The libpqcrypto software library for post-quantum cryptography

Daniel J. Bernstein
and many contributors

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Redesigning crypto for security

New requirements for crypto software engineering to avoid real-world crypto disasters:

- No data flow from secrets to array indices. Stops, e.g., 2016 CacheBleed attack.
- No data flow from secrets to branch conditions. Stops, e.g., 2018 RSA key-generation attack by Aldaya–García–Tapia–Brumley.
- No padding oracles. Stops, e.g., 2017 ROBOT attack.

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But wait, there’s more:

- **Centralizing randomness:**
  system has *one* central audited fast PRNG.
  Stops, e.g., Juniper fiasco discovered in 2015.

- **Avoiding unnecessary randomness:**
  use audited deterministic functions.
  Stops, e.g., 2017 ROCA attack.

- **Eliminate low-security options.**
  Stops, e.g., 2015 Logjam attack.
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Curve25519, Ed25519, etc.

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Example: Upgrading signatures.

- Use ECC, not RSA.

  Does the user really need “RSA signatures”? Or is the goal “high-security signatures”?
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Example: Upgrading signatures.

- Use ECC, not RSA. Does the user really need “RSA signatures”? Or is the goal “high-security signatures”?
- Use Curve25519, not NSA (NIST) curves. Simpler (and faster!) secure implementations.
- Use EdDS A (Ed25519), not NSA signatures. Avoid, e.g., hassle of implementing inversion.

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A modern cryptographic API

Most libraries provide simple all-in-one hashing:

```c
const unsigned char m[...];
unsigned long long mlen;
unsigned char h[crypto_hash_BYTES];
crypto_hash_sha256(h, m, mlen);
```
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crypto_sign_ed25519(sm,&smlen,m,mlen,sk);
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Implementation and deployment

Curve25519: iOS starting 2010; WhatsApp starting 2016; formal verif in Firefox starting 2017; etc.

NaCl software library (forks: TweetNaCl, libsodium): Curve25519, audited implementations, modern API.

Competitions: Modern API required for submissions to CAESAR, NIST PQC, NIST Lightweight Crypto.

SUPERCOP benchmarking framework:
Modern API, no requirement of constant-time etc. Currently 2330 implementations of 633 primitives.
All done?
The PQCRYPTO consortium

TU/e
BUNDES DRUCKEREI
DTU Danmarks Tekniske Universitet
Inria INVENTEURS DU MONDE NUMÉRIQUE
KU LEUVEN
NXP
Radboud Universiteit
University of Haifa

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Some broken systems in traditional PQ categories:
- Compact LWE, lattice-based encryption scheme.
- Edon-K, code-based encryption scheme.
- Giophantus, multivariate signature scheme.

Need detailed security analysis, not buzzwords.
50 signature systems in libpqcrypto

crypto_sign_dilithium{2,3,4}
crypto_sign_gui{184,312,448}
crypto_sign_luov{863256,890351,8117404,4849242,6468330,8086399}
crypto_sign_mqdss{48,64}
crypto_sign_picnicl{1,3,5}{fs,ur}
crypto_sign_qtesla{128,192,256}
crypto_sign_rainbow{1a,1b,1c,3b,3c,4a,5c,6a,6b}
crypto_sign_sphincs{f,s}{128,192,256}{haraka,sha256,shake256}
27 encryption systems in libpqcrypto

crypto_kem_bigquake{1,3,5}
crypto_kem_mceliece{6960119,8192128}
crypto_kem_kyber{512,768,1024}
crypto_kem_dags{3,5}
crypto_kem_frodokem{640,976}
crypto_kem_kindi{256342,256522,512222,512241,512321}
crypto_kem_newhope{512,1024}cca
crypto_kem_ntruhrss701
crypto_kem_{ntrulpr,sntrup}4591761
crypto_kem_ramstakers{216091,756839}
crypto_kem_{lightsaber,saber,firesaber}
NIST submissions vs. libpqcrypto

Each NIST submission includes software:
- a reference C implementation;
- in many cases, also fast implementations.

libpqcrypto integrates this software with
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- a unified Python interface;
- command-line sig/verif/enc/dec tools;
- command-line benchmarking tools.
C interface

```
unsigned char pk[pqcrypto_sign_gui184_PUBLICKEYBYTES];
unsigned char sk[pqcrypto_sign_gui184_SECRETKEYBYTES];
#define mlen 7
unsigned char m[mlen] = "hello\n";
unsigned char sm[pqcrypto_sign_gui184_BYTES + mlen];
unsigned long long smlen;
unsigned char t[sizeof sm];
unsigned long long tlen;
int main()
{
    if (pqcrypto_sign_gui184_keypair(pk,sk)) abort();
    if (pqcrypto_sign_gui184(sm,&smlen,m,mlen,sk)) abort();
    if (pqcrypto_sign_gui184_open(t,&tlen,sm,smlen,pk)) abort();
    if (tlen != mlen) abort();
    if (memcmp(t,m,mlen)) abort();
    return 0;
}
```
Python interface

Generate key pair:

\[
\text{pk, sk} = \text{pqcrypto.sign.gui184.keypair()}
\]

Sign message \( m \):

\[
\text{sm} = \text{pqcrypto.sign.gui184.sign}(m, \text{sk})
\]

Recover message from signed message:

\[
\text{m} = \text{pqcrypto.sign.gui184.open}(\text{sm, pk})
\]

If verification fails: exception and no output.
A larger Python example

Test script to sign and recover a message under a random key pair:

```python
import pqcrypto
sig = pqcrypto.sign.gui184
pk,sk = sig.keypair()
m = b"hello world"
sm = sig.sign(m,sk)
assert m == sig.open(sm,pk)
```
Command-line signature interface

Generate key pair:

    pq-keypair-gui184 5>publickey 9>secretkey

(Shell uses numbers to identify multiple outputs. Also makes tool easy to use from other languages.)

Sign message:

    pq-sign-gui184 <message 8<secretkey >sm

Recover message from signed message:

    pq-open-gui184 <sm 4<publickey >message
Benchmarking one system

$ pq-size-gui184
gui184 size
  publickey 422122
  secretkey 14985
  signature 45

$ pq-speed-gui184
gui184 speed
  keypair 375801649 378277969 389764325
  sign 13406823 18715903 40190324
  open 141531 141698 142025

$ pq-notes-gui184
gui184 implementation crypto_sign/gui184/pclmulqdq
gui184 version -
gui184 compiler gcc -fPIC -Wall -march=native
  -mtune=native -O3 -fomit-frame-pointer -fwrapv
## Benchmarking all systems

```bash
$ pq-size-all
dilithium2 size publickey 1184 secretkey 2800 signature 2044
dilithium3 size publickey 1472 secretkey 3504 signature 2701
dilithium4 size publickey 1760 secretkey 3856 signature 3366
gui184 size publickey 422122 secretkey 14985 signature 45
gui312 size publickey 1990045 secretkey 41755 signature 63
gui448 size publickey 5903405 secretkey 94757 signature 83
luov4849242 size publickey 7536 secretkey 32 signature 1746
luov6468330 size publickey 19973 secretkey 32 signature 3184
luov8086399 size publickey 40248 secretkey 32 signature 4850
luov8117404 size publickey 100989 secretkey 32 signature 521
luov863256 size publickey 15908 secretkey 32 signature 319
luov890351 size publickey 46101 secretkey 32 signature 441
mqdss48 size publickey 62 secretkey 32 signature 32882
mqdss64 size publickey 88 secretkey 48 signature 67800
picnic1lfs size publickey 33 secretkey 49 signature 34004
```

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Benchmarking all systems

picnicl1ur size publickey 33 secretkey 49 signature 53933
picnicl3fs size publickey 49 secretkey 73 signature 76744
picnicl3ur size publickey 49 secretkey 73 signature 121817
picnicl5fs size publickey 65 secretkey 97 signature 132828
picnicl5ur size publickey 65 secretkey 97 signature 209478
qtesla128 size publickey 4128 secretkey 2112 signature 3104
qtesla192 size publickey 8224 secretkey 8256 signature 6176
qtesla256 size publickey 8224 secretkey 8256 signature 6176
rainbow1a size publickey 152097 secretkey 100209 signature 64
rainbow1b size publickey 163185 secretkey 114308 signature 78
rainbow1c size publickey 192241 secretkey 143385 signature 104
rainbow3b size publickey 564535 secretkey 409463 signature 112
rainbow3c size publickey 720793 secretkey 537781 signature 156
rainbow4a size publickey 565489 secretkey 376141 signature 92
rainbow5c size publickey 1723681 secretkey 1274317 signature 204
rainbow6a size publickey 1351361 secretkey 892079 signature 118
Benchmarking all systems

rainbow6b size publickey 1456225 secretkey 1016868 signature 147
sphincs128haraka size publickey 32 secretkey 64 signature 16976
sphincs128sha256 size publickey 32 secretkey 64 signature 16976
sphincs128shake256 size publickey 32 secretkey 64 signature 16976
sphincs192haraka size publickey 48 secretkey 96 signature 35664
sphincs192sha256 size publickey 48 secretkey 96 signature 35664
sphincs192shake256 size publickey 48 secretkey 96 signature 35664
sphincs256haraka size publickey 64 secretkey 128 signature 49216
sphincs256sha256 size publickey 64 secretkey 128 signature 49216
sphincs256shake256 size publickey 64 secretkey 128 signature 49216
sphincss128haraka size publickey 32 secretkey 64 signature 8080
sphincss128sha256 size publickey 32 secretkey 64 signature 8080
sphincss128shake256 size publickey 32 secretkey 64 signature 8080
sphincss192haraka size publickey 48 secretkey 96 signature 17064
sphincss192sha256 size publickey 48 secretkey 96 signature 17064
sphincss192shake256 size publickey 48 secretkey 96 signature 17064
Benchmarking all systems

sphincss256haraka size publickey 64 secretkey 128 signature 2979
sphincss256sha256 size publickey 64 secretkey 128 signature 2979
sphincss256shake256 size publickey 64 secretkey 128 signature 2979
bigquake1 size publickey 25482 secretkey 14772 ciphertext 201 sessionkey 32
bigquake3 size publickey 84132 secretkey 30860 ciphertext 406 sessionkey 32
bigquake5 size publickey 149800 secretkey 41804 ciphertext 492 sessionkey 32
dags3 size publickey 11616 secretkey 2973704 ciphertext 2144 sessionkey 64
dags5 size publickey 11616 secretkey 2973704 ciphertext 2144 sessionkey 64
firesaber size publickey 1312 secretkey 3040 ciphertext 1472 sessionkey 32
frodokem640 size publickey 9616 secretkey 19872 ciphertext 9736
frodokem976 size publickey 15632 secretkey 31272 ciphertext 1576
kindi256342 size publickey 1184 secretkey 1472 ciphertext 1824 sessionkey 32
kindi256522 size publickey 1984 secretkey 2304 ciphertext 2752 sessionkey 32
kindi512222 size publickey 1456 secretkey 1712 ciphertext 2544 sessionkey 32
kindi512241 size publickey 1728 secretkey 2112 ciphertext 2752 sessionkey 32
kindi512321 size publickey 2368 secretkey 2752 ciphertext 3392 sessionkey 32

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kyber1024 size publickey 1440 secretkey 3168 ciphertext 1504 sessionkey 32
kyber512 size publickey 736 secretkey 1632 ciphertext 800 sessionkey 32
kyber768 size publickey 1088 secretkey 2400 ciphertext 1152 sessionkey 32
lightsaber size publickey 672 secretkey 1568 ciphertext 736 sessionkey 32
mceliece6960119 size publickey 1047319 secretkey 13908 ciphertext 226 sessionkey 32
mceliece8192128 size publickey 1357824 secretkey 14080 ciphertext 240 sessionkey 32
newhope1024cca size publickey 1824 secretkey 3680 ciphertext 220 sessionkey 32
newhope512cca size publickey 928 secretkey 1888 ciphertext 1120 sessionkey 32
ntruhrss701 size publickey 1138 secretkey 1418 ciphertext 1278 sessionkey 32
ntrulpr4591761 size publickey 1047 secretkey 1238 ciphertext 117 sessionkey 32
ramstakers216091 size publickey 27044 secretkey 54056 ciphertext 1088 sessionkey 32
ramstakers756839 size publickey 94637 secretkey 189242 ciphertext 1088 sessionkey 32
saber size publickey 992 secretkey 2304 ciphertext 1088 sessionkey 32
sntrup4591761 size publickey 1218 secretkey 1600 ciphertext 1047 sessionkey 32
Signature size \((y)\) vs. public-key size \((x)\)
The future

Various libpqcrypto goals and ongoing work:

- Following constant-time rules.  
  Already done for *some* implementations.
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▶ More tests, audits. Everything already passes Valgrind and ASan *except* NTRU-HRSS-KEM.
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- Less CPU time. Already many speedups.
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- Reducing code volume: e.g., SHA-3 merge.

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▶ Long term: Reduce number of primitives.