# **Probability and Its Applications**

Olav Kallenberg Foundations of Modern Probability Second Edition

From the reviews of the first edition:

"... Kallenberg's present book would have to qualify as the assimilation of probability par excellence. It is a great edifice of material, clearly and ingeniously presented, without any non-mathematical distractions. Readers wishing to venture into it may do so with confidence that they are in very capable hands."

-F.B. Knight, Mathematical Reviews

"... Indeed the monograph has the potential to become a (possibly even "the") major reference book on large parts of probability theory for the next decade or more." —M. Scheutzow, Zentralblatt

"The theory of probability has grown exponentially during the second half of the twentieth century and the idea of writing a single volume that could serve as a general reference for much of the modern theory seems almost foolhardy. Yet this is precisely what Professor Kallenberg has attempted in the volume under review and he has accomplished it brilliantly.... It is astonishing that a single volume of just over five hundred pages could contain so much material presented with complete rigor and still be at least formally self-contained...."

-R.K. Getoor, Metrica

This new edition contains four new chapters as well as numerous improvements throughout the text.

Olav Kallenberg was educated in Sweden, where he received his Ph.D. in 1972 from Chalmers University. After teaching for many years at Swedish universities, he moved in 1985 to the United States, where he is currently Professor of Mathematics at Auburn University. He is known for his book *Random Measures* (fourth edition, 1986) and for numerous research papers in all areas of probability. In 1977, he was the second recipient ever of the prestigious Rollo Davidson Prize from Cambridge University. In 1991 to 1994, he served as the Editor-in-Chief of *Probability Theory and Related Fields*.



# Preface to the Second Edition

# **Preface** to the First Edition

# 1. Measure Theory — Basic Notions

Measurable sets and functions measures and integration monotone and dominated convergence transformation of integrals product measures and Fubini's theorem L<sup>p</sup>-spaces and projection approximation measure spaces and kernels

# 2. Measure Theory — Key Results

Outer measures and extension Lebesgue and Lebesgue-Stieltjes measures Jordan-Hahn and Lebesgue decompositions Radon-Nikodým theorem Lebesgue's differentiation theorem functions of finite variation Riesz' representation theorem Haar and invariant measures

# 3. Processes, Distributions, and Independence

Random elements and processes distributions and expectation independence zero-one laws Borel-Cantelli lemma Bernoulli sequences and existence moments and continuity of paths

# 4. Random Sequences, Series, and Averages

Convergence in probability and in L<sup>p</sup> uniform integrability and tightness convergence in distribution convergence of random series strong laws of large numbers Portmanteau theorem continuous mapping and approximation coupling and measurability 23

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#### 5. Characteristic Functions and Classical Limit Theorems 83

Uniqueness and continuity theorem Poisson convergence positive and symmetric terms Lindeberg's condition general Gaussian convergence weak laws of large numbers domain of Gaussian attraction vague and weak compactness

## 6. Conditioning and Disintegration

Conditional expectations and probabilities regular conditional distributions disintegration conditional independence transfer and coupling existence of sequences and processes extension through conditioning

## 7. Martingales and Optional Times

Filtrations and optional times random time-change martingale property optional stopping and sampling maximum and upcrossing inequalities martingale convergence, regularity, and closure limits of conditional expectations regularization of submartingales

## 8. Markov Processes and Discrete-Time Chains

Markov property and transition kernels finite-dimensional distributions and existence space and time homogeneity strong Markov property and excursions invariant distributions and stationarity recurrence and transience ergodic behavior of irreducible chains mean recurrence times

#### 9. Random Walks and Renewal Theory

Recurrence and transience dependence on dimension general recurrence criteria symmetry and duality Wiener-Hopf factorization 103

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ladder time and height distribution stationary renewal process renewal theorem

## **10. Stationary Processes and Ergodic Theory**

Stationarity, invariance, and ergodicity discrete- and continuous-time ergodic theorems moment and maximum inequalities multivariate ergodic theorems sample intensity of a random measure subadditivity and products of random matrices conditioning and ergodic decomposition shift coupling and the invariant  $\sigma$ -field

## **11.** Special Notions of Symmetry and Invariance

Palm distributions and inversion formulas stationarity and cycle stationarity local hitting and conditioning ergodic properties of Palm measures exchangeable sequences and processes strong stationarity and predictable sampling ballot theorems entropy and information

# 12. Poisson and Pure Jump-Type Markov Processes

Random measures and point processes Cox processes, randomization, and thinning mixed Poisson and binomial processes independence and symmetry criteria Markov transition and rate kernels embedded Markov chains and explosion compound and pseudo-Poisson processes ergodic behavior of irreducible chains

# **13.** Gaussian Processes and Brownian Motion

Symmetries of Gaussian distribution existence and path properties of Brownian motion strong Markov and reflection properties arcsine and uniform laws law of the iterated logarithm Wiener integrals and isonormal Gaussian processes multiple Wiener-Itô integrals chaos expansion of Brownian functionals 224

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#### 14. Skorohod Embedding and Invariance Principles

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## 15. Independent Increments and Infinite Divisibility

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Relative compactness and tightness uniform topology on C(K, S)Skorohod's  $J_1$ -topology equicontinuity and tightness convergence of random measures superposition and thinning exchangeable sequences and processes simple point processes and random closed sets

#### 17. Stochastic Integrals and Quadratic Variation

Continuous local martingales and semimartingales quadratic variation and covariation existence and basic properties of the integral integration by parts and Itô's formula Fisk-Stratonovich integral approximation and uniqueness random time-change dependence on parameter

## 18. Continuous Martingales and Brownian Motion

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#### **19.** Feller Processes and Semigroups

Semigroups, resolvents, and generators closure and core Hille-Yosida theorem existence and regularization strong Markov property characteristic operator diffusions and elliptic operators convergence and approximation

#### **20.** Ergodic Properties of Markov Processes

transition and contraction operators ratio ergodic theorem space-time invariance and tail triviality mixing and convergence in total variation Harris recurrence and transience existence and uniqueness of invariant measure distributional and pathwise limits

## 21. Stochastic Differential Equations and Martingale Problems

Linear equations and Ornstein–Uhlenbeck processes strong existence, uniqueness, and nonexplosion criteria weak solutions and local martingale problems well-posedness and measurability pathwise uniqueness and functional solution weak existence and continuity transformation of SDEs strong Markov and Feller properties

## 22. Local Time, Excursions, and Additive Functionals

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#### 23. One-dimensional SDEs and Diffusions

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perturbation of dynamical systems
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Strassen's law of the iterated logarithm

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# A2. Some Special Spaces Function spaces measure spaces spaces of closed sets measure-valued functions projective limits

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