GLOBAL EDITION

Cryptography and Network Security

Principles and Practice

SEVENTH EDITION

William Stallings

Pearson

Cryptography and Network Security

Principles and Practice

Seventh Edition

Global Edition

William Stallings

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For Tricia: never dull, never boring,
the smartest and bravest person
I know

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CONTENTS

Notation 10

Preface 12

About the Author 18

PART ONE: BACKGROUND 19

Chapter 1 Computer and Network Security Concepts 19

1.1 Computer Security Concepts 21
1.2 The OSI Security Architecture 26
1.3 Security Attacks 27
1.4 Security Services 29
1.5 Security Mechanisms 32
1.6 Fundamental Security Design Principles 34
1.7 Attack Surfaces and Attack Trees 37
1.8 A Model for Network Security 41
1.9 Standards 43
1.10 Key Terms, Review Questions, and Problems 44

Chapter 2 Introduction to Number Theory 46

2.1 Divisibility and the Division Algorithm 47
2.2 The Euclidean Algorithm 49
2.3 Modular Arithmetic 53
2.4 Prime Numbers 61
2.5 Fermat's and Euler's Theorems 64
2.6 Testing for Primality 68
2.7 The Chinese Remainder Theorem 71
2.8 Discrete Logarithms 73
2.9 Key Terms, Review Questions, and Problems 78
Appendix 2A The Meaning of Mod 82

PART TWO: SYMMETRIC CIPHERS 85

Chapter 3 Classical Encryption Techniques 85

3.1 Symmetric Cipher Model 86
3.2 Substitution Techniques 92
3.3 Transposition Techniques 107
3.4 Rotor Machines 108
3.5 Steganography 110
3.6 Key Terms, Review Questions, and Problems 112

Chapter 4 Block Ciphers and the Data Encryption Standard 118

4.1 Traditional Block Cipher Structure 119
4.2 The Data Encryption Standard 129
4.3 A DES Example 131
4.4 The Strength of DES 134

4.5 Block Cipher Design Principles 135
4.6 Key Terms, Review Questions, and Problems 137

Chapter 5 Finite Fields 141

5.1 Groups 143
5.2 Rings 145
5.3 Fields 146
5.4 Finite Fields of the Form GF(p) 147
5.5 Polynomial Arithmetic 151
5.6 Finite Fields of the Form GF(2^n) 157
5.7 Key Terms, Review Questions, and Problems 169

Chapter 6 Advanced Encryption Standard 171

6.1 Finite Field Arithmetic 172
6.2 AES Structure 174
6.3 AES Transformation Functions 179
6.4 AES Key Expansion 190
6.5 An AES Example 193
6.6 AES Implementation 197
6.7 Key Terms, Review Questions, and Problems 202
Appendix 6A Polynomials with Coefficients in GF(2^8) 203

Chapter 7 Block Cipher Operation 207

7.1 Multiple Encryption and Triple DES 208
7.2 Electronic Codebook 213
7.3 Cipher Block Chaining Mode 216
7.4 Cipher Feedback Mode 218
7.5 Output Feedback Mode 220
7.6 Counter Mode 222
7.7 XTS-AES Mode for Block-Oriented Storage Devices 224
7.8 Format-Preserving Encryption 231
7.9 Key Terms, Review Questions, and Problems 245

Chapter 8 Random Bit Generation and Stream Ciphers 250

8.1 Principles of Pseudorandom Number Generation 252
8.2 Pseudorandom Number Generators 258
8.3 Pseudorandom Number Generation Using a Block Cipher 261
8.4 Stream Ciphers 267
8.5 RC4 269
8.6 True Random Number Generators 271
8.7 Key Terms, Review Questions, and Problems 280

PART THREE: ASYMMETRIC CIPHERS 283

Chapter 9 Public-Key Cryptography and RSA 283

9.1 Principles of Public-Key Cryptosystems 285
9.2 The RSA Algorithm 294
9.3 Key Terms, Review Questions, and Problems 308

Chapter 10 Other Public-Key Cryptosystems 313

10.1 Diffie-Hellman Key Exchange 314
10.2 Elgamal Cryptographic System 318
10.3 Elliptic Curve Arithmetic 321
10.4 Elliptic Curve Cryptography 330
10.5 Pseudorandom Number Generation Based on an Asymmetric Cipher 334
10.6 Key Terms, Review Questions, and Problems 336

PART FOUR: CRYPTOGRAPHIC DATA INTEGRITY ALGORITHMS 339

Chapter 11 Cryptographic Hash Functions 339

11.1 Applications of Cryptographic Hash Functions 341
11.2 Two Simple Hash Functions 346
11.3 Requirements and Security 348
11.4 Hash Functions Based on Cipher Block Chaining 354
11.5 Secure Hash Algorithm (SHA) 355
11.6 SHA-3 365
11.7 Key Terms, Review Questions, and Problems 377

Chapter 12 Message Authentication Codes 381

12.1 Message Authentication Requirements 382
12.2 Message Authentication Functions 383
12.3 Requirements for Message Authentication Codes 391
12.4 Security of MACs 393
12.5 MACs Based on Hash Functions: HMAC 394
12.6 MACs Based on Block Ciphers: DAA and CMAC 399
12.7 Authenticated Encryption: CCM and GCM 402
12.8 Key Wrapping 408
12.9 Pseudorandom Number Generation Using Hash Functions and MACs 413
12.10 Key Terms, Review Questions, and Problems 416

Chapter 13 Digital Signatures 419

13.1 Digital Signatures 421
13.2 Elgamal Digital Signature Scheme 424
13.3 Schnorr Digital Signature Scheme 425
13.4 NIST Digital Signature Algorithm 426
13.5 Elliptic Curve Digital Signature Algorithm 430
13.6 RSA-PSS Digital Signature Algorithm 433
13.7 Key Terms, Review Questions, and Problems 438

PART FIVE: MUTUAL TRUST 441

Chapter 14 Key Management and Distribution 441

14.1 Symmetric Key Distribution Using Symmetric Encryption 442
14.2 Symmetric Key Distribution Using Asymmetric Encryption 451
14.3 Distribution of Public Keys 454
14.4 X.509 Certificates 459

14.5 Public-Key Infrastructure 467
14.6 Key Terms, Review Questions, and Problems 469

Chapter 15 User Authentication 473

15.1 Remote User-Authentication Principles 474
15.2 Remote User-Authentication Using Symmetric Encryption 478
15.3 Kerberos 482
15.4 Remote User-Authentication Using Asymmetric Encryption 500
15.5 Federated Identity Management 502
15.6 Personal Identity Verification 508
15.7 Key Terms, Review Questions, and Problems 515

PART SIX: NETWORK AND INTERNET SECURITY 519

Chapter 16 Network Access Control and Cloud Security 519

16.1 Network Access Control 520
16.2 Extensible Authentication Protocol 523
16.3 IEEE 802.1X Port-Based Network Access Control 527
16.4 Cloud Computing 529
16.5 Cloud Security Risks and Countermeasures 535
16.6 Data Protection in the Cloud 537
16.7 Cloud Security as a Service 541
16.8 Addressing Cloud Computing Security Concerns 544
16.9 Key Terms, Review Questions, and Problems 545

Chapter 17 Transport-Level Security 546

17.1 Web Security Considerations 547
17.2 Transport Layer Security 549
17.3 HTTPS 566
17.4 Secure Shell (SSH) 567
17.5 Key Terms, Review Questions, and Problems 579

Chapter 18 Wireless Network Security 581

18.1 Wireless Security 582
18.2 Mobile Device Security 585
18.3 IEEE 802.11 Wireless LAN Overview 589
18.4 IEEE 802.11i Wireless LAN Security 595
18.5 Key Terms, Review Questions, and Problems 610

Chapter 19 Electronic Mail Security 612

19.1 Internet Mail Architecture 613
19.2 Email Formats 617
19.3 Email Threats and Comprehensive Email Security 625
19.4 S/MIME 627
19.5 Pretty Good Privacy 638
19.6 DNSSEC 639
19.7 DNS-Based Authentication of Named Entities 643
19.8 Sender Policy Framework 645
19.9 DomainKeys Identified Mail 648

19.10 Domain-Based Message Authentication, Reporting, and Conformance 654
19.11 Key Terms, Review Questions, and Problems 659

Chapter 20 IP Security 661

20.1 IP Security Overview 662
20.2 IP Security Policy 668
20.3 Encapsulating Security Payload 673
20.4 Combining Security Associations 681
20.5 Internet Key Exchange 684
20.6 Cryptographic Suites 692
20.7 Key Terms, Review Questions, and Problems 694

APPENDICES 696

Appendix A Projects for Teaching Cryptography and Network Security 696

A.1 Sage Computer Algebra Projects 697
A.2 Hacking Project 698
A.3 Block Cipher Projects 699
A.4 Laboratory Exercises 699
A.5 Research Projects 699
A.6 Programming Projects 700
A.7 Practical Security Assessments 700
A.8 Firewall Projects 701
A.9 Case Studies 701
A.10 Writing Assignments 701
A.11 Reading/Report Assignments 702
A.12 Discussion Topics 702

Appendix B Sage Examples 703

B.1 Linear Algebra and Matrix Functionality 704
B.2 Chapter 2: Number Theory 705
B.3 Chapter 3: Classical Encryption 710
B.4 Chapter 4: Block Ciphers and the Data Encryption Standard 713
B.5 Chapter 5: Basic Concepts in Number Theory and Finite Fields 717
B.6 Chapter 6: Advanced Encryption Standard 724
B.7 Chapter 8: Pseudorandom Number Generation and Stream Ciphers 729
B.8 Chapter 9: Public-Key Cryptography and RSA 731
B.9 Chapter 10: Other Public-Key Cryptosystems 734
B.10 Chapter 11: Cryptographic Hash Functions 739
B.11 Chapter 13: Digital Signatures 741

References 744

Credits 753

Index 754

ONLINE CHAPTERS AND APPENDICES[1]

PART SEVEN: SYSTEM SECURITY

Chapter 21 Malicious Software

21.1 Types of Malicious Software (Malware)
21.2 Advanced Persistent Threat
21.3 Propagation—Infected Content—Viruses
21.4 Propagation—Vulnerability Exploit—Worms
21.5 Propagation—Social Engineering—Spam E-mail, Trojans
21.6 Payload—System Corruption
21.7 Payload—Attack Agent—Zombie, Bots
21.8 Payload—Information Theft—Keyloggers, Phishing, Spyware
21.9 Payload—Stealthing—Backdoors, Rootkits
21.10 Countermeasures
21.11 Distributed Denial of Service Attacks
21.12 References
21.13 Key Terms, Review Questions, and Problems

Chapter 22 Intruders

22.1 Intruders
22.2 Intrusion Detection
22.3 Password Management
22.4 References
22.5 Key Terms, Review Questions, and Problems

Chapter 23 Firewalls

23.1 The Need for Firewalls
23.2 Firewall Characteristics and Access Policy
23.3 Types of Firewalls
23.4 Firewall Basing
23.5 Firewall Location and Configurations
23.6 References
23.7 Key Terms, Review Questions, and Problems

PART EIGHT: LEGAL AND ETHICAL ISSUES

Chapter 24 Legal and Ethical Aspects

24.1 Cybercrime and Computer Crime
24.2 Intellectual Property
24.3 Privacy
24.4 Ethical Issues
24.5 Recommended Reading
24.6 References
24.7 Key Terms, Review Questions, and Problems
24.A Information Privacy

[1] Online chapters, appendices, and other documents are at the Companion Website, available via the access card at the front of this book.

Appendix C Sage Exercises

Appendix D Standards and Standard-Setting Organizations

Appendix E Basic Concepts from Linear Algebra

Appendix F Measures of Secrecy and Security

Appendix G Simplified DES

Appendix H Evaluation Criteria for AES

Appendix I Simplified AES

Appendix J The Knapsack Algorithm

Appendix K Proof of the Digital Signature Algorithm

Appendix L TCP/IP and OSI

Appendix M Java Cryptographic APIs

Appendix N MD5 Hash Function

Appendix O Data Compression Using ZIP

Appendix P PGP

Appendix Q The International Reference Alphabet

Appendix R Proof of the RSA Algorithm

Appendix S Data Encryption Standard

Appendix T Kerberos Encryption Techniques

Appendix U Mathematical Basis of the Birthday Attack

Appendix V Evaluation Criteria for SHA-3

Appendix W The Complexity of Algorithms

Appendix X Radix-64 Conversion

Appendix Y The Base Rate Fallacy

Glossary

NOTATION

Symbol	Expression	Meaning
D, K	D(K, Y)	Symmetric decryption of ciphertext Y using secret key K
D, PR_a	D(PR_a, Y)	Asymmetric decryption of ciphertext Y using A's private key PR_a
D, PU_a	D(PU_a, Y)	Asymmetric decryption of ciphertext Y using A's public key PU_a
E, K	E(K, X)	Symmetric encryption of plaintext X using secret key K
E, PR_a	E(PR_a, X)	Asymmetric encryption of plaintext X using A's private key PR_a
E, PU_a	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	MAC(K, X)	Message authentication code of message X using secret key K
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.
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 mod m	Remainder after division of a by m
mod, $\equiv$	$a \equiv b \pmod{m}$	a mod m = b mod m
mod, $\not\equiv$	$a \not\equiv b \pmod{m}$	a mod m $\neq$ b mod 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	$\prod_{i=1}^{n} a_i$	$a_1 \times a_2 \times \cdots \times a_n$
$\mid$	$i \mid j$	i divides j, which means that there is no remainder when j is divided by i
$\lvert, \rvert$	$\lvert a \rvert$	Absolute value of a

Symbol	Expression	Meaning
$\|$	$x \| y$	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

WHAT'S NEW IN THE SEVENTH EDITION

In the four years since the sixth 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 sixth edition of this book was extensively reviewed by a number of professors who teach the subject and by professionals working in the field. The result is that, in many places, the narrative has been clarified and tightened, and illustrations have been improved.

Beyond these refinements to improve pedagogy and user-friendliness, there have been substantive changes throughout the book. Roughly the same chapter organization has been retained, but much of the material has been revised and new material has been added. The most noteworthy changes are as follows:

- **Fundamental security design principles:** Chapter 1 includes a new section discussing the security design principles listed as fundamental by the National Centers of Academic Excellence in Information Assurance/Cyber Defense, which is jointly sponsored by the U.S. National Security Agency and the U.S. Department of Homeland Security.
- **Attack surfaces and attack trees:** Chapter 1 includes a new section describing these two concepts, which are useful in evaluating and classifying security threats.
- **Number theory coverage:** The material on number theory has been consolidated into a single chapter, Chapter 2. This makes for a convenient reference. The relevant portions of Chapter 2 can be assigned as needed.
- **Finite fields:** The chapter on finite fields has been revised and expanded with additional text and new figures to enhance understanding.
- **Format-preserving encryption:** This relatively new mode of encryption is enjoying increasing commercial success. A new section in Chapter 7 covers this method.
- **Conditioning and health testing for true random number generators:** Chapter 8 now provides coverage of these important topics.
- **User authentication model:** Chapter 15 includes a new description of a general model for user authentication, which helps to unify the discussion of the various approaches to user authentication.
- **Cloud security:** The material on cloud security in Chapter 16 has been updated and expanded to reflect its importance and recent developments.
- **Transport Layer Security (TLS):** The treatment of TLS in Chapter 17 has been updated, reorganized to improve clarity, and now includes a discussion of the new TLS version 1.3.
- **Email Security:** Chapter 19 has been completely rewritten to provide a comprehensive and up-to-date discussion of email security. It includes:
  - New: discussion of email threats and a comprehensive approach to email security.
  - New: discussion of STARTTLS, which provides confidentiality and authentication for SMTP.

- — Revised: treatment of S/MIME has been updated to reflect the latest version 3.2.
- — New: discussion of DNSSEC and its role in supporting email security.
- — New: discussion of DNS-based Authentication of Named Entities (DANE) and the use of this approach to enhance security for certificate use in SMTP and S/MIME.
- — New: discussion of Sender Policy Framework (SPF), which is the standardized way for a sending domain to identify and assert the mail senders for a given domain.
- — Revised: discussion of DomainKeys Identified Mail (DKIM) has been revised.
- — New: discussion of Domain-based Message Authentication, Reporting, and Conformance (DMARC) allows email senders to specify policy on how their mail should be handled, the types of reports that receivers can send back, and the frequency those reports should be sent.

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 not only presents 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.

SUPPORT OF ACM/IEEE COMPUTER SCIENCE CURRICULA 2013

The book is intended for both academic and 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. The changes to this edition are intended to provide support of the ACM/IEEE Computer Science Curricula 2013 (CS2013). CS2013 adds Information Assurance and Security (IAS) to the curriculum recommendation as one of the Knowledge Areas in the Computer Science Body of Knowledge. The document states that IAS is now part of the curriculum recommendation because of the critical role of IAS in computer science education. CS2013 divides all course work into three categories: Core-Tier 1 (all topics should be included in the curriculum), Core-Tier-2 (all or almost all topics should be included), and elective (desirable to provide breadth and depth). In the IAS area, CS2013 recommends topics in Fundamental Concepts and Network Security in Tier 1 and Tier 2, and Cryptography topics as elective. This text covers virtually all of the topics listed by CS2013 in these three categories.

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

PLAN OF THE TEXT

The book is divided into eight parts.

- Background
- 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, and suggestions for further reading. 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.

INSTRUCTOR SUPPORT MATERIALS

The major goal of this text is to make it as effective a teaching tool for this exciting and fast-moving subject as possible. This goal is reflected both in the structure of the book and in the supporting material. The text is accompanied by the following supplementary material that will aid the instructor:

- **Solutions manual:** Solutions to all 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 with a separate file of answers.
- **Sample syllabuses:** The text contains more material than can be conveniently covered in one semester. Accordingly, instructors are provided with several sample syllabuses that guide the use of the text within limited time.

All of these support materials are available at the **Instructor Resource Center (IRC)** for this textbook, which can be reached through the publisher's Web site www.pearsonglobaleditions.com/stallings. To gain access to the IRC, please contact your local Pearson sales representative.

PROJECTS AND OTHER STUDENT EXERCISES

For many instructors, an important component of a cryptography or network 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 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:** Exercise designed to illuminate the key issues in intrusion detection and prevention.
- **Block cipher projects:** 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.
- **Firewall projects:** A portable network firewall visualization simulator, together with exercises for teaching the fundamentals of firewalls.
- **Case studies:** A set of real-world case studies, including learning objectives, case description, and a series of case discussion questions.
- **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.

This diverse set of projects and other student exercises enables the instructor to use the book as one component in a rich and varied learning experience and to tailor a course plan to meet the specific needs of the instructor and students. See Appendix A in this book for details.

THE SAGE COMPUTER ALGEBRA SYSTEM

One of the most important features of this book 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, which is included in this book.

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 exercises that can be assigned to students in the following categories:

- **Chapter 2—Number Theory and Finite Fields:** Euclidean and extended Euclidean algorithms, polynomial arithmetic, GF(2^4), Euler's Totient function, Miller–Rabin, factoring, modular exponentiation, discrete logarithm, and Chinese remainder theorem.
- **Chapter 3—Classical Encryption:** Affine ciphers and the Hill cipher.
- **Chapter 4—Block Ciphers and the Data Encryption Standard:** Exercises based on SDES.
- **Chapter 6—Advanced Encryption Standard:** Exercises based on SAES.
- **Chapter 8—Pseudorandom Number Generation and Stream Ciphers:** Blum Blum Shub, linear congruential generator, and ANSI X9.17 PRNG.
- **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.

ONLINE DOCUMENTS FOR STUDENTS

For this new edition, a tremendous amount of original supporting material for students has been made available online.

Purchasing this textbook new also grants the reader six months of access to the **Companion Website**, which includes the following materials:

- **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 20 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.
- **Key papers:** A number of 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 is useful in case the student wants to play around with the examples.

To access the Companion Website, follow the instructions for "digital resources for students" found in the front of this book.

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Part One: Background

Chapter 1

Computer and Network Security Concepts

1.1 **Computer Security Concepts**

A Definition of Computer Security
Examples
The Challenges of Computer Security

1.2 **The OSI Security Architecture**

1.3 **Security Attacks**

Passive Attacks
Active Attacks

1.4 **Security Services**

Authentication
Access Control
Data Confidentiality
Data Integrity
Nonrepudiation
Availability Service

1.5 **Security Mechanisms**

1.6 **Fundamental Security Design Principles**

1.7 **Attack Surfaces and Attack Trees**

Attack Surfaces
Attack Trees

1.8 **A Model for Network Security**

1.9 **Standards**

1.10 **Key Terms, Review Questions, and Problems**

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Describe the key security requirements of confidentiality, integrity, and availability.
- Describe the X.800 security architecture for OSI.
- Discuss the types of security threats and attacks that must be dealt with and give examples of the types of threats and attacks that apply to different categories of computer and network assets.
- Explain the fundamental security design principles.
- Discuss the use of attack surfaces and attack trees.
- List and briefly describe key organizations involved in cryptography standards.

This book focuses on two broad areas: cryptographic algorithms and protocols, which have a broad range of applications; and network and Internet security, which rely heavily on cryptographic techniques.

Cryptographic algorithms and protocols can be grouped into four main areas:

- **Symmetric encryption:** Used to conceal the contents of blocks or streams of data of any size, including messages, files, encryption keys, and passwords.
- **Asymmetric encryption:** Used to conceal small blocks of data, such as encryption keys and hash function values, which are used in digital signatures.
- **Data integrity algorithms:** Used to protect blocks of data, such as messages, from alteration.
- **Authentication protocols:** These are schemes based on the use of cryptographic algorithms designed to authenticate the identity of entities.

The field of **network and Internet security** consists of measures to deter, prevent, detect, and correct security violations that involve the transmission of information. That is a broad statement that covers a host of possibilities. To give you a feel for the areas covered in this book, consider the following examples of security violations:

1. User A transmits a file to user B. The file contains sensitive information (e.g., payroll records) that is to be protected from disclosure. User C, who is not authorized to read the file, is able to monitor the transmission and capture a copy of the file during its transmission.
2. A network manager, D, transmits a message to a computer, E, under its management. The message instructs computer E to update an authorization file to include the identities of a number of new users who are to be given access to that computer. User F intercepts the message, alters its contents to add or delete entries, and then forwards the message to computer E, which accepts the message as coming from manager D and updates its authorization file accordingly.

3. Rather than intercept a message, user F constructs its own message with the desired entries and transmits that message to computer E as if it had come from manager D. Computer E accepts the message as coming from manager D and updates its authorization file accordingly.
4. An employee is fired without warning. The personnel manager sends a message to a server system to invalidate the employee's account. When the invalidation is accomplished, the server is to post a notice to the employee's file as confirmation of the action. The employee is able to intercept the message and delay it long enough to make a final access to the server to retrieve sensitive information. The message is then forwarded, the action taken, and the confirmation posted. The employee's action may go unnoticed for some considerable time.
5. A message is sent from a customer to a stockbroker with instructions for various transactions. Subsequently, the investments lose value and the customer denies sending the message.

Although this list by no means exhausts the possible types of network security violations, it illustrates the range of concerns of network security.

1.1 COMPUTER SECURITY CONCEPTS

A Definition of Computer Security

The NIST *Computer Security Handbook* [NIST95] defines the term *computer security* as follows:

> **Computer Security:** The protection afforded to an automated information system in order to attain the applicable objectives of preserving the integrity, availability, and confidentiality of information system resources (includes hardware, software, firmware, information/data, and telecommunications).

This definition introduces three key objectives that are at the heart of computer security:

- **Confidentiality:** This term covers two related concepts:

  Data[1] confidentiality: Assures that private or confidential information is not made available or disclosed to unauthorized individuals.

  Privacy: Assures that individuals control or influence what information related to them may be collected and stored and by whom and to whom that information may be disclosed.

[1] RFC 4949 defines *information* as "facts and ideas, which can be represented (encoded) as various forms of data," and *data* as "information in a specific physical representation, usually a sequence of symbols that have meaning; especially a representation of information that can be processed or produced by a computer." Security literature typically does not make much of a distinction, nor does this book.

- **Integrity:** This term covers two related concepts:

  Data integrity: Assures that information (both stored and in transmitted packets) and programs are changed only in a specified and authorized manner.

  System integrity: Assures that a system performs its intended function in an unimpaired manner, free from deliberate or inadvertent unauthorized manipulation of the system.

- **Availability:** Assures that systems work promptly and service is not denied to authorized users.

These three concepts form what is often referred to as the **CIA triad**. The three concepts embody the fundamental security objectives for both data and for information and computing services. For example, the NIST standard FIPS 199 (*Standards for Security Categorization of Federal Information and Information Systems*) lists confidentiality, integrity, and availability as the three security objectives for information and for information systems. FIPS 199 provides a useful characterization of these three objectives in terms of requirements and the definition of a loss of security in each category:

- **Confidentiality:** Preserving authorized restrictions on information access and disclosure, including means for protecting personal privacy and proprietary information. A loss of confidentiality is the unauthorized disclosure of information.
- **Integrity:** Guarding against improper information modification or destruction, including ensuring information nonrepudiation and authenticity. A loss of integrity is the unauthorized modification or destruction of information.
- **Availability:** Ensuring timely and reliable access to and use of information. A loss of availability is the disruption of access to or use of information or an information system.

Although the use of the CIA triad to define security objectives is well established, some in the security field feel that additional concepts are needed to present a complete picture (Figure 1.1). Two of the most commonly mentioned are as follows:

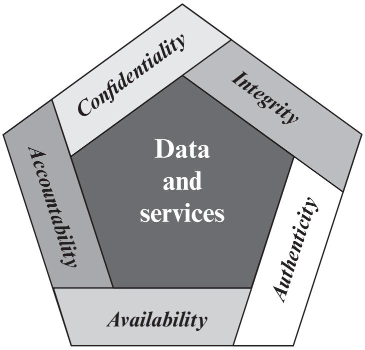


Figure 1.1 Essential Network and Computer Security Requirements

- **Authenticity:** The property of being genuine and being able to be verified and trusted; confidence in the validity of a transmission, a message, or message originator. This means verifying that users are who they say they are and that each input arriving at the system came from a trusted source.
- **Accountability:** The security goal that generates the requirement for actions of an entity to be traced uniquely to that entity. This supports nonrepudiation, deterrence, fault isolation, intrusion detection and prevention, and after-action recovery and legal action. Because truly secure systems are not yet an achievable goal, we must be able to trace a security breach to a responsible party. Systems must keep records of their activities to permit later forensic analysis to trace security breaches or to aid in transaction disputes.

Examples

We now provide some examples of applications that illustrate the requirements just enumerated.[2] For these examples, we use three levels of impact on organizations or individuals should there be a breach of security (i.e., a loss of confidentiality, integrity, or availability). These levels are defined in FIPS PUB 199:

- **Low:** The loss could be expected to have a limited adverse effect on organizational operations, organizational assets, or individuals. A limited adverse effect means that, for example, the loss of confidentiality, integrity, or availability might (i) cause a degradation in mission capability to an extent and duration that the organization is able to perform its primary functions, but the effectiveness of the functions is noticeably reduced; (ii) result in minor damage to organizational assets; (iii) result in minor financial loss; or (iv) result in minor harm to individuals.
- **Moderate:** The loss could be expected to have a serious adverse effect on organizational operations, organizational assets, or individuals. A serious adverse effect means that, for example, the loss might (i) cause a significant degradation in mission capability to an extent and duration that the organization is able to perform its primary functions, but the effectiveness of the functions is significantly reduced; (ii) result in significant damage to organizational assets; (iii) result in significant financial loss; or (iv) result in significant harm to individuals that does not involve loss of life or serious, life-threatening injuries.
- **High:** The loss could be expected to have a severe or catastrophic adverse effect on organizational operations, organizational assets, or individuals. A severe or catastrophic adverse effect means that, for example, the loss might (i) cause a severe degradation in or loss of mission capability to an extent and duration that the organization is not able to perform one or more of its primary functions; (ii) result in major damage to organizational assets; (iii) result in major financial loss; or (iv) result in severe or catastrophic harm to individuals involving loss of life or serious, life-threatening injuries.

[2] These examples are taken from a security policy document published by the Information Technology Security and Privacy Office at Purdue University.

Confidentiality Student grade information is an asset whose confidentiality is considered to be highly important by students. In the United States, the release of such information is regulated by the Family Educational Rights and Privacy Act (FERPA). Grade information should only be available to students, their parents, and employees that require the information to do their job. Student enrollment information may have a moderate confidentiality rating. While still covered by FERPA, this information is seen by more people on a daily basis, is less likely to be targeted than grade information, and results in less damage if disclosed. Directory information, such as lists of students or faculty or departmental lists, may be assigned a low confidentiality rating or indeed no rating. This information is typically freely available to the public and published on a school's Web site.

Integrity Several aspects of integrity are illustrated by the example of a hospital patient's allergy information stored in a database. The doctor should be able to trust that the information is correct and current. Now suppose that an employee (e.g., a nurse) who is authorized to view and update this information deliberately falsifies the data to cause harm to the hospital. The database needs to be restored to a trusted basis quickly, and it should be possible to trace the error back to the person responsible. Patient allergy information is an example of an asset with a high requirement for integrity. Inaccurate information could result in serious harm or death to a patient and expose the hospital to massive liability.

An example of an asset that may be assigned a moderate level of integrity requirement is a Web site that offers a forum to registered users to discuss some specific topic. Either a registered user or a hacker could falsify some entries or deface the Web site. If the forum exists only for the enjoyment of the users, brings in little or no advertising revenue, and is not used for something important such as research, then potential damage is not severe. The Web master may experience some data, financial, and time loss.

An example of a low integrity requirement is an anonymous online poll. Many Web sites, such as news organizations, offer these polls to their users with very few safeguards. However, the inaccuracy and unscientific nature of such polls is well understood.

Availability The more critical a component or service, the higher is the level of availability required. Consider a system that provides authentication services for critical systems, applications, and devices. An interruption of service results in the inability for customers to access computing resources and staff to access the resources they need to perform critical tasks. The loss of the service translates into a large financial loss in lost employee productivity and potential customer loss.

An example of an asset that would typically be rated as having a moderate availability requirement is a public Web site for a university; the Web site provides information for current and prospective students and donors. Such a site is not a critical component of the university's information system, but its unavailability will cause some embarrassment.

An online telephone directory lookup application would be classified as a low availability requirement. Although the temporary loss of the application may be an annoyance, there are other ways to access the information, such as a hardcopy directory or the operator.

The Challenges of Computer Security

Computer and network security is both fascinating and complex. Some of the reasons follow:

1. Security is not as simple as it might first appear to the novice. The requirements seem to be straightforward; indeed, most of the major requirements for security services can be given self-explanatory, one-word labels: confidentiality, authentication, nonrepudiation, or integrity. But the mechanisms used to meet those requirements can be quite complex, and understanding them may involve rather subtle reasoning.
2. In developing a particular security mechanism or algorithm, one must always consider potential attacks on those security features. In many cases, successful attacks are designed by looking at the problem in a completely different way, therefore exploiting an unexpected weakness in the mechanism.
3. Because of point 2, the procedures used to provide particular services are often counterintuitive. Typically, a security mechanism is complex, and it is not obvious from the statement of a particular requirement that such elaborate measures are needed. It is only when the various aspects of the threat are considered that elaborate security mechanisms make sense.
4. Having designed various security mechanisms, it is necessary to decide where to use them. This is true both in terms of physical placement (e.g., at what points in a network are certain security mechanisms needed) and in a logical sense (e.g., at what layer or layers of an architecture such as TCP/IP [Transmission Control Protocol/Internet Protocol] should mechanisms be placed).
5. Security mechanisms typically involve more than a particular algorithm or protocol. They also require that participants be in possession of some secret information (e.g., an encryption key), which raises questions about the creation, distribution, and protection of that secret information. There also may be a reliance on communications protocols whose behavior may complicate the task of developing the security mechanism. For example, if the proper functioning of the security mechanism requires setting time limits on the transit time of a message from sender to receiver, then any protocol or network that introduces variable, unpredictable delays may render such time limits meaningless.
6. Computer and network security is essentially a battle of wits between a perpetrator who tries to find holes and the designer or administrator who tries to close them. The great advantage that the attacker has is that he or she need only find a single weakness, while the designer must find and eliminate all weaknesses to achieve perfect security.
7. There is a natural tendency on the part of users and system managers to perceive little benefit from security investment until a security failure occurs.
8. Security requires regular, even constant, monitoring, and this is difficult in today's short-term, overloaded environment.
9. Security is still too often an afterthought to be incorporated into a system after the design is complete rather than being an integral part of the design process.

10. Many users and even security administrators view strong security as an impediment to efficient and user-friendly operation of an information system or use of information.

The difficulties just enumerated will be encountered in numerous ways as we examine the various security threats and mechanisms throughout this book.

1.2 THE OSI SECURITY ARCHITECTURE

To assess effectively the security needs of an organization and to evaluate and choose various security products and policies, the manager responsible for security needs some systematic way of defining the requirements for security and characterizing the approaches to satisfying those requirements. This is difficult enough in a centralized data processing environment; with the use of local and wide area networks, the problems are compounded.

ITU-T[3] Recommendation X.800, *Security Architecture for OSI*, defines such a systematic approach.[4] The OSI security architecture is useful to managers as a way of organizing the task of providing security. Furthermore, because this architecture was developed as an international standard, computer and communications vendors have developed security features for their products and services that relate to this structured definition of services and mechanisms.

For our purposes, the OSI security architecture provides a useful, if abstract, overview of many of the concepts that this book deals with. The OSI security architecture focuses on security attacks, mechanisms, and services. These can be defined briefly as

- **Security attack:** Any action that compromises the security of information owned by an organization.
- **Security mechanism:** A process (or a device incorporating such a process) that is designed to detect, prevent, or recover from a security attack.
- **Security service:** A processing or communication service that enhances the security of the data processing systems and the information transfers of an organization. The services are intended to counter security attacks, and they make use of one or more security mechanisms to provide the service.

In the literature, the terms *threat* and *attack* are commonly used to mean more or less the same thing. Table 1.1 provides definitions taken from RFC 4949, *Internet Security Glossary.*

[3] The International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T) is a United Nations-sponsored agency that develops standards, called Recommendations, relating to telecommunications and to open systems interconnection (OSI).

[4] The OSI security architecture was developed in the context of the OSI protocol architecture, which is described in Appendix L. However, for our purposes in this chapter, an understanding of the OSI protocol architecture is not required.

Table 1.1 Threats and Attacks (RFC 4949)

Threat
A potential for violation of security, which exists when there is a circumstance, capability, action, or event that could breach security and cause harm. That is, a threat is a possible danger that might exploit a vulnerability.

Attack
An assault on system security that derives from an intelligent threat; that is, an intelligent act that is a deliberate attempt (especially in the sense of a method or technique) to evade security services and violate the security policy of a system.

1.3 SECURITY ATTACKS

A useful means of classifying security attacks, used both in X.800 and RFC 4949, is in terms of *passive attacks* and *active attacks* (Figure 1.2). A passive attack attempts to learn or make use of information from the system but does not affect system resources. An active attack attempts to alter system resources or affect their operation.

Passive Attacks

Passive attacks (Figure 1.2a) are in the nature of eavesdropping on, or monitoring of, transmissions. The goal of the opponent is to obtain information that is being transmitted. Two types of passive attacks are the release of message contents and traffic analysis.

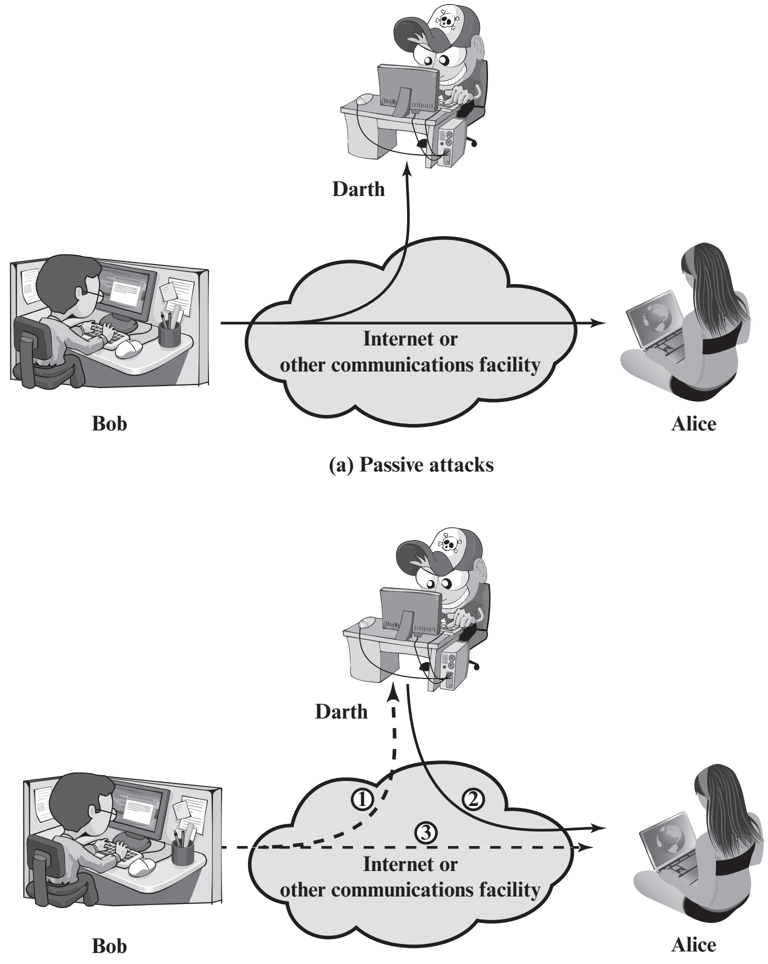
The **release of message contents** is easily understood. A telephone conversation, an electronic mail message, and a transferred file may contain sensitive or confidential information. We would like to prevent an opponent from learning the contents of these transmissions.

A second type of passive attack, **traffic analysis**, is subtler. Suppose that we had a way of masking the contents of messages or other information traffic so that opponents, even if they captured the message, could not extract the information from the message. The common technique for masking contents is encryption. If we had encryption protection in place, an opponent might still be able to observe the pattern of these messages. The opponent could determine the location and identity of communicating hosts and could observe the frequency and length of messages being exchanged. This information might be useful in guessing the nature of the communication that was taking place.

Passive attacks are very difficult to detect, because they do not involve any alteration of the data. Typically, the message traffic is sent and received in an apparently normal fashion, and neither the sender nor receiver is aware that a third party has read the messages or observed the traffic pattern. However, it is feasible to prevent the success of these attacks, usually by means of encryption. Thus, the emphasis in dealing with passive attacks is on prevention rather than detection.

Active Attacks

Active attacks (Figure 1.2b) involve some modification of the data stream or the creation of a false stream and can be subdivided into four categories: masquerade, replay, modification of messages, and denial of service.



(a) Passive attacks

(b) Active attacks

Figure 1.2 Security Attacks

A **masquerade** takes place when one entity pretends to be a different entity (path 2 of Figure 1.2b is active). A masquerade attack usually includes one of the other forms of active attack. For example, authentication sequences can be captured and replayed after a valid authentication sequence has taken place, thus enabling an authorized entity with few privileges to obtain extra privileges by impersonating an entity that has those privileges.

Replay involves the passive capture of a data unit and its subsequent retransmission to produce an unauthorized effect (paths 1, 2, and 3 active).

Modification of messages simply means that some portion of a legitimate message is altered, or that messages are delayed or reordered, to produce an unauthorized effect (paths 1 and 2 active). For example, a message meaning "Allow John Smith to read confidential file *accounts*" is modified to mean "Allow Fred Brown to read confidential file *accounts.*"

The **denial of service** prevents or inhibits the normal use or management of communications facilities (path 3 active). This attack may have a specific target; for example, an entity may suppress all messages directed to a particular destination (e.g., the security audit service). Another form of service denial is the disruption of an entire network, either by disabling the network or by overloading it with messages so as to degrade performance.

Active attacks present the opposite characteristics of passive attacks. Whereas passive attacks are difficult to detect, measures are available to prevent their success. On the other hand, it is quite difficult to prevent active attacks absolutely because of the wide variety of potential physical, software, and network vulnerabilities. Instead, the goal is to detect active attacks and to recover from any disruption or delays caused by them. If the detection has a deterrent effect, it may also contribute to prevention.

1.4 SECURITY SERVICES

X.800 defines a security service as a service that is provided by a protocol layer of communicating open systems and that ensures adequate security of the systems or of data transfers. Perhaps a clearer definition is found in RFC 4949, which provides the following definition: a processing or communication service that is provided by a system to give a specific kind of protection to system resources; security services implement security policies and are implemented by security mechanisms.

X.800 divides these services into five categories and fourteen specific services (Table 1.2). We look at each category in turn.[5]

Authentication

The authentication service is concerned with assuring that a communication is authentic. In the case of a single message, such as a warning or alarm signal, the function of the authentication service is to assure the recipient that the message is from the source that it claims to be from. In the case of an ongoing interaction, such as the connection of a terminal to a host, two aspects are involved. First, at the time of connection initiation, the service assures that the two entities are authentic, that is, that each is the entity that it claims to be. Second, the service must assure that the connection is not interfered with in such a way that a third party can masquerade as one of the two legitimate parties for the purposes of unauthorized transmission or reception.

Two specific authentication services are defined in X.800:

- **Peer entity authentication:** Provides for the corroboration of the identity of a peer entity in an association. Two entities are considered peers if they implement to same protocol in different systems; for example two TCP modules in two communicating systems. Peer entity authentication is provided for

[5] There is no universal agreement about many of the terms used in the security literature. For example, the term *integrity* is sometimes used to refer to all aspects of information security. The term *authentication* is sometimes used to refer both to verification of identity and to the various functions listed under integrity in this chapter. Our usage here agrees with both X.800 and RFC 4949.

Table 1.2 Security Services (X.800)

AUTHENTICATION

The assurance that the communicating entity is the one that it claims to be.

Peer Entity Authentication
Used in association with a logical connection to provide confidence in the identity of the entities connected.

Data-Origin Authentication
In a connectionless transfer, provides assurance that the source of received data is as claimed.

ACCESS CONTROL

The prevention of unauthorized use of a resource (i.e., this service controls who can have access to a resource, under what conditions access can occur, and what those accessing the resource are allowed to do).

DATA CONFIDENTIALITY

The protection of data from unauthorized disclosure.

Connection Confidentiality
The protection of all user data on a connection.

Connectionless Confidentiality
The protection of all user data in a single data block.

Selective-Field Confidentiality
The confidentiality of selected fields within the user data on a connection or in a single data block.

Traffic-Flow Confidentiality
The protection of the information that might be derived from observation of traffic flows.

DATA INTEGRITY

The assurance that data received are exactly as sent by an authorized entity (i.e., contain no modification, insertion, deletion, or replay).

Connection Integrity with Recovery
Provides for the integrity of all user data on a connection and detects any modification, insertion, deletion, or replay of any data within an entire data sequence, with recovery attempted.

Connection Integrity without Recovery
As above, but provides only detection without recovery.

Selective-Field Connection Integrity
Provides for the integrity of selected fields within the user data of a data block transferred over a connection and takes the form of determination of whether the selected fields have been modified, inserted, deleted, or replayed.

Connectionless Integrity
Provides for the integrity of a single connectionless data block and may take the form of detection of data modification. Additionally, a limited form of replay detection may be provided.

Selective-Field Connectionless Integrity
Provides for the integrity of selected fields within a single connectionless data block; takes the form of determination of whether the selected fields have been modified.

NONREPUDIATION

Provides protection against denial by one of the entities involved in a communication of having participated in all or part of the communication.

Nonrepudiation, Origin
Proof that the message was sent by the specified party.

Nonrepudiation, Destination
Proof that the message was received by the specified party.

use at the establishment of, or at times during the data transfer phase of, a connection. It attempts to provide confidence that an entity is not performing either a masquerade or an unauthorized replay of a previous connection.

- **Data origin authentication:** Provides for the corroboration of the source of a data unit. It does not provide protection against the duplication or modification of data units. This type of service supports applications like electronic mail, where there are no prior interactions between the communicating entities.