

CNS*2026 Halifax

TYPE - TUTORIAL • JULY 11 • SATURDAY

T Tutorial

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9:00am – 12:00pm

T From Graphs to Foundation Models: Modern Approaches to Neural Population Analysis Room 502*Speakers: Moein Khajehnejad, Adeel Razi, Forough Habibollahi*

The study of neuronal populations through graph and network theory provides powerful insights into brain organizational principles [1]. This half-day tutorial will focus on computational tools and modern learning paradigms for analyzing neuronal activity as networks, uncovering functional organization, and learning transferable representations of neural systems across scales and modalities.

The tutorial will feature two main components:

1. Graph Analysis of Neuronal Populations

Participants will learn to construct and analyze networks from neuronal activity using graph-theoretic approaches. Topics include adjacency matrix construction, modularity detection, and metrics such as clustering coefficients, centrality, and small-worldness to characterize neuronal communication and information flow [2,3,4]. Practical examples will use experimental datasets, including in vitro spike trains from CL1—demonstrating adaptive, task-oriented behavior in living neuronal cultures [5,6]—and example fMRI time series. Common pitfalls in interpreting functional connectivity and network-based analyses will also be discussed [7].

2. Foundation Models for Neural Data and Brain Networks

This component will provide a step-by-step introduction to modern machine learning models for neural data, progressing from sequence-to-sequence formulations to Transformer architectures and contemporary foundation models. Emphasis will be placed on developing intuition and understanding these methods from first principles, with concrete examples drawn from neural time series and network-structured data. A key example will be *BrainSymphony* [8], illustrating how foundation models can jointly capture neural dynamics and structure for downstream tasks such as classification, prediction, and biomarker discovery.

Beyond fMRI, the tutorial will discuss applications of foundation models across neuroscience, including causal discovery [9], electrophysiology tasks such as spike detection [10] and stimulus–response prediction [11], and representation learning [8,12]. Participants will gain hands-on exposure to Python-based workflows, alongside discussion of scalability, inductive biases, and open challenges in applying foundation models to neural systems.

Attendees will gain practical insight into combining graph-theoretic analysis with foundation models for neural population analysis, appealing to researchers in brain connectivity, neural computation, and representation learning.

References

- [1] Bullmore, E., & Sporns, O. (2009). Complex brain networks: graph theoretical analysis of structural and functional systems. *Nature Reviews Neuroscience*, 10(3), 186-198.
- [2] Rubinov, M., & Sporns, O. (2010). Complex network measures of brain connectivity: uses and interpretations. *NeuroImage*, 52(3), 1059-1069.
- [3] Khajehnejad, M., & Habibollahi, F., et al. (2023). On Complex Network Dynamics of an In-Vitro Neuronal System during Rest and Gameplay. In *NeurIPS 2023 Workshop on Symmetry and Geometry in Neural Representations*.
- [4] Khajehnejad, M., Habibollahi, F., Khajehnejad, A., French, C., Kagan, B. J., & Razi, A. (2024). Graph-Based Representation Learning of Neuronal Dynamics and Behavior. arXiv preprint arXiv:2410.00665.
- [5] Kagan, B. J., et al. (2022). In vitro neurons learn and exhibit sentience when embodied in a simulated game-world. *Neuron*, 110(23), 3952–3969.
- [6] Cortical Labs: <https://corticallabs.com/>
- [7] Bastos, A. M., & Schoffelen, J. M. (2015). A tutorial review of functional connectivity analysis methods and their interpretational pitfalls. *Frontiers in Systems Neuroscience*, 9, 175.

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[8] Khajehnejad, M., Habibollahi, F., & Razi, A. (2025). BrainSymphony: A Transformer-Driven Fusion of fMRI Time Series and Structural Connectivity. arXiv preprint arXiv:2506.18314.

[9] Nag, S., & Uludag, K. (2024). Transformer-aided dynamic causal model for scalable estimation of effective connectivity. *Imaging Neuroscience*, 2, 1-22.

[10] Wei, F., Mo, J., Zhang, K., Shen, H., Nagarajan, S., & Jiang, F. (2024). Nested deep learning model towards a foundation model for brain signal data. arXiv preprint arXiv:2410.03191.

[11] Wang, E. Y., Fahey, P. G., Ding, Z., Papadopoulos, S., Ponder, K., Weis, M. A., ... & Tolia, A. S. (2025). Foundation model of neural activity predicts response to new stimulus types. *Nature*, 640(8058), 470-477.

[12] Dong, Z., Li, R., Wu, Y., Nguyen, T. T., Chong, J., Ji, F., ... & Zhou, J. H. (2024). Brain-jepa: Brain dynamics foundation model with gradient positioning and spatiotemporal masking. *Advances in Neural Information Processing Systems*, 37, 86048-86073.

9:00am – 12:00pm	T Multiscale modeling with MOOSE and Jardesigner Room 505 <i>Speakers: Bhanu Priya Somashekar, Gautham Dathatreyan, Upinder Singh Bhalla, Subhasis Ray</i> MOOSE, the Multiscale Object-Oriented Simulation Environment (https://mooseneuro.org) is a system for modelling multiple scales in neuroscience, from biochemical pathways with reaction-diffusion systems to detailed biophysical models of single neurons and neuronal networks. This tutorial will provide participants with a brief overview of MOOSE and its ecosystem. We will start with a walkthrough of MOOSE installation, then demonstrate how to write Python scripts to setup and simulate simple biochemical and biophysical models. Participants will also learn how to load models defined in standard formats like SBML and NeuroML into MOOSE, and explore, modify, and simulate them using Python. Finally, the participants will see a demonstration of Jardesigner, a new browser-based graphical user interface for MOOSE that allows users to create multiscale models by putting together pre-built components, simulate them, and visualize the results with a few clicks.
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9:00am – 5:00pm

T **Building mechanistic biophysical models using NEURON and NetPyNE: from molecules to circuit dynamics to LFP/EEG measures** Room 501

Speakers: Valery Bragin, Adam Newton, Salvador Dura-Bernal, Robert McDougal, Bill Lytton

Understanding the brain requires studying its multiscale interactions, from molecules to cells to circuits and networks. Although vast experimental datasets are being generated across scales and modalities, integrating and interpreting this data remains a daunting challenge. This tutorial will highlight recent advances in mechanistic multiscale modeling and how it offers an unparalleled approach to integrate these data and provide insights into brain function and disease. Multiscale models facilitate the interpretation of experimental findings across different brain regions, brain scales (molecular, cellular, circuit, system), brain function (sensory perception, motor behavior, learning, etc), recording/imaging modalities (intracellular voltage, LFP, EEG, fMRI, etc) and disease/disorders (e.g., schizophrenia, epilepsy, ischemia, Parkinson's, etc). As such, it has a broad appeal to experimental, clinical and computational neuroscientists, as well as students and educators.

This tutorial will introduce multiscale modeling using two NIH-funded tools: the NEURON 9.0 simulator (<https://www.neuronsimulator.org>), including the Reaction-Diffusion (RxD) module, and the NetPyNE tool (<https://netpyne.org>). The tutorial will combine background, examples and hands on exercises covering the implementation of models at four key scales:

- (1) intracellular dynamics (e.g. calcium buffering, protein interactions),
- (2) single neuron electrophysiology (e.g. action potential propagation),
- (3) neurons in extracellular space (e.g. spreading depression), and
- (4) neuronal circuits, including dynamics such as oscillations and simulation of recordings such as local field potentials (LFP) and electroencephalography (EEG).

For circuit simulations, we will use NetPyNE, a high-level interface to NEURON supporting both programmatic and GUI specification that facilitates the development, parallel simulation, and analysis of biophysically detailed neuronal circuits. We conclude with an example combining all three tools that link intracellular/extracellular molecular dynamics with network spiking activity and LFP/EEG. The tutorial will incorporate the recent substantial developments and new features in both the NEURON and NetPyNE tools.

Relevant Publications:

Awile O, Kumbhar P, Cornu N, Dura-Bernal S, King JG, Lupton O, Magkanaris I, McDougal RA, Newton AJH, Pereira F, Savulescu A, Carnevale NT, Lytton WW, Hines ML, Schürmann F. **Modernizing the NEURON Simulator for Sustainability, Portability, and Performance.** *Frontiers in Neuroinformatics* 10.3389/fninf.2022.884046.

McDougal RA, Hines ML, Lytton WW. (2013) **Reaction-diffusion in the NEURON simulator.** <https://doi.org/10.3389/fninf.2013.00028>

Dura-Bernal S, Suter B, Gleeson P, Cantarelli M, Quintana A, Rodriguez F, Kedziora DJ, Chadderdon GL, Kerr CC, Neymotin SA, McDougal R, Hines M, Shepherd GMG, Lytton WW. (2019) **NetPyNE: a tool for data-driven multiscale modeling of brain circuits.** *eLife* 2019;8:e44494.

Dura-Bernal S, Herrera B, Lupascu C, Marsh BM, Gandolfi D, Marasco A, Neymotin SA, Romani A, Solinas S, Bazhenov M, Hay E, Migliore M, Reinmann M, Arhipov A (2024) **Large-scale mechanistic models of brain circuits with biophysically- and morphologically-detailed neurons.** *Journal of Neuroscience* 2 October 2024, 44 (40) e1236242024; DOI: 10.1523/JNEUROSCI.1236-24.2024.

1:00pm – 5:00pm

T From single-cell modeling to large-scale network dynamics with NEST Simulator

Room 505

*Speakers: Noah Ostendorf, Agnes Korcsak-Gorzo, Charl Linssen**For more details and materials related to this tutorial, please see the tutorial website: <https://clinssen.github.io/NEST-workshop/>*

NEST is an established open-source simulator for spiking neuronal networks that combines detailed biological modeling with high performance and scalability from laptops to HPC systems [1], and has supported hundreds of studies, including a large-scale model of human cortex [2]. In two independent modules, this tutorial highlights NEST's support for compartmental neuron models and advanced synaptic plasticity.

Compartmental neuron models are a detailed way of describing biological neurons, capturing their spatially extended morphology as systems of coupled ordinary differential equations. We introduce the recently introduced compartmental modeling feature in NEST, starting with model construction in NESTML of biologically motivated multi-compartment neurons with active channels and synaptic inputs [4], and then create interacting networks composed of compartmental neuron populations. By explicitly constructing compartmental trees, participants gain transparent and fine-grained control over model structure. We will build a simple ion channel model in NESTML, and show how it can be compiled, rewritten, and extended, providing a concrete template for user-defined model development. The tutorial demonstrates dendritic computations emerging from explicitly constructed compartmental neurons and networks, and offers a practical entry point for developing custom compartmental models.

As an example of advanced plasticity rules in NEST, we present supervised eligibility propagation, an online, biologically inspired learning rule that approximates backpropagation through time [3]. We show how this rule can be used to train functional spiking neural networks to learn a range of tasks, from which we highlight the classification and generation of handwritten characters. The tutorial covers the full research workflow from model construction and simulation to data analysis. Participants can follow the material hands-on and interactively via the EBRAINS cloud services in the browser without local installation, and are encouraged to bring an existing EBRAINS account or create one in advance.

[1] <https://nest-simulator.readthedocs.org/>

[2] <https://github.com/INM-6/microcircuit-PD14-model>

[3] https://nest-simulator.readthedocs.io/en/latest/auto_examples/eprop_plasticity/index.html

[4] <https://nestml.readthedocs.org/>

1:00pm – 5:00pm

T Let there be Neulite: A short introduction to a light-weight neuron simulator

Room 502

Speakers: Tadashi Yamazaki

Neulite is a light-weight neuron simulator designed for biophysically detailed single-neuron and network models [1]. It specifically targets neuron models from the Allen Cell-Types Database and can execute models described in the Brain Modeling ToolKit (BMTK) with minimum modification.

Neulite is built on the philosophy of a Minimum Viable Product (MVP). Unlike general-purpose simulators that aim for universal functionality, Neulite maintains an exceptionally concise kernel of approximately 2,000 lines of C code. This minimalist design allows for extreme performance optimization on specific hardware architectures and provides researchers with direct, transparent access to the underlying computational logic. By eliminating the complexity of larger engines, Neulite empowers users to easily modify simulation routines and implement custom features, ensuring full control over their specific modeling workflows.

This half-day tutorial is divided into two parts. In the first part, we will provide a general introduction to Neulite, set up the environment for BMTK and NEURON, and replicate BMTK Tutorials 1 and 4 using Neulite. The second part features a walk-through of the simulation kernel; we will examine the source code, progressing from a passive single-neuron model to a population-scale model.

Attendees are expected to bring a computer equipped with Python, a C compiler, and git.

Website: <https://numericalbrain.org/en/neulite/>

Reference:

[1] Rin Kuriyama*, Kaaya Akira*, Laura Green, Beatriz Herrera, Kael Dai, Mari Iura, Gilles Gouaillardet, Asako Terasawa, Taira Kobayashi, Jun Igarashi, Anton Arkhipov, Tadashi Yamazaki (*: equally contributed). Microscopic-Level Mouse Whole Cortex Simulation Composed of 9 Million Biophysical Neurons and 26 Billion Synapses on the Supercomputer Fugaku. in The International Conference for High Performance Computing, Networking, Storage and Analysis (SC '25), November 16–21, 2025, St Louis, MO, USA. ACM, New York, NY, USA, 11 pages. doi: 10.1145/3712285.3759819