Generic Related-key Attacks for HMAC

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Outline

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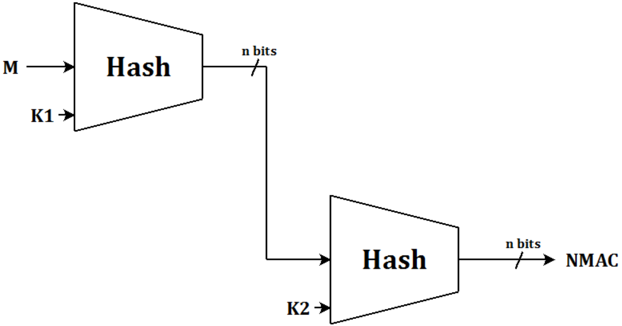
HMAC and NMAC (Bellare *et al.* - 1996)

A MAC outputs an n-bit value from a k-bit key K and an arbitrary long message M.

$$\texttt{NMAC}(K_1, K_2, M) = H(K_2, H(K_1, M))$$



HMAC and NMAC (Bellare *et al.* - 1996)

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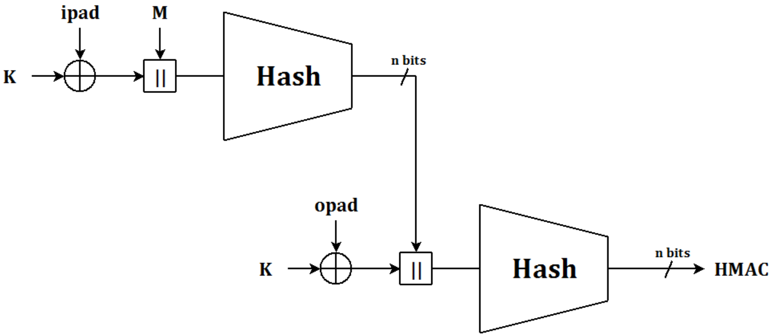
$$\texttt{HMAC}(K, M) = H(K \oplus \textbf{opad} \,||\, H(K \oplus \textbf{ipad} \,||\, M))$$



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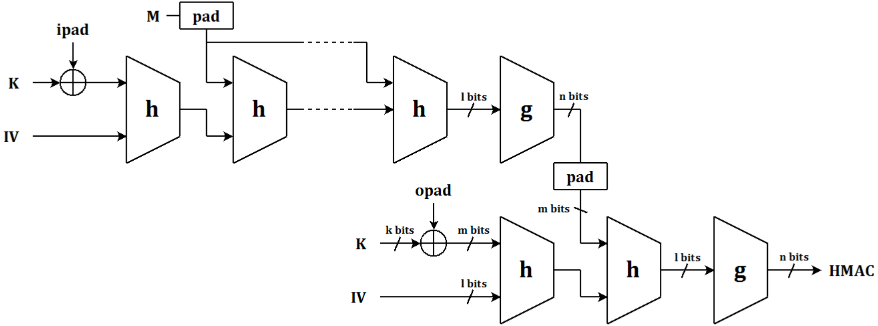


Outline

Known dedicated attacks on HMAC

Attack	Key Setting	Target	Size	#Rounds	Comp.	Ref.
Dist.-H	Single key	MD4	128	Full	$2^{121.5}$	[KBPH06]
Dist.-H	Single key	MD5	128	33/64	$2^{126.1}$	[KBPH06]
Dist.-H	Single Key	MD5	128	Full	2^{97}	[WYWZZ09]
Dist.-H	Single key	3p HAVAL	256	Full	$2^{228.6}$	[KBPH06]
Dist.-H	Single key	4p HAVAL	256	102/128	$2^{253.9}$	[KBPH06]
Dist.-H	Single key	SHA0	160	Full	2^{109}	[KBPH06]
Dist.-H	Single key	SHA1	160	43/80	$2^{154.9}$	[KBPH06]
Dist.-H	Single key	SHA1	160	50/80	$2^{153.5}$	[RR08]
Dist.-H	Related Key	SHA1	160	58/80	$2^{158.74}$	[RR08]
Inner key rec.	Single Key	MD4	128	Full	2^{63}	[CY06]
Inner key rec.	Single Key	SHA0	160	Full	2^{84}	[CY06]
Inner key rec.	Single Key	SHA1	64	34/80	2^{32}	[RR08]
Inner key rec.	Single Key	3p HAVAL	256	Full	2^{122}	[LCKSH08]
Full key rec.	Single Key	MD4	128	Full	2^{95}	[FLN07]
Full key rec.	Single Key	MD4	128	Full	2^{77}	[WOK08]

Known generic attacks on HMAC

Universal forgery attack costs 2^n computations (ideal)

Existential forgery attack costs $2^{l/2}$ computations (not ideal)

Distinguishing-R attack costs $2^{l/2}$ computations (not ideal)

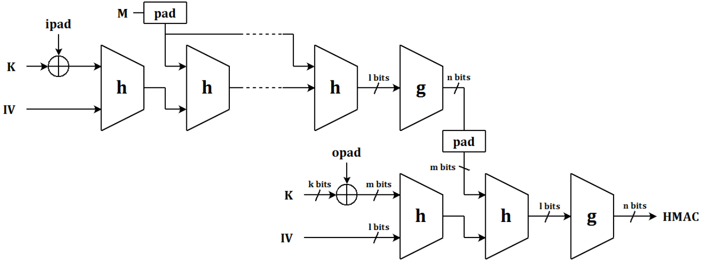
Distinguishing-H attack costs 2^l computations (ideal)

Known generic attacks on HMAC

Existential forgery attack costs $2^{l/2}$ computations (not ideal)

The procedure

- **step 1:** query $2^{l/2}$ messages and gather all pairs (M, M') that collides on the output
- **step 2:** for all colliding pairs, append an extra random message block M_1 and check if this new message pair $(M||M_1, M'||M_1)$ collides as well. Pick one such pair.
- **step 3:** append another extra random message block M_2 and query the MAC for message $M||M_2$. Then it is equal to the MAC for message $(M'||M_2)$



Known generic attacks on HMAC

Attack	**Key Setting**	**Generic Complexity**
Universal forgery	Single Key	2^n
Existential forgery	Single Key	$2^{l/2}$
Dist.-R	Single Key	$2^{l/2}$
Dist.-H	Single Key	2^l

Known generic attacks on HMAC

Attack	Key Setting	Generic Complexity
Universal forgery	Related Key	2^n ?
Existential forgery	Related Key	$2^{l/2}$?
Dist.-R	Related Key	$2^{l/2}$?
Dist.-H	Related Key	2^l ?

Outline

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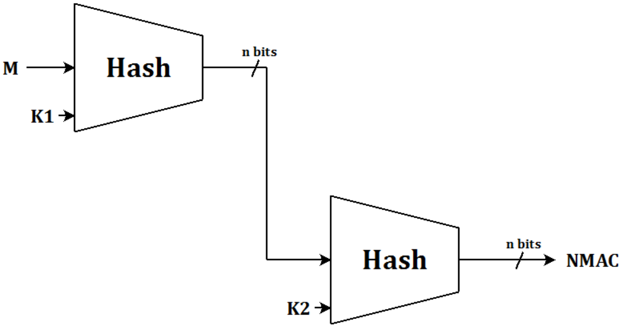
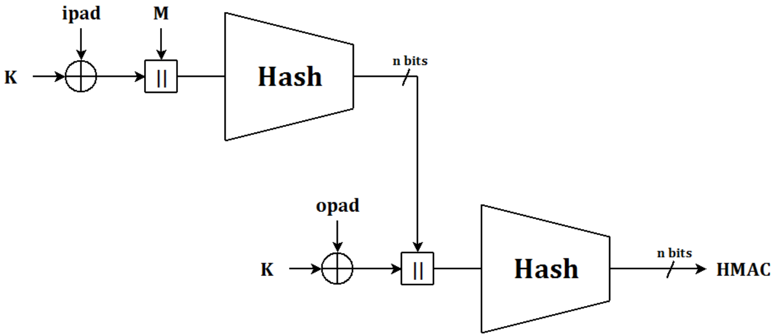
What weakness to attack ?

NMAC



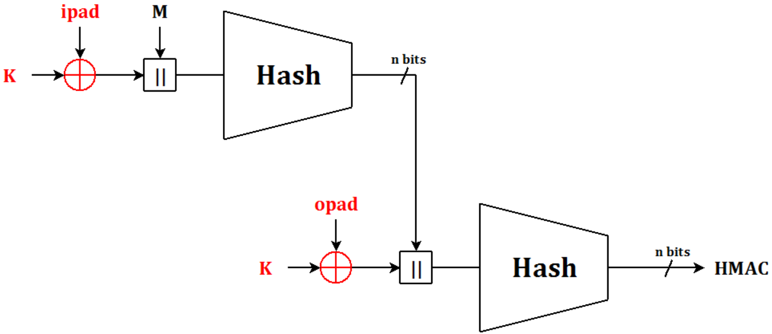
What weakness to attack ?

HMAC



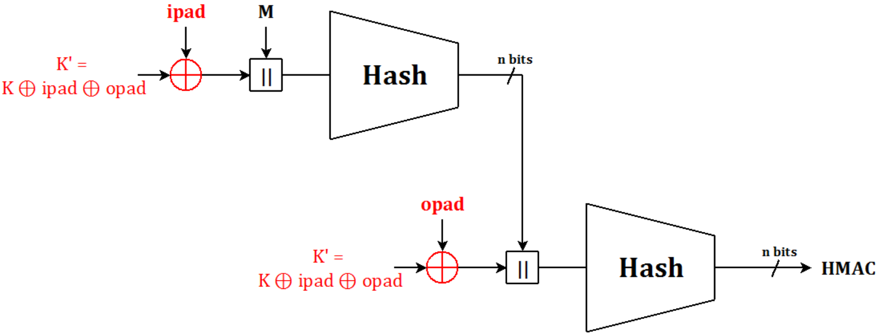
What weakness to attack ?

HMAC
(with key K)



What weakness to attack ?

HMAC
(with key $K' = K \oplus$ ipad $\oplus$ opad)



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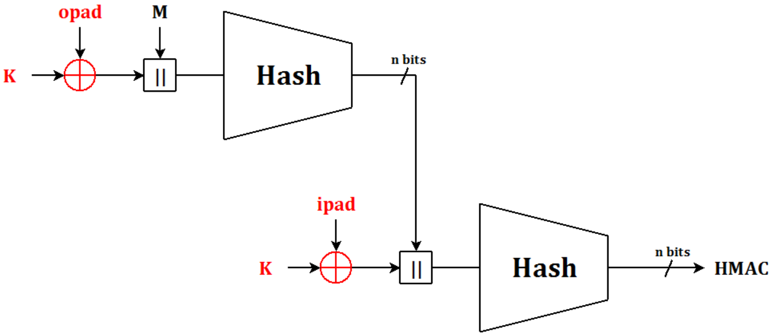
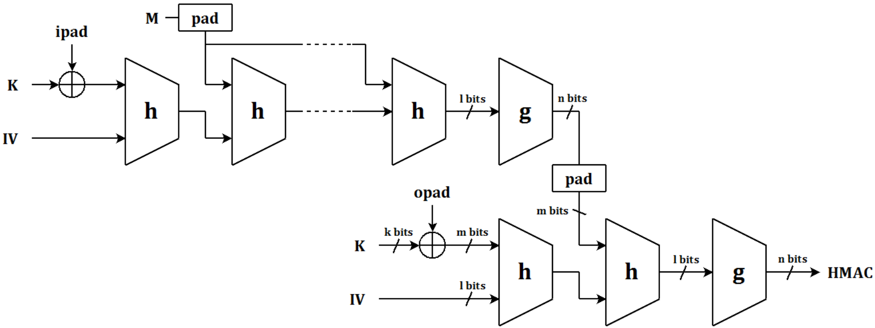


What to detect ?

HMAC

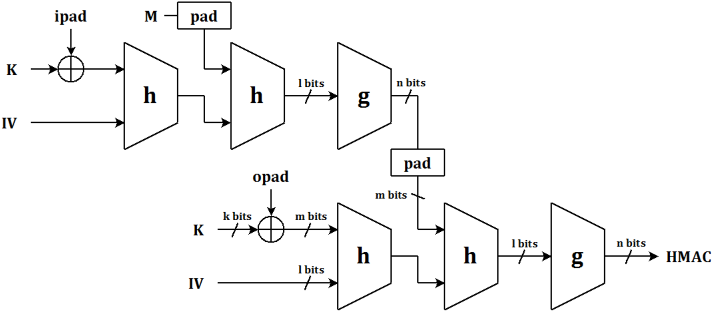
(with key K and arbitrary message)



What to detect ?

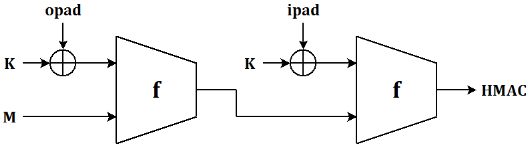
HMAC

(with key K and n-bit message)



What to detect ?

HMAC
(with key K and n-bit message)



What to detect ?

HMAC

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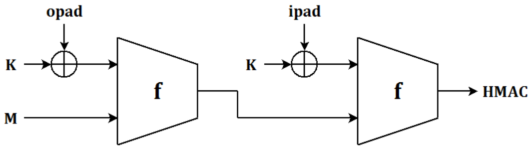
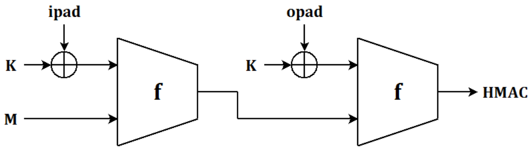
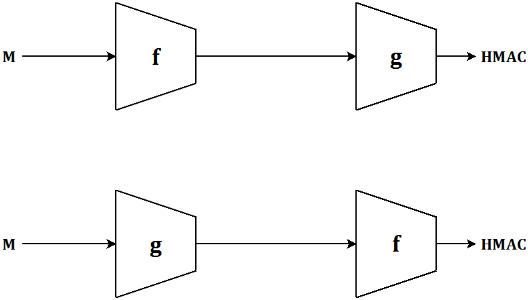




What to detect ?

HMAC

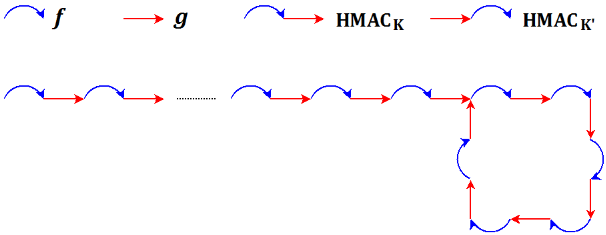
(with K and $K' = K \oplus \texttt{ipad} \oplus \texttt{opad}$ and n-bit message)



What to detect ?

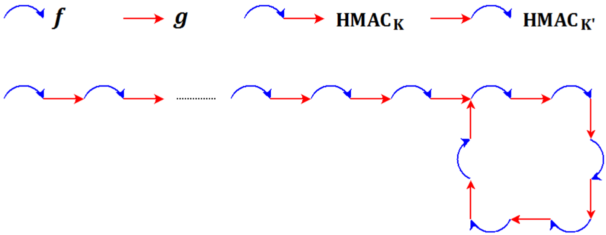
Functions $f(g(x))$ and $g(f(x))$ have a particular cycle structure:

there is a 1-to-1 correspondence between cycles of $f(g(x))$ **and** $g(f(x))$



How to detect the cycle structure ?

$\Longrightarrow$ by measuring cycles length



The game played (distinguishing-R in the related-key model):

The attacker can query two oracles, F_K and $F_{K'}$, that are instantiated either with $\texttt{HMAC}_K$ and $\texttt{HMAC}_{K'}$, or with two independent random functions R_K and $R_{K'}$. He must obtain non-negligible advantage in distinguishing the two cases:

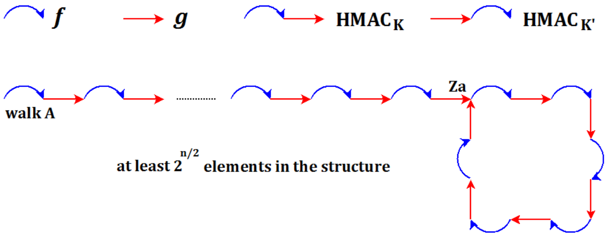
$$Adv(\mathcal{A}) = |\Pr[\mathcal{A}(\texttt{HMAC}_K, \texttt{HMAC}_{K'}) = 1] - \Pr[\mathcal{A}(R_K, R_{K'}) = 1]|$$

The attack

First step (walk A)

Start from an n-bit random input message, query F_K, and keep querying as new message the MAC just received. Continue so for about $2^{n/2} + 2^{n/2-1}$ queries until getting a collision among the MACs received.

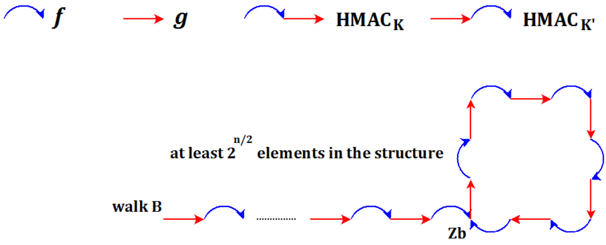
If no collision is found, or if the collision occurred in the $2^{n/2}$ first queries, the attacker outputs 0.



The attack

Second step (walk B)

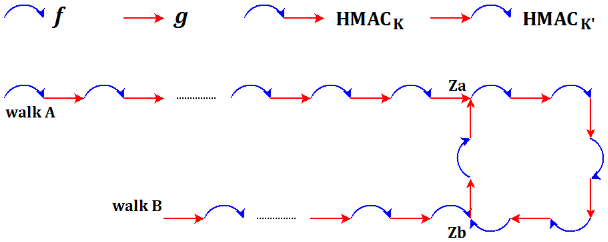
Do the same for oracle $F_{K'}$.



The attack

Third step (colliding walk A and walk B)

If the cycle of walk A has the same length as the one from walk B, then output 1. Otherwise output 0.



Results - distinguishing-R for HMAC with wide-pipe

The advantage of the attacker is non-negligible and **the complexity of the distinguisher** is about $2^{n/2} + 2^{n/2-1}$ computations for each of the first and second phase, thus **about** $2^{n/2+1}$ **computations in total**.

We implemented and verified the distinguisher. With SHA−2 truncated to 32 bits, we found two walks A and B that have the same cycle length of 79146 elements with 2^{17} computations. The best previously known attack for HMAC instantiated with SHA−2 truncated to 32 bits required 2^{128} computations.

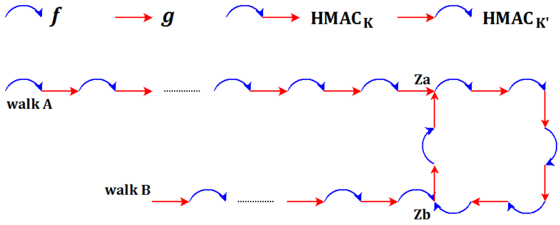
Attack	Key Setting	Target	Old Generic Complexity	New Generic Complexity
Dist.-R	Related Key	Wide-pipe	$2^{l/2}$	$2^{n/2+1}$

Outline

How to recover the intermediate internal state ?

We would like to know some of the intermediate internal state of $\texttt{HMAC}_K$ **and** $\texttt{HMAC}_{K'}$

Inside a colliding cycle for $\texttt{HMAC}_K$ and $\texttt{HMAC}_{K'}$, the input or output queries to $\texttt{HMAC}_K$ are intermediate internal state of $\texttt{HMAC}_{K'}$ (and vice-versa) ... but we don't know which one it is, so **we need to synchronize the cycles**

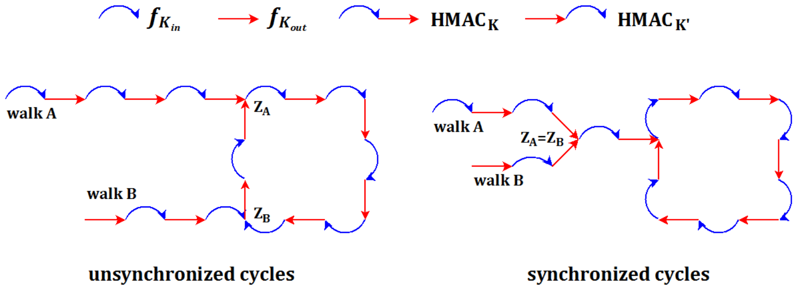


Synchronized and Unsynchronized cycles

There are two cases for a collision between walk A and walk B:

- collision in the tail
- collision in the cycle

If the collision happens in the tail, then the cycles are directly synchronized

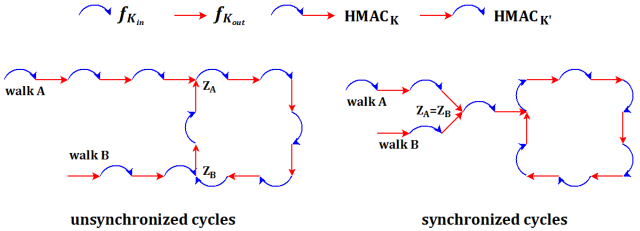


Synchronized and Unsynchronized cycles

We just build walk A and walk B with a tail long enough, such that the collision is likely to happen in the tail.

The procedure

- **step 1 (build walk A):** same as before, but just ensure that tail in walk A has size at least $2^{n/2-2}$
- **step 2 (build walk B):** same as step 1, but with queries to $K' = K \oplus \texttt{ipad} \oplus \texttt{opad}$
- **step 3:** check if the cycle have the same length, and if so, there is a good chance that it happened in the tail. Then you can recover the intermediate internal states.



Results - internal state recovery for HMAC

The complexity of the internal state recovery is **about** $2^{n/2+2}$ **queries and** 2^{l-n+1} **computations in total**.

Attack	**Key Setting**	**Target**	**Old Generic Complexity**	**New Generic Complexity**
Dist.-R	Related Key	Wide-pipe	$2^{l/2}$	$2^{n/2+1}$
Inner state rec.	Related Key	Narrow or Wide	2^{n}	$2^{n/2+2} + 2^{l-n+1}$

Outline

Existential forgery and distinguish-H attack

- **once we have recovered an internal state, forging a valid MAC is easy**
- **if we can recover an internal state, then distinguish-H is easy**

The **complexity to forge a valid MAC or distinguish-H** is the complexity of the internal state recovery ($2^{n/2+2} + 2^{l-n+1}$ **computations**)

Attack	**Key Setting**	**Target**	**Old Generic Complexity**	**New Generic Complexity**
Dist.-R	Related Key	Wide-pipe	$2^{l/2}$	$2^{n/2+1}$
Inner state rec.	Related Key	Narrow or Wide	2^n	$2^{n/2+2} + 2^{l-n+1}$
Ex. forgery	Related Key	Wide-pipe	$2^{l/2}$	$2^{n/2+2} + 2^{l-n+1}$
Dist.-H	Related Key	Narrow or Wide	2^l	$2^{n/2+2} + 2^{l-n+1}$

Outline

Our results

Our attacks on HMAC work when the key has length m, or $m - 1$ because ipad $=$ 0x3636 $\cdots$ 36 and opad $=$ 0x5C5C $\cdots$ 5C

$\Longrightarrow$ **The choice of ipad and opad was in fact important**

Attack	Key Setting	Target	Old Generic Complexity	New Generic Complexity
Dist.-R	Related Key	Wide-pipe	$2^{l/2}$	$2^{n/2+1}$
Inner state rec.	Related Key	Narrow or Wide	2^{n}	$2^{n/2+2} + 2^{l-n+1}$
Ex. forgery	Related Key	Wide-pipe	$2^{l/2}$	$2^{n/2+2} + 2^{l-n+1}$
Dist.-H	Related Key	Narrow or Wide	2^{l}	$2^{n/2+2} + 2^{l-n+1}$

Patching HMAC

1^{st} try:

We use a different IV for the hash function in the inner and outer call ...
... but that would require to change the H definition and implementations

2^{nd} try:

We truncate the HMAC output ...
... but having a smaller output reduces the expected security

Our solution:

Just **prepend a "0" bit to the message** M:

- no more possible for the attacker to synchronize the computation chains: the inner and outer function are made distinct
- no need to change the specification of H, even better: can be done on top of HMAC implementations
- almost zero performance drop

Thank you for your attention !