CSE 484 / CSE M 584: Computer Security and Privacy

Software Security: Buffer Overflow Attacks

(continued)

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Looking Forward

- Today: More buffer overflows + defenses
- Wednesday: one more day on software security
- Friday: guest lecture by David Aucsmith
- Next week: start crypto

- Ethics form due **Wednesday**
- Homework #1 due **Friday**
- Lab #1 out this week (please form groups!)

- Section this week: Lab 1

Last Time: Basic Buffer Overflows

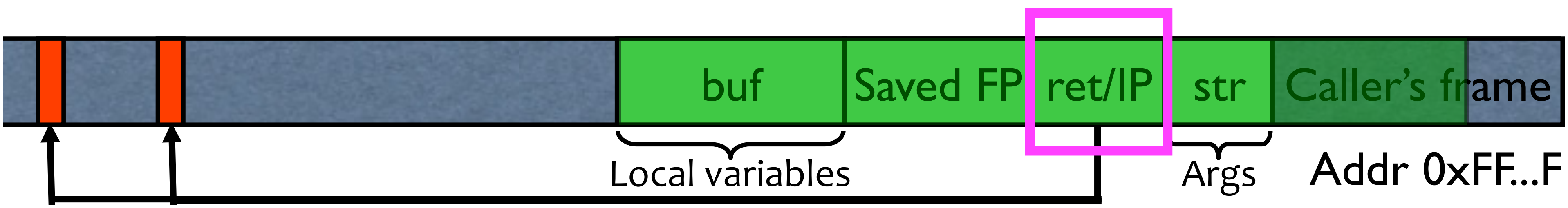
- Memory pointed to by str is copied onto stack…

```
void func(char *str) {
        char buf[126];
        strcpy(buf,str);
   }
```

strcpy does NOT check whether the string at *str contains fewer than 126 characters

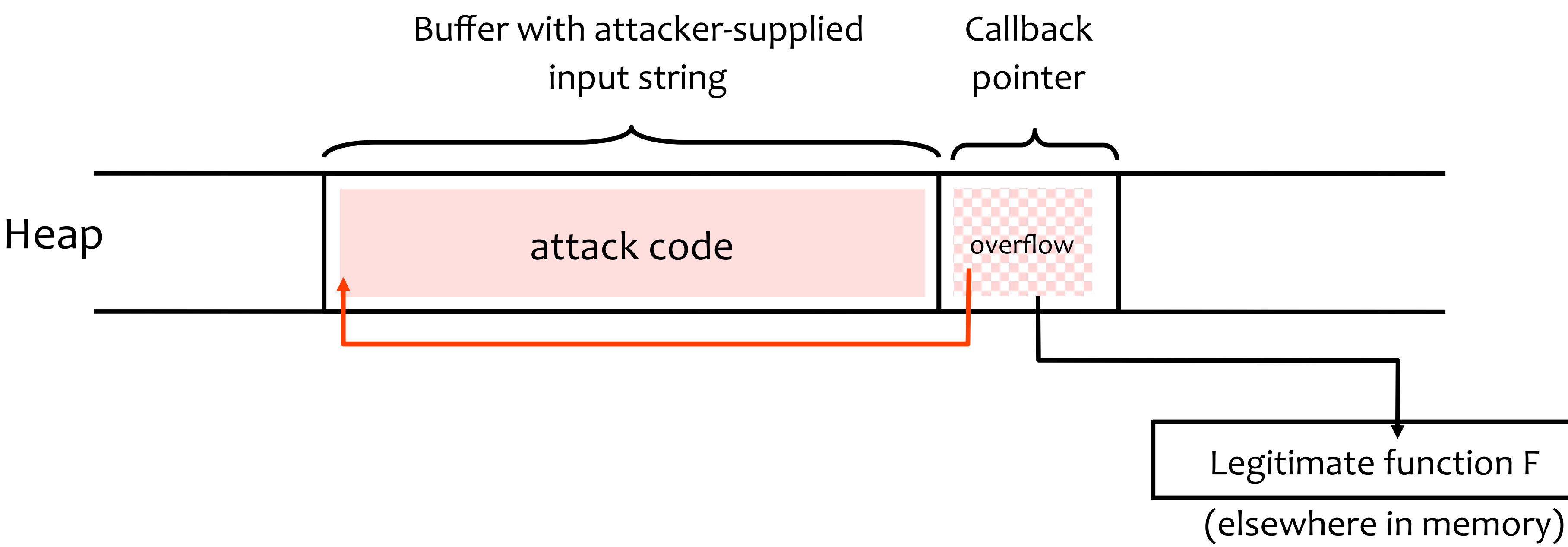
- If a string longer than 126 bytes is copied into buffer, it will overwrite adjacent stack locations.

This will be interpreted as return address!



Another Variant: Function Pointer Overflow

- C uses function pointers for callbacks: if pointer to F is stored in memory location P, then another function G can call F as (*P)(…)



Other Overflow Targets

- Format strings in C
  - More details today
- Heap management structures used by malloc()
  - More details in section

- These are all attacks you can look forward to in Lab #1 ☺

Variable Arguments in C

- In C, can define a function with a variable number of arguments
  - Example: void printf(const char* format, …)
- Examples of usage:

```
printf("hello, world");
printf("length of '%s' = %d\n", str, str.length());
printf("unable to open file descriptor %d\n", fd);
```

Format specification encoded by special % characters

%d,%i,%o,%u,%x,%X – integer argument
%s – string argument
%p – pointer argument (void *)
Several others

Format Strings in C

- Proper use of printf format string:

```
int foo = 1234;
printf("foo = %d in decimal, %X in hex",foo,foo);
```

This will print:

```
foo = 1234 in decimal, 4D2 in hex
```

- Sloppy use of printf format string:

```
char buf[14] = "Hello, world!";
printf(buf);
// should've used printf("%s", buf);
```

What happens if buffer contains format symbols starting with % ???

Implementation of Variable Args

- Special functions va_start, va_arg, va_end compute arguments at run-time

```
void printf(const char* format, ...)
{
      int i; char c; char* s; double d;
      va_list ap; /* declare an "argument pointer" to a variable arg list */
      va_start(ap, format); /* initialize arg pointer using last known arg */

      for (char* p = format; *p != '\0'; p++) {
         if (*p == '%') {
            switch (*++p) {
               case 'd':
                  i = va_arg(ap, int); break;
               case 's':
                  s = va_arg(ap, char*); break;
               case 'c':
                  c = va_arg(ap, char); break;
               }
               ... /* etc. for each % specification */
            }
      }
      ...

      va_end(ap);  /* restore any special stack manipulations */
}
```

printf has an internal stack pointer

Format Strings in C

- Proper use of printf format string:

```
int foo=1234;
printf("foo = %d in decimal, %X in hex",foo,foo);
```

This will print:

```
foo = 1234 in decimal, 4D2 in hex
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- Sloppy use of printf format string:

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char buf[14] = "Hello, world!";
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What happens if buffer contains format symbols starting with % ???

Format Strings in C

If the buffer contains format symbols starting with %, the location pointed to by printf's internal stack pointer will be interpreted as an argument of printf.

This can be exploited to move printf's internal stack pointer!

- Sloppy use of printf format string:

```
char buf[14] = "Hello, world!";
printf(buf);
// should've used printf("%s", buf);
```

What happens if buffer contains format symbols starting with % ???

Viewing Memory

- %x format symbol tells printf to output data on stack

```
printf("Here is an int:  %x",i);
```

- What if printf does not have an argument?

```
char buf[16]="Here is an int:  %x";
printf(buf);
```

- Or what about:

```
char buf[16]="Here is a string:  %s";
printf(buf);
```

Viewing Memory

- %x format symbol tells printf to output data on stack

```
printf("Here is an int:  %x",i);
```

- What if printf does not have an argument?

```
char buf[16]="Here is an int:  %x";
printf(buf);
```

  - Stack location pointed to by printf's internal stack pointer will be interpreted as an int. (What if crypto key, password, ...?)

- Or what about:

```
char buf[16]="Here is a string:  %s";
printf(buf);
```

  - Stack location pointed to by printf's internal stack pointer will be interpreted as a pointer to a string

Writing Stack with Format Strings

- %n format symbol tells printf to write the number of characters that have been printed

```
printf("Overflow this!%n",&myVar);
```

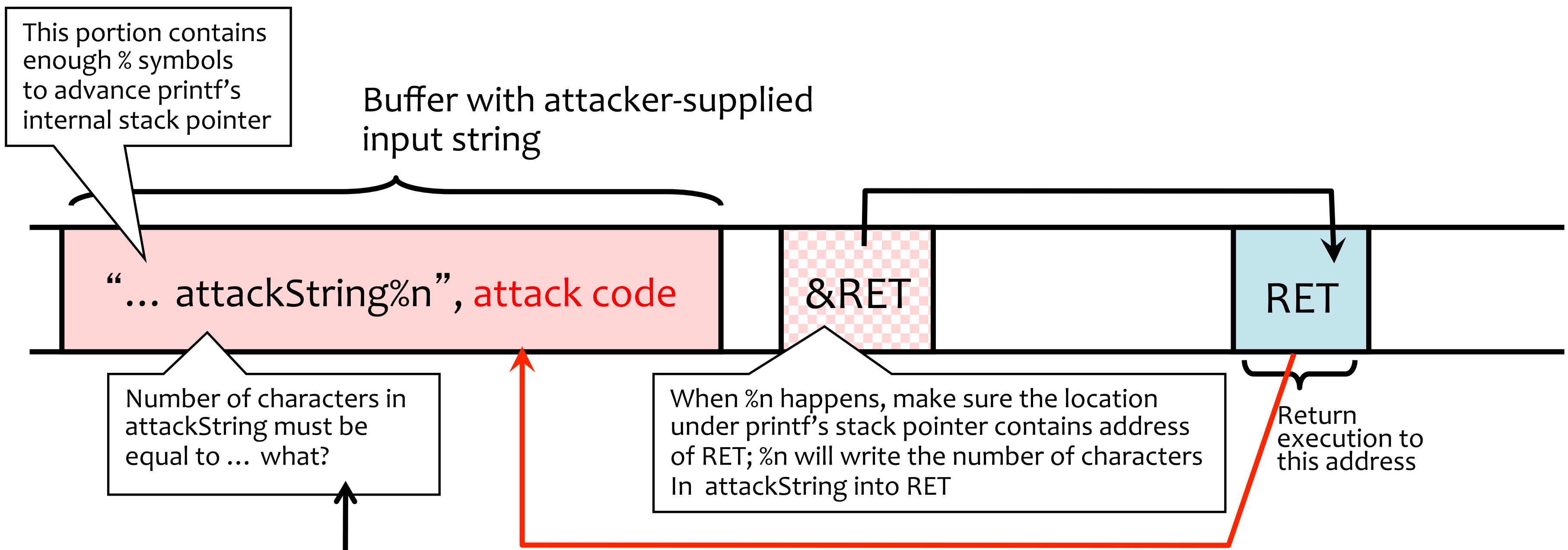
  - Argument of printf is interpeted as destination address
  - This writes 14 into myVar ("Overflow this!" has 14 characters)

- What if printf does not have an argument?

```
char buf[16]="Overflow this!%n";
printf(buf);
```

  - Stack location pointed to by printf's internal stack pointer will be **interpreted as address** into which the number of characters will be written.

Using %n to Overwrite Return Address



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", 10) will print three spaces followed by the integer: "   10"
That is, %n will print 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)

Recommended Reading

- It will be hard to do Lab 1 without reading:
  – Smashing the Stack for Fun and Profit
  – Exploiting Format String Vulnerabilities
- Links to these readings are posted on the course schedule.

Buffer Overflow: Causes and Cures

- Typical 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

- We'll talk about a few defenses today:
  1. Prevent execution of untrusted code
  2. Stack "canaries"
  3. Encrypt pointers
  4. Address space layout randomization

W⊕X / DEP

- Mark all writeable memory locations as non-executable
  - Example: Microsoft's Data Execution Prevention (DEP)
  - This blocks (almost) all code injection exploits
- Hardware support
  - AMD "NX" bit, Intel "XD" bit (in post-2004 CPUs)
  - Makes memory page non-executable
- Widely deployed
  - Windows (since XP SP2), Linux (via PaX patches), OS X (since 10.5)

What Does W⊕X Not Prevent?

- Can still corrupt stack …
  - … or function pointers or critical data on the heap
- As long as "saved EIP" points into existing code, W⊕X protection will not block control transfer
- This is the basis of return-to-libc exploits
  - Overwrite saved EIP with address of any library routine, arrange stack to look like arguments
- Does not look like a huge threat
  - Attacker cannot execute arbitrary code, especially if system() is not available

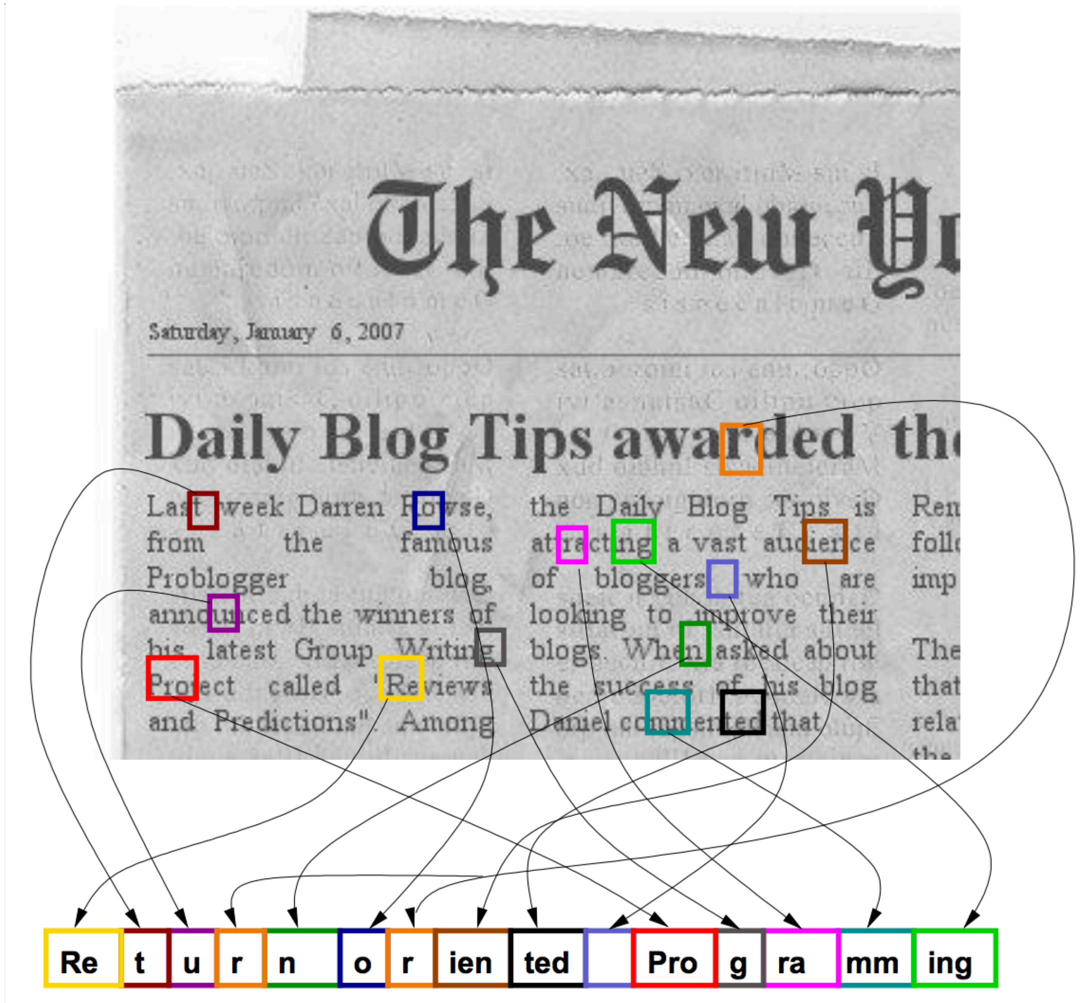
return-to-libc on Steroids

- 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 (ESP)
    - Guess what? Its value is under attacker's control!
  - Use it as the new value for EIP
    - Now control is transferred to an address of attacker's choice!
  - Increment ESP to point to the next word on the stack

Chaining RETs for Fun and Profit

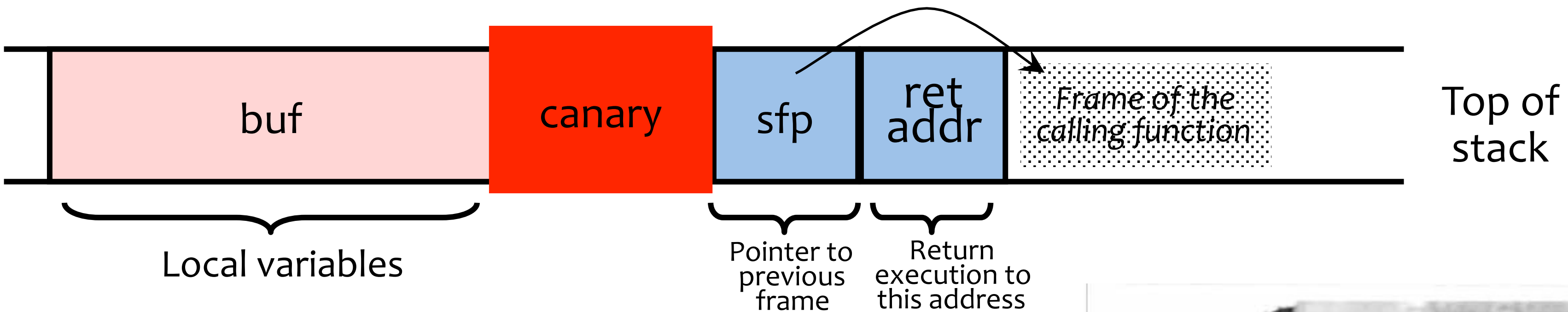
- Can chain together sequences ending in RET
  - Krahmer, "x86-64 buffer overflow exploits and the borrowed code chunks exploitation technique" (2005)
- What is this good for?
- Answer [Shacham et al.]: everything
  - Turing-complete language
  - Build "gadgets" for load-store, arithmetic, logic, control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

Return-Oriented Programming



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



Run-Time Checking: StackGuard

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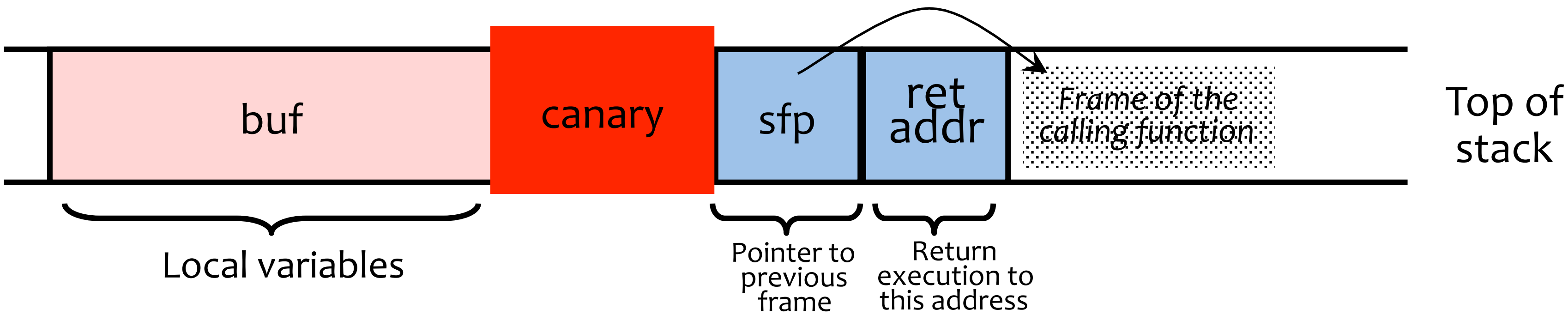


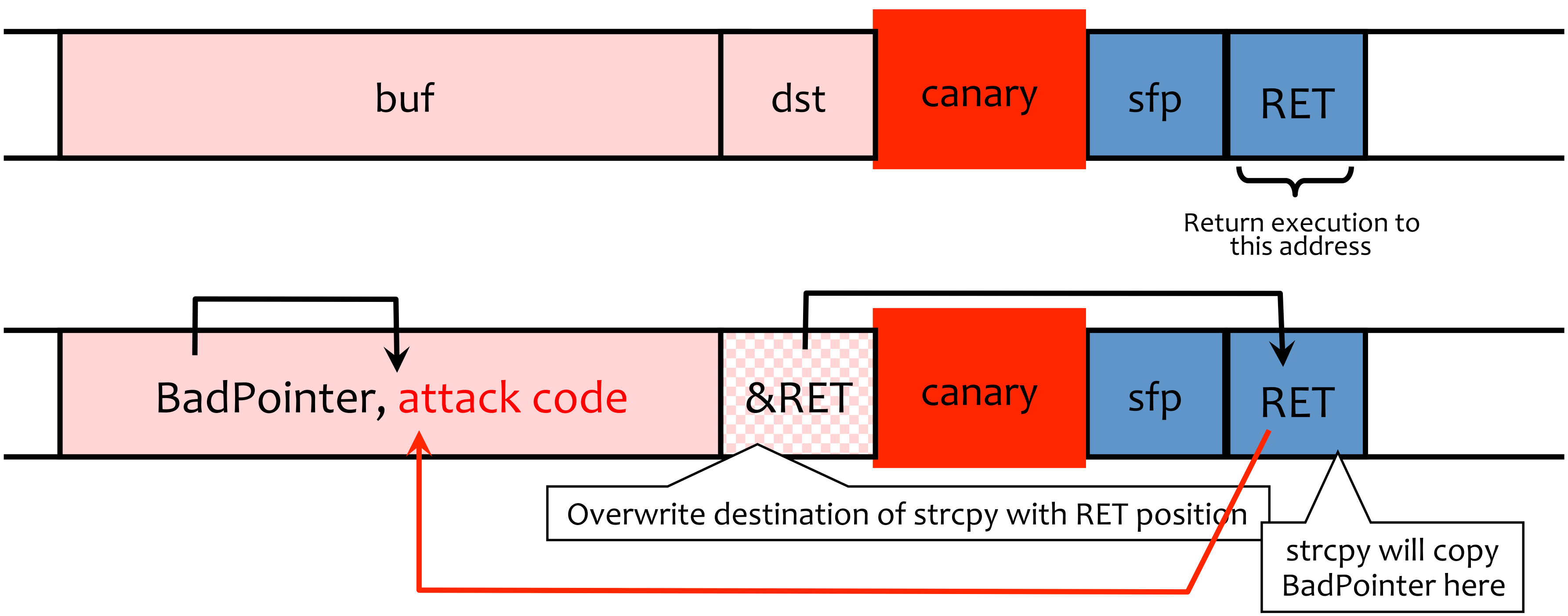
- Choose random canary string on program start
  - Attacker can't guess what the value of canary will be
- Terminator canary: "\0", newline, linefeed, EOF
  - String functions like strcpy won't copy beyond "\0"

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

Defeating StackGuard

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

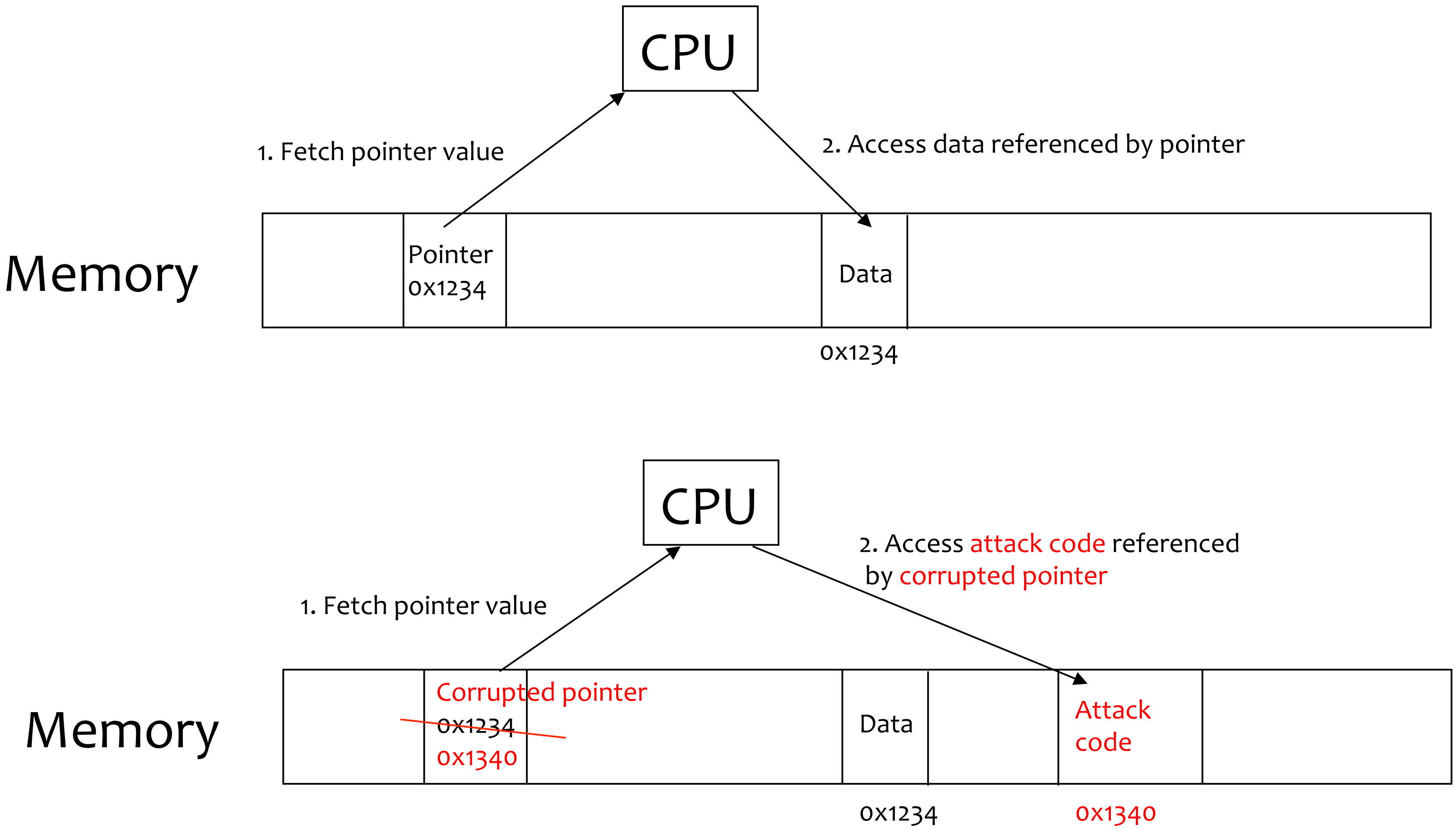


PointGuard

- Attack: overflow a function pointer so that it points to attack code
- Idea: encrypt all pointers while in memory
  - Generate a random key when program is executed
  - Each pointer is XORed with this key when loaded from memory to registers or stored back into memory
    - Pointers cannot be overflowed while in registers
- Attacker cannot predict the target program's key
  - Even if pointer is overwritten, after XORing with key it will dereference to a "random" memory address

[Cowan]

Normal Pointer Dereference



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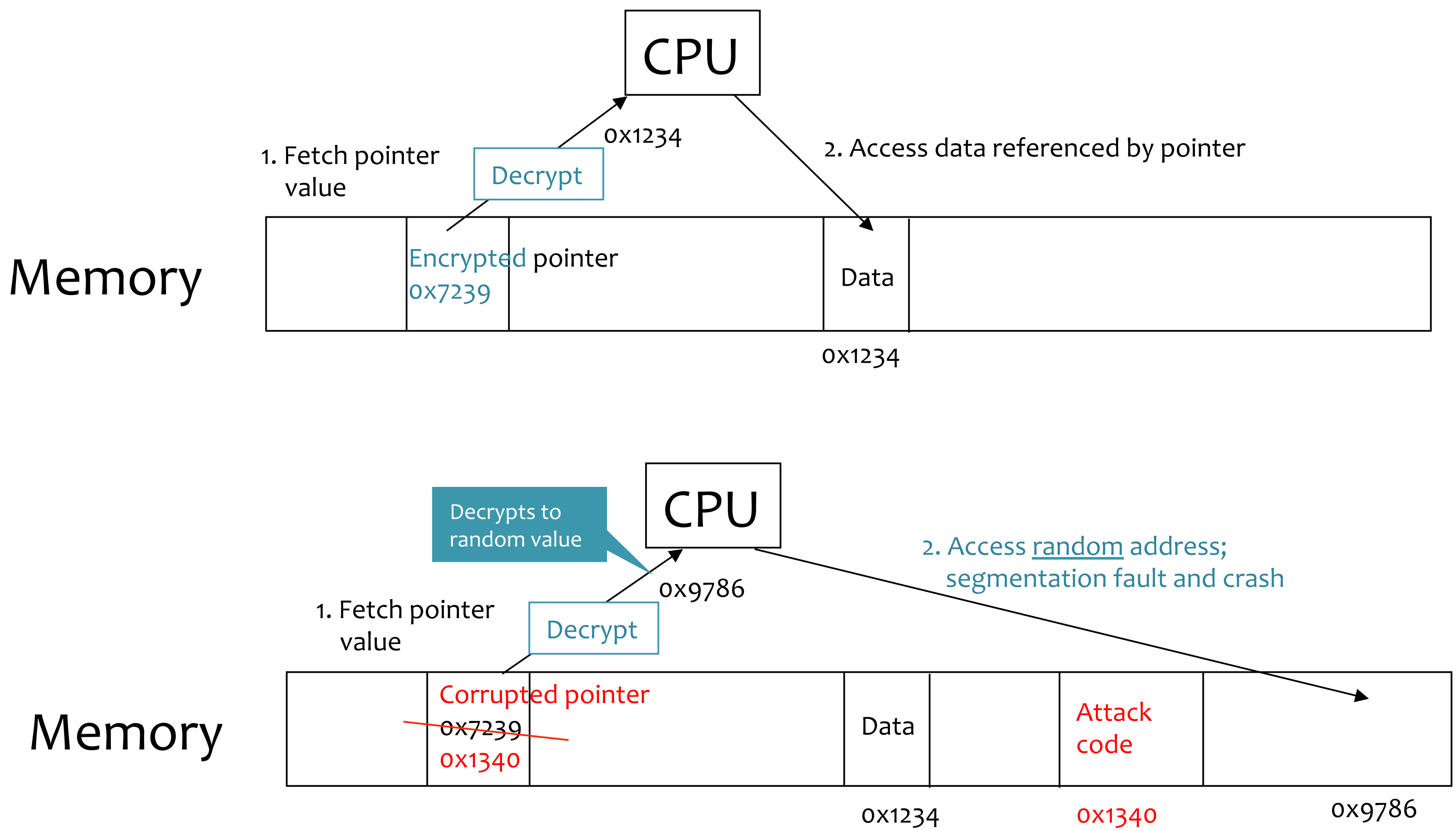
PointGuard Dereference



PointGuard Issues

- Must be very fast
  - Pointer dereferences are very common
- Compiler issues
  - Must encrypt and decrypt <u>only</u> 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?

ASLR: Address Space Randomization

- Map shared libraries to a random location in process memory
  - Attacker does not know addresses of executable code
- Deployment (examples)
  - Windows Vista: 8 bits of randomness for DLLs
  - Linux (via PaX): 16 bits of randomness for libraries
  - Even Android
  - More effective on 64-bit architectures
- Other randomization methods
  - Randomize system call ids or instruction set

Example: ASLR in Vista

- Booting Vista twice loads libraries into different locations:

ntlanman.dll	0x6D7F0000	Microsoft® Lan Manager
ntmarta.dll	0x75370000	Windows NT MARTA provider
ntshrui.dll	0x6F2C0000	Shell extensions for sharing
ole32.dll	0x76160000	Microsoft OLE for Windows

ntlanman.dll	0x6DA90000	Microsoft® Lan Manager
ntmarta.dll	0x75660000	Windows NT MARTA provider
ntshrui.dll	0x6D9D0000	Shell extensions for sharing
ole32.dll	0x763C0000	Microsoft OLE for Windows

ASLR Issues

- NOP slides and heap spraying to increase likelihood for custom code (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

Other Possible Solutions

- Use safe programming languages, e.g., Java
  - What about legacy C code?
  - (Note that Java is not the complete solution)
- Static analysis of source code to find overflows
- Dynamic testing: “fuzzing”
- LibSafe: dynamically loaded library that intercepts calls to unsafe C functions and checks that there’s enough space before doing copies
  - Also doesn’t prevent everything