Towards a universal field-theoretic framework for neural networks

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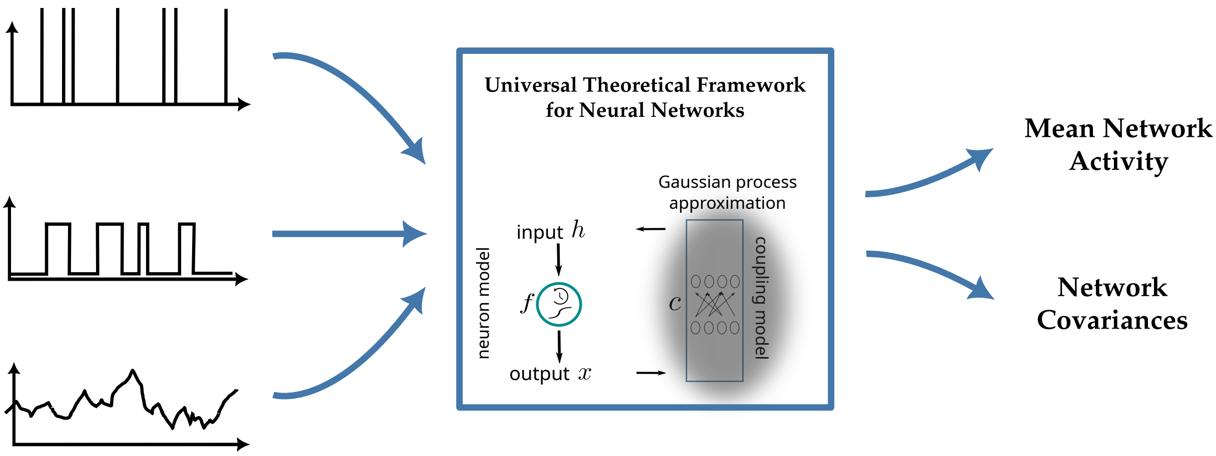
The brain is a complex information processing system with structure and dynamics across a wide range of spatial and temporal scales shaped by correlated activity between its individual constituents. Even at the particular description level of neurons and synapses, there is a large variety of neuron and connectivity models [1] to describe features of biological neural systems. These include the discrete nature of neuronal spiking, sparse and heterogeneous recurrent connectivity at local scales vs structured connection patterns at global scales, as well as internal and external sources of variability and stochasticity. Most of these models require distinct theoretical frameworks [2, 3, 4] to predict their dynamical behavior. Differences in theoretical treatments, underlying explicit and implicit assumptions and involved approximation techniques hinder the comparison of results across models as well as the transfer of methods and prohibit a systematic analysis of the impact of individual modeling choices on the overall neural network dynamics and function.

In this work we introduce a theoretical framework which does not depend on a particular model specification but rather constructs a pipeline of analysis steps in a model-agnostic manner (Figure left). The framework only requires causality in the translation from neuronal inputs to outputs and in the conversion of neuronal outputs to network inputs. The formalism is based on field theoretical methods for disordered systems and approximates the summed inputs to neurons as Gaussian processes (Figure center). This approach self-consistently treats mean activities and covariances on equal footing and thereby allows us to analyze the coordinated network dynamics on local and global scales even in non-stationary scenarios and across a wide range of dynamical regimes (Figure right). This helps to compare the influence of different model features on neural activity statistics and to identify classes of models that produce the same dynamical features on the network level.



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