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UCS will publish monographs, lecture notes and selected edited contributions aimed at communicating new findings to a large multidisciplinary audience.
Lectures in Supercomputational Neuroscience

Dynamics in Complex Brain Networks

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Preface

Computational neuroscience has become a very active field of research in the last decades. Improved experimental facilities, new mathematical techniques and especially the exponential increase of computational power have lead to stunning new insights into the functioning of the brain. Scientists begin to endeavor simulating the brain from the bottom level of single neurons to the top-level of cognitive behavior. The “Blue Brain Project” (http://bluebrainproject.epfl.ch/) for example, is a hallmark for this approach.

Many scientists are attracted to this highly interdisciplinary field of research, in which only the combined efforts of neuroscientists, biologists, psychologists, physicists and mathematicians, computer scientists, engineers and other specialists, e.g. from anthropology, linguistics, or medicine, seem to be able to shift the limits of our knowledge. However, one of the most common problems of interdisciplinary work is to find a “common language”, i.e., an effective way to discuss problems with colleagues with a different scientific background. Therefore, an introduction into this field has to familiarize the reader with aspects from various relevant fields in an intelligible way.

This book is an introduction to the field of computational neuroscience from a physicist’s perspective, regarded as neurophysics, with in depth contributions of systems neuroscientists. It is based upon the lectures delivered during the 5th Helmholtz Summer School on Supercomputational Physics:

“Complex Networks in Brain Dynamics”

held in September 2005 at the University of Potsdam.

The book-title Lectures in Supercomputational Neuroscience: Dynamics in Complex Brain Networks is motivated by the methods and outcomes of the Summer School: A conceptual model for complex networks of neurons is introduced, which incorporates many important features of the “real” brain, such as different types of neurons, various brain areas, inhibitory and excitatory coupling and plasticity of the network. The model is then implemented in an MPI (message-passing interface)-based parallel computer code, running
at appropriate supercomputers, that is introduced and discussed in detail in this book. But beyond the mere presentation of the C-program, the text will enable the reader to modify and adapt the algorithm for his/her own research.

The first part of the book (Neurophysiology) gives an introduction to the physiology of the brain on different levels, ranging from the rather large areas of the brain down to individual neurons. Various models for individual neurons are discussed as well as models for the “communication” among these neuronal oscillators. An outlook on cognition and learning is also given in this first part.

The second part (Complex Networks) outlines the dynamics of ensembles of neurons forming different types of networks. Recently developed new approaches based on complex networks with special emphasis on the relationships between structure and function of complex systems are presented. The topology of such a network, i.e., how the neurons are coupled, plays an important role for the behavior of the ensemble. Even though the network of the $10^{10}$ neurons in a human brain is much too complex to be modeled with our present knowledge, the conceptual models presented here are a promising starting point and allow gaining insight into the principles of complex networks in brain dynamics. This part covers all aspects from the basics of networks, their topology and how to quantify them, to the structure and function of complex cortical networks up to collective behavior of large networks such as clustered synchronization. New techniques for the analysis of data of complex networks are also introduced. They allow not only to study large populations of neurons but also to study (neural) oscillators with more than one time scale, e.g. spiking and bursting neurons.

The third part (Cognition and Higher Perception) presents results about how structural units of the brain (columns) can be described and how networks of neurons can be used to model cognition and perception as measured by the electroencephalogram. It is shown how networks of simple neuronal models can be used to model, e.g., reaction times from psychological experiments.

The forth part (Implementations) discusses the implementation of a model of a network of networks of neurons in an MPI-based C-code. The code is modular in the sense that the model(s) for the neurons, the topology of the network, the coupling and many further parameters can easily be changed and adapted. The main point is to outline how in principle many different features can be implemented in a computer code, rather than presenting a cutting-edge algorithm. The computer code is available for download (http://www.agnld.uni-potsdam.de). In this part we also discuss that computational neuroscience is not simply about parallelizing normal computer code. A very important component of it is the implementation of specially adapted algorithms. An example of such a computer code will be given in this chapter.

In the fifth and final part (Applications), three groups of students of the Summer School, discuss the results they obtained running the code on
supercomputers. After studying the parameter space for large networks of Morris-Lecar neurons, they use a map of cortical connections from a cat’s brain, which was obtained based on experimental studies. In their simulations they consider multiple spatio-temporal scales and study the patterns for synchronized firing of neurons in different brain areas. Results of simulations for different network topologies and neuronal models are also summarized here. These chapters will be helpful to those who are planning to apply the parallel code for their own research, as they give a very practical account of how to actually perform simulations. They point at crucial problems and show how to overcome pitfalls when simulating based on the MPI code.

We hope that this book will help graduate students and researchers to access the field of computational neuroscience and to develop and improve high-end, parallel computer codes for the simulation of large networks of neurons.

Last, but not least, we wish to thank all lecturers and the coordinators of the 5th Helmholtz Summer School on Supercomputational Physics; Ma-men Romano, Lucia Zemanová, and Gorka Zamora-López for their assistance; the Land Brandenburg for main funding, EU, NoE, and EU-Network BioSim (contract No. LSHB–CT–2004–005137) for further support; the University of Potsdam for making access to its supercomputer cluster available and also for logistics. Finally, we thank James Ong for his careful proof-reading of the complete book.

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Contents

Part I Neurophysiology

1 Foundations of Neurophysics
Peter beim Graben .................................................. 3

2 Synapses and Neurons: Basic Properties and Their Use in Recognizing Environmental Signals
Henry D. I. Abarbanel, Julie S. Haas and Sachin S. Talathi ........... 49

Part II Complex Networks

3 Structural Characterization of Networks Using the Cat Cortex as an Example
Gorka Zamora-López, Changsong Zhou and Jürgen Kurths ............ 77

4 Organization and Function of Complex Cortical Networks
Claus C. Hilgetag and Marcus Kaiser .................................. 107

5 Synchronization Dynamics in Complex Networks
Changsong Zhou, Lucia Zemanová and Jürgen Kurths ................. 135

6 Synchronization Analysis of Neuronal Networks by Means of Recurrence Plots
André Bergner, Maria Carmen Romano, Jürgen Kurths and Marco Thiel .......................................................... 177
Part III Cognition and Higher Perception

7 Neural and Cognitive Modeling with Networks of Leaky Integrator Units
Peter beim Graben, Thomas Liebscher and Jürgen Kurths ............ 195

8 A Dynamic Model of the Macroparameters
James J. Wright ......................................................... 225

Part IV Implementations

9 Building a Large-Scale Computational Model of a Cortical Neuronal Network
Lucia Zemanová, Changsong Zhou and Jürgen Kurths ............ 251

10 Maintaining Causality in Discrete Time Neuronal Network Simulations
Abigail Morrison and Markus Diesmann ........................... 267

11 Sequential and Parallel Implementation of Networks
Werner von Bloh .......................................................... 279

Part V Applications

12 Parametric Studies on Networks of Morris-Lecar Neurons
Steffen Tietsche, Francesca Sapuppo and Petra Sinn ................ 319

13 Traversing Scales: Large Scale Simulation of the Cat Cortex Using Single Neuron Models
Martin Vejmelka, Ingo Fründ and Ajay Pillai ....................... 331

14 Parallel Computation of Large Neuronal Networks with Structured Connectivity
Marconi Barbosa, Karl Dockendorf, Miguel Escalona, Borja Ibarz, Aris Miliotis, Irene Sendiña-Nadal, Gorka Zamora-López and Lucia Zemanová ......................................................... 343

Index ............................................................................. 369