Morello and the challenges of a capability-based ABI

Linux Plumbers Conference

LINUX PLUMBERS CONFERENCE
August 24-28, 2020

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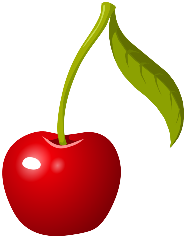
24 August 2020

A world of capabilities

CHERI and Morello

- CHERI: a hardware architecture, part of a research project led by Cambridge University
- Based on the concept of hardware capabilities, added on top of a conventional ISA
  - Aim: spatial safety, but also temporal safety
  - Has been implemented on top of MIPS and RISC-V
- Morello: a research program, led by Arm, funded by the UK government
  - Also a **prototype** architecture, extending Armv8 with CHERI concepts
  - Also a quad-core prototype board implementing the Morello arch
    → Will allow for realistic performance measurements



☆ Introduction to the Morello program: Richard Grisenthwaite on Digital Security by Design (slides)

Quick anatomy of a capability in Morello

128 bits of “regular” data

- 64-bit value (address)
- Bounds (compressed)
- Permissions (Load, Store, Execute, …)
- Object type

→ Can all be set directly

1 “magic” bit

- Unforgeable validity tag
  - In registers: next to 128-bit data
  - In memory: stored separately

→ Cannot be set by software*

→ Cleared by any invalid operation

Note: “the tag of capability C is set” == “C is *valid*”

The rules of the game

Validation Dereferencing a capability pointer only succeeds if:

- Tag is set
- Access within bounds
- Permissions allow it
- Not sealed

Provenance Only specific instructions may construct valid capabilities

- Arbitrary writes to memory zero the corresponding tag(s)

Monotonicity Bounds and permissions can only be restricted, not extended

☆ Excellent overview: An Introduction to CHERI

☆ A proposal for a provenance-aware model in C2x: N2362

Capabilities in practice

C language mappings

Hybrid-capability

- Capabilities as a C extension
- `__capability` pointer annotation
  - For instance: `char* __capability`
- Explicit instantiation of capabilities
  - Often derived from global capabilities

Pure-capability

- Capabilities embedded in C
- All pointers are capabilities
- Automatic instantiation of capabilities
  - Modified memory allocators
  - Stack management
  - Extended relocations

+ Compiler and runtime support for manipulating and preserving capabilities

Hybrid/Pure-cap: typical usage

- Hybrid-cap: mostly useful for specialized code (bits of kernel, libc, etc.)
  - Capabilities must be propagated explicitly (`__capability` everywhere ☹)
  - Library functions do not take capabilities!
  - But: less disruptive at runtime (contained capability checks)
- Pure-cap: everything else (all “normal” software)
  - Natural model for a capability architecture
  - All the benefits of capability checks (bounds, permissions, monotonicity, …)
  - No or very few code changes required
  - But: (some) runtime cost, bugs to fix!
- In low-level software, hybrid-cap allows for controlled usage before switching to pure-cap

Lightweight compartmentalization

- Isolation of software components through capabilities
- Same address space, but access constrained by capabilities
  - By default: a compartment can only access its own memory
  - Can be extended by passing tightly bounded capabilities
- More lightweight and scalable than processes, cheaper IPC
  - Typical use-case: isolation between browser tabs
- *Many* possible implementations and usage models…
- Strong use-case for the pure-cap model

☆ Much more about this: Hardware support for compartmentalisation

☆ Also: CHERI: A Hybrid Capability-System Architecture for Scalable Software Compartmentalization

The pure-capability ABI

Holy pointers

- `sizeof(void*) == 16` and unforgeable tag attached
- Completely new ABI (think 32-bit → 64-bit transition)
- Transparent for most software
- Main exception: low-level software
  - C runtime
  - Memory allocators
  - JITs
  - In general: code making assumption about pointers

Pain points

Pointers must be handled with care

- Big enough + aligned enough storage
- Pointers cannot be stored in arbitrary integers: only `(u)intptr_t` is valid
- Bitwise operations can be tricky
- In general: address ≠ pointer
  - Still 64-bit addresses!
  - `intptr_t` has a 64-bit value range, but is 128-bit large
- Certain patterns around memory allocation can be problematic (especially `realloc()`)

☆ Everything about pure-cap: CHERI C/C++ Programming Guide

Here be dragons: supporting the pure-cap ABI in userspace

The goal

Support userspace programs built in the pure-cap ABI

- Use the right types: all pointers at the kernel-user interface are capabilities
- Honor capability metadata: access memory “as if” dereferencing the capability
- Create capabilities for userspace with appropriate bounds and permissions
- Retain the base 64-bit ABI (32-bit not required)

→ Has been achieved on CheriBSD!

[CheriBSD: adaptation of FreeBSD for CHERI]

☆ More on pure-cap in CheriBSD: CheriABI paper

Pointers in the kernel-user ABI

- Where they appear:
  - Syscalls (arguments, struct members)
  - A few other places (initial stack layout, signal handlers)
- How they are used:
  - Most common: user specifying where data should be read/written
    - Data accessed via user mappings using `copy_to_user()` and friends (e.g. `read()`)
    - Data accessed via kernel mappings using `get_user_pages()` (e.g. `readv()`)
  - Less common: kernel providing userspace with a pointer to some object
    - `mmap()` and friends
    - `argv`
  - Rare: arbitrary user data, stored by the kernel without processing
    - For instance `epoll_ctl()` and `epoll_wait()`

User pointers as capabilities

- Good: all user pointers are annotated with `__user` in Linux
- Hope for turning `void __user *` into a capability… with caveats
- Need a mechanism for enforcing capability bounds / permissions

A `long` issue

- `long` is *everywhere* in Linux
- Strong assumption that `long` is big enough to hold any scalar type…
- …therefore can be used to represent *a lot* of things, in particular:
  - Addresses (fine) and/or pointers (not fine!)
  - Catch-all type (especially in syscalls)
- *Really* bad for multiplexed syscalls: `ptrace()`, `fcntl()`, **`ioctl()`**

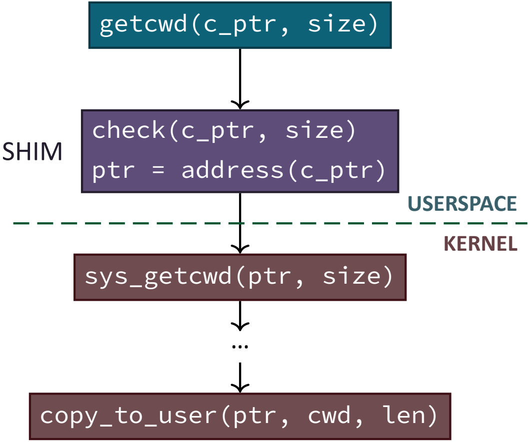
Sounds overwhelming?

Avoiding dragons: a userspace shim

Userspace shim: principles

A stepping stone: userspace shim library

- Lives between libc and the kernel
- Checks input capabilities ("as-if" dereferenced by the kernel)
- Two-way ABI conversion
- Unmodified kernel-user ABI



Userspace shim: limitations

- Does not enforce any security boundary (raw 64-bit syscalls still available)
- Requires explicit checking of capabilities (extra cost)
  - Checking C-strings is inherently racy
- Needs to know whenever pointers are passed — not easy with multiplexed syscalls
  - ioctl almost impossible to handle reliably:

    ```
    $ git grep '\.unlocked_ioctl'| wc -l
    ```

    593

    + out-of-tree drivers!
- Complications whenever the kernel stores user pointers

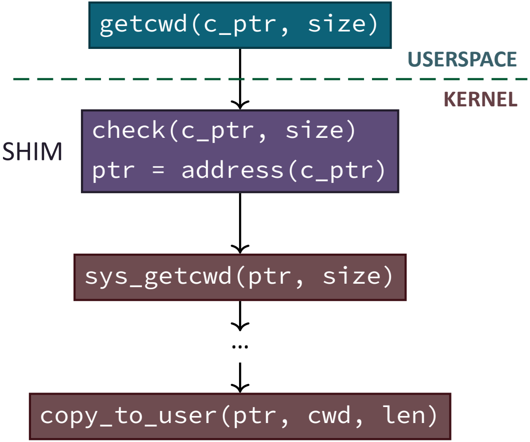
Getting bolder: a kernel shim

An arch-specific in-kernel shim

- New kernel-user ABI: pure-cap
- Non-invasive shim in arch code
- Security boundary enforced
- Pure-cap as a secondary ABI(?)

→ Attempted on `arm64`

→ Experimental implementation in CheriBSD



Kernel shim: limitations

- Same as the userspace shim (security aside)
  - Somewhat easier to implement if making changes to generic code
- Only existing mechanism for a secondary ABI: COMPAT
  - Typical situation: `void __user *argp = compat_ptr(arg);`
  - Major obstacle: COMPAT pointers must fit in `void __user *`!
- Would have to define a new mechanism…

Fighting dragons: propagate the capabilities

So `long`…

- All user pointers in the kernel become capabilities
- Capabilities propagated down to the point of use (typically uaccess routines)
- New integer type to represent user pointers: `intuserptr_t`?
  - Note: `intmax_t` not the right type: "[…] integer type capable of *representing any value of any signed integer* type"
- `long` **must** be replaced whenever it may represent a user pointer
- Clearly an invasive approach

User ABIs

- Pure-cap must become the primary ABI
- 64-bit ABI becomes COMPAT
- Cleaner approach, especially for uaccess
  - User memory always accessed via capabilities, regardless of the task's ABI

Option 1: hybrid-cap kernel

- Turn `void __user *` into a capability
  - `__user` on the wrong side of `*` ☹
  - `void __capability *` deprecated, but works in most cases
  - `#define __user __capability` worth a try!
- `intcap_t` available for storing capabilities
- Potential issue with uapi headers being built in different ABIs (hybrid-cap kernel, pure-cap userspace)
  - All pointers should already be annotated with `__user`, but may not be enough

→ Current approach used by CheriBSD

Option 2: pure-cap kernel

- The “proper” way
- Requires eradicating `long` everywhere it may represent any pointer
- Comes with all the benefits of pure-cap code…
- …but also the usual difficulties of porting low-level code to CHERI
- Potential performance impact

→ Experimental implementation in CheriBSD

Common issues

- Explicit checking still needed for indirect accesses (`get_user_pages()`)
- `memcpy()` should not always copy tags
- `mmap()` interface unfriendly with capabilities
  - `mprotect()` does not return a pointer
    → which capability permissions should `mmap()` return?

☆ More on `mmap()`'s flaws: Is it time to replace mmap? (slides)

Looking forward

Overview

- 2 main approaches for supporting pure-cap in userspace:

Shim	Wrapping around 64-bit syscalls: non-invasive, but fragile
Propagate	Making all user pointers capabilities: “proper” approach but invasive

- Supporting pure-cap on Linux: painful in one way or another
- But: has been done on FreeBSD!

Morello project status

- First release in October, watch `https://www.morello-project.org/`
  - “Core” kernel support for Morello, unmodified ABI
  - Userspace shim library
  - Minimal Android with limited pure-cap support
- Morello support in CheriBSD to be published soon
- Starting now: new kernel-user ABI definition, investigation into the “propagate” approach
  - Many aspects of the ABI yet to be properly defined

☆ More info on the roadmap: Morello Software and Toolchain Work in Arm (slides)

arm

Food for thought

Wider efforts in Linux that would be beneficial:

- Proper multi-ABI support
- Start the `long` war
- `void __user *` → `void * __user`

Resources

- CHERI landing page
- An Introduction to CHERI (technical report)
- CHERI C/C++ Programming Guide (technical report)
- CheriABI: Enforcing Valid Pointer Provenance… (paper)
- Compartmentalization:
  - Hardware support for compartmentalisation (technical report)
  - CHERI: A Hybrid Capability-System Architecture for Scalable Software Compartmentalization (paper)
- Morello program:
  - Richard Grisenthwaite’s talk at the Digital Security by Design workshop (slides)
  - Mark Nicholson’s talk “Morello Software and Toolchain Work in Arm” (slides)
- Brooks Davis’s talk “Is it time to replace mmap?” (slides)

Contacts

- CHERI community discussion mailing list (appropriate for generic Morello discussions as well)
- Or just drop me an email: <first>.<last><at>arm.com ☺

Thank You
Danke
Merci
谢谢
ありがとう
Gracias
Kiitos
감사합니다
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شكرًا
ধন্যবাদ
תודה