Networks of low-power CMOS neuromorphic neurons with robust neuromodulation capabilities for intelligent and adaptable neuromorphic systems

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Background and motivations

Neuromorphic engineering:

- Goals: Address complexity and energy issues in modern digital machines
- Inspired by biology: replicate computational principles of the brain in integrated circuits
- Aim for intelligent, versatile, and energy-efficient systems *[Bartolozzi, Indiveri, et al. 2022]*

State-of-the-art neuromorphic designs: efficient computations (spike-based machine learning hardware), but lacking biological flexibility and robustness ⇒ unsuitable for adaptive signal processing or intelligent actuation.

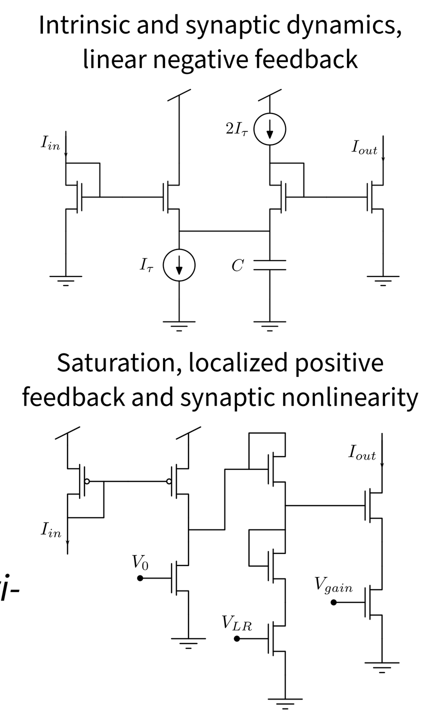
In this poster: demonstration of the neuromodulation capabilities of a novel neuron design, and potential applications for robust and versatile pattern generation for embodied intelligence, with the same robustness and adaptability as computational models *[Dethier, Drion, et al. 2015]*.

Neuromodulation in our neuromorphic neuron

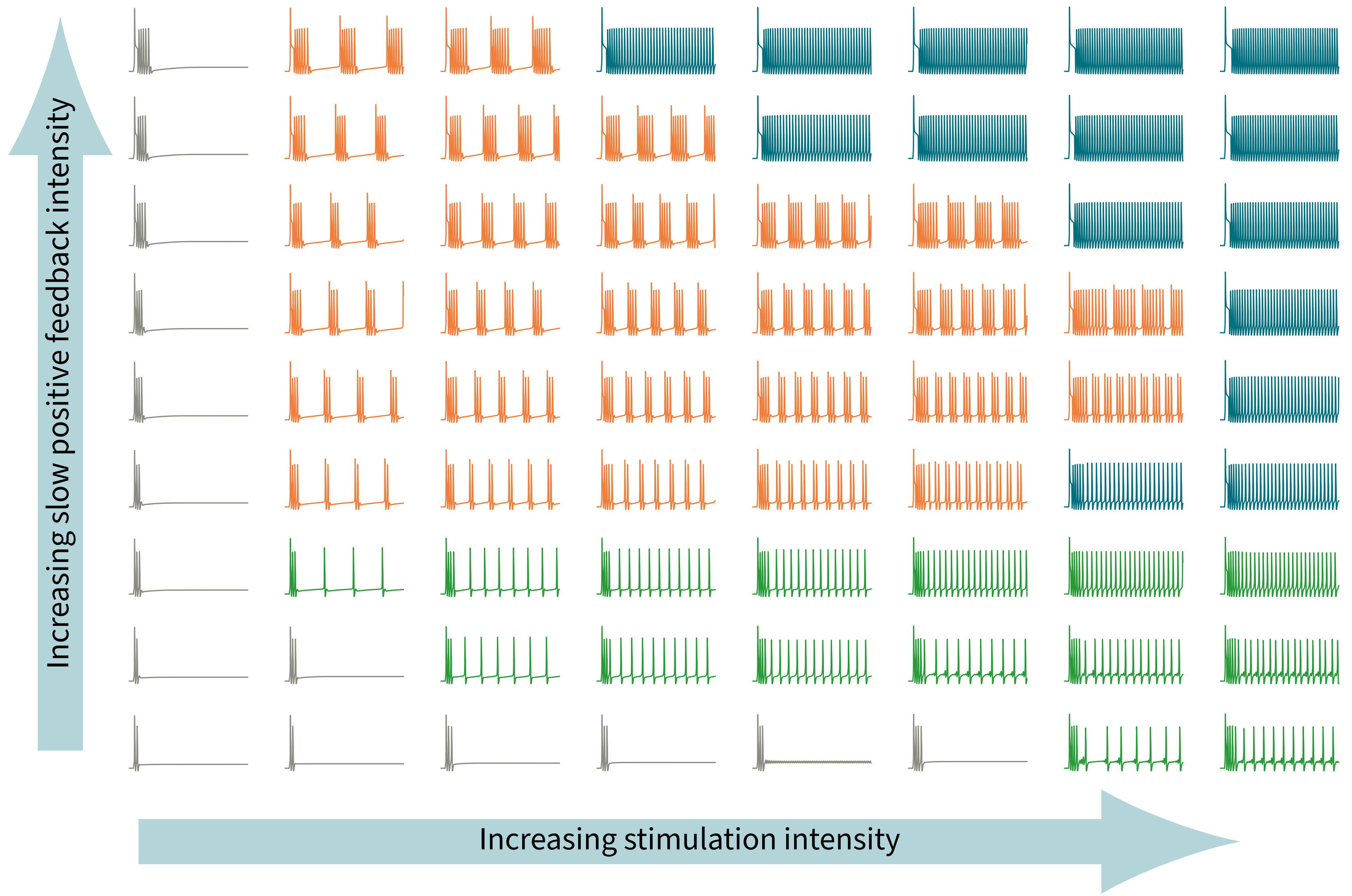
Our novel neuromorphic circuits:

- **Fully analog** CMOS **current-mode** neurons and synapses
- Robust **neuromodulation** (changing the way neurons process and convey information depending on external factors)
- Implementing modern advances in computational neuroscience *[Drion, Franci, et al. 2015]* to faithfully replicate biological behaviors
- Multiscale circuit feedback analysis ⇒ predictable and robust neuromodulation
- Power efficient: About **10 µW** per neuron in full bursting activity

Currently simulated in Cadence® Virtuoso®, with chip tape-out and experiments on the way.



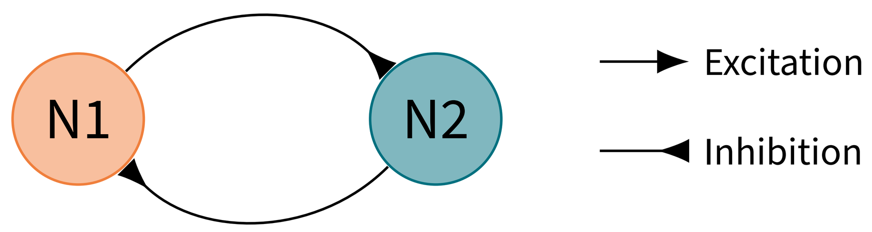
Response of the neuron circuit to increasing input current strengths. Variation of one tuning parameter ⇒ changes in activity (neuromodulation).



Neuromodulation: reliable switch between **type-I excitability**, **type-II excitability** and **tonic bursting**. Other physiological characteristics: after-depolarization potentials and rebound bursting.

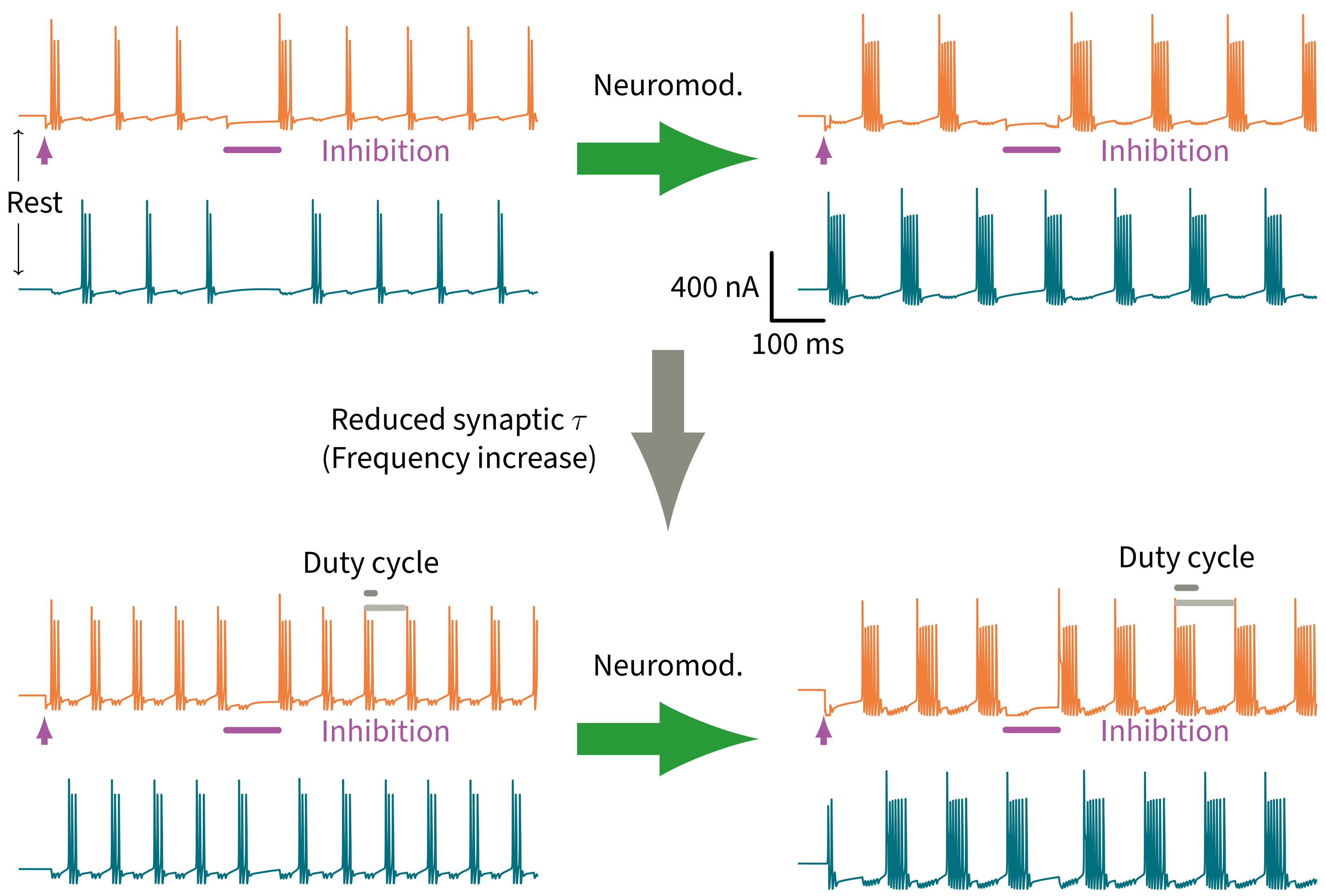
Neuromorphic half-center oscillators for rhythmic actuation

Simple but powerful architecture: two interconnected neurons inhibiting each other ⇒ alternating bursts of activity. Fundamental neural circuits playing a crucial role in muscle coordination control in vertebrates and invertebrates alike.



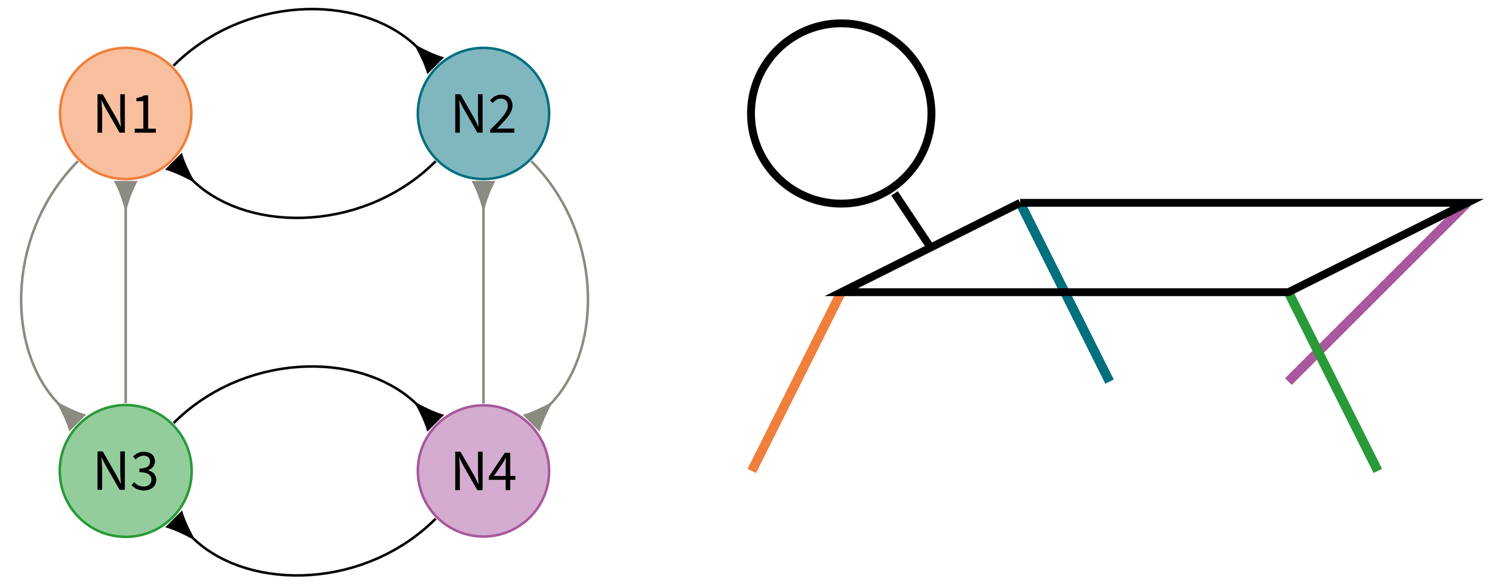
Rebound bursting: feature of biological neurons that our novel model brings to neuromorphic engineering. When a hyperpolarized (*i.e.* inhibited) neuron is dis-inhibited, it will fire a burst in the process of going back to its resting state. This feature allows robust, **self-sustaining oscillations** of the half-center oscillator.

Simulation setup: neurons initially at rest, pulses of **inhibition** introduced to initiate and disrupt oscillations. Exploration of the effects of neuromodulation and synaptic properties on the duty cycle and frequency of the bursts.

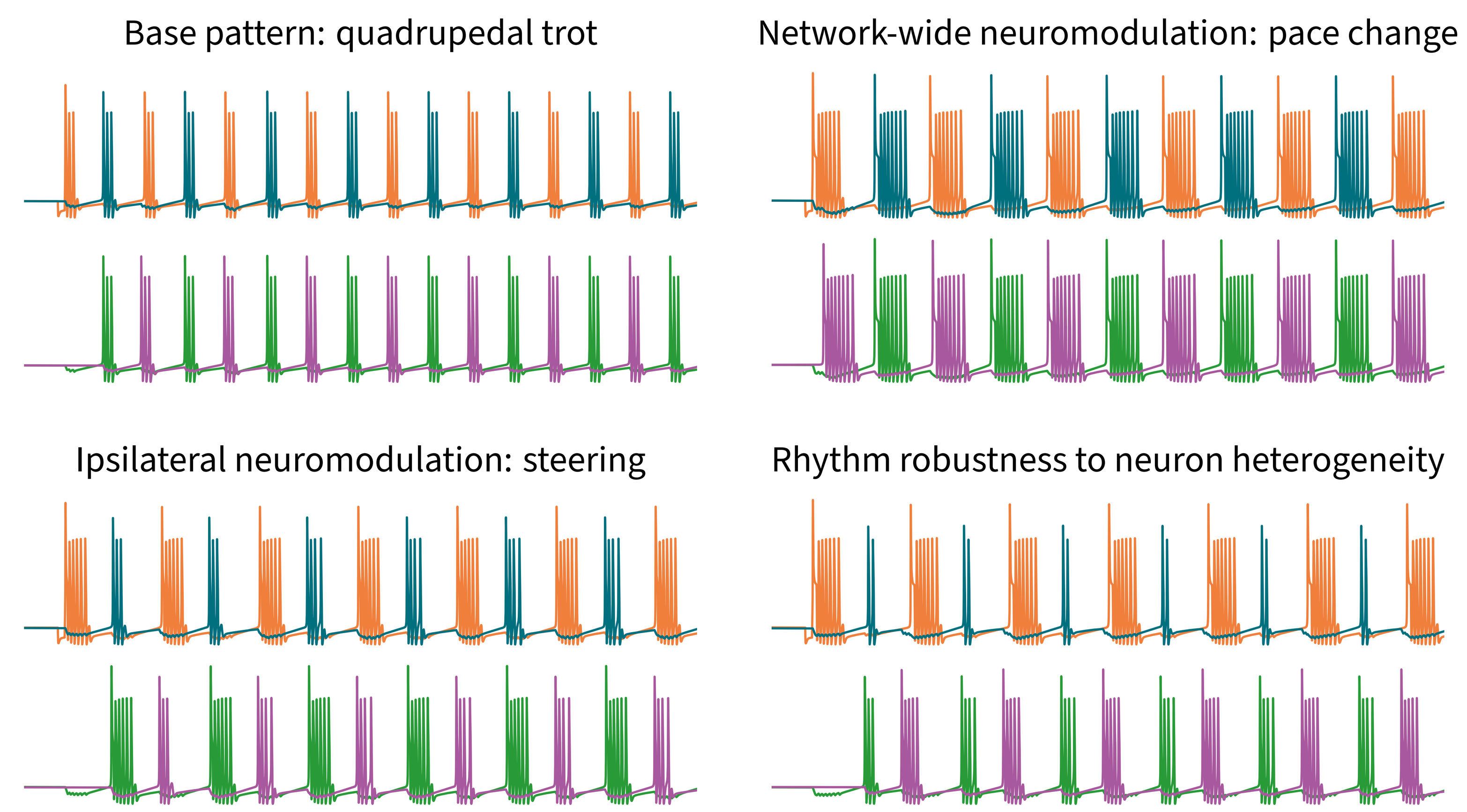


Higher-order pattern generators for embodied locomotion

Central pattern generators (CPGs): specialized neural networks generating rhythmic motor patterns for walking, swimming, flying, breathing, ... without continuous sensory inputs. Essential for creating coordinated and repetitive movements in a robust and flexible manner.



Each neuron of a CPG can be **individually neuromodulated** to produce **different locomotion patterns** while preserving the robust global rhythm of the system.



Conclusions

Using **a single parameter**, our neuron circuit can robustly change between **different neuronal excitability types**.

- In **robotic actuation**: providing a way to **dynamically adjust movement patterns** in response to external stimuli
- In **artificial neural networks**: layer of **dynamic control**, allowing networks to **adapt to environmental perturbations** or **switch tasks**, keeping synaptic weights for learning
- **Biologically plausible** neuron behaviors ⇒ potential **biomedical applications**

Analog neuromorphic hardware ⇒ **decrease in power consumption** of several orders of magnitude compared to digital simulations of neural architectures.

We have demonstrated that neuromorphic CPGs are a natural fit to generate and control actuation patterns in locomotion systems, thanks to their robustness and tunability. The introduction of neuromodulation in hardware neural networks is a pivotal development toward energy-efficient embodied agents that can more easily adapt their behavior to their perceived environment.

Future work

- Chip layout and experimental validation of simulations
- Sensory feedback control system design
- Exploration of practical applications in robotic actuation and active prosthetics

References

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