CSE 484: Computer Security

Software Security: Buffer Overflow Attacks and More

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Announcements + Logistics

- Things Due:
  - Reading #1 today!
- Lab 1:
  - **Going out soon**
  - If you haven't filled out the partner survey, we can't help you with finding one!
- Office Hours:
  - TBA

- Next week:
  - Paper discussion at the beginning of class.

Learning new languages/tools/etc

- Security often requires rapidly acclimating to new tech
- You don’t need mastery
- Running into a system/language/construct you don’t know is expected, and expected to be hard!
- Don’t understand a term in class? Ask!

This week's paper

- "Low-level Software Security: Attacks and Defenses"

Last time…

- Threat models
  - Assets
  - Adversaries
  - Vulnerabilities
  - Threats
  - Risks

(SOME OF) SOFTWARE SECURITY

Bugs, Vulnerabilities, and Exploits

- Bug
  – Not working quite right
- Vulnerability
  – A malfunction that can be used for an adversary's goals
- Exploit
  – The mechanical set of operations to make use of a vulnerability

Adversarial Failures

- Software bugs are bad
  - Consequences can be serious
- Even worse when an intelligent adversary wishes to exploit them!
  - Intelligent adversaries: Force bugs into "worst possible" conditions/states
  - Intelligent adversaries: Pick their targets

Aside: The Weird Machine

- An exploit can also be considered a *program* for a *weird machine*
- If you are more formally-inclined, check out:
  - https://www.cs.dartmouth.edu/~sergey/wm/

Many types of vulnerability

- Pollev.com/dkohlbre
- Talk to your neighbors, define one you’ve heard of (or ask about one you don’t know!)

Memory Corruption Bugs

- Buffer overflows bugs: Big class of bugs
  - Normal conditions: Can sometimes cause systems to fail
  - Adversarial conditions: Attacker able to violate security of your system (control, obtain private information, ...)
- Stack, Heap both possibilities

A note on languages

- We're going to be assuming code is written in an *unsafe language*
  - Like C

- Fundamentally, we care about the executed binary
  - So the language is sometimes immaterial

BUFFER OVERFLOWS

A Bit of History: Morris Worm

- Worm was released in 1988 by Robert Morris
  - Graduate student at Cornell, son of NSA chief scientist
  - Convicted under Computer Fraud and Abuse Act,
    - 3 years probation and 400 hours of community service
- Worm was intended to propagate slowly and harmlessly measure the size of the Internet
- Due to a coding error, it created new copies as fast as it could and overloaded infected machines
- $10-100M worth of damage

Morris Worm and Buffer Overflow

- One of the worm's propagation techniques was a buffer overflow attack against a vulnerable version of `fingerd` on VAX systems
  - By sending special string to finger daemon, worm caused it to execute code creating a new worm copy

Overflows remain a common source of vulnerabilities and exploits today!

(Especially in embedded systems.)

Aside: Famous Internet Worms

- Morris worm (1988): overflow in `fingerd`
  - 6,000 machines infected
- CodeRed (2001): overflow in MS-IIS server
  - 300,000 machines infected in 14 hours
- SQL Slammer (2003): overflow in MS-SQL server
  - 75,000 machines infected in **10 minutes** (!!)
- Sasser (2005): overflow in Windows LSASS
  - Around 500,000 machines infected

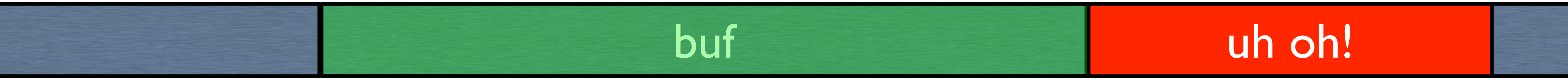
… And More

- Conficker (2008-09): overflow in Windows RPC
  – Around 10 million machines infected (estimates vary)
- Stuxnet (2009-10): several zero-day overflows + same Windows RPC overflow as Conficker
  – Windows print spooler service
  – Windows LNK shortcut display
  – Windows task scheduler
- Flame (2010-12): same print spooler and LNK overflows as Stuxnet
  – Targeted cyperespionage virus
- These days, worms are uncommon

Attacks on Memory Buffers

- Buffer is a pre-defined data storage area inside computer memory (stack or heap)
- Typical situation:
  - A function takes some input that it writes into a pre-allocated buffer.
  - The developer forgets to check that the size of the input isn't larger than the size of the buffer.
  - Uh oh.
    - "Normal" bad input: crash
    - "Adversarial" bad input : take control of execution

Stack Buffers

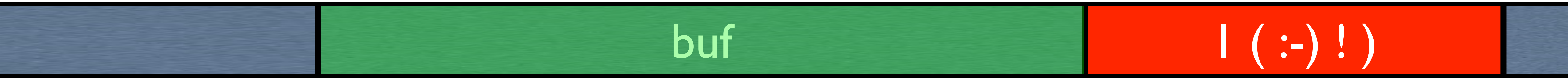


- Suppose Web server contains this function

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

- No bounds checking on strcpy()
- If str is longer than 126 bytes
  - Program may crash
  - Attacker may change program behavior

Example: Changing Flags



- Suppose Web server contains this function

```
void func(char *str) {
        byte auth = 0;
        char buf[126];
        ...
        strcpy(buf,str);
        ...
    }
```

- Authenticated variable non-zero when user has extra privileges
- Morris worm also overflowed a buffer to overwrite an authenticated flag in fingerd

Memory Layout

- Text region: Executable code of the program
- Heap: Dynamically allocated data
- Stack: Local variables, function return addresses; grows and shrinks as functions are called and return

What happens on function call?

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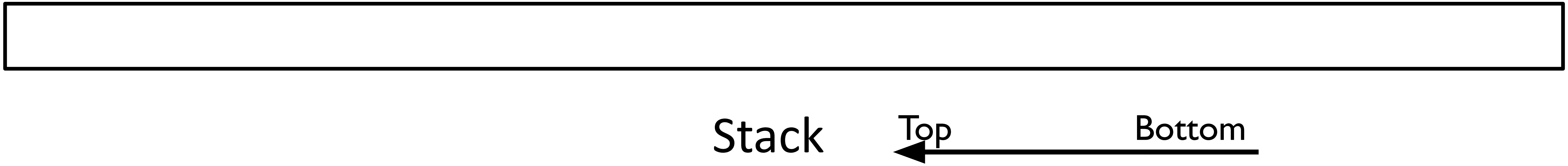


Stack Buffers

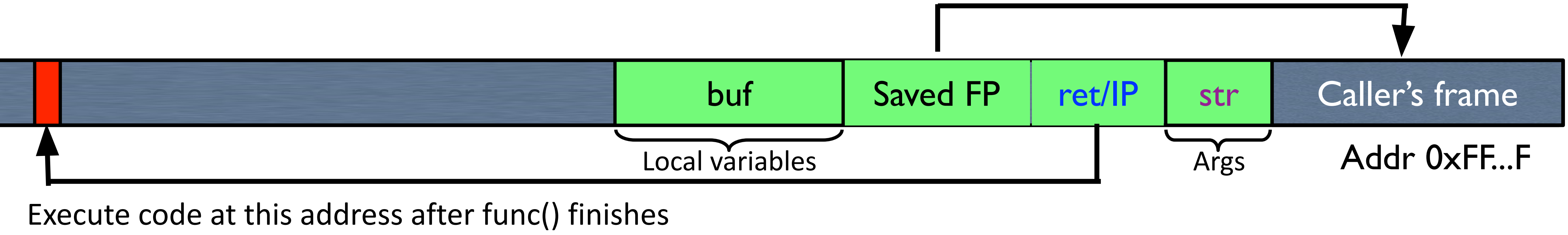
- Suppose Web server contains this function:

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

Allocate local buffer (126 bytes reserved on stack)

Copy argument into local buffer

- When this function is invoked, a new frame (activation record) is pushed onto the stack.



What if Buffer is Overstuffed?

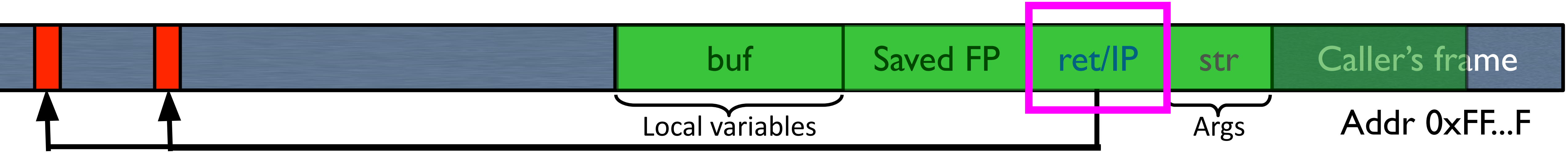
- Memory pointed to by str is copied onto stack…

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

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

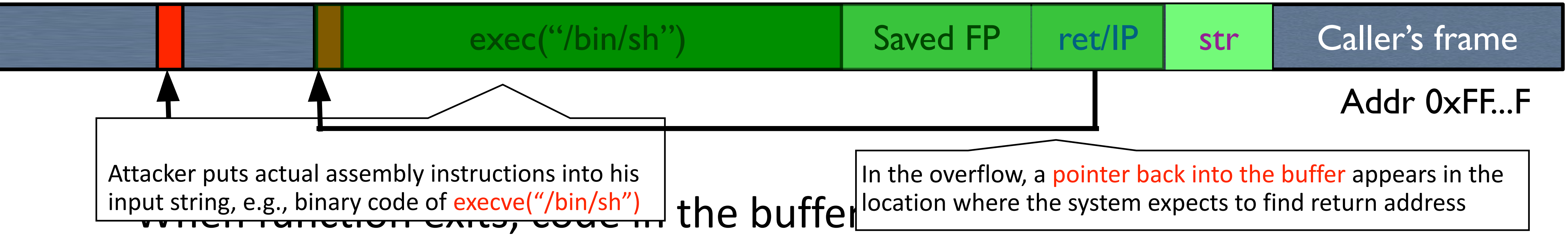
- If a string longer than 126 bytes is copied into buffer, it will overwrite adjacent stack locations.

This will be interpreted as return address!



Executing Attack Code

- Suppose buffer contains attacker-created string
  - For example, str points to a string received from the network as the URL



- When function exits, code in the buffer will be executed, giving attacker a shell **("shellcode")**
  - Root shell if the victim program is setuid root

Buffer Overflows Can Be Tricky…

- Overflow portion of the buffer must contain correct address of attack code in the RET position
  - The value in the RET position must point to the beginning of attack assembly code in the buffer
    - Otherwise application will (probably) crash with segfault
  - **Attacker must correctly guess in which stack position his/her buffer will be when the function is called**

Problem: No Bounds Checking

- strcpy does <u>not</u> check input size
  - strcpy(buf, str) simply copies memory contents into buf starting from *str until "\0" is encountered, ignoring the size of area allocated to buf
- Many C library functions are unsafe
  - strcpy(char *dest, const char *src)
  - strcat(char *dest, const char *src)
  - gets(char *s)
  - scanf(const char *format, …)
  - printf(const char *format, …)

Does Bounds Checking Help?

- strncpy(char *dest, const char *src, size_t n)
  - If strncpy is used instead of strcpy, no more than n characters will be copied from *src to *dest
    - Programmer has to supply the right value of n
- Potential overflow in htpasswd.c (Apache 1.3):

```
strcpy(record,user);
strcat(record,":");
strcat(record,cpw);
```

Copies username ("user") into buffer ("record"), then appends ":" and hashed password ("cpw")

- Published fix:

```
strncpy(record,user,MAX_STRING_LEN-1);
strcat(record,":")
strncat(record,cpw,MAX_STRING_LEN-1);
```

Does Bounds Checking Help? Pollev Discussion Time

- strncpy(char *dest, const char *src, size_t n)
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- Published fix:

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strncpy(record,user,MAX_STRING_LEN-1);
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```

Consider these changes

Apache 1.3 had the following code:

```
strcpy(record, user);
strcat(record, ”:”);
strcat(record, cpw);
```

The published fix:

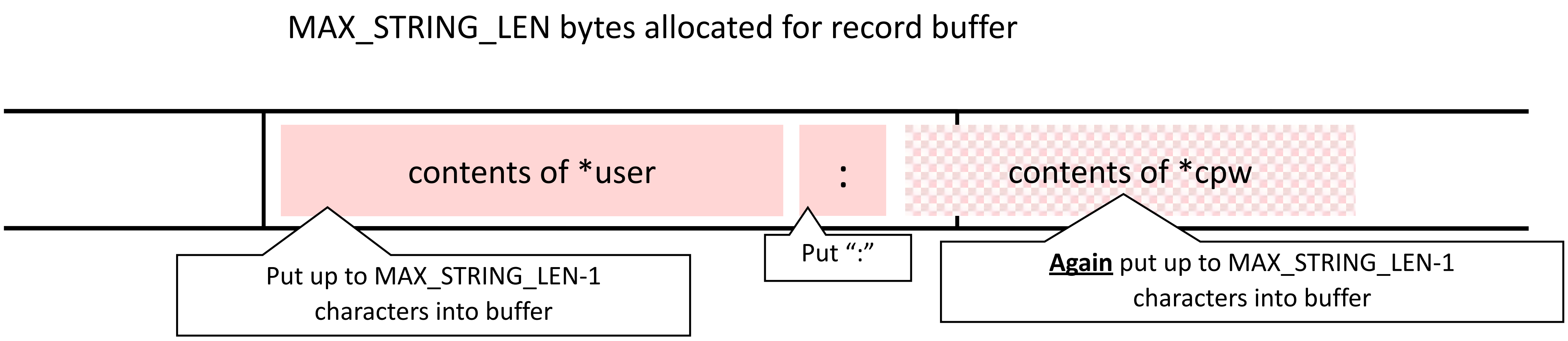
```
strncpy(record, user, MAX_STRING_LEN-1);
strcat(record,”:”);
strncat(record, cpw, MAX_STRING_LEN-1);
```

Is this fix good? If so, why? If not, why not?

Misuse of strncpy in htpasswd "Fix"

- Published "fix" for Apache htpasswd overflow:

```
strncpy(record,user,MAX_STRING_LEN-1);
strcat(record,":")
strncat(record,cpw,MAX_STRING_LEN-1);
```



Consider this homebrewed copy:

```
void mycopy(char *input) {
   char buffer[512];
   int i;

   for (i=0; i<=512; i++) {
      buffer[i] = input[i];
   }

}
```

Consider this homebrewed copy:

```
void mycopy(char *input) {
   char buffer[512];
   int i;

   for (i=0; i<=512; i++) {
      buffer[i] = input[i];
   }

}
```

This will copy **513** characters into buffer. Oops!

Off-By-One Overflow

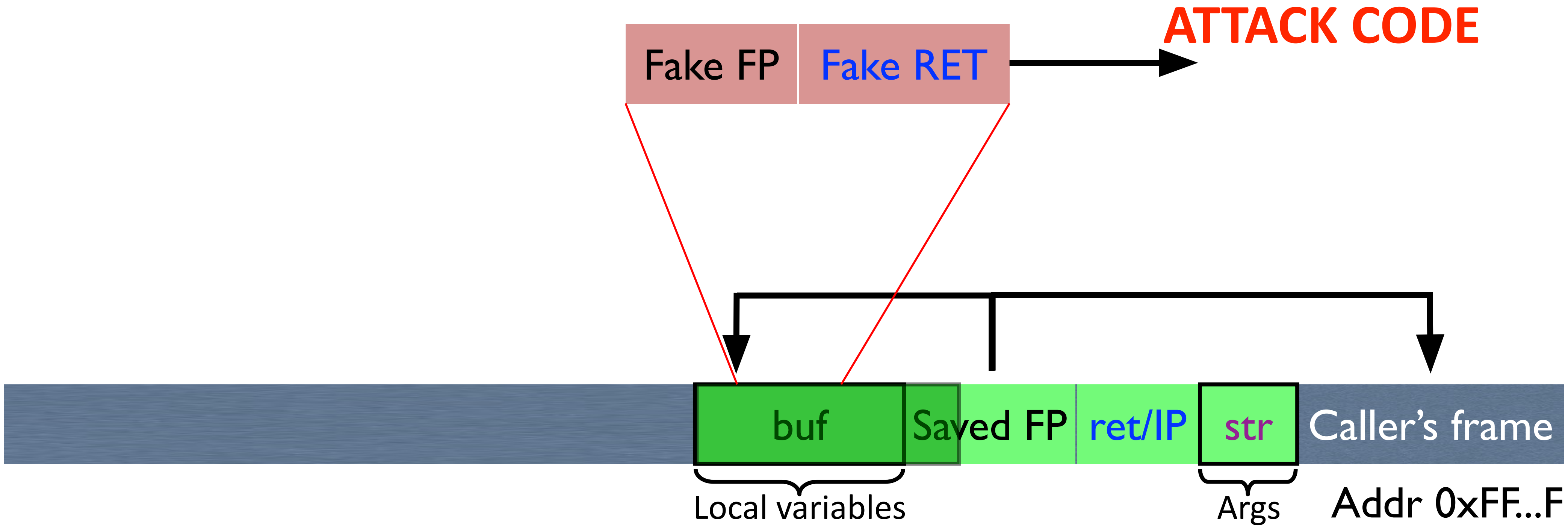
- Home-brewed range-checking string copy

```
 void mycopy(char *input) {
     char buffer[512]; int i;

     for (i=0; i<=512; i++)
         buffer[i] = input[i];
}
void main(int argc, char *argv[]) {
     if (argc==2)
        mycopy(argv[1]);
}
```

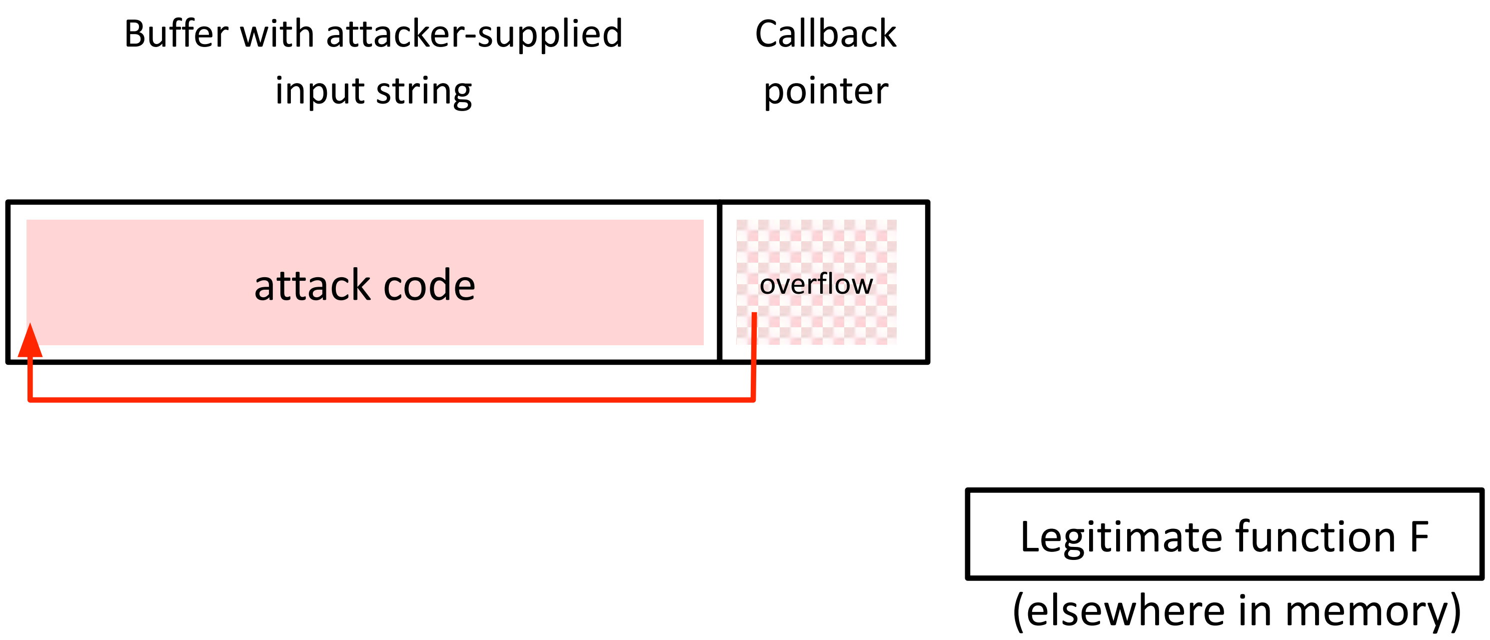
- 1-byte overflow: can't change RET, but can change pointer to previous stack frame…

Frame Pointer Overflow



Another Variant: Function Pointer Overflow

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



A note on assembly

- You will need to read some assembly
- Its all x86_32 assembly
- There are two syntaxes (I'm sorry)

Shall we do one live?

Other Overflow Targets

- Format strings in C
  - We'll walk through this one today
- Heap management structures used by malloc()
  - Techniques have changed wildly over time

- 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 */

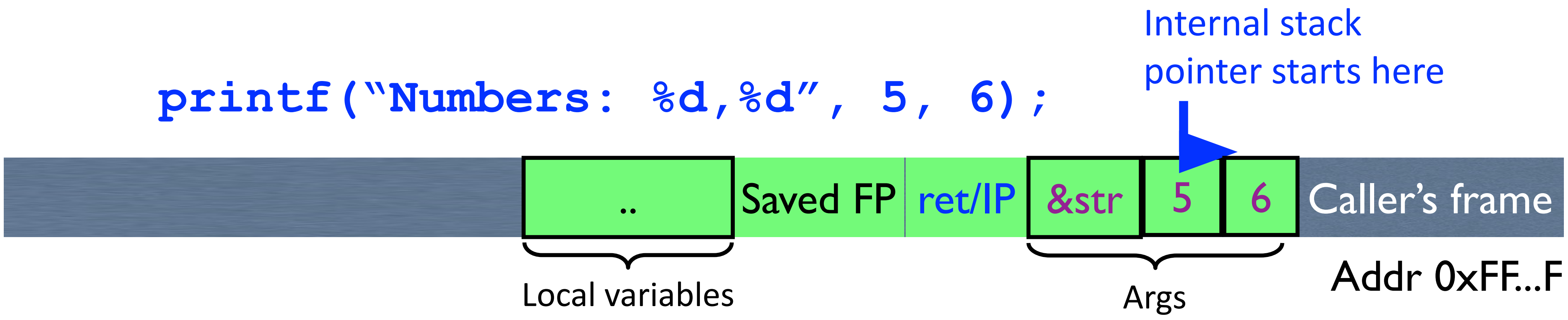
     for (char* p = format; *p != '\0'; p++) {
        if (*p == '%') {
           switch (*++p) {
              case 'd':
                 i = va_arg(ap, int); break;
              case 's':
                 s = va_arg(ap, char*); break;
              case 'c':
                 c = va_arg(ap, char); break;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

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

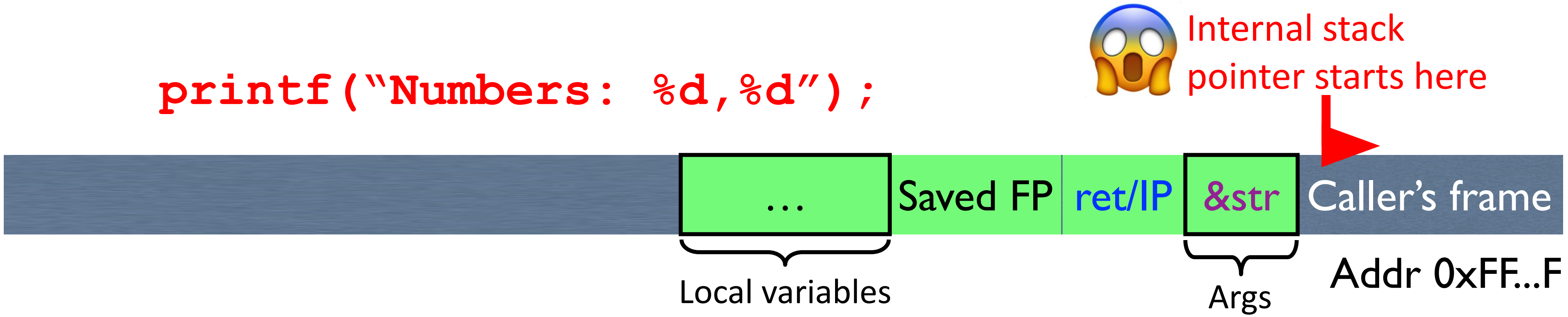
This is simplified code, e.g., handles %d but not %10d

Closer Look at the Stack

```
printf("Numbers: %d,%d", 5, 6);
```




```
printf("Numbers: %d,%d");
```



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);
```

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 % ???

Break!

- Back at:

- Think about varargs (printf) calls…

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

Try This At Home

```
#include <stdio.h>

int main()
{
    char *buf = "%08x\t%08x\t%08x\t%08x\n";
    printf(buf);
}
```

Compiled with gcc

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

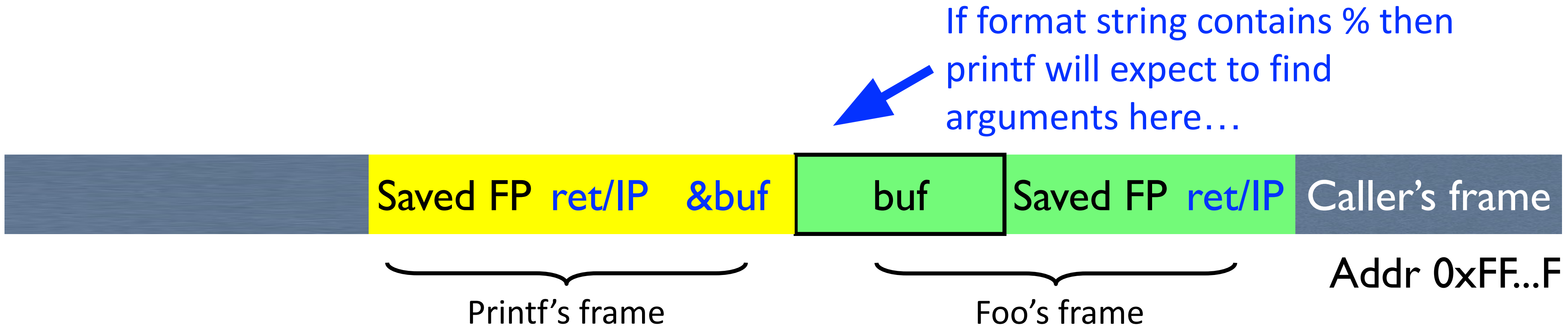
- Printf takes a variable number of arguments
  - E.g., printf("Here's an int: %d", 10);
- Assumptions about input can lead to trouble
  - E.g., printf(buf) when buf="Hello world" versus when buf="Hello world %d"
  - Can be used to advance printf's internal stack pointer
  - Can read memory
    - E.g., 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

“Weird Machines”

- Way of thinking about exploits (the best way ☺️)
- Treat each discrete side-effect as an ‘instruction’
- Synthesize a ‘program’ from these instructions
- This is now your exploit!

How Can We Attack This?

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

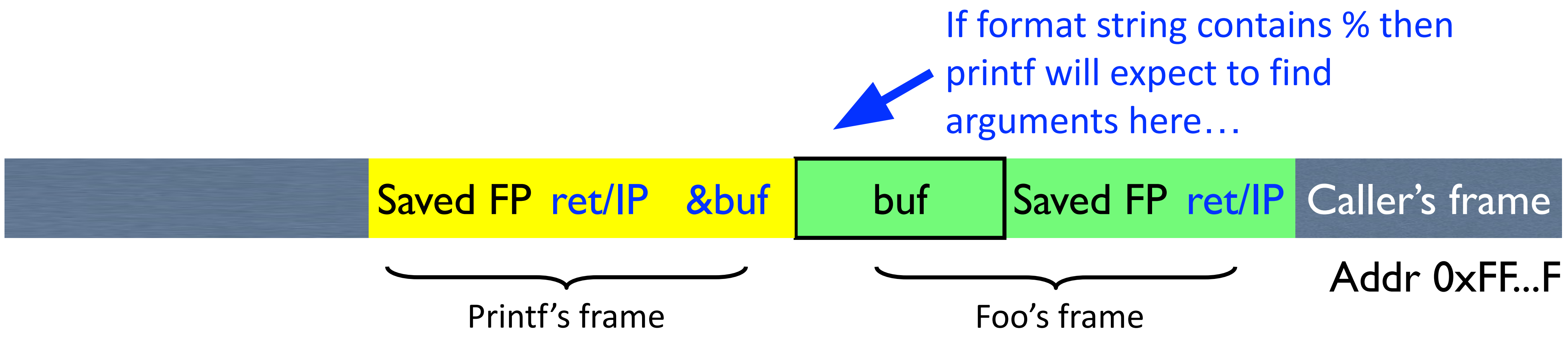


What should the string returned by readUntrustedInput() contain?

Different compilers / compiler options / architectures might vary

Pollev and Discussion Time

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

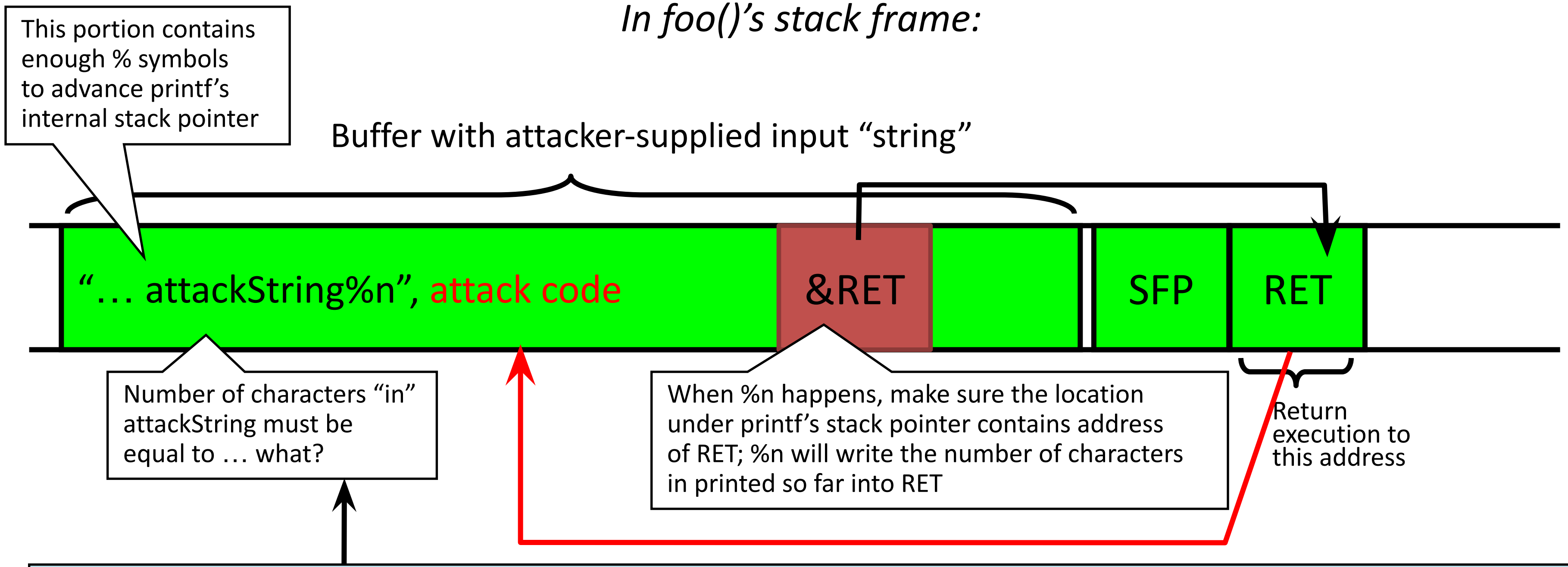


What should the string returned by readUntrustedInput() contain?

Different compilers / compiler options / architectures might vary

Using %n to Overwrite Return Address

In foo()'s stack frame:



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)

Lab 1 will go out soon

- Significant help from doing these readings:
  - Smashing the Stack for Fun and Profit
  - Exploiting Format String Vulnerabilities
- I'll go through partner requests shortly
- Live example of sploit0 next week at the beginning of class