教育部高等教育司推荐
国外优秀信息科学与技术系列教学用书

离散数学结构

（第五版 影印版）

DISCRETE MATHEMATICAL STRUCTURES

(Fifth Edition)

■ Bernard Kolman
Robert C. Busby
Sharon Cutler Ross

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Prentice Hall

高等教育出版社
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前　言

20世纪末，以计算机和通信技术为代表的信息科学和技术对世界经济、科技、军事、教育和文化等产生了深刻影响。信息科学技术的迅速普及和应用，带动了世界范围信息产业的蓬勃发展，为许多国家带来了丰厚的回报。

进入21世纪，尤其随着我国加入WTO，信息产业的国际竞争将更加激烈。我国信息产业虽然在20世纪末取得了迅猛发展，但与发达国家相比，甚至与印度、爱尔兰等国家相比，还有很大差距。国家信息化的发展速度和信息产业的国际竞争能力，最终都将取决于信息科学技术人才的质量和数量。引进国外信息科学和技术优秀教材，在有条件的学校推动开展英语授课或双语教学，是教育部为加快培养大批高质量的信息技术人才采取的一项重要举措。

为此，教育部要求由高等教育出版社首先开展信息科学和技术教材的引进试点工作。同时提出了两点要求，一是要高水平，二是要低价格。在高等教育出版社和信息科学技术引进教材专家组的努力下，经过比较短的时间，第一批引进的20多种教材已经陆续出版。这套教材出版后受到了广泛的好评，其中有不少是世界信息科学技术领域著名专家、教授的经典之作和反映信息科学技术最新进展的优秀作品，代表了目前世界信息科学技术教育的一流水平，而且价格也是最优惠的，与国内同类自编教材相当。

这项教材引进工作是在教育部高等教育司和高教社的共同组织下，由国内信息科学技术领域的专家、教授广泛参与，在对大量国外教材进行多次遴选的基础上，参考了国内和国外著名大学相关专业的课程设置进行系统引进的。其中，John Wiley公司出版的贝尔实验室信息科学研究中心副总裁Silberschatz教授的经典著作《操作系统概念》，是我们经过反复谈判，做了很多努力才得以引进的。William Stallings先生曾编写了在美国深受欢迎的信息科学技术系列教材，其中有多种教材获得过美国教材和学术著作者协会颁发的计算机科学与工程教材奖，这批引进教材中就有他的两本著作。留美中国学者Jiawei Han先生的《数据挖掘》是该领域中具有里程碑意义的著作。由达特茅斯学院Thomas Cormen和麻省理工学院、哥伦比亚大学的几

位学者共同编著的经典著作《算法导论》，在经历了11年的锤炼之后于2001年出版了第二版。目前任教于美国Massachusetts大学的James Kurose教授，曾在美国三所高校先后10次获得杰出教师或杰出教学奖，由他主编的《计算机网络》出版后，以其体系新颖、内容先进而倍受欢迎。在努力降低引进教材售价方面，高等教育出版社了大量和细致的工作。这套引进的教材体现了权威性、系统性、先进性和经济性等特点。

教育部也希望国内和国外的出版商积极参与此项工作，共同促进中国信息技术教育和信息产业的发展。我们在与外商的谈判工作中，不仅要坚定不移地引进国外最优秀的教材，而且还要千方百计地将版权转让费降下来，要让引进教材的价格与国内自编教材相当，让广大教师和学生负担得起。中国的教育市场巨大，外国出版公司和国内出版社要通过扩大发行数量取得效益。

在引进教材的同时，我们还应做好消化吸收，注意学习国外先进的教学思想和教学方法，提高自编教材的水平，使我们的教学和教材在内容体系上，在理论与实践的结合上，在培养学生的动手能力上能有较大的突破和创新。

目前，教育部正在全国35所高校推动示范性软件学院的建设和实施，这也是加快培养信息科学技术人才的重要举措之一。示范性软件学院要立足于培养具有国际竞争力的实用性软件人才，与国外知名高校或著名企业合作办学，以国内外著名IT企业为实践教学基地，聘请国内外知名教授和软件专家授课，还要率先使用引进教材开展教学。

我们希望通过这些举措，能在较短的时间，为我国培养一大批高质量的信息技术人才，提高我国软件人才的国际竞争力，促进我国信息产业的快速发展，加快推动国家信息化进程，进而带动整个国民经济的跨越式发展。

教育部高等教育司

二〇〇二年三月

原版前言

对于大学一二年级的教学来说，离散数学是一门很有趣的课程，原因有几个方面。它的内容是数学，但它的大多数应用和超过半数的学生来自于计算机科学。因此，了解本书主题的编写动机，并事先了解它们的应用，是十分重要而必要的策略。此外，这门课程所涵盖的题材广泛，内容丰富，所以教材的内容须精心安排，清晰易懂，并用适当的教学法强调关键概念。同时，也希望学生能够掌握并运用一项重要的新技能：书写数学证明的能力。要写出优秀的计算机程序，这是一项非常好的训练。

数学系学生可使用本书作为离散数学基本概念的入门书，并作为向更高级数学概念发展的基础。如果仅限于此，那么书中涉及计算机科学的一些特定应用可以略去或者单独作为重要的例子选用。本书也可作为计算机科学或者计算机工程课程的教材，它为与计算机相关的许多基本概念打下基础，并且为这些概念提供连贯的发展和共同的主题。教师很容易通过参考每章的必备知识设计出与各章内容相一致的、适当的课程。

方法

首先，我们认为将课程内容所涵盖的领域和深度限制在大学一二年级所教的基础课程的水平上是明智的。我们认为本书所选定的一系列主题能够真正适用于计算机科学和其他学科，并且这些内容是以一种符合逻辑、有条理的方式给出的。在介绍这些主题的同时，也指明了如何更深入地研究这些课题。这种方法使得本书能够成为高年级课程的一种很好的参考。

其次，将大量的定义和抽象理论压缩到最低限度，并且用这种方式来组织各个主题，给出它们的相互联系。关系和有向图被视为同一基本数学概念的两个方面，有向图是关系的图形表示。所以，该基本概念实际上用来作为本书介绍其他所有概念的基础，包括函数、偏序、图和数学结构。本书所介绍的每个新概念尽可能使用前面学过的内容，并且以这种方式展开，从而简化后续的更复杂的概念。

第五版有什么新内容？

由于关系和有向图这两个关键概念在本书中起着统一的作用，所以，我们仍然相信本书非常适合课堂教学。这一版以编码为线索，全面阐述了这两个概念，包括效率、有效性和安全性。新加的两个小节，Other Mathematical Structures（其他数学结构）和Public Key Cryptology（公钥密码学），是这种思路的主要组成部分，但相关的少部分内容插入在第 1 章。这一版的习题量比前一版增加了 25% 以上。无论对本书做了怎样的

改动，但是我们的目标依然同前四版一样：**以一种简明的、学生能够理解的方式，来介绍离散数学的基本概念及其某些应用。**

- 从第 1 章开始，就介绍了密码学的思想，并且描述了该领域的基本概念，最后介绍了公钥密码学。新增加的内容从各个方面介绍了编码：效率、有效性和安全性。
- 新加了一节，Other Mathematical Structures，介绍环和域的基本概念，特别是 Z_p。
- 给学生学习建模技巧提供了更多的机会。无论是建模、抽象、模式识别，还是问题求解，了解问题的数学本质的能力都是在更高一级的数学课程中取得成功的一个关键因素。
- 理解证明并写出简单的数学证明是一个重要的课程目标。证明方法不仅仅是在正式的介绍证明方法的章节中给予介绍，而且在教材中的许多场合要求学生阅读、分析、完成并给出证明。
- 本书包含有更多的应用，包括关系数据库、校验位、各种密码以及加权投票系统。
- 每章都增加了一些新的习题，重点放在对概念的多种描述上。与第四版相比增加了大约 400 道习题。
- 每章开始有一个简短的历史回顾，介绍一些在该章所涉及的领域中做出过重要贡献的学者。
- 与前几版相比，增加了关于同构的内容，这些内容贯穿全书。
- 开发了关于加权投票系统、Petri 网和 Catalan 数的附加学生实验。有些实验放在适当的章节中，其他的实验则集中放在附录 B 中。这些实验作业为学生提供了发现、探索以及写作的机会，并且是专门针对协同工作而设计的。
- 这一版继续在全书中编排了关于证明和证明技巧的讨论，包括对大部分证明的注解、与证明各命题的技巧相关的习题以及关于证明的提示。许多新的习题为培养学生阅读和书写证明的能力提供了更多的实践机会。
- 每一章都有一组复习题。这些复习题主要是概念性的，用来帮助学生理解本章的主要概念。
- 增加了一个术语表，便于快速参考查询。
- 在前几版内容的基础上，索引中新加了大约 100 个与新的概念和例子有关的词条。

习题

习题是本书的重要组成部分。许多习题本质上都是计算型的，其余的则是理论型的。本书后面的许多习题以及实验都要求口头解答，关于实验下面将进一步说明。帮助培养证明书写技巧的习题要求学生分析证明、增加论据或完成一些未完成的证明。

为了帮助学生理解基本原理和掌握方法，许多新的习题中增加了关于指导和实践的内容。所有序号为奇数的习题、复习题以及自测题的答案均放在本书的后面。所有习题解答可在《**教师解答手册**》中找到，该手册可以从原出版社免费得到（只提供给任课教师）。该手册中包含有关于每章的教学思想、实验的目的和评分准则的注解，还包含一个试题库。

实验

从第 1 章到第 10 章，每章最后都有一个学生实验。这些实验为学生提供发现和探索问题的机会，或者帮助学生更深入地认识各章中所讨论的主题。这些实验是作为课外经验来设计的，并且适合作为小组作业。每个实验都需要做比章节练习多得多的书写工作。附录 B 是一些附加实验，每个实验的内容、必备知识以及目的都可以在《教师解答手册》中找到。

章末材料

每章均包含有证明提示（Tips for Proofs）、便于复习的主要概念的总结、一系列编码练习、一个实验、一系列概念性复习题以及涵盖本章内容的自测题。

章节结构

第 1 章讲述本课程的基础知识，包括集合、子集及其运算，数列，整数的性质（包括以 n 为基数的表示），矩阵以及数学结构。本章的目的是帮助学生培养在多种层面上识别模式的技能。第 2 章讨论逻辑以及相关的内容，包括证明方法和数学归纳法。虽然关于证明的讨论基于此章，但有关证明的注释贯穿全书。第 3 章论述计数，包括排列、组合、鸽巢原理、概率基础以及递归关系。

第 4 章讲述关系的基本类型和性质以及关系的有向图表示。此外，本章还讨论了矩阵和其他数据结构的关系。第 5 章讨论函数的概念，并且给出了许多重要的函数例子，包括计算机科学中特别感兴趣的一些函数；还简要介绍了函数增长的基础知识和应用。第 6 章讨论偏序集，包括格和布尔代数。为了找出布尔表达式的布尔函数的符号表示，加入了图形化的卡诺图方法。第 7 章介绍有向树和无向树及其应用。初等图论以及其在运输网络和匹配问题中的应用是第 8 章的重点。

第 9 章又回到数学结构，介绍了半群、群、环和域的基本概念。基于前几章的知识，只引入了几个新的概念。第 10 章主要讨论有限状态机，它是前面几章概念的补充和有效应用。第 11 章讨论了编码的差错检验、纠错以及安全性问题。附录 A 讨论了算法和伪码。本书中的某些例子和习题使用的是这里介绍的简化伪码，忽略这些内容不会破坏内容的连续性。附录 B 给出一些附加实验，它们是本教材各章主题的扩充或者预习。

致谢

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最后，还要向下列人员表达最诚挚的谢意：制作编辑 Debbie Ryan，执行编辑 George Lobell，助理编辑 Jennifer Brady 以及 Prentice Hall 出版公司的全体员工，因为他们的热情，关心和永不言败的合作精神，才让本书从策划、设计、制作到市场销售都得以顺利地进行。

B. K.
R. C. B.
S. C. R.

寄语学生

这门课程很可能在几个方面与你以前学过的数学课程有所不同。要解的方程很少，公式甚至更少，而且只有少量的步骤。虽然有一些定义和定理需要学习，但仅靠死记硬背将使你很难通过这门课程。深刻理解概念并能够在各种环境下应用它们，是你成功的基础。

本书的优点是内容丰富、生动，而且实用。本书的主题是日常生活、数学、计算机科学以及其他领域中的应用的基础。这些主题相互联系，互为基础，有助于你掌握所涉及的概念。

这门课程有两个显著的特点，一是高度的抽象，二是比你以前学过的数学课程更强调证明。关于抽象，这里举一个例子。在学习代数时，我们知道乘法对加法的分配律，而在这门课程中，我们将把分配律概念予以抽象，并研究这一概念在许多种运算中的应用，而不仅仅是乘法和加法。

另一个特点是证明。在你继续阅读本书之前，让我们告诉你在本书中是如何处理证明的。你的目标是能够读懂证明，并且能够独立进行证明。帮助你达到这一目标的方法也许能使你重新想起写作课程中所学到的知识。学习写一篇有说服力的文章，或有意义的十四行诗，或其他风格的文章，是一个很复杂的过程。首先，你必须阅读、分析并研究大量的范文。然后，你才能尝试以某种风格动手写作。一般来说，这包括草稿版、修改版、评阅、润色和改写，最后创作出一篇有说服力的文章，或者一首优秀的十四行诗，或者其他指定风格的文章。总之，写作没有任何公式或固定的套路。

同写作课程的作品一样，证明也是有结构和风格的。本书将提供大量的证明供你阅读和分析。某些习题要求你对证明进行概括、分析和评论。其他的习题则要求你完成一些未完成的证明。最后，你有许多机会自己构造一个证明。相信我们，阅读和书写证明是一项可学习的技能。

更广义地讲，我们希望本书能帮助你成为一个有效的沟通能手，一个思想评论家，一个善于思考的学习者，一个具有创新精神的解决问题的能手。

衷心祝愿你取得成功和有趣的体验。

Bernard Kolman
Robert C. Busby
Sharon Cutler Ross

Preface

Discrete mathematics is an interesting course to teach and to study at the freshman and sophomore level for several reasons. Its content is mathematics, but most of its applications and more than half its students are from computer science. Thus careful motivation of topics and previews of applications are important and necessary strategies. Moreover, there are a number of substantive and diverse topics covered in the course, so a text must proceed clearly and carefully, emphasizing key ideas with suitable pedagogy. In addition, the student is often expected to develop an important new skill: the ability to write a mathematical proof. This skill is excellent training for writing good computer programs.

This text can be used by students in mathematics as an introduction to the fundamental ideas of discrete mathematics, and a foundation for the development of more advanced mathematical concepts. If used in this way, the topics dealing with specific computer science applications can be ignored or selected independently as important examples. The text can also be used in a computer science or computer engineering curriculum to present the foundations of many basic computer-related concepts and provide a coherent development and common theme for these ideas. The instructor can easily develop a suitable course by referring to the chapter prerequisites which identify material needed by that chapter.

Approach

First, we have limited both the areas covered and the depth of coverage to what we deem prudent in a first course taught at the freshman and sophomore level. We have identified a set of topics that we feel are of genuine use in computer science and elsewhere and that can be presented in a logically coherent fashion. We have presented an introduction to these topics along with an indication of how they can be pursued in greater depth. This approach makes our text an excellent reference for upper-division courses.

Second, the material has been organized and interrelated to minimize the mass of definitions and the abstraction of some of the theory. Relations and digraphs are treated as two aspects of the same fundamental mathematical idea, with a directed graph being a pictorial representation of a relation. This fundamental idea is then used as the basis of virtually all the concepts introduced in the book, including functions, partial orders, graphs, and mathematical structures. Whenever possible, each new idea introduced in the text uses previously encountered material and, in turn, is developed in such a way that it simplifies the more complex ideas that follow.

What Is New in the Fifth Edition

We continue to believe that this book works well in the classroom because of the unifying role played by the two key concepts: relations and digraphs. In this edition we have woven in a thread of coding in all its aspects, efficiency, effectiveness, and security. Two new sections, Other Mathematical Structures and Public Key Cryptology are the major components of this thread, but smaller related insertions begin in Chapter 1. The number of exercises for this edition has been increased by more than 25%. Whatever changes we have made, our objective has remained the same as in the first four editions: *to present the basic notions of discrete mathematics and some of its applications in a clear and concise manner that will be understandable to the student.*

- A cryptology thread begins in Chapter 1 and presents the basic ideas of the field. The thread concludes in Public Key Cryptology. Included now is coding in all its aspects, efficiency, effectiveness, and security.
- A new section, Other Mathematical Structures, introduces the basic concepts of rings and fields, in particular Z_p.
- More opportunities for students to build modeling skills are provided. Whether seen as modeling, abstraction, pattern recognition, or problem solving, the ability to see the mathematical bones of a problem is a critical factor for success in higher-level mathematics courses.
- Understanding proofs and writing simple proofs are important course goals. More occasions for students to read, analyze, complete, and produce proofs are presented throughout the text, not just in the sections that introduce formal proofs.
- More applications are included. Among these are relational databases, check digits, a variety of ciphers, and weighted voting systems.
- New exercises have been added to each chapter. Greater emphasis has been placed on multiple representations of concepts. There are approximately 400 more exercises than in the fourth edition.
- A brief historical commentary opens each chapter and introduces some of the major contributors to that chapter's topics.
- Isomorphism is presented in more contexts than before throughout the book.
- Additional student experiments have been developed on weighted voting systems, Petri nets, and Catalan numbers. Experiments have been integrated into appropriate chapters and others are gathered in Appendix B. These assignments provide opportunities for exploration and discovery, as well as for writing, and are designed for collaborative work.
- This edition continues to weave the discussion of proofs and proof techniques throughout the book with comments on most proofs, exercises related to the mechanics of proving statements, and Tips for Proofs sections. Many of the new exercises provide more practice in building proof-reading and proof-writing skills.
- Each chapter now has a set of review questions. These are mainly conceptual in nature and help students identify the "big" ideas of the chapter.
- A glossary for quick reference is now included.
- The index contains approximately 100 new entries related to both new concepts and to new examples for material in previous editions.

■ Exercises

The exercises form an integral part of the book. Many are computational in nature, whereas others are of a theoretical type. Many of the latter and the experiments, to be further described below, require verbal solutions. Exercises to help develop proof-writing skills ask the student to analyze proofs, amplify arguments, or complete partial proofs. Guidance and practice in recognizing key elements and patterns have been extended in many new exercises. Answers to all odd-numbered exercises, review questions, and self-test items appear in the back of the book. Solutions to all exercises appear in the **Instructor's Solutions Manual**, which is available (to instructors only) gratis from the publisher. The Instructor's Solutions Manual also includes notes on the pedagogical ideas underlying each chapter, goals and grading guidelines for the experiments, and a test bank.

Experiments

Chapters 1 through 10 each end with a student experiment. These provide opportunities for discovery and exploration, or a more in-depth look at topics discussed in the text. They are designed as extended-time, out-of-class experiences and are suitable for group work. Each experiment requires significantly more writing than section exercises do. Some additional experiments are to be found in Appendix B. Content, prerequisites, and goals for each experiment are given in the Instructor's Solutions Manual.

End-of-Chapter Material

Each chapter contains Tips for Proofs, a summary of Key Ideas for Review, a set of Coding Exercises, an Experiment, a set of conceptual Review Questions, and a Self-Test covering the chapter's material.

Organization

Chapter 1 contains material that is fundamental to the course. This includes sets, subsets, and their operations; sequences; properties of the integers, including base n representations; matrices; and mathematical structures. A goal of this chapter is to help students develop skills in identifying patterns on many levels. Chapter 2 covers logic and related material, including methods of proof and mathematical induction. Although the discussion of proof is based on this chapter, the commentary on proofs continues throughout the book. Chapter 3, on counting, deals with permutations, combinations, the pigeonhole principle, elements of probability, and recurrence relations.

Chapter 4 presents basic types and properties of relations, along with their representation as directed graphs. Connections with matrices and other data structures are also explored in this chapter. Chapter 5 deals with the notion of a function and gives important examples of functions, including functions of special interest in computer science. An introduction to the growth of functions is developed. Chapter 6 covers partially ordered sets, including lattices and Boolean algebras. A symbolic version for finding a Boolean function for a Boolean expression joins the pictorial Karnaugh method. Chapter 7 introduces directed and undirected trees along with applications of these ideas. Elementary graph theory with applications to transport networks and matching problems is the focus of Chapter 8.

In Chapter 9 we return to mathematical structures and present the basic ideas of semigroups, groups, rings, and fields. By building on work in previous chapters, only a few new concepts are needed. Chapter 10 is devoted to finite-state machines. It complements and makes effective use of ideas developed in previous chapters. Chapter 11 finishes our discussion of coding for error detecting and correction and for security purposes. Appendix A discusses algorithms and pseudocode. The simplified pseudocode presented here is used in some text examples and exercises; these may be omitted without loss of continuity. Appendix B gives some additional experiments dealing with extensions or previews of topics in various parts of the course.

Optional Supplements

There is available with this text a 406 page workbook: *Practice Problems in Discrete Mathematics* by Boyana Obrenic. It consists entirely of problem sets with fully worked out solutions. It is available free when shrinkwrapped with the textbook: ISBN 013-124112-5 (text and supplement). In addition, there is a 316 page

workbook: *Discrete Mathematics Workbook* by James Bush. This item has outlines of key ideas, key terms, and sample problem sets (with solutions). It is available free when shrinkwrapped with the textbook: ISBN 013-124113-3 (text and supplement).

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B.K.
R.C.B.
S.C.R.

A Word to Students

This course is likely to be different from your previous mathematics courses in several ways. There are very few equations to solve, even fewer formulas, and just a handful of procedures. Although there will be definitions and theorems to learn, rote memorization alone will not carry you through the course. Understanding concepts well enough to apply them in a variety of settings is essential for success.

The good news is that there is a wealth of interesting and useful material in this text. We have chosen topics that form a basis for applications in everyday life, mathematics, computer science, and other fields. We have also chosen the topics so that they fit together and build on each other; this will help you to master the concepts covered.

Two distinctive features of this course are a higher level of abstraction and more emphasis on proofs than you have perhaps encountered in earlier mathematics courses. Here is an example of what we mean by abstraction. When you studied algebra, you learned the distributive property of multiplication over addition. In this course, you will abstract the concept of a distributive property and investigate this idea for many pairs of operations, not just multiplication and addition.

The other feature is proofs. Before you close the book right here, let us tell you something about how proofs are handled in this book. The goals are for you to be able to read proofs intelligently and to produce proofs on your own. The way we help you to these goals may remind you of your composition classes. Learning to write a persuasive essay or a meaningful sonnet or other composition style is a complicated process. First, you read, analyze, and study many examples. Next you try your hand at the specific style. Typically this involves draft versions, revisions, critiques, polishing, and rewriting to produce a strong essay or a good sonnet or whatever form is required. There are no formulas or rote procedures for writing.

Proofs, like the products of a composition course, have structures and styles. We give you lots of proofs to read and analyze. Some exercises ask that you outline, analyze, or critique a proof. Other exercises require the completion of partial proofs. And finally, there are many opportunities for you to construct a proof on your own. Believe us, reading and writing proofs are learnable skills.

On a larger scale, we hope this text helps you to become an effective communicator, a critical thinker, a reflective learner, and an innovative problem solver.

Best wishes for a successful and interesting experience.

Bernard Kolman

Robert C. Busby

Sharon Cutler Ross

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