Neuromorphic in-memory learning with analog integrated circuits and nanoscale memristive devices

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Building intelligent systems that can learn continuously under tight energy constraints remains a central challenge for edge computing. While modern AI relies heavily on offline training and digital acceleration, the brain suggests a different paradigm: local learning, analog computation, and tight coupling between memory and processing. This talk explores how these principles can be translated into practical neuromorphic hardware through joint advances in learning algorithms and mixed-signal circuits. I will first present voltage-dependent synaptic plasticity (VDSP) [1], [2], a local and unsupervised learning rule designed for nanoscale memristive synapses. Instead of relying on precise spike timing, VDSP uses the neuron's internal state as the learning signal, enabling compact implementations of online learning without complex peripheral circuitry. This approach allows learning rules to be expressed directly in device physics and mapped across different memory technologies, including filamentary and ferroelectric synapses. The second part of the talk focuses on hardware realization through the UNICO neuromorphic chip [3], which integrates analog CMOS neurons with memristive synapses into self-learning neural building blocks. I will describe circuit strategies that enable ultra-low-power neurons to interact reliably with nanoscale memories while preserving local plasticity and configurability. The resulting systems demonstrate compact neural networks that can adapt in real time while operating within the constraints of edge hardware.
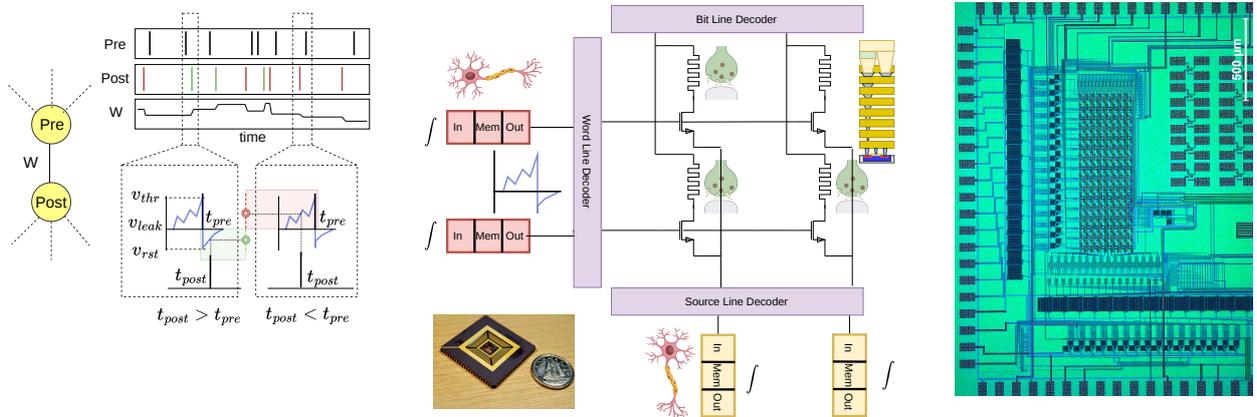

Figure 1: VDSP learning rule, architecture of CMOS-RRAM Neural Building Block (NBB), and optical micrograph of UNICO ASIC.

References

[1] N. Garg et al., "Voltage-dependent synaptic plasticity: Unsupervised probabilistic hebbian plasticity rule based on neurons membrane potential," *Frontiers in Neuroscience*, vol. 16, p. 983 950, 2022.

[2] N. Garg et al., "Unsupervised local learning based on voltage-dependent synaptic plasticity for resistive and ferroelectric synapses," *Communications Materials*, 2026.

[3] N. Garg et al., "Versatile cmos analog lif neuron for memristor-integrated neuromorphic circuits," in *2024 International Conference on Neuromorphic Systems (ICONS)*, IEEE, 2024, pp. 185–192.