DAVENPORT

probability and random processes

random processes

an introduction for applied scientists and engineers

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preface

This book, intended as a text for a first course in probability and random processes, can be used either for self-study or in a formal classroom setting. In the classroom context, the first eight chapters could form a one-semester subject on probability with the last six chapters (plus possible supplementary material at the discretion of the instructor) following as a semester course on random processes. Alternatively, most of the key ideas in both probability and random processes could be covered in one semester by a judicious selection of sections. The prerequisites are calculus for the first eight chapters and calculus plus a prior, or concurrent, introduction to Fourier theory for the remainder.

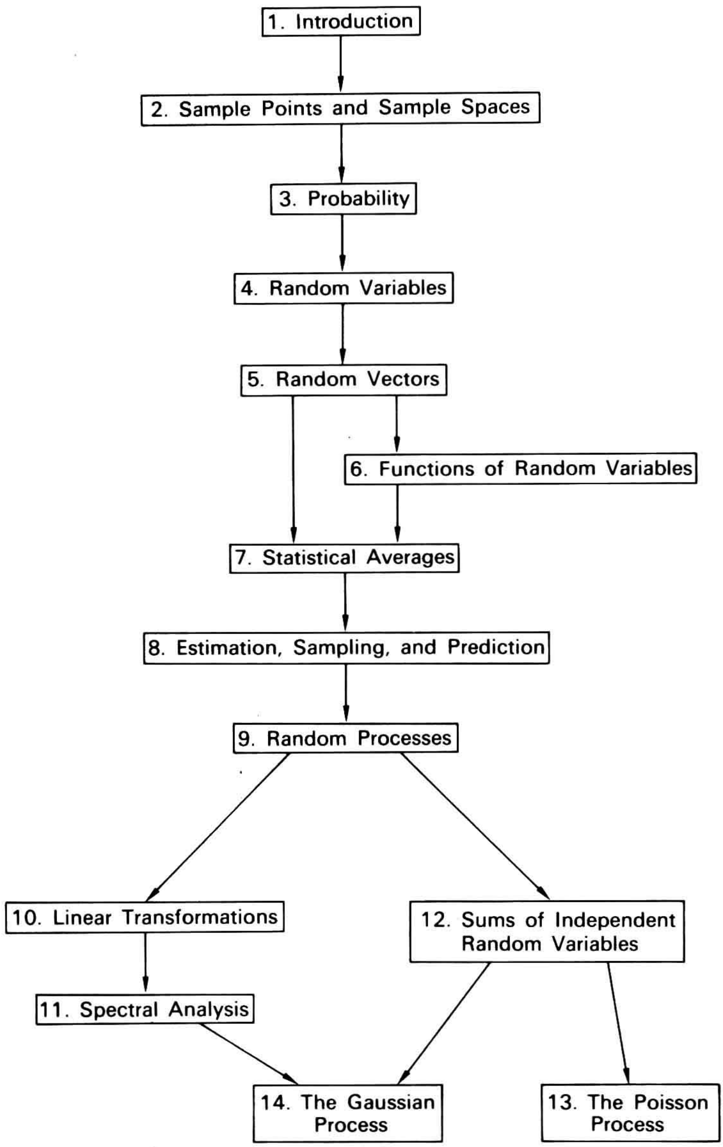
Over the past ten years or so I have taught this material to such disparate groups as first-year graduate students in electrical engineering and engineers and applied scientists trained in a variety of technical fields who have returned to the academic world for study some ten to twenty years after graduating from college. As that teaching progressed, I became increasingly convinced of the need for a text which, while directed towards students mainly interested in applications, would present to the student the underlying mathematical issues in a readable and technically honest way. In particular, I felt the need for a text which would give an indication as to how the theoretical complexity of the more advanced mathematical treatments arises from the logical difficulties inherent in the subject and is not due simply to the natural (or unnatural) perversity of the mathematician. I hope that this is such a text.

Since I believe strongly that each of us learns by doing rather than by passive observation, I have attempted to get the reader to develop a significant fraction of the key concepts and results by including them in the exercises. The exercises in this book are thus an integral part of the text and should *all* be worked out by the reader (except possibly the ones designated as supplementary). With this fact in mind, and since one of my main objectives was to write a text which could be used for self-study, complete solutions to all of the exercises are available in a supplementary book by Professor Amedeo Odoni and myself. In view of the wide availability of other books in the field, however, it did not seem necessary to also include a set of problems without solutions for class quizzes and home problems.

Since the spring of 1968 a project has been underway at the MIT Center for Advanced Engineering Study to develop a course on this material for use in industrial locations. That course is based in part upon this book and in part upon a set of videotape lectures made by Professor Harry L. Van Trees, Jr. Further information about the lecture tapes and an accompanying study guide may be obtained from the Director of the MIT Center for Advanced Engineering Study.

Of the many people who contributed to this book a few get my special thanks: my students; the secretaries of the MIT Center for Advanced Engineering Study (in particular, Mrs. Elizabeth Liljegren Borken) for the typing of the various versions of the manuscript; Richard H. Lee of WGBH, Boston, for critically reviewing most of the early chapters; John T. Fitch of the MIT-CAES for critically reviewing the entire manuscript; Professor Harry L. Van Trees, Jr., for his comments and suggestions for changes; Professor Amedeo Odoni for working up the final version of the solutions to the exercises; and last, but not least, Professor Harold S. Mickley, Director of the MIT-CAES, for both his critical comments and his generous support of the project.

Wilbur B. Davenport, Jr.



Interdependence of Chapters

to the reader

The section is the key to the numbering system used in this book; sections are single-numbered throughout a given chapter. Equations, exercises, figures, and tables are all double-numbered within a given section, and references to these items are given accordingly: "Eq. (2.4)" (Equation 4 in Section 2). There are occasional cross-references to elements in other chapters, and for this purpose the following conventions are used: (*a*) a cross-reference to a section in another chapter would be double-numbered, for example, "see Sec. 10.3" (Section 3 of Chapter 10); (*b*) cross-references to other items are then triple-numbered, for example, "cf. Fig. 12.4.2" (the second figure in Section 4 of Chapter 12).

Certain sections, subsections, and exercises throughout the work are of a supplementary nature and may be omitted or scanned without loss of continuity. The *headings* for such supplementary materials are printed in a lighter type in a manner that sets them off from the main outline of the work, that is, **Exercise 1** versus Exercise 1 (supplementary).

The symbol ■ is used to denote the end of a proof, while the symbol □ denotes the end of an exercise.

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*** *Supplementary section***

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1
Introduction

1 RANDOMNESS AND AVERAGES

In many physical problems of interest, there is an element of uncertainty, or unpredictability, or randomness; no matter how much we might know of the past history of a given phenomenon, we are essentially unable to predict its future behavior precisely. For example, no matter how many times we flip a coin and observe the outcome, we are unable to predict exactly the outcome of the next flip. The reasons for our inability to predict are varied: We may not know all of the causal forces at work; we may not have enough data about the initial conditions in the problem; the forces at work may be so complicated that a calculation of their combined effect is not feasible; or there actually may be some basic indeterminacy at work in the problem at hand. We shall call such unpredictable phenomena *random phenomena*.

As an example of a random phenomenon, consider the queuing problem of "customers" waiting to be served at a serving station, in particular, data blocks in buffer storage in a data processing system.

Here the time of arrival of a given customer at the entrance to the queue (the waiting line or buffer store) may well be unpredictable. Further, the time required to service a customer may also vary from customer to customer in an apparently random manner. Questions then as to the number of customers in the queue at some future time, their length of time in the queue, the number to be served in a given time interval, etc., are all incapable of being precisely answered ahead of time.

Next, let us consider the problem of mechanical vibrations set up in a spacecraft structure by variations in the thrust generated by a solid-fuel rocket engine. Here the mechanical and chemical inhomogeneities in the fuel cause variations in the burning rate and hence in the thrust generated. In any practical case then, we have a situation in which the precise behavior is far too complex to predict in detail and, accordingly, we act as though the resultant vibrations are random in nature.

Finally, let us consider the problem of measuring seismic disturbances at some point on the ocean bottom. In particular, suppose that we wish to accomplish this purpose by placing a seismometer on the ocean bottom and communicating its output to a distant point by means of acoustic waves transmitted through the ocean itself. Now acoustic transmissions through the ocean are perturbed in many ways, for example: multipath effects due to acoustic reflections from both the ocean bottom and surface, acoustic refraction effects due to variations of the water temperature from point to point, acoustic scattering effects due to the presence of plankton, schools of fish, etc. Thus we have here not only the unpredictability of the basic seismic data itself, but also the uncertainties created by the acoustic transmission path.

While in each of the above examples we are unable to predict the future in detail, we often do find experimentally that certain *average* properties exhibit a useful regularity. In the acoustic transmission case, the received energy averaged over seconds does not vary greatly over minutes, and the received energy averaged over a period of a month does not differ greatly from that averaged over the same month a year previously. Such a regularity of averages is an experimentally verifiable phenomenon in many different physical situations which supposedly involve randomly varying quantities. Since averages often do exhibit such a regularity, and are thus reasonably predictable, it seems desirable to make a study of a calculus of averages. This is the domain of the mathematical theory of probability and statistics.

We shall, in the remainder of this chapter, first study the problem of calculating averages of known data and thereby introduce the concept of *relative frequency;* we shall then look at the stability of empirical averages such as relative frequency when measured over longer and

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