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An Introduction to Modeling Neuronal Dynamics

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Preface

This book is intended as a text for a one-semester course on mathematical and computational neuroscience for upper-level undergraduate and first-year graduate students of mathematics, the natural sciences, engineering, or computer science. An undergraduate introduction to differential equations is more than enough mathematical background. Only a slim, high school-level background in physics is assumed and none in biology.

Each chapter is intended to be studied, with some omissions of course, in a 50-minute class. Not all topics discussed in earlier chapters reappear in later chapters. For instance, Chapters 15, 16, 19, 22, 27, 28, 33, and 34 could be skipped without loss of continuity. I have attempted to write in such a way that the students will be able to read the chapters on their own before coming to class, so that class time can be used for answering questions and discussing the material.

The programs generating the figures of the book are available online. To the caption of each figure generated by a MATLAB code, I have added in brackets the name of the directory in which the code generating the figure can be found. (For a very small number of figures that serve illustrative purposes only, but don't show results of substantial computations, the code is not made available.)

Exercises labeled (∗) require MATLAB programming, often using one of the MATLAB programs generating one of the figures as a starting point. Exercises labeled (†) are more difficult than the others. The exercises are deliberately at a fairly wide range of levels of difficulty. Which to assign (or whether to assign others) must of course depend on who are the students who take the course.

Very many topics have been omitted, in an effort to make the book short enough so that one can (with moderate selectivity) teach a one-semester course out of it. My decisions on what to include reflect what I find interesting, of course, but also what I know. In particular, I do not comment on how "macroscopic" behavior emerges: locomotion, decision-making, memory recall, value judgements, etc. The reason is that I don't know. Most of the book is about basic differential equations, models of neurons, synapses, and oscillating networks.

Oscillations in neuronal networks have been of great interest to neuroscientists for many decades. They arguably represent the simplest form of coherent network behavior in the brain. One of the most interesting facts about brain oscillations is that they provide a possible mechanism by which Hebbian cell assemblies, thought to be the basic unit of information storage in the brain, can be created and held together. Some of the later chapters are directly or indirectly about this topic. I included two chapters about plasticity, since plasticity, i.e., the ability to learn, is clearly the most interesting property of brain matter and also because it seems plausible that plasticity would play a role in the creation of oscillatory cell assemblies.

Models as simple as those discussed in this book obviously don't come close to reproducing the complexities of real brains. This criticism applies to all of computational neuroscience, even when the models are much more complex than those in this book. The complexity of the brain is staggering, and we cannot currently reproduce it faithfully in mathematical models or computational simulations, both because many aspects are just not sufficiently well known experimentally and because computers are not (yet) powerful enough. It is my view that computational modeling in neuroscience should not (yet) be viewed as a way of simulating brain circuits, but as a way of (1) suggesting hypotheses that can be tested experimentally or (2) *refuting* heuristic biological arguments. For these purposes, fully faithful, realistic modeling is clearly not required. In particular, while it is impossible to *prove* a heuristic, biological argument using simulations of a simplifying model, it is possible to *refute* such an argument by creating a model satisfying all assumptions used in the heuristic argument and showing that the conclusion of the argument fails to hold in the model.

I would like to thank Nancy Kopell, from whom I have learned much of what I know about dynamics in neuroscience and with whom I have collaborated on many research projects over the years. I am very grateful to the many people who made helpful comments and suggestions on drafts of this book, including Nancy Kopell, Horacio Rotstein, several students at Tufts University (in particular Jeffrey Carlson, Elise Ewing, and Melody Takeuchi), and several students at Boston University (in particular Julia Chartove, Alex Gelastopoulos, and Erik Roberts). Last but not least, I would like to thank my friends behind the counter at the True Grounds Cafe in Somerville, Massachusetts, where much of the work on this book was done.

Medford, MA, USA Christoph Börgers
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