A Superconducting Platform for Energy-efficient Spiking Neural Networks

MIT AI Hardware 2023 Symposium

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Superconducting nanowire SNNs

Superconducting spiking neural networks (SSNNs) are a promising technology for neuromorphic computing, with their potential for high energy efficiency and fast processing speeds. Two key components used in SSNNs are Josephson junctions and superconducting nanowires, both of which can emulate the firing behavior of neurons. Superconducting nanowires offer certain advantages over Josephson junctions:
- Higher voltage potentials, thus larger fan-out and easier interface with transistors.
- Low-loss transmission lines for interconnections between neurons.
- Compact and tunable inductors can be designed, thanks to the high kinetic inductance.
- Intrinsic stochastic behavior due to thermal fluctuations.
- Three-terminal switches can be designed: nanocryotron [1] and heater nanocryotron [2].
- Higher resistance to magnetic noise.

In general, nanowires have lower operating frequencies and higher energy consumption with respect to Josephson junctions, but their action potentials can be directly read out. Therefore, nanowires are more suitable for studying neural dynamics and learning.

Relaxation oscillations

Relaxation oscillator patterned on a 20-nm thin film of niobium nitride with e-beam lithograpgy at MIT.

[3]   [4]

Neuron-synapse-neuron connection

Thermal connection with heater nanocryotron [5]

Comparison with other technologies

Estimated without cooling power

[4]

Neuron: simulation and experiment

The nanowire neuron is composed of two relaxation oscillators that mimic the ion channels in the neural membrane of the soma (Hodgkin–Huxley model).

Stochastic behavior

Class I behavior

[6]   [5]

The nanowire neuron mimics different biological behaviors:
- Stochastic activation function.
- Refractory period: minimum time between two adjacent action potentials.
- Class I behavior: the spiking frequency depends on the input potential.
- A transmission line can mimic the axon delay for temporal coding.

Synapse: simulation and experiment

Nanocryotron

Integrator

Simulation

Mimicking slow release of neurotransmitters

[3]

Weight tunability

Inhibitory control   Excitatory control   Experiment

The bias current of the nanocryotron is the synaptic weight that can be linearly tuned.

Applications

We demonstrated neural networks in SPICE simulation for three different applications:
- Classification of 9-pixel images with single-pixel errors using inductive synapses.
- Inversion of Laplacian matrices with rate coding (least square error: 6e-3 after 40 μs).
- Implementation of a biological function based on the competition between neurons firing stochastically: winner-takes-all (using inductive synapses).

Image classification

Inductive synapse (integrator with inductive coupling)

[6]

Matrix inversion

[5]

Winner-takes-all

[6]

Acknowledgments

[1] McCaughan, Adam N., Berggren, Karl K. *Nano Letters* 14.10 (2014): 5748-5753
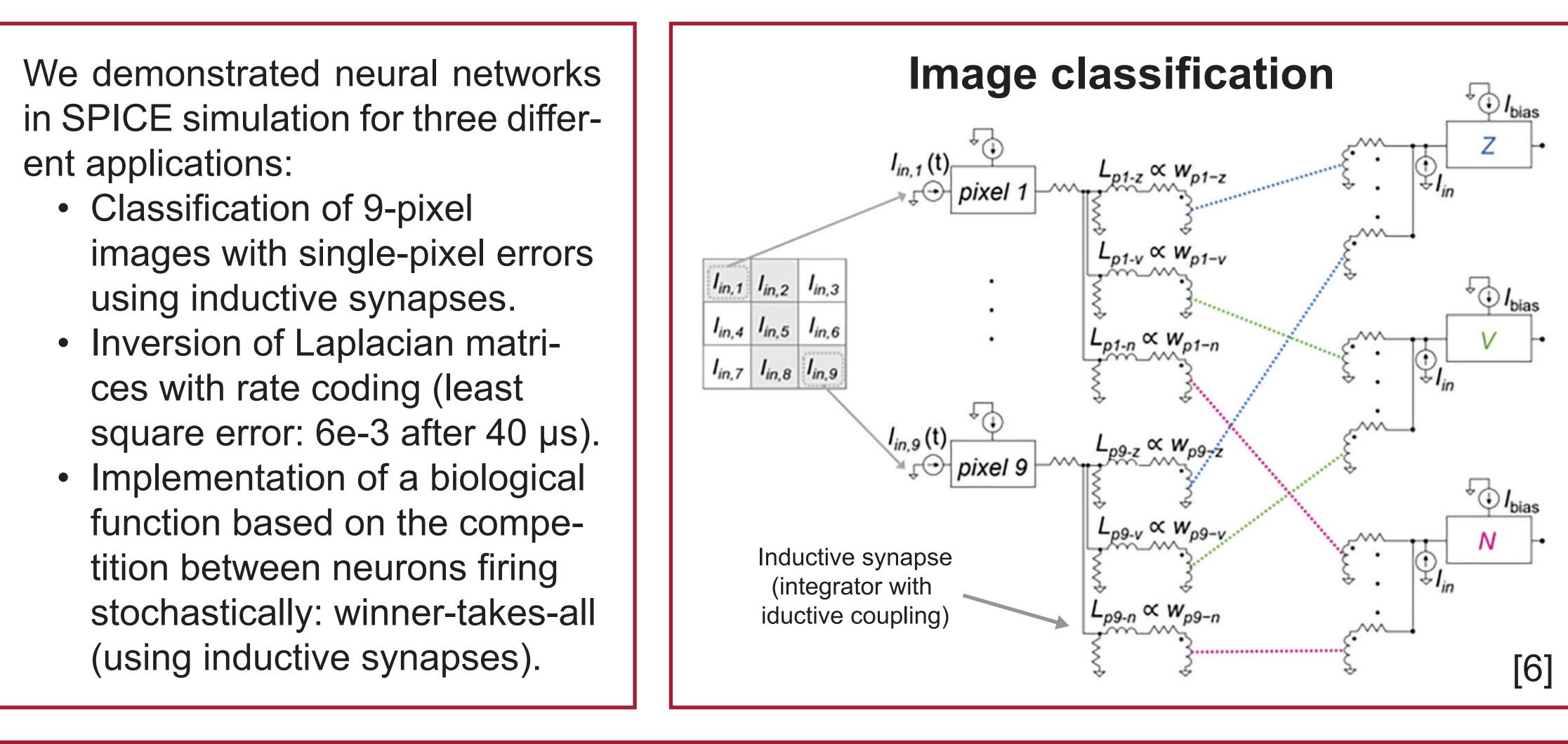[2] Baghdadi, Reza, et al. *Phys. Rev. Applied* 14, 054011 (2020)
[3] Castellani, Matteo. Master thesis, *Polytechnic University of Turin* (2021).
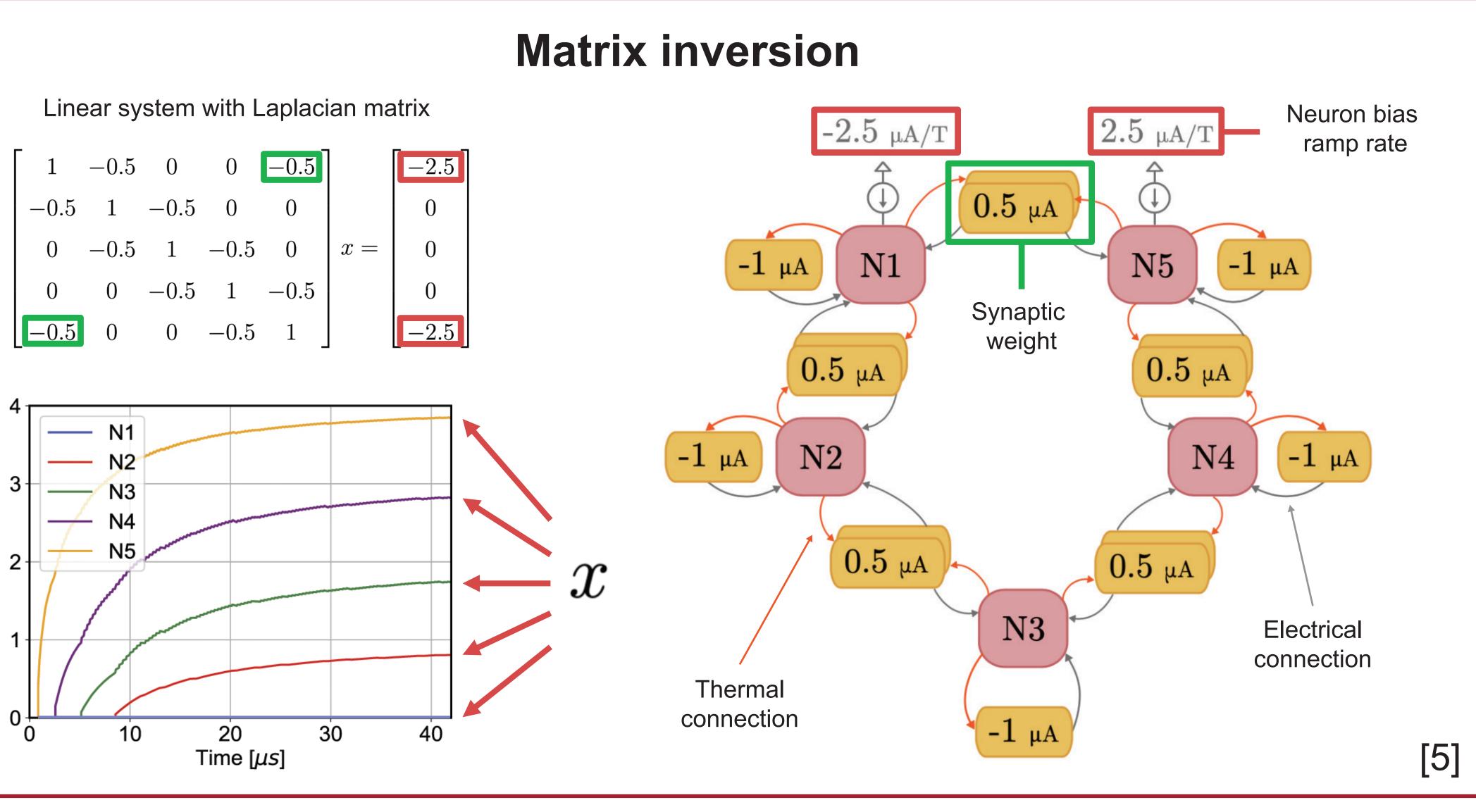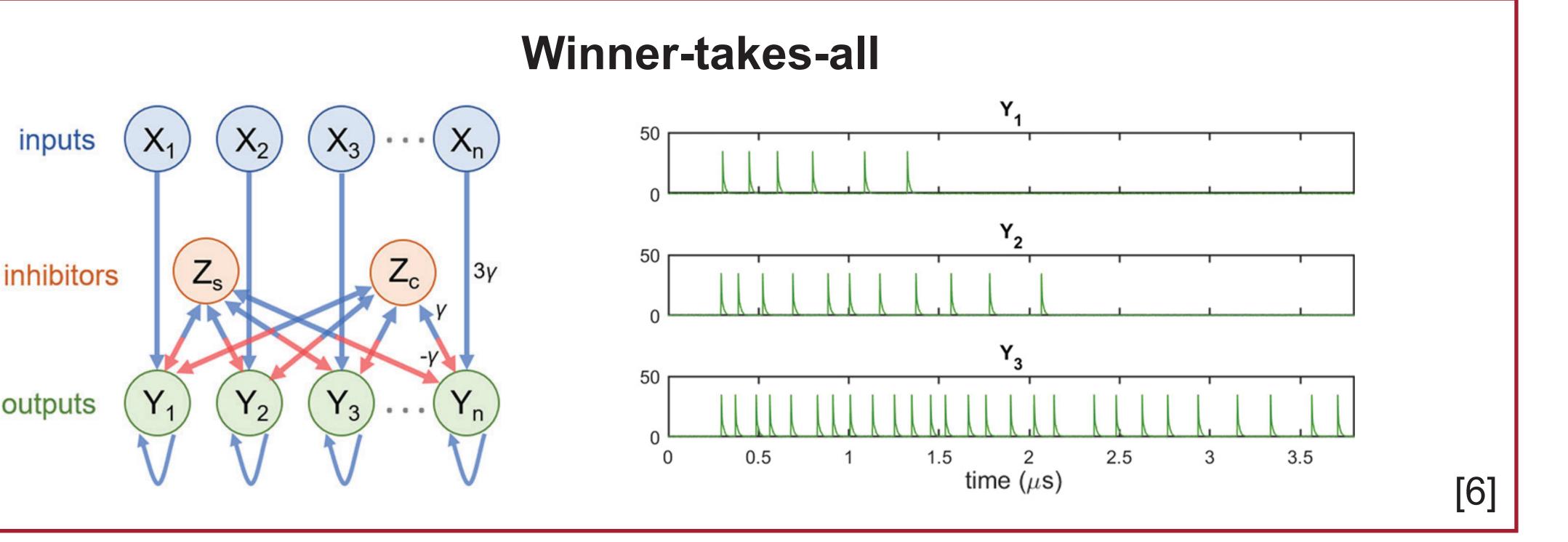[4] Toomey, Emily, et al. *Front. Neurosci.* 13 (2019): 933.
[5] Lombo, Andres E. et al. *Neuromorph. Comput. Eng.* 2 034011 (2022).
[6] Toomey, Emily, et al. *Nano Letters* 20.11 (2020): 8059-8066.

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