A general theory of neural population dynamics

Gianni Valerio Vinci[1,2], Roberto Benzi[3,4], Maurizio Mattia[1]

1 Natl. Center for Radiation Protection and Computational Physics, Istituto Superiore di Sanita’
2 PhD 2Program in Physics, Dept. of Physics, “Tor Vergata” University of Rome
3 Dept. of Physics and INFN, “Tor Vergata” University of Rome
4 Centro Ricerche “E. Fermi,” 00184, Roma, Italy

The brain is arguably the most complex system known to man. Describing the dynamics of interacting networks of neurons is in fact one of the most challenging open problems in theoretical neuroscience. If we look at neural populations as a physical system, we have a finite network of coupled nonlinear stochastic nodes, which are constantly driven outside of equilibrium by external stimuli. Those characteristics are severe obstacles from a theoretical point of view. As a consequence, a coherent and general theory that describes the dynamics of neural populations from first principles, i.e., starting from the microscopic description of the single neurons, is still lacking.

A particularly important framework in computational neuroscience is the population density approach that borrows the concept of mean-field theory in statistical physics. In this talk, I will present a number of new results in this framework, that allows making a significant step forward a general theory of neural population dynamics.

In particular, I will show how it is possible to extend the standard mean-field theory to include finite-size effects that inevitably arise when we consider a population of a finite number of neurons and may play a major role in nonlinear dynamical regimes, like in the case of multistable networks. The stochastic nature of finite-size effects is fully captured by the new theory even far outside of equilibrium which is the typical regime encountered in experiments. Moreover, the derivation is independent of the model of neuron used.

A second result I will present is related to the dimensional reduction of the mean-field theory. It is in fact possible to obtain a closed system in terms of mesoscopic quantities such as the population firing rate and mean membrane potential without the necessity to solve complicated nonlinear equations for the full population density. To achieve this closure different ansatzes were made in the past, limiting the spectrum of the possible applications of low-dimensional theories. Here, I will present a general approach working even for out-of-equilibrium open systems, and it is analytical for the case of a network of leaky integrate-and-fire neurons.

In conclusion, thanks to the results I will present, it is possible to build a bridge between different scales and try to answer a number of important questions such as: how much do the single neuron details influence the mesoscopic population dynamics? What is the role of the endogenous noise of neural population activity and what is the nonlinear response of this kind of systems to arbitrary external stimuli?

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