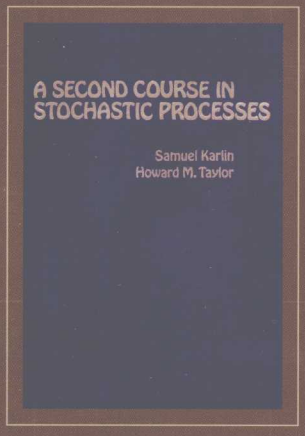
TURING 图灵原版数学·统计学系列 27

A Second Course in Stochastic Processes

随机过程高级教程

（英文版）

[美] Samuel Karlin
Howard M. Taylor 著



人民邮电出版社
POSTS & TELECOM PRESS

0211.6/Y9=2
2009.

TURING 图灵原版数学·统计学系列

A Second Course in Stochastic Processes

随机过程高级教程

（英文版）

[美] Samuel Karlin
Howard M. Taylor 著

人民邮电出版社
北　京

图书在版编目（CIP）数据

随机过程高级教程：英文 /（美）卡林（Karlin, S.），（美）泰勒（Taylor, H. M.）著. —北京：人民邮电出版社，2009.1
（图灵原版数学·统计学系列）
ISBN 978-7-115-19181-6

Ⅰ. 随… Ⅱ. ①卡…②泰… Ⅲ. 随机过程—教材—英文
Ⅳ. O211.6

中国版本图书馆 CIP 数据核字（2008）第 175887 号

内 容 提 要

本书是《随机过程初级教程》的姊妹篇，涉及范围十分广泛，内容包括马尔可夫链的代数方法、转移概率的比定理及应用、连续时间马尔可夫链、扩散过程、复合随机过程、独立同分布随机变量部分和的波动理论、排队过程等，每章末都有很丰富的习题，并附有代表性的参考书目，非常便于进一步学习。

本书适合从事各领域随机过程研究和应用的读者阅读和参考。

图灵原版数学·统计学系列

随机过程高级教程（英文版）

◆ 著 [美] Samuel Karlin Howard M.Taylor
责任编辑 明永玲

◆ 人民邮电出版社出版发行 北京市崇文区夕照寺街 14 号
邮编 100061 电子函件 315@ptpress.com.cn
网址 http://www.ptpress.com.cn
北京隆昌伟业印刷有限公司印刷

◆ 开本：700×1000 1/16
印张：35
字数：504 千字 2009 年 1 月第 1 版
印数：1－2 000 册 2009 年 1 月北京第 1 次印刷
著作权合同登记号 图字：01-2008-4298 号

ISBN 978-7-115-19181-6/O1

定价：89.00 元

读者服务热线：(010)88593802 印装质量热线：(010)67129223
反盗版热线：(010)67171154

版权声明

A Second Course in Stochastic Processes by Samuel Karlin and Howard M. Taylor, ISBN: 978-0-12-398650-4.

Copyright © 1981 by Elsevier. All rights reserved.

Authorized English language reprint edition published by the Proprietor.

ISBN: 978-981-272-228-7.

Copyright© 2009 by Elsevier (Singapore) Pte Ltd. All rights reserved.

Elsevier (Singapore) Pte Ltd.
3 Killiney Road
#08-01 Winsland House I
Singapore 239519
Tel：(65)6349-0200
Fax：(65)6733-1817

First Published 2009
2009年初版

Printed in China by POSTS & TELECOM PRESS under special arrangement with Elsevier (Singapore) Pte Ltd. This edition is authorized for sale in China only, excluding Hong Kong SAR, Macao SAR and Taiwan. Unauthorized export of this edition is a violation of the Copyright Act. Violation of this Law is subject to Civil and Criminal Penalties.

本书英文影印版由Elsevier (Singapore) Pte Ltd.授权人民邮电出版社在中华人民共和国境内独家发行．本版仅限在中华人民共和国境内（不包括香港、澳门特别行政区和台湾地区）出版及标价销售．未经许可之出口，视为违反著作权法，将受法律之制裁．

本书封底贴有Elsevier防伪标签，无标签者不得销售．

PREFACE

This *Second Course* continues the development of the theory and applications of stochastic processes as promised in the preface of *A First Course*[①]. We emphasize a careful treatment of basic structures in stochastic processes in symbiosis with the analysis of natural classes of stochastic processes arising from the biological, physical, and social sciences.

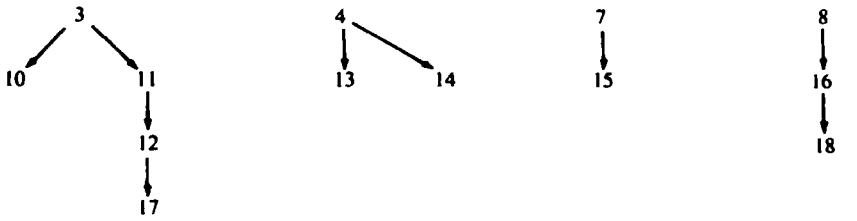
Apart from expanding on the topics treated in the first edition of this work but not incorporated in *A First Course,* this volume presents an extensive introductory account of the fundamental concepts and methodology of diffusion processes and the closely allied theory of stochastic differential equations and stochastic integrals. A multitude of physical, engineering, biological, social, and managerial phenomena are either well approximated or reasonably modeled by diffusion processes; and modern approaches to diffusion processes and stochastic differential equations provide new perspectives and techniques impinging on many subfields of pure and applied mathematics, among them partial differential equations, dynamical systems, optimal control problems, statistical decision procedures, operations research, studies of economic systems, population genetics, and ecology models.

A new chapter discusses the elegant and far-reaching distributional formulas now available for a wide variety of functionals (e.g., first-passage time, maximum, order statistics, occupation time) of the process of sums of independent random variables. The identities, formulas, and results in this chapter have important applications in queueing and renewal theory, for statistical decision procedures, and elsewhere.

① 指本书姊妹篇*A First Course in Stochastic Processes*，英文影印版和中文版《随机过程初级教程》已由人民邮电出版社出版.

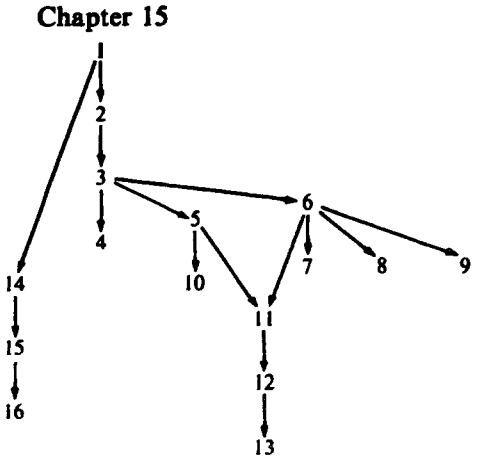
此为试读,需要完整PDF请访问: www.ertongbook.com

The logical dependence of the chapters in *A Second Course* is shown by the diagram below (consult also the preface to *A First Course* on the relationships of Chapters 1–9).



The book can be coupled to *A First Course* in several ways, depending on the background and interests of the students. The discussion of Markov chains in *A First Course* can be supplemented with parts of the more advanced Chapters 10–12, and 14. The material on fluctuation theory of sums of independent random variables (Chapters 12 and 17), perhaps supplemented by some parts of the chapter on queueing processes (Chapter 18), may be attractive and useful to students of operations research and statistics. Chapter 16, on compounding stochastic processes, is designed as an enticing introduction to a hierarchy of relevant models, including models of multiple species population growth, of migration and demographic structures, of point processes, and compositions of Poisson processes (Lévy processes).

We strongly recommend devoting a semester to diffusion processes (Chapter 15). The dependence relationships of the sections of Chapter 15 are diagrammed below. Section 1 provides a generalized description of various characterizations of diffusion. The examples of Section 2, which need not be absorbed in their totality, are intended to hint at the rich diversity of natural models of diffusion processes; the emphasis on biological examples reflects the authors' personal interests, but diffusion models abound in other sciences as well. Sections 3–5 point up the utility and tractability of diffusion process analysis. Section 6 takes up the boundary classification of one-dimensional diffusion processes; Section 7, on the same topic, is more technical. Section 8 provides constructions of diffusions with different types of boundary behavior. Sections 9 and 10 treat a number of topics motivated by problems of population genetics and statistics. The formal (general) theory of Markov processes with emphasis on applications to diffusions is elaborated in Sections 11 and 12. Section 13 exhibits the spectral representations for several classical diffusion models, which are of some interest because of their connections with classical special functions. The key concepts, a host of examples, and some methods of stochastic differential equations and stochastic integrals are introduced in Sections 14–16.



As noted in the earlier prefaces, we have drawn freely on the thriving literature of applied and theoretical stochastic processes without citing specific articles. A few representative books are listed at the end of each chapter and may be consulted profitably as a guide to more advanced material.

We express our gratitude to Stanford University, the Weizmann Institute of Science in Israel, and Cornell University for providing a rich intellectual environment and facilities indispensable for the writing of this text. The first author is grateful for the continuing grant support provided by the National Science Foundation and the National Institutes of Health that permitted an unencumbered concentration on a number of the concepts of this book and on its various drafts. We are also happy to acknowledge our indebtedness to many colleagues who have offered constructive criticisms, among them Professor M. Taqqu of Cornell, Dr. S. Tavaré of the University of Utah, Professors D. Iglehart and M. Harrison of Stanford, and Professor J. Kingman of Oxford. Finally, we thank our students P. Glynn, E. Cameron, J. Raper, R. Smith, L. Tierney, and P. Williams for their assistance in checking the problems, and for their helpful reactions to early versions of Chapter 15.

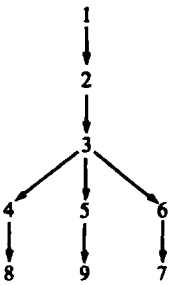
PREFACE TO *A FIRST COURSE*

The purposes, level, and style of this new edition conform to the tenets set forth in the original preface. We continue with our tack of developing simultaneously theory and applications, intertwined so that they refurbish and elucidate each other.

We have made three main kinds of changes. First, we have enlarged on the topics treated in the first edition. Second, we have added many exercises and problems at the end of each chapter. Third, and most important, we have supplied, in new chapters, broad introductory discussions of several classes of stochastic processes not dealt with in the first edition, notably martingales, renewal and fluctuation phenomena associated with random sums, stationary stochastic processes, and diffusion theory.

Martingale concepts and methodology have provided a far-reaching apparatus vital to the analysis of all kinds of functionals of stochastic processes. In particular, martingale constructions serve decisively in the investigation of stochastic models of diffusion type. Renewal phenomena are almost equally important in the engineering and managerial sciences especially with reference to examples in reliability, queueing, and inventory systems. We discuss renewal theory systematically in an extended chapter. Another new chapter explores the theory of stationary processes and its applications to certain classes of engineering and econometric problems. Still other new chapters develop the structure and use of diffusion processes for describing certain biological and physical systems and fluctuation properties of sums of independent random variables useful in the analyses of queueing systems and other facets of operations research.

The logical dependence of chapters is shown by the diagram below. Section 1 of Chapter 1 can be reviewed without worrying about details. Only Sections 5 and 7 of Chapter 7 depend on Chapter 6. Only Section 9 of Chapter 9 depends on Chapter 5.



An easy one-semester course adapted to the junior-senior level could consist of Chapter 1, Sections 2 and 3 preceded by a cursory review of Section 1, Chapter 2 in its entirety, Chapter 3 excluding Sections 5 and/or 6, and Chapter 4 excluding Sections 3, 7, and 8. The content of the last part of the course is left to the discretion of the lecturer. An option of material from the early sections of any or all of Chapters 5–9 would be suitable.

The problems at the end of each chapter are divided into two groups: the first, more or less elementary; the second, more difficult and subtle.

The scope of the book is quite extensive, and on this account, it has been divided into two volumes. We view the first volume as embracing the main categories of stochastic processes underlying the theory and most relevant for applications. In *A Second Course* we introduce additional topics and applications and delve more deeply into some of the issues of *A First Course*. We have organized the edition to attract a wide spectrum of readers, including theorists and practitioners of stochastic analysis pertaining to the mathematical, engineering, physical, biological, social, and managerial sciences.

The second volume of this work, *A Second Course in Stochastic Processes*, will include the following chapters: (10) Algebraic Methods in Markov Chains; (11) Ratio Theorems of Transition Probabilities and Applications; (12) Sums of Independent Random Variables as a Markov Chain; (13) Order Statistics, Poisson Processes, and Applications; (14) Continuous Time Markov Chains; (15) Diffusion Processes; (16) Compounding Stochastic Processes; (17) Fluctuation Theory of Partial Sums of Independent Identically Distributed Random Variables; (18) Queueing Processes.

As noted in the first preface, we have drawn freely on the thriving literature of applied and theoretical stochastic processes. A few representative references are included at the end of each chapter; these may be profitably consulted for more advanced material.

We express our gratitude to the Weizmann Institute of Science, Stanford University, and Cornell University for providing a rich intellectual environment and facilities indispensable for the writing of this text. The first author is grateful for the continuing grant support provided by the Office of Naval Research that permitted an unencumbered concentration on a number of the concepts and drafts of this book. We are also happy to acknowledge our indebtedness to many colleagues who have offered a variety of constructive criticisms. Among others, these include Professors P. Brockwell of La Trobe, J. Kingman of Oxford, D. Iglehart and S. Ghurye of Stanford, and K. Itô and S. Stidham, Jr. of Cornell. We also thank our students M. Nedzela and C. Macken for their assistance in checking the problems and help in reading proofs.

SAMUEL KARLIN
HOWARD M. TAYLOR

PREFACE TO FIRST EDITION

Stochastic processes concern sequences of events governed by probabilistic laws. Many applications of stochastic processes occur in physics, engineering, biology, medicine, psychology, and other disciplines, as well as in other branches of mathematical analysis. The purpose of this book is to provide an introduction to the many specialized treatises on stochastic processes. Specifically, I have endeavored to achieve three objectives: (1) to present a systematic introductory account of several principal areas in stochastic processes, (2) to attract and interest students of pure mathematics in the rich diversity of applications of stochastic processes, and (3) to make the student who is more concerned with application aware of the relevance and importance of the mathematical subleties underlying stochastic processes.

The examples in this book are drawn mainly from biology and engineering but there is an emphasis on stochastic structures that are of mathematical interest or of importance in more than one discipline. A number of concepts and problems that are currently prominent in probability research are discussed and illustrated.

Since it is not possible to discuss all aspects of this field in an elementary text, some important topics have been omitted, notably stationary stochastic processes and martingales. Nor is the book intended in any sense as an authoritative work in the areas it does cover. On the contrary, its primary aim is simply to bridge the gap between an elementary probability course and the many excellent advanced works on stochastic processes.

Readers of this book are assumed to be familiar with the elementary theory of probability as presented in the first half of Feller's classic *Introduction to*

此为试读,需要完整PDF请访问: www.ertongbook.com

Probability Theory and Its Applications. In Section 1, Chapter 1 of my book the necessary background material is presented and the terminology and notation of the book established. Discussions in small print can be skipped on first reading. Excercises are provided at the close of each chapter to help illuminate and expand on the theory.

This book can serve for either a one-semester or a two-semester course, depending on the extent of coverage desired.

In writing this book, I have drawn on the vast literature on stochastic processes. Each chapter ends with citations of books that may profitably be consulted for further information, including in many cases bibliographical listings.

I am grateful to Stanford University and to the U.S. Office of Naval Research for providing facilities, intellectual stimulation, and financial support for the writing of this text. Among my academic colleagues I am grateful to Professor K. L. Chung and Professor J. McGregor of Stanford for their constant encouragement and helpful comments; to Professor J. Lamperti of Dartmouth, Professor J. Kiefer of Cornell, and Professor P. Ney of Wisconsin for offering a variety of constructive criticisms; to Dr. A. Feinstein for his detailed checking of substantial sections of the manuscript, and to my students P. Milch, B. Singer, M. Feldman, and B. Krishnamoorthi for their helpful suggestions and their assistance in organizing the exercises. Finally, I am indebted to Gail Lemmond and Rosemarie Stampfel for their superb technical typing and all-around administrative care.

SAMUEL KARLIN

CONTENTS OF *A FIRST COURSE*

Chapter 1 ELEMENTS OF STOCHASTIC PROCESSES

1. Review of Basic Terminology and Properties of Random Variables and Distribution Functions 2. Two Simple Examples of Stochastic Processes 3. Classification of General Stochastic Processes 4. Defining a Stochastic Process

Chapter 2 MARKOV CHAINS

1. Definitions 2. Examples of Markov Chains 3. Transition Probability Matrices of a Markov Chain 4. Classification of States of a Markov Chain 5. Recurrence 6. Examples of Recurrent Markov Chains 7. More on Recurrence

Chapter 3 THE BASIC LIMIT THEOREM OF MARKOV CHAINS AND APPLICATIONS

1. Discrete Renewal Equation 2. Proof of Theorem 1.1 3. Absorption Probabilities 4. Criteria for Recurrence 5. A Queueing Example 6. Another Queueing Model 7. Random Walk

Chapter 4 CLASSICAL EXAMPLES OF CONTINUOUS TIME MARKOV CHAINS

1. General Pure Birth Processes and Poisson Processes 2. More about Poisson Processes 3. A Counter Model 4. Birth and Death Processes 5. Differential Equations of Birth and Death Processes 6. Examples of Birth and Death Processes 7. Birth and Death Processes with Absorbing States 8. Finite State Continuous Time Markov Chains

Chapter 5 **RENEWAL PROCESSES**

1. Definition of a Renewal Process and Related Concepts 2. Some Examples of Renewal Processes 3. More on Some Special Renewal Processes 4. Renewal Equations and the Elementary Renewal Theorem 5. The Renewal Theorem 6. Applications of the Renewal Theorem 7. Generalizations and Variations on Renewal Processes 8. More Elaborate Applications of Renewal Theory 9. Superposition of Renewal Processes

Chapter 6 **MARTINGALES**

1. Preliminary Definitions and Examples 2. Supermartingales and Submartingales 3. The Optional Sampling Theorem 4. Some Applications of the Optional Sampling Theorem 5. Martingale Convergence Theorems 6. Applications and Extensions of the Martingale Convergence Theorems 7. Martingales with Respect to σ-Fields 8. Other Martingales

Chapter 7 **BROWNIAN MOTION**

1. Background Material 2. Joint Probabilities for Brownian Motion 3. Continuity of Paths and the Maximum Variables 4. Variations and Extensions 5. Computing Some Functionals of Brownian Motion by Martingale Methods 6. Multidimensional Brownian Motion 7. Brownian Paths

Chapter 8 **BRANCHING PROCESSES**

1. Discrete Time Branching Processes 2. Generating Function Relations for Branching Processes 3. Extinction Probabilities 4. Examples 5. Two-Type Branching Processes 6. Multi-Type Branching Processes 7. Continuous Time Branching Processes 8. Extinction Probabilities for Continuous Time Branching Processes 9. Limit Theorems for Continuous Time Branching Processes 10. Two-Type Continuous Time Branching Process 11. Branching Processes with General Variable Lifetime

Chapter 9 **STATIONARY PROCESSES**

1. Definitions and Examples 2. Mean Square Distance 3. Mean Square Error Prediction 4. Prediction of Covariance Stationary Processes 5. Ergodic Theory and Stationary Processes 6. Applications of Ergodic Theory 7. Spectral Analysis of Covariance Stationary Processes 8. Gaussian Systems 9. Stationary Point Processes 10. The Level-Crossing Problem

Appendix **REVIEWS OF MATRIX ANALYSIS**

1. The Spectral Theorem 2. The Frobenius Theory of Positive Matrices

Index

CONTENTS

Chapter 10

ALGEBRAIC METHODS IN MARKOV CHAINS

1. Preliminaries .. 1
2. Relations of Eigenvalues and Recurrence Classes .. 3
3. Periodic Classes .. 6
4. Special Computational Methods in Markov Chains .. 10
5. Examples .. 14
6. Applications to Coin Tossing .. 18

Elementary Problems .. 23
Problems .. 25
Notes .. 30
References .. 30

Chapter 11

RATIO THEOREMS OF TRANSITION PROBABILITIES AND APPLICATIONS

1. Taboo Probabilities .. 31
2. Ratio Theorems .. 33

3. Existence of Generalized Stationary Distributions 37
4. Interpretation of Generalized Stationary Distributions 42
5. Regular, Superregular, and Subregular Sequences for Markov Chains .. 44
6. Stopping Rule Problems 50
Elementary Problems 65
Problems 65
Notes 70
References 71

Chapter 12

SUMS OF INDEPENDENT RANDOM VARIABLES AS A MARKOV CHAIN

1. Recurrence Properties of Sums of Independent Random Variables .. 72
2. Local Limit Theorems 76
3. Right Regular Sequences for the Markov Chain $\{S_n\}$ 83
4. The Discrete Renewal Theorem 93
Elementary Problems 95
Problems 96
Notes 99
References 99

Chapter 13

ORDER STATISTICS, POISSON PROCESSES, AND APPLICATIONS

1. Order Statistics and Their Relation to Poisson Processes 100
2. The Ballot Problem 107
3. Empirical Distribution Functions 113
4. Some Limit Distributions for Empirical Distribution Functions .. 119
Elementary Problems 124
Problems 125
Notes 137
References 137

Chapter 14

CONTINUOUS TIME MARKOV CHAINS

1. Differentiability Properties of Transition Probabilities 138
2. Conservative Processes and the Forward and Backward Differential Equations 143
3. Construction of a Continuous Time Markov Chain from Its Infinitesimal Parameters 145

4. Strong Markov Property 149
Problems 152
Notes 156
References 156

Chapter 15

DIFFUSION PROCESSES

1. General Description 157
2. Examples of Diffusion 169
3. Differential Equations Associated with Certain Functionals .. 191
4. Some Concrete Cases of the Functional Calculations 205
5. The Nature of Backward and Forward Equations and Calculation of Stationary Measures 213
6. Boundary Classification for Regular Diffusion Processes 226
7. Some Further Characterizations of Boundary Behavior 242
8. Some Constructions of Boundary Behavior of Diffusion Processes .. 251
9. Conditioned Diffusion Processes 261
10. Some Natural Diffusion Models with Killing 272
11. Semigroup Formulation of Continuous Time Markov Processes .. 285
12. Further Topics in the Semigroup Theory of Markov Processes and Applications to Diffusions 305
13. The Spectral Representation of the Transition Density for a Diffusion 330
14. The Concept of Stochastic Differential Equations 340
15. Some Stochastic Differential Equation Models 358
16. A Preview of Stochastic Differential Equations and Stochastic Integrals 368
Elementary Problems 377
Problems 382
Notes 395
References 395

Chapter 16

COMPOUNDING STOCHASTIC PROCESSES

1. Multidimensional Homogeneous Poisson Processes 398
2. An Application of Multidimensional Poisson Processes to Astronomy .. 404
3. Immigration and Population Growth 405
4. Stochastic Models of Mutation and Growth 408
5. One-Dimensional Geometric Population Growth 413
6. Stochastic Population Growth Model in Space and Time 416
7. Deterministic Population Growth with Age Distribution 419
8. A Discrete Aging Model 425

此为试读,需要完整PDF请访问: www.ertongbook.com