

A User's Guide to Measure Theoretic Probability

This book grew from a need to teach a rigorous probability course to a mixed audience – statisticians, mathematically inclined biostatisticians, mathematicians, economists, and students of finance – at the advanced undergraduate/introductory graduate level, without the luxury of a course in measure theory as a prerequisite. The core of the book covers the basic topics of independence, conditioning, martingales, convergence in distribution, and Fourier transforms. In addition, there are numerous sections treating topics traditionally thought of as more advanced, such as coupling and the KMT strong approximation, option pricing via the equivalent martingale measure, and Fernique's inequality for Gaussian processes.

In a further break with tradition, the necessary measure theory is developed via the identification of integrals with linear functionals on spaces of measurable functions, allowing quicker access to the full power of the measure theoretic methods.

The book is not just a presentation of mathematically rigorous theory; it is also a discussion of why some of that theory takes its current form and how anyone could have thought of those clever ideas in the first place. It is intended as a secure starting point for anyone who needs to invoke rigorous probabilistic arguments and to understand what they mean.

David Pollard is Professor of Statistics and Mathematics at Yale University in New Haven, Connecticut. His interests center on probability, measure theory, theoretical and applied statistics, and econometrics. He believes strongly that research and teaching (at all levels) should be intertwined. His book, *Convergence of Stochastic Processes* (Springer-Verlag, 1984), successfully introduced many researchers and graduate students to empirical process theory.

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DAVID POLLARD
Yale University



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Preface

This book began life as a set of handwritten notes, distributed to students in my one-semester graduate course on probability theory, a course that had humble aims: to help the students understand results such as the strong law of large numbers, the central limit theorem, conditioning, and some martingale theory. Along the way they could expect to learn a little measure theory and maybe even a smattering of functional analysis, but not as much as they would learn from a course on Measure Theory or Functional Analysis.

In recent years the audience has consisted mainly of graduate students in statistics and economics, most of whom have not studied measure theory. Most of them have no intention of studying measure theory systematically, or of becoming professional probabilists, but they do want to learn some rigorous probability theory—in one semester.

Faced with the reality of an audience that might have neither the time nor the inclination to devote itself completely to my favorite subject, I sought to compress the essentials into a course as self-contained as I could make it. I tried to pack into the first few weeks of the semester a crash course in measure theory, with supplementary exercises and a whirlwind exposition (Appendix A) for the enthusiasts. I tried to eliminate duplication of mathematical effort if it served no useful role. After many years of chopping and compressing, the material that I most wanted to cover all fit into a one-semester course, divided into 25 lectures, each lasting from 60 to 75 minutes. My handwritten notes filled fewer than a hundred pages.

I had every intention of making my little stack of notes into a little book. But I couldn't resist expanding a bit here and a bit there, adding useful reference material, spelling out ideas that I had struggled with on first acquaintance, slipping in extra topics that my students have seemed to need when writing dissertations, and pulling in material from other courses I have taught and neat tricks I have learned from my friends. And soon it wasn't so little any more.

Many of the additions ended up in starred Sections, which contain harder material or topics that can be skipped over without loss of continuity.

My treatment includes a few eccentricities that might upset some of my professional colleagues. My most obvious departure from tradition is in the use of linear functional notation for expectations, an approach I first encountered in books by de Finetti. I attempt to explain the virtues of this notation in the first two Chapters. Another slight novelty—at least for anyone already exposed to the Kolmogorov interpretation of conditional expectations—appears in my treatment of conditioning, in Chapter 5. For many years I have worried about the wide gap between the free-wheeling conditioning calculations of an elementary probability course and the formal manipulations demanded by rigor. I claim that a treatment starting from the idea of conditional distributions offers one way of bridging the gap,

at least for many of the statistical applications of conditioning that have troubled me the most.

The twelve Chapters and six Appendixes contain general explanations, remarks, opinions, and blocks of more formal material. Theorems and Lemmas contain the most important mathematical details. Examples contain gentler, or less formal, explanations and illustrations. Supporting theoretical material is presented either in the form of Exercises, with terse solutions, or as Problems (at the ends of the Chapters) that work step-by-step through material that missed the cutoff as Exercises, Lemmas, or Theorems. Some Problems are routine, to give students an opportunity to digest the ideas in the text without great mental effort; some Problems are hard.

A possible one-semester course

Here is a list of the material that I usually try to cover in the one-semester graduate course.

Chapter 1: Spend one lecture on why measure theory is worth the effort, using a few of the Examples as illustrations. Introduce de Finetti notation, identifying sets with their indicator functions and writing \mathbb{P} for both probabilities of sets and expectations of random variables. Mention, very briefly, the fair price Section as an alternative to the frequency interpretation.

Chapter 2: Cover the unstarred Sections carefully, but omitting many details from the Examples. Postpone Section 7 until Chapter 3. Postpone Section 8 until Chapter 6. Describe briefly the generating class theorem for functions, from Section 11, without proofs.

Chapter 3: Cover Section 1, explaining the connection with the elementary notion of a density. Take a short excursion into Hilbert space (explaining the projection theorem as an extension of the result for Euclidean spaces) before presenting the simple version of Radon-Nikodym. Mention briefly the classical concept of absolute continuity, but give no details. Maybe say something about total variation.

Chapter 4: Cover Sections 1 and 2, leaving details of some arguments to the students. Give a reminder about generating classes of functions. Describe the construction of $\mu \otimes \Lambda$, only for a finite kernel Λ , via the iterated integral. Cover product measures, using some of the Examples from Section 4. Explain the need for the blocking idea from Section 6, using the Maximal Inequality to preview the idea of a stopping time. Mention the truncation idea behind the version of the SLLN for independent, identically distributed random variables with finite first moments, but skip most of the proof.

Chapter 5: Discuss Section 1 carefully. Cover the high points of Sections 2 through 4. (They could be skipped without too much loss of continuity, but I prefer not to move straight into Kolmogorov conditioning.) Cover Section 6.

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Chapter 6: Cover Sections 1 through 4, but skipping over some Examples. Characterize uniformly integrable martingales, using Section 6 and some of the material postponed from Section 8 of Chapter 2, unless short of time.

Chapter 7: Cover the first four Sections, skipping some of the examples of central limit theorems near the end of Section 2. Downplay multivariate results.

Chapter 8: Cover Sections 1, 2, 4, and 6.

If time is left over, cover a topic from the remaining Chapters.

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Finally, I thank Lauren Cowles for years of good advice, and for her inexhaustible patience with an author who could never stop tinkering.

David Pollard
New Haven

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