

Introduction to
Probability Models

9th edition

SHELDON M. ROSS



**Introduction to
Probability Models**
Ninth Edition

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Ninth Edition

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*University of California
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Preface



This text is intended as an introduction to elementary probability theory and stochastic processes. It is particularly well suited for those wanting to see how probability theory can be applied to the study of phenomena in fields such as engineering, computer science, management science, the physical and social sciences, and operations research.

It is generally felt that there are two approaches to the study of probability theory. One approach is heuristic and nonrigorous and attempts to develop in the student an intuitive feel for the subject which enables him or her to “think probabilistically.” The other approach attempts a rigorous development of probability by using the tools of measure theory. It is the first approach that is employed in this text. However, because it is extremely important in both understanding and applying probability theory to be able to “think probabilistically,” this text should also be useful to students interested primarily in the second approach.

New to This Edition

The ninth edition contains the following new sections.

- Section 3.7 is concerned with compound random variables of the form $S_N = \sum_{i=1}^N X_i$, where N is independent of the sequence of independent and identically distributed random variables $X_i, i \geq 1$. It starts by deriving a general identity concerning compound random variables, as well as a corollary of that identity in the case where the X_i are positive and integer valued. The corollary is then used in subsequent subsections to obtain recursive formulas for the probability mass function of S_N , when N is a Poisson distribution (Subsection 3.7.1), a binomial distribution (Subsection 3.7.2), or a negative binomial distribution (Subsection 3.7.3).

- Section 4.11 deals with hidden Markov chains. These models suppose that a random signal is emitted each time a Markov chain enters a state, with the distribution of the signal depending on the state entered. The Markov chain is hidden in the sense that it is supposed that only the signals and not the underlying states of the chain are observable. As part of our analysis of these models we present, in Subsection 4.11.1, the Viterbi algorithm for determining the most probable sequence of first n states, given the first n signals.
- Section 8.6.4 analyzes the Poisson arrival single server queue under the assumption that the working server will randomly break down and need repair.

There is also new material in almost all chapters. Some of the more significant additions being the following.

- Example 5.9, which is concerned with the expected number of normal cells that survive until all cancer cells have been killed. The example supposes that each cell has a weight, and the probability that a given surviving cell is the next cell killed is proportional to its weight.
- A new approach—based on time sampling of a Poisson process—is presented in Subsection 5.4.1 for deriving the probability mass function of the number of events of a nonhomogeneous Poisson process that occur in any specified time interval.
- There is additional material in Section 8.3 concerning the $M/M/1$ queue. Among other things, we derive the conditional distribution of the number of customers originally found in the system by a customer who spends a time t in the system before departing. (The conditional distribution is Poisson.) In Example 8.3, we illustrate the inspection paradox, by obtaining the probability distribution of the number in the system as seen by the first arrival after some specified time.

Course

Ideally, this text would be used in a one-year course in probability models. Other possible courses would be a one-semester course in introductory probability theory (involving Chapters 1–3 and parts of others) or a course in elementary stochastic processes. The textbook is designed to be flexible enough to be used in a variety of possible courses. For example, I have used Chapters 5 and 8, with smatterings from Chapters 4 and 6, as the basis of an introductory course in queueing theory.

Examples and Exercises

Many examples are worked out throughout the text, and there are also a large number of exercises to be solved by students. More than 100 of these exercises have been starred and their solutions provided at the end of the text. These starred problems can be used for independent study and test preparation. An Instructor's Manual, containing solutions to all exercises, is available free to instructors who adopt the book for class.

Organization

Chapters 1 and 2 deal with basic ideas of probability theory. In Chapter 1 an axiomatic framework is presented, while in Chapter 2 the important concept of a random variable is introduced. Subsection 2.6.1 gives a simple derivation of the joint distribution of the sample mean and sample variance of a normal data sample.

Chapter 3 is concerned with the subject matter of conditional probability and conditional expectation. "Conditioning" is one of the key tools of probability theory, and it is stressed throughout the book. When properly used, conditioning often enables us to easily solve problems that at first glance seem quite difficult. The final section of this chapter presents applications to (1) a computer list problem, (2) a random graph, and (3) the Polya urn model and its relation to the Bose-Einstein distribution. Subsection 3.6.5 presents k -record values and the surprising Ignatov's theorem.

In Chapter 4 we come into contact with our first random, or stochastic, process, known as a Markov chain, which is widely applicable to the study of many real-world phenomena. Applications to genetics and production processes are presented. The concept of time reversibility is introduced and its usefulness illustrated. Subsection 4.5.3 presents an analysis, based on random walk theory, of a probabilistic algorithm for the satisfiability problem. Section 4.6 deals with the mean times spent in transient states by a Markov chain. Section 4.9 introduces Markov chain Monte Carlo methods. In the final section we consider a model for optimally making decisions known as a Markovian decision process.

In Chapter 5 we are concerned with a type of stochastic process known as a counting process. In particular, we study a kind of counting process known as a Poisson process. The intimate relationship between this process and the exponential distribution is discussed. New derivations for the Poisson and nonhomogeneous Poisson processes are discussed. Examples relating to analyzing greedy algorithms, minimizing highway encounters, collecting coupons, and tracking the AIDS virus, as well as material on compound Poisson processes, are included

in this chapter. Subsection 5.2.4 gives a simple derivation of the convolution of exponential random variables.

Chapter 6 considers Markov chains in continuous time with an emphasis on birth and death models. Time reversibility is shown to be a useful concept, as it is in the study of discrete-time Markov chains. Section 6.7 presents the computationally important technique of uniformization.

Chapter 7, the renewal theory chapter, is concerned with a type of counting process more general than the Poisson. By making use of renewal reward processes, limiting results are obtained and applied to various fields. Section 7.9 presents new results concerning the distribution of time until a certain pattern occurs when a sequence of independent and identically distributed random variables is observed. In Subsection 7.9.1, we show how renewal theory can be used to derive both the mean and the variance of the length of time until a specified pattern appears, as well as the mean time until one of a finite number of specified patterns appears. In Subsection 7.9.2, we suppose that the random variables are equally likely to take on any of m possible values, and compute an expression for the mean time until a run of m distinct values occurs. In Subsection 7.9.3, we suppose the random variables are continuous and derive an expression for the mean time until a run of m consecutive increasing values occurs.

Chapter 8 deals with queueing, or waiting line, theory. After some preliminaries dealing with basic cost identities and types of limiting probabilities, we consider exponential queueing models and show how such models can be analyzed. Included in the models we study is the important class known as a network of queues. We then study models in which some of the distributions are allowed to be arbitrary. Included are Subsection 8.6.3 dealing with an optimization problem concerning a single server, general service time queue, and Section 8.8, concerned with a single server, general service time queue in which the arrival source is a finite number of potential users.

Chapter 9 is concerned with reliability theory. This chapter will probably be of greatest interest to the engineer and operations researcher. Subsection 9.6.1 illustrates a method for determining an upper bound for the expected life of a parallel system of not necessarily independent components and (9.7.1) analyzing a series structure reliability model in which components enter a state of suspended animation when one of their cohorts fails.

Chapter 10 is concerned with Brownian motion and its applications. The theory of options pricing is discussed. Also, the arbitrage theorem is presented and its relationship to the duality theorem of linear program is indicated. We show how the arbitrage theorem leads to the Black–Scholes option pricing formula.

Chapter 11 deals with simulation, a powerful tool for analyzing stochastic models that are analytically intractable. Methods for generating the values of arbitrarily distributed random variables are discussed, as are variance reduction methods for increasing the efficiency of the simulation. Subsection 11.6.4 introduces the

important simulation technique of importance sampling, and indicates the usefulness of tilted distributions when applying this method.

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Introduction to Probability Theory



1.1. Introduction

Any realistic model of a real-world phenomenon must take into account the possibility of randomness. That is, more often than not, the quantities we are interested in will not be predictable in advance but, rather, will exhibit an inherent variation that should be taken into account by the model. This is usually accomplished by allowing the model to be probabilistic in nature. Such a model is, naturally enough, referred to as a probability model.

The majority of the chapters of this book will be concerned with different probability models of natural phenomena. Clearly, in order to master both the “model building” and the subsequent analysis of these models, we must have a certain knowledge of basic probability theory. The remainder of this chapter, as well as the next two chapters, will be concerned with a study of this subject.

1.2. Sample Space and Events

Suppose that we are about to perform an experiment whose outcome is not predictable in advance. However, while the outcome of the experiment will not be known in advance, let us suppose that the set of all possible outcomes is known. This set of all possible outcomes of an experiment is known as the *sample space* of the experiment and is denoted by S .

Some examples are the following.

1. If the experiment consists of the flipping of a coin, then

$$S = \{H, T\}$$

where H means that the outcome of the toss is a head and T that it is a tail.

2 1 Introduction to Probability Theory

2. If the experiment consists of rolling a die, then the sample space is

$$S = \{1, 2, 3, 4, 5, 6\}$$

where the outcome i means that i appeared on the die, $i = 1, 2, 3, 4, 5, 6$.

3. If the experiments consists of flipping two coins, then the sample space consists of the following four points:

$$S = \{(H, H), (H, T), (T, H), (T, T)\}$$

The outcome will be (H, H) if both coins come up heads; it will be (H, T) if the first coin comes up heads and the second comes up tails; it will be (T, H) if the first comes up tails and the second heads; and it will be (T, T) if both coins come up tails.

4. If the experiment consists of rolling two dice, then the sample space consists of the following 36 points:

$$S = \left\{ \begin{array}{l} (1, 1), (1, 2), (1, 3), (1, 4), (1, 5), (1, 6) \\ (2, 1), (2, 2), (2, 3), (2, 4), (2, 5), (2, 6) \\ (3, 1), (3, 2), (3, 3), (3, 4), (3, 5), (3, 6) \\ (4, 1), (4, 2), (4, 3), (4, 4), (4, 5), (4, 6) \\ (5, 1), (5, 2), (5, 3), (5, 4), (5, 5), (5, 6) \\ (6, 1), (6, 2), (6, 3), (6, 4), (6, 5), (6, 6) \end{array} \right\}$$

where the outcome (i, j) is said to occur if i appears on the first die and j on the second die.

5. If the experiment consists of measuring the lifetime of a car, then the sample space consists of all nonnegative real numbers. That is,

$$S = [0, \infty)^* \blacksquare$$

Any subset E of the sample space S is known as an *event*. Some examples of events are the following.

- 1'. In Example (1), if $E = \{H\}$, then E is the event that a head appears on the flip of the coin. Similarly, if $E = \{T\}$, then E would be the event that a tail appears.
- 2'. In Example (2), if $E = \{1\}$, then E is the event that one appears on the roll of the die. If $E = \{2, 4, 6\}$, then E would be the event that an even number appears on the roll.

*The set (a, b) is defined to consist of all points x such that $a < x < b$. The set $[a, b]$ is defined to consist of all points x such that $a \leq x \leq b$. The sets $(a, b]$ and $[a, b)$ are defined, respectively, to consist of all points x such that $a < x \leq b$ and all points x such that $a \leq x < b$.

- 3'. In Example (3), if $E = \{(H, H), (H, T)\}$, then E is the event that a head appears on the first coin.
- 4'. In Example (4), if $E = \{(1, 6), (2, 5), (3, 4), (4, 3), (5, 2), (6, 1)\}$, then E is the event that the sum of the dice equals seven.
- 5'. In Example (5), if $E = (2, 6)$, then E is the event that the car lasts between two and six years. ■

For any two events E and F of a sample space S we define the new event $E \cup F$ to consist of all outcomes that are either in E or in F or in both E and F . That is, the event $E \cup F$ will occur if *either* E or F occurs. For example, in (1) if $E = \{H\}$ and $F = \{T\}$, then

$$E \cup F = \{H, T\}$$

That is, $E \cup F$ would be the whole sample space S . In (2) if $E = \{1, 3, 5\}$ and $F = \{1, 2, 3\}$, then

$$E \cup F = \{1, 2, 3, 5\}$$

and thus $E \cup F$ would occur if the outcome of the die is 1 or 2 or 3 or 5. The event $E \cup F$ is often referred to as the *union* of the event E and the event F .

For any two events E and F , we may also define the new event EF , sometimes written $E \cap F$, and referred to as the *intersection* of E and F , as follows. EF consists of all outcomes which are *both* in E and in F . That is, the event EF will occur only if both E and F occur. For example, in (2) if $E = \{1, 3, 5\}$ and $F = \{1, 2, 3\}$, then

$$EF = \{1, 3\}$$

and thus EF would occur if the outcome of the die is either 1 or 3. In Example (1) if $E = \{H\}$ and $F = \{T\}$, then the event EF would not consist of any outcomes and hence could not occur. To give such an event a name, we shall refer to it as the null event and denote it by \emptyset . (That is, \emptyset refers to the event consisting of no outcomes.) If $EF = \emptyset$, then E and F are said to be *mutually exclusive*.

We also define unions and intersections of more than two events in a similar manner. If E_1, E_2, \dots are events, then the union of these events, denoted by $\bigcup_{n=1}^{\infty} E_n$, is defined to be that event which consists of all outcomes that are in E_n for at least one value of $n = 1, 2, \dots$. Similarly, the intersection of the events E_n , denoted by $\bigcap_{n=1}^{\infty} E_n$, is defined to be the event consisting of those outcomes that are in all of the events $E_n, n = 1, 2, \dots$.

Finally, for any event E we define the new event E^c , referred to as the *complement* of E , to consist of all outcomes in the sample space S that are not in E . That is, E^c will occur if and only if E does not occur. In Example (4)

if $E = \{(1, 6), (2, 5), (3, 4), (4, 3), (5, 2), (6, 1)\}$, then E^c will occur if the sum of the dice does not equal seven. Also note that since the experiment must result in some outcome, it follows that $S^c = \emptyset$.

1.3. Probabilities Defined on Events

Consider an experiment whose sample space is S . For each event E of the sample space S , we assume that a number $P(E)$ is defined and satisfies the following three conditions:

- (i) $0 \leq P(E) \leq 1$.
- (ii) $P(S) = 1$.
- (iii) For any sequence of events E_1, E_2, \dots that are mutually exclusive, that is, events for which $E_n E_m = \emptyset$ when $n \neq m$, then

$$P\left(\bigcup_{n=1}^{\infty} E_n\right) = \sum_{n=1}^{\infty} P(E_n)$$

We refer to $P(E)$ as the probability of the event E .

Example 1.1 In the coin tossing example, if we assume that a head is equally likely to appear as a tail, then we would have

$$P(\{H\}) = P(\{T\}) = \frac{1}{2}$$

On the other hand, if we had a biased coin and felt that a head was twice as likely to appear as a tail, then we would have

$$P(\{H\}) = \frac{2}{3}, \quad P(\{T\}) = \frac{1}{3} \quad \blacksquare$$

Example 1.2 In the die tossing example, if we supposed that all six numbers were equally likely to appear, then we would have

$$P(\{1\}) = P(\{2\}) = P(\{3\}) = P(\{4\}) = P(\{5\}) = P(\{6\}) = \frac{1}{6}$$

From (iii) it would follow that the probability of getting an even number would equal

$$\begin{aligned} P(\{2, 4, 6\}) &= P(\{2\}) + P(\{4\}) + P(\{6\}) \\ &= \frac{1}{2} \quad \blacksquare \end{aligned}$$

Remark We have chosen to give a rather formal definition of probabilities as being functions defined on the events of a sample space. However, it turns out that these probabilities have a nice intuitive property. Namely, if our experiment is repeated over and over again then (with probability 1) the proportion of time that event E occurs will just be $P(E)$.

Since the events E and E^c are always mutually exclusive and since $E \cup E^c = S$ we have by (ii) and (iii) that

$$1 = P(S) = P(E \cup E^c) = P(E) + P(E^c)$$

or

$$P(E^c) = 1 - P(E) \quad (1.1)$$

In words, Equation (1.1) states that the probability that an event does not occur is one minus the probability that it does occur.

We shall now derive a formula for $P(E \cup F)$, the probability of all outcomes either in E or in F . To do so, consider $P(E) + P(F)$, which is the probability of all outcomes in E plus the probability of all points in F . Since any outcome that is in both E and F will be counted twice in $P(E) + P(F)$ and only once in $P(E \cup F)$, we must have

$$P(E) + P(F) = P(E \cup F) + P(EF)$$

or equivalently

$$P(E \cup F) = P(E) + P(F) - P(EF) \quad (1.2)$$

Note that when E and F are mutually exclusive (that is, when $EF = \emptyset$), then Equation (1.2) states that

$$\begin{aligned} P(E \cup F) &= P(E) + P(F) - P(\emptyset) \\ &= P(E) + P(F) \end{aligned}$$

a result which also follows from condition (iii). [Why is $P(\emptyset) = 0$?]

Example 1.3 Suppose that we toss two coins, and suppose that we assume that each of the four outcomes in the sample space

$$S = \{(H, H), (H, T), (T, H), (T, T)\}$$

is equally likely and hence has probability $\frac{1}{4}$. Let

$$E = \{(H, H), (H, T)\} \quad \text{and} \quad F = \{(H, H), (T, H)\}$$

That is, E is the event that the first coin falls heads, and F is the event that the second coin falls heads.

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