

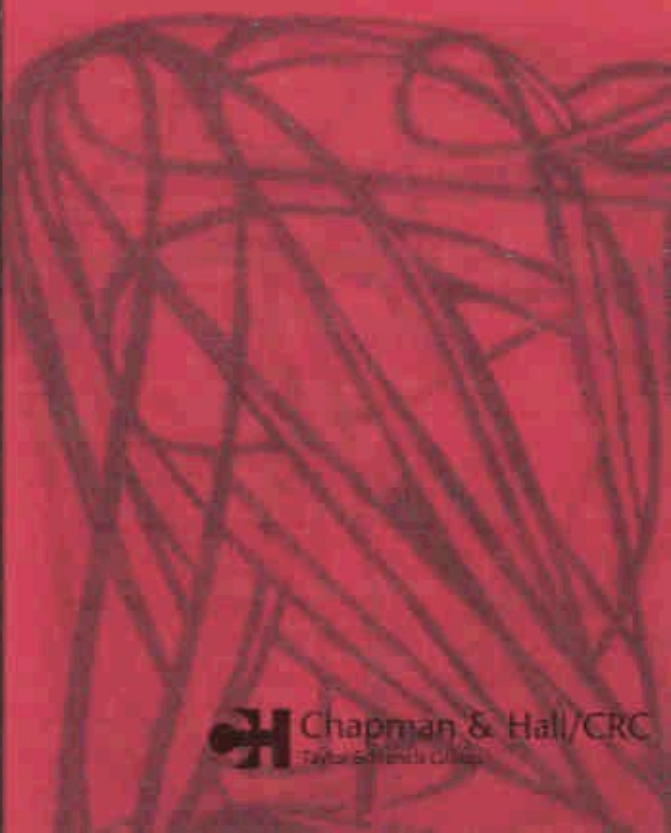
DISCRETE MATHEMATICS AND ITS APPLICATIONS
Series editor KENNETH H. ROSEN

CRYPTOGRAPHY

THEORY AND PRACTICE

THIRD EDITION

DOUGLAS R. STINSON



 Chapman & Hall/CRC
Taylor & Francis Group

Contents

1	Classical Cryptography	1
1.1	Introduction: Some Simple Cryptosystems	1
1.1.1	The Shift Cipher	3
1.1.2	The Substitution Cipher	7
1.1.3	The Affine Cipher	8
1.1.4	The Vigenère Cipher	12
1.1.5	The Hill Cipher	13
1.1.6	The Permutation Cipher	19
1.1.7	Stream Ciphers	21
1.2	Cryptanalysis	26
1.2.1	Cryptanalysis of the Affine Cipher	27
1.2.2	Cryptanalysis of the Substitution Cipher	29
1.2.3	Cryptanalysis of the Vigenère Cipher	32
1.2.4	Cryptanalysis of the Hill Cipher	36
1.2.5	Cryptanalysis of the LFSR Stream Cipher	37
1.3	Notes	39
	Exercises	39
2	Shannon's Theory	45
2.1	Introduction	45
2.2	Elementary Probability Theory	46
2.3	Perfect Secrecy	48
2.4	Entropy	54
2.4.1	Huffman Encodings	56
2.5	Properties of Entropy	59
2.6	Spurious Keys and Unicity Distance	62
2.7	Product Cryptosystems	67
2.8	Notes	70
	Exercises	70

3	Block Ciphers and the Advanced Encryption Standard	73
3.1	Introduction	73
3.2	Substitution-Permutation Networks	74
3.3	Linear Cryptanalysis	79
3.3.1	The Piling-up Lemma	80
3.3.2	Linear Approximations of S-boxes	82
3.3.3	A Linear Attack on an SPN	84
3.4	Differential Cryptanalysis	89
3.5	The Data Encryption Standard	95
3.5.1	Description of DES	95
3.5.2	Analysis of DES	100
3.6	The Advanced Encryption Standard	102
3.6.1	Description of AES	103
3.6.2	Analysis of AES	108
3.7	Modes of Operation	109
3.8	Notes and References	113
	Exercises	114
4	Cryptographic Hash Functions	119
4.1	Hash Functions and Data Integrity	119
4.2	Security of Hash Functions	121
4.2.1	The Random Oracle Model	122
4.2.2	Algorithms in the Random Oracle Model	123
4.2.3	Comparison of Security Criteria	127
4.3	Iterated Hash Functions	129
4.3.1	The Merkle-Damgård Construction	131
4.3.2	The Secure Hash Algorithm	137
4.4	Message Authentication Codes	140
4.4.1	Nested MACs and HMAC	141
4.4.2	CBC-MAC and Authenticated Encryption	144
4.5	Unconditionally Secure MACs	145
4.5.1	Strongly Universal Hash Families	148
4.5.2	Optimality of Deception Probabilities	151
4.6	Notes and References	153
	Exercises	155
5	The RSA Cryptosystem and Factoring Integers	161
5.1	Introduction to Public-key Cryptography	161
5.2	More Number Theory	163
5.2.1	The Euclidean Algorithm	163
5.2.2	The Chinese Remainder Theorem	167
5.2.3	Other Useful Facts	170
5.3	The RSA Cryptosystem	173
5.3.1	Implementing RSA	174

5.4	Primality Testing	178
5.4.1	Legendre and Jacobi Symbols	179
5.4.2	The Solovay-Strassen Algorithm	182
5.4.3	The Miller-Rabin Algorithm	186
5.5	Square Roots Modulo n	187
5.6	Factoring Algorithms	189
5.6.1	The Pollard $p - 1$ Algorithm	189
5.6.2	The Pollard Rho Algorithm	191
5.6.3	Dixon's Random Squares Algorithm	194
5.6.4	Factoring Algorithms in Practice	199
5.7	Other Attacks on RSA	201
5.7.1	Computing $\phi(n)$	201
5.7.2	The Decryption Exponent	202
5.7.3	Wiener's Low Decryption Exponent Attack	207
5.8	The Rabin Cryptosystem	211
5.8.1	Security of the Rabin Cryptosystem	213
5.9	Semantic Security of RSA	215
5.9.1	Partial Information Concerning Plaintext Bits	215
5.9.2	Optimal Asymmetric Encryption Padding	218
5.10	Notes and References	225
	Exercises	226
6	Public-key Cryptography and Discrete Logarithms	233
6.1	The ElGamal Cryptosystem	233
6.2	Algorithms for the Discrete Logarithm Problem	236
6.2.1	Shanks' Algorithm	236
6.2.2	The Pollard Rho Discrete Logarithm Algorithm	238
6.2.3	The Pohlig-Hellman Algorithm	241
6.2.4	The Index Calculus Method	244
6.3	Lower Bounds on the Complexity of Generic Algorithms	246
6.4	Finite Fields	250
6.5	Elliptic Curves	254
6.5.1	Elliptic Curves over the Reals	255
6.5.2	Elliptic Curves Modulo a Prime	257
6.5.3	Properties of Elliptic Curves	261
6.5.4	Point Compression and the ECIES	262
6.5.5	Computing Point Multiples on Elliptic Curves	265
6.6	Discrete Logarithm Algorithms in Practice	267
6.7	Security of ElGamal Systems	268
6.7.1	Bit Security of Discrete Logarithms	268
6.7.2	Semantic Security of ElGamal Systems	272
6.7.3	The Diffie-Hellman Problems	273
6.8	Notes and References	274
	Exercises	275

7	Signature Schemes	281
7.1	Introduction	281
7.2	Security Requirements for Signature Schemes	284
7.2.1	Signatures and Hash Functions	286
7.3	The ElGamal Signature Scheme	287
7.3.1	Security of the ElGamal Signature Scheme	289
7.4	Variants of the ElGamal Signature Scheme	292
7.4.1	The Schnorr Signature Scheme	293
7.4.2	The Digital Signature Algorithm	294
7.4.3	The Elliptic Curve DSA	297
7.5	Provably Secure Signature Schemes	299
7.5.1	One-time Signatures	299
7.5.2	Full Domain Hash	304
7.6	Undeniable Signatures	307
7.7	Fail-stop Signatures	313
7.8	Notes and References	317
	Exercises	318
8	Pseudo-random Number Generation	323
8.1	Introduction and Examples	323
8.2	Indistinguishability of Probability Distributions	327
8.2.1	Next Bit Predictors	330
8.3	The Blum-Blum-Shub Generator	336
8.3.1	Security of the BBS Generator	339
8.4	Probabilistic Encryption	344
8.5	Notes and References	349
	Exercises	350
9	Identification Schemes and Entity Authentication	353
9.1	Introduction	353
9.2	Challenge-and-Response in the Secret-key Setting	356
9.2.1	Attack Model and Adversarial Goals	361
9.2.2	Mutual Authentication	363
9.3	Challenge-and-Response in the Public-key Setting	367
9.3.1	Certificates	367
9.3.2	Public-key Identification Schemes	368
9.4	The Schnorr Identification Scheme	371
9.4.1	Security of the Schnorr Identification Scheme	374
9.5	The Okamoto Identification Scheme	378
9.6	The Guillou-Quisquater Identification Scheme	383
9.6.1	Identity-based Identification Schemes	386
9.7	Notes and References	387
	Exercises	388

10 Key Distribution	393
10.1 Introduction	393
10.2 Diffie-Hellman Key Predistribution	397
10.3 Unconditionally Secure Key Predistribution	399
10.3.1 The Blom Key Predistribution Scheme	399
10.4 Key Distribution Patterns	406
10.4.1 Fiat-Naor Key Distribution Patterns	409
10.4.2 Mitchell-Piper Key Distribution Patterns	410
10.5 Session Key Distribution Schemes	414
10.5.1 The Needham-Schroeder Scheme	415
10.5.2 The Denning-Sacco Attack on the NS Scheme	416
10.5.3 Kerberos	417
10.5.4 The Bellare-Rogaway Scheme	421
10.6 Notes and References	424
Exercises	424
11 Key Agreement Schemes	429
11.1 Introduction	429
11.2 Diffie-Hellman Key Agreement	429
11.2.1 The Station-to-station Key Agreement Scheme	431
11.2.2 Security of STS	432
11.2.3 Known Session Key Attacks	436
11.3 MTI Key Agreement Schemes	438
11.3.1 Known Session Key Attacks on MTI/A0	441
11.4 Key Agreement Using Self-certifying Keys	444
11.5 Encrypted Key Exchange	448
11.6 Conference Key Agreement Schemes	450
11.7 Notes and References	453
Exercises	455
12 Public-key Infrastructure	457
12.1 Introduction: What is a PKI?	457
12.1.1 A Practical Protocol: Secure Socket Layer	459
12.2 Certificates	461
12.2.1 Certificate Life-cycle Management	463
12.3 Trust Models	464
12.3.1 Strict Hierarchy Model	464
12.3.2 Networked PKIs	466
12.3.3 The Web Browser Model	467
12.3.4 Pretty Good Privacy	468
12.4 The Future of PKI?	471
12.4.1 Alternatives to PKI	471
12.5 Identity-based Cryptography	472
12.5.1 The Cocks Identity-based Encryption Scheme	473

12.6 Notes and References	479
Exercises	480
13 Secret Sharing Schemes	481
13.1 Introduction: The Shamir Threshold Scheme	481
13.1.1 A Simplified (t, t) -threshold Scheme	485
13.2 Access Structures and General Secret Sharing	486
13.2.1 The Monotone Circuit Construction	488
13.2.2 Formal Definitions	493
13.3 Information Rate and Construction of Efficient Schemes	496
13.3.1 The Vector Space Construction	498
13.3.2 An Upper Bound on the Information Rate	505
13.3.3 The Decomposition Construction	509
13.4 Notes and References	513
Exercises	514
14 Multicast Security and Copyright Protection	517
14.1 Introduction to Multicast Security	517
14.2 Broadcast Encryption	518
14.2.1 An Improvement using Ramp Schemes	528
14.3 Multicast Re-keying	531
14.3.1 The Blacklisting Scheme	533
14.3.2 The Naor-Pinkas Re-keying Scheme	534
14.3.3 Logical Key Hierarchy	537
14.4 Copyright Protection	539
14.4.1 Fingerprinting	540
14.4.2 Identifiable Parent Property	542
14.4.3 2-IPP Codes	544
14.5 Tracing Illegally Redistributed Keys	548
14.6 Notes and References	552
Exercises	552
Further Reading	557
Bibliography	561
Index	583