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978-1-107-07919-9 - Advanced State Space Methods for Neural and Clinical Data
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Advanced State Space Methods for Neural and Clinical Data

This authoritative work provides an in-depth treatment of state space methods, with a range of applications in neural and clinical data.

Advanced and state-of-the-art research topics are detailed, including topics in state space analyses, maximum likelihood methods, variational Bayes, sequential Monte Carlo, Markov chain Monte Carlo, nonparametric Bayesian and deep learning methods. Details are provided on practical applications in neural and clinical data, whether this is characterizing time series data from neural spike trains recorded from the rat hippocampus, the primate motor cortex, or the human EEG, MEG or fMRI, or physiological measurements of heartbeats or blood pressures.

With real-world case studies of neuroscience experiments and clinical data sets, and written by expert authors from across the field, this is an ideal resource for anyone working in neuroscience and physiological data analysis.

Zhe Chen is Assistant Professor at the New York University School of Medicine, having previously worked at the RIKEN Brain Science Institute, Harvard Medical School, and Massachusetts Institute of Technology. He is a Senior Member of the IEEE and an editorial board member of *Neural Networks* (Elsevier). Professor Chen has received a number of awards including the Early Career Award from the Mathematical Biosciences Institute, and has had his work funded by the US National Science Foundation.

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Preface

In the modern age of the digital world, gigantic amounts of data have been recorded or collected. It remains a great challenge to process and analyze the "big data". Many neurophysiological, physiological, clinical and behavioral data are dynamic by the nature of the experiments or the way they are collected. These signals could be complex, noisy, and often multivariate and multimodal. How to develop efficient statistical methods to characterize these data and extract information that reveals underlying biological or physiological mechanisms remains an active and important research topic. In recent years, numerous advanced computational statistics, signal processing, and machine-learning methods have been developed and there is rapidly growing interest in applying these methods to data analysis in neuroscience, physiology and medicine.

The state space model (SSM) is referred to a class of probabilistic graphical models (Koller & Friedman 2009), which describe the probabilistic dependence between the latent state variable and the observed measurement. The state or the measurement can be either continuous or discrete. The term "state space" originated in 1960s in the area of control engineering (Kalman 1960). SSM provides a general framework for analyzing deterministic and stochastic dynamical systems that are measured or observed through a stochastic process. The SSM framework has been successfully applied in engineering, statistics, computer science and economics to solve a broad range of dynamical systems problems. The most celebrated examples of SSM include the linear dynamical system and the associated inference algorithm: Kalman filter (Kalman 1960), and the hidden Markov model (HMM) (Rabiner 1989). Despite plenty of successful examples applying state space analyses to neural and clinical data, there remain many challenges in data analysis, for either developing new mathematical theories and statistical models, or developing efficient algorithms tuned for large-scale data sets, or catering for highly complex (multimodal or multiscale) and nonstationary data. In order to pave the way for further advancement in these research areas, it is important to recognize these challenges and exchange new ideas among researchers and practitioners.

It is important to point out that the modeling and analysis principles discussed in this book are general and equally valuable for time series analyses in many other disciplines, such as climatology, politics, finance, chemical engineering, consumer marketing and computer networking.

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Road map and readership

This edited volume aims to recognize these challenges and provide a forum to discuss new ideas and new applications along the line of SSMs and state space analysis. Active and expert researchers with diverse backgrounds have contributed their recent innovative work and shared their critical thinking with the reader who have special interests in signal processing or statistical analysis as applied to the aforementioned research fields. The topics of this edited volume include switching SSMs, Bayesian inference, variational and Monte Carlo methods, EEG (electroencephalography) or MEG (magnetoencephalography) inverse problems, neural decoding and prosthetics, cardiovascular signal processing, data mining and onsite clinical monitoring.

The book is divided into two main parts. The first part focuses on state space modeling and analysis for neural data, and the second part focuses on state space methods for clinical data. Each chapter covers a specific topic of the SSM or its application area. Individual chapters are content independent and can be read or used separately for educational purpose. For starters, it is recommended to follow the arranged chapter order to study the materials.

The first two chapters are for pedagogic purpose. Following the introductory Chapter 1, Chapter 2 by Barber and Chiappa presents a tutorial overview of latent Markov models and related inference or learning methods. Part I consists of eight chapters (Chapters 3 through 10). Chapter 3 by Fukushima, Yamashita and Sato presents a detailed overview of state space methods for MEG source reconstruction problem. Chapter 4 by Galka and colleagues discusses autoregressive (AR) modeling of fMRI (functional magnetic resonance imaging) time series using state space analysis. Chapter 5 by Moran discusses SSMs and their spectral decomposition in dynamic causal modeling. Chapter 6 by Macke, Büsing and Sahani discusses the estimation of state and model parameters in SSMs of spike train observations. Chapter 7 by Latimer, Huk and Pillow discusses Bayesian inference for a class of latent stepping and ramping models derived from neuronal spike train data. Chapter 8 by Chen, Kloosterman and Wilson presents probabilistic approaches to analyze rat hippocampal ensemble spike data. Chapter 9 by Wu and Liu is dedicated to neural coding in motor cortex using SSMs with hidden states. Chapter 10 by Smith focuses on state space analysis of behavioral data in learning experiments. Part II consists of five chapters (Chapters 11 through 15). Chapter 11 by Lehman and colleagues presents a method for discovering shared dynamics in physiological time series and illustrates its application to patient monitoring in intensive care unit. Chapter 12 by Nemati and Adams presents a new approach to identify outcome-discriminative dynamics in multivariate physiological cohort time series. Chapter 13 by Chen and Barbieri presents a dynamic point process framework for assessing heartbeat dynamics and cardiovascular functions. Chapter 14 by Westover and colleagues presents a modeling and control platform for burst suppression in the case of managing medical coma. Finally, Chapter 15 by Oster and Clifford discusses the signal quality indices for state space electrophysiological signal processing.

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Despite many diverse research themes, several important topics have been repeatedly visited in many chapters:

- Adaptive Bayesian filtering methods, which include the Kalman filter (Chapters 4, 9 and 15), particle filter (Chapter 7) and point process filter (Chapters 8 and 13).
- Switching probabilistic models, which include the switching AR model (Chapters 2, 11 and 12), switching Kalman filter (Chapters 2 and 15) and switching HMM (Chapters 2 and 11).
- The expectation maximization (EM) algorithm and its variants (Chapters 4, 6, 8, 9 and 12).
- Variational Bayes (VB) methods (Chapters 3 and 8).
- Markov chain Monte Carlo (MCMC) methods (Chapters 6, 7, 10 and 11).

This book will expect a wide range of readers (electrical/biomedical/medical engineers, statisticians, and computer scientists). As a practical guide, the book will appeal to researchers interested in applying statistics, signal processing and machine-learning techniques to neural and clinical data. State-of-the-art techniques and a comprehensive bibliography are provided. As an educational source, the book can also be used as complementary teaching material for graduate students in engineering or medical schools. No specific knowledge is required to read this book, although a basic background in probability theory would be helpful.

It is noteworthy that the topic of SSM is rather broad, and it is nearly impossible to cover every aspect or all technical details in this volume. As complementary reading materials, several excellent books may be used for study:

- Barber, D., Cemgil, A. T. & Chiappa, S., editors (2011). *Bayesian Time Series Models*, Cambridge University Press.
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- Cohen, M. X. (2014). *Analyzing Neural Time Series Data: Theory and Practice*, MIT Press.

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