# Time Series for Economics and Finance

Focusing on methods for data that are ordered in time, this textbook provides a comprehensive guide to analyzing time series data using modern techniques from data science. It is specifically tailored to economics and finance applications, aiming to provide students with rigorous training. Chapters cover Bayesian approaches, nonparametric smoothing methods, machine learning, and continuous time econometrics. Theoretical and empirical exercises, concise summaries, bolded key terms, and illustrative examples are included throughout to reinforce key concepts and bolster understanding. Ancillary materials include datasets for self-study and PowerPoint lecture slides, a solutions manual, and additional exercises for instructors. With its clear and accessible style, this textbook is an essential tool for advanced undergraduate and graduate students in economics, finance, and statistics.

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# Time Series for Economics and Finance

**Oliver Linton**
University of Cambridge

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**To my exceptional wife, Jianghong Song, and my children Marco, Silvia, Alexander, and Florence.**

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# Preface

This work grew out of my teaching and research. Unfortunately, as a student I missed the glory days of the LSE Time Series School, and so this book will not cover general to specific modelling or parsimonious encompassing, but I try to cover the relevant tools of modern time series analysis as practiced by econometricians, now. There are so many excellent time series books, varying from the extremely rigorous like Brockwell and Davis (2006) to extremely practical books with only computer code and no justifications or understanding, and my book is somewhere in between. Time series is a bizarrely neglected topic in many econometrics and statistics graduate programs, and is facing new challenges from the machine learning community, whose main target of prediction is one historically treated under time series. I think an understanding of the key principles underlying dynamic models and their application is still very valuable for a lot of practical work in economics and finance. I have tried to update the classic corpus in the direction of where empirical practice is in economics and finance, including discussions about alternative inference methods like bootstrap that can be justified under weaker assumptions than in the classical setting. I also include material on smoothing methods, which are about flexible functional form where nonlinearity is potentially an issue, and so-called machine learning methods designed to accommodate large numbers of predictor variables. These methods are justly celebrated for their potential to improve predictions, and no doubt will take more central stage in graduate education in the future. I include some proofs, but in other cases refer the reader to where the original can be found. I left forecasting to the end, because it is about anticipating the future.

The book is intended to be used as a text for advanced undergraduates and graduate students in economics, finance, and statistics who are interested in time series, its applications, and the methodology needed to understand and interpret those applications. Some prerequisites include a course that covers probability, statistics, and linear regression, the ideas of which are central to the study of time series, along with some basic knowledge of matrices and linear algebra. In the interests of space I do not provide a full set of background results in linear algebra and econometrics, just the bare minimum of definitions. Likewise, I do not provide explicit help in programming. The book allows for different selections of material depending on the needs of students and instructors. One could just cover linear time series, including Chapters 2–9 and Chapter 13. One could instead cover nonlinear and nonparametric methods through Chapters 10–13. I have taught parts of this material at Yale University, the London School of Economics, the University of Cambridge, Humboldt University, Shandong University, SHUFE, Renmin University, and Minho University, and I thank the many students for their feedback over the years.

The book contains many terms in bold face, which can then be investigated further by internet search. In terms of software resources, `EViews` is a very useful package that does a lot of the procedures in this book, and I use it in some of the empirical illustrations



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included. However, it is not free and it has some limitations. `R` is free software with many shared user-created packages for doing everything from data scraping to Bayesian vector autoregression, and is highly recommended. A full list of available `R` packages can be found at https://cran.r-project.org. Ancillary materials include datasets (see Appendix D for detailed descriptions), the figures included throughout the book, some code in different languages such as `MATLAB`, `GAUSS`, and `R`, and an instructor's manual. They are available online at www.cambridge.org/lintontimeseries.

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# Notation and Conventions

- In this book I use the dating convention yyyymmddhhmmss.
- I use $\xrightarrow{P}$ to denote convergence in probability and $\Longrightarrow$ to denote weak convergence (or convergence in distribution).
- $\log(x)$ is the natural logarithm unless otherwise stated.
- $\mathbb{R}$ is the set of real numbers, $\mathbb{C}$ is the set of complex numbers including $\mathrm{i} = \sqrt{-1}$, $\mathbb{Z}$ is the set of integers $0, \pm 1, \pm 2, \ldots$, and $\mathbb{N}$ is the set of positive integers 1,2,. . .
- $'$ denotes differentiation.
- $^{\intercal}$ denotes matrix transpose.
- I say $1(A) = 1$ if the event $A$ is true and zero otherwise.
- I use $X_n = O(n)$ to mean that $X_n/n$ is bounded for a deterministic sequence $X_n$ as $n \to \infty$, and for a stochastic sequence I use the Landau $O_P, o_P$ notation. Specifically, for a sequence of random variables $X_n$, I write $X_n = o_P(\delta_n)$ if $\delta_n^{-1} X_n \xrightarrow{P} 0$ for deterministic $\delta_n \to 0$ as $n \to \infty$. I write $X_n = O_P(\delta_n)$ if essentially there is a random variable $X$ for which $\left|\delta_n^{-1} X_n\right| \leq X$ for large $n$.
- I use $\simeq$ to generically denote an approximation.
- I use $\sim$ to mean to have the same distribution as.
- I do not have a bracketing convention like some journals, but I do have a preference for round curved things over square ones.



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