PACStack: Authenticated Call Stack

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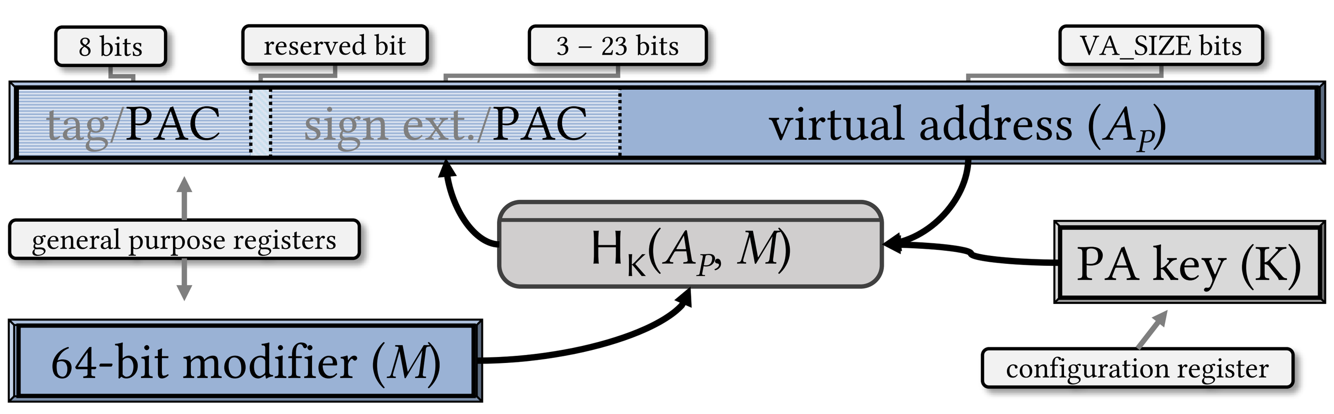
https://pacstack.github.io

How can hardware-assistance for *Pointer Authentication* efficiently and precisely verify *function return addresses* and resist reuse attacks without additional hardware?

Pointer Authentication deployed in ARMv8.3-A

- General purpose hardware primitive *approximating pointer integrity*
- Adds Pointer Authentication Code (PAC) into unused bits of pointer
- PAC: keyed, tweakable MAC from *pointer address* and 64-bit *modifier*
- PA keys protected by hardware, modifier decided where pointer used
- Vulnerable to pointer reuse if modifier is not unique to a pointer value



Structure of an authenticated pointer

High-level idea

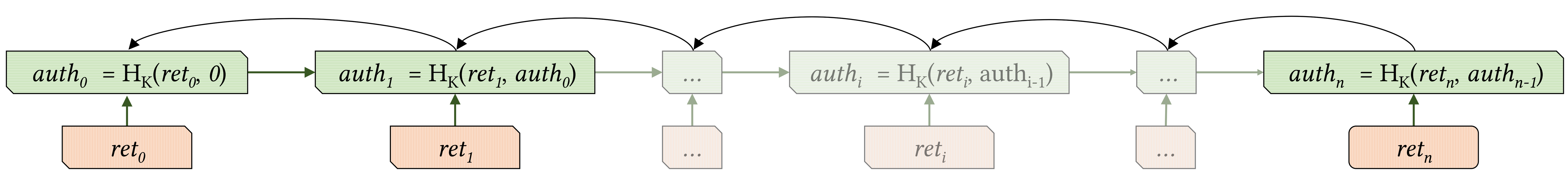
- *Authenticated Call Stack* (ACS) is a *chained MAC* of return addresses
- Provide modifier (*auth*) for the return address by *cryptographically binding it to all previous return addresses* in the call stack
- This makes modifier *statistically unique to a particular control-flow path*, preventing reuse and allowing precise verification of returns

ACS implementation using PA: PACStack

Two variants:

1. Generate 32-bit *auth* with `pacga` instruction and store on stack
2. Generate 16-bit *auth* with `pacib` instruction and embed in PAC-bits

- Topmost $auth_n$ always stored securely in *dedicated CPU register*



ACS is a chained MAC of tokens $auth_i$, $i \in [0, n-1]$ cryptographically bound to corresponding return addresses, ret_i, $i \in [0, n]$, and $auth_n$

Mitigation of hash-collisions: authentication token masking

- **Challenge**: PAC collisions occur on average after $1.253 * 2^{b/2}$ return addresses (e.g., 321 addresses for b=16)
- **Solution:** Prevent *recognizing* collisions by masking each *auth* with pseudo-random mask generated using `pacib(0x0,` $auth_{i-1}$`)`

Attack	w/o Masking	w/ Masking
Reuse previous auth collision	1	2^{-b}
Guess auth to existing call-site	2^{-b}	2^{-b}
Guess auth to arbitrary address	2^{-2b}	2^{-2b}

Maximum probability of success for different attacks

Comparison: ACS / PACStack vs. shadow stacks

Shadow stacks are precise, but have drawbacks:

- Software shadow stacks suffer from large performance overheads
- *A parallel shadow stack / dedicating a register* increase performance, but leave shadow stack vulnerable if its location in memory is known
- Hardware shadow stacks are efficient and secure, but require dedicated, single purpose support and isolated / integrity protected memory

ACS / PACStack provide *probabilistic guarantees*, but has benefits:

- Can be instantiated with any MAC, e.g., *hardware-assisted utilizing PA*
- Very efficient when utilizing hardware-assisted primitives
- No isolated / integrity protected memory (beyond single register)

Impact on performance in C-language benchmarks

Estimated performance impact based on PA with QARMA cipher on 1.2GHz ARM core and PA-analogue (4 cycles / PA instruction):

- **0.9%** performance overhead in *SPEC CPU 2017* benchmarks (geometric mean, 0.4% without masking)
- **0.5%** performance overhead in *nbench byte 2.2.3* benchmarks (geometric mean, <0.3% without masking)

Generalizing ACS to other use cases

Provides efficient authenticated stack using ARM PA that can be used for:

- protecting other stack data, e.g., frame pointer or read-only variables
- frame-by-frame unwinding of the call stack in C++ exceptions
- reusable library for protecting other critical data structures (e.g., in kernel code, language runtime, applications etc.)

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