Camouflage: Hardware-assisted CFI for the ARM Linux kernel

Rémi Denis-Courmont
Huawei Technologies, Finland
remi@remlab.net

Hans Liljestrand
Aalto University, Finland
Hans Liljestrand
Hans Liljestrand

Carlos Chinea
Huawei Technologies, Finland
carlos.chinea.perez@huawei.com

Jan-Erik Ekberg
Huawei Technologies, Finland
Jan-Erik Ekberg
Jan-Erik Ekberg

Abstract—Software control flow integrity (CFI) solutions have been applied to the Linux kernel for memory protection. Due to performance costs, deployed software CFI solutions are coarse grained. In this work, we demonstrate a precise hardware-assisted kernel CFI running on widely-used off-the-shelf processors. Specifically, we use the ARMv8.3 pointer authentication (P Auth) extension and present a design that uses it to achieve strong security guarantees with minimal performance penalties. Furthermore, we show how deployment of such security primitives in the kernel can significantly differ from their user space application.

1. Introduction

The Linux kernel open source community has recently directed much effort on improving the security and attack resistance of the kernel. This is evident from both a good track record in fixing reported vulnerabilities, but also in the number of new security features introduced in the kernel. These include security solutions adapted from user space mechanisms such as address space layout randomization (ASLR) [1], W+X memory policies or coarse-grained CFI integration [2]. Performance costs prevent the use of powerful security solutions such as fine-grained CFI. Nonetheless, the currently integrated mechanisms preclude many crude memory attacks, such as code injection, inside the kernel.

Still, more than 50% of the recently reported CVEs on kernel vulnerabilities relate to memory errors [4]. Moreover, new advanced attacks, such as, control-flow bending [5] or data-oriented programming (DOP) [6], are likely to eventually be used as part of kernel exploit chains. At the same time, new hardware memory-safety features are introduced into ARM and Intel processors. To date, most of the design evolution in this domain has targeted the protection of user applications, under the assumption that transferring the hardware mechanisms into kernel space is straightforward. In this paper, we argue that this is only partially true, and use the recent ARMv8.3-PAuth extension as an example of this.

We apply PAuth to the Linux kernel to prevent the exploitation of bugs that could, for instance, lead to root privilege escalation or leakage of system secrets. This requires non-trivial changes and additions to prior PAuth-based schemes. Because of programming patterns used within the kernel, approaches that focus only on function pointers are ineffective in kernel context. Our design accommodates and protects such patterns by also protecting pointers to critical data structures, such as the use of operations tables that contain function pointers. The PAuth keys are not banked, i.e., they must be switched out when entering or exiting kernel space. We demonstrate a novel design that uses execute-only memory (XOM) to securely set kernel keys without exposing them to an adversary that can read kernel memory. The contributions of this paper are:

1) A secure architecture for kernel PAuth key management, that does not depend on traps to higher exception levels (ELs).
2) A design for maintaining binary compatibility between non-PAuth processors and a protected kernel and modules.
3) A PAuth instrumentation scheme that is compatible and effective with Linux kernel coding patterns.
4) A hardened PAuth backwards CFI scheme that is robust against replay attacks despite kernel task stack shallowness.

2. Background

2.1. Code reuse attacks on AArch64

The AArch64 call instructions save the function return address in the link register (LR). The canonical prologue for a non-leaf function then stores it and the caller’s frame pointer (FP) on the stack (Listing 1). The epilogue conversely restores the FP and LR values from the stack. In this scenario, a memory vulnerability—e.g., stack-buffer overflows—may enable an attacker to overwrite the frame record and control LR when the RET is invoked [7]. The attacker can then redirect the execution flow to an arbitrary address, e.g., for return-oriented programming (ROP) [8]. Similarly, jump-oriented programming (JOP) [9] attacks corrupt instructions pointers in memory before they are consumed by an indirect jump BR or call BLR instruction. Alternatively, attacks may target function pointers indirectly referenced in data structures, such as C++ virtual table pointers [10].

Listing 1. The AArch64 frame record is used to store and restore the FP and LR values in the function prologue and epilogue, respectively.

| Line | Description |
|------|-------------|
| 1    | func: // Prologue |
| 2    | stp fp, lr, [sp, #-16]! |
| 3    | mov fp, sp |
| 4    | // ... |
| 5    | // Epilogue |
| 6    | ldp fp, lr, [sp], #16 |
| 7    | ret |

1. unless disabled by compiler optimizations
2. AArch64 pointer authentication (PAuth)

ARMv8.3-A introduces the PAuth extension (see also Section 3). It substitutes unused bits in AArch64 pointers to store a keyed message authentication code (MAC). We follow ARM notation, and call the MAC a pointer authentication code (PAC). The PAC is, by default, generated using the QARMA [11] algorithm. It is derived from a secret key, the pointer’s address and a modifier. On load, a pointer can be authenticated against the same secret key and modifier. PAuth can be used to build statistical CFI and data flow integrity (DFI). Starting from version 5.0, the Linux kernel enables the use of PAuth in user space and for kernel virtual machines (KVM) guests but not kernel space. The LLVM/Clang and GCC compilers support backward-edge CFI with PAuth but use only the stack pointer (SP) as modifier(Listing 2). If the LR value saved on the stack was overwritten during between the prologue and the epilogue, then the AUTIA instruction should detect a mismatch in the PAC, and set LR to an invalid address, such that RET triggers an instruction fault exception, rather than execute the attacker’s ROP chain.

The kernel tracks keys in the per-thread thread_struct in-kernel structure, and installs the keys of the switched-to thread during user context switch. The exec() system call will automatically generate a new set of keys whenever a new user address space is instantiated. By default, keys are shared by all tasks in a single address space, but an architecture-specific prctl() call is available to manually provision keys per thread.

2.3. Kernel-user separation

The Linux kernel implements a 1:1 threading model, i.e., one kernel task is allocated for each user thread in user mode (EL0). When a user thread invokes a system call, execution flow is transferred to the kernel exception handler in kernel mode (EL1). SP is banked on AArch64, i.e., the processor keeps track of the value separately for each EL. However the general-purpose registers (GPRs) and the system registers holding the current PAuth keys are shared between all ELs. Consequently, the exception handler must save the processor state before executing the system call in EL1, and afterwards restore it before returning to EL0. The same sequence also occurs when user space triggers an exception, or when an asynchronous interrupt is encountered when a user thread is running. Because the PAuth keys are not banked, they must be set on kernel entry if PAuth is to be used within the kernel. Conversely, the PAuth keys of the running user process must be restored when the kernel returns to EL0.

3. Threat model and requirements

3.1. Threat model

We assume a powerful adversary with full control over unprivileged user processes, including the capability to launch arbitrary processes and invoke arbitrary system calls. We further assume that the adversary can use a memory corruption bug in the kernel system call interface to read and write kernel memory. However, the adversary cannot modify write-protected memory (including XOM). This limitation can be realized by locking down memory management unit (MMU) system control registers and tables via the hypervisor [12]. Nonetheless, the adversary can leak kernel secrets in readable memory and overwrite pointers in writable memory regions.

3.2. Requirements

Our goal is to protect kernel call-flow by protecting the integrity of vulnerable pointers. Specifically, we use PAuth to fulfill the following requirements:

- **Integrity**: Detect corruption of pointers that affect kernel control flow and mitigate the scope of pointer reuse (R1).
- **Robustness**: Protect configuration and confidentiality of PAuth keys used by the kernel (R2).
- **Deployability**: Limit the impact on existing kernel coding patterns and existing kernel code (R3).
- **Performance**: Minimize performance overhead in terms of execution time and memory use in practical use cases (R4).
- **Compatibility**: Maintain the existing user space application binary interface (ABI) and PAuth functionality (R5).

3.3. Challenges

The prior kernel support for PAuth targets only EL0 usage. When we now apply PAuth to protect the Linux kernel, we need to address security challenges arising from the different software and hardware context present in EL1:

3.3.1. Key allocation

PAuth supports five simultaneously active keys per processor core. All kernel tasks share the same address space, and so use the same set of keys. Kernel PAuth key configuration must be protected to prevent modification of the keys (R2). However, we must also maintain the existing Linux ABI on AArch64, which guarantees that PAuth keys are usable in EL0 (R5). Consequently, keys must be changed on kernel entry and exit.

3.3.2. Key confidentiality

Kernel keys must remain constant from system boot to system halt so that signed pointers remain verifiable throughout. Therefore, when the kernel is not running, the kernel keys must be preserved in EL1 memory so that the operating system (OS) scheduler can restore them when switching between ELs. To maintain key confidentiality, we must both prevent the reading of the PAuth keys from system registers and memory (R2).
4. Design

4.1. Key management

PAuth keys must be available on boot. Therefore, the bootloader uses a pseudo-random number generator (PRNG) to generate them and then stores them in XOM before starting the kernel. XOM is mapped in kernel space but its permissions are enforced by the hypervisor, and so it allows secure storage of the keys with minimal performance impact. The key values are encoded within the executable code of a function that has the sole purpose of writing the kernel keys into the system configuration registers. Because the code cannot be read it cannot be disassembled to extract the keys. After completion, the function clears all GPRs to prevent the keys from being leaked. This ensures that kernel keys are usable as soon as the kernel boots.

The kernel only needs to set the PAuth register values, it need not be able to read the keys; hence we can use static code analysis to verify that no code exists in the kernel, including the loadable kernel modules (LKMs), which would read the keys from system registers. We also check that no code exists that would corrupt the PAuth flags in the SCTLR_EL1 register and thus disable the kernel keys.

4.2. Backward-edge CFI

The reference implementation of backward-edge CFI with PAuth is vulnerable to replay attacks within a given thread because the values of the modifier, SP, often repeat. This problem is accentuated for the task stacks within the kernel, where system calls made by a given user thread run with same shallow kernel stack (of 16 KiB). Moreover, each user thread has its own kernel stack that is aligned on a 4 KiB boundary, such that the 12 lower order bits of SP repeat across threads. To mitigate such attacks, we construct the modifier by concatenating the low order 32 bits of SP with the low order 32 bits of the address of the function, which is inferred from the current program counter (PC).

4.3. Pointer Integrity

Protecting all kernel pointers would be prohibitive for performance reasons. Instead, we explicitly mark select pointers for protection in the kernel source code. To ease software engineering efforts, we plan to add a new source code attribute to annotate pointer members in compound type declarations. The compiler could then automatically insert the signing and authenticating PAuth instructions. Moreover, this would allow the compiler to use combined PAuth instructions, such as the authenticated branch-and-link BLRAA, instead of a PACIB and BLR pair. Our evaluated prototype uses inline assembler macros instead, which wrap PAuth in C code, for use when assigning or evaluating a signed pointer.

To ward off reuse attacks, we use a modifier constructed by concatenating the low-order 48 bits of the containing object’s address with a 16-bits constant that uniquely identifies a certain member of a certain object type. Since AArch64 uses only 48 bits of address space, the modifier uniquely identifies the object in memory at a given time. The 16-bits constant then segregates pointers at the same address based on their type. The same modifier construction is used to protect function and data pointers.

4.4. Forward-edge CFI

Vulnerabilities stemming from writable and corruptible function pointers within kernel memory are well-known and understood. Consequently, most kernel function pointers are stored in static operations structures. The operations structures are located in the read-only section .rodata which cannot be tampered (Section 3.1). This is functionally similar to C++ language virtual method tables, in the simplified scenario of pure-virtual classes directly inherited by final concrete derived classes, without multiple inheritance.

Many kernel object types embed pointers to operations structures. This approach saves memory if more than one object of a given type is allocated, and mitigates the risk of corrupted function pointers. Nevertheless, Cook notes that forward-edge CFI is still necessary for the kernel. Indeed, there are still writable function pointers in the Linux kernel that need to be integrity protected using PAuth, including: 1) pointers in hardware-specific device drivers that do not follow best practices, and 2) lone function pointers, which typically are not put in operations structures (since it would not save memory for a single pointer).

4.5. Data flow integrity (DFI)

Because function pointers are often replaced with operations tables, an attacker could try to modify the pointers to the tables instead of the function pointers. Consequently, our design must also protect pointers to operations tables. For instance, the struct file structure describes an open file. It contains the f_ops pointer to const struct file_operations, that contains a large number of function pointers. Those function pointers are provided by the file system or device driver backing the given open file. In this case, f_ops needs to be protected even though it is a data pointer, not a function pointer, to ensure effective forward-edge CFI in the kernel. We use the same modifier scheme for both data and function pointers. We also note that the same approach for protecting pointers could be used to protect other sensitive pointers, such as the f_cred pointer to file credentials in the struct file structure.

In conclusion, our full implementation uses 3 of the 5 keys:
• one instruction key for backward-edge CFI,
• the other instruction key for forward-edge CFI,
• one of the two data keys for DFI.

4.6. Run-time linkage

Most kernel pointers are initialized only at run-time, but a few are set within static/global structure instances. When such a statically initialized pointer is integrity-protected with PAuth, its PAC must be computed before any kernel code attempts to authenticate and use the pointer. For instance, a struct work_struct object, describing a deferred execution callback, can be initialized statically in kernel sources using a C pre-processor macro, DECLARE_WORK, instead of using the INIT_WORK function at run-time. To address this corner case, a new executable and linkable format (ELF) section is inserted into the kernel (and LKMs). This section consists of a table of all statically initialized signed

2. In normal position-independent code (PIC), the .data.relro section would be used instead.
pointers, not dissimilar to the existing relocation table sections. Each entry in the table specifies: 1) the location of a to-be-signed pointer, 2) the PAuth key to use, and 3) the 16-bit constant for the modifier. Macros such as DECLARE_WORK are altered so that they automatically define and insert an entry in the table. Then, at early boot, after Linux kernel self-relocation, the table is iterated through and each pointer is signed in place. An equivalent procedure is applied when loading an LKM at run-time.

5. Implementation

Our prototype is based on version 5.2 of the Linux kernel, running on QEMU[18]. We believe that our findings broadly apply to other Unix-like kernels on AArch64. We add support for our architecture to a proprietary firmware bootloader and the hypervisor. This includes the generation of pseudo-random kernel keys at boot time, much like the random seed for kernel ASLR, and XOM, which is described next. Our compiler modifications are based on LLVM 8.0.

5.1. Execute-only memory (XOM)

The bootloader generates the pseudo-random PAuth keys for the kernel and updates the kernel PAuth key function before the kernel boots (Figure 1). This conceals the kernel keys without requiring a costly switch to a higher EL when setting keys at run-time (1). Each 128-bits PAuth key is defined by a pair of 64-bits system registers. The setter runs before interrupts are re-enabled to prevent key leakage and then loads the keys into GPRs using the MOV2 and MOVK move-immediate instructions that encode the values in the instructions themselves. The keys are then assigned from the GPRs with MSR. All relevant GPRs are zeroed out before the function returns. The memory page containing the function is mapped as XOM by the hypervisor, which prevents: 1) reading the immediate values from the instructions, 2) writing to modify the code or keys, and 3) execution in EL0. As shown in (12), XOM security properties are enforced by a proprietary hypervisor, which also prevents, for instance, tampering with MMU system registers.

5.2. Return address protection

To contain the risk of a replay attack against backward-edge CFI, we change the PAuth modifier used for signing return addresses, so that it varies by the called function. The compiler is modified to emit function prologues and epilogues as in listing[3]. The move-from-SP instruction (Line 3) is necessary because AArch64 does not allow SP as an operand of a bit field move instruction (Line 4). LLVM-generated AArch64 code only saves and restores SP from memory when a variable size stack allocation occurs, and as of Linux version 5.0 SP is always restored by adding an immediate value to it (as on line 6) so it cannot be corrupted.

We also provide functionally equivalent prologue and epilogue patterns in assembler macros frame_push and frame_pop. These need to be used in hand-written functions, such as in optimized single instruction multiple data (SIMD) procedures, but also in the context-switching function cpu_switch_to. In that particular function, we additionally need to sign the switched-from kernel task’s SP and authenticate the switched-to task’s SP using our pointer integrity scheme, so as to protect the SPs of tasks that are scheduled out.

5.3. Pointer Integrity

Like outlined in Section 4, most kernel function pointers are read-only and need no memory protection. However, a number of them do remain, predominantly within specific device drivers. A semantic search using Coccinelle [19] over the complete Linux version 5.2 source code yields 1285 function pointer members assigned at run-time, residing in 504 different compound types. We expect that for 229 out of the 504 types—i.e., those with more than one function pointer—should follow existing kernel practices [16] and be converted to use read-only operations structures.

Our prototype employs a unified approach to protect pointers, i.e., 1) the remaining isolated function pointers, 2) sensitive, writable data pointers, and 3) data pointers to read-only operations structures. We use a PAuth modifier with a 16-bits constant identifying the combination of the containing type and the compound type member, combined with the 48-bits address of the containing object. We define in-line PAuth assembler convenience macros to easily sign and authenticate the pointers. For instance, to access or assign the operations pointer of an open file:

- One setter, set_file_ops(), signs and stores the pointer into a struct file object, e.g.:
  ```c
  const struct file_operations my_ops = ... /\* ... */
  struct file *fp;
  /\* ... */
  set_file_ops(fp, &my_ops);
  ```
- One getter, file_ops() loads, authenticates and returns the operations pointer from an object (Listing[4]), e.g.:
  ```c
  struct file *fp;
  /\* ... */
  file_ops(fp)->read(fp, buf, len, NULL);
  ```

Based on these patterns, we have written a Coccinelle [19] semantic patch that can semi-automatically adjust the kernel source code with the appropriate PAuth modifier applied when loading an LKM at run-time.

Listing 3. The SP is signed with a custom modifier.

```plaintext
1 function: // Prologue: sign LR
2   adr ip0, function
3   mov ip1, sp
4   bfi ip0, ip1, #32, #32
5   pacib lr, ip0
6   stp fp, lr, [sp, #16]!
```
Listing 4. A file operations pointer is authenticated before an indirect call.

```
// load signed fp->f_ops from fp (x0)
l dr x8, [x0, #40]
move w9, #0xfb45
bf i x9, x0, #16, #48 // modifier
aut db x8, x9 // authenticate f_ops
ldr x8, [x8, #16] // load read
blr x8 // call read pointer
```

5.4. Brute force mitigation

PA Cs can have up to 31 bits, but with typical Linux page and virtual address configurations the space remaining for the PACs is 15 bits (see Section 3). This lies well within practical reach of a brute force attack by an attacker-controlled local application. Consecutive pointer authentication failures must therefore be limited.

When the authentication of a pointer fails, a memory fault exception is raised due to an invalid memory address. By default, a memory fault inside the Linux kernel will unconditionally terminate the user process (SIGKILL signal), and depending on the context also trigger an OOPS and halt the system. We change the kernel configuration to halt after a limited number of PAuth failures have occurred, as they constitute a strong indication of an attempt at kernel bug exploitation.

5.5. Backward compatibility

Our implementation has a build-time option to issue machine code for either AArch64 version 8.3 (or higher) only, or for older versions. To support this, PAuth includes backwards-compatible PACIB1716 and AUTIB1716 instructions, which behave as no-ops on older processors. As no such instructions exist for PAuth data (D) keys, in this case we use the same key for instructions- and data pointer protection.

6. Evaluation

6.1. Functional verification

For functional verification, we use the AArch64 system emulation from the open-source QEMU tool, which supports ARMv8.3-A and PAuth. However, QEMU is not cycle-accurate and hence it cannot be used for performance evaluation. As hardware with ARMv8.3-A is not yet generally available, we replace all PAuth instructions with the PA-analogue used in prior work on PAuth. The PA analogue is an instruction sequence that exhibits the estimated computational overhead of PAuth, i.e., 4-cycles per instruction. In the same spirit, all writes to PAuth key system registers (which do not exist on ARMv8.0-A) are substituted with writes to another register without side effects, namely CONTEXTIDR_EL1. For performance evaluation, we run our customized Linux kernel on a Raspberry Pi 3 ARMv8-A device. We compare our measurements against a baseline measured on the Ubuntu v5.0 kernel running on the same hardware. All error bars show standard deviation for $n = 20$.

6.1.3. System calls

The performance impact at system call level is measurable as a double-digit percentual overhead, as measured using the lmbench kernel micro-benchmarking tool (Figure 3). The impact is due to a comparatively high rate of function calls to computation, as is visible in kernel system call implementations. When measured with user space workloads (Figure 4), the geometric mean of the overhead drops to less than 4%.

6.2. Security Evaluation

For our design to protect kernel control flow, we must protect the integrity of all necessary pointers and prevent the leakage of PAuth keys. As discussed in Section 3, these pointers are function pointers in writable memory and data pointers to the operations structures. Based on our threat model (Section 3.1), read-only memory cannot be corrupted as the memory mappings are protected by the hypervisor. Other protected pointers are signed and verified using PAuth.
6.2.2. Key confidentiality

When stored in memory, the confidentiality of the PAuth keys is provided by XOM. During execution, the keys are loaded into registers from XOM and could thus be leaked if the key-setting process were preempted. To avoid this, the key-setting function disables preemption and clears all registers before returning. The PAuth keys are readable in the configurations registers. However, because MRS system register read instructions immediately address the read register, key reads can be trivially found and rejected (e.g., when loading a module).

6.2.3. Kernel PAuth verification oracles

Our threat model includes an adversary with arbitrary user space access. Consequently the attacker could try to find a PAuth verification oracle. The user space process uses a randomly assigned key, and thus cannot verify kernel pointers. Our design introduces a threshold for allowed PAC authentication failures to prevent non-critical sections of kernel code from being used as an oracle. Any failures are also logged, ensuring that such vulnerable code paths can be fixed.

6.3. Compliance

Our solution does not retain ISO C language semantics, since we bind the object / function address to the PACs, e.g., functions like `memcpy()` or byte-wise pointer copying / casting does fail without code adaptation. Also, extra assumptions made by the Linux kernel, such as: 1) All pointer types have the same representation or 2) Null pointer values are represented by zero bits, do not hold for PAuth. Our protection does provide, e.g., strong protection against replay, which would not be possible if those assumptions were met. We conclude that the benefit of strong memory protection outweighs the lack of compliance.

6.4. Approach analysis

We select protected pointers for DFI and forward-edge CFI only in a semi-automated manner. For the Linux kernel, this brings finer grained coverage and lower run-time overhead, considering the large amount of read-only pointers, which need no protection. This solution also provides better replay protection than would be permitted by pure ISO C language rules. We surmise that protecting all writable function pointers can be achieved with reasonable engineering effort within the Linux community.

7. Related work

Most of the work on hardware-assisted memory protection with ARM PAuth has had user applications as their focus. First out was the Qualcomm white-paper on simple return-edge CFI with PAuth, using SP as the only modifier. Apple proposal for forward-edge protection is similar to ours. However, their approach to protect vtable’s differs: the vtable pointers are protected with zero as PAuth modifier. This approach preserves `memcpy`, but is susceptible to reuse attacks. Also, Apple signs all pointers in the vtable. In contrast, we store them in read-only memory to avoid unnecessary signing of pointers.

The first academic presentation on the subject was PARTS, who presented a more fine-grained solution for both forward- and backward-edge CFI protection, as well as data pointer protection. For backward-edge CFI, our hardened solution offers security equal to PARTS. However, to assign unique function identifiers, PARTS requires linkage time optimization (LTO), which is intrinsically incompatible with LKMs and not (yet) widely supported by Linux build systems. We improve on the modifier construction as discussed in Section 5.3. Furthermore, we also remedied a PARTS shortcoming, where the lower 16 bits of SP are prone to replay attacks across different threads, whose respective stacks may well be separated by an exact multiple of \(2^{16} = 65536\) bytes within the kernel address space.

The PAuth mechanism has also been applied to stack canaries, and to a chained (authentication) solution for fully protecting the stack frames against reuse attacks. None of these projects considered the kernel as a target for their protection efforts, and with the exception of the authenticated stack, they are not readily applicable for kernel protection.

Ferri et al proposed managing (application) keys in hypervisor mode (EL2) (or secure firmware mode (EL3)) using dedicated traps to a higher EL. Kernel keys could potentially also be managed that way. However the hypervisor traps that this scheme relies on exist primarily to prevent virtual machines from accessing PAuth system registers under a legacy PAuth-unaware hypervisor. The traps can also be used for lazy initialization of PAuth support by the hypervisor, but they are not intended and optimized for frequent occurrence.

For memory protection in the Linux kernel, PaX implements backward- and forward-edge CFI in software respectively.
using stack canaries and type-based cookie matching. Moreira et al. refines software forward-edge kernel CPI by disallowing indirect calls to never indirectly referenced functions. Recent patches by ARM enable return address protection but expose the kernel PAuth keys in memory.

8. Conclusions and Future work

To date, there has been a lack of academic contributions on how to apply hardware-assisted memory protection features in processors to the operating system kernel. In this work, we provide a first architectural glimpse on how the Linux kernel can accommodate pointer integrity. Moreover, we show that this can be done at acceptable performance cost by using hardware assistance such as PAuth. We also convey the insight that memory and memory references are treated differently in the kernel, compared to how they are handled in user space. This hopefully also encourages more research on OS kernel memory protection; today there are several memory-protection mechanisms that have appeared or have been announced for both ARM and Intel platforms, and all of them could by themselves or in combination be used to strengthen the OS kernel against run-time attacks.

For this particular work, there are also a few unexplored directions that we leave for future examination. Attacks targeting the interrupt handler could potentially modify or replace kernel register content, e.g. modifiers or previously authenticated pointers. Register spills pose a similar threat to the integrity of register content, e.g. modifiers or previously authenticated pointers. With cross-layer signed pointers, this might also require a processor flag to select the active—i.e., kernel or user—set of keys.

In conclusion, our work demonstrates how to realize call-flow protection within the kernel by leveraging the ARMv8.3-A PAuth extension. Our evaluation indicates that such comprehensive protection can be achieved with minimal performance overhead (less than < 4% lmbench). By accounting for practical deployment limitations, e.g., performance constraints and preservation of existing ABIs, this work is applicable beyond a research setting.

Acknowledgements

This work was supported by the European Research Institute of Huawei Technologies.

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## Appendix A.

### Virtual Memory System Architecture version 8 (VMSA\textsuperscript{v8})

The AArch64 Virtual Memory System Architecture version 8 (VMSA\textsuperscript{v8}) represents virtual memory addresses, or pointers, as 64-bits values. However the virtual address space does not use the entirety of the 64 bits. The maximum virtual address space size is 48 bits – or 52 bits with the Large Virtual Address extension, ARMv8.2-LVA. Additionally, VMSA\textsuperscript{v8} divides the address space in two ranges, each with their own translation tables.

For a given virtual memory address, the translation table is selected by bit 55 (notated \(x\) below). By convention, the first translation table (TTBR\(_0\)\_EL1) maps the address space of the current user process, while the second table (TTBR\(_1\)\_EL1) maps kernel addresses. In a typical run-time configuration, such as that of Ubuntu operating system, the address space has 49 bits: In addition to bit 55, the lower \(49 - 1 = 48\) bits are used. The remaining bits are sign-extended (Table \ref{tab:TTBR}.

### A.1. Address tagging

VMSA\textsuperscript{v8} optionally ignores the top byte (bits 56-63) of addresses. Linux enables this feature for user space addresses but leaves it disabled for kernel-space addresses (except in debug builds with the kernel address sanitizer (KASAN) enabled). Assuming the usual page size of 4 KiB, user and kernel addresses are laid out as shown in Table \ref{tab:TTBR} where \(t\) are ignored (tag) bits, and \(a\) are addressing bits. 8 bits and 16 bits are effectively meaningless sign extension respectively for user and kernel addresses.

### A.2. Execute-only memory (XOM) on AArch64

XOM is a type of memory mapping which has only execute permission, i.e., neither read nor write permission. XOM is already available with VMSA\textsuperscript{v8} for user space applications (in EL0). However the translation table format of VMSA\textsuperscript{v8} is such that any memory mapping is implicitly readable at EL1, which precludes XOM in kernel.

To achieve XOM in EL1, we need to use the second stage of translation, which comes with AArch64 hardware virtualization (EL2). In that case, the read permission can be controlled in the translation table by the hypervisor.

### Appendix B.

#### AArch64 pointer authentication

ARMv8.3-A, the third major revision of ARMv8-A, introduces the PAuth. This extension adds three new classes of machine instructions to AArch64:

- PAC...instructions sign a pointer: they replace the “unused” bits with a MAC before storing the authenticated pointer to memory.
- AUT...instructions authenticate a pointer: they check that the MAC matches the pointer value after loading a 64-bits authenticated pointer it from memory.
- XPAC...instructions strip the MAC from an authenticated pointer. This is primarily intended for debugging purposes.

The MAC is based on an implementation-defined (i.e. processor-dependent) cryptographic hash algorithm with a 128-bits secret key, 64-bits input and 32-bits output. In reference implementations, QARMA \cite{QARMA} is used as the hash algorithm, although this is not mandated by ARM \cite{ARM}.

The sign extension bits are substituted with bits from MAC, forming the PAC; extraneous MAC bits are discarded. An authenticated pointer would match the following pattern, where \(c\) represents a MAC bit.

#### B.1. Keys

PAuth supports five distinct keys simultaneously on a given processor core:

- two keys, IA and IB, to sign instruction pointers, i.e. function pointers or function call return addresses,
- two keys, DA and DB, to sign data pointers, and
- one key, GA, to sign generic data separately (not constrained by the address space layout).

Each key is configured at run-time via dedicated privileged system registers. Since a system register can only hold 64 bits, two registers are defined for each key, or ten registers in total.

Also each key has its own signing instruction: PACIA, PACIB, PACDA, PACDB and PACGA. Likewise, each key except for the generic data key, has its own authenticating instruction: AUTIA, AUTIB, AUTDA and AUTDB.

#### B.2. Modifier

The different keys allow for a limited degree of segregation between different contexts. For instance, out of the two instruction keys:

- On the one hand, key IA could be used to sign return addresses, providing backward-edge CFI.
- On the other hand, key IB could be used to sign function pointers, providing forward-edge CFI.

To protect against trivial replay attacks, whereby two pointers signed the same key, a cryptographic salt is necessary. That is the role of the ”modifier” register.

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### Table 1. VMSA\textsuperscript{v8} address ranges

| Address range | Bit 55 | Usage |
|---------------|-------|-------|
| 0xfffffffffffffffe – 0xffffffff000000000000 | 0 | User |
| 0xfffffffffffffffe – 0x2000000000000000 | 1 | Kernel |
| 0x0000000000000000 – 0x0000000000000000 | 0 | Invalid |

### Table 2. AArch64 pointer on Linux

| User pointer (\(x = 0\)) | | |
|---------------------------|---|---|
| Tag | x | Sign extension | Page number | Page offset |
| 63-56 | 55 | 54-48 | 47-12 | 11-0 |
| 11111111 | 1 | 111...111 | aaa...aaa | aaa...aaa |

| Kernel pointer (\(x = 1\)) | | |
|---------------------------|---|---|
| Sign ext. | x | Sign extension | Page number | Page offset |
| 63-56 | 55 | 54-48 | 47-12 | 11-0 |
| 11111111 | 1 | 111...111 | aaa...aaa | aaa...aaa |