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Sandia National Laboratories

Identifying Recurrent Causal Activity Patterns in Spiking Neural Networks

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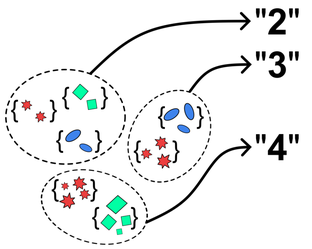
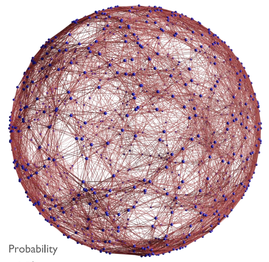
Introduction

- Neuromorphic computing and neuroscience both seek computational abstractions for spiking neural networks.
- Computational abstractions emerge from equivalence relations.

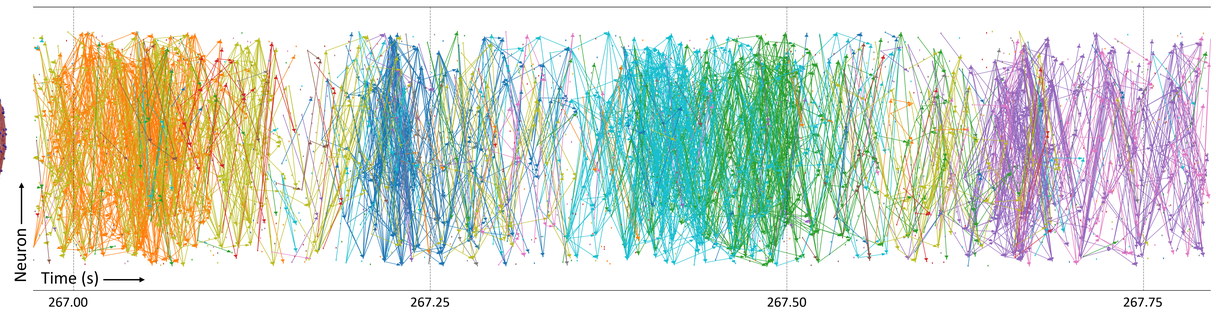


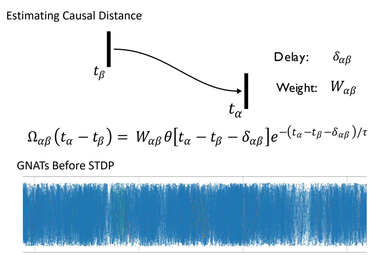
- Equivalence relations defining spiking neural computations should be intrinsically defined in spiking neural networks.
- Spiking neural computation must be grounded by synaptic interactions between neurons.

Graphical Neural Activity Threads (GNATs)

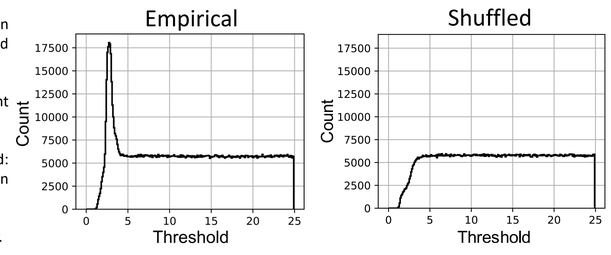


The network consists of 6000 Izhikevich model neurons distributed on the surface of a sphere (subset, top). The E/I ratio is 80/20. Neurons connect with probability given by a sigmoid function of distance (bottom). Synapses were assigned random conduction delays between 1-20 ms. The network was evolved with random input and STDP for 10 simulated minutes before analysis.

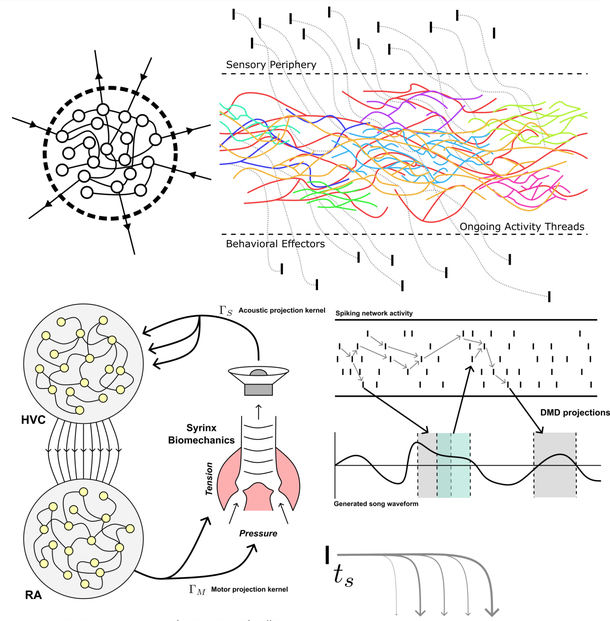




- Causal relations between spikes define a directed acyclic graph (DAG).
- DAG splits into disjoint components: GNATs.
- GNATs are well-defined: edges do not depend on free parameters.
- GNATs emerge from STDP.



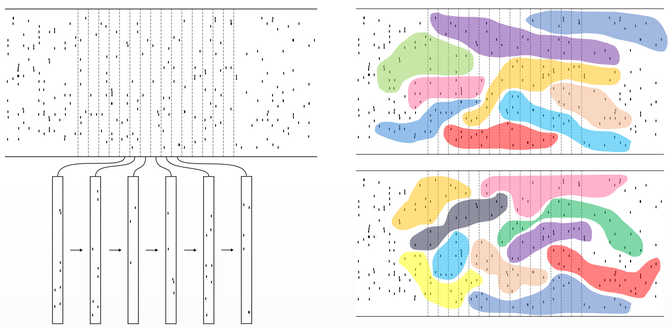
Next Steps



New **CRCNS** project (FY25-FY27) "Decomposing Neural Dynamics"

- Couple spiking neural networks to nonlinear dynamical systems (e.g. birdsong)
- Use Dynamic Mode Decomposition techniques to isolate sensorimotor projection kernels
- Spike coupling to dynamic modes "close the loop" and extend GNATs through a dynamical system
- Identify GNATs that support specific behaviors

Decomposing Neural Activity

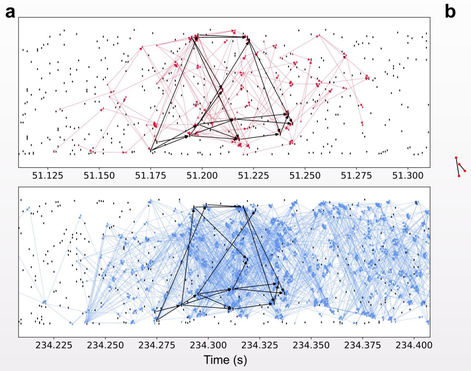


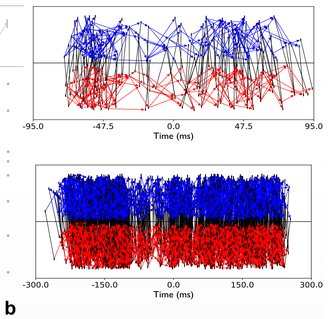
- Neural state vectors are defined by time bins *relative to the experimenter's clock*
- Computations are defined by the sequence of state vectors.
- Variability requires a probabilistic description of dynamics linking successive state vectors.
- There is no *a priori* reason the brain should respect external time bins

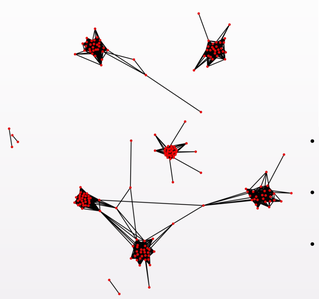
- The connectome establishes causal relationships between spikes
- This causal relation is intrinsic to the neural circuit and *independent from the experimenter.*
- Synaptic relations bind spikes into disjoint, temporally-extended partitions.
- Distinct underlying *causal* processes could produce similar *temporal* sequences. Which one matters for computation?

Identifying Isomorphic GNATs

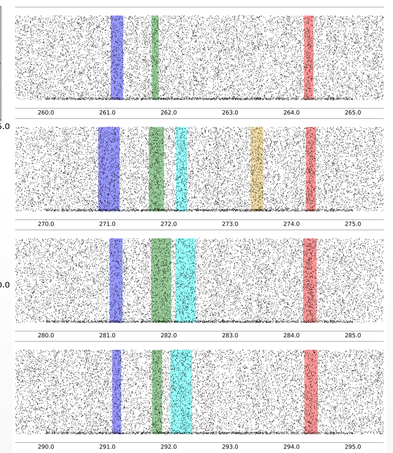
- (Quasi) isomorphic GNATs correspond to connected subgraphs of a product graph.
- Synaptic interaction is local in space and time: quadtree data structures accelerate computation.
- Isomorphic GNAT extraction is efficient for large datasets.





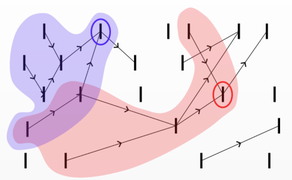


Shared subsequences divide GNATs into structured "computational classes"

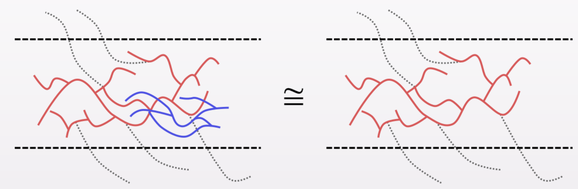


- Separate GNATs share subsequences of causally-related spikes (**a,** black).
- GNATs exhibit compositionality: isomorphic subsequences may be recombined into new threads.
- In **b**, we represent GNATs as vertices and shared subsequences as edges. Clusters appear corresponding to distinct computations.
- These clusters correspond to repeatable input-triggered subsequences in the larger population (above).

GNATs and Topology



- GNAT DAG induces a *finite* topology on spikes.
- Continuous maps must respect causal order.
- The topology provides for homotopy equivalence between GNATs.
- Postulate: homotopy equivalence describes equivalent computations.



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Preprint: https://arxiv.org/abs/2306.16684
GNATFinder code: https://github.com/sandialabs/GNATFinder

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