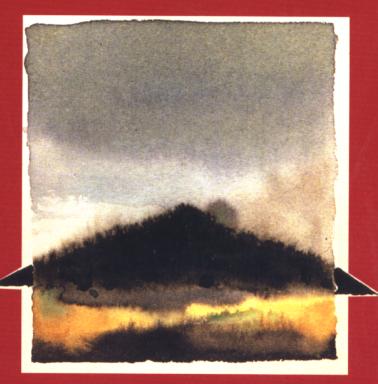
"... the best introduction to cryptography I've ever seen....The book the National Security Agency wanted never to be published..."

-Wired magazine

MORE THAN 100,000 COPIES SOLD SECOND EDITION

APPLIEDCRYPTOGRAPHY



Protocols, Algorithms, and Source Code in C

BRUCE SCHNEIER

from reviews of the first edition of

* 1

APPLIED CRYPTOGRAPHY

Protocols, Algorithms, and Source Code in C

"... the definitive text on the subject...."

—Software Development Magazine

"... good reading for anyone interested in cryptography."

--BYTE

"This book should be on the shelf of any computer professional involved in the use or implementation of cryptography."

—IEEE Software

"... dazzling ... fascinating ... This book absolutely must be on your bookshelf ..."

-PC Techniques

"... comprehensive ... an encyclopedic work ..."

—The Cryptogram

"... a fantastic book on cryptography today. It belongs in the library of anyone interested in cryptography or anyone who deals with information security and cryptographic systems."

—Computers & Security

"An encyclopedic survey \dots could well have been subtitled 'The Joy of Encrypting' \dots a useful addition to the library of any active or would-be security practitioner."

—Cryptologia

"... encyclopedic... readable... well-informed... picks up where Dorothy Denning's classic *Cryptography and Data Security* left off a dozen years ago.... This book would be a bargain at twice the price."

—:login:

"This is a marvelous resource—the best book on cryptography and its application available today."

—Dorothy Denning Georgetown University

"... Schneier's book is an indispensable reference and resource.... I recommend it highly."

—Martin Hellman Stanford University

Errata

A list of the errors found in this book along with corresponding corrections is updated periodically. For the most recent electronic version, send email to:

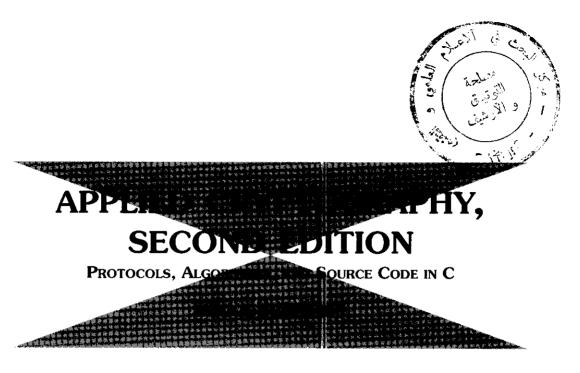
schneier@counterpane.com

For the most recent printed version, send a stamped, self-addressed envelope to:

AC Corrections Counterpane Systems 101 E. Minnekaka Parkway Minneapolis, MN 55419

Readers are encouraged to distribute electronic or printed versions of this list to other readers of this book.







John Wiley & Sons, Inc.

New York • Chichester • Brisbane • Toronto • Singapore

Publisher: Katherine Schowalter

Editor: Phil Sutherland

Assistant Editor: Allison Roarty Managing Editor: Robert Aronds

Text Design & Composition: North Market Street Graphics

Designations used by companies to distinguish their products are often claimed as trademarks. In all instances where John Wiley & Sons, Inc. is aware of a claim, the product names appear in initial capital or all capital letters. Readers, however, should contact the appropriate companies for more complete information regarding trademarks and registration.

This text is printed on acid-free paper.

Copyright © 1996 by Bruce Schneier Published by John Wiley & Sons, Inc.

All rights reserved. Published simultaneously in Canada.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold with the understanding that the publisher is not engaged in rendering legal, accounting, or other professional service. If legal advice or other expert assistance is required, the services of a competent professional person should be sought.

In no event will the publisher or author be liable for any consequential, incidental, or indirect damages (including damages for loss of business profits, business interruption, loss of business information, and the likel arising from the use or inability to use the protocols and algorithms in this book, even if the publisher or author has been advised of the possibility of such damages.

Some of the protocols and algorithms in this book are protected by patents and copyrights. It is the responsibility of the reader to obtain all necessary patent and copyright licenses before implementing in software any protocol or algorithm in this book. This book does not contain an exhaustive list of all applicable patents and copyrights.

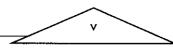
Some of the protocols and algorithms in this book are regulated under the United States Department of State International Traffic in Arms Regulations. It is the responsibility of the reader to obtain all necessary export licenses before implementing in software for export any protocol or algorithm in this book.

Reproduction or translation of any part of this work beyond that permitted by section 107 or 108 of the 1976 United States Copyright Act without the permission of the copyright owner is unlawful. Requests for permission or further information should be addressed to the Permissions Department, John Wiley & Sons, Inc.

Library of Congress Cataloging-in-Publication Data:

```
Schneier, Bruce
Applied Cryptography Second Edition : protocols, algorithms, and source code in C / Bruce Schneier.
p. cm.
Includes bibliographical references (p. 675).
ISBN 0-471-12845-7 (cloth : acid-free paper). — ISBN 0-471-11709-9 [paper : acid-free paper]
Computer security. 2. Telecommunication—Security measures.
Cryptography. 1. Title.
QA76.9.A25835 1996
005.8'2 de20 95-12398
CIP
```

Printed in the United States of America 20, 19, 18, 17, 16, 15, 14, 13, 12



Contents in Brief

Foreword by Whitfield Diffie
Preface
About the Author
1 Foundations

Part I Cryptographic Protocols

- 2 Protocol Building Blocks
- 3 Basic Protocols
- 4 Intermediate Protocols
- 5 Advanced Protocols
- 6 Esoteric Protocols

Part II Cryptographic Techniques

- 7 Key Length
- 8 Key Management
- 9 Algorithm Types and Modes
- 10 Using Algorithms

Part III Cryptographic Algorithms

- 11 Mathematical Background
- 12 Data Encryption Standard (DES)
- 13 Other Block Ciphers
- 14 Still Other Block Ciphers
- 15 Combining Block Ciphers
- 16 Pseudo-Random-Sequence Generators and Stream Ciphers
- 17 Other Stream Ciphers and Real Random-Sequence Generators
- 18 One-Way Hash Functions
- 19 Public-Key Algorithms
- 20 Public-Key Digital Signature Algorithms
- 21 Identification Schemes
- 22 Key-Exchange Algorithms
- 23 Special Algorithms for Protocols

Part IV The Real World

- 24 Example Implementations
- 25 Politics

Afterword by Matt Blaze

Part V Source Code

References

Contents

Foreword by Whitfield Diffie xv
Preface xix
How to Read this Book xx
Acknowledgments xxii
About the Author xxiii

1 FOUNDATIONS 1

- 1.1 Terminology 1
- 1.2 Steganography 9
- 1.3 Substitution Ciphers and Transposition Ciphers 10
- 1.4 SIMPLE XOR 13
- 1.5 ONE-TIME PADS 15
- 1.6 Computer Algorithms 17
- 1.7 Large Numbers 17

PART I CRYPTOGRAPHIC PROTOCOLS

2 PROTOCOL BUILDING BLOCKS 21

- 2.1 Introduction to Protocols 21
- 2.2 Communications Using Symmetric Cryptography 28
- 2.3 One-Way Functions 29
- 2.4 One-Way Hash Functions 30
- 2.5 Communications Using Public-Key Cryptography 31
- 2.6 DIGITAL SIGNATURES 34
- 2.7 Digital Signatures with Encryption 41
- 2.8 RANDOM AND PSEUDO-RANDOM-SEQUENCE GENERATION 44

	3 BASIC PROTOCOLS 47
3.1	Key Exchange 47
3.2	Authentication 52
3.3	Authentication and Key Exchange 56
3.4	FORMAL ANALYSIS OF AUTHENTICATION AND KEY-EXCHANGE PROTOCOLS 65
3.5	MULTIPLE-KEY PUBLIC-KEY CRYPTOGRAPHY 68
3.6	Secret Splitting 70
3.7	Secret Sharing 71
3.8	CRYPTOGRAPHIC PROTECTION OF DATABASES 73

4 INTERMEDIATE PROTOCOLS 75

- 4.1 Timestamping Services 75
- 4.2 Subliminal Channel 79
- 4.3 Undeniable Digital Signatures 81
- 4.4 Designated Confirmer Signatures 82
- 4.5 Proxy Signatures 83
- 4.6 Group Signatures 84
- 4.7 FAIL-STOP DIGITAL SIGNATURES 85
- 4.8 COMPUTING WITH ENCRYPTED DATA 85
- 4.9 BIT COMMITMENT 86
- 4.10 Fair Coin Fluis 89
- 4.11 Mental Poker 92
- 4.12 One-Way Accumulators 95
- 4.13 ALL-OR-NOTHING DISCLOSURE OF SECRETS 96
- 4.14 KEY ESCROW 97

5 ADVANCED PROTOCOLS 101

- 5.1 Zero-Knowledge Proofs 101
- 5.2 Zero-Knowledge Proofs of Identity 109
- 5.3 Blind Signatures 112
- 5.4 IDENTITY-BASED PUBLIC-KEY CRYPTOGRAPHY 115
- 5.5 OBLIVIOUS TRANSFER 116
- 5.6 Oblivious Signatures 117
- 5.7 SIMULTANEOUS CONTRACT SIGNING 118
- 5.8 Digital Certified Mail 122
- 5.9 SIMULTANEOUS EXCHANGE OF SECRETS 123

6 ESOTERIC PROTOCOLS 125

- 6.1 Secure Elections 125
- 6.2 Secure Multiparty Computation 134
- 6.3 Anonymous Message Broadcast 137
- 6.4 Digital Cash 139

PART II CRYPTOGRAPHIC TECHNIQUES

_			
7	KEY	LENGTH	151

7 1	SYMMETRIC KI	EV LENCTH	151
/ . 1	O I MIME I RIC N	ET LENGTH	1:11

- 7.2 Public-Key Key Length 158
- 7.3 Comparing Symmetric and Public-Key Key Length 165
- 7.4 BIRTHDAY ATTACKS AGAINST ONE-WAY HASH FUNCTIONS 165
- 7.5 How Long Should a Key Be? 166
- 7.6 CAVEAT EMPTOR 168

8 KEY MANAGEMENT 169

- 8.1 Generating Keys 170
- 8.2 Nonlinear Keyspaces 175
- 8.3 Transferring Keys 176
- 8.4 VERIFYING KEYS 178
- 8.5 Using Keys 179
- 8.6 Updating Keys 180
- 8.7 STORING KEYS 180
- 8.8 BACKUP KEYS 181
- 8.9 Compromised Keys 182
- 8.10 LIFETIME OF KEYS 183
- 8.11 Destroying Keys 184
- 8.12 Public-Key Key Management 185

9 ALGORITHM TYPES AND MODES 189

- 9.1 ELECTRONIC CODEBOOK MODE 189
- 9.2 BLOCK REPLAY 191
- 9.3 CIPHER BLOCK CHAINING MODE 193
- 9.4 Stream Ciphers 197
- 9.5 Self-Synchronizing Stream Ciphers 198
- 9.6 CIPHER-FEEDBACK MODE 200
- 9.7 Synchronous Stream Ciphers 202
- 9.8 OUTPUT-FEEDBACK MODE 203
- 9.9 Counter Mode 205
- 9.10 OTHER BLOCK-CIPHER MODES 206
- 9.11 Choosing a Cipher Mode 208
- 9.12 Interleaving 210
- 9.13 BLOCK CIPHERS VERSUS STREAM CIPHERS 210

10 USING ALGORITHMS 213

- 10.1 Choosing an Algorithm 214
- 10.2 Public-Key Cryptography versus Symmetric Cryptography 216
- 10.3 Encrypting Communications Channels 216
- 10.4 ENCRYPTING DATA FOR STORAGE 220
- 10.5 HARDWARE ENCRYPTION VERSUS SOFTWARE ENCRYPTION 223

10.7 10.8	Compression, Encoding, and Encryption Detecting Encryption 226 Hiding Ciphertext in Ciphertext 227 Destroying Information 228	226
	PART III CRYPTOGRAPHIC A	ALGORITHMS
111	11 MATHEMATICAL BACKGROUND INFORMATION THEORY 233	233

- 11.2 Complexity Theory 237
- 11.3 Number Theory 242
- 11.4 Factoring 255
- 11.5 Prime Number Generation 258
- 11.6 Discrete Logarithms in a Finite Field 261

12 DATA ENCRYPTION STANDARD (DES) 265

- 12.1 Background 265
- 12.2 Description of DES 270
- 12.3 SECURITY OF DES 278
- 12.4 DIFFERENTIAL AND LINEAR CRYPTANALYSIS 285
- 12.5 The Real Design Criteria 293
- 12.6 DES VARIANTS 294
- 12.7 How Secure Is DES Today? 300

13 OTHER BLOCK CIPHERS 303

- 13.1 Lucifer 303
- 13.2 Madryga *304*
- 13.3 NewDES 306
- 13.4 FEAL 308
- 13.5 REDOC 311
- 13.6 LOKI 314
- 13.7 Khufu and Khafre 316
- 13.8 RC2 318
- 13.9 IDEA 319
- 13.10 MMB 325
- 13.11 CA-1.1 327
- 13.12 Skipjack 328

14 STILL OTHER BLOCK CIPHERS 331

- 14.1 GOST 331
- 14.2 CAST 334
- 14.3 Blowfish 336
- 14.4 SAFER 339
- 14.5 3-Way 341

хi

14.6	Crab 342
	SXAL8/MBAL 344
	RC5 344
	Other Block Algorithms 346
	THEORY OF BLOCK CIPHER DESIGN 346
	Using One-Way Hash Functions 351
	Choosing a Block Algorithm 354
14.12	Choosing A block Algorithm 554
	15 COMBINING BLOCK CIPHERS 357
15.1	
	TRIPLE ENCRYPTION 358
	Doubling the Block Length 363
	OTHER MULTIPLE ENCRYPTION SCHEMES 363
	CDMF Key Shortening 366
	WHITENING 366
	CASCADING MULTIPLE BLOCK ALGORITHMS 367
15.8	
13.6	COMBINING MOLITILE DLOCK ALGORITHMS 500
	16 PSEUDO-RANDOM-SEQUENCE
	GENERATORS AND STREAM CIPHERS 369
16.1	LINEAR CONGRUENTIAL GENERATORS 369
	LINEAR FEEDBACK SHIFT REGISTERS 372
	DESIGN AND ANALYSIS OF STREAM CIPHERS 379
	STREAM CIPHERS USING LFSRs 381
	A5 389
	Hughes XPD/KPD 389
	Nanoteq 390
	RAMBUTAN 390
	Additive Generators 390
	Gifford 392
	ALGORITHM M 393
	PKZIP 394
10.12	I NZII U/4
	17 OTHER STREAM CIPHERS AND REAL
	RANDOM-SEQUENCE GENERATORS 397
17.1	RC4 397
17.2	SEAL 398
17.3	WAKE 400
17.4	FEEDBACK WITH CARRY SHIFT REGISTERS 402
17.5	STREAM CIPHERS USING FCSRs 405
17.6	Nonlinear-Feedback Shift Registers 412
17.7	OTHER STREAM CIPHERS 413
17.8	System-Theoretic Approach to Stream-Cipher Design 415
17.9	
17.10	

17.11	Cascading Multiple Stream Ciphers 419
17.12	CHOOSING A STREAM CIPHER 420
17.13	Generating Multiple Streams from a
	Single Pseudo-Random-Sequence Generator 420
17.14	Real Random-Sequence Generators 421
	18 ONE-WAY HASH FUNCTIONS 429
18.1	BACKGROUND 429
	Snefru 431
	N-Hash 432
	MD4 435
	MD5 436
	MD2 441
18.7	Secure Hash Algorithm (SHA) 441
	RIPE-MD 445
18.9	HAVAL 445
18.10	Other One-Way Hash Functions 446
	One-Way Hash Functions Using Symmetric Block Algorithms 446
	Using Public-Key Algorithms 455
	Choosing a One-Way Hash Function 455
18.14	Message Authentication Codes 455
	19 PUBLIC-KEY ALGORITHMS 461
19.1	
19.2	
19.3	RSA 466
	Pohlig-Hellman 474
19.5	Rabin 475
19.6	ELGAMAL 476
19.7	McEliece 479
	Elliptic Curve Cryptosystems 480
	LUC 481
19.10	FINITE AUTOMATON PUBLIC-KEY CRYPTOSYSTEMS 482
	20 PUBLIC-KEY DIGITAL SIGNATURE ALGORITHMS 483
20.1	DIGITAL SIGNATURE ALGORITHM (DSA) 483
20.2	DSA Variants 494
20.3	
20.4	Discrete Logarithm Signature Schemes 496
20.5	
20.6	ESIGN 499
20.7	Cellular Automata 500

21 IDENTIFICATION SCHEMES 503

20.8 OTHER PUBLIC-KEY ALGORITHMS 500

21.1 Feige-Fiat-Shamir 503

	Contents	/
21.3	Guillou-Quisquater 508 Schnorr 510 Converting Identification Schemes to Signature Schemes 512	
	22 KEY-EXCHANGE ALGORITHMS 513	
22.1	Diffie-Hellman 513	
22.2	STATION-TO-STATION PROTOCOL 516	
00.0	Creation In Theorem Dates December 2017	

- 22.3 Shamir's Three-Pass Protocol 516
- 22.4 COMSET 517
- 22.5 ENCRYPTED KEY EXCHANGE 518
- 22.6 FORTIFIED KEY NEGOTIATION 522
- 22.7 Conference Key Distribution and Secret Broadcasting 523

23 SPECIAL ALGORITHMS FOR PROTOCOLS 527

- 23.1 Multiple-Key Public-Key Cryptography 527
- 23.2 Secret-Sharing Algorithms 528
- 23.3 Subliminal Channel 531
- 23.4 Undeniable Digital Signatures 536
- 23.5 Designated Confirmer Signatures 539
- 23.6 Computing with Encrypted Data 540
- 23.7 FAIR COIN FLIPS 541
- 23.8 One-Way Accumulators 543
- 23.9 All-or-Nothing Disclosure of Secrets 543
- 23.10 Fair and Failsafe Cryptosystems 546
- 23.11 Zero-Knowledge Proofs of Knowledge 548
- 23.12 BLIND SIGNATURES 549
- 23.13 Oblivious Transfer 550
- 23.14 Secure Multiparty Computation 551
- 23.15 Probabilistic Encryption 552
- 23.16 Quantum Cryptography 554

PART IV THE REAL WORLD

24 EXAMPLE IMPLEMENTATIONS 561

- 24.1 IBM SECRET-KEY MANAGEMENT PROTOCOL 561
- 24.2 MITRENET 562
- 24.3 ISDN 563
- 24.4 STU-III 565
- 24.5 Kerberos 566
- 24.6 KRYPTOKNIGHT 571
- 24.7 SESAME 572
- 24.8 IBM COMMON CRYPTOGRAPHIC ARCHITECTURE 573
- 24.9 ISO AUTHENTICATION FRAMEWORK 574
- 24.10 Privacy-Enhanced Mail (PEM) 577
- 24.11 Message Security Protocol (MSP) 584

24.12	PRETTY	Good	Privacy	(PGP)	584
		_			

- 24.13 SMART CARDS 587
- 24.14 Public-Key Cryptography Standards (PKCS) 588
- 24.15 Universal Electronic Payment System (UEPS) 589
- 24.16 CLIPPER 591
- 24.17 CAPSTONE 593
- 24.18 AT&T Model 3600 Telephone Security Device (TSD) 594

25 POLITICS 597

- 25.1 National Security Agency (NSA) 597
- 25.2 National Computer Security Center (NCSC) 599
- 25.3 National Institute of Standards and Technology (NIST) 600
- 25.4 RSA DATA SECURITY, INC. 603
- 25.5 Public Key Partners 604
- 25.6 International Association for Cryptographic Research (IACR) 605
- 25.7 RACE Integrity Primitives Evaluation (RIPE) 605
- 25.8 CONDITIONAL ACCESS FOR EUROPE (CAFE) 606
- 25.9 ISO/IEC 9979 607
- 25.10 Professional, Civil Liberties, and Industry Groups 608
- 25.11 SCLCRYPT 608
- 25.12 CYPHERPUNKS 609
- 25.13 PATENTS 609
- 25.14 U.S. EXPORT RULES 610
- 25.15 FOREIGN IMPORT AND EXPORT OF CRYPTOGRAPHY 617
- 25.16 Legal Issues 618

Afterword by Matt Blaze 619

PART V SOURCE CODE

Source Code 623

References 675