

Applied Cryptography

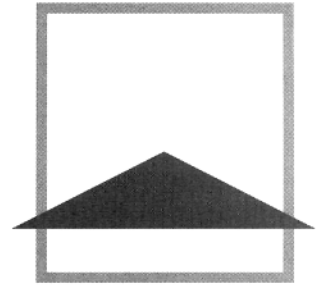
Protocols, Algorithms,
and Source Code
in C

Bruce Schneier



John Wiley & Sons, Inc.

NEW YORK • CHICHESTER • BRISBANE • TORONTO • SINGAPORE



Contents

FOREWORD by Whitfield Diffie	xi
PREFACE	xv
How to Read This Book	xvi
Acknowledgments	xviii
CHAPTER 1	
Foundations	I
1.1 Terminology	1
1.2 Classical Cryptography	8
1.3 Large Numbers	15
PART ONE	
CRYPTOGRAPHIC PROTOCOLS	17
CHAPTER 2	
Protocol Building Blocks	19
2.1 Introduction to Protocols	19
2.2 Communications Using Symmetric Cryptography	26
2.3 One-Way Functions	27
2.4 One-Way Hash Functions	28
2.5 Communications Using Public-Key Cryptography	29
2.6 Digital Signatures	31
2.7 Digital Signatures with Encryption	37
2.8 Random and Pseudo-Random Sequence Generation	39

CHAPTER 3		
Basic Protocols		42
3.1	Key Exchange	42
3.2	Authentication	47
3.3	Authentication and Key Exchange	51
3.4	Multiple-Key Public-Key Cryptography	56
3.5	Secret Splitting	58
3.6	Secret Sharing	59
3.7	Cryptographic Protection of Databases	61
3.8	Timestamping Services	61
CHAPTER 4		
Intermediate Protocols		66
4.1	Subliminal Channel	66
4.2	Undeniable Digital Signatures	68
4.3	Fail-Stop Digital Signatures	69
4.4	Group Signatures	70
4.5	Computing with Encrypted Data	71
4.6	Bit Commitment	71
4.7	Fair Coin Flips	74
4.8	Mental Poker	78
CHAPTER 5		
Advanced Protocols		82
5.1	Fair Cryptosystems	82
5.2	All-or-Nothing Disclosure of Secrets	83
5.3	Zero-Knowledge Proofs of Knowledge	84
5.4	Zero-Knowledge Proofs of Identity	91
5.5	Blind Signatures	93
CHAPTER 6		
Esoteric Protocols		97
6.1	Oblivious Transfer	97
6.2	Simultaneous Contract Signing	99
6.3	Digital Certified Mail	103
6.4	Simultaneous Exchange of Secrets	104
6.5	Secure Elections	105
6.6	Secure Multiparty Computation	114
6.7	Digital Cash	117
6.8	Anonymous Message Broadcast	124
PART TWO		
CRYPTOGRAPHIC TECHNIQUES		127
CHAPTER 7		
Keys		129
7.1	Key Length	129
7.2	Key Management	139
7.3	Public-Key Key Management	152

CHAPTER 8

Using Algorithms**154**

8.1	Block Cipher Modes	154	
8.2	Multiple Encryption	165	
8.3	Stream Ciphers	168	
8.4	Stream Ciphers vs. Block Ciphers	176	
8.5	Public-Key Cryptography vs. Symmetric Cryptography		177
8.6	Encrypting Communications Networks	178	
8.7	Encrypting Data for Storage	180	
8.8	Hardware Encryption vs. Software Encryption		181
8.9	File Erasure	183	
8.10	Choosing an Algorithm	183	

PART **THREE****CRYPTOGRAPHIC ALGORITHMS****187**

CHAPTER 9

Mathematical Background**189**

9.1	Information Theory	189	
9.2	Complexity Theory	193	
9.3	Number Theory	198	
9.4	Factoring	211	
9.5	Prime Number Generation	213	
9.6	Discrete Logarithms in a Finite Field		216

CHAPTER 10

Data Encryption Standard (DES)**219**

10.1	Data Encryption Standard (DES)	219	
10.2	DES Variants	241	

CHAPTER 11

Other Block Algorithms**244**

11.1	Lucifer	244	
11.2	Madryga	245	
11.3	NewDES	247	
11.4	FEAL-N	249	
11.5	REDOC	252	
11.6	LOKI	255	
11.7	Khufu and Khafre	257	
11.8	RC2 and RC4	259	
11.9	IDEA	260	
11.10	MMB	266	
11.11	CA-1.1	268	
11.12	Skipjack	269	
11.13	Using One-Way Hash Functions	270	
11.14	Other Block Algorithms	272	
11.15	Which Block Algorithm Is Best?	272	

CHAPTER 12

Public-Key Algorithms **273**

- 12.1 Background 273
- 12.2 Diffie-Hellman 275
- 12.3 Knapsack Algorithms 277
- 12.4 RSA 281
- 12.5 Pohlig-Hellman 288
- 12.6 Rabin 289
- 12.7 Feige-Fiat-Shamir 291

CHAPTER 13

More Public-Key Algorithms **297**

- 13.1 Guillou-Quisquater 297
- 13.2 Ong-Schnorr-Shamir 299
- 13.3 ElGamal 300
- 13.4 Schnorr 302
- 13.5 Digital Signature Algorithm (DSA) 304
- 13.6 ESIGN 314
- 13.7 McEliece 316
- 13.8 Okamoto 92 317
- 13.9 Cellular Automata 317
- 13.10 Elliptic Curve Cryptosystems 317
- 13.11 Other Public-Key Algorithms 318
- 13.12 Which Public-Key Algorithm Is Best? 320

CHAPTER 14

One-Way Hash Functions **321**

- 14.1 Background 321
- 14.2 Snefru 324
- 14.3 N-Hash 326
- 14.4 MD4 329
- 14.5 MD5 329
- 14.6 MD2 333
- 14.7 Secure Hash Algorithm (SHA) 333
- 14.8 RIPE-MD 336
- 14.9 HAVAL 336
- 14.10 Other One-Way Hash Functions 337
- 14.11 Using Symmetric Block Algorithms 338
- 14.12 Using Public-Key Algorithms 344
- 14.13 Which One-Way Hash Function Is Best? 345
- 14.14 Key-Dependent One-Way Hash Functions 345

CHAPTER 15

Random Sequence Generators and Stream Ciphers **347**

- 15.1 Pseudo-Random Sequence Generators 347
- 15.2 Stream Ciphers 356

15.3	Real Random Sequence Generators	368	
15.4	Generating Numbers and Nonuniform Distributions		372
15.5	Generating Random Permutations	374	

CHAPTER 16

Special Algorithms for Protocols **376**

16.1	Key Exchange	376	
16.2	Encrypted Key Exchange	378	
16.3	Multiple-Key Public-Key Cryptography		381
16.4	Secret Broadcasting	382	
16.5	Secret Sharing Algorithms	383	
16.6	Subliminal Channel	387	
16.7	Undeniable Digital Signatures	392	
16.8	Computing with Encrypted Data	395	
16.9	Fair Coin Flips	395	
16.10	Fair Cryptosystems	398	
16.11	All-or-Nothing Disclosure of Secrets		399
16.12	Zero-Knowledge Proofs of Knowledge		401
16.13	Blind Signatures	403	
16.14	Oblivious Transfer	404	
16.15	Secure Multiparty Computation		404
16.16	Probabilistic Encryption	406	
16.17	Quantum Cryptography	408	

PART FOUR
THE REAL WORLD

411

CHAPTER 17

Example Implementations **413**

17.1	IBM Secret-Key Management Protocol		413
17.2	Mitrenet	414	
17.3	ISDN	415	
17.4	Kerberos	417	
17.5	Kryptoknight	425	
17.6	ISO Authentication Framework	425	
17.7	Privacy-Enhanced Mail (PEM)	428	
17.8	Message Security Protocol (MSP)		436
17.9	Pretty Good Privacy (PGP)	436	
17.10	Clipper	437	
17.11	CAPSTONE	438	

CHAPTER 18

Politics **439**

18.1	National Security Agency (NSA)	439	
18.2	National Computer Security Center (NCSC)		440
18.3	National Institute of Standards and Technology (NIST)		441
18.4	RSA Data Security, Inc.	444	

18.5	International Association of Cryptographic Research (IACR)	445	
18.6	Sci.crypt	445	
18.7	Cypherpunks	445	
18.8	Research and Development in Advanced Communication Technologies in Europe (RACE)		446
18.9	Electronic Frontier Foundation (EFF)	446	
18.10	Computer Professionals for Social Responsibility (CPSR)		446
18.11	Patents	447	
18.12	Export Rules	448	
18.13	Legal Issues	454	

PART **FIVE** SOURCE CODE

SOURCE CODE		457
VIGENERE, BEAUFORD, VARIANT BEAUFORD		457
ENIGMA	460	
DES	467	
LUCIFER	485	
NEWDES	491	
FEAL-8	495	
FEAL-NX	502	
REDOC III	507	
LOKI 91	511	
IDEA	519	
N-HASH	532	
MD5	542	
SECURE HASH ALGORITHM		549
SECRET SHARING	557	
REFERENCES		571
INDEX		605