

INDEX

Numbers

0-RTT data, 267
3DES (triple DES), 67, 82–83.
See also DES

A

A5/1, 21, 98–101
Aaronson, Scott, 185, 193, 281, 293
active attacker, 318
adaptive corruption, 318
Advanced Encryption Standard (AES),
 61, 67
 AddRoundKey, 68–70
 block size, 62
 vs. DES, 67, 90
 and GCM, 164–167, 171, 173
 implementations, 71–74
 internals, 67–70
 KeyExpansion, 68–69
 MixColumns, 68–69
 with Poly1305, 148
 and provable security, 50
 security of, 73
 ShiftRows, 68–69
 SubBytes, 68–69
 and TLS 1.3, 265–266
Advanced Vector Extensions (AVX), 63
AEAD (authenticated encryption with
 associated data), 18, 160,
 169–170
AES. *See* Advanced Encryption
 Standard
AES-CBC, 78
AESENC instruction, 72
AESENCLAST instruction, 73
AES-GCM
 efficiency, 166
 internals, 164–165
 security, 166

and small tags, 173
and weak hash keys, 171–173
AES native instructions (AES-NI), 72
AEZ, 174
aggregate signature protocols, 311–314
AKA (authenticated key
 agreement), 220–221
algebraic attacks, 96
Alvisi, Lorenzo, 136
amplitude, 274–279
Apple, 243, 246
application-specific integrated circuit
 (ASIC), 89
arithmetization, 328
associated data, 160
asymmetric encryption, 3, 18. *See also*
 RSA
attack costs, 47–49
attack models, 12
 black-box, 13–14
 gray-box, 14
 for key agreement protocols, 221
authenticated ciphers, 160
 with associated data, 160–161
 functional criteria, 163
 nonces, 161–162
 online, 163
 performance, 162–163
 permutation-based, 169–171
 security, 162
 streamability, 163
authenticated decryption, 160
authenticated Diffie–Hellman, 224–226
authenticated encryption (AE), 18, 157
 AES-GCM, 164–167, 171–173
 authenticated ciphers, 160–163
 OCB, 167–169
 permutation-based AEAD, 169–171
 SIV, 169
 using MACs, 158–160

- authenticated encryption with
 - associated data (AEAD), 18, 160, 169–170
 - authenticated key agreement (AKA), 220–221
 - authentication tag, 18. *See also*
 - authenticated encryption; MACs
 - AVX (Advanced Vector Extensions), 63
- B**
- backtracking resistance, 30
 - backward secrecy, 30
 - `BcryptGenRandom()` function, 37–38
 - Bellare, Mihir, 155
 - Bellaso, Giovan Battista, 5
 - Bellcore attack, 211
 - Bernstein, Daniel J., 57, 106, 110, 148, 151, 244, 248, 283
 - big-number libraries, 206
 - bilinearity, 312
 - binary exponentiation, 207
 - birthday attacks, 120
 - birthday paradox, 120
 - Bitcoin, 116, 297, 299–302, 306, 307
 - bit security, 46–48
 - BLAKE, 131
 - BLAKE2, 115, 133–135, 143
 - BLAKE2b, 134
 - BLAKE2s, 134
 - compression function, 134–135
 - design rationale, 134
 - blinding attacks, 203
 - block ciphers, 61. *See also*
 - Advanced Encryption Standard
 - block size, 62–63
 - CBC mode, 76–78
 - codebook attacks, 63
 - CTR mode, 80–82
 - decryption algorithm, 62
 - ECB mode, 74–76
 - encryption algorithm, 62
 - Feistel schemes, 66–67
 - key schedule, 64
 - meet-in-the-middle attacks, 82–83
 - modes of operation, 74
 - padding oracle attacks, 83–85
 - round keys, 64–65
 - rounds, 64
 - security goals, 62
 - slide attacks, 64–65
 - substitution-permutation networks, 65–66
- BLS curve, 312
- BLS signature, 312–313
- Bluetooth, 88
- Boneh, Dan, 214
- Bos, Joppe W., 251
- broadcast attack model, 105
- Brumley, David, 214
- brute-force attacks, 45, 100–101
- C**
- CA (certificate authority), 258–262, 269–270
 - cache-timing attacks, 72
 - Caesar cipher, 4–5
 - CAESAR competition, 174
 - Canetti, Ran, 155
 - carry-less multiplication (CLMUL), 165
 - CBC. *See* cipher block chaining
 - CBC-MAC, 146–147
 - CCA (chosen-ciphertext attackers), 13–14
 - CCM (counter with CBC-MAC), 174, 265
 - CDH (computational Diffie–Hellman), 218–219
 - certificate authority (CA), 258–262, 269–270
 - certificate chain, 259, 269
 - ChaCha20, 106, 131, 151, 265
 - chaining values, 122
 - Chinese remainder theorem (CRT), 210–211
 - chosen-ciphertext attackers (CCA), 13–14
 - chosen-message attacks, 140
 - chosen-plaintext attackers (CPA), 13
 - Chrome browser, 129, 271
 - Chuang, Isaac, 293
 - cipher-based MAC (CMAC), 146–147
 - cipher block chaining (CBC), 76–78
 - ciphertext stealing, 79
 - padding, 78–79
 - padding oracle attacks, 83–85

- ciphers, 3
 ciphertext, 4
 ciphertext-only attackers (COAs), 13
 ciphertext stealing, 79
 circuit, 328
 C language, 91
 Clay Mathematics Institute, 50, 185
 client certificate, 268
 clique problem, 184
 CLMUL (carry-less multiplication), 165
 closest vector problem (CVP), 287
 CMAC (cipher-based MAC), 146–147
 CMAC-AES, 169
 code-based cryptography, 285–286
 codebook attacks, 63, 101
 Codenomicon, 270
 coding problems, 194
 Cohen, Henri, 251
 Cold War, 61
 collision resistance, 119–120, 123,
 305–306
 completeness, 324
 complexity. *See* computational
 complexity
 complexity class, 182
 complex numbers, 275
 compression functions, 122
 in BLAKE2, 134–135
 Davies–Meyer construction, 124–125
 in Merkle–Damgård
 construction, 122
 in SHA-1, 127
 computational complexity, 178
 bounds, 182
 classes, 182
 comparison, 180
 constant factors, 179
 constant time, 179
 exponential, 179–181
 exponential factorial, 181
 linear, 179
 linearithmic, 179
 polynomial, 180–183
 quadratic, 180
 superpolynomial, 180
 computational complexity theory, 177
 computational Diffie–Hellman
 (CDH), 218–219
 computational hardness, 178
 computational security, 44–46
 confidentiality, 3, 21, 116, 162
 confusion, 65, 303
 constant-time implementations, 154
 Coppersmith, Don, 213
 counter mode (CTR), 80–82, 102, 164
 counter with CBC-MAC (CCM),
 174, 265
 CPA (chosen-plaintext attackers), 13
 CRCs (cyclic redundancy checks), 116
 CRT (Chinese remainder theorem),
 210–211
 CryptAcquireContext() function, 34
 CryptGenRandom() function, 37
 Crypto++, 214
 Cryptocat, 41
 cryptographic security, 43. *See also*
 security
 CTR (counter mode), 80–82, 102, 164
 cube attacks, 96
 Curve448, 265
 Curve25519, 248, 265
 Curve41417, 248
 CVP (closest vector problem), 287
 cyclic redundancy checks (CRCs), 116

D

- Dahlin, Mike, 136
 Damgård, Ivan, 122, 237
 Data Encryption Standard. *See* DES
 Datagram Transport Layer Security
 (DTLS), 257
 Davies–Meyer construction, 124–125,
 127, 134
 decisional Diffie–Hellman (DDH)
 assumption, 219
 problem, 218–219
 dedicated hardware, 90
 DeMillo, Richard A., 214
 DES (Data Encryption Standard), 61, 90
 vs. AES, 67, 90
 block size, 62
 double DES, 83
 Feistel schemes in, 66–67
 3DES, 67, 82–83
 deterministic random bit generator
 (DRBG), 16, 30, 88

- /dev/random*, 36–37
/dev/urandom, 34–37
 Diehard, 33
 differential cryptanalysis, 109
 Diffie, Whittfield, 195, 215
 Diffie–Hellman problem, 194
 Diffie–Hellman protocol, 241
 anonymous, 223–224
 authenticated, 224–227
 CDH problem, 218
 DDH problem, 218–219
 function, 216–217
 generating parameters, 217
 and key agreement, 219–222, 241
 MQV protocol, 227–228
 and shared secrets, 216, 228–229
 in TLS, 215, 229, 264–265
 twin problem, 219
 unsafe group parameters, 229–230
 diffusion, 65–66, 304
 digest, 116
 DigiNotar, 269
 digital signatures, 116–117, 196,
 202–205
 discrete logarithm problem (DLP),
 189–191
 and CDH problem, 218
 ECDLP, 240–241
 and Shor’s algorithm, 281–282
 dishonest majority, 318
 distribution, 26–27
 domain separation, 305–306
 drand48, 32
 DRBG (deterministic random bit
 generator), 16, 30, 88
 DTLS (Datagram Transport Layer
 Security), 257
 Durumeric, Zakir, 40
- E**
- ECB (electronic codebook), 74
 ECC (elliptic curve cryptography), 231
 ECDH (elliptic curve Diffie–Hellman),
 241, 249, 292
 ECDLP (elliptic curve discrete
 logarithm problem), 240–241
 ECDSA. *See* elliptic curve digital
 signature algorithm
- ECIES (elliptic curve integrated
 encryption scheme), 246
 Ed25519, 244, 250
 Ed448-Goldilocks, 248
 EdDSA, 244
 Einstein–Podolsky–Rosen (EPR)
 paradox, 274
 elliptic curve cryptography (ECC), 231
 elliptic curve Diffie–Hellman (ECDH),
 241, 249, 292
 elliptic curve digital signature
 algorithm (ECDSA), 241, 321
 and bad randomness, 249
 vs. RSA signatures, 243–244
 signature generation, 242
 signature verification, 242–243
 elliptic curve discrete logarithm
 problem (ECDLP), 240–241
 elliptic curve integrated encryption
 scheme (ECIES), 246
 elliptic curves, 231
 addition law, 235
 Curve25519, 248, 265
 Curve41417, 248
 Curve448, 265
 Edwards curves, 233, 244
 groups, 239–240
 with integers, 233–234
 NIST curves, 247–248
 order, 240
 pairing, 312
 point at infinity, 236, 239–240, 314
 point doubling, 237–238
 point multiplying, 238–239
 prime curves, 247
 Weierstrass form, 232
 embarrassingly parallel, 48, 100
 Encapsulating Security Payload
 (ESP), 263
 encrypt-and-MAC, 158–159
 encryption, 3
 asymmetric, 18
 at-rest, 17
 in-transit, 17
 randomized, 15–16
 security, 12
 encrypt-then-MAC, 158, 159–160, 164
 entanglement, 274, 277

entropy, 27–31, 36–37
 entropy pool, 29–31
 EPR (Einstein–Podolsky–Rosen) paradox, 274
 error-correcting codes, 285
 ESP (Encapsulating Security Payload), 263
 eSTREAM competition, 97, 106, 113
 Ethereum, 306
 eth roots, 199
 Euler’s theorem, 212
 Euler’s totient function, 196
 exponentiation, 206–208, 210
 extended Euclidean algorithm, 198

F

factorials, 9
 factoring methods, 187
 factoring problem, 50–51, 186
 and NP-completeness, 188–189
 solving with Shor’s algorithm, 281–282
 factorization, 187–188, 191–192
 fast correlation attacks, 96
 fault injection, 211
 FDH (Full Domain Hash), 205
 feedback shift registers (FSRs), 90–92
 cycle, 92
 feedback function, 90
 linear, 93–95
 nonlinear, 96
 period, 92
 Feistel schemes, 66–67
 Ferguson, Niels, 30, 173
 FHE (fully homomorphic encryption), 20
 Fiat–Shamir transform, 327, 330
 field-programmable gate array (FPGA), 89
 filtered LFSR, 95–96
 first-preimage resistance, 118
 fixed points, 125
 Flame, 137
 Flexible Round-Optimized Schnorr Threshold (FROST), 321
 forgery attacks, 140
 format-preserving encryption (FPE), 19–20

Fortuna, 30–31
 forward secrecy, 221–222, 225, 228
 in authenticated DH, 225
 in TLS 1.3, 268–269
 Fouque, Pierre-Alain, 155
 FOX, 66
 FPGA (field-programmable gate array), 89
 frequency analysis, 6
 Frey, Gerhard, 251
 FROST (Flexible Round-Optimized Schnorr Threshold), 321
 FSRs. *See* feedback shift registers
 full diffusion, 110
 Full Domain Hash (FDH), 205
 fully homomorphic encryption (FHE), 20

G

GCD (greatest common divisor), 40, 198, 211, 282
 GCHQ (Government Communications Headquarters), 216
 GCM (Galois Counter Mode), 158, 164, 173. *See also* AES-GCM
`gcm_ghash_clmul` function, 165
 general number field sieve (GNFS), 187, 218
`getrandom()` system call, 36
 GHASH, 165–166, 171–172
 Gilbert, Edgar, 148
 Git, 115
 GitHub, 55
 Gmail, 268, 270
 GMR-1, 113
 GMR-2, 113
 GNFS (general number field sieve), 187, 218
 GNU Multiple Precision (GMP), 206
 Go, 152, 206, 208
 Goldberg, Ian, 39, 321
 Goldwasser, Shafi, 22
 Google, 129, 258–261, 269, 270
 Chrome browser, 129, 271
 GOST, 61, 67
 Govaerts, René, 137
 Government Communications Headquarters (GCHQ), 216

- Grain-128a, 97–98
 graphics processing unit (GPU),
 101, 178
 greatest common divisor (GCD), 40,
 198, 211, 282
 Grøstl, 131
 groups
 axioms, 190
 commutativity, 190
 cyclic, 190
 finite, 190
 generator, 190
 in RSA, 196–197
 Grover’s algorithm, 282–283
 GSM mobile communication, 88, 140
 guess-and-determine attacks, 100–101
- H**
- Hadamard gate, 278–279
 Halderman, Alex, 40, 251
 hardness assumption, 189
 hard problems, 177. *See also*
 computational complexity
 closest vector problem, 287
 discrete logarithm problem,
 189–191
 factoring problem, 50–51, 186
 learning with errors, 194, 286
 multivariate quadratic
 equations, 287
 NP-complete problem, 183–186
 P vs. NP problem, 185–186
 and provable security, 50–51
 short integer solution, 194, 286
 hardware, 72, 113
 hash-based cryptography, 288–289
 hash-based MACs, 144–145
 hash functions, 115. *See also* Merkle–
 Damgård construction
 collisions in, 119–121
 compression functions, 122
 Davies–Meyers construction,
 124–125
 in digital signatures, 116
 iterative, 122
 keyed, 139
 multicollisions, 123–124
 noncryptographic, 116
- P vs. NP problem, 185–186
 preimage resistance, 117–119
 in proof-of-storage protocols,
 136–137
 security notions, 116
 sponge functions, 122, 125–126
 3-collisions, 123
 universal, 148–149
 unpredictability, 117
 hash values, 116, 117–121
 Heartbleed, 256, 270
 Hellman, Martin, 195, 215
 Heninger, Nadia, 40, 251
 heuristic security, 50, 52–53
 HMAC-based KDF (HKDF), 229, 265
 HMACs (hash-based MACs), 144–146
 honest majority, 318
 HTTPS, 258
 insecure, 166, 193
 keys for, 53, 56
 over TLS, 104, 215, 256
- I**
- iCloud, 270
 identity gate, 278
 IES (integrated encryption
 scheme), 246
 IETF (Internet Engineering Task
 Force), 134, 164, 250, 314
 IKE (Internet Key Exchange), 146
 imaginary number, 275
 IND-CPA, 15–17
 indifferentiability, 137
 indistinguishability (IND), 15
 initial value (IV), 76, 81, 89, 122, 147
 integrated encryption scheme
 (IES), 246
 integrity, of data, 19, 116, 140
 Intel, 38, 73, 165
 Internet Engineering Task Force
 (IETF), 134, 164, 250, 314
 Internet Key Exchange (IKE), 146
 internet of things (IoT), 255
 intractable problems. *See* hard
 problems
 invalid curve attack, 249–250
 invalid key, 314–315
 invasive attacks, 14

ion traps, 284
ipad, 144
IPSec (Internet Protocol Security), 140, 144, 146, 160, 164, 263
iterative hashing, 122
IV (initial value), 76, 81, 89, 122, 147

J

Jager, Tibor, 250
Java, 22, 32, 152
JH, 131

K

KDF. *See* key derivation function
Keccak, 126, 131–133, 171. *See also* SHA-3
Kelsey, John, 30, 41, 50
Kerckhoffs, Auguste, 6, 13
Kerckhoffs’s principle, 13
key agreement protocols, 53, 216, 219
 AKA, 220–221
 attack models, 221
 breaches, 221, 225, 228
 data leaks, 221, 226, 268
 eavesdroppers, 216, 218
 forward secrecy, 221–222, 225, 228
 performance, 222
 security goals, 221
key cancellation attack, 309–310, 315–316
key confirmation, 226, 228
key control, 221, 225
key derivation function (KDF), 53
 in DH functions, 216, 229
 in ECIES, 246
 in TLS 1.3, 265–266
key generation, 39, 40, 198, 323
key-generation algorithm, 53, 54
key management, 323
key scheduling algorithms (KSAs), 102–104
key wrapping, 55
knapsack problem, 184
knowledge extractor, 326
known-message attack, 140
known-plaintext attackers (KPAs), 13, 100
Knudsen, Lars, 51

Kohno, Tadayoshi, 31
Kotla, Ramakrishna, 136
Kozierok, Charles, 257
Krawczyk, Hugo, 155, 230
Krovetz, Ted, 168
KSAs (key scheduling algorithms), 102–104
Kupyna, 127

L

Lagrange interpolation, 319
lattice-based cryptography, 286–287
lattice problems, 194, 287, 291
learning with errors (LWE), 286, 291
least significant bit (LSB), 179, 207
length-extension attacks, 135–136, 142–143
Let’s Encrypt, 271
Leurent, Gaëtan, 155
linear code, 285–286
linear combination, 33
linear feedback shift registers (LFSRs), 93
 in A5/1, 98–100
 filtered, 95–96
 in Grain-128a, 97–98
 polynomials, 93
 security, 95
linear transformation, 33, 93, 287
Linux, 34, 36, 74, 152
Lipton, Richard J., 214
logarithm, 27, 46
long-term key, 225
lower bound, 45
low-exponent attacks, 209
LSB (least significant bit), 179, 207
Lucifer, 66
LWE (learning with errors), 286, 291

M

MacBook, 154, 191, 209
MACs (message authentication codes), 139
 authentication tag, 140
 CBC-MAC, 146–147
 chosen-message attacks, 140
 CMAC, 146–147
 dedicated designs, 148

- MACs (*continued*)
 - encrypt-and-MAC, 158–159
 - encrypt-then-MAC, 158, 159–160, 164
 - forgery attacks, 140
 - HMAC, 144–146
 - MAC-then-encrypt, 158–160
 - vs. PRFs, 141–142
 - replay attacks, 141
 - timing attacks, 140–142
 - Wegman–Carter, 149–150
- MAC-then-encrypt, 158–160
- MacWilliams, F.J., 148
- malleability, 199–200
- man-in-the-middle attacks, 220, 223–224, 256
- mask generating function, 202
- matrix multiplication, 278
- McEliece cryptosystem, 285–286
- MD5, 122, 127, 133
- M–D construction. *See* Merkle–Damgård construction
- measurement (quantum physics), 274, 278
- MediaWiki, 40
- meet-in-the-middle (MitM) attacks, 82–83
- memory, 48
- memory footprint, 63
- Menezes–Qu–Vanstone (MQV), 227–228, 241
- Merkle, Ralph, 122, 137, 216, 297
- Merkle–Damgård (M–D)
 - construction, 122
 - length-extension attacks, 135–136, 142–145
 - multicollisions, 123–124
 - padding, 123
 - security, 123
- Merkle’s puzzles, 216
- Mersenne Twister (MT) algorithm, 32, 40, 305
- message authentication codes. *See*
 - MACs
- Micali, Silvio, 22
- Microsoft, 111, 131
- Microsoft Windows CryptoAPI, 208
- misuse resistance, 162
- MitM (meet-in-the-middle) attacks, 82–83
- mode of operation, 7–8, 61, 74
- Moore, Jonathan, 251
- most significant bit (MSB), 32, 147, 150, 229
- MQ (multivariate quadratics), 287
- MQV (Menezes–Qu–Vanstone), 227–228, 241
- MT (Mersenne Twister) algorithm, 32, 40, 305
- `mt_rand`, 32, 40
- multicollisions, 123–124
- multiparty computation (MPC), 316
- multisignature protocols, 306
- multivariate cryptography, 287–288
- multivariate problems, 194
- multivariate quadratics (MQ), 287
- MuSig, 310–311

N

- Naehrig, Michael, 251, 312
- Netscape, 39, 257
- network-based intrusion detection systems (NIDS), 115
- Neves, Samuel, 133, 135
- NFSR (nonlinear feedback shift register), 96–98
- Nguyen, Phong Q., 155
- Nielsen, Michael, 293
- NIST (National Institute of Standards and Technology), 33, 61, 67, 129–131, 247–248, 289–291
- NM (nonmalleability), 15
- nonces, 80–82, 88–89
 - predictability, 161–162
 - reuse, 111, 169
 - in TLS records, 263
 - WEP insecurity, 103–104
- nondeterministic polynomial time class. *See* NP class
- noninteractive zero-knowledge (NIKZ), 326–327
- nonlinear equation, 33, 96
- nonlinear feedback shift register (NFSR), 96–98
- nonmalleability (NM), 15
- nonrepudiation, 202

- nonuniform distribution, 27
- NP** (nondeterministic polynomial time) class, 182–183
- NP-complete problem, 183–185
 - NP-hard problem, 185–186
- NSA (National Security Agency), 10, 85, 105, 127, 129, 227, 244, 247, 273
- NSS library, 214
- number field sieve, 218
- ## 0
- OAEP. *See* Optimal Asymmetric Encryption Padding
- OCB (offset codebook)
- efficiency, 168–169
 - internals, 167–168
 - security, 168
- one-time pad, 9
- encrypting with, 9–10
 - security, 10–11, 12, 44
- one-way function, 117
- opad, 144
- OpenSSH, 148, 159, 231, 246, 248
- OpenSSL toolkit
- generating DH parameters, 217
 - generating keys, 53–54, 192–193
 - GHASH bug, 165
 - Heartbleed, 256, 270
 - unsafe DH group parameters, 229–230
- Optimal Asymmetric Encryption Padding (OAEP), 56, 200
- encoded message, 201
 - mask generating function, 202
- ## P
- P** (polynomial time) class, 180–185
- P** vs. **NP**, 185–186
- padding, 22, 78–79, 83–84, 123
- OAEP, 56, 200
 - zero padding, 263
- padding oracle attacks, 22, 83–84
- pairing, 312
- parallelism, 47–48
- parallelizability, 162, 166, 168
- parent process ID (PPID), 39
- passive attacker, 318
- password, 53, 55, 141
- Peikert, Chris, 291
- perfect secrecy, 9
- period, 92–94, 97–98, 281–282
- permutation, 6
- permutation-based AEAD, 169–171
 - pseudorandom, 62, 150
 - security, 7, 8–9
 - in sponge functions, 125–126
 - trapdoor, 196, 197–199
- PID (process ID), 39
- pigeonhole principle, 119
- PKCS (Public-Key Cryptography Standards), 200–201
- plaintext, 4
- PLD (programmable logic device), 89
- Poly1305, 148–151
- Poly1305-AES, 150–151
- polynomials, 93
- multiplication, 165–166
 - primitive, 93–94
- polynomial time (**P**) class, 180–185
- post-quantum cryptography, 274, 285
- code-based, 285–286
 - hash-based, 288–289
 - lattice-based, 286–287
 - multivariate, 287–288
- Post-Quantum Cryptography Standardization project, 289
- post-quantum security, 283, 304
- power-analysis attacks, 208
- PPID (parent process ID), 39
- PQCrypto, 293
- precomputation, 48, 222
- prediction resistance, 30
- preimage resistance, 117–119
- Preneel, Bart, 137
- preshared key (PSK), 265, 267
- PRFs. *See* pseudorandom functions
- prime numbers, 187
- prime number theorem, 187
- private keys, 18, 195
- PRNGs. *See* pseudorandom number generators
- Probabilistic Signature Scheme (PSS), 203–205
- probability, 11, 26

probability distribution, 26–27
process ID (PID), 39
programmable logic device (PLD), 89
proof-of-storage protocols, 136–137
proof-of-work, 300
provable security, 50–53
pseudorandom functions (PRFs), 139
 vs. MACs, 141–142
 security, 141
pseudorandom number generators
 (PRNGs), 28–30
 cryptographic, 32–33
 and entropy, 39–40
 Fortuna, 30–31
 generating on Unix, 34–36
 generating on Windows, 37–38
 hardware-based, 38
 noncryptographic, 32, 40
 security, 30
pseudorandom permutation (PRP), 62,
 67, 150
PSK (preshared key), 265, 267
PSPACE, 182
PSS (Probabilistic Signature Scheme),
 203–205
public-key cryptography, 18, 231
Public-Key Cryptography Standards
 (PKCS), 201
public-key cryptosystem, 215
public keys, 195
PyCrypto, 70
Pythagorean theorem, 275
Python language, 70, 75, 80–81,
 102, 212

Q

Qualys, 271
quantum bit (qubit), 274, 276–279, 284
quantum byte, 277
quantum circuits, 278
quantum computers, 188–189, 274
quantum gates, 277–279
quantum mechanics, 274
quantum random number generators
 (QRNGs), 29
quantum speedup, 279
 exponential, 280
 quadratic, 280

quarter-round function, 106–107
qubit (quantum bit), 274, 276–279, 284
R
randomness, 25
random number generators (RNGs),
 28–29
random oracle, 117
Ray, Marsh, 74
RC4, 89, 102
 broken implementation, 111–113
 in TLS, 104–105
 in WEP, 103–104
RDRAND instruction, 38
RDSEED instruction, 38
reduction, 50
replay attacks, 142, 220, 330
Rho method, 120–121
Rijndael, 67
ring-LWE, 291
Rivest, Ron, 102
Rivest–Shamir–Adleman. *See* RSA
RNGs (random number generators),
 28–29
Rogaway, Phillip, 168, 169
rogue key attack, 310
root of unity, 212
rounds, 53
round trips, 222
round-trip times (RTTs), 267
RSA (Rivest–Shamir–Adleman), 195
 Bellcore attack, 211–212
 CRT, 210–211
 vs. ECDSA, 243–244
 encryption, 199
 and factoring problem, 50–51, 186
 FDH, 205
 groups, 196–197
 implementations, 205–206
 key generation, 208–209
 modulus, 212
 OAEP, 200–202
 private exponents, 212–213
 private keys, 54, 197, 198
 problem, 218
 PSS, 203–204, 205
 public exponents, 197
 public keys, 197

- secret exponents, 197
 - security, 198
 - shared moduli, 212–213
 - signatures, 202–205
 - small exponents, 208–209
 - speed, 208–210
 - square-and-multiply, 207–208
 - textbook encryption, 199–200
 - textbook signature, 203
 - trapdoor permutation, 196, 197, 199
 - RSAES-OAEP, 200
 - RSA Security, 102
 - RTT (round-trip times), 267
- S**
- Saarinen, Markku-Juhani O., 132, 173
 - safe prime, 217
 - SageMath, 191, 198, 239
 - Salsa20, 106
 - attacking, 110–111
 - column-round function, 108
 - double-round function, 107
 - internal state, 107
 - and nonlinear relations, 110
 - quarter-round function, 106–107
 - row-round function, 107
 - Salsa20/8, 110–111
 - salt, 204
 - sandwich MAC, 144
 - satellite phone (satphone), 113
 - S-boxes (substitution boxes), 65
 - scheduling problems, 184
 - Schneier, Bruce, 30, 31, 41, 131
 - Schnorr, Claus-Peter, 244, 307
 - Schnorr signature protocol, 307–309
 - Schnorr’s proof-of-knowledge protocol, 325–326
 - Schwenk, Jörg, 250
 - searchable encryption, 20
 - search algorithm, 178
 - second-preimage resistance, 118
 - secret-prefix MAC, 143, 145
 - secret sharing, 319
 - additive, 319
 - threshold, 319
 - secret-suffix MAC, 143
 - secure channel, 216, 256
 - secure cookie, 268
 - Secure Hash Algorithm with Keccak (SHAKE), 132
 - Secure Shell (SSH), 55, 140, 144, 159, 160, 241, 262
 - Secure Socket Layer (SSL), 39, 255, 257
 - security
 - bit, 46–47
 - computational, 44–45
 - cryptographic, 43
 - goals, 12, 15
 - heuristic, 50, 52–53
 - levels, choosing, 49–50
 - margin, 53
 - notions, 12, 15–17
 - post-quantum, 283
 - proof, 46
 - provable, 50–52
 - semantic, 15, 16
 - session key, 53, 219
 - SHA-0, 127–128
 - SHA-1, 127–129, 266
 - SHA-2, 129–133
 - SHA-224, 129–130
 - SHA-256, 117, 123, 129–130, 242, 297, 300
 - compression function, 130, 146
 - security, 130–131, 297
 - SHA-3, 126, 132–133, 229
 - competition, 131–132
 - security, 133–134
 - Zoo, 137
 - SHA-384, 130
 - SHA-512, 130
 - SHAKE (Secure Hash Algorithm with Keccak), 132
 - Shamir’s secret sharing, 319
 - Shannon, Claude, 10
 - SHAs (Secure Hash Algorithms), 126
 - Shor, Peter, 281
 - Shor’s algorithm, 281–282
 - short integer solution (SIS), 286
 - Shrimpton, Tom, 169
 - side-channel attacks, 14, 65, 153, 292
 - Signal, 292
 - signatures, 116, 196, 202–205
 - SIM card, 220
 - Simon’s problem, 280–281

- S**
 Simple Mail Transfer Protocol (SMTP), 229, 257
 simulator, 326
 SipHash, 151–152, 155
 SipRound function, 151–152
 SIS (short integer solution), 286
 SIV (synthetic IV), 169
 Skein, 131
 slide attacks, 64–65
 sliding window method, 208
 Sloane, N.J., 149
 SM3, 127
 SMTP (Simple Mail Transfer Protocol), 229, 257
 SNOW3G, 102
 Somorovsky, Juraj, 250
 soundness, 324
 space complexity, 182
 SPHINCS+, 289–290
 SPNs (substitution–permutation networks), 65–66, 68
 sponge functions, 122, 125–126, 155
 absorbing phase, 126
 capacity, 126
 squeezing phase, 126
 square-and-multiply, 207–208
 SSH (Secure Shell), 55, 140, 144, 159, 160, 241, 262
 SSL (Secure Socket Layer), 39, 255, 257
 SSL Labs, 271
 static corruption, 318
 statistical test, 33–34
 streamability, 163, 167–169
 stream ciphers, 87
 counter-based, 89
 encryption and decryption, 88
 hardware-oriented, 89–90
 keystream, 88
 nonce reuse, 111
 software-oriented, 101
 stateful, 89
 Streebog, 127
 substitution boxes (S-boxes), 65
 substitution–permutation networks (SPNs), 65–68
 substitutions, 7
 superconducting circuits, 284
 superposition, 274
 symmetric encryption, 3, 18
 synthetic IV (SIV), 169
- T**
 tags, 18. *See also* authenticated encryption; MACs
 TEA, 137
 threshold signature protocol, 316
 time complexity, 180–182
 time-memory trade-off (TMTTO)
 attacks, 21, 48, 101
 timing attacks, 153–154, 208, 292
 TLS (Transport Layer Security), 39, 88, 140, 142, 159, 255
 ClientHello, 257, 264–267
 and Diffie–Hellman, 229
 downgrade protection, 266–267
 handshake, 257, 258–268
 history of, 257
 RC4 in, 102, 104–106
 record, 262
 record payload, 262
 record protocol, 257, 262
 security, 256, 268–271
 ServerHello, 257, 264–267
 session resumption, 267–268
 single round-trip handshake, 267
 version 1.3, 265–267
 zero padding, 263
 TLS Working Group (TLSWG), 271
 TMTTO (time-memory trade-off)
 attacks, 21, 48, 101
 TOFU (trust-on-first-use), 262
 traffic analysis, 263
 Transport Layer Security. *See* TLS
 trapdoor permutations, 196, 197, 199
 trapdoors, 196, 197–199
 traveling salesman problem, 184
 triple DES (3DES), 67, 82–83
 trusted third party, 258
 trust-on-first-use (TOFU), 262
 Turing Award, 216
 tweakable encryption (TE), 20–21
- U**
 UDP (User Datagram Protocol), 257
 unforgeability, 140
 uniform distribution, 27

unitary matrix, 279
universal hash functions, 148–149
Unix, 34
unpredictability, 117
upper bound, 46

V

Vandewalle, Joos, 137
van Oorschot, Paul C., 137
Vigenère, Blaise de, 5
Vigenère cipher, 5–6
virtual private network (VPN), 104

W

Wagner, David, 39, 41, 64, 112
Wegman–Carter MAC, 149–150, 155
Weierstrass form, 232
WEP (Wireless Encryption Protocol),
 102, 103–104
Wiener, Michael, 57, 137, 213
Wi-Fi, 87, 103–104
Wilcox-O’Hearn, Zooko, 133, 135
Windows, 37–38
Winnerlein, Christian, 133

Winternitz one-time signature

(WOTS), 288–289

Wireless Encryption Protocol (WEP),
 102, 103–104

WPA2, 174

Wustrow, Eric, 40, 251

X

Xbox, 137
XOR swap, 112–113

Y

Yao, Andrew C., 230
Yarrow, 30
Yung, Moti, 305

Z

zero-knowledge proof (ZKP),
 323–324
noninteractive, 326
0-RTT data, 267
Zhao, Yunlei, 230
zkSNARK, 327–329
ZUC, 102