Heterogeneous Grid Attractors: Stability and Geometry in Neuromorphic Systems

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Biological neural circuits and mixed-signal neuromorphic ones share a fundamental constraint: computation must be carried out by heterogeneous units in real-time. In the brain, heterogeneity is present at many scales, from molecular and synaptic all the way up to the circuit level. In neuromorphic systems, the same constraint arises from device mismatch. Yet most theoretical treatments in computational neuroscience assume homogeneous units, leaving the computational role of heterogeneity poorly understood.

Here, we design and study a hardware-aware grid attractor network (Fig. 1) motivated by the well-established role of grid cells in spatial navigation and their more recent interpretation as a computational scaffold for factorized representations of cognitive variables [1]. We characterize how heterogeneity in membrane and synaptic time constants affects two key properties of the network.

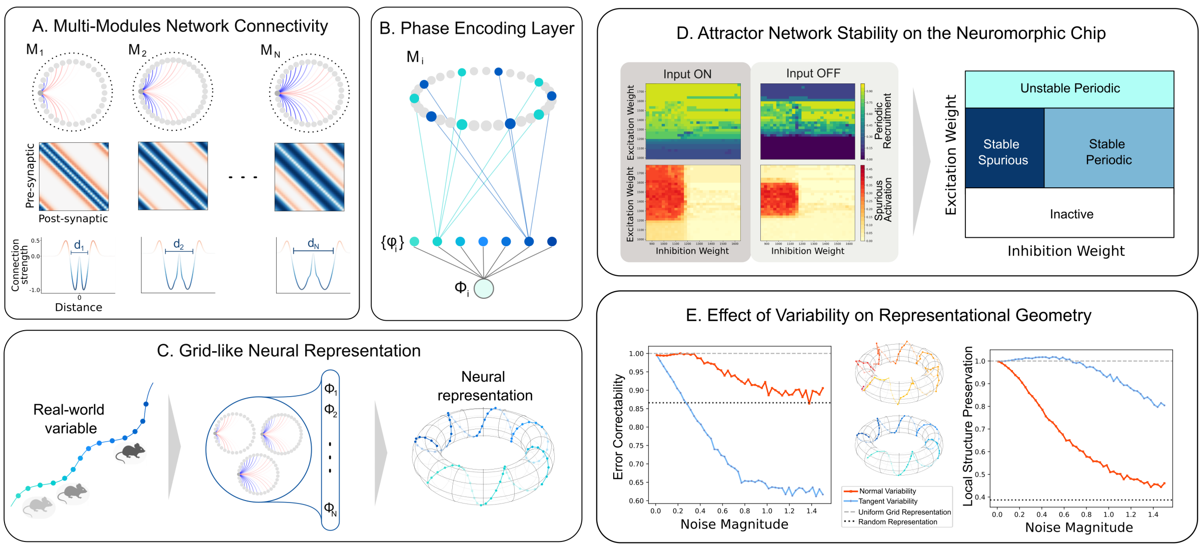

Figure 1: (A–C) Multi-module attractor architecture. (D) Phase diagram of attractor stability on the DYNAP-SE chip as a function of excitation/inhibition weight under input-on and input-off conditions. (E) Effect of variability direction on the geometry of the neural representation, normalized to the uniform grid case.

First, we show that operating in the appropriate excitation/inhibition regime enables robust, input-specific attractor states despite parameter variability. Second, we study how variability in module activity affects the geometry of the neural representation: perturbations tangent to the representation manifold reduce error correctability, the average minimum distance between attractor states, while perturbations normal to it degrade local structure preservation, nearest-neighbour ordering from input to representation space. Crucially, pairwise cross-module correlations in activity define structured perturbation directions; depending on whether these project onto the tangent or normal directions of the manifold, they selectively impair one property while sparing the other. Robustness results are validated on the DYNAP-SE neuromorphic chip [2]. Our findings suggest that the correlation structure of variability is a key determinant of representational quality, opening a design framework for neuromorphic systems and offering new predictions for neural coding theory.

[1] Chandra et al., Nature, 638, 739–751, 2025.

[2] Moradi et al., IEEE Trans. Biomed. Circuits Syst., 12(1), 106–122, 2018.