Large-scale model development from the NEST perspective

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We view models of cortical networks at the resolution of neurons and synapses as formal frameworks for the integration of experimental data from different sources and scales. On the structural level these models assess the consistency of experimental data and expose gaps in our knowledge. Furthermore, only mathematical models bring anatomical data into contact with data on the neuronal activity emerging in cortical networks. The vision is that such models serve as building blocks for ever more complete models of brain function and testbeds for theoretical investigations.

A recent full-density model of a 1 mm^2 microcircuit of early sensory cortex [1] illustrates this role of physiology-based models as integrators and platforms by bringing together knowledge from over 50 papers, being used in at least 17 peer-reviewed studies, and cited in at least 61. The reasons for the wide and rapid uptake have not been formally investigated. However, the availability of an executable model description in the meta-simulation language PyNN [2], inclusion as an example in current releases of the NEST simulation code, as well as publication via Open Source Brain [3] likely contribute. Shimoura et al. [4] achieved a reproduction of the work using the Brian simulator [5].

The problem of reproducibility of results in computational neuroscience [6] became apparent a decade ago when the first large-scale projects formed in Europe [7], and the field is still striving for suitable terminology and technology, as demonstrated by the recent special issue "Reproducibility and Rigour in Computational Neuroscience" of Frontiers in Neuroinformatics. The NEST Inititiative is working with the community and in international projects like the European Human Brain Project (HBP) to foster collaboration and advance methodology that promotes reproducibility.

Despite its success, the microcircuit model can be criticized as underconstrained, as each neuron receives half of the synapses from distant sources. In addition, the model does not exhibit prominent characteristics of cortical activity like substantial power at low frequencies. Cortical architecture, i.e. the area-specific cellular and laminar composition of the cortical network, is related to the connectivity between areas, which forms a hierarchical and recurrent network at the brain scale. Based on the aforementioned work on the cortical microcircuit, our recent study [8] integrates data on cortical architecture and axonal tracing data into a multi-scale framework describing one hemisphere of macaque vision-related cortex. We represent each area by the network below 1 mm^2 of cortical surface. These circuits are modeled with their natural number of neurons and synapses. Simulations confirm a realistic activity regime after adjustments of the connectivity within the margins of error [9] with the help of mean-field theory. At a sufficiently large coupling between the areas, spike patterns, the distribution of spike rates, and the power spectrum of the activity are compatible with in-vivo resting-state data. Furthermore, the matrix of correlations between the activities of areas is as similar to the experimentally measured functional connectivity of resting-state fMRI as can be expected based on inter-individual differences. This correspondence on multiple spatial scales is achieved in a metastable state exhibiting time scales much larger than any time constant of the system.

The increased complexity of brain-scale models poses new challenges for the reproducibility and reusability of results by the computational neuroscience community.

First, only executable model descriptions enable the effective communication between scientists and the reproducibility of results. Furthermore, the information required to instantiate a model in the memory of a computer is only one aspect of the modeling process. The experimental data entering the model span multiple scales and come from different sources. Algorithms are required to collate the data and derive the final model parameters. Often, data are only partially available such that quantitative hypotheses need to be formulated to bridge the gaps. As a consequence researchers can only add new data to the model or modify assumptions if they have access to the construction process. Hence, the workflow of data integration also needs to be documented in an executable format. The complete model description comprises a substantial amount of source code. Therefore, we explore the transfer of our experience from software development to model construction using a code review platform. On the example of our multi-area model, we trace the development of a publishable executable workflow of model construction and discuss the difficulties we encountered in the process.

Second, simulating multi-area models at the level of resolution of neurons and synapses taxes the largest supercomputers available. Thus, models are only reproducible in practice if the community has access to corresponding computer resources. Alongside the hardware, a simulation code is needed which reduces the required resources in terms of memory and time to a minimum while providing the neuroscientist with a homogeneous environment from laptops to supercomputers. The talk presents our recent progress [10] and points out that the phase of network instantiation as opposed to the propagation of the dynamics can become the bottleneck of a simulation [11]. High-level model descriptions need to be designed such that simulation engines can efficiently parallelize the instantiation.

Still, solving the equations for microscopically parallel system on conventional computers with their rather coarse-grained parallelism consumes considerable energy, and reaching real-time or accelerated speeds is difficult. Therefore, we also explore neuromorphic computing as an alternative computing platform. The talk presents recent progress in this area [12], in which we ported the full-density microcircuit model to the SpiNNaker hardware system. The finding is relevant because it lays the foundation for simulating even larger cortical networks by already approximating the full number of synapses per neuron.

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