Preface

This book is a rudimentary attempt to generate a coherent understanding of neurobiological systems from the perspective of what has become known as 'systems neuroscience.' What is described in these pages is the result of a five year collaboration aimed at trying to characterize the myriad, fascinating neurobiological systems that we encounter every day. Not surprisingly, this final (for now) product is vastly different from its ancestors. But, like them, it is first and foremost a *synthesis* of current ideas in computational, or theoretical, neuroscience. We have adopted and extended ideas about neural coding, neural computation, physiology, communications theory, control theory, representation, dynamics, and probability theory. The value of presenting a synthesis of this material, rather than presenting it as a series of loosely connected ideas, is to provide, we hope, both theoretical and practical insight into the functioning of neural systems not otherwise available. For example, we are not only interested in knowing what a particular neuron's tuning curve looks like, or how much information that neuron *could* transmit, we want to understand how to combine this evidence to learn about the possible function of the system, and the likely physiological characteristics of its component parts. Attempting to construct a general framework for understanding neurobiological systems provides a novel way to address these kinds of issues.

Our intended audience is quite broad, ranging from physiologists to physicists, and advanced undergraduates to seasoned researchers. Nevertheless, we take there to be three main audiences for this book. The first consists of neuroscientists who are interested in learning more about how to best characterize the systems they explore experimentally. Often the techniques used by neuroscientists are chosen for their immediate convenience—e.g., the typical 'selectivity index' calculated from some ratio of neuron responses—but the limitations inherent in these choices for characterizing the systemic coding properties of populations of neurons are often serious, though not immediately obvious (Mechler and Ringach 2002). By adopting the three principles of neural engineering that we present, these sorts of measures can be replaced by others with a more solid theoretical foundation. More practically speaking, we also want to encourage the recent trend for experimentalists to take seriously the insights gained from using detailed computational models. Unfortunately, there is little literature aimed at providing clear, general methods for developing such models at the systems level. The explicit methodology we provide, and the many examples we present, are intended to show precisely how these three principles can be used to build the kinds of models that experimental neuroscientists can exploit. To aid the construction of such models, we have developed a simulation environment for large-scale neural models that is available at `http://compneuro.uwaterloo.ca/`.

The second audience consists of the growing number of engineers, physicists, and computer scientists interested in learning more about how their quantitative tools relate to the brain. In our view, the major barrier these researchers face in applying proven mathematical techniques to neurobiological systems is an appreciation of the important *differences* between biological and traditionally engineered systems. We provide quantitative examples, and discuss how to understand biological systems using the familiar techniques of linear algebra, signal processing, control theory, and statistical inference. As well, the examples we present give a sense of which neural systems are appropriate targets for particular kinds of computational modeling, and how to go about modeling such systems; this is important for those readers less familiar with the neurosciences in general.

Our third audience is the computational neuroscience community; i.e., those familiar with the kind of approach we are taking towards characterizing neurobiological systems. Because we claim to develop a general approach to understanding neural systems, we suspect that researchers already familiar with the current state of computational neuroscience may be interested in our particular synthesis, and our various extensions of current results. These readers will be most interested in how we bring together considerations of single neuron signal processing and population codes, how we characterize neural systems as (time-varying nonlinear) control structures, and how we apply our techniques for generating large-scale, realistic simulations. As well, we present a number of novel models of commonly modeled systems (e.g., the lamprey locomotor system, the vestibular system, and working memory systems) which should provide these readers with a means of comparing our framework to other approaches.

Computational neuroscience is a rapidly expanding field, with new books being published at a furious rate. However, we think, as do others, that there is still something missing: a general, unified framework (see section 1.6 for further discussion). For instance, past books on neural coding tend to focus on the analysis of individual spiking neurons (or small groups of neurons), and texts on simulation techniques in neuroscience focus either at that same low level or on higher-level cognitive models. In contrast, we attempt to bridge the gap between low-level and high-level modeling. As well, we do not focus on models of a specific neural system as a number of recent books have, but rather on principles and methods for modeling and understanding diverse systems. Furthermore, this work is not a collection of previously published papers, or an edited volume consisting of many, often conflicting, perspectives. Rather, it presents a single, coherent picture of how to understand neural function from single cells to complex networks. Lastly, books intended as general overviews of the field tend to provide a summary of common single cell models, representational assumptions, and analytical and modeling techniques. We have chosen to present only that material relevant to constructing a unified framework. We do not want to insinuate that these various approaches are not essential; indeed we draw very heavily on much of this work. However, these are not attempts to provide a *unified* framework—one which *synthesizes* common models, assumptions, and techniques—for understanding neural systems. We, in contrast, have this as a central goal.

The fact that there are so many book-length discussions of the topics we address should serve as a warning: we are not providing a comprehensive overview of computational neuroscience. But, given the prevalence of recent calls for a neuroscientific theory, we think that trying to construct a unified approach is a useful undertaking. There are points in the book where we make strong claims regarding the ability of the framework (and underlying theory) to unify our understanding of neural systems. Often we do this for rhetorical reasons: stating the strongest position is often a way to make the position clear. When pushed, however, we refer to this framework as a 'zeroth-order guess' about how neural systems function. We think, then, that there is lots of work left to do (see `http://compneuro.uwaterloo.ca/` for a long list). Nevertheless, we feel that even a zeroth-order guess is better than no guess at all, and is likely, once articulated, to lead to better guesses. As a result, even if we turn out to be terribly wrong, we do think this framework is useful for organizing ideas about neurobiological systems. It has proven immensely useful to us, we sincerely hope others will find some utility in it as well.