CSE 484/M584: Computer Security (and Privacy)

Spring 2025

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UW Instruction Team: David Kohlbrenner, Yoshi Kohno, Franziska Roesner, Nirvan Tyagi. Thanks to Dan Boneh, Dieter Gollmann, Dan Halperin, John Manferdelli, John Mitchell, Vitaly Shmatikov, Bennet Yee, and many others for sample slides and materials

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Microsoft rolls out AI screenshot tool dubbed 'privacy nightmare'

2 hours ago

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Imran Rahman-Jones
Technology reporter

Admin

- Lab 1b due next Wednesday.
  - Start early (hopefully already)
- Homework 1 is posted
  - Should be relatively quick
  - Good chance to discuss something in detail with classmates!
- Reminders:
  - There are helpful exercises in your lab 1 repo!
  - There is a separate writeup on the assignments page for frame pointers and printf exploitation (no new information)

Threat modeling again again again

- You are taking a course that has a required assignment every lecture.
- The course uses Gradescope to manage those assignments, which go ‘live’ near the beginning of class, and are due at the end.
- How can you ensure you get credit for these assignments without attending class?

- How might that approach be mitigated or detected?

In-class components

- Please don’t make this adversarial!
- If you come to class, complete the component during the designated time.
- If you miss class, complete it *while watching the recorded lecture.*
  - Don’t fill it out, and then watch lecture.
- This type of think-pair-share and discuss format has well-studied benefits to learning
  - It also is very low stakes, and takes minimal amounts of time.

Hardening binaries

Buffer Overflow: Causes and Cures

- Classical memory exploit involves code injection
  - Put malicious code at a predictable location in memory, usually masquerading as data
  - Trick vulnerable program into passing control to it

- Possible defenses:
  1. Prevent execution of untrusted code
  2. Detect overflows
  3. Validate pointers
  4. Address space layout randomization
  5. Code analysis
  6. Better interfaces
  7. …

ASLR: Address Space Randomization

- Randomly arrange address space of key data areas for a process
  - Base of executable region
  - Position of stack
  - Position of heap
  - Position of libraries
- Introduced by Linux PaX project in 2001
- Adopted by OpenBSD in 2003
- Adopted by Linux in 2005

ASLR: Address Space Randomization

- Deployment (examples)
  - Linux kernel since 2.6.12 (2005+)
  - Android 4.0+
  - iOS 4.3+ ; OS X 10.5+
  - Microsoft since Windows Vista (2007)

- Attacker goal: Guess or figure out target address (or addresses)
  - (Think about how poor printf usage might help an attacker!)

Attacking ASLR

- **NOP sleds** and **heap spraying** to increase likelihood for adversary's code to be reached (e.g., on heap)
- Brute force attacks or memory disclosures to map out memory on the fly
  - Disclosing a single address can reveal the location of all code within a library, depending on the ASLR implementation
  - Remember our printf vulnerabilities!

Defense: Executable Space Protection

- Mark all writeable memory locations as non-executable
  - **This blocks many code injection exploits**
- Hardware support
  - AMD "NX" bit (no-execute), Intel "XD" bit (execute disable) (in post-2004 CPUs)
  - Makes memory page non-executable
- Widely deployed
  - Windows XP SP2+ (2004), Linux since 2004 (check distribution), OS X 10.5+ (10.4 for stack but not heap), Android 2.3+

What Does “Executable Space Protection” Not Prevent?

- Can still corrupt stack …
  - … or function pointers
  - … or critical data on the heap
- **As long as RET points into existing code, executable space protection will not block control transfer!**

  → return-to-libc exploits

return-to-libc

- Overwrite saved return address with address of any library routine

- Does not look like a huge threat?
  - …

return-to-libc

- Overwrite saved return address with address of any library routine
  - Arrange stack to look like arguments
- Does not look like a huge threat
  - …
  - We can call *any* function we want!
  - Say, exec ☺

return-to-libc++

- Insight: Overwritten saved EIP need not point to the *beginning* of a library routine
- **Any** existing instruction in the code image is fine
  - Will execute the sequence starting from this instruction
- What if instruction sequence contains RET?
  - Execution will be transferred… to where?
  - Read the word pointed to by stack pointer (SP)
    - Guess what? Its value is under attacker's control!
  - Use it as the new value for IP
    - Now control is transferred to an address of attacker's choice!
  - Increment SP to point to the next word on the stack

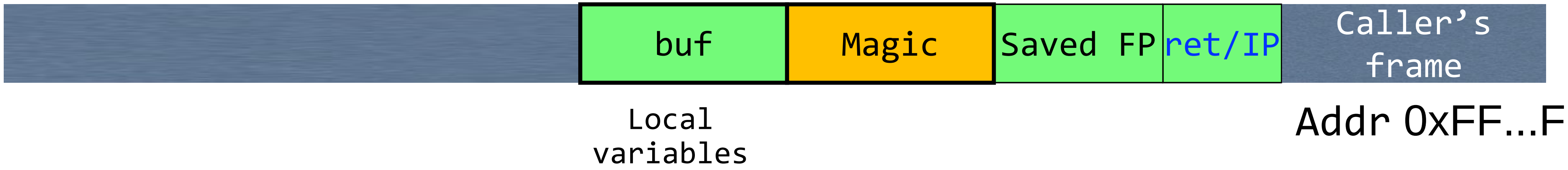
Chaining RETs

- Can chain together sequences ending in RET
  - Krahmer, "x86-64 buffer overflow exploits and the borrowed code chunks exploitation technique" (2005)
- What is this good for?
- Answer [Shacham et al.]: everything
  - Turing-complete language
  - Build "gadgets" for load-store, arithmetic, logic, control flow, system calls
  - Attack can perform arbitrary computation using no injected code at all – return-oriented programming
- Truly, a "weird machine"

Return-to-libc

Defense: ???

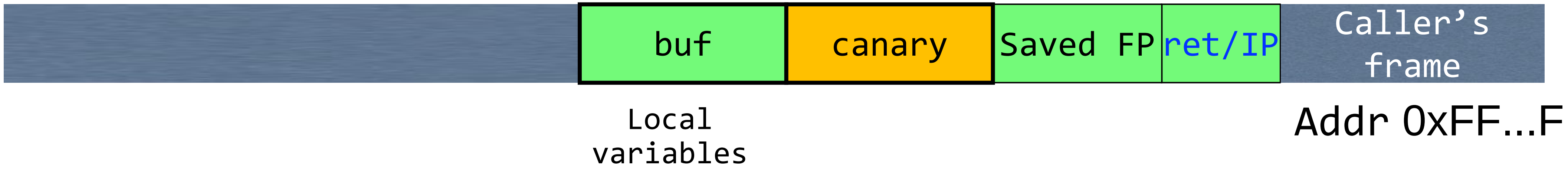
- Choose a random value (Magic) at program startup
- Push that value onto the stack at the start of every function.



- Now what?
- If your adversary wants to do a classical stack-based buffer overflow, what will happen?
- How can we use this magic value for defense?

Defense: Run-Time Checking: StackGuard

- Embed "canaries" (stack cookies) in stack frames and verify their integrity prior to function return
  - Any overflow of local variables will damage the canary



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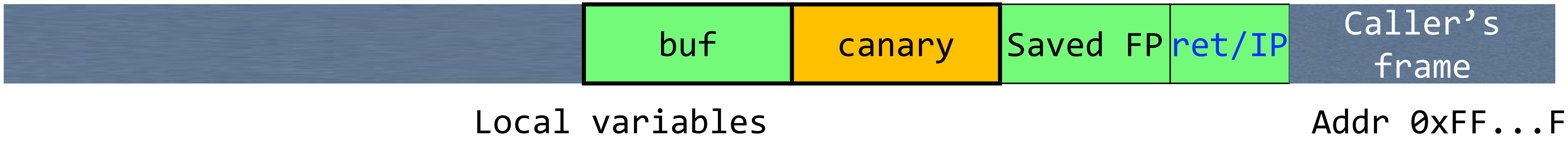


- Choose random canary string on program start
  - Attacker can't guess what the value of canary will be
- Canary contains: "\0", newline, linefeed, EOF
  - String functions like strcpy won't copy beyond "\0"

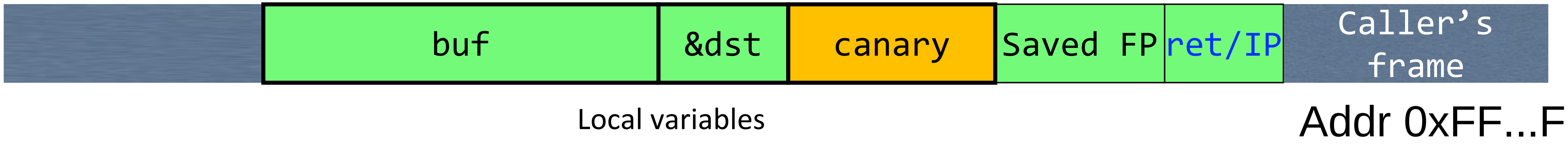
StackGuard Implementation

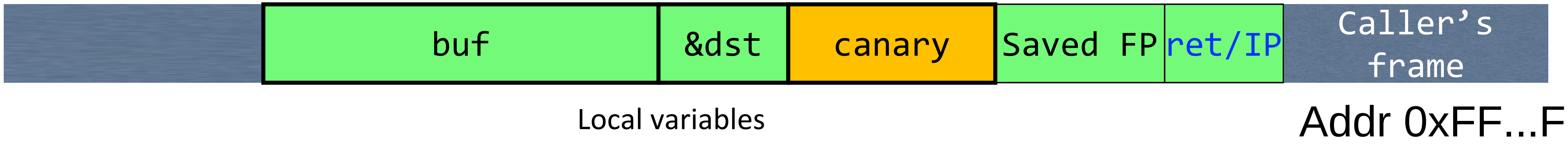
- StackGuard requires code recompilation
- Checking canary integrity prior to every function return causes a performance penalty
  - For example, 8% for Apache Web server at one point in time

Defeating StackGuard

- StackGuard can be defeated
  - A single memory write where the attacker controls both the value and the destination is sufficient

```
foo() {
    char *dst;
    char buf[…];
...
    strcpy(buf, readUntrustedInput());
    strcpy(dst, buf);
```





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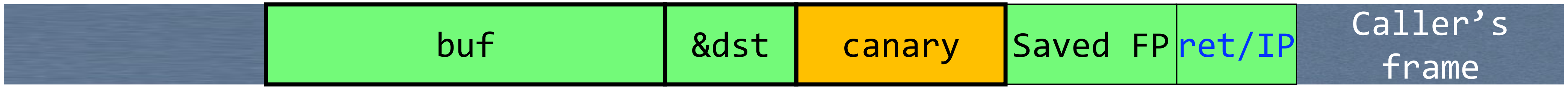

Local variables

Addr 0xFF...F

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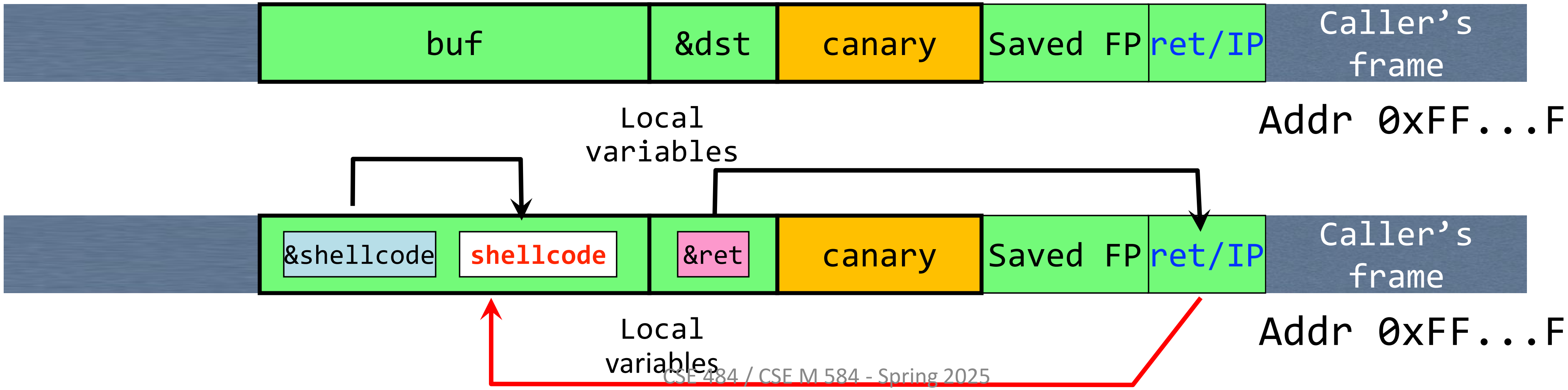
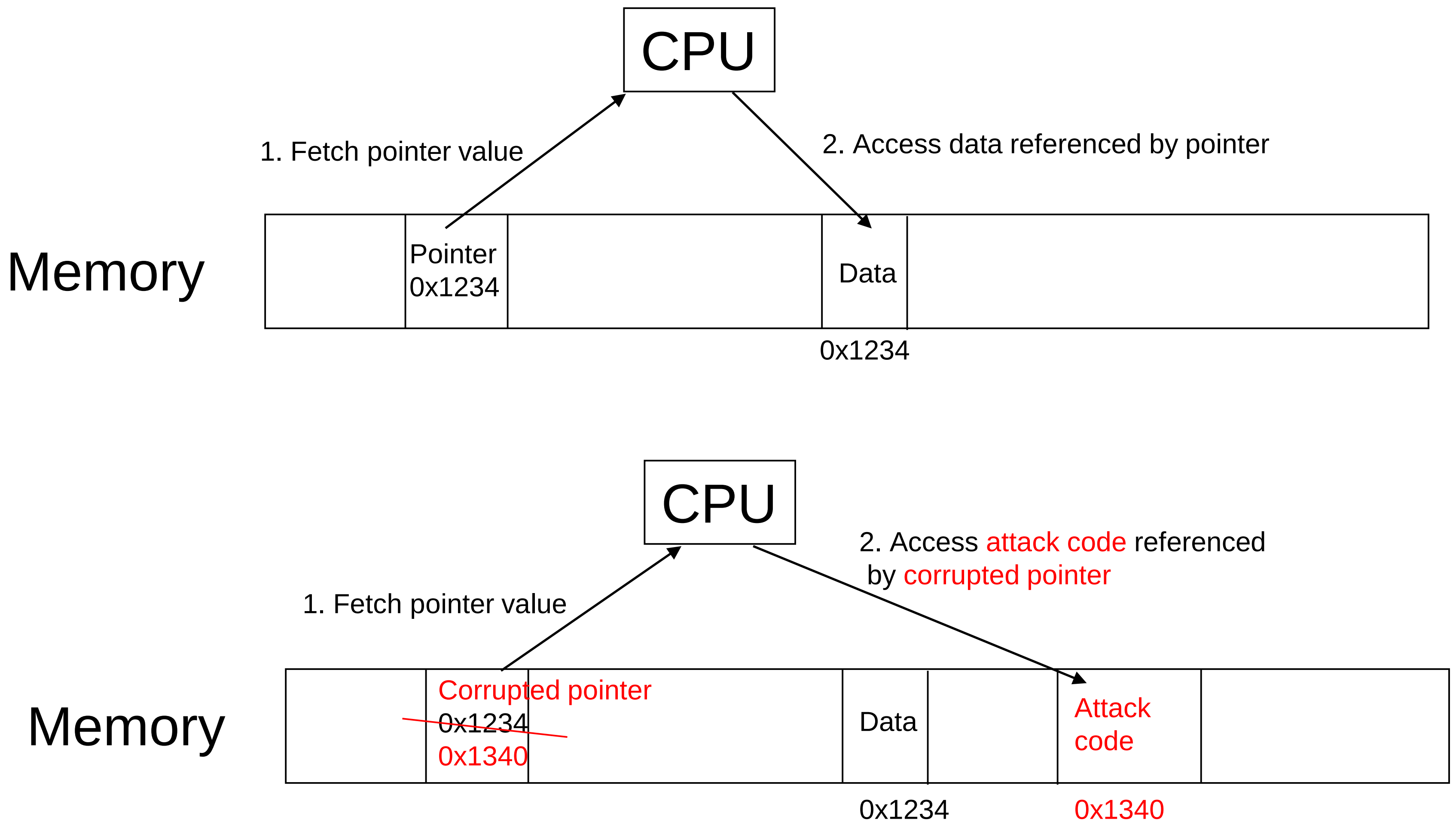


Pointer integrity protections (e.g. PointGuard, PAC, etc.)

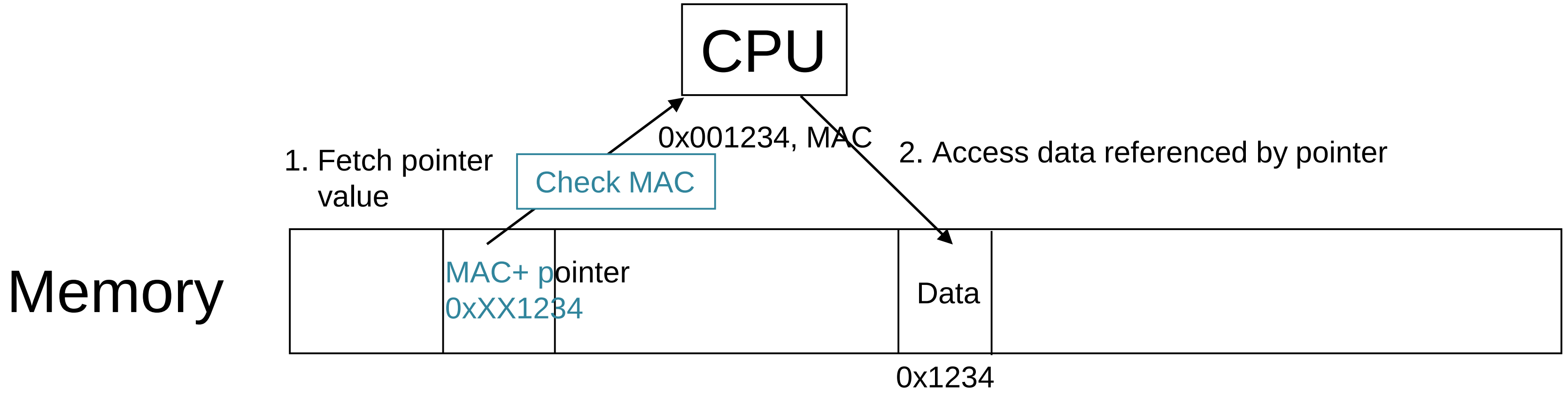
- Attack: overwrite a pointer (heap date, ret, function pointer, etc.)
- Idea: encrypt all pointers while in memory
  - Generate a random key when program is executed
  - Each pointer is encrypted/XOR'd/MAC'd with this key when in memory
    - Pointers cannot be overflowed while in registers
- Attacker cannot predict the target program's key
  - If XOR/encrypt: adversary cannot predict what a corrupted pointer will do (mostly)
  - If integrity (MAC) then the program can *detect* a modified pointer.

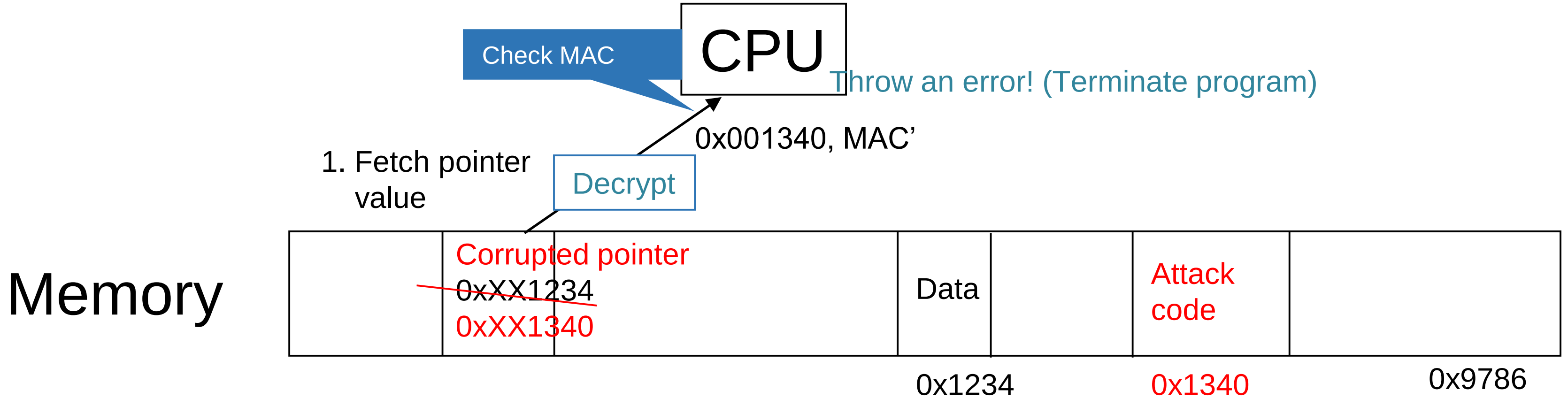
[Cowan]

Normal Pointer Dereference



Modern PAC Dereference





CFI: Control flow integrity

- Idea: enforce branches to terminate 'where expected'
  - … which is where?
- Well, at the start of functions!
  - We shouldn't ever '`call`' into the middle of something!
  - Put a special instruction at the start of every function: `endbr64`
- What about jumps (`je,jz`…)?
- … What about `ret`?

Defense: Shadow stacks

- Idea: protect the *backwards edge* (return addresses on the stack)!
- Store them on… a different stack!
  - A *hidden* stack
- On function call/return
  - Store/retrieve the return address from shadow stack
- Or store on both main stack and shadow stack, and compare for equality at function return
- 2020/2021 Hardware Support emerges (e.g., Intel Tiger Lake, AMD Ryzen PRO 5000)

Challenges With Shadow Stacks

- Where do we put the shadow stack?
  - Can the attacker figure out where it is? Can they access it?
- How fast is it to store/retrieve from the shadow stack?
- How *big* is the shadow stack?
- Is this compatible with all software?
- (Still need to consider data corruption attacks, even if attacker can't influence control flow.)

Defense: Better string functions!

- strcpy is bad
- strncpy is… also bad (no null terminator! Returns dest!)

Defense: Better string functions!

- strcpy is bad
- strncpy is… also bad (no null terminator! Returns dest!)
- BSD to the rescue: strlcpy
  - size_t strlcpy(char *dest, const char *src, size_t n);
    - Always NUL terminates
    - Returns len(src)

Ushering out strlcpy()

By **Jonathan Corbet**
August 25, 2022

With all of the complex problems that must be solved in the kernel, one might think that copying a string would draw little attention. Even with the hazards that C strings present, simply moving some bytes should not be all that hard. But string-copy functions have been a frequent subject of debate over the years, with different variants being in fashion at times. Now it seems that the BSD-derived `strlcpy()` function may finally be on its way out of the kernel.

What does a modern program do?

Normal, reasonable gcc config, (no optimization)

```
0000122d <foo>:
    122d:       f3 0f 1e fb             endbr32
    1231:       55                      push   %ebp
    1232:       89 e5                   mov    %esp,%ebp
    1234:       53                      push   %ebx
    1235:       81 ec 34 01 00 00       sub    $0x134,%esp
    123b:       e8 b9 00 00 00          call   12f9 <__x86.get_pc_thunk.ax>
    1240:       05 88 2d 00 00          add    $0x2d88,%eax
    1245:       8b 55 08                mov    0x8(%ebp),%edx
    1248:       89 95 d4 fe ff ff       mov    %edx,-0x12c(%ebp)
    124e:       65 8b 0d 14 00 00 00    mov    %gs:0x14,%ecx
    1255:       89 4d f4                mov    %ecx,-0xc(%ebp)
    1258:       31 c9                   xor    %ecx,%ecx
    125a:       8b 95 d4 fe ff ff       mov    -0x12c(%ebp),%edx
    1260:       83 c2 04                add    $0x4,%edx
    1263:       8b 12                   mov    (%edx),%edx
    1265:       83 ec 08                sub    $0x8,%esp
    1268:       52                      push   %edx
    1269:       8d 95 dc fe ff ff       lea    -0x124(%ebp),%edx
    126f:       52                      push   %edx
    1270:       89 c3                   mov    %eax,%ebx
    1272:       e8 49 fe ff ff          call   10c0 <strcpy@plt>
    1277:       83 c4 10                add    $0x10,%esp
    127a:       90                      nop
    127b:       8b 4d f4                mov    -0xc(%ebp),%ecx
    127e:       65 33 0d 14 00 00 00    xor    %gs:0x14,%ecx
    1285:       74 05                   je     128c <foo+0x5f>
    1287:       e8 f4 00 00 00          call   1380 <__stack_chk_fail_local>
    128c:       8b 5d fc                mov    -0x4(%ebp),%ebx
    128f:       c9                      leave
    1290:       c3                      ret
```

Our custom gcc config

```
080491ad <foo>:
 80491ad:       55                      push   %ebp
 80491ae:       89 e5                   mov    %esp,%ebp
 80491b0:       81 ec 18 01 00 00       sub    $0x118,%esp
 80491b6:       8b 45 08                mov    0x8(%ebp),%eax
 80491b9:       83 c0 04                add    $0x4,%eax
 80491bc:       8b 00                   mov    (%eax),%eax
 80491be:       50                      push   %eax
 80491bf:       8d 85 e8 fe ff ff       lea    -0x118(%ebp),%eax
 80491c5:       50                      push   %eax
 80491c6:       e8 95 fe ff ff          call   8049060 <strcpy@plt>
 80491cb:       83 c4 08                add    $0x8,%esp
 80491ce:       90                      nop
 80491cf:       c9                      leave
 80491d0:       c3                      ret
```

Wait…

Attu/umnak's gcc config

```
080491ad <foo>:
 80491ad:       55                      push   %ebp
 80491ae:       89 e5                   mov    %esp,%ebp
 80491b0:       81 ec 28 01 00 00       sub    $0x128,%esp
 80491b6:       8b 45 08                mov    0x8(%ebp),%eax
 80491b9:       83 c0 04                add    $0x4,%eax
 80491bc:       8b 00                   mov    (%eax),%eax
 80491be:       83 ec 08                sub    $0x8,%esp
 80491c1:       50                      push   %eax
 80491c2:       8d 85 e0 fe ff ff       lea    -0x120(%ebp),%eax
 80491c8:       50                      push   %eax
 80491c9:       e8 92 fe ff ff          call   8049060 <strcpy@plt>
 80491ce:       83 c4 10                add    $0x10,%esp
 80491d1:       90                      nop
 80491d2:       c9                      leave
 80491d3:       c3                      ret
```

T_T

Our custom gcc config

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```

Other Big Classes of Defenses

- Use safe programming languages, e.g., Java, Rust
  - What about legacy C code?

- Static analysis of source code to find overflows
- Dynamic testing: “fuzzing”

Fuzz Testing

- Generate “random” inputs to program
  - Sometimes conforming to input structures (file formats, etc.)
- See if program crashes
  - If crashes, found a bug
  - Bug may be exploitable
- Surprisingly effective

- Now standard part of development lifecycle