Password Hashing Competition second round candidates – tests report (version 1)

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Abstract

The second round of Password Hashing Competition presents some tweaked and some new versions of submitted algorithms. This report tries to run several specific test cases to verify usability of the provided candidates. Tests include portability (use on different platform), illustration of dependence between run time and memory use and input parameters. The last test covers specific key-derivation application.

Contents

1 Introduction

This report extends benchmarks of the Password Hashing Competition(PHC) [1] candidates for the first round [2] and covers tweaked versions of the submitted candidates.

This report is not meant as a performance test comparison (submitted candidates are often reference implementations written for better readability and not performance). The main intention of these tests is to compare limits and generic behavior of algorithms and also uncover technical problems for deployment.

1.1 Algorithms

All submitted candidates for the second PHC round are selected for tests: Argon [3] (with Argon2i and Argon2d), battcrypt [4], Catena framework [5] (in two instances Catena-Dragonfly and Catena-Butterfly, Lyra2 [6], MAKWA [7], Parallel [8], POMELO [9], Pufferfish [10] and yescrypt [11].

Candidates MAKWA and Parallel do not have memory cost attribute, so tests are limited.

In addition, I selected subset of candidates and run specific key-derivation use case test (intended use is to replace key derivation function in disk encryption application).

1.2 Environment

Tests were run on 64bit Linux operating system (both kernel and userspace is fully 64bit), on two platforms

- X86-64: Lenovo X230 notebook with i5-3320M, 2.60GHz CPU and 16GB RAM with AES-NI and SSE instructions available (typical user notebook configuration with additional memory)
- PPC64: PowerPC7 server in big-endian mode, 128GB RAM (for endianess and portability tests)

Tests intentionally do not use parallel attribute and run all algorithms with one thread only.

1.3 Code repository and compilation fixes

The repository includes copy of submitted source code of PHC algorithms and compiles static library for each algorithm.

Variable cost tests use special utility that measures difference in used memory using *getrusage()* system call. So tests measure real additional memory that running process requests from operating system.

Run time measurement is using *clock_gettime(CLOCK_MONOTONIC)* on the Linux platform.

The test run as a special forked process started for each test separately, tests are repeated for 5 times and arithmetic mean (for the time) or maximum (for the memory) of measurements is used.

Algorithms that provides optimized variant are tested separately (only AES-NI and SSE variants). Because AES-NI and SSE instructions are not usable on PowerPC system, only reference implementations run (and compile) there.

The repository with source code and logs is available on GitHub: `https://github.com/mbroz/PHCtest`.

All changes to submitted code are tracked by quilt, see *patches* subdirectory in git (separate for every algorithm). There are tweaks to code to allow compilation on different platform (PPC64).

Important fixes:

- Argon: unsupported includes and pre-processor macros for gcc, unconditional use of non-standard 128bit integer types.
- Argon: tweaked PHS() function (added m_thread option) is not C-only compatible and cause crashes.
- Argon: several mixed unsigned int / uint32_t / size_t parameters in attributes are incompatible and cause crashes.
- Argon2: Used current git version with fixes.
- Argon, battcrypt, Parallel: missing extern C specifier for PHS().
- Lyra2: use only one thread.
- Makefiles: removed -march=native for reference versions (not portable to PPC64).
- Makefiles: removed SSE, AVX, etc. options for generic reference versions (not portable to PPC64).

1.4 PHS function prototype

The PHC competition [1] required all candidates to provide this C function interface:

```
int PHS(void *out, size_t outlen,            /* output */
        const void *in, size_t inlen,        /* input */
        const void *salt, size_t saltlen,    /* salt */
        unsigned int t_cost,                 /* time cost */
        unsigned int m_cost);                /* memory cost */
```

Following tests are using *only this provided function* as the interface to algorithms.

1.5 Parameters

The candidate functions do not implement the API parameters consistently. Some functions implement only one of the cost parameters (memory or time) and the scale differs significantly.

The following tests take the password hash function as a black-box, supposing that invalid or unsupported parameters combination is detected and function returns an error.

2 TEST1: Vectors and endianess test

Some algorithms do not provides own test vectors (specifically not for PHS() interface), so different strategy was used: all variable input tests produced logs of input parameters and output hash in the first round and these logs are used to determine that algorithms still provides the same output (including optimized variant). Vectors are stored in *hash_vectors* sub-directory.
For x86-64 platform:

- all algorithms pass tests in repeated run.
- optimized variants match the reference output (Argon-AESNI, Argon2i-SSe, Argon2d-SSE, Lyra2-SSE, POMELO-SSE and yescrypt-SSE). Note that this applies *only with applied fixes* for PHC() function mentioned in section 1.3.

For PPC64 (big-endian) platform:

- Optimized variants (AESNI and SSE) cannot be tested.
- Vectors passed: battcrypt, MAKWA, Parallel, yescrypt.
- Vectors *fail*: Argon, Argon2i, Argon2d, Catena-Butterfly, Catena-Dragonfly, Lyra2, POMELO, Pufferfish.

This test apparently shows that most of the implementations is not portable yet. One clear issue is that initial hash include often algorithm parameters in initial round in platform native mode instead of using conversion macros before hashing.

3 TEST2: Dieharder test

The output of hashing functions should pass basic randomness tests. Fail in these tests usually indicates some serious internal problem. (While passing tests indicate in fact nothing:-)

The test generates 32-bytes hashes of consecutive little-endian integer (4 bytes) with fixed 16 byte salt. Output is written into file (for time reasons the file size is limited to 400MB). All algorithms use minimal values of memory cost and time cost.

The dieharder testsuite is run with file input generator (dieharder -a -f file -g 201).

No problems were detected in this test (test was run only on x86-64 platform).

4 Parameters tests

The following tests use one variable attribute (memory cost, time cost, input or output length) while all other parameters are fixed.

Note the attributes limits are not yet aligned to suggested attributes in reference papers. It can contain unsupported combinations (but these should be detected with function failure).

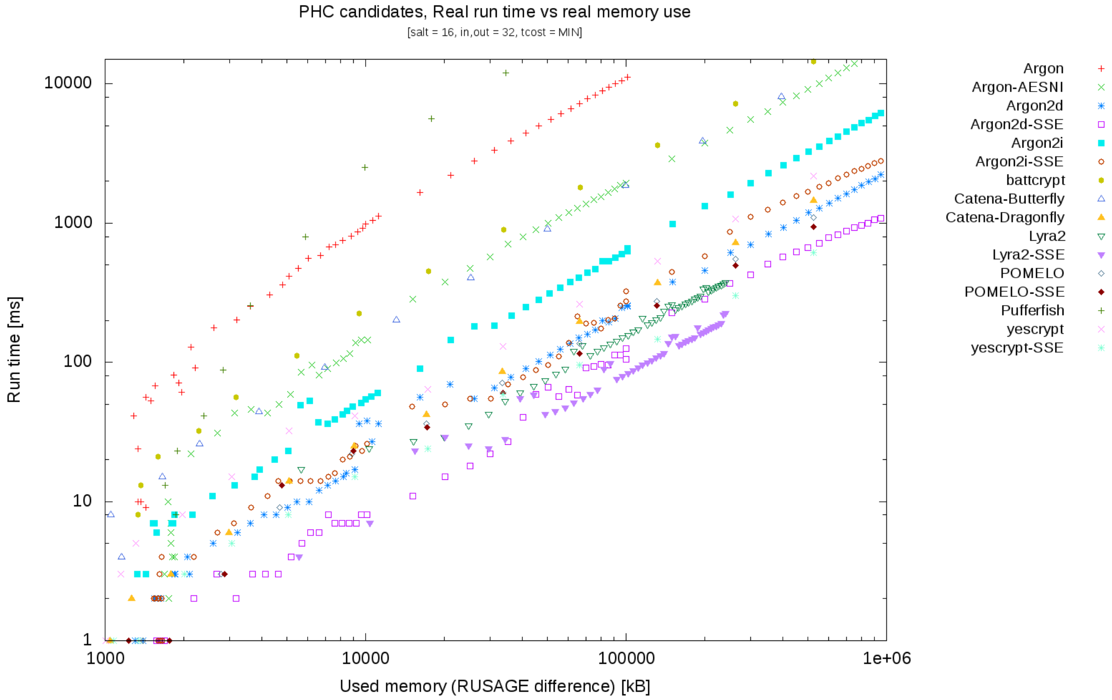
4.1 TEST3: Variable memory cost

The goal is to verify and compare real used memory according to the memory cost parameter. Test also compares impact to run time (large used memory accesses are expensive). Test increases memory cost according to Table 1 and measures used memory and run time. Other parameters are fixed: salt 16 bytes, input 32 bytes, output 32 bytes.

Candidate	Memory min	step	max	time cost
Argon	0	var.	1000000	0
Argon-AESNI	0	var.	1000000	0
Argon2d	0	var.	1000000	0
Argon2d-SSE	0	var.	1000000	0
Argon2i	0	var.	1000000	0
Argon2i-SSE	0	var.	1000000	0
battcrypt	0	1	16	0
Catena-Butterfly	0	1	24	1
Catena-Dragonfly	0	1	24	1
Lyra2	0	200	10000	1
Lyra2-SSE	0	200	10000	1
MAKWA	-	-	-	-
POMELO	0	1	17	0
POMELO-SSE	0	1	17	0
Parallel	-	-	-	-
Pufferfish	0	1	16	0
yescrypt	0	1	20	0
yescrypt-SSE	0	1	20	0

Table 1: Used parameters for the variable memory cost test.

Figures 2 and 3 illustrate real measured data. Figure 1 then shows combined dependence of real used memory and run-time.



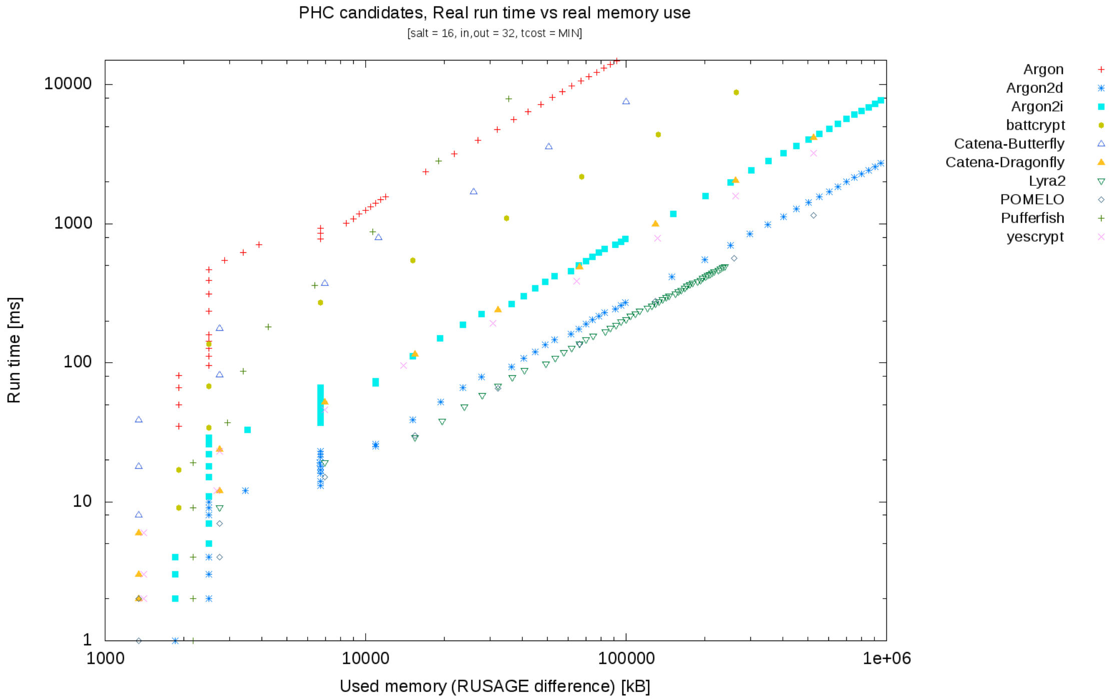


Figure 1: Real used memory vs real time (X86-64, PPC64).

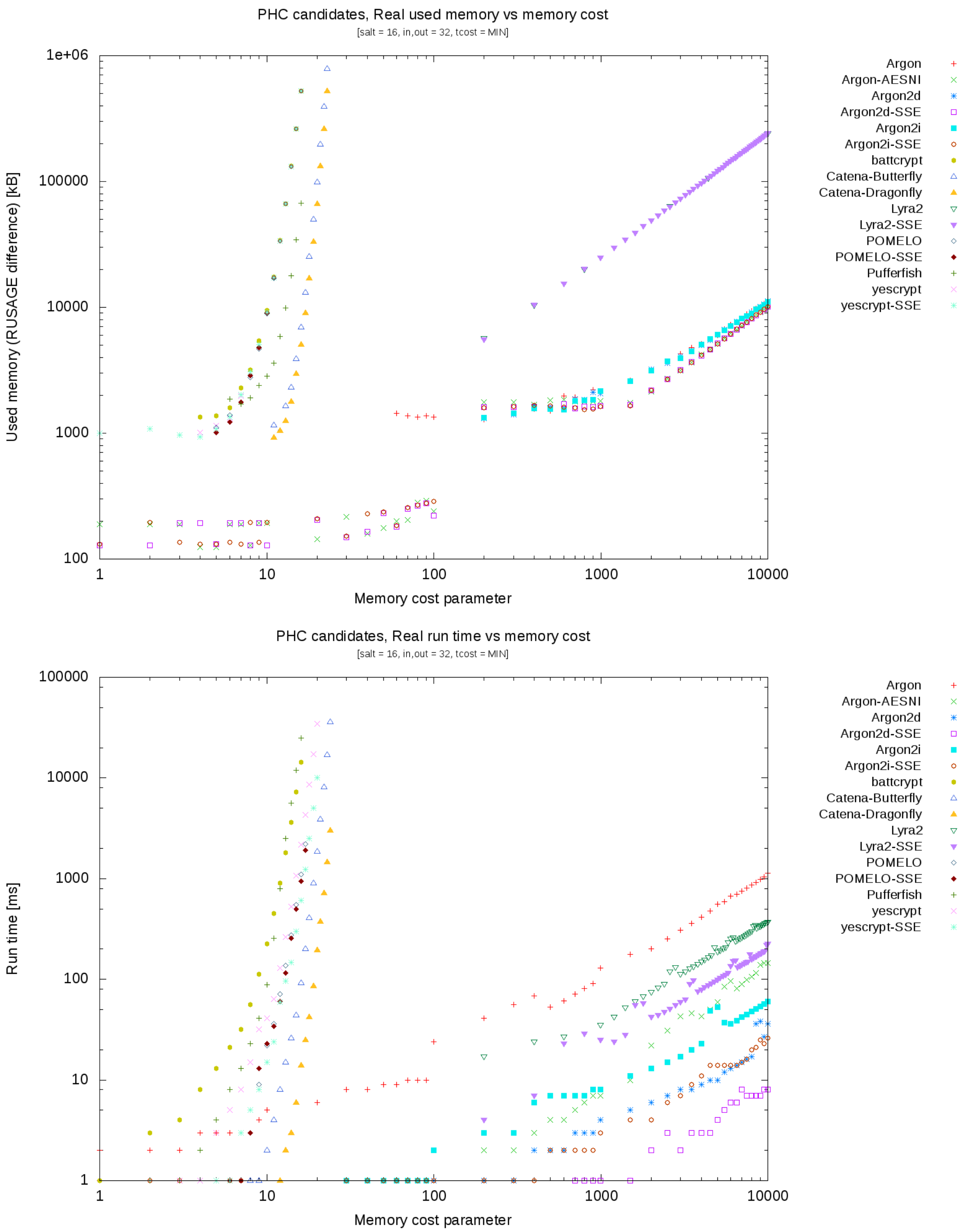
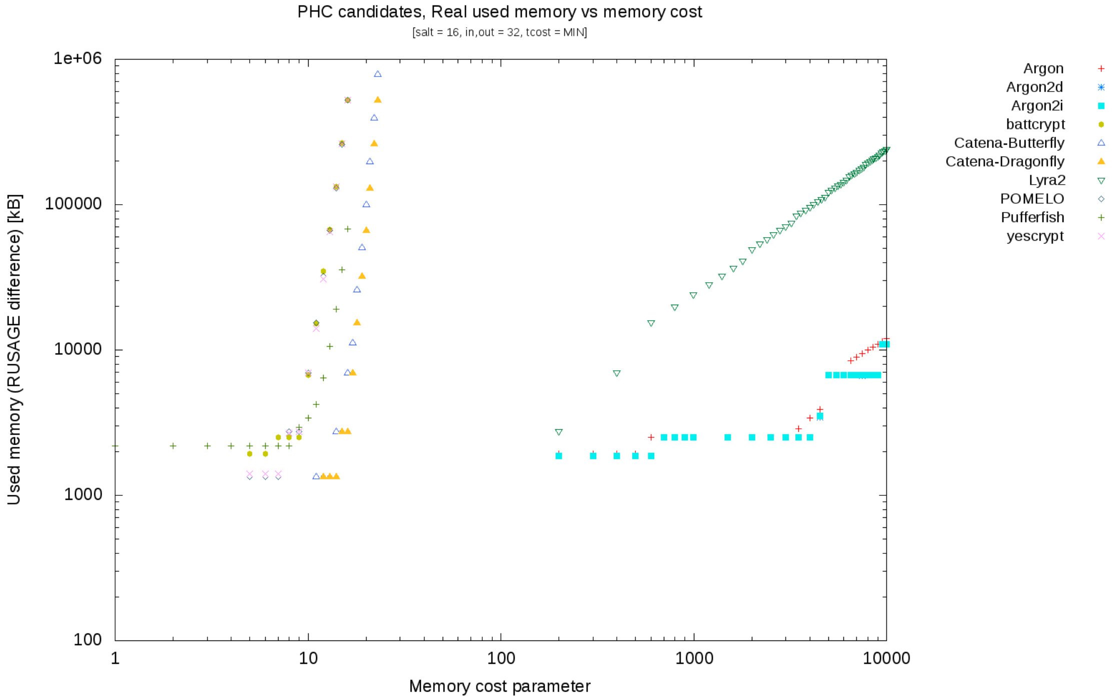


Figure 2: Used memory and time dependence on m_cost parameter (x86-64).



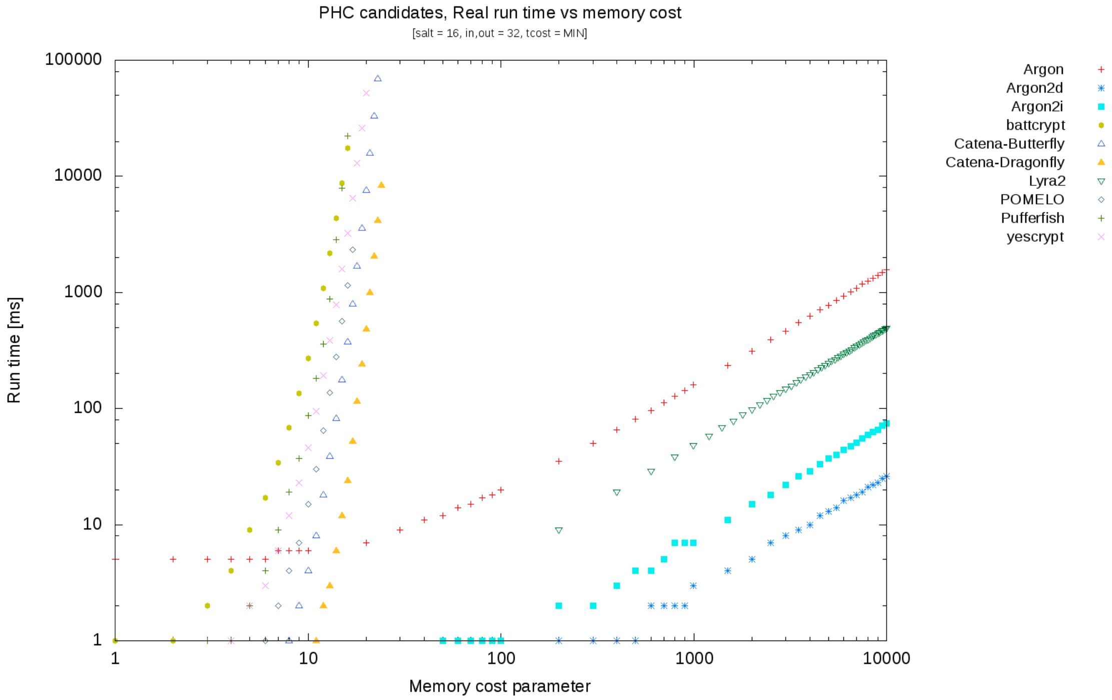


Figure 3: Used memory and time dependence on m_cost parameter (PPC64).

4.2 TEST4: Variable time cost

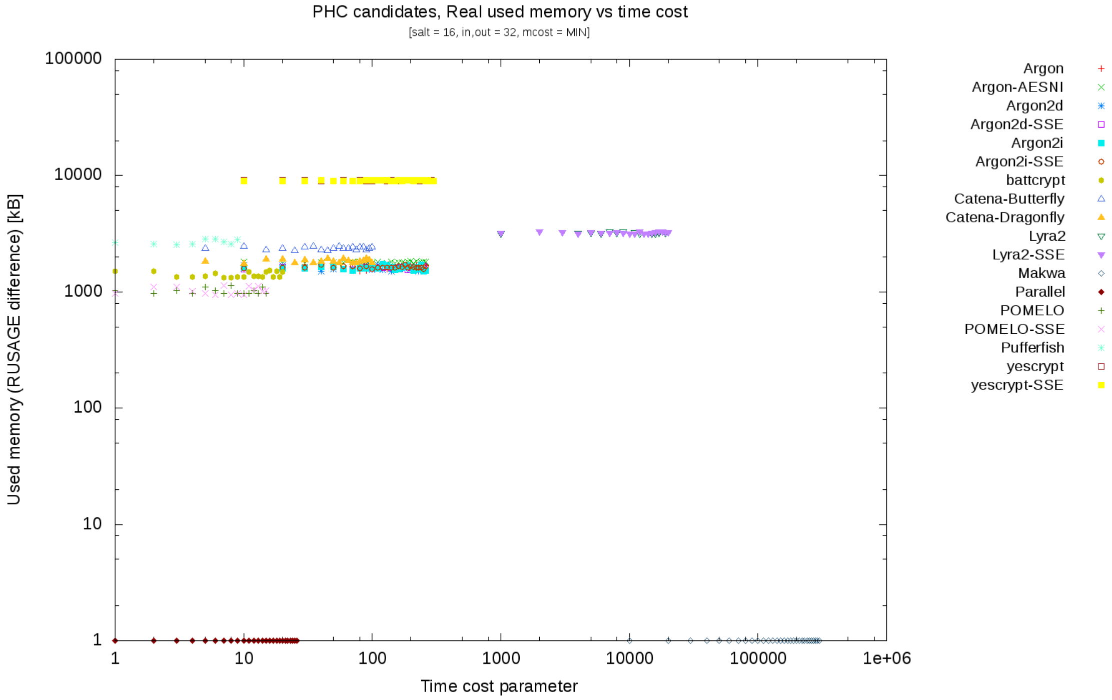
The goal is to verify and compare run time according to the time cost parameter. Test also compares impact to used memory (in theory there shouldn't be significant increase).

Test increases time cost according to Table 2 and measures used memory and run time. Other parameters are fixed: salt 16 bytes, input 32 bytes, output 32 bytes.

Candidate	Time min	step	max	memory cost
Argon	0	10	260	500
Argon-AESNI	0	10	260	500
Argon2d	0	10	250	500
Argon2d-SSE	0	10	250	500
Argon2i	0	10	260	500
Argon2i-SSE	0	10	260	500
battcrypt	0	1	20	5
Catena-Butterfly	0	5	100	14
Catena-Dragonfly	0	5	100	14
Lyra2	0	1000	20000	100
Lyra2-SSE	0	1000	20000	100
MAKWA	0	10000	300000	0
POMELO	0	1	26	0
POMELO-SSE	0	1	15	5
Parallel	0	1	15	5
Pufferfish	0	1	9	10
yescrypt	0	10	300	10
yescrypt-SSE	0	10	300	10

Table 2: Used parameters for the variable time cost test.

Figure 4 (for x86-64) and Figure 5 (for PPC64) illustrate real measured data.



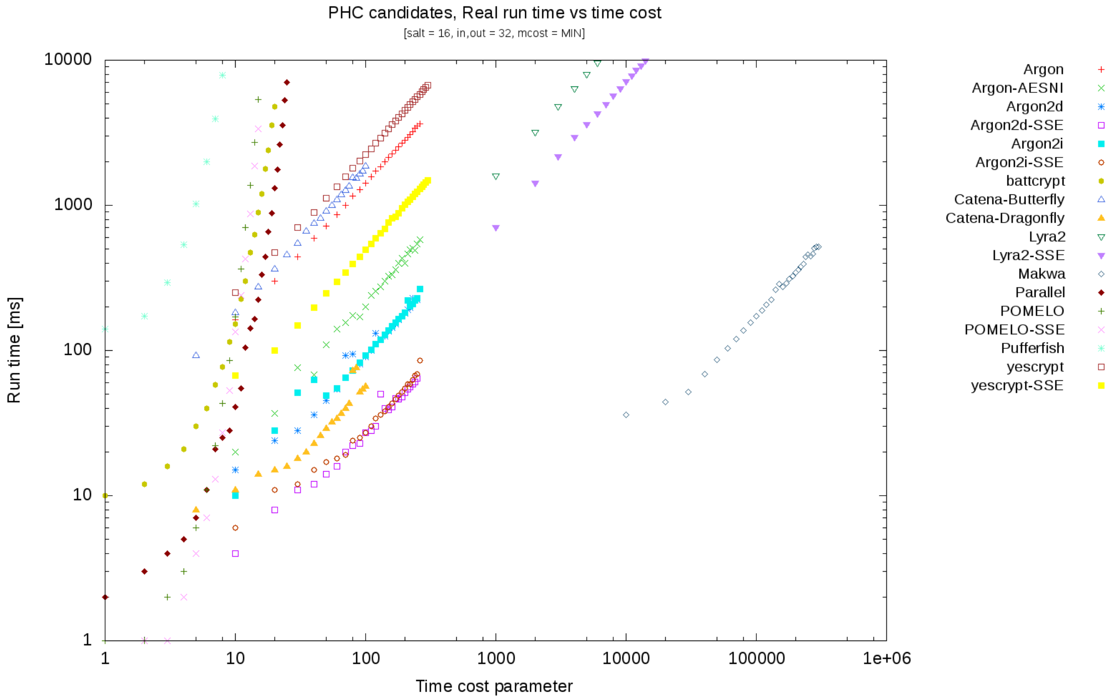


Figure 4: Used memory and time dependence on time cost parameter (X86-64).

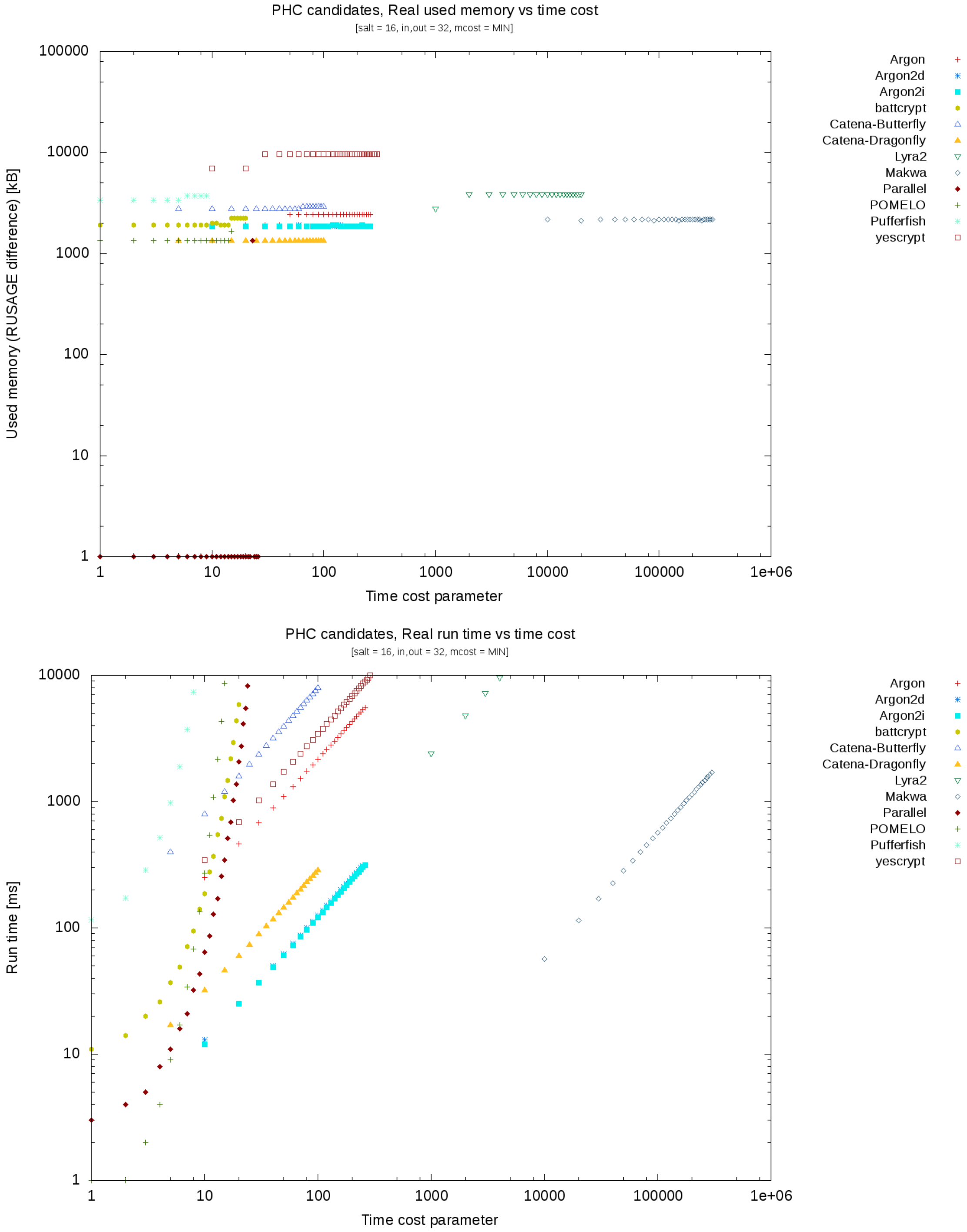


Figure 5: Used memory and time dependence on time cost parameter (PPC64).

5 Password input and hash output length

These tests should illustrate that run time is not dependent on input and output length.

5.1 TEST5: Impact of input length to run time

The input is random password increased from 1 to 300 bytes.

Other parameters are fixed to parameters in Table 3 (memory cost and time cost chosen to be minimal, just to provide run time around 50ms on the particular machine).

Parameters are: salt 16 bytes, output 32 bytes, input 1 - 300, step 1 byte.

Candidate	Memory cost	Time cost
Argon	0	2000
Argon-AESNI	0	1500
Argon2d	100	255
Argon2d-SSE	100	255
Argon2i	100	300
Argon2i-SSE	100	500
battcrypt	0	17
Catena-Butterfly	10	60
Catena-Dragonfly	14	100
Lyra2	6	500
Lyra2-SSE	6	1000
MAKWA	0	30000
POMELO	0	11
POMELO-SSE	0	13
Parallel	0	14
Pufferfish	0	12
yescrypt	10	1
yescrypt-SSE	10	10

Table 3: Used parameters for input and output length tests.

Figure 6 (for x86-64) illustrates real measured data.

5.2 TEST6: Impact of output lengths to run time

The output is increased from 1 to 300 bytes.

Other parameters are fixed to parameters in Table 3 (memory cost and time cost chosen to be minimal, just to provide run time around 50ms on the particular machine).

Parameters are: salt 16 bytes, input 32 bytes, output 1 - 300, step 1 byte.

Figure 7 (for x86-64) illustrates real measured data.

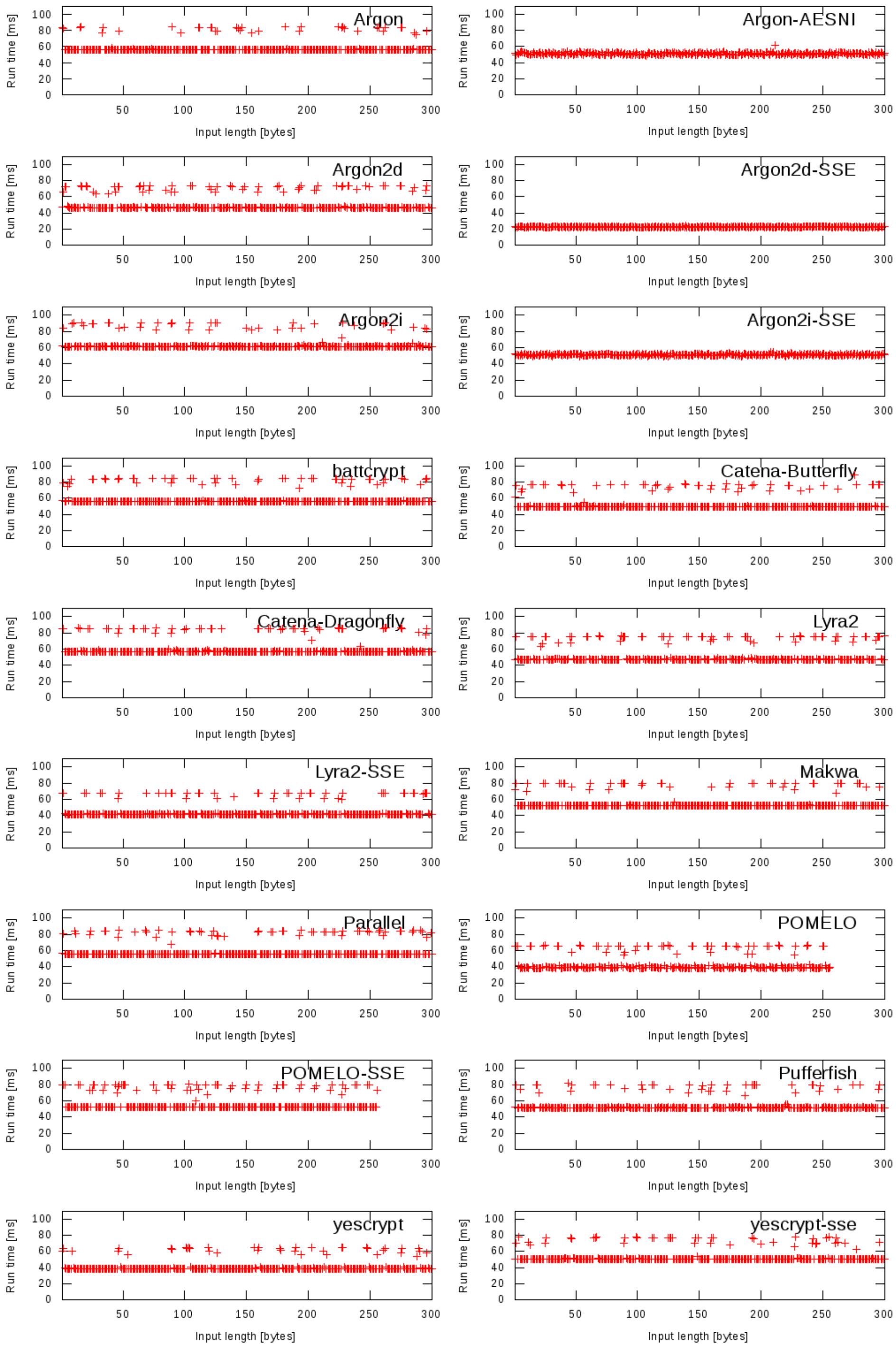


Figure 6: Input length test (X86-64).

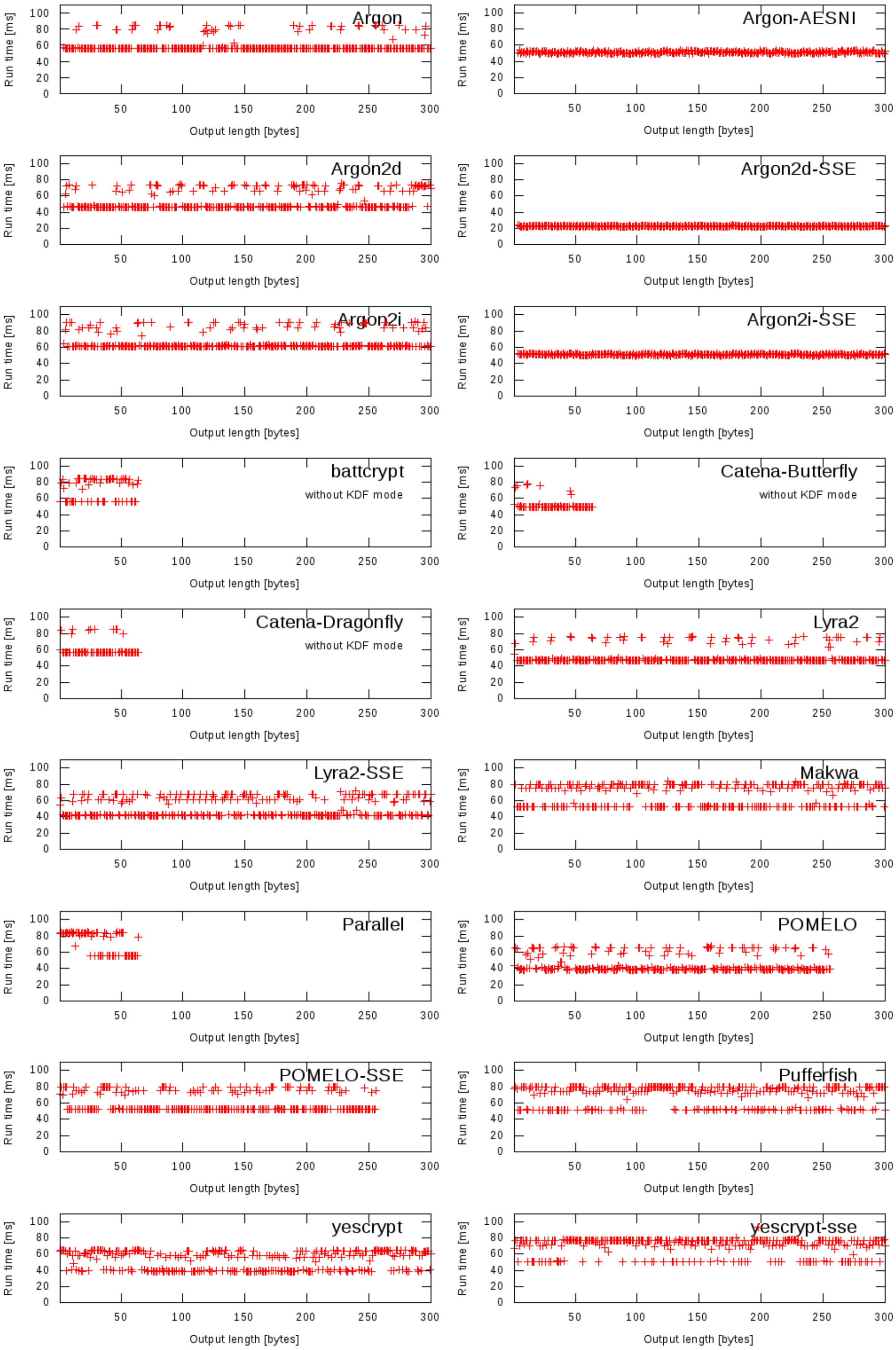


Figure 7: Output length test (X86-64).

6 TEST7: Use case test for KDF

This test tries to answer the question if a function is able to provide usable parameters on the real test machine for the given set of memory and time use conditions.

The test limits memory to 1MB, 100MB or 1GB and also limits runtime (the first is minimum with the required memory limit, the second is approximate 1 second and the last one is approximate 20 seconds). The selection of one second simulates the default iteration time used in existing LUKS FDE system, 20 seconds represents limit which is usually yet acceptable for users when waiting for unlocking of a device.

Because attributes can be set in discrete steps only, measured time and memory for different candidates are slightly different and cannot be directly compared to each other. The Table 5 contains used parameters, the Table 4 then just conclusion if it is possible to provide particular tested case on this system.

Note that Catena and battcrypt require code change for KDF mode and this test run in hashing mode only. The KDF modification mainly provides variable length output and because we need only 64 bytes (that equals internal block size) the modification can be ignored for this particular test case.

Candidate	Memory	Reference			Optimized		
		min	$\sim$1s	$\sim$20s	min	$\sim$1s	$\sim$20s
Argon	1MB	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
	100MB	[11.6s] $\checkmark$	$\times$	$\checkmark$	[1.8s] $\checkmark$	$\checkmark$	$\checkmark$
	1GB	[119.1s] $\checkmark$	$\times$	$\times$	[18.0s] $\checkmark$	$\times$	$\checkmark$
Argon2i	1MB	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
	100MB	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
	1GB	[6.6s] $\checkmark$	$\times$	$\checkmark$	[2.9s] $\checkmark$	$\times$	$\checkmark$
battcrypt	1MB	$\checkmark$	$\checkmark$	$\checkmark$	n/a		
	100MB	[3.6s] $\checkmark$	$\times$	$\checkmark$			
	1GB	[28.8s] $\checkmark$	$\times$	$\times$			
Catena Butterfly	1MB	$\checkmark$	$\checkmark$	$\times$	n/a		
	100MB	[1.8s] $\checkmark$	$\times$	$\checkmark$			
	1GB	[35.6s] $\checkmark$	$\times$	$\times$			
Catena Dragonfly	1MB	$\checkmark$	$\times$	$\times$	n/a		
	100MB	$\checkmark$	$\checkmark$	$\checkmark$			
	1GB	[2.9s] $\checkmark$	$\times$	$\checkmark$			
Lyra2	1MB	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
	100MB	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
	1GB	[1.6s]$\checkmark$	$\times$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
POMELO	1MB	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
	100MB	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
	1GB	[2.1s] $\checkmark$	$\times$	$\checkmark$	[1.8s] $\checkmark$	$\times$	$\checkmark$
yescrypt	1MB	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
	100MB	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
	1GB	[4.2s] $\checkmark$	$\times$	$\checkmark$	[1.2s] $\checkmark$	$\times$	$\checkmark$

Table 4: Ability to cover preset limits

Candidate	Memory	m_cost	t_cost min	t_cost ~1s	t_cost ~20s
Argon	1MB	1024	2	32	700
	100MB	102400	2	×	58
	1GB	1024000	2	×	5
Argon-AESNI	1MB	1024	2	410	8200
	100MB	102400	2	5	103
	1GB	1024000	2	×	9
Argon2i	1MB	1024	2	540	10400
	100MB	102400	2	5	95
	1GB	1024000	2	×	9
Argon2i-SSE	1MB	1024	2	1000	40000
	100MB	102400	2	12	300
	1GB	1024000	2	×	24
battcrypt	1MB	6	0	17	26
	100MB	14	0	×	6
	1GB	17	0	×	×
Catena Butterfly	1MB	14	1	250	× n/a
	100MB	20	1	×	11
	1GB	24	1	×	×
Catena Dragonfly	1MB	15	1	× n/a	× n/a
	100MB	21	1	5	125
	1GB	24	1	×	12
Lyra2	1MB	67	1	20000	400000
	100MB	5000	1	35	720
	1GB	43000	1	×	27
Lyra2-SSE	1MB	67	1	30000	600000
	100MB	5000	1	45	930
	1GB	43000	1	4	109
POMELO	1MB	7	0	10	15
	100MB	14	0	3	7
	1GB	17	0	×	4
POMELO-SSE	1MB	7	0	12	16
	100MB	14	0	3	8
	1GB	17	0	×	5
yescrypt	1MB	8	0	170	3700
	100MB	14	0	3	55
	1GB	17	0	×	7
yescrypt-SSE	1MB	8	0	900	19000
	100MB	14	0	12	238
	1GB	17	0	×	27

Table 5: Used parameters for the run time example.

7 TEST8: Number of rounds normalized

Figure 9 (for x86-64) is try to show normalized output according to number of rounds (underlying function calls) and increasing memory (128 – 256 – 512 KiB, 1 – 2 – 4 – 8 – 16 –32 –64 –128 – 256 – 512 MiB, 1 – 2 GiB). The memory and time cost parameters are calculated according to Table 6.

The table is taken from email sent to the PHC list `http://article.gmane.org/gmane.comp.security.phc/2550` by Steve Thomas.

Name	t_cost for 2x	t_cost for 3x	t_cost for 4x	t_cost for 5x	m_cost calculation
Argon	2	3	4	5	x
battcrypt	0	1	2	-	$log_2(x) - 3$
Catena	2	3	4	5	$log_2(x) + 4$
Lyra2	2	3	4	5	$x/24$
POMELO	1	-	2	-	$log_2(x) - 3$
Pufferfish	-	0	-	1	$log_2(x)$
yescrypt	3	4	5	6	$log_2(x)$

Table 6: Parameters for number of rounds.

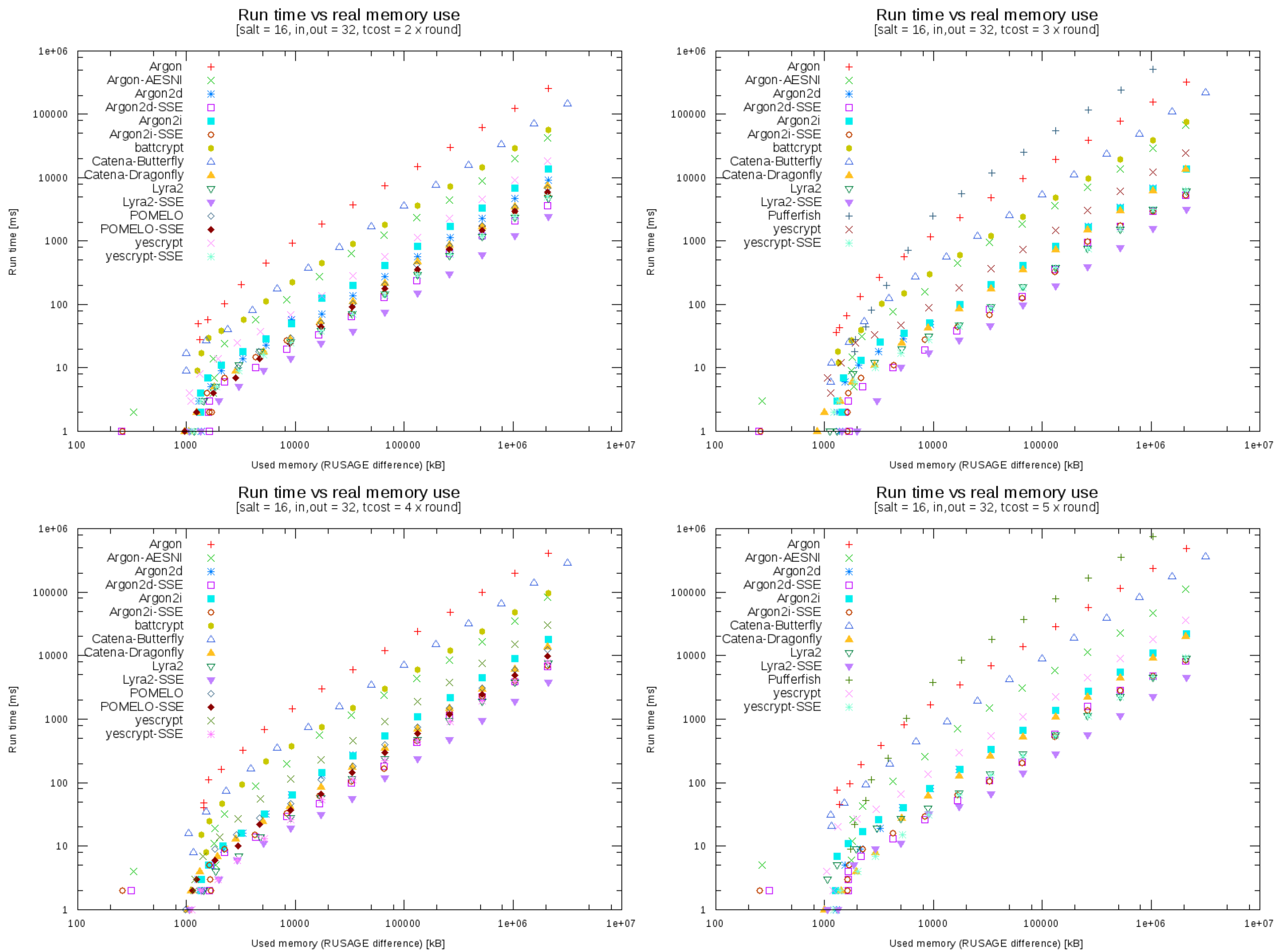


Figure 8: Real used memory and run time (normalized to performed rounds, X86-64).

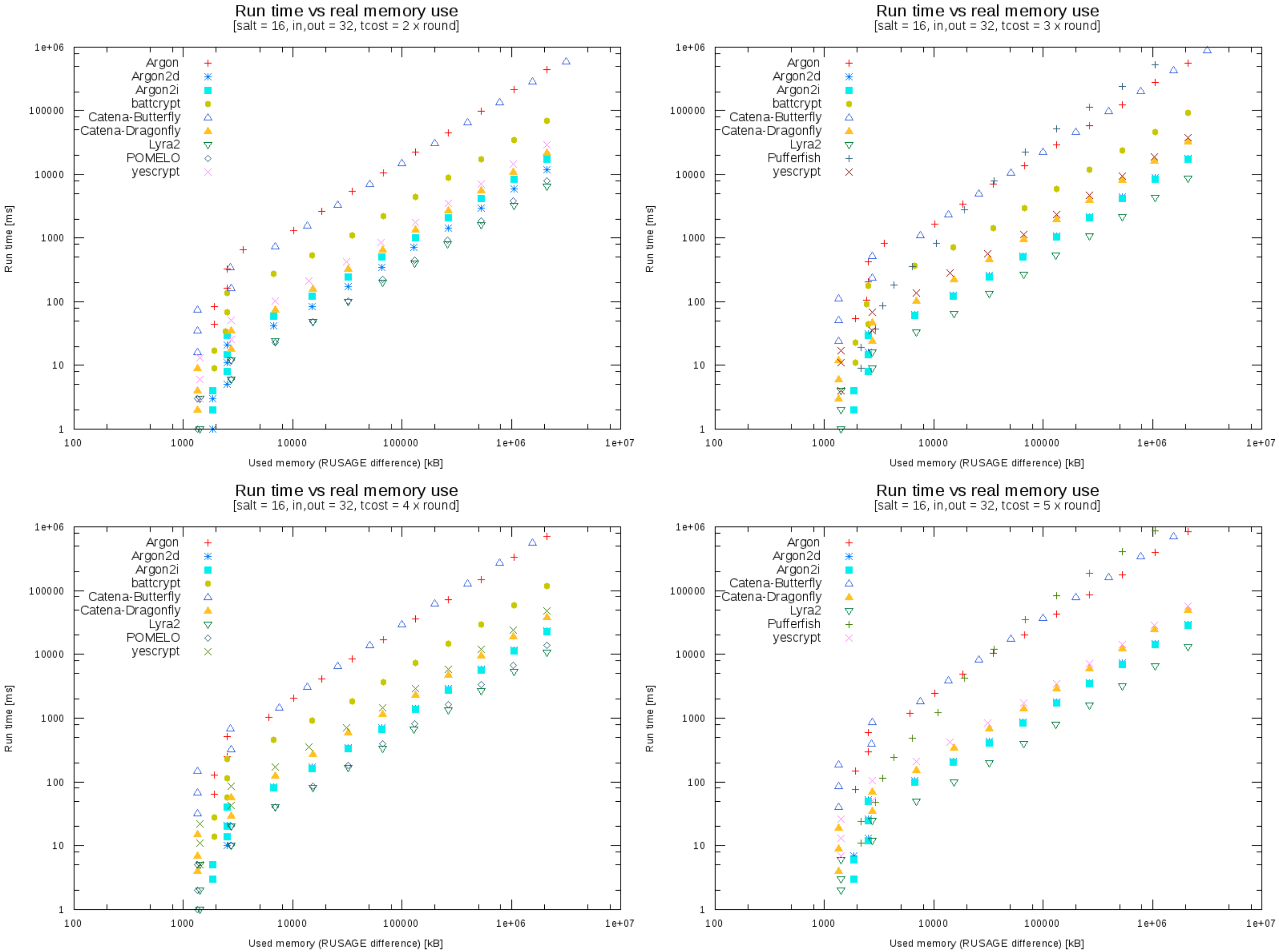


Figure 9: Real used memory and run time (normalized to performed rounds, PPC64).

8 Conclusion

Provided tests illustrates limits and some issues with PHC candidates functions.

Unfortunately there are also implementation issues. As *TEST1* shows, some candidates are not prepared to run in big-endian environment without changes. These are technical problems which can be easily fixed later.

TEST3 and *TEST4* show that all candidates (except MAKWA and Parallel) are able to setup time and memory cost but some quite limits possible range of usable attributes.

The *TEST5* shows that functions can take at least 300 character long input (except POMELO which is limited to 255). *TEST6* is just illustration of the fact that some function need modifications if variable length output is requested.

The key-derivation *TEST7* simulates one specific use case. Even here is visible that some candidates are not able to provide flexible enough limits.

TEST8 was added after some discussions on PHC mailing list, it tries to normalize measured data to number of rounds. It is still lacking some proper adjustments, for example yescrypt internals rounds should be changed to match other candidates.

References

[1] Password hashing competition, 2014. `https://password-hashing.net/`.

[2] Milan Broz. Benchmarks of the PHC candidates, November 2014. `http://htmlpreview.github.io/?https://github.com/mbroz/PHCtest/blob/master/output/index.html`.

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[6] Marcos A. Simplicio Jr., Leonardo C. Almeida, Ewerton R. Andrade, Paulo S. L. M. Barreto, and Marcos. The Lyra2 reference guide, January 2015.

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[11] Alexander Peslyak. yescrypt – a password hashing competition submission, January 2015.