Warmup: C bugs. What looks off here?

```
hashOut.data = hashes + SSL_MD5_DIGEST_LEN;
hashOut.length = SSL_SHA1_DIGEST_LEN;
if ((err = SSLFreeBuffer(&hashCtx)) != 0)
    goto fail;
if ((err = ReadyHash(&SSLHashSHA1, &hashCtx)) != 0)
    goto fail;
if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
    goto fail;
if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
    goto fail;
if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
    goto fail;
    goto fail;
if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
    goto fail;

err = sslRawVerify(...);
```

CSE 484: Computer Security and Privacy

Software Security: More!

Spring 2024

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Logistics

- HW1 due **tonight**
- 584 reading 1 due Friday
- Lab 1 is running

Last time…

- Stack smashing and overwriting return pointers
- “Computing” with printf

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 interpreted 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.

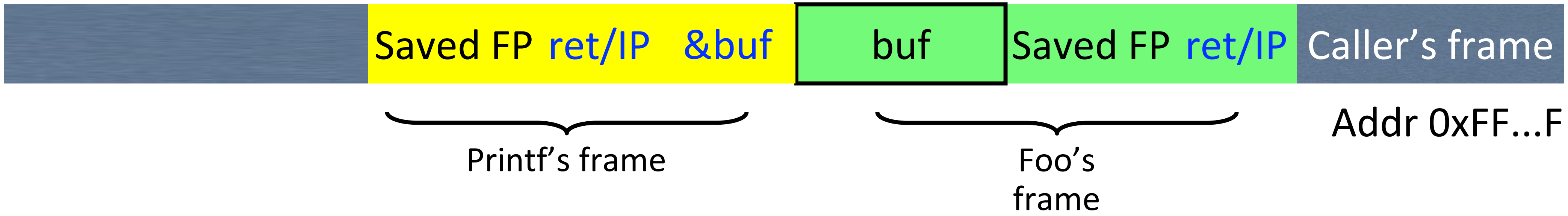
Summary of Printf Risks

- 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 stack pointer
  - Can read memory
    - E.g., printf(“%x”) will print in hex format whatever printf’s internal stack 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 SP is pointing to at the time

How Can We Attack This?

```
foo() {
        char buf[2048];
        strncpy(buf, readUntrustedInput(), sizeof(buf));
        printf(buf); //vulnerable
}
```

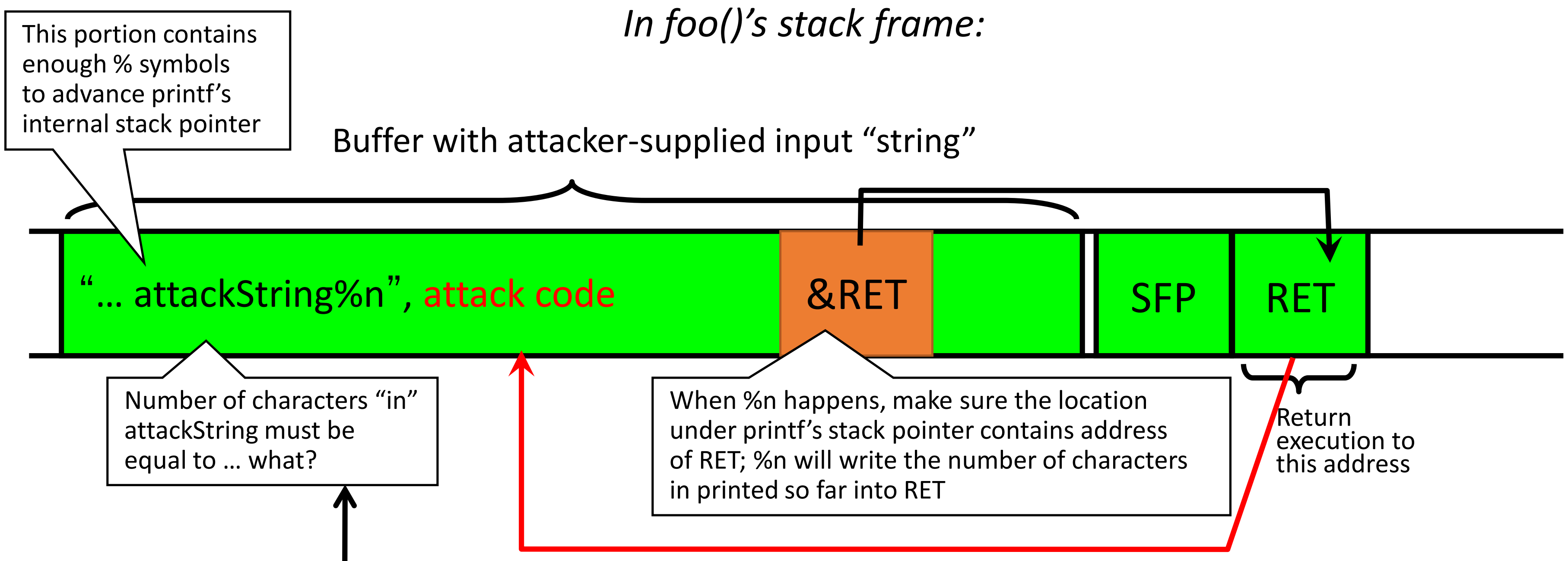
If format string contains % then printf will expect to find arguments here…



What should the string returned by readUntrustedInput() contain?

Different compilers / compiler options / architectures might vary

Using %n to Overwrite Return 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)

The exploitation twilight zone

- During an exploitation attempt sometimes you have to ‘let it run’
  - Overflow a buffer
  - Change things
  - Let program run for ‘a bit’
  - Everything triggers!

- Printf exploit a perfect example

Recommended Reading

- It will be hard to do Lab 1 without:
  - Reading (see assignments):
    - Smashing the Stack for Fun and Profit
    - Exploiting Format String Vulnerabilities

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

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 ☺

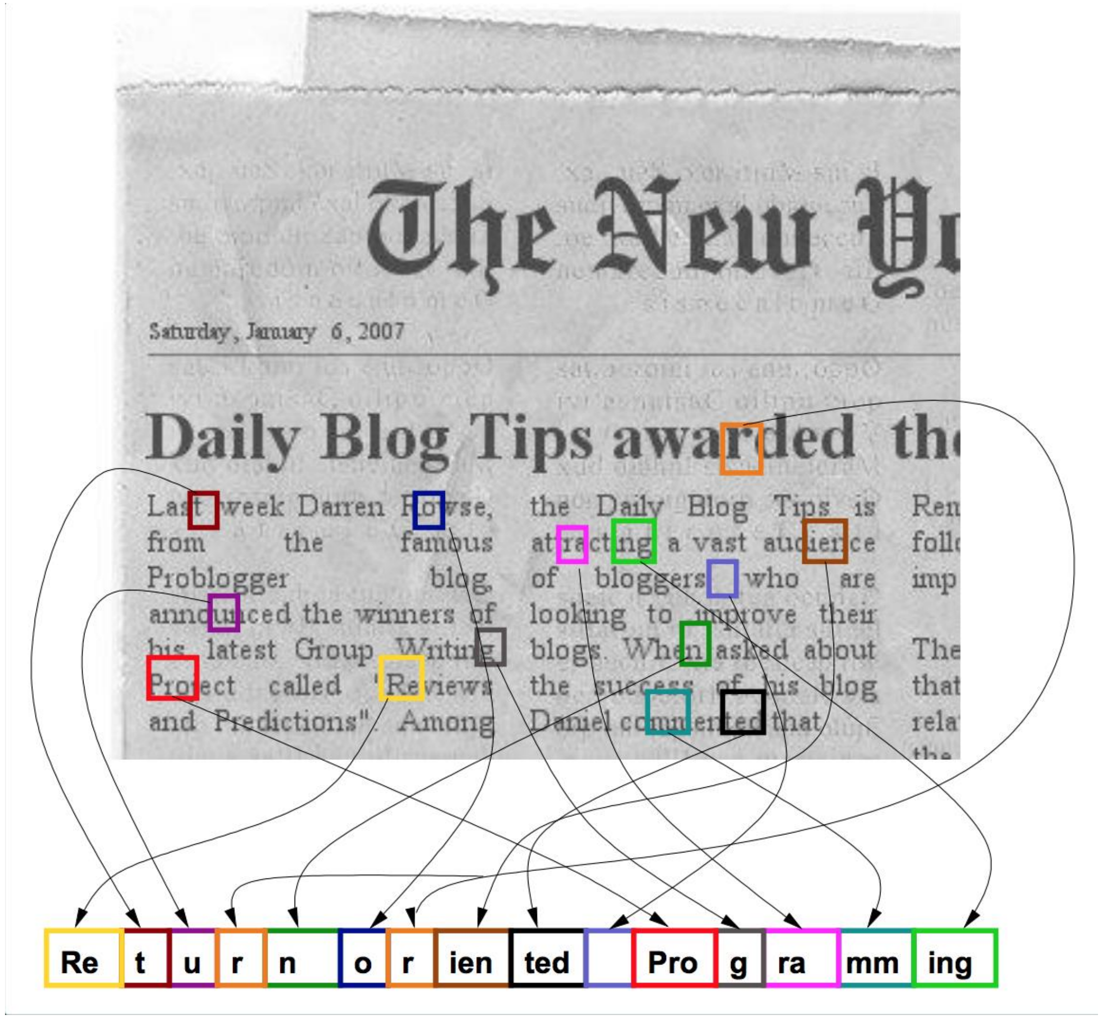
return-to-libc++

- 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

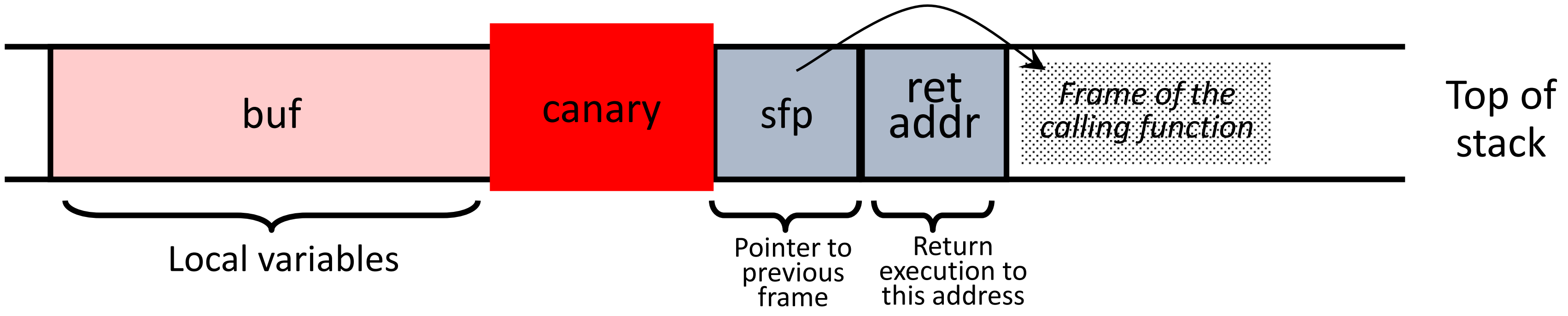
- Can chain together sequences ending in RET
  - Krahmer, "x86-64 buffer overflow exploits and the borrowed code chunks exploitation technique" (2005)
- What is this good for?
- Answer [Shacham et al.]: everything
  - Turing-complete language
  - Build "gadgets" for load-store, arithmetic, logic, control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

Return-Oriented Programming



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



Defense: Run-Time Checking: StackGuard

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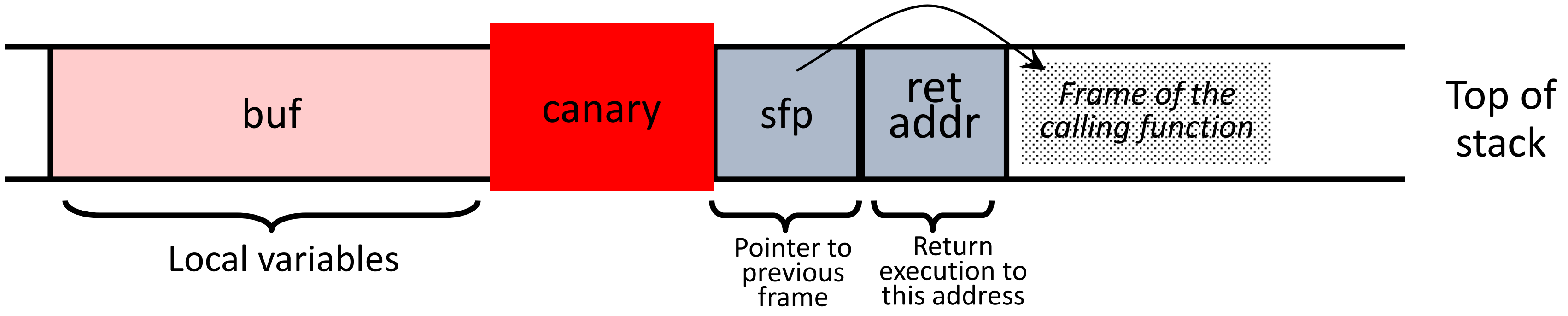

- Choose random canary string on program start
  - Attacker can’t guess what the value of canary will be
- Canary contains: “\0”, newline, linefeed, EOF
  - String functions like strcpy won’t copy beyond “\0”

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