# How fast is cryptography?

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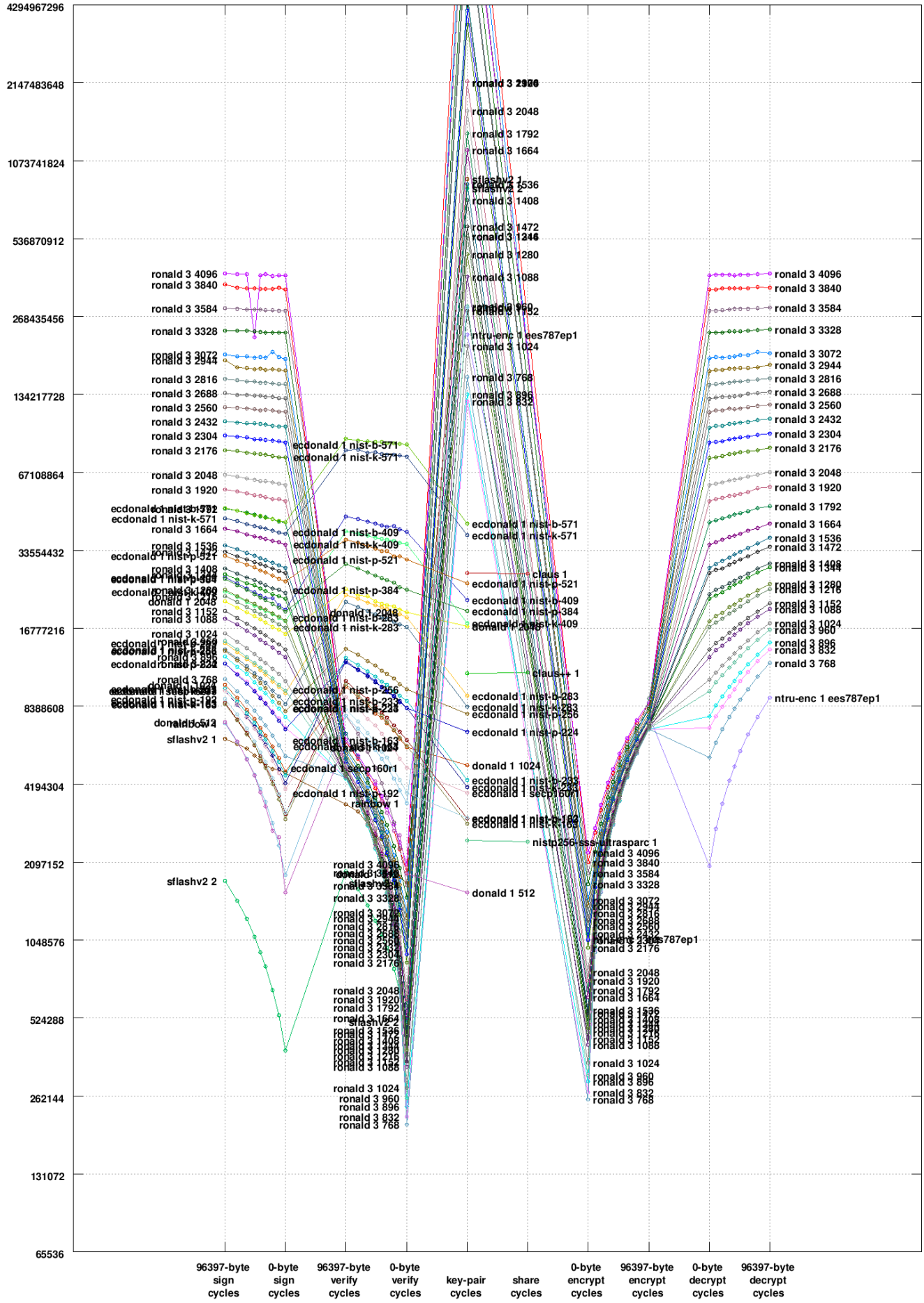
Part of the eBATS project
(ECRYPT Benchmarking
of Asymmetric Systems):
`www.ecrypt.eu.org/ebats`

. . . in ECRYPT's VAMPIRE lab:
`www.ecrypt.eu.org`


4294967296
2147483648
1073741824
536870912
268435456
134217728
67108864
33554432
16777216
8388608
4194304
2097152
1048576
524288
262144
131072
65536
96397-byte sign cycles
0-byte sign cycles
96397-byte verify cycles
0-byte verify cycles
key-pair cycles
share cycles
0-byte encrypt cycles
96397-byte encrypt cycles
0-byte decrypt cycles
96397-byte decrypt cycles
ronald 3 4096
ronald 3 3840
ronald 3 3584
ronald 3 3328
ronald 3 3072
ronald 3 2944
ronald 3 2816
ronald 3 2688
ronald 3 2560
ronald 3 2432
ronald 3 2304
ronald 3 2176
ronald 3 2048
ronald 3 1920
ronald 3 1792
ronald 3 1664
ronald 3 1536
ronald 3 1472
ronald 3 1408
ronald 3 1344
ronald 3 1280
ronald 3 1216
ronald 3 1152
ronald 3 1088
ronald 3 1024
ronald 3 960
ronald 3 896
ronald 3 832
ronald 3 768
ntru-enc 1 ees787ep1
sflashv2 1
sflashv2 2
ecdonald 1 nist-b-571
ecdonald 1 nist-k-571
ecdonald 1 nist-b-409
ecdonald 1 nist-k-409
ecdonald 1 nist-p-521
ecdonald 1 nist-p-384
ecdonald 1 nist-b-283
ecdonald 1 nist-k-283
ecdonald 1 nist-p-256
ecdonald 1 nist-b-233
ecdonald 1 nist-k-233
ecdonald 1 nist-p-224
ecdonald 1 nist-b-163
ecdonald 1 nist-k-163
ecdonald 1 secp160r1
ecdonald 1 nist-p-192
rainbow 1
donald 1 2048
donald 1 1024
donald 1 512
claus 1
claus++ 1
nistp256-sse2-ultrasparc 1

`donald 1024` is software
that uses the OpenSSL library
to implement 1024-bit DSA.

Some space measurements
for `donald 1024`:

148 bytes in secret key.
128 bytes in public key.

40-byte overhead
to sign 23-byte message.

40-byte overhead
to sign 147-byte message.

40-byte overhead
to sign 709-byte message.

Timings of `donald 1024` on
a 2137MHz Intel Core 2 Duo,
`katana`, in 64-bit mode:

1041400 cycles
to sign a 59-byte message.
(This is median of many
successive measurements:
1034320 1034360 1038944
1044200 1040432 1041920
1041400 1045296 1049856 etc.)

1246312 cycles
to verify the signature.

1084424 cycles
to generate a key pair.

Timings of `donald 1024` on
an 800MHz Intel Pentium M 6d8,
`atlas`, in 32-bit mode:

2778564 cycles
to sign a 59-byte message.

3329580 cycles
to verify the signature.
(3303976 3336154 3298904
3297910 3892409 3356303
3301620 3298139 3319748 etc.
Note the 3892409 jump.)

2939180 cycles
to generate a key pair.

And: amd64 AMD Athlon 64 X2;
amd64 AMD Opteron 250; same;
amd64 Intel Pentium 4 f43;
ia64 HP Itanium II; same;
ppc32 Motorola PowerPC G4;
sparcv9 Sun UltraSPARC IV;
x86 Intel Pentium 52c, 133MHz!;
x86 AMD Athlon 622;
x86 Intel Pentium III 68a;
x86 Intel Pentium III 6b1; same;
x86 Intel Pentium 4 f12;
x86 Intel Xeon f25; same;
x86 Intel Pentium 4 f26;
x86 Intel Pentium 4 f29; same;
x86 Intel Pentium 4 f41.

| | | |
|---|---|---|
| Signing 59 bytes with `donald` `1024` | 793647 | Itanium II |
| | 842993 | Athlon 64 X2 |
| | 1041400 | Core 2 Duo |
| | 2176845 | P4 f43 |
| | 2778564 | PM 6d8 |
| | 2990808 | Athlon 622 |
| | 3626841 | PIII 6b1 |
| | 3729408 | PIII 68a |
| | 4185764 | P4 f26 |
| | 4252822 | P4 f41 |
| | 4411412 | Xeon f25 |
| | 4665480 | P4 f12 |
| | 4727730 | USPARC IV |
| | 5704242 | P1 52c |
| | 5732928 | PowerPC G4 |

| | |
|---|---|
| Signing 59 bytes with `donald` 2048 | 1805770 Itanium II |
| | 2387880 Athlon 64 X2 |
| | 3207200 Core 2 Duo |
| | 6861675 P4 f43 |
| | 8775306 PM 6d8 |
| | 9727110 Athlon 622 |
| | 11942839 PIII 6b1 |
| | 12023567 PIII 68a |
| | 12953340 P4 f41 |
| | 13145028 P4 f26 |
| | 13279464 Xeon f25 |
| | 14527024 P4 f12 |
| | 15906325 USPARC IV |
| | 18835618 P1 52c |
| | 20117584 PowerPC G4 |

`ecdonald` uses OpenSSL
to implement ECDSA
with various elliptic curves.

`secp160r1`: 60-byte secret,
40-byte public, 40-byte overhead.
`nist-k-163`: 63, 42, 42. And `b`.
`nist-p-192`: 72, 48, 48.
`nist-p-224`: 84, 56, 56.
`nist-k-233`: 90, 60, 60.
`nist-p-256`: 96, 64, 64.
`nist-k-283`: 108, 72, 72.
`nist-p-384`: 144, 96, 96.
`nist-k-409`: 156, 104, 104.
`nist-p-521`: 198, 132, 132.
`nist-k-571`: 216, 144, 144.

| | |
|---|---|
| Signing 59 bytes with `ec donald nist-p-192` | 1539854 Athlon 64 X2 |
| | 1564616 Core 2 Duo |
| | 2078855 Itanium II |
| | 2843992 P4 f43 |
| | 3075466 PM 6d8 |
| | 3235785 USPARC IV |
| | 3341610 Athlon 622 |
| | 3444960 PowerPC G4 |
| | 3887873 PIII 6b1 |
| | 4275010 PIII 68a |
| | 4501108 P4 f26 |
| | 4517456 Xeon f25 |
| | 4619136 P4 f12 |
| | 5277690 P4 f41 |
| | 8934562 P1 52c |

Verification on Pentium 4 f41:

```
 1883115 donald 512
 5226810 donald 1024
 6292440 ecdonald nist-p-192
 6465570 ecdonald secp160r1
 8614845 ecdonald nist-p-224
10061108 ecdonald nist-k-163
10968060 ecdonald nist-b-163
11182065 ecdonald nist-p-256
15582517 donald 2048
19568820 ecdonald nist-k-233
21496155 ecdonald nist-b-233
25563608 ecdonald nist-p-384
35552528 ecdonald nist-k-283
39450120 ecdonald nist-b-283
```

But wait, there's more!

`ronald`: RSA signatures.

`sflashv2`, contributed by Goubin/Courtois/Icart: SFLASHv2 MQ signatures.

`rainbow`, contributed by Ding/Schmidt: Rainbow MQ signatures.

`bls`, contributed by Scott: pairing-based short signatures.

Many different parameters.
Total: 110 signature systems.
Let's compare a few.

Verification on Pentium 4 f29:

```
   216488 ronald 1024
   421428 sflashv2
   535888 ronald 2048
  1643700 ronald 4096
  2939944 rainbow
  5108824 donald 1024
  5621296 ecdonald p-192
  9692816 ecdonald p-256
 15037960 donald 2048
 30479432 bls
```

Signing, same CPU:

```
   327292 sflashv2
  1254616 rainbow
  2498280 bls
  4212528 donald 1024
  4527152 ecdonald p-192
  8021896 ecdonald p-256
 11041108 ronald 1024
 12417592 donald 2048
 57801612 ronald 2048
318750812 ronald 4096
```

Key-pair generation, same CPU:

```
   4380304 donald 1024
   4410428 ecdonald p-192
   7819568 ecdonald p-256
  14435940 donald 2048
  20060932 bls
 226258044 ronald 1024
 275282008 rainbow
 447858256 sflashv2
2273511680 ronald 2048
23087093020 ronald 4096
```

Key bytes and $(23, 709)$ overhead:

| | | | | |
|---|---|---|---|---|
| 72 | 48 | 48 | 48 | `ecd p-192` |
| 96 | 64 | 64 | 64 | `ecd p-256` |
| 20 | 120 | 20 | 20 | `bls` |
| 148 | 128 | 40 | 40 | `donald 1024` |
| 1024 | 128 | 105 | 43 | `ronald 1024` |
| 276 | 256 | 40 | 40 | `donald 2048` |
| 2048 | 256 | 233 | 43 | `ronald 2048` |
| 4096 | 512 | 489 | 43 | `ronald 4096` |
| 2823 | 19266 | 37 | 37 | `sflashv2` |
| 20107 | 31680 | 43 | 43 | `rainbow` |

Note the 43-byte overhead for `ronald 4096` to sign 709-byte message. "Message recovery."

But wait, there's more!

`claus` and `claus++`:
Classic DH mod a 1024-bit prime,
using OpenSSL and GMP/NTL.

`curve25519-gaudry`, contributed
by Gaudry: ECDH mod $2^{255} - 19$.

`nistp256-sss-ultrasparc`,
contributed by Nawaz/Gong:
ECDH using NIST P-256.

`ntru-enc`, contributed by Etzel.

`surf127eps`, contributed by
Gaudry/Houtmann/Thomé:
genus-2 HECDH mod $2^{127} - 735$.

DH cycles on Pentium 4 f29:

```
 3105704 surf127eps
 3119684 curve25519-gaudry
13644364 claus++
24422484 claus
```

DH cycles on Core 2 Duo:

```
  591504 curve25519-gaudry
  658128 surf127eps
 4555240 claus++
 5734944 claus
```

DH cycles on UltraSPARC:

```
 2537798 nistp256-sss
11237085 claus++
27377275 claus
```

Complete database of
time/space/etc. measurements
is available online
in a documented format
designed for easy parsing.

Many signature systems,
encryption systems, DH;
many message lengths;
22 different machines;
many successive measurements;
3550495 lines overall.
80 megabytes compressed.

## Collecting the measurements

Built an API for BATs (Benchmarkable Asymmetric Tools) such as `donald`.

API specifies functions such as `keypair` for BATs to implement.

API was designed to minimize effort required to write a BAT. Examples: some BATs handle long messages; some BATs insist on short messages; some BATs are parametrized; some BATs insist on specific sizes; BATs can assume that GMP is available.

Built BATMAN (Benchmarking of Asymmetric Tools on Multiple Architectures, Non-interactively) software that measures BATs.

BATMAN tries (e.g.)
`donald 1024` on `katana`
under many compilers,
selects the best compiler
for `donald 1024` on `katana`,
and measures `donald 1024`
on `katana` with that compiler.

BAT can specify
multiple "tunings"
to try with each compiler.

To save time,
if a compiler flunks
some simple tests on `katana`,
BATMAN skips the compiler
for all BATs on `katana`.

Median of cycle counts is
much more stable than average.
Allows very fast measurements.

Collecting complete database
took tolerable amount
of CPU time:
27819 seconds on `katana`,
548297 seconds on a
533MHz PowerPC G4, etc.

## Why measure many machines?

Performance of cryptography
is heavily influenced by CPU
(and other machine features).

Switching from $\mu$s to cycles
reduces CPU dependence
but does not eliminate it.

Paper 1: "$X$: 20000 P4 cycles."
Paper 2: "$Y$: 15% faster, 17000
PM cycles." Often $Y$ is slower
than $X$ on *both* P4 and PM!

Sometimes $Y$ is faster than $X$ on
one CPU but slower on another.

How VAMPIRE adds CPUs:

1. Find machine with usable OS, including reasonable compiler.
Surely we can share?

2. Port GMP/NTL/OpenSSL.
Sometimes quite difficult.
Need better config scripts.

3. Set up a BATMAN account.

4. Port BATMAN. Usually easy.

5. Run BATMAN. Very easy.
(Can imagine fully automatic timing of subsequent BATs in appropriate sandboxes.)

## Security evaluations

Do users want the
smallest, fastest cryptosystems?
Not exactly.

Users want the
smallest, fastest cryptosystems
*that provide an*
*acceptable security level*.

Can reduce time and space
by reducing security level.
Example: `donald 512`
is faster than `donald 1024`.

eBATS API allows BAT to
state its conjectured security level.

Much harder to verify than
time/space measurements, but
still extremely important for users.

VAMPIRE plans to highlight
security-aware comparisons
in the next eBATS report.

Question: Should BATtacks
be separated from BATs,
allowing cryptanalysts
to submit separate declarations?

# More BATs; faster BATs

Existing BATs cover
many public-key systems.
Often state-of-the-art software.
Thanks for all the contributions!

Implement additional systems?
e.g. more post-quantum systems?

Speed up existing systems?

Modify systems to save space?

Protect against timing attacks
and other side-channel attacks?

VAMPIRE is developing
more BATs . . . and so are you!
e.g. `mceliece-1` from Sendrier.

Some BAT speedups
will need API extensions:

- Signers with state:
  e.g., Merkle hash trees.
- Batch operations:
  e.g., batch DSA verification.
- $(k, m, s)$ compression:
  e.g., Bleichenbacher's
  vanishing RSA.

The eBATS competition:
Build the most efficient
public-key software.

Speed improvements should be
easy to express in BATs.
If not, let us know!

Space improvements should be
easy to express in BATs.
If not, let us know!

All improvements should be
visible in the eBATS results.
If not, let us know!

# More types of cryptography

`ciphercycles`: toolkit for benchmarking secret-key authenticated encryption. Heavy reuse of BATMAN structure and software. Results presented at SASC 2007.

Identity-based encryption? Hash functions? Merge everything into ECRYPT VAMPIRE Grand Unified Cryptographic-Primitive Benchmarking Toolkit? Need better acronym than EVGUCPBT.

# Timeline

2005.08: D.VAM.1,
survey of operation counts.

2006.02: D.VAM.7,
initial plans for eBATS.

2007.03: D.VAM.9,
comprehensive report on
first-stage measurements.

2007.06.15: Submit more BATs!

2007.07: Second report.

2007.12: Third report.

2008.05: Fourth report.