op-amp and differential amplifier based analog circuit for neuron

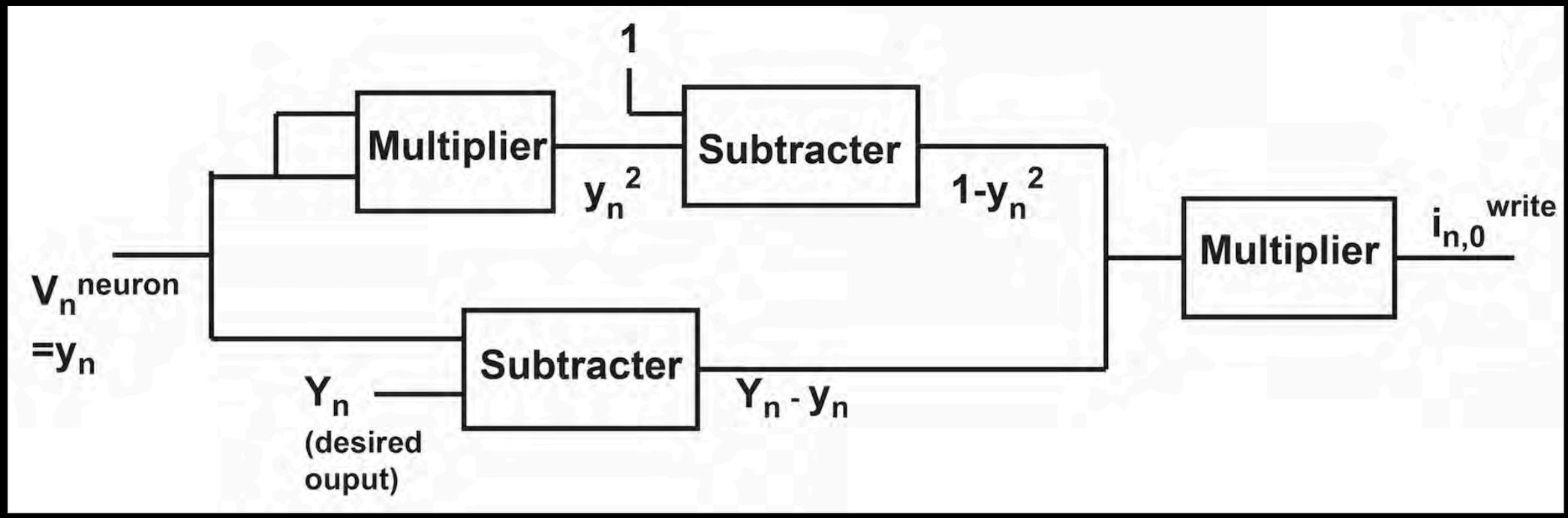


tan sigmoid activation function:

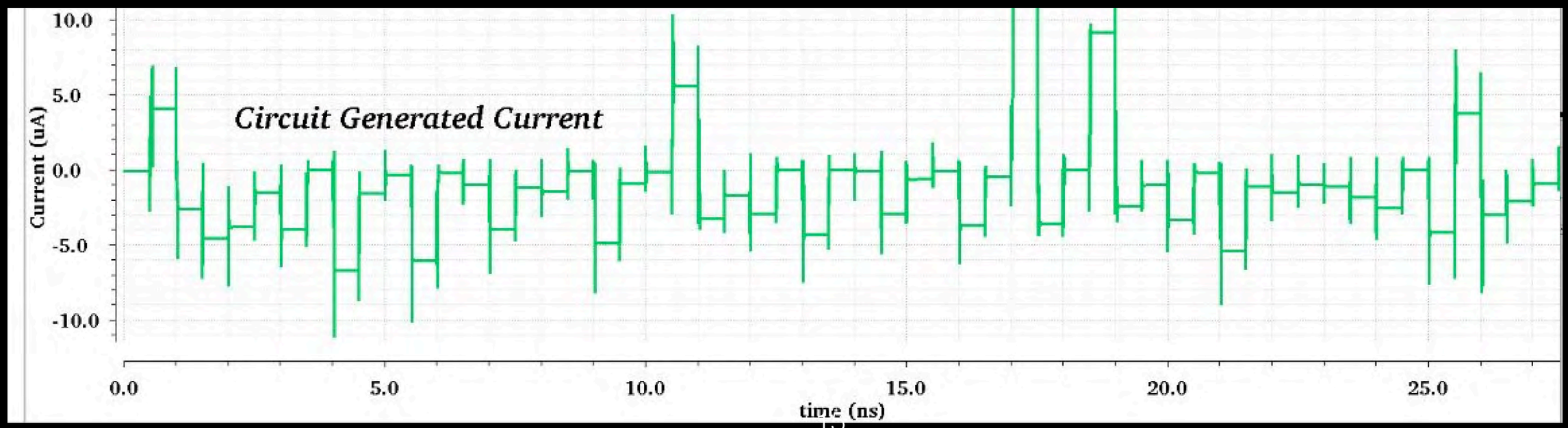
$$y_n = f(z_n) = \frac{2}{1 + e^{-\lambda z_n}} - 1$$

Results from our research group

On chip learning of spintronic FCNN on MNIST dataset

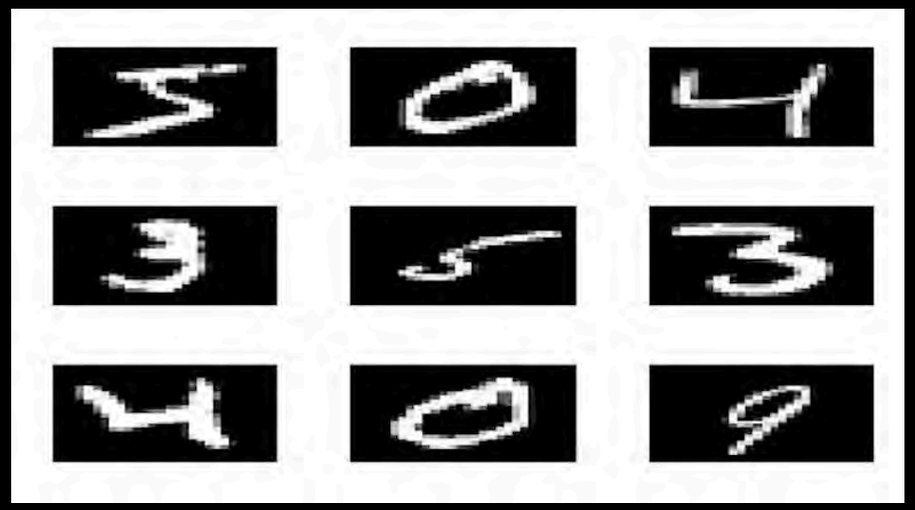


SGD calculation and write current generation circuit



Results from our research group

On chip learning of spintronic FCNN on MNIST dataset



1000 train samples, 100 test samples.
10,000 epochs

Train accuracy: 97 %
Test accuracy: ~ 65%

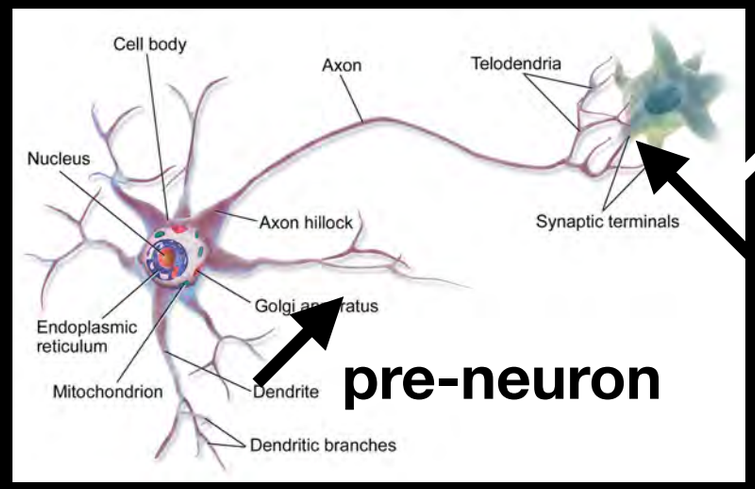
A. Dankar et al. , under preparation

- **To improve test accuracy hidden layers will be needed, but then implementing SGD calculation circuit (backpropagation) in hardware is hard because weights of synapses are needed in the calculation.**

- **We turn towards hardware neural network that already exists in nature: the brain.**

Theme of my research as faculty

Brain Inspired Spiking Neural Network (SNN)

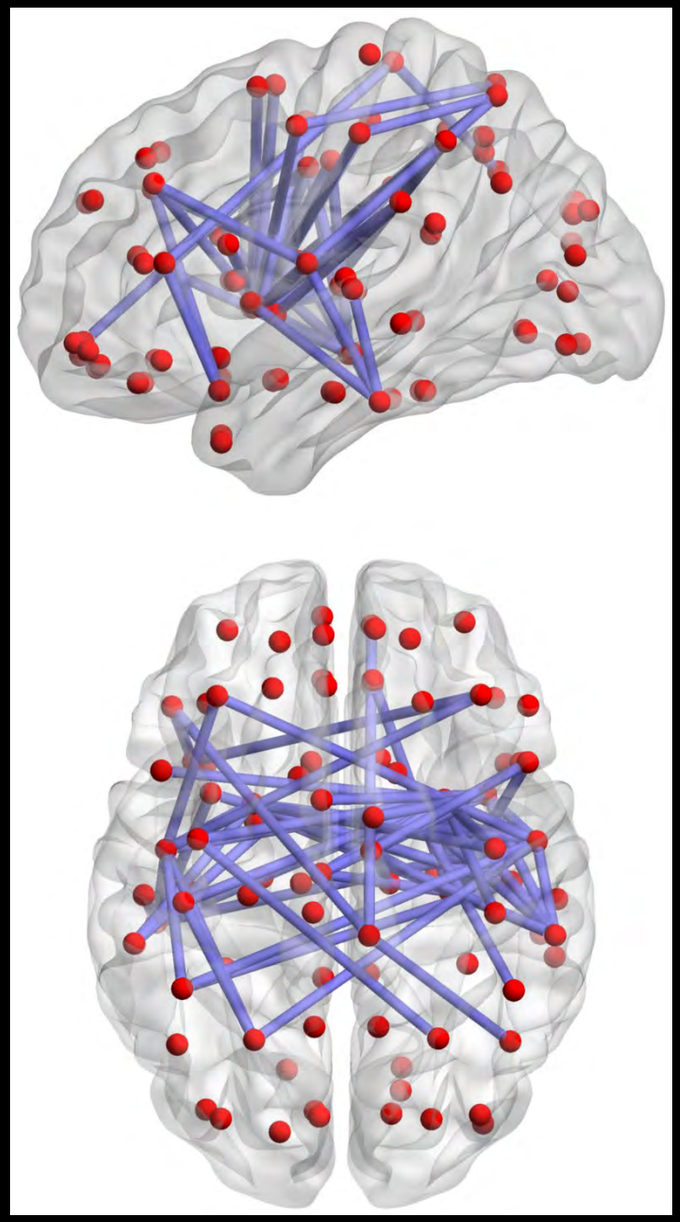


post-neuron

synapse

pre-neuron

Neuron connected to another neruon by synapse

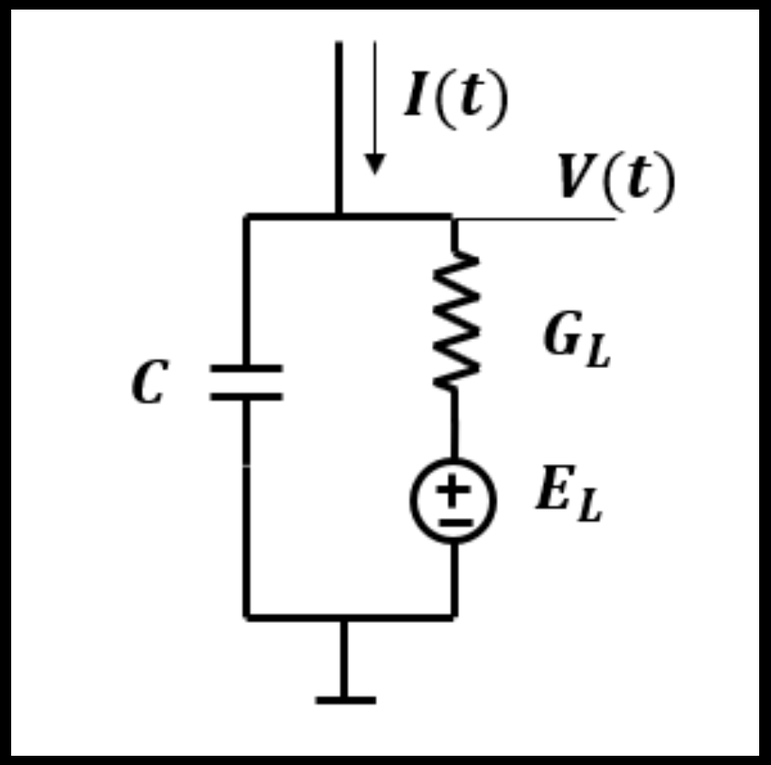


10^{11} neurons interconnected through 10^{15} synapses

Theme of my research as faculty

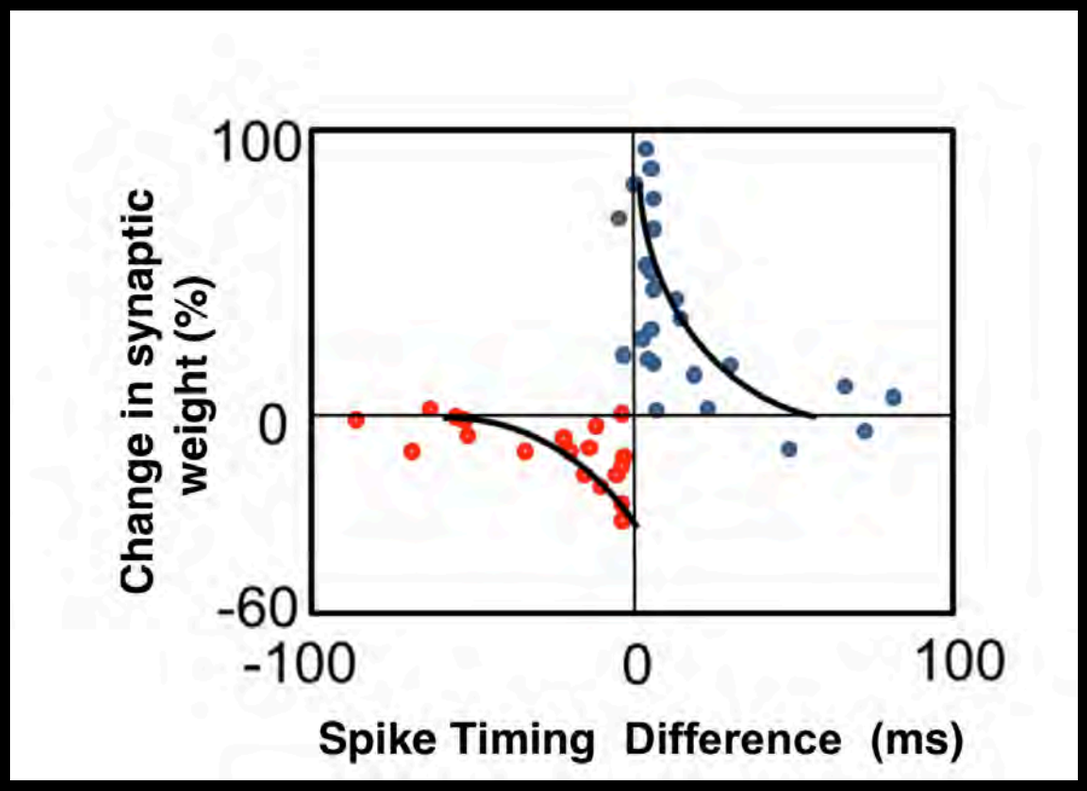
Brain Inspired Spiking Neural Network (SNN)

Model for neuron:
Leaky Integrate and Fire (LIF)



Whenever V(t) reaches a threshold, it spikes and goes back to rest potential E_L

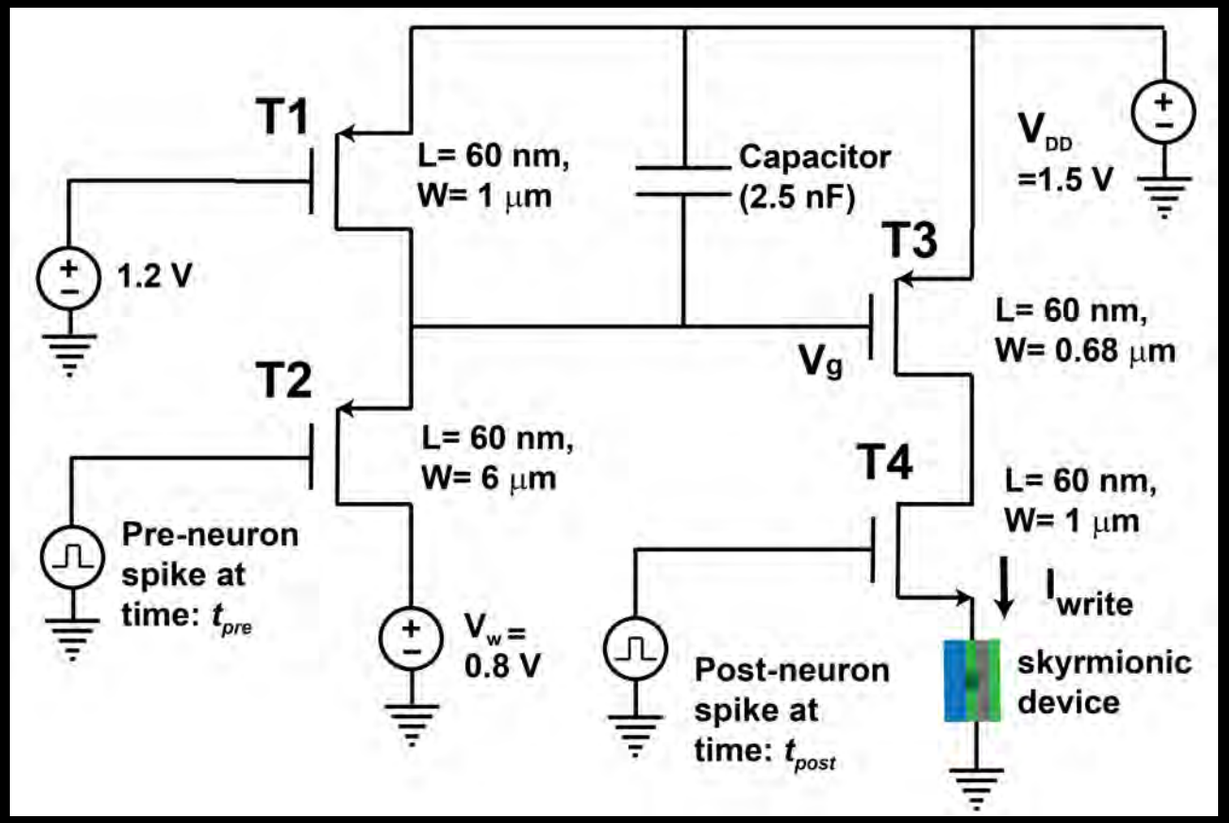
Model for synapse:
Spike Time Dependent Plasticity (STDP)

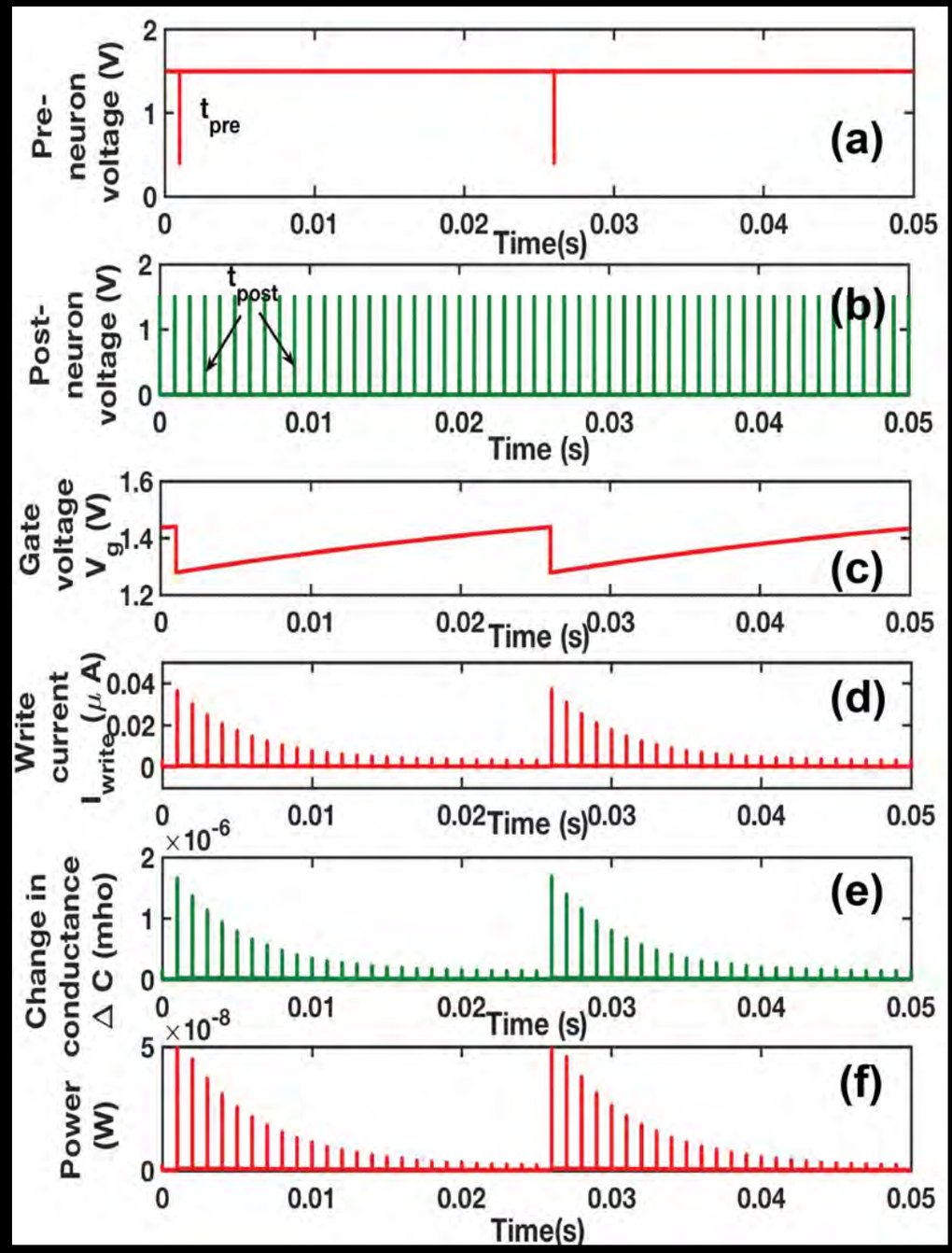


Data obtained from rat's hippocampus (*Bi, Poo, J. Neuroscience 1998*)
Increase in weight of synapse decreases exponentially with time gap between pre- neuron and post neuron spike

Results from our research group

Design of spintronic- transistor circuit to emulate STDP

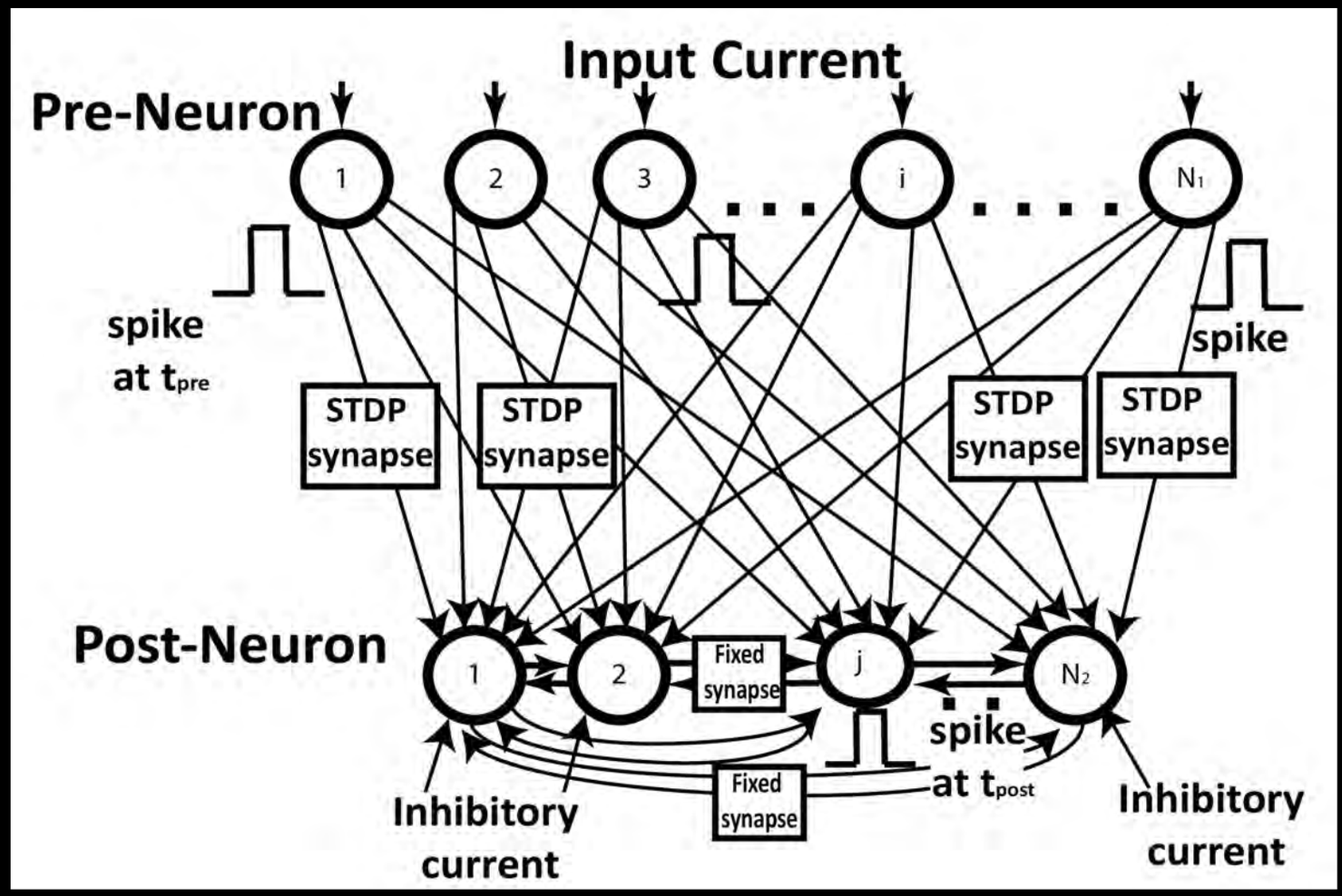




Since write current (Iwrite) decays exponentially with (t_{post} - t_{pre}) conductance decays exponentially too and so does weight of the synapse (STDP).

Results from our research group

Design of spintronic- transistor circuit based STDP enabled SNN



Performance on popular machine learning datasets:

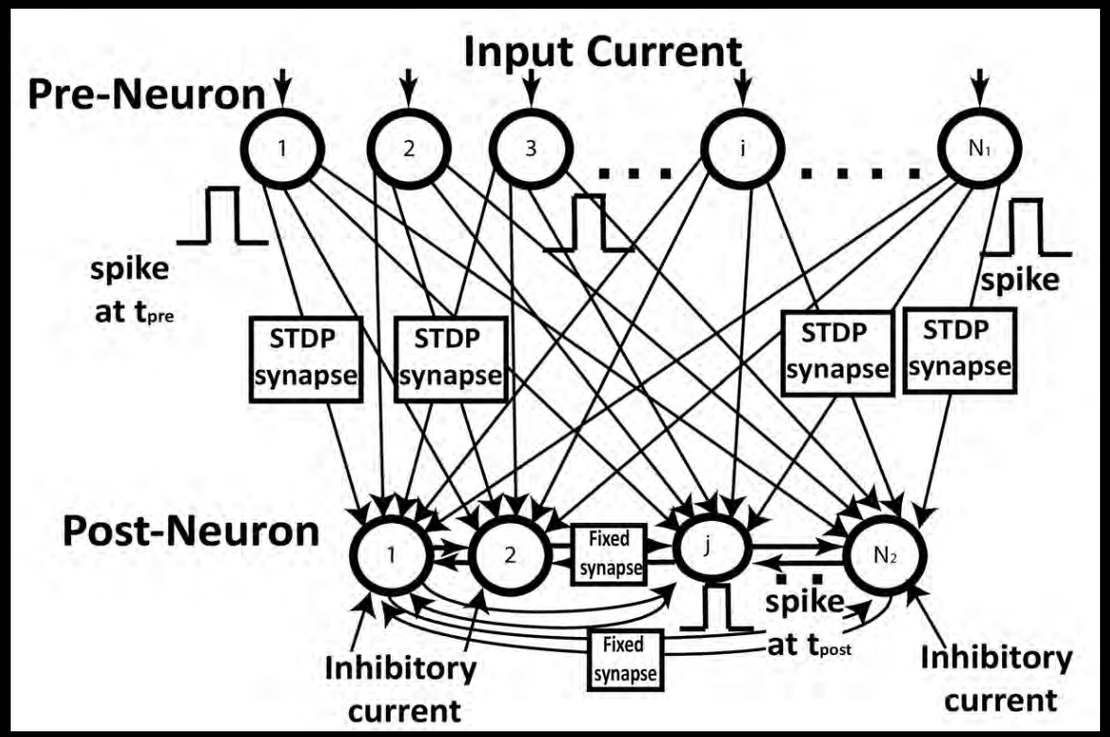
Dataset	Number of epochs	Training Accuracy(%)	Test accuracy(%)	Total Energy (nJ)	Average Energy per weight update (fJ)
Fisher's Iris	10	87	93	0.59	8.83
WBC	10	91	91	0.56	0.745

In collaboration with Prof. Udayan Ganguly, IIT Bombay

U. Sahu et al. submitted.

Results from our research group

Training STDP enabled SNN on MNIST dataset

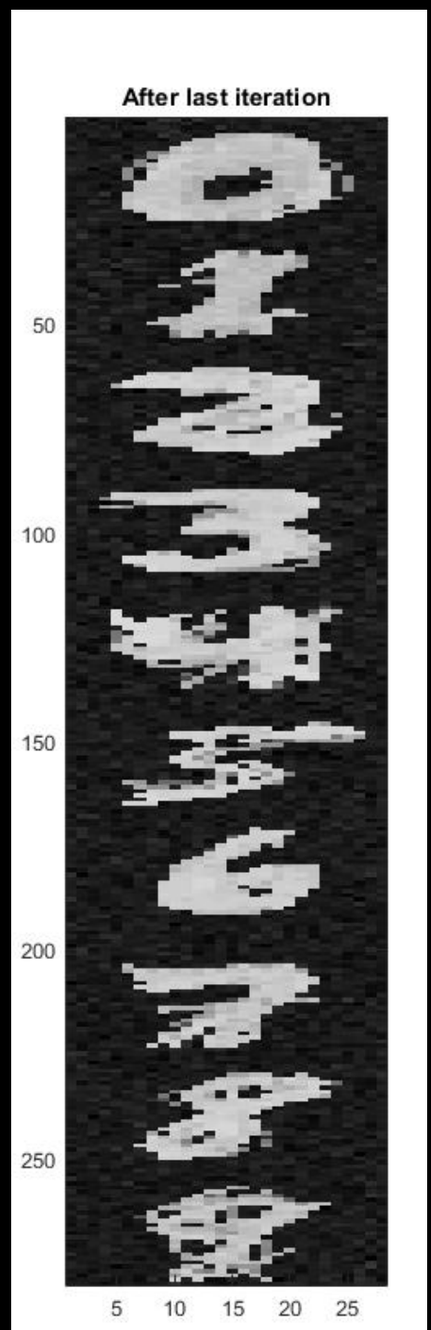


100 train samples, 100 test samples.
50 epochs

Train accuracy: 91 %
Test accuracy: 55%

In collaboration with Prof. Udayan Ganguly, IIT Bombay

Direct visualization of weights of the synapses



Summary of Results and Future Work

- Simulated spintronic synapse devices through micromagnetics and benchmarked them against experiments.

- Implemented in simulations on-chip learning of different types of neural networks using spintronics.

- Future goal: Fabricate and characterize such spintronic neural networks.

- Future goal: Explore more learning paradigms closer to actual functioning of the brain.

Natural and Artificial Intelligence Through Spintronics (NAITS) Group

Thanks to Indian Academy of Sciences
for the Associateship and organising the seminar

Thank you for you attention!