

Overview of the Candidates for the Password Hashing Competition And their Resistance against Garbage-Collector Attacks

Eik List, Stefan Lucks, and Jakob Wenzel
<first name>.<last name>@uni-weimar.de

Bauhaus-Universität Weimar

Abstract. In this work we provide an overview of the candidates of the Password Hashing Competition (PHC) regarding to their functionality, e.g., client-independent update and server relief, their security, e.g., memory-hardness and side-channel resistance, and its general properties, e.g., memory usage and underlying primitives. Furthermore, we introduce two kinds of attacks, called Garbage-Collector and Weak Garbage-Collector Attack, exploiting the memory handling of a candidate. The following overview considers all candidates which are not yet withdrawn from the competition.

Keywords: Password Hashing Competition, Overview, Garbage-Collector Attacks

1 Introduction

Typical adversaries against password-hashing algorithms try plenty of password candidates in parallel, which becomes a lot more costly if they need a huge amount of memory for each candidate. The defender (the honest party), on the other hand, will only compute a single hash, and the memory-cost parameters should be chosen such that the required amount of memory is easily available to the defender.

But, memory-demanding password scrambling may also provide a completely new attack opportunity for an adversary, exploiting the handling of the target’s machine memory. We introduce the two following attack models: (1) Garbage-Collector Attacks, where an adversary has access to the internal memory of the target’s machine **after** the password scrambler terminated; and (2) Weak Garbage-Collector Attacks, where the password itself (or a value derived from the password using an efficient function) is written to the internal memory and almost never overwritten during the runtime of the password scrambler. If a password scrambler is vulnerable in either one of the attack models, it may be possible to significantly reduce the effort for testing a password candidate.

Remark 1. For our theoretic consideration of the proposed attacks, we assume a natural implementation of the algorithms, e.g., that some possible mentioned overwriting of the internal state **after** the invocation of an algorithm is neglected due to optimization.

2 (Weak) Garbage-Collector Attacks and their Application to ROMix and `scrypt`

In this section we first provide a definition of our attack models, i.e., the Garbage-Collector (GC) attack and the Weak Garbage-Collector (WGC) attack. For illustration, we first show that ROMix (the core of `scrypt` [19]) is vulnerable against a GC attack (this was already shown in [11], but without a formal definition of the GC attack), and second, we show that `scrypt` is also vulnerable against a WGC attack.

2.1 The (Weak) Garbage-Collector Attack

The basic idea of this attack is to exploit the management of the memory and the internal state of password-hashing algorithms. More detailed, the goal of an adversary is to find out a valid preimage for a given password-hash value without taking the whole effort of computing the corresponding password-hashing algorithm for each candidate. Next, we formally define the term Garbage-Collector Attack.

Algorithm 1 The algorithm `script` [19] and its core operation ROMix.

<code>script</code> Input: pwd {Password} s {Salt} G {Cost Parameter} Output: x {Password Hash} 10: $x \leftarrow \text{PBKDF2}(pwd, s, 1, 1)$ 11: $x \leftarrow \text{ROMix}(x, G)$ 12: $x \leftarrow \text{PBKDF2}(pwd, x, 1, 1)$ 13: return x	ROMix Input: x {Initial State}, G {Cost Parameter} Output: x {Hash value} 20: for $i = 0, \dots, G - 1$ do 21: $v_i \leftarrow x$ 22: $x \leftarrow H(x)$ 23: end for 24: for $i = 0, \dots, G - 1$ do 25: $j \leftarrow x \bmod G$ 26: $x \leftarrow H(x \oplus v_j)$ 27: end for 28: return x
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Definition 1 (Garbage-Collector Attack). Let $PS_G(\cdot)$ be a memory-demanding password scrambler that depends on a memory-cost parameter G . Furthermore, let v denote the internal state of $PS_G(\cdot)$ after its termination. Let \mathcal{A} be a computationally unbounded but always halting adversary conducting a garbage-collector attack. We say that \mathcal{A} is successful if some knowledge about v reduces the runtime of \mathcal{A} for testing a password candidate x from $\mathcal{O}(PS_G(x))$ to $\mathcal{O}(f(x))$ with $\mathcal{O}(f(x)) \lll \mathcal{O}(PS_G(x))$, $\forall x \in \{0, 1\}^*$.

In the following we define the Weak Garbage-Collector Attack (WGCA), which exploits the fact that the password pwd or the hash of the password $H(pwd)$ must be in memory (or at least recomputed) in the last step of a password scrambler.

Definition 2 (Weak Garbage-Collector Attack). Let $PS_G(\cdot)$ be a password scrambler that depends on a memory-cost parameter G , and let $F(\cdot)$ be an underlying function of $PS_G(\cdot)$ that can be efficiently computed. We say that an adversary \mathcal{A} is successful in terms of a weak garbage-collector attack if a value $y = F(pwd)$ remains in memory during (almost) the entire runtime of $PS_G(pwd)$, where pwd denotes the secret input.

Thus, an algorithm is vulnerable to a WGC attack, if either the secret input x or a value directly derived from x , using an efficient function F , has to be in memory during the invocation of a password scrambler. An adversary that is capable of reading the internal memory of a password scrambler during its invocation, gains knowledge about v . Thus, it can reduce the effort for filtering invalid password candidates by just computing $v' = F(x)$ and checking whether $v = v'$, where x denotes the current password candidate. Note that the function F can also be given by the identity function. Then, the plain password remains in memory, rendering WGC attacks trivial.

2.2 (Weak) Garbage-Collector Attacks on `script`

Garbage-Collector Attack on ROMix. Algorithm 1 describes the necessary details of the `script` password scrambler together with its core function ROMix. The pre- and post-whitening steps are given by one call (each) of the standardized key-derivation function PBKDF2 [15], which we consider as a single call to a cryptographically secure hash function. The ROMix function takes the initial state x and the memory-cost parameter G as inputs. First, ROMix initializes an array v of size $G \cdot n$ by iteratively applying a cryptographic hash function H (see Lines 20-23), where n denotes the output size of H in bits. Second, ROMix accesses the internal state at randomly computed points j to update the password hash (see Lines 24-27).

It is easy to see that the value v_0 is a plain hash (using PBKDF2) of the original secret pwd (see Line 10). Further, from the overall structure of `script` and ROMix it follows that the internal memory is written once but never overwritten (Lines 20-23). Thus, all values v_0, \dots, v_{G-1} can be accessed by a garbage-collector adversary \mathcal{A} after the termination of `script`. For each password candidates pwd' , \mathcal{A} can now simply compute $x' \leftarrow \text{PBKDF2}(pwd')$ and check whether $x' = v_0$. If so, pwd' is a valid preimage. Thus, \mathcal{A} can test each possible candidate in $\mathcal{O}(1)$, rendering an attack against `script` (or especially ROMix) practical (and even memory-less).

As a possible countermeasure, one can simply overwrite v_0, \dots, v_{G-1} after running ROMix. Nevertheless, this step might be removed by a compiler due to optimization, since it is algorithmically ineffective.

Weak Garbage-Collector Attack on *script*. In Line 12 of Algorithm 1, *script* invokes the key-derivation function PBKDF2 the second time using again the password *pwd* as input again. Thus, *pwd* has to be stored in memory during the entire invocation of *script*, which implies that *script* is vulnerable to WGC attacks.

3 Overview

Before we present the tables containing the comparison of the candidates for the Password Hashing Competition (PHC), we introduce the necessary notions (see Table 1) to understand the tables.

Identifier	Description
Primitives/Structures	
BC	Block cipher
SC	Stream cipher
PERM	Keyless permutation
HF	Hash function
BRG	Bit-Reversal Graph
DBG	Double-Butterfly Graph
General Properties	
CIU	Supports client-independent update
SR	Supports server relief
KDF	Usable as Key-Derivation Function (requires outputs to be pseudorandom)
FPO	Using floating-point operations
Flexible	Underlying primitive can be replaced
Iteration	Algorithm is based on iterations/rounds
Security Properties	
GCA Res.	Resistant against garbage-collector attacks (see Definition 1)
WGCA Res.	Resistant against weak garbage-collector attacks (see Definition 2)
SCA Res.	Resistant against side-channel attacks. Vulnerability may result from the existence of a password-dependent memory-access pattern or from using RSA-based systems requiring p and q to be used.
ROM-port	Special form of memory hardness [8].
Shortcut	Is it possible to bypass the main (memory and time) effort of an algorithm by knowing additional parameters, e.g., the Blum integers p and q for MAKWA which are used to compute the modulo n .

Table 1. Notations used in Tables 2, 3, and 4.

Algorithm	Based On	Iteration	Memory Usage	Parallel	Underlying Primitive		Underlying Mode
					BC/SC/PERM	HF	
AntCrypt		✓	32 kB	part.	-	SHA-512	-
ARGON	AES	✓	1 kB - 1 GB	✓	AES (5R)	-	-
battcrypt		✓	128 kB - 128 MB	part.	Blowfish-CBC	SHA-512	-
CATENA	BRG/DBG	✓	8 MB	part.	-	BLAKE2b	-
CENTRIFUGE		✓	2 MB	-	AES-256	SHA-512	-
EARWORM		✓	1 MB (ROM)	✓	AES (1R)	SHA-256	PBKDF2 _{HMAC}
Gambit	Sponge	✓	50 MB	-	Keccak _f	-	-
Lanarea DF		✓	256 B	-	-	BLAKE2b	-
Lyra2	Sponge	✓	400 MB - 1 GB	-	BLAKE2b (CF)	-	-
MAKWA	Squarings	✓	negl.	✓	-	SHA-256	HMAC
MCS_PHS		✓	negl.	-	-	MCSSHA-8	-
ocrypt	scrypt	✓	1 MB - 1 GB	-	ChaCha	CubeHash	-
Parallel		✓	negl.	✓	-	SHA-512	-
PolyPassHash	Shamir Sec. Sharing	-	negl.	-	AES	SHA-256	-
POMELO		✓	2 MB - 8 GB	part.	-	-	-
Pufferfish	Blowfish/bcrypt	✓	4 - 16 kB	-	Blowfish	SHA-512	HMAC
Rig	BRG	✓	15 MB	part.	-	BLAKE2b	-
scrypt		✓	1MB	-	Salsa20/8	-	PBKDF2
<i>schvrch</i>		✓	8 MB	part.	-	-	-
Tortuga	Sponge & rec. Feistel	✓	◦	-	Turtle	-	-
SkinnyCat	BRG	✓	◦	-	-	SHA-*/BLAKE2*	-
TwoCats	BRG	✓	◦	✓	-	SHA-*/BLAKE2*	-
Yarn		✓	◦	part.	BLAKE2b (CF), AES	-	-
yescrypt	scrypt	✓	3 MB (RAM)/3 GB (ROM)	part.	Salsa20/8	SHA-256	PBKDF2 _{HMAC}

Table 2. Overview of PHC Candidates and their general properties. The values in the column "Memory" come from the authors recommendation for password hashing or are marked as '◦' if no recommendation exists. The entry "A (CF)" denotes that only the compression function of algorithm A is used. An entry $A(XR)$ denotes that an algorithm A is reduced to X rounds. The **scrypt** password scrambler is just added for comparison. If an algorithm can only be partially be computed in parallel, we marked the corresponding entry with 'part.'. Note that POMELO and *schvrch* do not depend on an existing underlying primitive but on an own construction.

Algorithm	CIU	SR	FPO	Flexible
AntCrypt	✓	-	✓	part.
ARGON	✓	✓	-	✓
battcrypt	✓	-	-	part.
CATENA	✓	✓	-	✓
CENTRIFUGE	-	-	-	✓
EARWORM	-	✓	-	-
Gambit	-	✓	opt.	part.
Lanarea DF	-	✓	-	✓
Lyra2		✓	-	part.
MAKWA	part.	-	-	✓
MCS_PHS	-	✓	-	part.
ocrypt	-	-	-	✓
Parallel	✓	✓	-	✓
PolyPassHash	✓	-	-	✓
POMELO	✓	-	✓	-
Pufferfish	-	-	-	part.
Rig	✓	✓	-	✓
scrypt	-	-	-	-
<i>schvrch</i>	-	-	-	-
Tortuga	-	-	-	-
SkinnyCat	-	✓	-	✓
TwoCats	✓	✓	-	✓
Yarn	-	✓	-	-
yescrypt	-	-	-	-

Table 3. Even if the authors of a scheme do not claim to support client-independent update (CIU) or server relief, we checked for the possibility and marked the corresponding entry in the table with '✓' or 'part.' if possible or possible under certain requirements, respectively. Note that we say that an algorithm does not support SR when it requires the whole state to be transmitted. Moreover, we say that an algorithm does not support CIU if any additional information to the password hash itself is required. Note that CATENA refers to both instantiations, i.e., CATENA-BRG and CATENA-DBG

Algorithm	Memory-Hardness	KDF	GCA Resistance	WGCA Resistance	SCA Resistance	Security Analysis	Shortcut
AntCrypt	✓	✓	✓	✓	✓*	✓*	-
ARGON	✓	✓	✓	✓	-	✓	-
battcrypt	✓	✓	✓	-	✓	✓*	-
CATENA-BRG	✓	✓	-	✓	✓	✓	-
CATENA-DBG	λ	✓	✓	✓	✓	✓	-
CENTRIFUGE	✓*	✓	✓	-	✓	✓*	-
EARWORM	ROM-port	-	✓	-	✓	✓	-
Gambit	✓*	✓	✓	✓	✓	✓*	-
Lanarea DF	✓*	✓	✓	✓	part.	✓*	-
Lyra2	✓	✓	✓	✓	part.	✓	-
MAKWA	-	✓	✓	✓	part.	✓	✓
MCS_PHS	-	✓	-	✓	✓	-	-
ocrypt	✓*	✓	✓	✓	-	✓*	-
Parallel	-	✓	✓	✓	✓	✓*	-
PolyPassHash	-	-	-	-	-	✓	✓
POMELO	-	-	✓	✓	part.	✓*	-
Pufferfish	✓*	✓	✓	✓	-	✓*	-
Rig	λ	✓	✓	✓	✓	✓	-
<i>scrypt</i>	sequential	✓	-	-	-	✓	-
<i>schurch</i>	-	-	✓	✓	✓	✓*	-
Tortuga	✓*	✓	✓	✓	✓	✓*	-
SkinnyCat	sequential	✓	✓*	-	part.	✓	-
TwoCats	sequential	✓	✓*	-	part.	✓	-
Yarn	✓*	-	✓	-	-	✓*	-
yescrypt	ROM-port	✓	✓*	-	-	✓*	-

Table 4. Overview over the security properties of PHC candidates. An entry supplemented by ‘*’ (as for Memory-Hard. and Security Analysis), denotes that there exists not sophisticated analysis or proofs for the given claim/assumption. For GCA/WGCA Res., ‘✓*’ denotes that this kind of resistance is only given under certain conditions. For SCA Res., ‘part.’ (partial) means that only one or more parts (but not all) provide resistance against side-channel attacks.

4 Resistance of PHC Candidates against (W)GC Attacks

In this section we briefly discuss potential weaknesses of each PHC candidate regarding to garbage-collector (GC) and weak-garbage-collector (WGC) attacks or argue why it provides resistance against such attacks. Note that we assume the reader to be familiar with the internals of the candidates since we only concentrate on those parts of the candidates that are relevant regarding to GC/WGC attacks.

AntCrypt [9]. The internal state of AntCrypt is initialized with the secret pwd . During the hashing process, the state is overwritten `outer_rounds` \times `inner_rounds` times, which thwarts GC attacks. Moreover, since pwd is used only to initialize the internal state, WGC attacks are not applicable.

ARGON [3]. First, the internal state derived from pwd is the input to the padding phase. After the padding phase, the internal state is overwritten by applying the functions `ShuffleSlices` and `SubGroups` at least L times. Based on this structure, and since pwd is used only to initialize the state, ARGON is not vulnerable against GC/WGC attacks.

battcrypt [24]. Within battcrypt, the plain password is used only once, namely to generate a value $key = \text{SHA-512}(\text{SHA-512}(\text{salt} \parallel \text{pwd}))$. The value key is then used to initialize the internal state, which is expanded afterwards. In the *Work* phase, the internal state is overwritten `t_cost` \times `m_size` times using password-dependent indices. Thus, GC attacks are not applicable.

Note that the value key is used in the three phases *Initialize blowfish*, *Initialize data*, and *Finish*, whereas it is overwritten in the phase *Finish* the first time. Thus, key must remain in memory until the final phase, rendering the following WGC attack possible: For each password candidates x and the known value $salt$, compute $key' = \text{SHA512}(\text{SHA512}(\text{salt} \parallel x))$ and check whether $key' = key$. If so, mark x as a valid password candidate.

Catena [11]. CATENA has two instantiations CATENA-BRG and CATENA-DBG, which are based on a (G, λ) -Bit-Reversal Graph and a (G, λ) -Double-Butterfly Graph, respectively. Both instantiations use an array of G elements each as their internal state. This state is overwritten $\lambda - 1$ times for CATENA-BRG and $(2 \log_2(G) - 1) \cdot \lambda + 2 \log_2(G) - 2$ times for CATENA-DBG. Hence, when considering CATENA-BRG, a GC adversary with access to the state can reduce the effort for testing a password candidate by a factor of $1/\lambda$. When considering CATENA-DBG, the reduction of the computational cost of an adversary is negligible. The authors mention this fact by recommending CATENA-DBG when considering GC attacks.

For CATENA-BRG as well as CATENA-DBG, the password pwd is used only to initialize the internal state. Thus, both instantiations provide resistance against WGC attacks.

CENTRIFUGE [1]. The internal state of size `p_mem` \times `outlen` byte is initialized with a seed S derived from the password and the salt as follows: $S = H(s_L \parallel s_R)$, where $s_L \leftarrow H(pwd \parallel \text{len}(pwd))$ and $s_R \leftarrow H(\text{salt} \parallel \text{len}(\text{salt}))$. Furthermore, S is used as the initialization vector (*IV*) and the key for the CFB encryption. The internal state is then at least updated `p_time` times by the data-dependent application of S-boxes and the CFB encryption, rendering GC attacks not possible for CENTRIFUGE. Nevertheless, the final step of CENTRIFUGE is to encrypt the internal state again, requiring the key and the *IV*, which therefore must remain in memory during the invocation of CENTRIFUGE. Thus, the following WGC attack is applicable:

1. Compute $s_R \leftarrow H(\text{salt} \parallel \text{len}(\text{salt}))$
2. For every password candidate x :
 - (a) Compute $s'_L \leftarrow H(x \parallel \text{len}(x))$ and $S' = H(s'_L \parallel s_R)$, and compare if $S' = IV$
 - (b) If yes: mark x as a valid password candidate
 - (c) If no: go to Step 2

EARWORM [12]. EARWORM maintains an array called *arena* of size $2^{m_cost} \times L \times W$ 128-bit blocks, where $W = 4$ and $L = 64$ are recommended by the authors. This read-only array is randomly initialized (using an additional secret input which has to be constant within a given system) and used as AES round keys. Since the values within this array do not depend on the secret *pwd*, knowledge about *arena* does not help any malicious garbage collector. Within the main function of EARWORM (WORKUNIT), an internal state *scratchpad* is updated multiple times using password-dependent accesses to *arena*. Thus, a GC adversary cannot profit from knowledge about *scratchpad*, rendering GC attacks not applicable.

Within the function WORKUNIT, the value *scratchpad.tmpbuf* is derived directly from the password as follows:

$$scratchpad.tmpbuf \leftarrow \text{EWPRF}(pwd, 01 \parallel salt, 16W),$$

where EWPRF denotes $\text{PBKDF2}_{\text{HMAC-SHA256}}$ with the first input denoting the secret key. This value is updated only at the end of WORKUNIT using the internal state. Thus, it has to be in memory during almost the whole invocation of EARWORM, rendering the following WGC attack possible: For each password candidate x and the known value *salt*, compute $y = \text{EWPRF}(x, 01 \parallel salt, 16W)$ and check whether *scratchpad.tmpbuf* = y . If so, mark x as a valid password candidate.

Gambit [21]. Gambit bases on a duplex-sponge construction [2] maintaining two internal states S and M , where S is used to subsequently update M . First, password and salt are absorbed into the sponge and after one call to the underlying permutation, the squeezed value is written to the internal state M and processed r times (number of words in the ratio of S). The output after the r steps is optionally XORed with an array lying in the ROM. After that, M is absorbed into S again. This step is executed t times, where t denotes the time-cost parameter. The size of M is given by m , the memory-cost parameter. Continuously updating the states M and S thwarts GC attacks. Moreover, since *pwd* is used only to initialize the state within the sponge construction, WGC attacks are not applicable.

Lanarea DF [18]. Lanarea DF maintains a matrix (internal state) consisting of $16 \cdot 16 \cdot m_cost$ byte values, where m_cost denotes the memory-cost parameter. After the password-independent setup phase, the password is processed by the internal pseudorandom function producing the array (h_0, \dots, h_{31}) , which determines the positions on which the internal state is accessed during the core phase (thus, allowing cache-timing attacks). In the core phase, the internal state is overwritten $t_cost \times m_cost \times 16$ times, rendering GC attacks impossible. Moreover, the array (h_0, \dots, h_{31}) is overwritten $t_cost \times m_cost$ times which thwarts WGC attacks.

Lyra2 [14]. The Lyra2 password scrambler (and KDF) is based on a duplex sponge construction, which absorbs the password, the salt, and some tweak in the first step of its algorithm. The authors indicate that the password can be overwritten from this point on, rendering WGC attacks impossible. Due to the fact that the password is absorbed to the sponge state and this state is continuously overwritten, GC attacks are not applicable.

Makwa [22]. MAKWA has not been designed to be a memory-demanding password scrambler. Its strength is based on a high number of squarings modulo a composite (Blum) integer n . The plain (or hashed) password is used twice to initialize the internal state, which is then processed by squarings modulo n . Thus, neither GC nor WGC attacks are applicable for MAKWA.

MCS_PHS [17]. Depending on the size of the output, MCS_PHS applies iterated hashing operations, reducing the output size of the hash function by one byte in each iteration – starting from 64 bytes. Note that the memory-cost parameter m_cost is used only to increase the size of the initial chaining value T_0 . The secret input *pwd* is used once, namely when computing the value T_0 and can be deleted afterwards, rendering WGC attacks not applicable. Furthermore, since the output of MCS_PHS is computed by iteratively applying the underlying hash function (without handling an internal state which has to be placed in memory), GC attacks are not possible.

ocrypt [10]. The basic idea of ocrypt is similar to that of **scrypt**, besides the fact that the random memory accesses are determined by the output of a stream cipher (ChaCha) instead of a hash function cascade. The output of the stream cipher determines which element of the internal state is updated, which

consists of $2^{17+m_{cost}}$ 64-bit words. During the invocation of `ocrypt`, the password is used only twice: (1) as input to `CubeHash`, generating the key for the stream cipher and (2) to initialize the internal state. Neither the password nor the output of `CubeHash` are used again after the initialization. Thus, `ocrypt` is not vulnerable to WGC attacks.

The internal state is processed $2^{17+t_{cost}}$ times, where in each step one word of the state is updated. Since the indices of the array elements accessed depend only on the password and not on the content, GC attacks are not possible by observing the internal state after the invocation of `ocrypt`.

Remark 2. Note that the authors of `ocrypt` claim side-channel resistance since the indices of the array elements are chosen in a password-independent way. But, as the password (beyond other inputs) is used to derive the key of the underlying stream cipher, this assumption does not hold, i.e., the output of the stream cipher depends on the password, rendering (theoretical) cache-timing attacks possible.

Parallel [25]. `Parallel` has not been designed to be a memory-demanding password scrambler. Instead, it is highly optimized to be computed in parallel. First, a value `key` is derived from the secret input `pwd` and the salt by

$$key = \text{SHA-512}(\text{SHA-512}(\text{salt}) \parallel \text{pwd}).$$

The value `key` is used (without being changed) during the `CLEAR WORK` phase of `Parallel`. Since this phase defines the main effort for computing the password hash, it is highly likely that a WGC adversary can gain knowledge about `key`. Then, the following WGC attack is possible: For each password candidate `x` and the known value `salt`, compute `y = SHA-512(SHA-512(salt) || x)` and check whether `key = y`. If so, mark `x` as a valid password candidate. Since the internal state is only given by the subsequently updated output of `SHA-512`, GC attacks are not applicable for `Parallel`.

PolyPassHash [5]. `PolyPassHash` denotes a threshold system with the goal to protect an individual password (hash) until a certain number of correct passwords (and their corresponding hashes) are known. Thus, it aims at protecting an individual password hash within a file containing a lot of password hashes, rendering `PolyPassHash` not to be a password scrambler itself. The protection lies in the fact that one cannot easily verify a target hash without knowing a minimum number of hashes (this technical approach is referred to as `PolyHashing`). In the `PolyHashing` construction, one maintains a (k, n) -threshold cryptosystem, e.g., Shamir Secret Sharing. Each password hash $h(pwd_i)$ is blinded by a share $s(i)$ for $1 \leq i \leq k \leq n$. The value $z_i = h(pwd_i) \oplus s(i)$ is stored in a so-called `PolyHashing` store at index i . The shares $s(i)$ are not stored on disk. But, to be efficient, a legal party, e.g., a server of a social networking system, has to store at least k shares in the RAM to on-the-fly compare incoming requests on-the-fly. Thus, this system only provides security against adversaries which are only able to read the hard disk but not the volatile memory (RAM).

Since the secret (of the threshold cryptosystem) or at least the k shares have to be in memory, GC attacks are possible by just reading the corresponding memory. The password itself is only hashed and blinded by $s(i)$. Thus, if an adversary is able to read the shares or the secret from memory, it can easily filter wrong password candidates, i.e., making `PolyPassHash` vulnerable against WGC attacks.

POMELO [27]. `POMELO` contains three update functions $F(S, i)$, $G(S, i, j)$, and $H(S, i)$, where S denotes the internal state and i and j the indices at which the state is accessed. Those functions update at most two state words per invocation. The functions F and G provide deterministic random-memory accesses (determined by the cost parameter t_{cost} and m_{cost}), whereas the function H provides random-memory accesses determined by the password, rendering `POMELO` at least partially vulnerable to cache-time attacks. Since the password is used only to initialize the state, which itself is overwritten about $2^{2 \cdot t_{cost}} + 2$ times, `POMELO` provides resistance against GC and WGC attacks.

Pufferfish [13]. The main memory used within `Pufferfish` is given by a two-dimensional array consisting of $2^{5+m_{cost}}$ 512-bit values, which is regularly accessed during the password hash generation. The first steps of `Pufferfish` are given by hashing the password. The result is then overwritten $2^{5+m_{cost}} + 3$ times, rendering WGC attacks not possible. The state word containing the hash of the password ($S[0][0]$) is overwritten $2^{t_{cost}}$ times. Thus, there does not exist a shortcut for an adversary, rendering GC attacks impossible.

Rig [6]. Rig maintains two arrays a (sequential access) and k (bit-reversal access). Both arrays are iteratively overwritten $r \cdot n$ times, where r denotes the round parameter and n the iteration parameter. Thus, rendering Rig resistant against GC attacks. Note that within the setup phase, a value α is computed by

$$\alpha = H_1(x) \quad \text{with} \quad x = \text{pwd} \parallel \text{len}(\text{pwd}) \parallel \dots,$$

Since the first α (which is directly derived from the password) is only used during the initialization phase, WGC attacks are not applicable.

schvrch [26]. The password scrambler *schvrch* maintains an internal state of $256 \cdot 64$ -bit words (2 kB), which is initialized with the password, salt and their corresponding lengths, and the final output length. After this step, the password can be overwritten in memory. This state is processed t_cost times by a function *revolve()*, which affects in each invocation all state words. Next, after applying a function *stir()* (again, changing all state entries), it expands the state to m_cost times the state length. Each part (of size state length) is then processed to update the internal state, producing the hash after each part was processed. Thus, the state word initially containing the password is overwritten $t_cost \cdot m_cost$ times, rendering GC attacks impossible. Further, neither the password nor a value directly derived from it is required during the invocation of *schvrch*, which thwarts WGC attacks.

Tortuga [23]. GC and WGC attacks are not possible for *Tortuga* since the password is absorbed to the underlying sponge structure, which is then processed at least two times by the underlying keyed permutation (Turtle block cipher [4]), and neither the password nor a value derived from it has to be in memory.

SkinnyCat and TwoCats [7]. *SkinnyCat* is a subset of the *TwoCats* scheme optimized for implementation. It maintains a 256-bit state $state$ and an array of 2^{m_cost+8} 32-bit values (mem). The algorithm computes the value

$$PRK = \text{Hash}(\text{len}(\text{pwd}), \text{len}(\text{salt}), \dots, \text{pwd}, \text{salt})$$

at the beginning. The value PRK is not only used in the initialization phase of the internal state, but also as an input in the forelast step of *SkinnyCat*. Thus, an adversary that gains knowledge about the value PRK is able to launch the following WGC attack: For each password candidates x and the known value $salt$, compute $PRK' = \text{Hash}(\text{len}(x), \text{len}(salt), \dots, x, salt)$ and check whether $PRK = PRK'$. If so, mark x as a valid password candidate.

Both *SkinnyCat* and *TwoCats* consist of two phases each. The first phase updates the first half of the memory (early memory) $mem[0, \dots, memlen/(2 \cdot blocklen) - 1]$, where the memory is accessed in a password-independent manner. The second phase updates the second half of the memory $mem[memlen/(2 \cdot blocklen), \dots, memlen/blocklen - 1]$, where the memory is accessed in a password-dependent manner. Thus, both schemes provide only partial resistance against cache-timing attacks. Since the first half of the memory is written password-independently, a GC adversary can use the knowledge about the early memory to launch the following GC attack:

1. Obtain $mem[0, \dots, memlen/(2 \cdot blocklen) - 1]$ and PRK from memory
2. Create a state $state'$ and an array mem' of the same size as $state$ and mem , respectively
3. Set $fromAddr = \text{slidingReverse}(1) \cdot blocklen$, $prevAddr = 0$, and $toAddr = blocklen$
4. For each password candidate x :
 - (a) Compute PRK' as drescribed using the password candidate x
 - (b) Initialize $state'$ and mem' as prescribed using PRK'
 - (c) Compute $state'[0] = (state'[0] + mem'[1]) \oplus mem'[fromAddr + +]$
 - (d) Compute $state'[0] = \text{ROTATE_LEFT}(state'[0], 8)$
 - (e) Compute $mem'[blocklen + 1] = state'[0]$
 - (f) Check whether $mem'[blocklen + 1] = mem[blocklen + 1]$
 - (g) If yes: mark x as a valid password candidate
 - (h) If no: go to Step 4.

Note that *TwoCats* allows to set an input flag causing the early memory to be overwritten. Thus, this GC attack is only possible if this flag is not set. Nevertheless, the WGC attack works for both schemes.

Yarn [16]. Yarn maintains two arrays *state* and *memory*, consisting of *par* and 2^{m_cost} 16-byte blocks, respectively. The array *state* is initialized using the salt. Afterwards, *state* is processed using the BLAKE2b compression function with the password *pwd* as message, resulting in an updated array *state1*. This array has to be stored in memory since it is used as input to the final phase of Yarn. The array *state* is expanded afterwards and further, it is used to initialize the array *memory*. Next, *memory* is updated continuously. Both *memory* and *state* are overwritten continuously. The array *state1* is overwritten at the latest in the final phase of Yarn. Thus, GC attacks are not possible for Yarn. Nevertheless, the array *state1* is directly derived from *pwd* and stored until the final phase occurs. Thus, the following WGC attack is possible:

1. Compute $h \leftarrow \text{BLAKE2B_GENERATEINITIALSTATE}(\text{outlen}, \text{salt}, \text{pers})$ as in the first phase of Yarn
2. For each password candidate x :
 - (a) Compute $h' \leftarrow \text{BLAKE2B_CONSUMEINPUT}(h, x)$
 - (b) Compute $\text{state1}' \leftarrow \text{TRUNCATE}(h', \text{outlen})$ and check whether $\text{state1}' = \text{state1}$

yescrypt [20]. The yescrypt password scrambler maintains two lookup tables V and $VROM$, where V is located in the RAM and $VROM$ in the ROM. The array $VROM$ is only accessed, if the flag `YESCRYPT_RW` is set. Also, only when `YESCRYPT_RW` is set, the array in the RAM is overwritten partially. Note that yescrypt can be reduced to `script` by activating the corresponding flags. Based on this structure, the same GC attacks as on `script` (see Section 2.2) are possible when:

- ... `YESCRYPT_RW` is not set, i.e., the RAM is never overwritten.
- ... the ROM is used but the frequency mask is not zero, where the frequency mask determines if the ROM is accessed or not.

Since yescrypt also uses the password in the final invocation of PBKDF2, the same WGC attack as for `script` (see Section 2.2) is applicable.

5 Conclusion

In this work we provided an overview of the first-round candidates of the Password Hashing Competition, which are not yet withdrawn. Further, we analyzed each algorithm regarding to its vulnerability against garbage-collector and weak garbage-collector attacks. Even if both attacks require access to the memory on the target's machine, they show a potential weakness, which should be taken into consideration. As a result, we have shown GC attacks on `CATENA-BRG`, `MCS_PHS`, `PolyPassHash`, `script`, `SkinnyCat`, `TwoCats`, and `yescrypt`, whereas the attacks on `SkinnyCat`, `TwoCats` and `yescrypt` work only under certain requirements. Additionally, we have shown that WGC attacks are possible for `battercrypt`, `CENTRIFUGE`, `EARWORM`, `PolyPassHash`, `script`, `SkinnyCat`, `TwoCats`, `Yarn`, and `yescrypt`.

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