CSE P564: Computer Security and Privacy

More More Binary Exploitation (and Defenses)

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

Paper discussion

The Eternal War in Memory

Pick one/more of the following to discuss

- How useful do you find the ‘taxonomy-ification’ of exploits? Does it seem complete?
- Were you aware of these protection mechanism? (Have you ever interacted with hardening settings?)
- What is the primary reason this paper had to be written?
- Would it look the same/different/similar in 2024?

Back to binary security

Summary of problems/techniques so far

- Classic overflow:
  - Unbounded (sploit 0/1) – Targeting saved return addresses
  - Limited overflow (sploit 2/3) – Targeting saved return addresses OR frame pointers
- Heap management / double `free`:
  - Heap metadata structures are inline with data
  - Reuse of pointers can be dangerous!
- Variable args/printf:
  - Using % specifiers to read memory
    - Also to manipulate the internal argument pointer!
  - Using %n to *write* to a memory location
    - Remember it expects a pointer as argument!

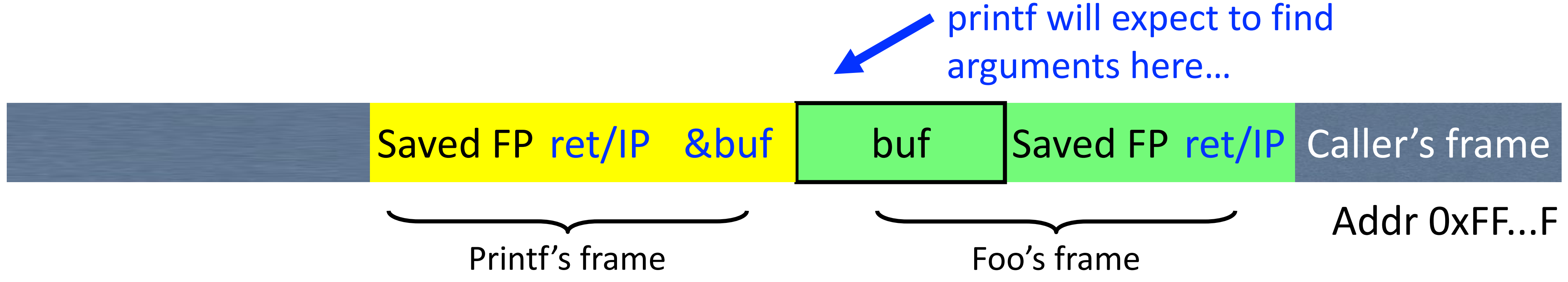
Summary of using printf maliciously

- Printf takes a variable number of arguments
  - E.g., printf(“Here’s an int: %d”, 10);
- Assumptions about input can lead to trouble
  - E.g., printf(buf) when buf=“Hello world” versus when buf=“Hello world %d”
  - Can be used to advance printf’s internal argument pointer
  - Can read memory
    - E.g., printf(“%x”) will print in hex format whatever printf’s internal argument pointer is pointing to at the time
  - Can write memory
    - E.g., printf(“Hello%n”); will write “5” to the memory location specified by whatever printf’s internal argument pointer is pointing to at the time

How Can We Attack This?

```
foo() {
    char buf[1024];
    strncpy(buf, readUntrustedInput(), sizeof(buf)-1);
    printf(buf); //vulnerable
}
```

If format string contains % then printf will expect to find arguments here…



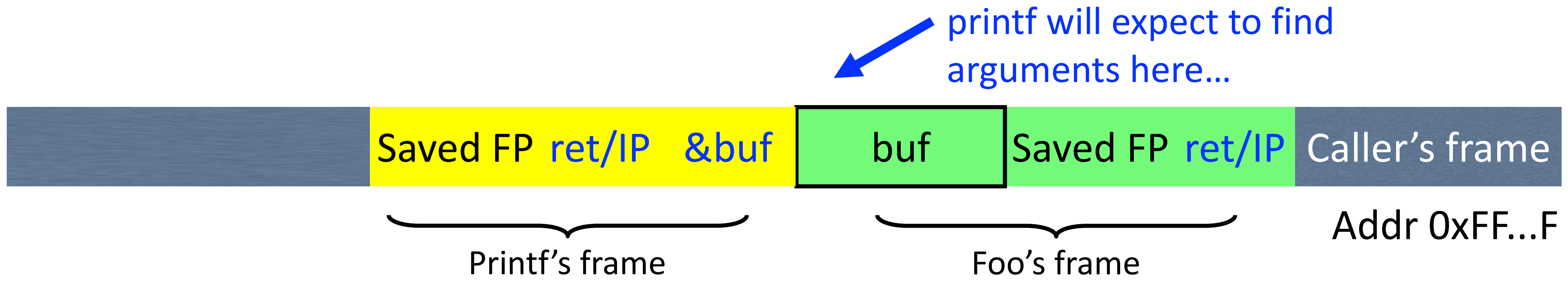
What should the string returned by `readUntrustedInput()` contain?

Different compilers / compiler options / architectures might vary

Discussion time!

```
foo() {
    char buf[1024];
    strncpy(buf, readUntrustedInput(), sizeof(buf)-1);
    printf(buf); //vulnerable
}
```

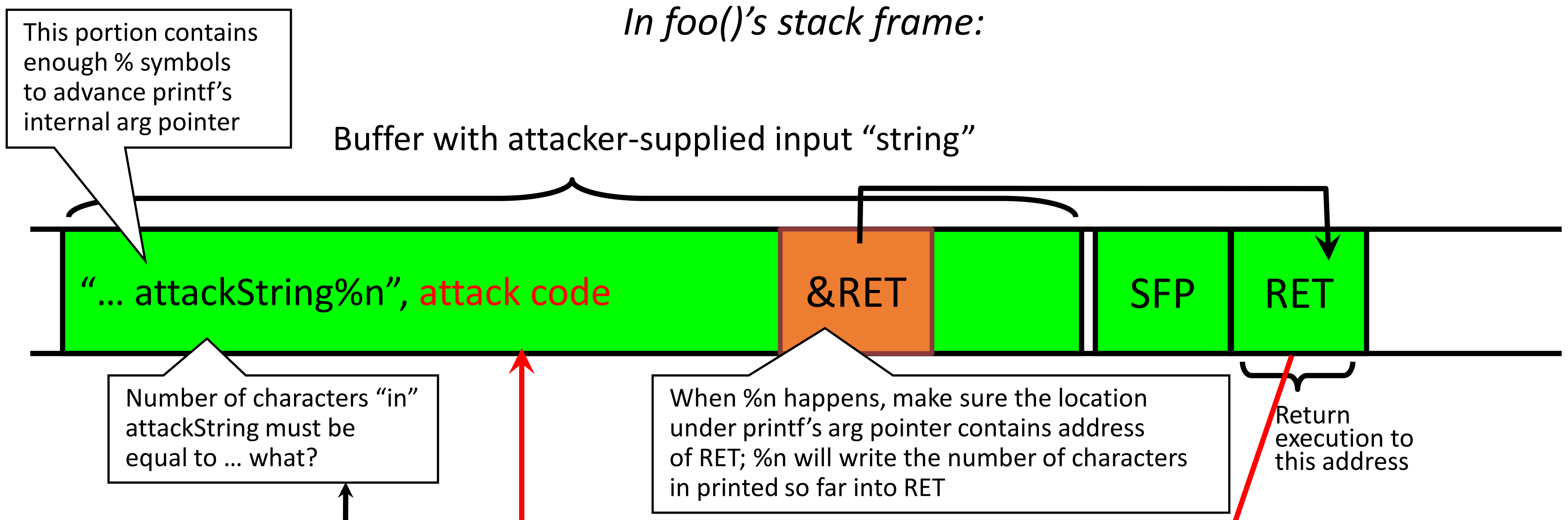
If format string contains % then printf will expect to find arguments here…



What should the string returned by `readUntrustedInput()` contain?

Different compilers / compiler options / architectures might vary

Using %n to overwrite things


This portion contains enough % symbols to advance printf's internal arg pointer
In foo()'s stack frame:
Buffer with attacker-supplied input "string"
"… attackString%n", attack code
&RET
SFP
RET
Number of characters "in" attackString must be equal to … what?
When %n happens, make sure the location under printf's arg pointer contains address of RET; %n will write the number of characters in printed so far into RET
Return execution to this address

Why is "in" in quotes? C allows you to concisely specify the "width" to print, causing printf to pad by printing additional blank characters without reading anything else off the stack.

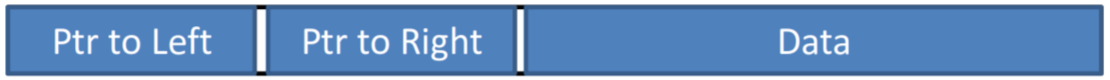
Example: printf("%5d%n", 10) will print three spaces followed by the integer: "   10"
That is, the %n will write 5, not 2.

Key idea: do this 4 times with the right numbers to overwrite the return address byte-by-byte. (4x %n to write into &RET, &RET+1, &RET+2, &RET+3)

Heap buffer exploitation

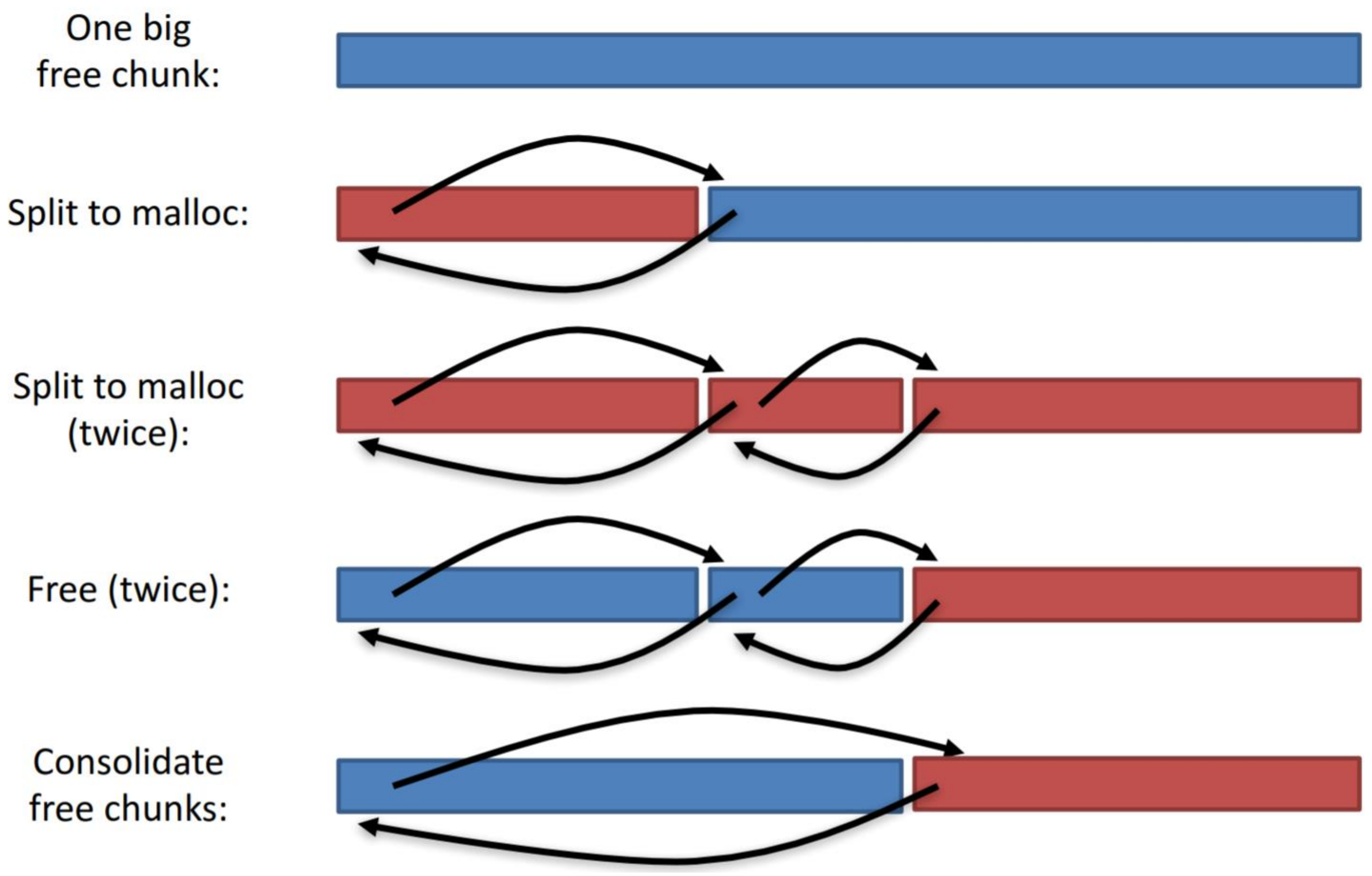
- Read “Once upon a free()” (linked in handout)
- Read through the tmalloc.c implementation
  - It is a complete malloc!
  - Manages things in ‘arena’

Chunk header definition



```
typedef union CHUNK_TAG
{
  struct
    {
      union CHUNK_TAG *l;       /* leftward chunk */
      union CHUNK_TAG *r;       /* rightward chunk + free bit (see below) */
    } s;
  ALIGN x;
} CHUNK;

/*
 * we store the freebit -- 1 if the chunk is free, 0 if it is busy --
 * in the low-order bit of the chunk's r pointer.
 */
```

Chunk Maintenance



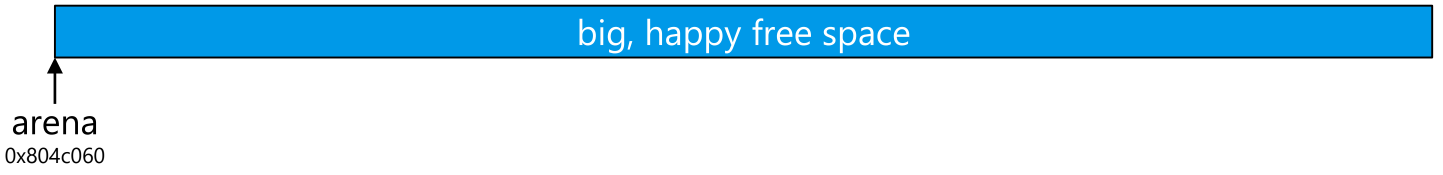
Refer to https://gitlab.cs.washington.edu/snippets/43 for a `tmalloc` implementation.

`tmalloc.h` usage example

```c
1.  int main(){
2.      char* dyn;
3.      char* input =
    "\xa1\xa2\xa3\xa4\xa5\xa6\xa7\xa8\xa9";

4.      dyn = tmalloc(10);

5.      if(dyn == NULL){
6.          fprintf(stderr, "err\n");
7.          exit(EXIT_FAILURE);
8.      }

9.      memcpy(dyn, input, 10);

10.     tfree(dyn);

11.     return  0;
12. }
```

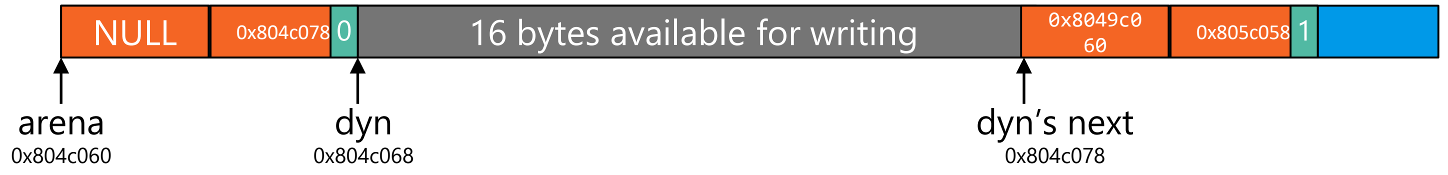
Before `tmalloc` call (line 4):

```
0x804c060 <arena>:      0x00000000    0x00000000    0x00000000    0x00000000
0x804c070 <arena+16>:   0x00000000    0x00000000    0x00000000    0x00000000
0x804c080 <arena+32>:   0x00000000    0x00000000    0x00000000    0x00000000
0x804c090 <arena+48>:   0x00000000    0x00000000    0x00000000    0x00000000
```



After `tmalloc` call: chunk pointers created

```
0x804c060 <arena>:      0x00000000    0x0804c078    0x00000000    0x00000000
0x804c070 <arena+16>:   0x00000000    0x00000000    0x0804c060    0x0805c059
0x804c080 <arena+32>:   0x00000000    0x00000000    0x00000000    0x00000000
0x804c090 <arena+48>:   0x00000000    0x00000000    0x00000000    0x00000000
```



Printed with: x /16xw arena

tmalloc.h usage example

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8.      }

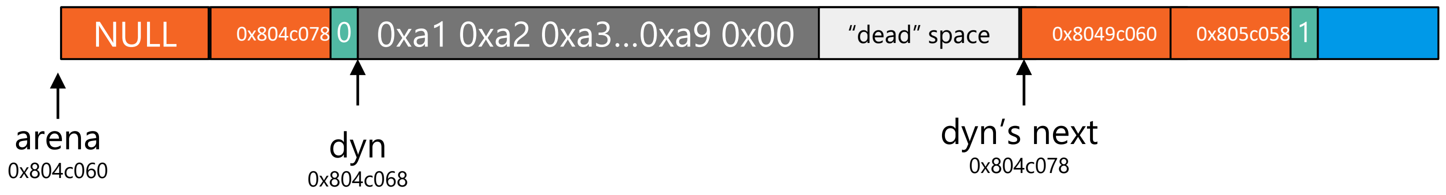
9.      memcpy(dyn, input, 10);

10.     tfree(dyn);

11.     return  0;
12. }
```

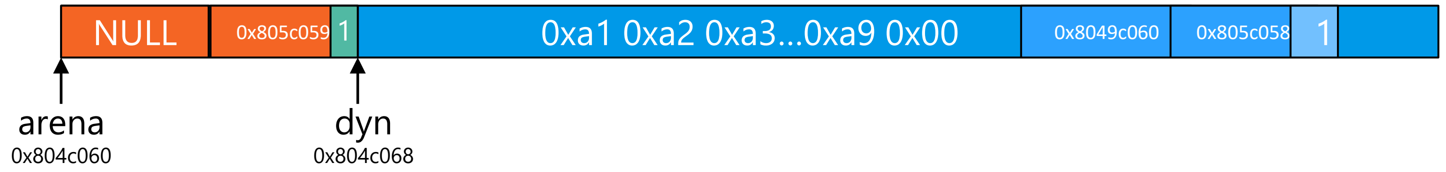
After the copy in line 9:

```
0x804c060 <arena>:     0x00000000   0x0804c078   0xa4a3a2a1   0xa8a7a6a5
0x804c070 <arena+16>:  0x000000a9   0x00000000   0x0804c060   0x0805c059
0x804c080 <arena+32>:  0x00000000   0x00000000   0x00000000   0x00000000
0x804c090 <arena+48>:  0x00000000   0x00000000   0x00000000   0x00000000
```



After the tfree, the chunk is coalesced (line 10)

```
0x804c060 <arena>:     0x00000000   0x0805c059   0xa4a3a2a1   0xa8a7a6a5
0x804c070 <arena+16>:  0x000000a9   0x00000000   0x0804c060   0x0805c059
0x804c080 <arena+32>:  0x00000000   0x00000000   0x00000000   0x00000000
0x804c090 <arena+48>:  0x00000000   0x00000000   0x00000000   0x00000000
```



Printed with: x /16xw arena

Binary defenses

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

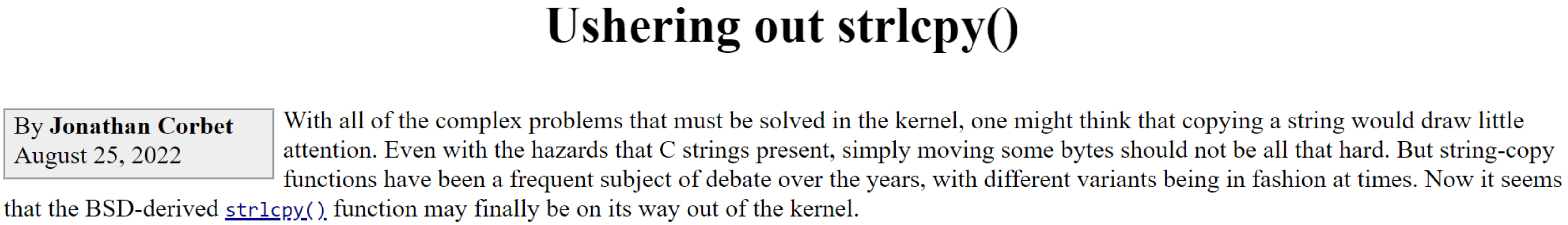
- Possible defenses:
  1. Prevent execution of untrusted code
  2. Stack "canaries"
  3. Encrypt pointers
  4. Address space layout randomization
  5. Code analysis
  6. Better interfaces
  7. …

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.

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)
- ASLR more effective on 64-bit architectures

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
  - Example: Microsoft's Data Execution Prevention (DEP)
  - **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 ret (IP) with address of any library routine

- Does not look like a huge threat?
  - …

- Gradescope time

return-to-libc

- Overwrite saved ret (IP) 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++

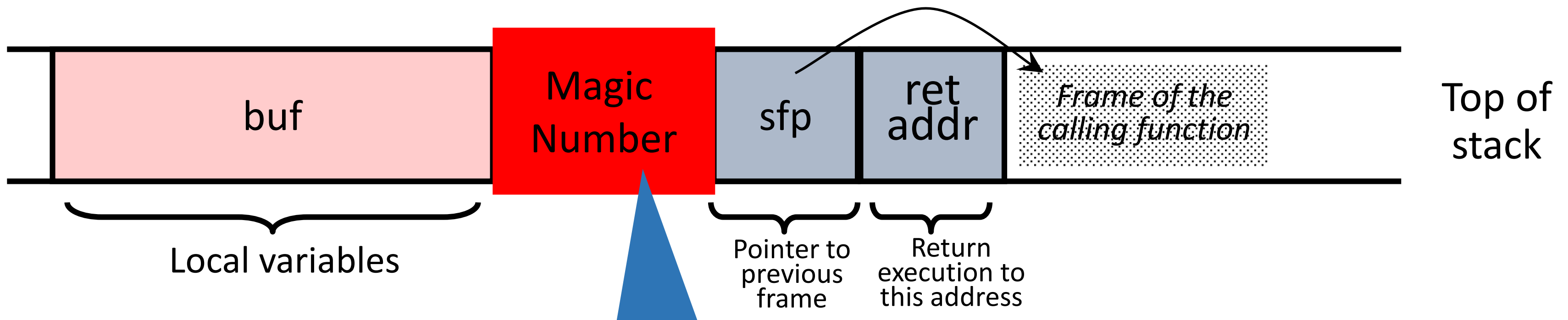
- Insight: Overwritten saved EIP need not point to the *beginning* of a library routine
- **Any** existing instruction in the code image is fine
  - Will execute the sequence starting from this instruction
- What if instruction sequence contains RET?
  - Execution will be transferred… to where?
  - Read 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”

Defense: Run-Time Checking

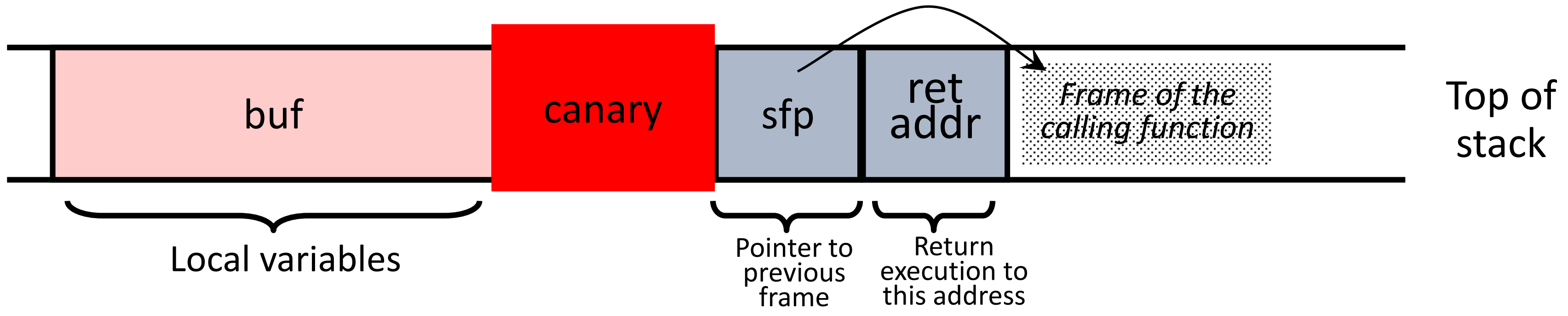
Gradescope: Why would this be useful? How could a program use this to protect against buffer overflows?


buf
Magic Number
sfp
ret addr
Frame of the calling function
Top of stack
Local variables
Pointer to previous frame
Return execution to this address

Choose randomly at the start of the program execution, keep constant during this program run.

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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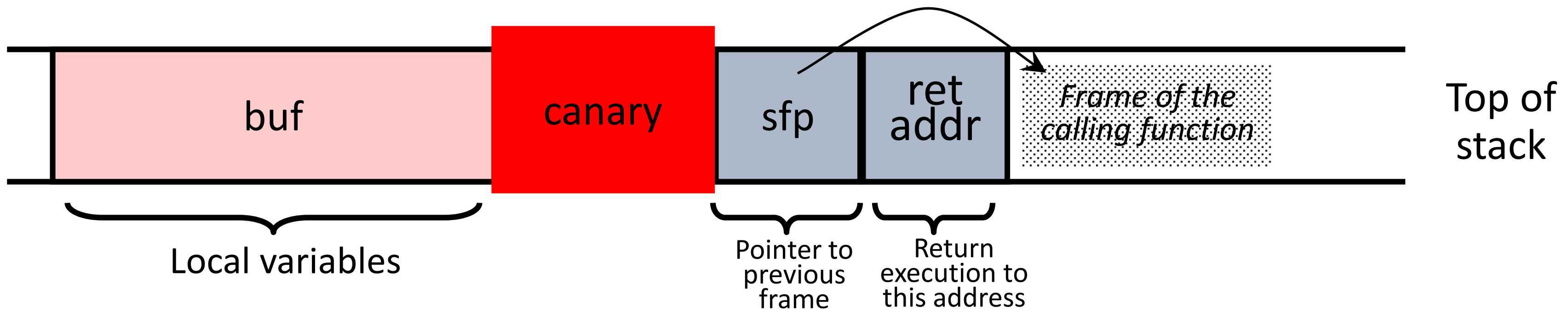

buf
canary
sfp
ret addr
Frame of the calling function
Top of stack
Local variables
Pointer to previous frame
Return execution to this address

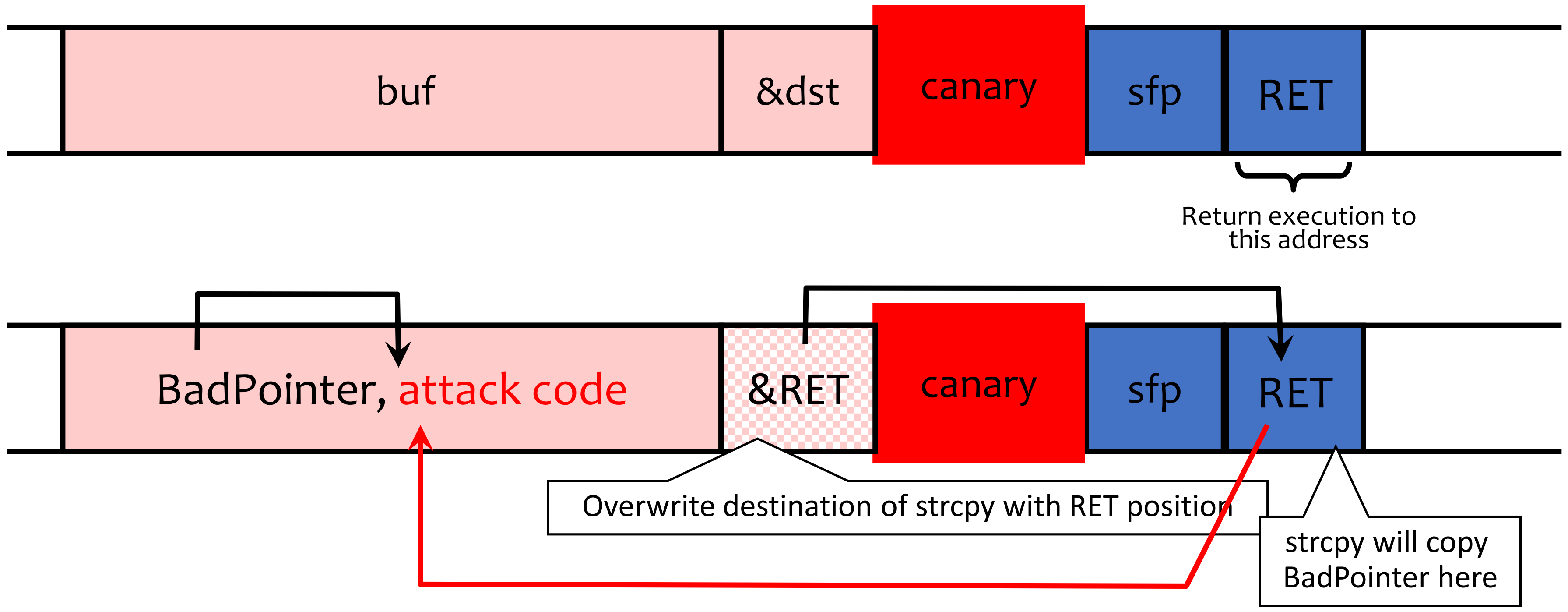
- Choose random canary string on program start
  - Attacker can't guess what the value of canary will be
- Canary contains: "\0", newline, linefeed, EOF
  - String functions like strcpy won't copy beyond "\0"

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
- Suppose program contains copy(buf,attacker-input) and copy(dst,buf)
  - Example: dst is a local pointer variable
  - Attacker controls both buf and dst

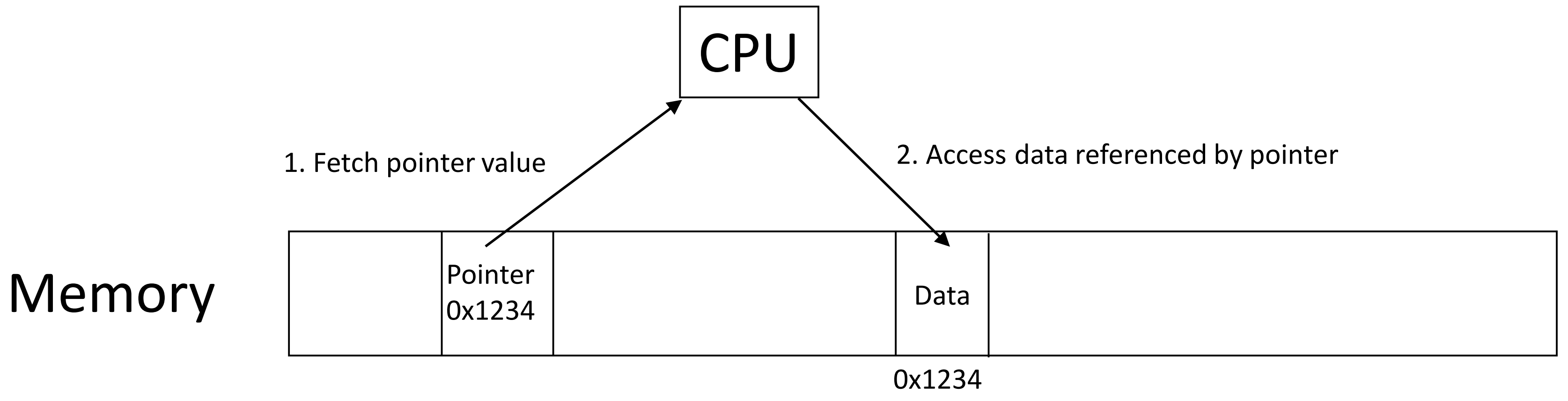

buf
&dst
canary
sfp
RET
Return execution to this address
BadPointer, attack code
&RET
canary
sfp
RET
Overwrite destination of strcpy with RET position
strcpy will copy BadPointer here

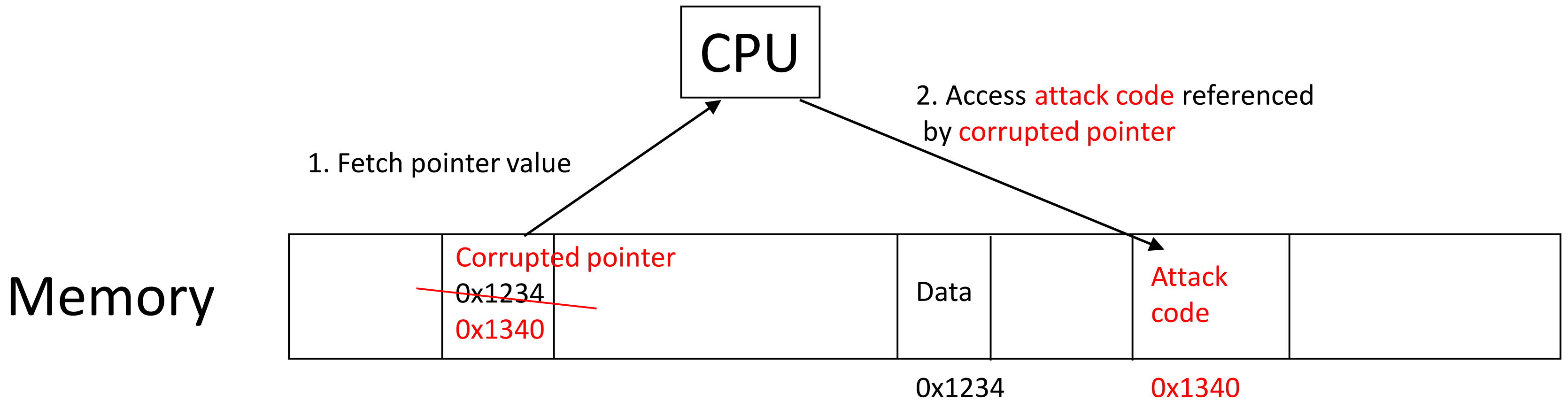
Pointer integrity protections (e.g. PointGuard, PAC, etc.)

- 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]

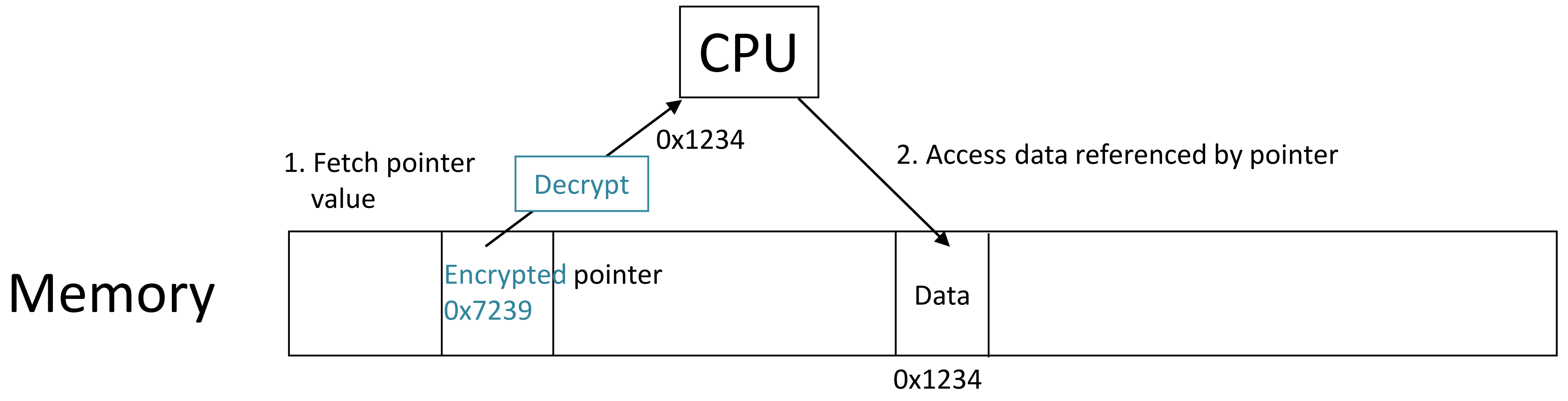
Normal Pointer Dereference

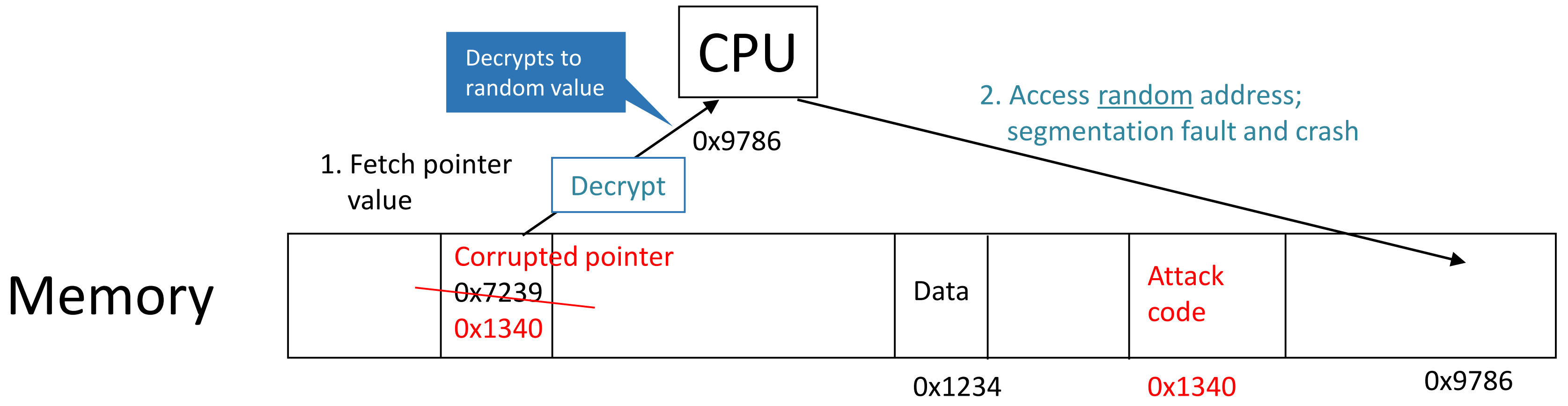




[Cowan]

PointGuard (Old, XOR style) Dereference

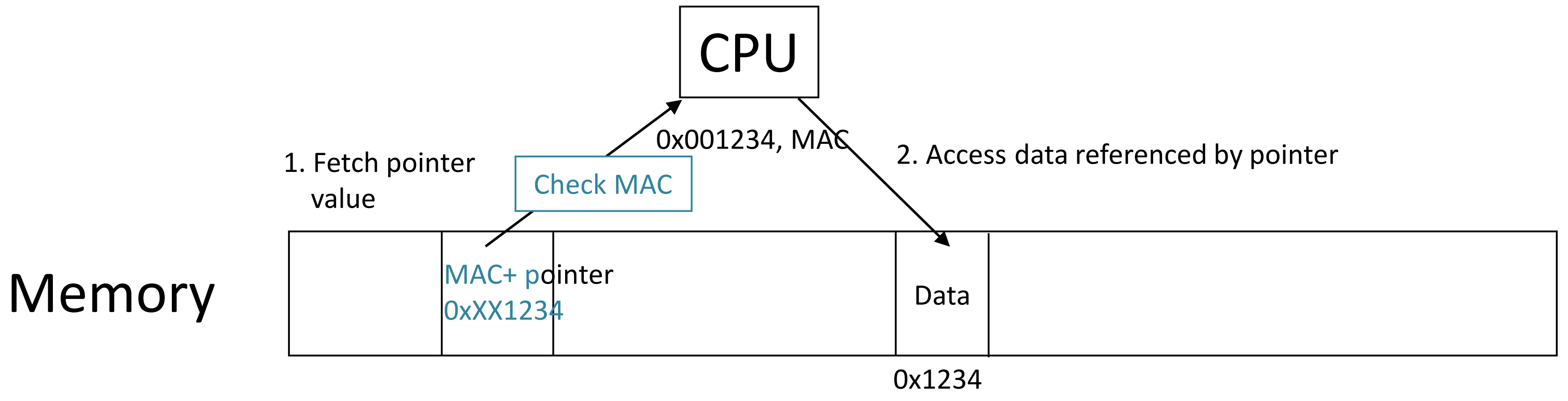


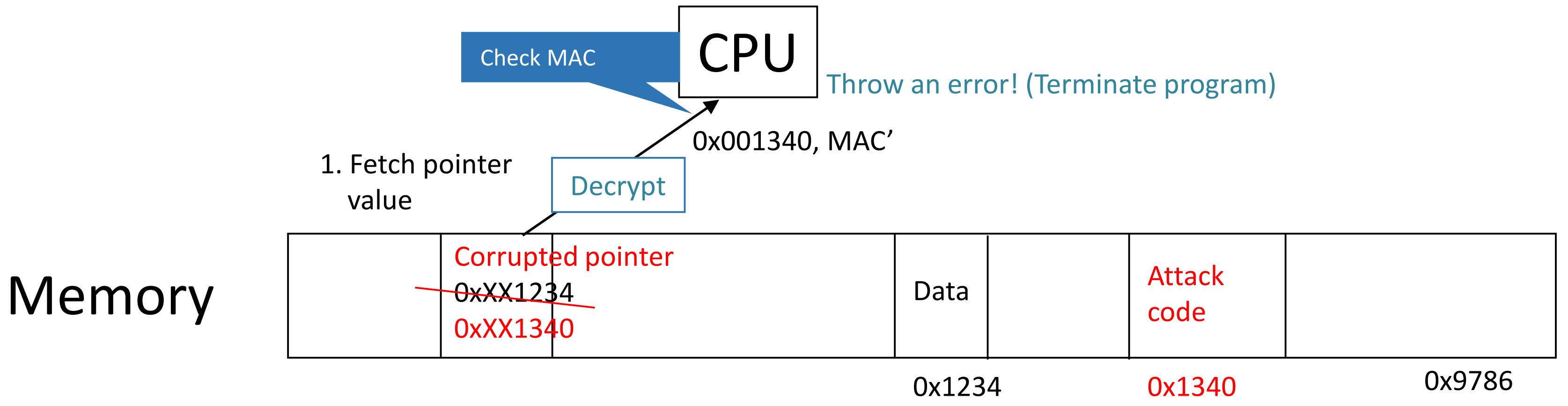


PointGuard Issues

- Must be very fast
  - Pointer dereferences are very common
- Compiler issues
  - Must encrypt and decrypt only pointers
  - If compiler "spills" registers, unencrypted pointer values end up in memory and can be overwritten there
- Attacker should not be able to modify the key
  - Store key in its own non-writable memory page
- PG'd code doesn't mix well with normal code
  - What if PG'd code needs to pass a pointer to OS kernel?

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.)

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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080491ad <foo>:
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 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
```

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

More attack techniques

Other Common Software Security Issues…

Another Class of Vulnerability: (Gradescope)

```
char buf[80];
void vulnerable() {
     long long len = get_int_from_attacker();
     char *p = get_string_from_attacker();
     int32_t buflen = sizeof(buf);
     if (len > buflen) {
          error("length too large”);
         return;
     }
     memcpy(buf, p, len);
}
```

Snippet 1

```
size_t len = read_int_from_attacker();
char *buf;
buf = malloc(len+5);
read(fd, buf, len);
```

Snippet 2

```
void *memcpy(void *dst, const void * src, size_t n);
```

```
typedef unsigned int size_t;
```

Implicit Cast

```
char buf[80];
void vulnerable() {
     long long len = get_int_from_attacker();
     char *p = get_string_from_attacker();
     int32_t buflen = sizeof(buf);
     if (len > buflen) {
          error("length too large”);
         return;
     }
     memcpy(buf, p, len);
}
```

Snippet 1

- If len is negative
- Then len > buflen may pass
- Any memcpy may copy huge amounts of input into buf.

```
void *memcpy(void *dst, const void * src, size_t n);
```

```
typedef unsigned int size_t;
```

Integer Overflow

- What if len is large (e.g., len = 0xFFFFFFFF)?
- Then len + 5 = 4 (on many platforms)
- Result: Allocate a 4-byte buffer, then read a lot of data into that buffer.

```
size_t len = read_int_from_attacker();
char *buf;
buf = malloc(len+5);
read(fd, buf, len);
```

Snippet 2

```
void *memcpy(void *dst, const void * src, size_t n);
```

```
typedef unsigned int size_t;
```

Another Type of Vulnerability

- Consider this code:

```
if (access(“file”, W_OK) != 0) {
    exit(1); // user not allowed to write to file
}

fd = open(“file”, O_WRONLY);
write(fd, buffer, sizeof(buffer));
```

- **Goal:** Write to file only with permission
- What can go wrong?

TOCTOU (Race Condition)

- TOCTOU = “Time of Check to Tile of Use”

```
if (access(“file”, W_OK) != 0) {
    exit(1); // user not allowed to write to file
}

fd = open(“file”, O_WRONLY);
write(fd, buffer, sizeof(buffer));
```

- **Goal:** Write to file only with permission
- Attacker (in another program) can change meaning of “file” between access and open:

```
    symlink("/etc/passwd", "file");
```

Something Different: Password Checker

- Functional requirements
  - PwdCheck(RealPwd, CandidatePwd) should:
    - Return TRUE if RealPwd matches CandidatePwd
    - Return FALSE otherwise
  - RealPwd and CandidatePwd are both 8 characters long

Password Checker

- Functional requirements
  - `PwdCheck(RealPwd, CandidatePwd)` should:
    - Return TRUE if RealPwd matches CandidatePwd
    - Return FALSE otherwise
  - RealPwd and CandidatePwd are both 8 characters long
- Implementation (like TENEX system)

```
PwdCheck(RealPwd, CandidatePwd)  // both 8 chars
    for(int i=0; i<8; i++){
        if (RealPwd[i] != CandidatePwd[i])
            return FALSE;
    }
    return TRUE;
```

- Clearly meets functional description

Attacker Model

```
PwdCheck(RealPwd, CandidatePwd)  // both 8 chars
    for(int i=0; i<8; i++){
        if (RealPwd[i] != CandidatePwd[i])
            return FALSE;
    }
    return TRUE;
```

- Attacker can guess CandidatePwds through some standard interface
- Naive: Try all 256^8 = 18,446,744,073,709,551,616 possibilities
- Is it possible to derive password more quickly?

Try it

dkohlbre.com/cew