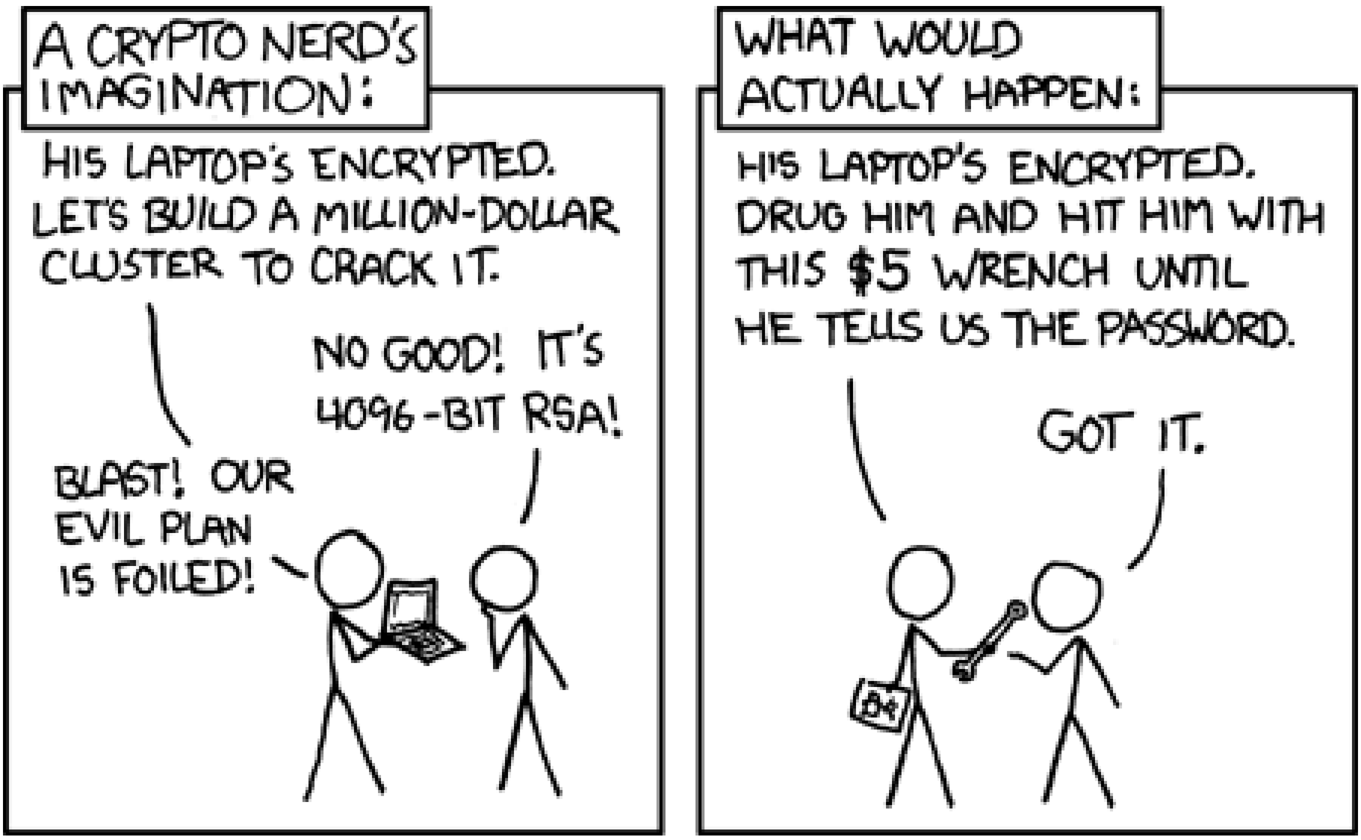
NaCl: a new crypto library

D. J. Bernstein, U. Illinois Chicago
& T. U. Eindhoven
Tanja Lange, T. U. Eindhoven

Joint work with:
Peter Schwabe, R. U. Nijmegen



xkcd.com/538/

AES-128, RSA-2048, etc.
are widely accepted standards.

Obviously infeasible to break
by best attacks in literature.

Implementations are available
in public cryptographic libraries
such as OpenSSL.

Common security practice is
to use those implementations.

AES-128, RSA-2048, etc.
are widely accepted standards.

Obviously infeasible to break
by best attacks in literature.

Implementations are available
in public cryptographic libraries
such as OpenSSL.

Common security practice is
to use those implementations.

But cryptography is still
a disaster! Complete failures
of confidentiality and integrity.

We have designed+implemented a new cryptographic library, NaCl ("salt"), to address the underlying problems.

nacl.cr.yp.to: source and extensive documentation.

Acknowledgments:
code contributions from Matthew Dempsky (Mochi Media), Niels Duif (Eindhoven), Emilia Käsper (Leuven), Adam Langley (Google), Bo-Yin Yang (Academia Sinica).

Most of the Internet
is cryptographically unprotected.
Primary goal of NaCl: Fix this.

Main task: **public-key authenticated encryption**.

Alice has a message m for Bob.

Uses Bob's public key and Alice's secret key to compute authenticated ciphertext c.
Sends c to Bob.

Bob uses Alice's public key and Bob's secret key to verify and recover m.

Alice using a
typical cryptographic library:

Generate random AES key.
Use AES key to encrypt packet.
Hash encrypted packet.
Read RSA key from wire format.
Use key to sign hash.
Read Bob's key from wire format.
Use key to encrypt signature etc.
Convert to wire format.

Plus more code:
allocate storage,
handle errors, etc.

Alice using NaCl:

`c = crypto_box(m,n,pk,sk)`

Alice using NaCl:

`c = crypto_box(m,n,pk,sk)`

32-byte secret key `sk`.
32-byte public key `pk`.
24-byte nonce `n`.
`c` is 16 bytes longer than `m`.

All objects are C++ `std::string` variables represented in wire format, ready for storage/transmission.

C NaCl: similar, using pointers; no memory allocation, no failures.

Bob verifying, decrypting:

```
m=crypto_box_open(c,n,pk,sk)
```

Initial key generation:

```
pk = crypto_box_keypair(&sk)
```

Bob verifying, decrypting:

`m=crypto_box_open(c,n,pk,sk)`

Initial key generation:

`pk = crypto_box_keypair(&sk)`

Can instead use **signatures** for public messages:

`pk = crypto_sign_keypair(&sk)`

64-byte secret key,
32-byte public key.

`sm = crypto_sign(m,sk)`

64 bytes overhead.

`m = crypto_sign_open(sm,pk)`

“This sounds too simple!
Don’t applications need more?”

“This sound too simple!
Don’t applications need more?”

Examples of applications
using NaCl’s `crypto_box`:

DNSCurve and DNSCrypt,
high-security authenticated
encryption for DNS queries;
deployed by OpenDNS.

QUIC, Google’s TLS replacement.

MinimaLT in Ethos OS,
faster TLS replacement.

Threema, encrypted-chat app.

Related projects

Various ports, repackaging, language bindings, etc.: e.g., github.com/jedisct1/libsodium

TweetNaCl: NaCl in 100 tweets; on the path towards full audit. Bernstein, van Gastel, Janssen, Lange, Schwabe, Smetsers.
tweetnacl.cr.yp.to
twitter.com/tweetnacl

Benchmarking of >1000 crypto implementations using same API:
bench.cr.yp.to

No secret load addresses

2005 Osvik–Shamir–Tromer:
65ms to steal Linux AES key
used for hard-disk encryption.
Attack process on same CPU
but without privileges.

Almost all AES implementations
use fast lookup tables.
Kernel's secret AES key
influences table-load addresses,
influencing CPU cache state,
influencing measurable timings
of the attack process.
65ms to compute influence^{-1}.

Most cryptographic libraries
still use secret load addresses
but add "countermeasures"
intended to obscure influence
upon the CPU cache state.
Not confidence-inspiring;
likely to be breakable.

Most cryptographic libraries still use secret load addresses but add “countermeasures” intended to obscure influence upon the CPU cache state. Not confidence-inspiring; likely to be breakable.

NaCl systematically avoids *all* loads from addresses that depend on secret data. Eliminates this type of disaster.

Timing attack+defense tutorial: Schwabe talk tomorrow 11:00.

No secret branch conditions

2011 Brumley–Tuveri:
minutes to steal another machine's OpenSSL ECDSA key.
Secret branch conditions influence timings.

Most cryptographic software has many more small-scale variations in timing:
e.g., `memcmp` for IPsec MACs.

No secret branch conditions

2011 Brumley–Tuveri:
minutes to steal another
machine's OpenSSL ECDSA key.
Secret branch conditions
influence timings.

Most cryptographic software
has many more small-scale
variations in timing:
e.g., `memcmp` for IPsec MACs.

NaCl systematically avoids
all branch conditions
that depend on secret data.
Eliminates this type of disaster.

No padding oracles

1998 Bleichenbacher:
Decrypt SSL RSA ciphertext
by observing server responses
to $\approx 10^6$ variants of ciphertext.

SSL first inverts RSA,
then checks for “PKCS padding”
(which many forgeries have).
Subsequent processing applies
more serious integrity checks.

Server responses reveal
pattern of PKCS forgeries;
pattern reveals plaintext.

Typical defense strategy:
try to hide differences
between padding checks and
subsequent integrity checks.

But hard to get this right:
see, e.g., Lucky 13 and POODLE.

Typical defense strategy:
try to hide differences
between padding checks and
subsequent integrity checks.

But hard to get this right:
see, e.g., Lucky 13 and POODLE.

NaCl does not decrypt
unless message is authenticated.
Verification procedure rejects
all forgeries in constant time.
Attacks are further constrained
by per-nonce key separation
and standard nonce handling.

Centralizing randomness

2008 Bello: Debian/Ubuntu OpenSSL keys for 1.5 years had only 15 bits of entropy.

Debian developer had removed a subtle line of OpenSSL randomness-generating code.

Centralizing randomness

2008 Bello: Debian/Ubuntu OpenSSL keys for 1.5 years had only 15 bits of entropy.

Debian developer had removed a subtle line of OpenSSL randomness-generating code.

NaCl uses `/dev/urandom`, the OS random-number generator. Reviewing this kernel code is much more tractable than reviewing separate RNG code in every security library.

Centralization allows OS to merge many entropy sources into pool feeding many applications.

Merging is deterministic and auditable. Can survive many bad/failing/malicious sources if there is one good source.

Centralization allows OS to
merge many entropy sources into
pool feeding many applications.

Merging is deterministic and
auditable. Can survive many
bad/failing/malicious sources
if there is one good source.

Huge step backwards:
Intel's RDRAND in applications.
Single entropy source; no backup;
likely to be poorly cloned;
backdoorable (CHES 2013);
non-auditable. Not used in NaCl.

Avoiding unnecessary randomness

2010 Bushing–Marcan–Segher–Sven: Sony ignored ECDSA requirement of new randomness for each signature. $\Rightarrow$ Signatures leaked PS3 code-signing key.

Avoiding unnecessary randomness

2010 Bushing–Marcan–Segher–Sven: Sony ignored ECDSA requirement of new randomness for each signature. $\Rightarrow$ Signatures leaked PS3 code-signing key.

NaCl has *deterministic* `crypto_box` and `crypto_sign`. Randomness only for `keypair`. Eliminates this type of disaster.

Also simplifies testing. NaCl uses automated test battery from `bench.cr.yp.to`.

Avoiding pure crypto failures

2008 Stevens–Sotirov–Appelbaum–Lenstra–Molnar–Osvik–de Weger exploited MD5 $\Rightarrow$ rogue CA cert.

Avoiding pure crypto failures

2008 Stevens–Sotirov–
Appelbaum–Lenstra–Molnar–
Osvik–de Weger exploited
MD5 $\Rightarrow$ rogue CA cert.
2012 Flame: new MD5 attack.

Avoiding pure crypto failures

2008 Stevens–Sotirov–
Appelbaum–Lenstra–Molnar–
Osvik–de Weger exploited
MD5 $\Rightarrow$ rogue CA cert.
2012 Flame: new MD5 attack.

Fact: By 1996, a few years after the introduction of MD5, Preneel and Dobbertin were calling for MD5 to be scrapped.

NaCl *pays attention to cryptanalysis* and makes very conservative choices of cryptographic primitives.

Speed

Crypto performance problems often lead users to reduce cryptographic security levels or give up on cryptography.

Example 1: Google SSL used RSA-1024 until 2013.

Security note:
Analyses in 2003 concluded that RSA-1024 was breakable; e.g., 2003 Shamir–Tromer estimated 1 year, $\approx 10^7$ USD.
RSA Labs and NIST response: Move to RSA-2048 by 2010.

Example 2: Tor used RSA-1024 until 2013 switch to Curve25519.

Example 3: DNSSEC uses RSA-1024: "tradeoff between the risk of key compromise and performance. . . "

Example 4: OpenSSL on ARM uses secret AES load addresses.

Example 5:
`https://sourceforge.net/account`
is protected by SSL but
`https://sourceforge.net/develop`
turns off crypto: redirects to
`http://sourceforge.net/develop`.

NaCl has no low-security options.

e.g. `crypto_box` always
encrypts *and* authenticates.

e.g. no RSA-1024;
not even RSA-2048.

NaCl has no low-security options.

e.g. `crypto_box` always
encrypts *and* authenticates.

e.g. no RSA-1024;
not even RSA-2048.

Remaining risk:
Users find NaCl too slow $\Rightarrow$
switch to low-security libraries
or disable crypto entirely.

NaCl has no low-security options.

e.g. `crypto_box` always
encrypts *and* authenticates.

e.g. no RSA-1024;
not even RSA-2048.

Remaining risk:
Users find NaCl too slow $\Rightarrow$
switch to low-security libraries
or disable crypto entirely.

How NaCl avoids this risk:
NaCl is exceptionally fast.
Much faster than other libraries.
Keeps up with the network.

NaCl operations per second for any common packet size, using AMD Phenom II X6 1100T CPU ($190 in 2011):

`crypto_box`: $>$80000.

`crypto_box_open`: $>$80000.

`crypto_sign_open`: $>$70000.

`crypto_sign`: $>$180000.

NaCl operations per second
for any common packet size,
using AMD Phenom II X6 1100T
CPU ($190 in 2011):

crypto_box: >80000.

crypto_box_open: >80000.

crypto_sign_open: >70000.

crypto_sign: >180000.

Handles arbitrary packet floods
up to ≈30 Mbps per CPU,
depending on protocol details.

But wait, it's even faster!

1. Pure secret-key crypto
for any packet size:
80000 1500-byte packets/second
fill up a 1 Gbps link.

2. Pure secret-key crypto
for many packets
from same public key,
if application splits
`crypto_box` into
`crypto_box_beforenm` and
`crypto_box_afternm`.

3. Very fast rejection
of forged packets
under known public keys:
no time spent on decryption.

(This doesn't help much
for forgeries under *new* keys,
but flooded server can
continue providing fast service
to *known* keys.)

4. Fast batch verification,
doubling speed of
`crypto_sign_open`
for valid signatures.

Also fast on small devices.

"NEON crypto" (CHES 2012)
on 1GHz ARM Cortex-A8 core:
498349 cycles (2000/second)
+ 7.78 cycles/byte (1 Gbps)
for `box`; and for `verify`:
624846 cycles (1600/second).

Also fast on small devices.

“NEON crypto” (CHES 2012)
on 1GHz ARM Cortex-A8 core:
498349 cycles (2000/second)
+ 7.78 cycles/byte (1 Gbps)
for `box`; and for `verify`:
624846 cycles (1600/second).

1GHz Cortex-A8 was high-end
smartphone core in 2010: e.g.,
Samsung Exynos 3110 (Galaxy S);
TI OMAP3630 (Motorola Droid
X); Apple A4 (iPad 1/iPhone 4).

Also fast on small devices.

“NEON crypto” (CHES 2012) on 1GHz ARM Cortex-A8 core: 498349 cycles (2000/second) + 7.78 cycles/byte (1 Gbps) for `box`; and for `verify`: 624846 cycles (1600/second).

1GHz Cortex-A8 was high-end smartphone core in 2010: e.g., Samsung Exynos 3110 (Galaxy S); TI OMAP3630 (Motorola Droid X); Apple A4 (iPad 1/iPhone 4).

2013: Allwinner A13, $5 in bulk.

Cryptographic details

The main NaCl work we did: achieve very high speeds *without* compromising security.

ECC, not RSA: much stronger security record.

Curve25519, not NSA/NIST curves: `safecurves.cr.yp.to`

Salsa20, not AES: much larger security margin.

Poly1305, not HMAC: information-theoretic security.

EdDSA, not ECDSA: collision-resilience et al.

Case study: EdDSA

1985 ElGamal signatures:
(R, S) is signature of M
if $B^{H(M)} \equiv A^R R^S \pmod q$
and $R, S \in \{0, 1, \ldots, q-2\}$.

Here q is standard prime,
B is standard base,
A is signer's public key,
$H(M)$ is hash of message.

Signer generates A and R
as secret powers of B;
easily solves for S.

1990 Schnorr improvements:

1. Hash R in the exponent:
$B^{H(M)} \equiv A^{H(R)} R^S$.
Reduces attacker control.

2. Replace three exponents with two exponents:
$B^{H(M)/H(R)} \equiv A R^{S/H(R)}$.
Saves time in verification.

3. Simplify by relabeling S:
$B^{H(M)/H(R)} \equiv A R^S$.
Saves time in verification.

4. Merge the hashes:
$B^{H(R,M)} \equiv A R^S$.
$\Rightarrow$ Resilient to H collisions.

5. Eliminate inversions for signer:
$B^S \equiv RA^{H(R,M)}$.
Simpler, faster.

6. Compress R to $H(R, M)$.
Saves space in signatures.

7. Use half-size H output.
Saves space in signatures.

5. Eliminate inversions for signer:
$B^S \equiv RA^{H(R,M)}$.
Simpler, faster.

6. Compress R to $H(R, M)$.
Saves space in signatures.

7. Use half-size H output.
Saves space in signatures.

Subsequent research:
extensive theoretical study of
security of Schnorr's system.

5. Eliminate inversions for signer: $B^S \equiv RA^{H(R,M)}$.
Simpler, faster.

6. Compress R to $H(R, M)$.
Saves space in signatures.

7. Use half-size H output.
Saves space in signatures.

Subsequent research:
extensive theoretical study of security of Schnorr's system.

But patented. $\Rightarrow$ DSA, ECDSA avoided most improvements.

5. Eliminate inversions for signer:
$B^S \equiv RA^{H(R,M)}$.
Simpler, faster.

6. Compress R to $H(R, M)$.
Saves space in signatures.

7. Use half-size H output.
Saves space in signatures.

Subsequent research:
extensive theoretical study of
security of Schnorr's system.

But patented. $\Rightarrow$ DSA, ECDSA
avoided most improvements.

Patent expired in 2008.

EdDSA (CHES 2011 Bernstein–Duif–Lange–Schwabe–Yang):

Use elliptic curves in "complete -1-twisted Edwards" form.
$\Rightarrow$ very high speed,
natural side-channel protection,
no exceptional cases.

Skip signature compression.
Support batch verification.

Use double-size H output,
and include A as input.

Generate R deterministically
as a secret hash of M.
$\Rightarrow$ Avoid PlayStation disaster.