Simulating Excitable Neuromorphic Systems at Scale

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Neuromorphic engineering offers an architectural paradigm that exploits events and rhythms as its means of processing. Despite understanding its components and observing many natural instances, we still lack a systematic design framework for neuromorphic systems. The difficulty deepens when one moves beyond simplified models of neurons (e.g., leaky integrate-and-fire) to biophysically richer spiking models (e.g., Hodgkin–Huxley), which embody many of the properties that give the neuromorphic paradigm its definitive advantages. At the core of any systematic framework of design are scalable methods for simulation, but such methods remain largely absent from the neuromorphic literature. Existing numerical integration (NI) methods fall short in handling the stiff, nonlinear systems of ordinary differential equations that characterize biophysically rich spiking neural networks. This necessitates a change of approach for simulating neuromorphic systems.

Operator-theoretic solvers have been recently proposed as an alternative to NI methods for simulating neuromorphic systems [1]. Unlike time-stepping NI solvers, this class of methods uses a signal-to-signal mapping. It operates through input–output transformations rather than stepwise evolution, mitigating stiffness-related issues. Nevertheless, making any complex system tractable requires identifying and exploiting its underlying structures. For neuromorphic systems, this structure is the hierarchy of the spatio-temporal architecture. Intuitively, the neuromorphic behavior can be viewed at different levels of complexity. At the finest level, every detail is captured, whereas moving to a coarser level neglects event details while retaining the event and its principal attributes (e.g., timing). This hierarchy enables refining and coarsening without loss of critical information, offering a pathway to simulation at scale.

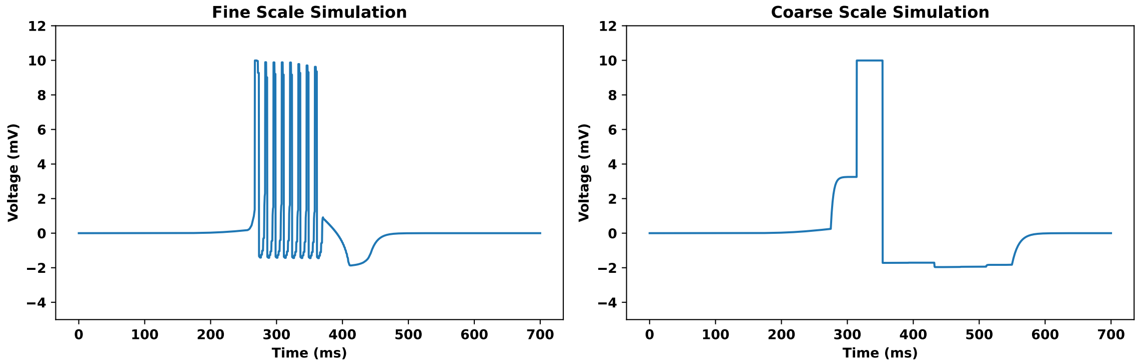

Figure 1: Simulation of a bursting neuron both at fine scale and coarse scale. The coarsening does not remove any component of the model, and it is only the scale that changes. The operator-theoretic approach ensures robust event-capturing without running into numerical issues.

To slide between levels of complexity, known as **scales**, one requires a systematic mechanism that enables transitions between the scale of interest. Our proposed approach is not an irreversible model reduction scheme, as no parts of the model are discarded. In fact, by choosing a coarse scale, all the elements that require finer scales are averaged out and systematically coarsened. This permits tractable simulation of hierarchical neuromorphic systems as one starts at the coarsest scale and then systematically refines the scale, eliminating the need to deal with the entire complexity at once.

[1] A. Shahhosseini et al., IEEE CDC, 2025.