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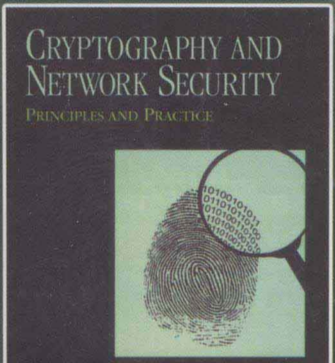
——原理与实践（第五版）

Cryptography and Network Security

Principles and Practice, Fifth Edition



CRYPTOGRAPHY AND NETWORK SECURITY

PRINCIPLES AND PRACTICE

Fifth Edition

WILLIAM STALLINGS

英文版

［美］ William Stallings 著

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内容简介

本书系统介绍了密码编码学与网络安全的基本原理和应用技术。全书主要包括五个部分：对称密码部分讲解传统加密技术、高级加密标准等；非对称密码部分讲解数论、公钥加密、RSA；第三部分讨论了加密哈希函数、消息认证、数字签名等主题；第四部分分析了密钥管理、用户认证协议；网络与Internet安全部分探讨的是传输层安全、无线网络安全、电子邮件安全及IP安全的问题。最后，两个附录给出了各章的项目练习和一些例子。配套网站包含大量的延伸性内容。

本书可作为高校计算机专业、网络安全专业、通信安全专业等相关专业的本科生和研究生的教材，也可供相关技术人员参考使用。

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出版说明

21世纪初的5至10年是我国国民经济和社会发展的重要时期，也是信息产业快速发展的关键时期。在我国加入WTO后的今天，培养一支适应国际化竞争的一流IT人才队伍是我国高等教育的重要任务之一。信息科学和技术方面人才的优劣与多寡，是我国面对国际竞争时成败的关键因素。

当前，正值我国高等教育特别是信息科学领域的教育调整、变革的重大时期，为使我国教育体制与国际化接轨，有条件的高等院校正在为某些信息学科和技术课程使用国外优秀教材和优秀原版教材，以使我国在计算机教学上尽快赶上国际先进水平。

电子工业出版社秉承多年来引进国外优秀图书的经验，翻译出版了“国外计算机科学教材系列”丛书，这套教材覆盖学科范围广、领域宽、层次多，既有本科专业课程教材，也有研究生课程教材，以适应不同院系、不同专业、不同层次的师生对教材的需求，广大师生可自由选择和自由组合使用。这些教材涉及的学科方向包括网络与通信、操作系统、计算机组织与结构、算法与数据结构、数据库与信息处理、编程语言、图形图像与多媒体、软件工程等。同时，我们也适当引进了一些优秀英文原版教材，本着翻译版本和英文原版并重的原则，对重点图书既提供英文原版又提供相应的翻译版本。

在图书选题上，我们大都选择国外著名出版公司出版的高校教材，如Pearson Education培生教育出版集团、麦格劳－希尔教育出版集团、麻省理工学院出版社、剑桥大学出版社等。撰写教材的许多作者都是蜚声世界的教授、学者，如道格拉斯·科默(Douglas E. Comer)、威廉·斯托林斯(William Stallings)、哈维·戴特尔（Harvey M. Deitel)、尤利斯·布莱克（Uyless Black）等。

为确保教材的选题质量和翻译质量，我们约请了清华大学、北京大学、北京航空航天大学、复旦大学、上海交通大学、南京大学、浙江大学、哈尔滨工业大学、华中科技大学、西安交通大学、国防科学技术大学、解放军理工大学等著名高校的教授和骨干教师参与了本系列教材的选题、翻译和审校工作。他们中既有讲授同类教材的骨干教师、博士，也有积累了几十年教学经验的老教授和博士生导师。

在该系列教材的选题、翻译和编辑加工过程中，为提高教材质量，我们做了大量细致的工作，包括对所选教材进行全面论证；选择编辑时力求达到专业对口；对排版、印制质量进行严格把关。对于英文教材中出现的错误，我们通过与作者联络和网上下载勘误表等方式，逐一进行了修订。

此外，我们还将与国外著名出版公司合作，提供一些教材的教学支持资料，希望能为授课老师提供帮助。今后，我们将继续加强与各高校教师的密切联系，为广大师生引进更多的国外优秀教材和参考书，为我国计算机科学教学体系与国际教学体系的接轨做出努力。

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To Antigone never
dull never boring
the smartest
person I know

THE WILLIAM STALLINGS BOOKS ON COMPUTER

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A comprehensive survey that has become the standard in the field, covering (1) data communications, including transmission, media, signal encoding, link control, and multiplexing; (2) communication networks, including circuit- and packet-switched, frame relay, ATM, and LANs; (3) the TCP/IP protocol suite, including IPv6, TCP, MIME, and HTTP, as well as a detailed treatment of network security. **Received the 2007 Text and Academic Authors Association (TAA) award for the best Computer Science and Engineering Textbook of the year.** ISBN 0-13-243310-9

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NOTATION

Even the natives have difficulty mastering this peculiar vocabulary.

—*The Golden Bough,* Sir James George Frazer

Symbol	Expression	Meaning
D, K	$\mathrm{D}(K, Y)$	Symmetric decryption of ciphertext Y using secret key K
D, PR_a	$\mathrm{D}(PR_a, Y)$	Asymmetric decryption of ciphertext Y using A's private key PR_a
D, PU_a	$\mathrm{D}(PU_a, Y)$	Asymmetric decryption of ciphertext Y using A's public key PU_a
E, K	$\mathrm{E}(K, X)$	Symmetric encryption of plaintext X using secret key K
E, PR_a	$\mathrm{E}(PR_a, X)$	Asymmetric encryption of plaintext X using A's private key PR_a
E, PU_a	$\mathrm{E}(PU_a, X)$	Asymmetric encryption of plaintext X using A's public key PU_a
K		Secret key
PR_a		Private key of user A
PU_a		Public key of user A
MAC, K	$\mathrm{MAC}(K, X)$	Message authentication code of message X using secret key K
$\mathrm{GF}(p)$		The finite field of order p, where p is prime. The field is defined as the set Z_p together with the arithmetic operations modulo p.
$\mathrm{GF}(2^n)$		The finite field of order 2^n
Z_n		Set of nonnegative integers less than n
gcd	$\gcd(i, j)$	Greatest common divisor; the largest positive integer that divides both i and j with no remainder on division.
mod	$a \bmod m$	Remainder after division of a by m
mod, $\equiv$	$a \equiv b \pmod{m}$	$a \bmod m = b \bmod m$
mod, $\not\equiv$	$a \not\equiv b \pmod{m}$	$a \bmod m \neq b \bmod m$
dlog	$\mathrm{dlog}_{a,p}(b)$	Discrete logarithm of the number b for the base a (mod p)
φ	$\phi(n)$	The number of positive integers less than n and relatively prime to n. This is Euler's totient function.
Σ	$\sum_{i=1}^{n} a_i$	$a_1 + a_2 + \cdots + a_n$
Π	$\prod_{i=1}^{n} a_i$	$a_1 \times a_2 \times \cdots \times a_n$

$\vert$	$i \mid j$	i divides j, which means that there is no remainder when j is divided by i
$\vert, \vert$	$\vert a \vert$	Absolute value of a
$\Vert$	$x \Vert y$	x concatenated with y
$\approx$	$x \approx y$	x is approximately equal to y
$\oplus$	$x \oplus y$	Exclusive-OR of x and y for single-bit variables; Bitwise exclusive-OR of x and y for multiple-bit variables
$\lfloor, \rfloor$	$\lfloor x \rfloor$	The largest integer less than or equal to x
$\in$	$x \in S$	The element x is contained in the set S.
$\longleftrightarrow$	$A \longleftrightarrow (a_1, a_2, \ldots, a_k)$	The integer A corresponds to the sequence of integers $(a_1, a_2, \ldots, a_k)$

PREFACE

"The tie, if I might suggest it, sir, a shade more tightly knotted. One aims at the perfect butterfly effect. If you will permit me —"

"What does it matter, Jeeves, at a time like this? Do you realize that Mr. Little's domestic happiness is hanging in the scale?"

"There is no time, sir, at which ties do not matter."

—*Very Good, Jeeves!* P. G. Wodehouse

In this age of universal electronic connectivity, of viruses and hackers, of electronic eavesdropping and electronic fraud, there is indeed no time at which security does not matter. Two trends have come together to make the topic of this book of vital interest. First, the explosive growth in computer systems and their interconnections via networks has increased the dependence of both organizations and individuals on the information stored and communicated using these systems. This, in turn, has led to a heightened awareness of the need to protect data and resources from disclosure, to guarantee the authenticity of data and messages, and to protect systems from network-based attacks. Second, the disciplines of cryptography and network security have matured, leading to the development of practical, readily available applications to enforce network security.

OBJECTIVES

It is the purpose of this book to provide a practical survey of both the principles and practice of cryptography and network security. In the first part of the book, the basic issues to be addressed by a network security capability are explored by providing a tutorial and survey of cryptography and network security technology. The latter part of the book deals with the practice of network security: practical applications that have been implemented and are in use to provide network security.

The subject, and therefore this book, draws on a variety of disciplines. In particular, it is impossible to appreciate the significance of some of the techniques discussed in this book without a basic understanding of number theory and some results from probability theory. Nevertheless, an attempt has been made to make the book self-contained. The book presents not only the basic mathematical results that are needed but provides the reader with an intuitive understanding of those results. Such background material is introduced as needed. This approach helps to motivate the material that is introduced, and the author considers this preferable to simply presenting all of the mathematical material in a lump at the beginning of the book.

INTENDED AUDIENCE

The book is intended for both academic and a professional audiences. As a textbook, it is intended as a one-semester undergraduate course in cryptography and network security for computer science, computer engineering, and electrical engineering majors. It covers the material in IAS2 Security Mechanisms, a core area in the Information Technology body of knowledge; NET4 Security, another core area in the Information Technology body of knowledge; and IT311, Cryptography, an advanced course; these subject areas are part of the ACM/IEEE Computer Society Computing Curricula 2005.

The book also serves as a basic reference volume and is suitable for self-study.

PLAN OF THE BOOK

The book is divided into seven parts (see Chapter 0 for an overview):

- Symmetric Ciphers
- Asymmetric Ciphers
- Cryptographic Data Integrity Algorithms
- Mutual Trust
- Network and Internet Security
- System Security
- Legal and Ethical Issues

The book includes a number of pedagogic features, including the use of the computer algebra system Sage and numerous figures and tables to clarify the discussions. Each chapter includes a list of key words, review questions, homework problems, suggestions for further reading, and recommended Web sites. The book also includes an extensive glossary, a list of frequently used acronyms, and a bibliography. In addition, a test bank is available to instructors.

ONLINE DOCUMENTS FOR STUDENTS

For this new edition, a tremendous amount of original supporting material has been made available online, in the following categories.

- **Online chapters:** To limit the size and cost of the book, four chapters of the book are provided in PDF format. This includes three chapters on computer security and one on legal and ethical issues. The chapters are listed in this book's table of contents.
- **Online appendices:** There are numerous interesting topics that support material found in the text but whose inclusion is not warranted in the printed text. A total of fifteen online appendices cover these topics for the interested student. The appendices are listed in this book's table of contents.
- **Homework problems and solutions:** To aid the student in understanding the material, a separate set of homework problems with solutions are available. These enable the students to test their understanding of the text.
- **Key papers:** Twenty-four papers from the professional literature, many hard to find, are provided for further reading.
- **Supporting documents:** A variety of other useful documents are referenced in the text and provided online.
- **Sage code:** The Sage code from the examples in Appendix B in case the student wants to play around with the examples.

Purchasing this textbook now grants the reader six months of access to this online material. See the access card bound into the front of this book for details.

INSTRUCTIONAL SUPPORT MATERIALS

To support instructors, the following materials are provided:

- **Solutions Manual:** Solutions to end-of-chapter Review Questions and Problems.
- **Projects Manual:** Suggested project assignments for all of the project categories listed below.
- **PowerPoint Slides:** A set of slides covering all chapters, suitable for use in lecturing.
- **PDF Files:** Reproductions of all figures and tables from the book.
- **Test Bank:** A chapter-by-chapter set of questions.

All of these support materials are available at the Instructor Resource Center (IRC) for this textbook, which can be reached via personhighered.com/stallings or by clicking on the button labeled "Book Info and More Instructor Resources" at this book's Web Site WilliamStallings.com/Crypto/Crypto5e.html. To gain access to the IRC, please contact your local Prentice Hall sales representative via pearsonhighered.com/educator/replocator/requestSalesRep.page or call Prentice Hall Faculty Services at 1-800-526-0485.

INTERNET SERVICES FOR INSTRUCTORS AND STUDENTS

There is a Web site for this book that provides support for students and instructors. The site includes links to other relevant sites, transparency masters of figures and tables in the book in PDF (Adobe Acrobat) format, and PowerPoint slides. The Web page is at **WilliamStallings.com/Crypto/Crypto5e.html**. For more information, see Chapter 0.

New to this edition is a set of homework problems with solutions available at this Web site. Students can enhance their understanding of the material by working out the solutions to these problems and then checking their answers.

An Internet mailing list has been set up so that instructors using this book can exchange information, suggestions, and questions with each other and with the author. As soon as typos or other errors are discovered, an errata list for this book will be available at WilliamStallings.com. In addition, the Computer Science Student Resource site at **WilliamStallings.com/StudentSupport.html** provides documents, information, and useful links for computer science students and professionals.

PROJECTS AND OTHER STUDENT EXERCISES

For many instructors, an important component of a cryptography or security course is a project or set of projects by which the student gets hands-on experience to reinforce concepts from the text. This book provides an unparalleled degree of support, including a projects component in the course. The IRC not only includes guidance on how to assign and structure the projects, but it also includes a set of project assignments that covers a broad range of topics from the text.

- **Sage Projects:** Described in the next section.
- **Hacking Project:** This exercise is designed to illuminate the key issues in intrusion detection and prevention.
- **Block Cipher Projects:** This is a lab that explores the operation of the AES encryption algorithm by tracing its execution, computing one round by hand, and then exploring the various block cipher modes of use. The lab also covers DES. In both cases, an online Java applet is used (or can be downloaded) to execute AES or DES.
- **Lab Exercises:** A series of projects that involve programming and experimenting with concepts from the book.
- **Research Projects:** A series of research assignments that instruct the student to research a particular topic on the Internet and write a report.
- **Programming Projects:** A series of programming projects that cover a broad range of topics and that can be implemented in any suitable language on any platform.
- **Practical Security Assessments:** A set of exercises to examine current infrastructure and practices of an existing organization.
- **Writing Assignments:** A set of suggested writing assignments organized by chapter.
- **Reading/Report Assignments:** A list of papers in the literature — one for each chapter — that can be assigned for the student to read and then write a short report.

See Appendix A for details.

THE SAGE COMPUTER ALGEBRA SYSTEM

One of the most important new features for this edition is the use of Sage for cryptographic examples and homework assignments. Sage is an open-source, multiplatform, freeware package that implements a very powerful, flexible, and easily learned mathematics and computer algebra system. Unlike competing systems (such as Mathematica, Maple, and MATLAB), there are no licensing agreements or fees involved. Thus, Sage can be made available on computers and networks at school, and students can individually download the software to their own personal computers for use at home. Another advantage of using Sage is that students learn a powerful, flexible tool that can be used for virtually any mathematical application, not just cryptography.

The use of Sage can make a significant difference to the teaching of the mathematics of cryptographic algorithms. This book provides a large number of examples of the use of Sage covering many cryptographic concepts in Appendix B.

Appendix C lists exercises in each of these topic areas to enable the student to gain hands-on experience with cryptographic algorithms. This appendix is available to instructors at the IRC for this book. Appendix C includes a section on how to download and get started with Sage, a section on programming with Sage, and includes exercises that can be assigned to students in the following categories:

- **Chapter 2 — Classical Encryption:** Affine ciphers and the Hill cipher.
- **Chapter 3 — Block Ciphers And The Data Encryption Standard:** Exercises based on SDES.

- **Chapter 4 — Basic Concepts In Number Theory And Finite Fields:** Euclidean and extended Euclidean algorithms, polynomial arithmetic, and GF(24).
- **Chapter 5 — Advanced Encryption Standard:** Exercise based on SAES.
- **Chapter 6 — Pseudorandom Number Generation And Stream Ciphers:** Blum Blum Shub, linear congruential generator, and ANSI X9.17 PRNG.
- **Chapter 8 — Number Theory:** Euler's Totient function, Miller Rabin, factoring, modular exponentiation, discrete logarithm, and Chinese remainder theorem.
- **Chapter 9 — Public-Key Cryptography And RSA:** RSA encrypt/decrypt and signing.
- **Chapter 10 — Other Public-Key Cryptosystems:** Diffie-Hellman, elliptic curve
- **Chapter 11 — Cryptographic Hash Functions:** Number-theoretic hash function.
- **Chapter 13 — Digital Signatures:** DSA.

WHAT'S NEW IN THE FIFTH EDITION

The changes for this new edition of *Cryptography and Network Security* are more substantial and comprehensive than those for any previous revision.

In the three years since the fourth edition of this book was published, the field has seen continued innovations and improvements. In this new edition, I try to capture these changes while maintaining a broad and comprehensive coverage of the entire field. To begin this process of revision, the fourth edition was extensively reviewed by a number of professors who teach the subject. In addition, a number of professionals working in the field reviewed individual chapters. The result is that, in many places, the narrative has been clarified and tightened, and illustrations have been improved. Also, a large number of new "field-tested" problems have been added.

One obvious change to the book is a revision in the organization, which makes for a clearer presentation of related topics. There is a new Part Three, which pulls together all of the material on cryptographic algorithms for data integrity, including cryptographic hash functions, message authentication codes, and digital signatures. The material on key management and exchange, previously distributed in several places in the book, is now organized in a single chapter, as is the material on user authentication.

Beyond these refinements to improve pedagogy and user friendliness, there have been major substantive changes throughout the book. Highlights include:

- **Euclidean and extended Euclidean algorithms (revised):** These algorithms are important for numerous cryptographic functions and algorithms. The material on the Euclidean and extended Euclidean algorithms for integers and for polynomials has been completely rewritten to provide a clearer and more systematic treatment.
- **Advanced Encryption Standard (revised):** AES has emerged as the dominant symmetric encryption algorithm, used in a wide variety of applications. Accordingly, this edition has dramatically expanded the resources for learning about and understanding this important standard. The chapter on AES has been revised and expanded, with additional illustrations and a detailed example, to clarify the presentation. Examples and assignments using Sage have been added. And the book now includes an AES cryptography lab, which enables the student to gain hands-on experience with AES cipher internals and modes of use. The lab makes use of an AES calculator applet, available at this book's Web site, that can encrypt or decrypt test data values using the AES block cipher.