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POINTER AUTHENTICATION ABI + ELF-BASED PLATFORMS

ANTON KOROBEYNIKOV

CODE POINTERS AND THEIR LIFECYCLES

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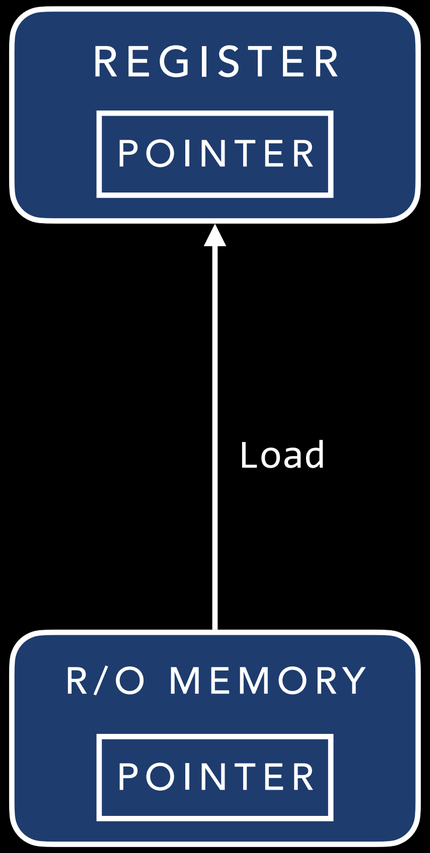

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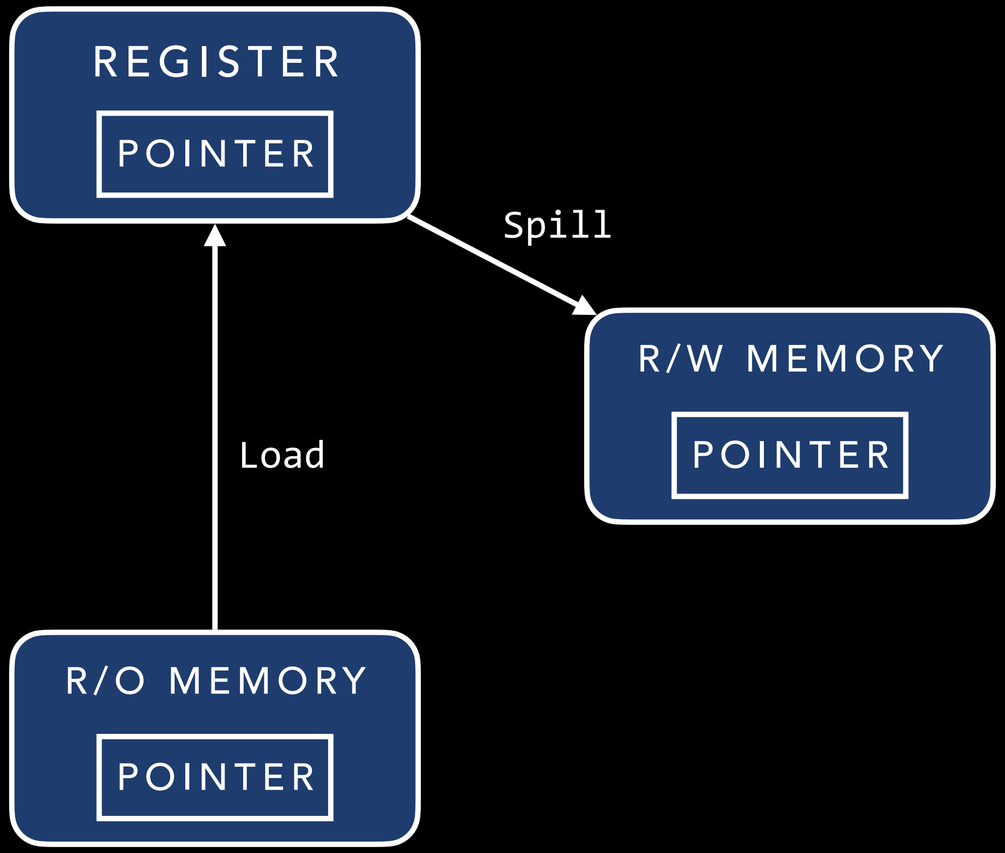

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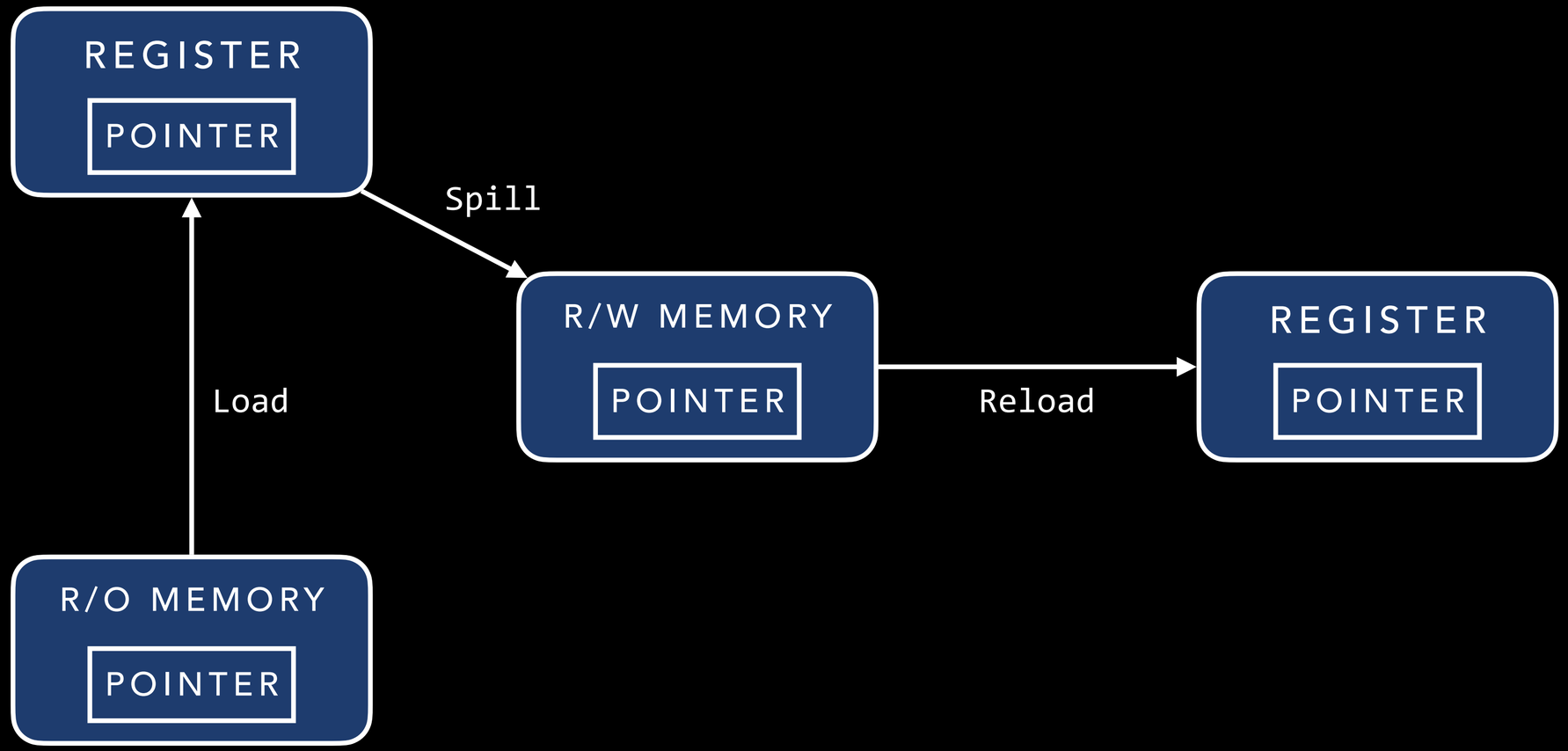

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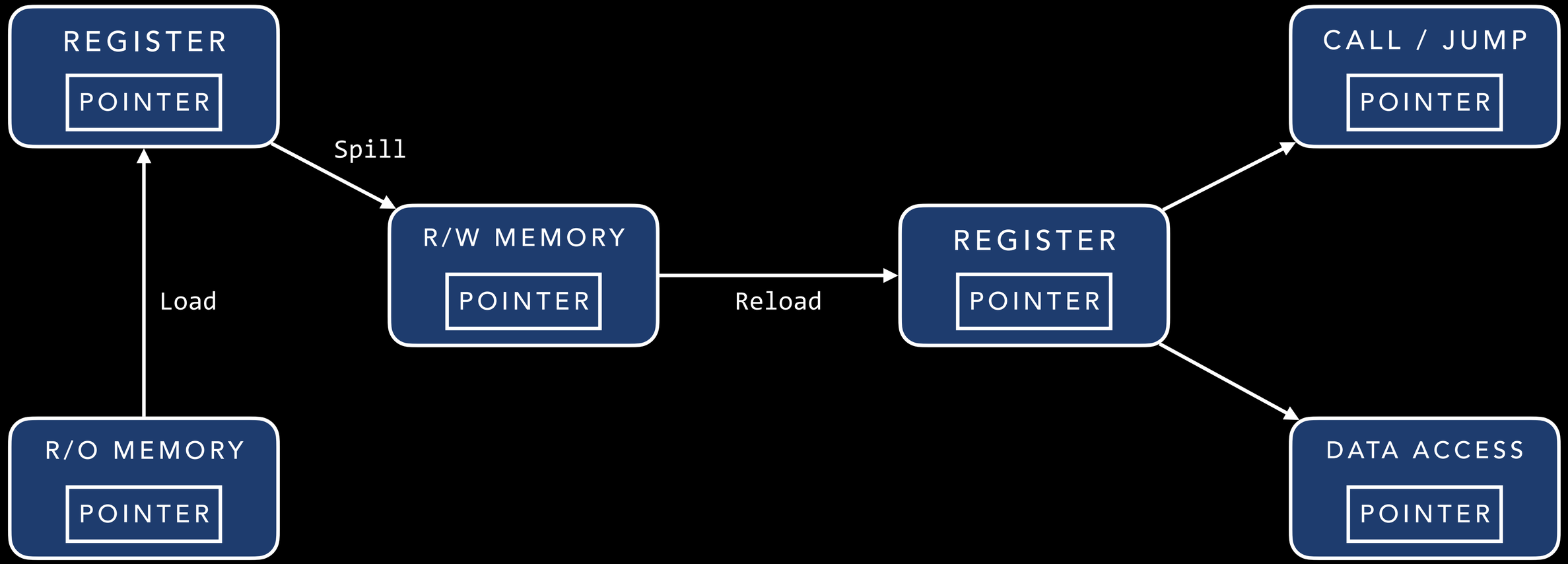
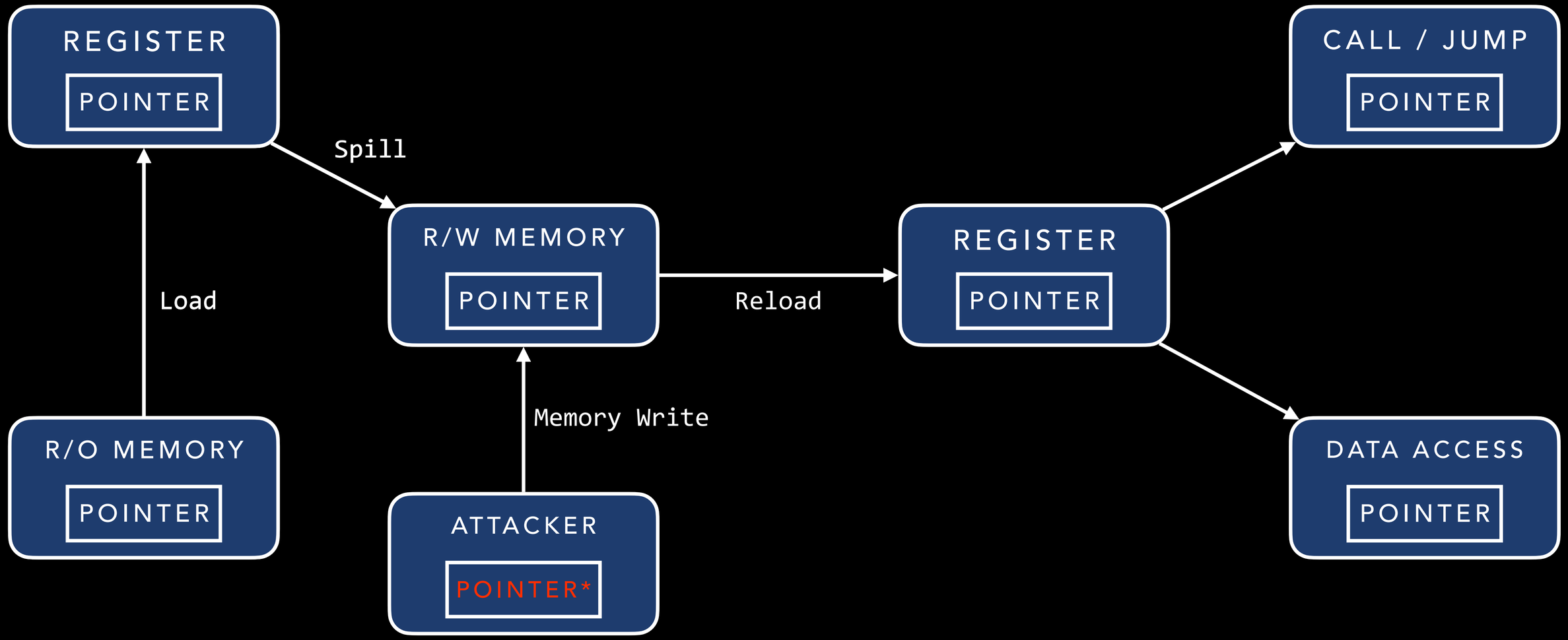


SUBSTITUTION ATTACKS



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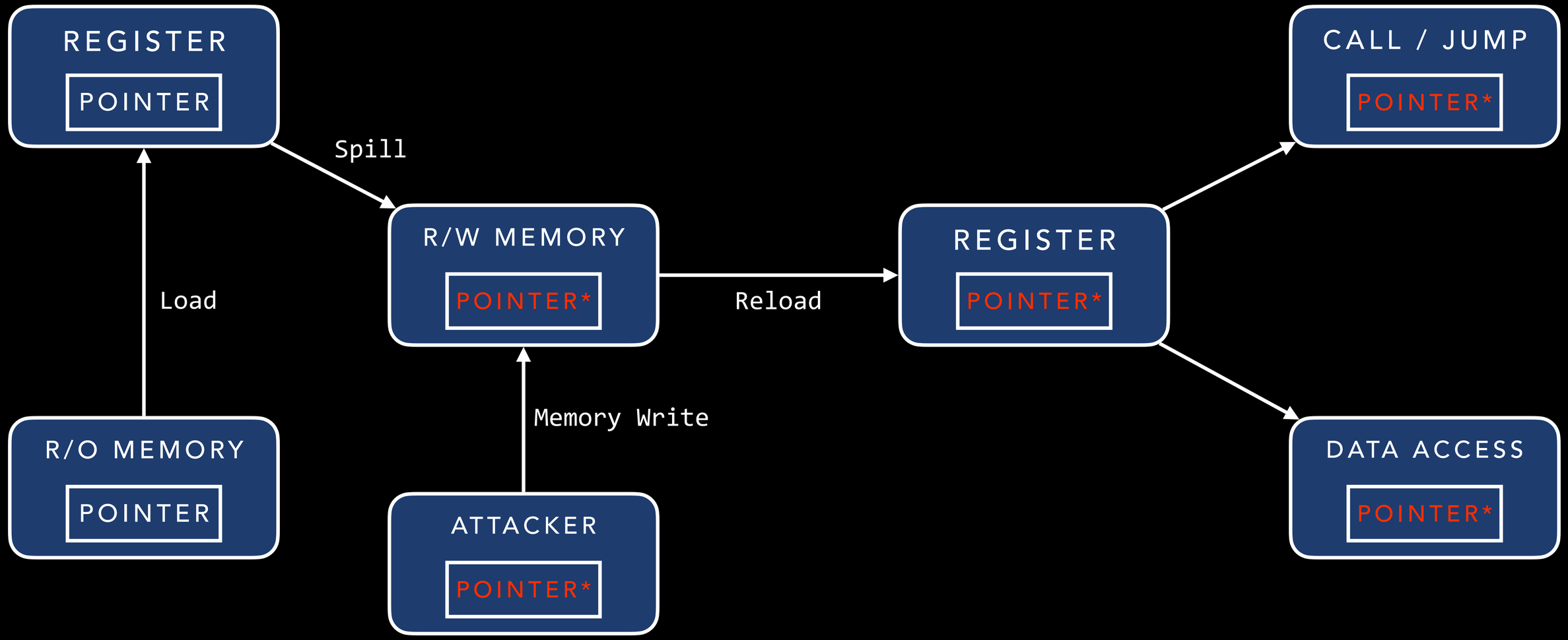
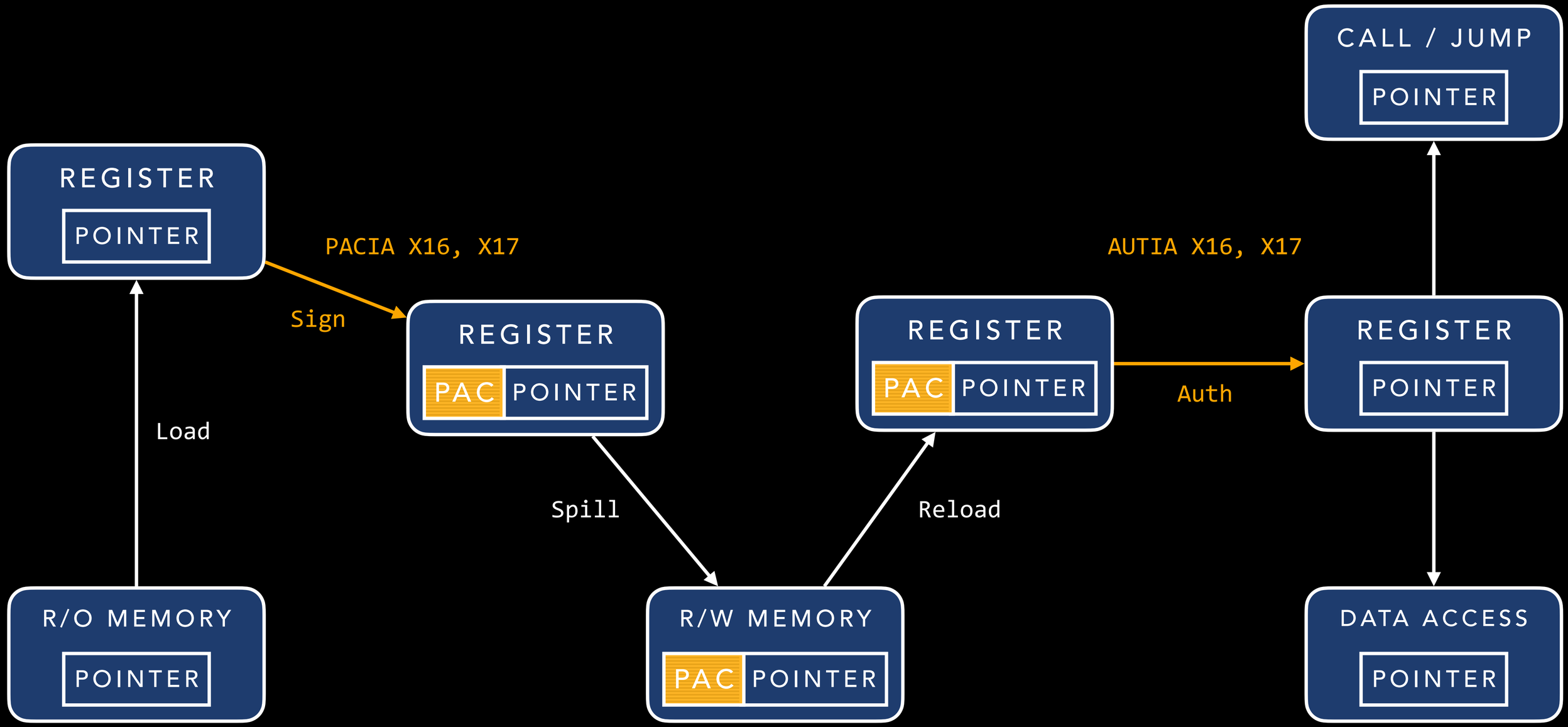
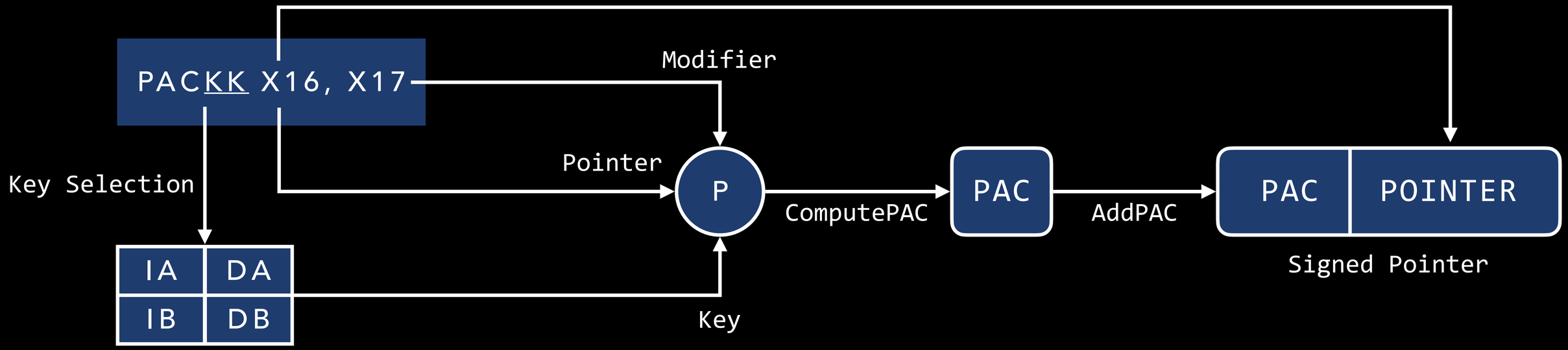


POINTER AUTHENTICATION



HOW DOES IT WORK?



POINTER AUTHENTICATION: ISA

- Armv8.3: signed pointers
  - Additional changes in Armv8.5 and Armv8.6
- Overall: 48 instructions
  - Some of them in HINT space: nops are on older CPU cores

ISA VS HIGH-LEVEL-LANGUAGES

PACxx

AUTxx

XPACxx

ISA VS HIGH-LEVEL-LANGUAGES

PACxx

AUTxx

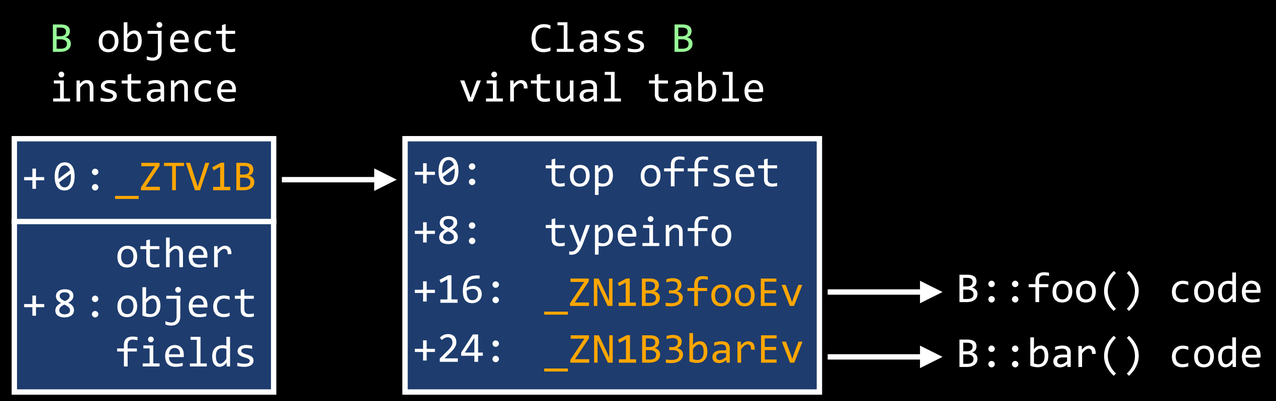
XPACxx

vs

```
class B : public A {
public:
    void foo() const override;
    void bar() const override;
};

int test(const A &obj) {
    obj.bar();
    return 0;
}
```

ISA VS HIGH-LEVEL-LANGUAGES



POINTER AUTHENTICATION C++ ABI

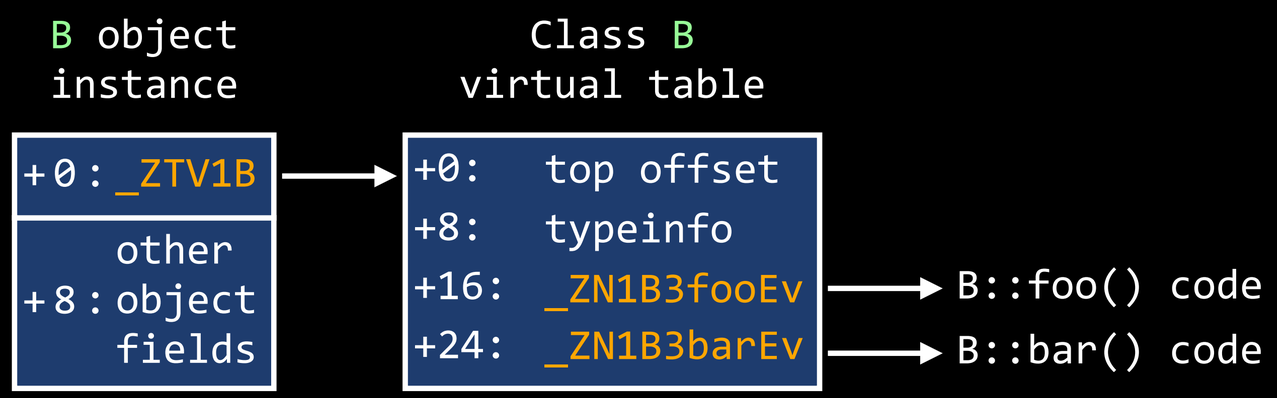
- Developed by Apple to use on Mac hardware
- Presented on LLVM US Developers Meeting 2019
  - arm64e: An ABI for Pointer Authentication – *Ahmed Bougacha, John McCall*
- Available as arm64e architecture since Apple A12 (~2018)
- Until recently was only available in Apple downstream clang fork.

https://github.com/swiftlang/llvm-project/blob/next/clang/docs/PointerAuthentication.rst

ELEMENTS OF C++ PAUTH ABI

Sources of indirect branches:

- returns
- switches
- symbol imports (GOT)
- C function pointers
- C++ virtual functions
- C++ member pointers
- static object constructors
- computed gotos
- …



ABI rule (signing scheme) specifies key and how to compute the modifier

DIVERSITY

- Armv8.3 allows arbitrary 64-bit modifiers to be used
- Address diversity: can use storage address of a pointer as modifier
  - Copying of pointer requires resigning
- Semantic diversity: can use semantics of the pointed code/data as a modifier
  - Derived from declaration, type, or particular usage …
- Top 16 bits of address is usually reserved
  - Can combine address and semantic diversity (small *constant discriminator*)

PAUTH + ELF

- PAuth ABI Extension to ELF for the Arm® 64-bit Architecture (*pauthabielf64*)
  - Currently in Alpha state
  - https://github.com/ARM-software/abi-aa/blob/main/pauthabielf64/pauthabielf64.rst
- Set of ELF-specific relocations & relocation operations
- Marking schema
  - Entry in `.note.gnu.property` section
- Platform decisions
  - RELRO GOT
  - PLT GOT signing

LLVM 19: STATUS

- The majority of required frontend patches were ported from Apple clang
  - Thanks to Ahmed, John, Akira, Oliver et al!
- Generic pauth codegen support ported from Apple clang
- Implemented ELF-specific pauth codegen
- Implemented object file & linker support for pauth relocations
- Added experimental `pauthtest` ABI for AArch64/Linux

LLVM testsuite passes on AArch64/Linux with `pauthtest` ABI

PAUTHTEST

- ABI to test pointer authentication on AArch64 Linux
- Mostly follows Apple arm64e for signing schema, etc.
- Enable via `-mabi=pauthtest` or `pauthest` environment in target triple (e.g. `aarch64-gnu-linux-pauthtest`)
  - `-mabi` is normalized to environment in triple, similar to `eabihf` on 32-bit ARM.
- ELF marking:
  - “LLVM Linux” test vendor (`0x10000002`)
  - Encodes entire signing schema in place of version making catching mismatches easier
- Requires pauth-enabled standard library

KNOWN ISSUES

- Few corner cases with no-op casts (mostly around `noexcept`)
- No diagnostics for some unsupported computed gotos (code will crash though)
- libunwind might materialize pointers in not very secure way across exceptions being thrown
- Enabling pauth for platform is manual: no hooks for signing schema, etc.

TBD

- PRs under review
  - Signed GOT support
  - TLS support
- `__ptrauth` qualifier
  - See RFC: https://discourse.llvm.org/t/rfc-ptrauth-qualifier/
- Optimizations & relaxations
  - Some already available in Apple downstream tree
- Some code unification & cleanup
- Documentation!

NEW PLATFORM

- Pointer Authentication ABI is an ABI:
  - Cannot safely mix code that uses different ABIs
- Could be deployed on bare-metal platform as default ABI
- Could be deployed on commodity platform as an isolated part
  - OS kernel
  - System-critical process

COMPONENTS OF PAUTH SUPPORT

- Kernel support
- Signing schema
- Marking and versioning
- Runtime libraries

KERNEL SUPPORT

- Key allocation & management
  - Set of 5 128-bit keys
  - Some of them are expected to be process-dependent
- Key preservation during context switches
- Protect values of X16 / X17
- Do you have fork()?

SIGNING SCHEMA

- Lots of variations and customizations in signing scheme:
  - Discriminator usage
  - Objects to sign, etc.
- Every variation effectively defines a new ABI
- Cannot safely mix code that uses different ABIs
- Default set (aka `arm64e` or `pauthtest`) is good enough to start
  - Decide about function pointer type discrimination

Do you want to expose all options and knobs that may change ABI?

VERSION & MARKING

https://github.com/ARM-software/abi-aa/blob/main/pauthabielf64/pauthabielf64.rst#elf-marking

- Uses `.note.gnu.property` section
  - Need to define platform
  - Need to define ABI version
- Might want to encode some additional metadata in the version
- See if base compatibility mode is enough for platform's purposes

Both static linker and dynamic loader are expected to check ABI compatibility

LIBRARIES

- Compiler runtime:
  - libc++, libunwind and compiler-rt should work out of the box
- Dynamic loader:
  - Support for pauth relocations
  - Shared libraries, lazy symbol resolution and interop with unsigned code
  - GOT and PLT GOT choices
- C standard library:
  - Static constructors / destructors (including e.g. `atexit`)
  - `setjmp / longjmp`
  - signals

Can use musl+pauth PoC implementation from https://github.com/access-softek/musl/

TESTING

- Testing security-related code is non-trivial
  - Matching for expected code sequences
  - Checking final binaries
- Crashing testsuite
  - Try to perform a pointer substitution in different contexts
  - PAuth works: substitution fails => test crashes
  - PAuth does not work: substitution success => no crash
  - WIP, to be released soon
- Maybe a way to extend BOLT-based analysis tools?
  - EuroLLVM 2024: Does LLVM implement security hardenings correctly? A BOLT-based static analyzer to the rescue? – *Kristof Beyls*

Q & A