Theory and Practice of Secure Systems

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http://www.cs.utexas.edu/~shmat/courses/cs380s/

Course Logistics

- Lectures: Tuesday and Thursday, 2-3:30pm
- Instructor: Vitaly Shmatikov
  - Office: TAYLOR 4.115C
  - Office hours: Tuesday, 3:30-4:30pm (after class)
  - Open door policy – don't hesitate to stop by!
- TA: Rolf Rolles
  - Office hours: Wed, 1-2pm in ENS 31NQ, desk #4
- No textbook; we will read a fair number of research papers
- Watch the course website for lecture notes, assignments, and reference materials

Grading

- Homeworks: 40% (4 homeworks, 10% each)
  - Homework problems will be based on research papers
- Midterm: 15%
- Project: 45%
  - Computer security is a contact sport – the best way to understand it is to get your hands dirty
  - Projects can be done individually or in small teams
  - Project proposal due in late September
    - More details later
  - I will provide a list of potential project ideas, but don't hesitate to propose your own

Prerequisites

- Basic understanding of operating systems and memory management
  - At the level of an undergraduate OS course
- Some familiarity with cryptography is helpful
  - Cryptographic hash functions, public-key and symmetric cryptosystems
- Undergraduate course in complexity and/or theory of computation
- Ask me if you are not sure whether you are qualified to take this course

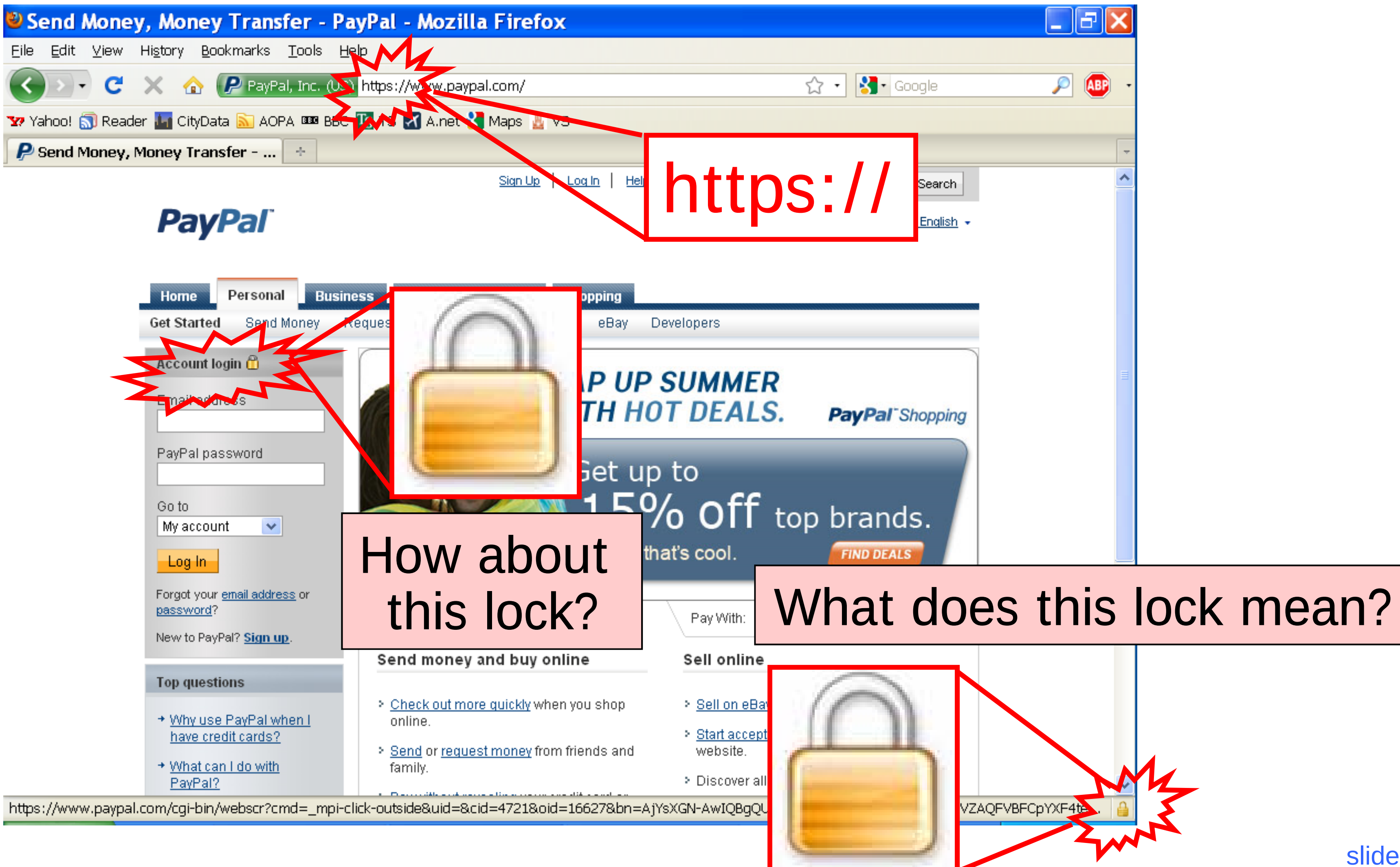
What This Course is Not About

- Not a comprehensive course on computer security
- Not a course on cryptography
  - We will cover some crypto when talking about provable security
- Not a seminar course
  - We will read and understand state-of-the-art research papers, but you'll also have to do some actual work ☺
- Focus on several specific research areas
  - Mixture of theory and systems (very unusual!)
- You have a lot of leeway in picking your project

Correctness vs. Security

- Program or system correctness:
  program satisfies specification
  - For reasonable input, get reasonable output
- Program or system security:
  program properties preserved in face of attack
  - For <u>un</u>reasonable input, output not completely disastrous
- Main difference: adversary
  - Active interference from a malicious agent
  - It is very difficult to come up with a model that captures <u>all</u> possible adversarial actions
    - Look at how adversary is modeled in “systems” and in “theory”

The Meaning of the Lock



Theme #1: Software Security

- Vulnerabilities and attacks
  - Memory corruption attacks
  - Access control violations and concurrency attacks
  - Web security: browsers and Web applications
  - Side-channel attacks (if time permits): timing, power
- Detecting and containing malicious behavior
  - Isolation, reference monitors, intrusion detection
- Preventing attacks
  - Memory protection
  - Applications of static analysis to security
  - Information flow control

Theme #2: Privacy

- Theoretical models
  - Semantic security
  - Secure multi-party computation
  - Introduction to zero knowledge
  - Key concept: provable security
- Data privacy
  - Query auditing and randomization
  - Privacy-preserving data mining
  - Differential privacy

And Now
Our Feature Presentation

Famous Internet Worms

- Morris worm (1988): overflow in fingerd
  - 6,000 machines infected (10% of existing Internet)
- 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 (2004): overflow in Windows LSASS
  - Around 500,000 machines infected

Responsible for user authentication in Windows

- Conficker (2008-09): overflow in Windows Server
  - Around 10 million machines infected (estimates vary)

Why Are We Insecure?

[Chen et al. 2005]

- 126 CERT security advisories (2000-2004)
- Of these, 87 are memory corruption vulnerabilities
- 73 are in applications providing remote services
  - 13 in HTTP servers, 7 in database services, 6 in remote login services, 4 in mail services, 3 in FTP services
- Most exploits involve illegitimate control transfers
  - Jumps to injected attack code, return-to-libc, etc.
  - Therefore, most defenses focus on control-flow security
- But exploits can also target configurations, user data and decision-making values

Memory Exploits

- Buffer is a data storage area inside computer memory (stack or heap)
  - Intended to hold pre-defined amount of data
  - If executable code is supplied as “data”, victim’s machine may be fooled into executing it
    - Code will self-propagate or give attacker control over machine
- Attack can exploit <u>any</u> memory operation
  - Pointer assignment, format strings, memory allocation and de-allocation, function pointers, calls to library routines via offset tables

Stack Buffers

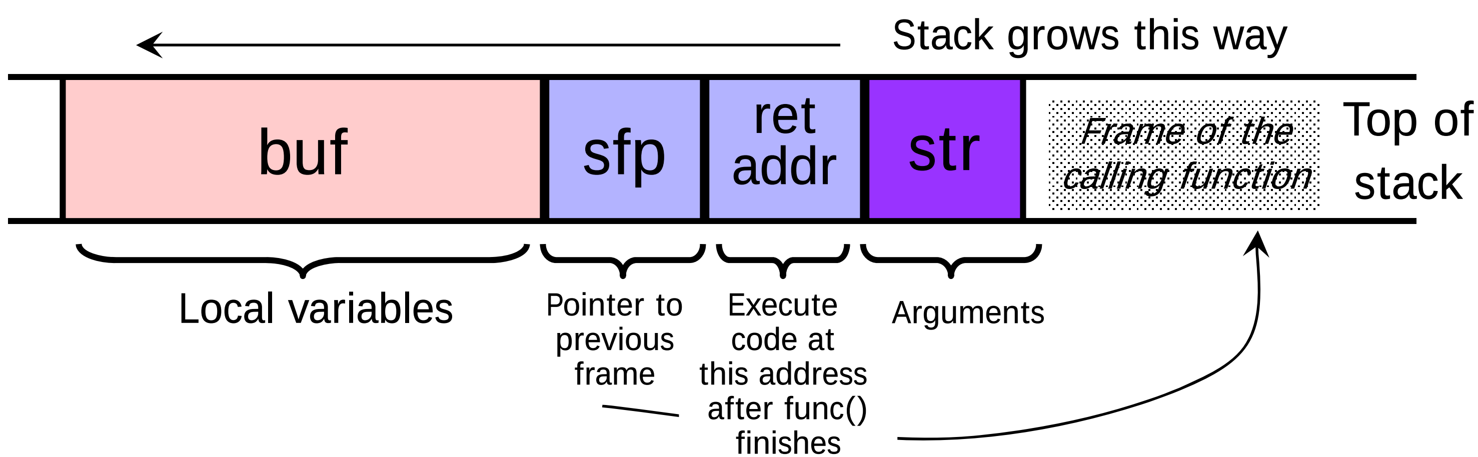
- Suppose Web server contains this function

```
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 is pushed onto the stack



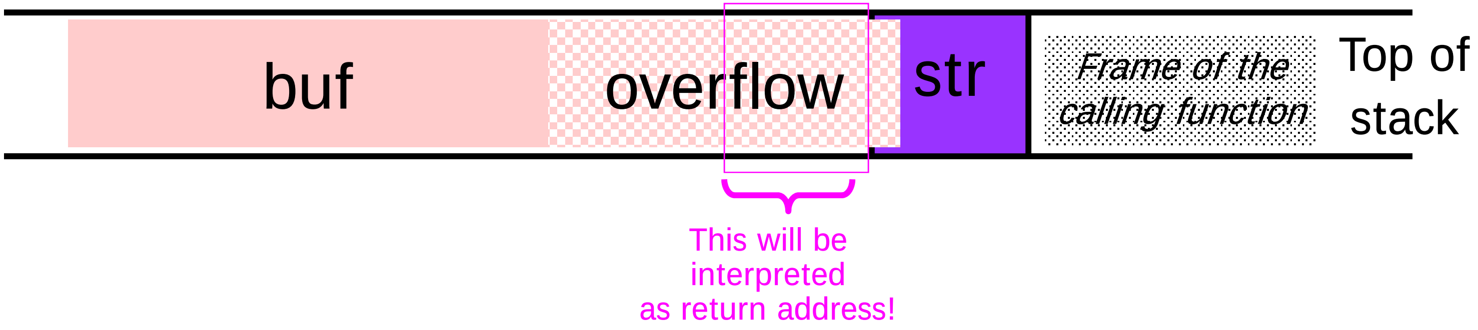
What If Buffer Is Overstuffed?

- Memory pointed to by str is copied onto stack...

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

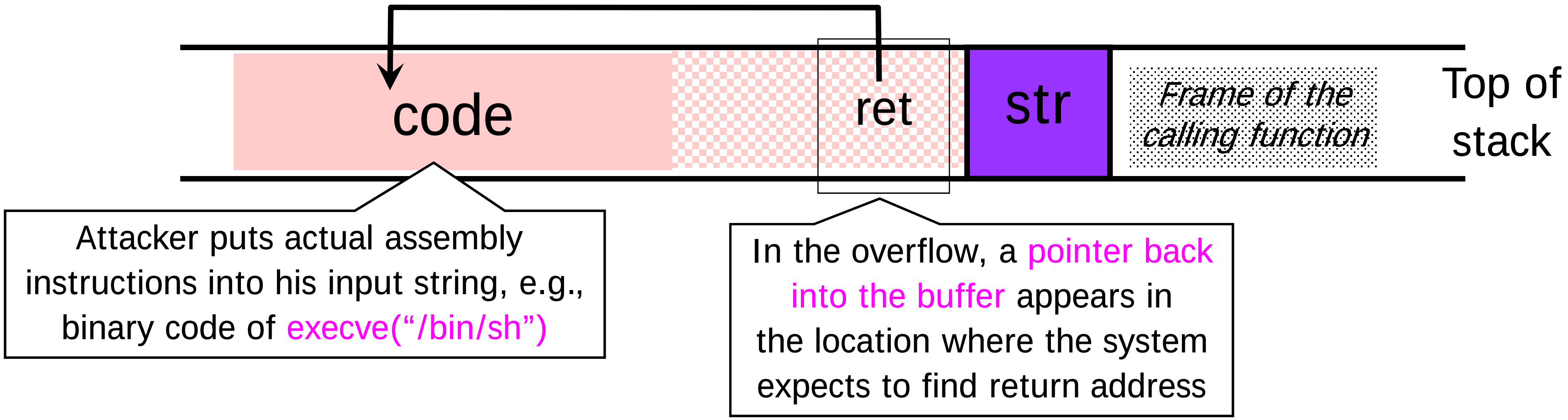
strcpy does not check whether the string at *str contains fewer than 126 characters

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



Executing Attack Code

- Suppose buffer contains attacker-created string
  - For example, *str contains a string received from the network as input to some network service daemon



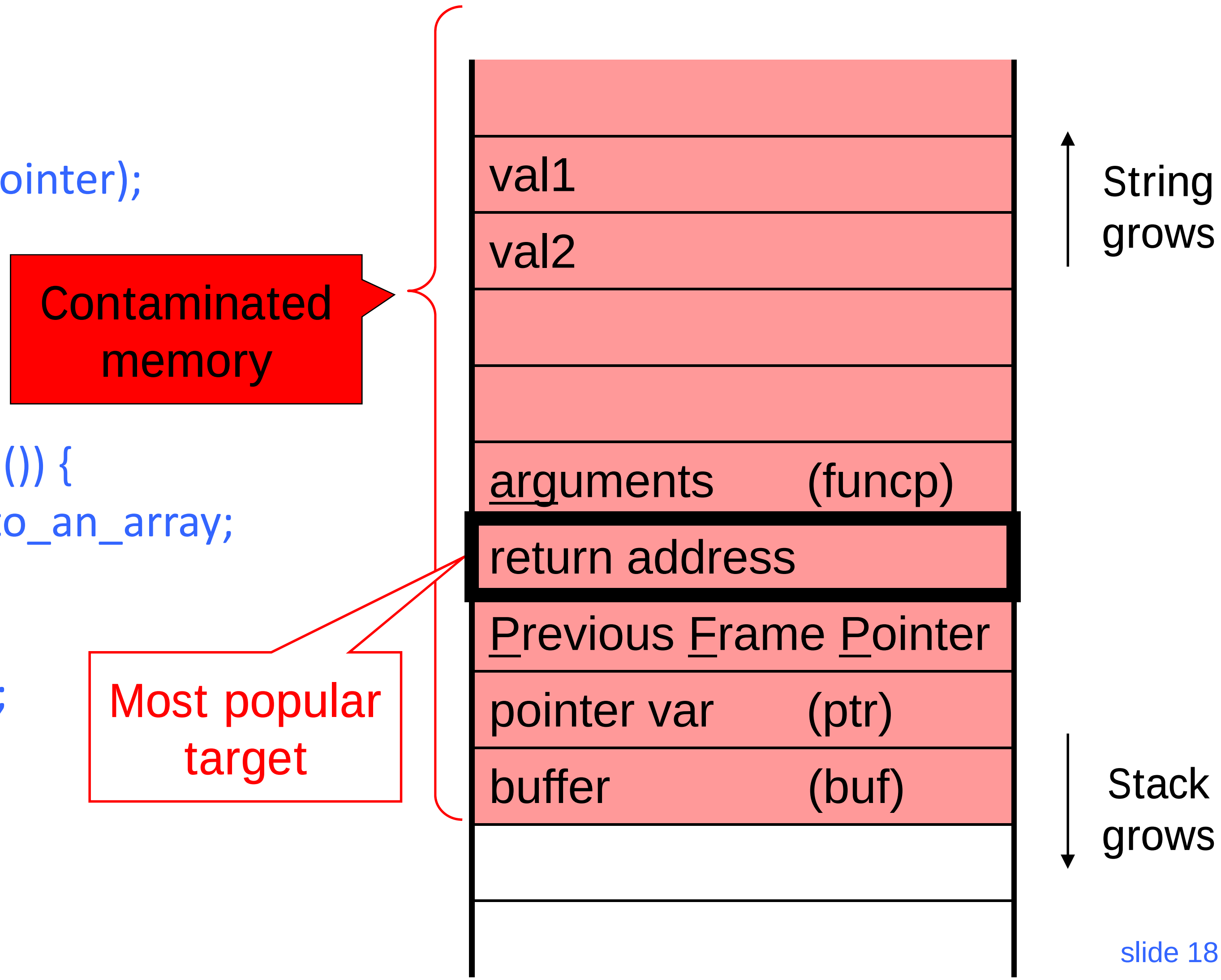
- When function exits, code in the buffer will be executed, giving attacker a shell
  - Root shell if the victim program is setuid root

Buffer Overflow Issues

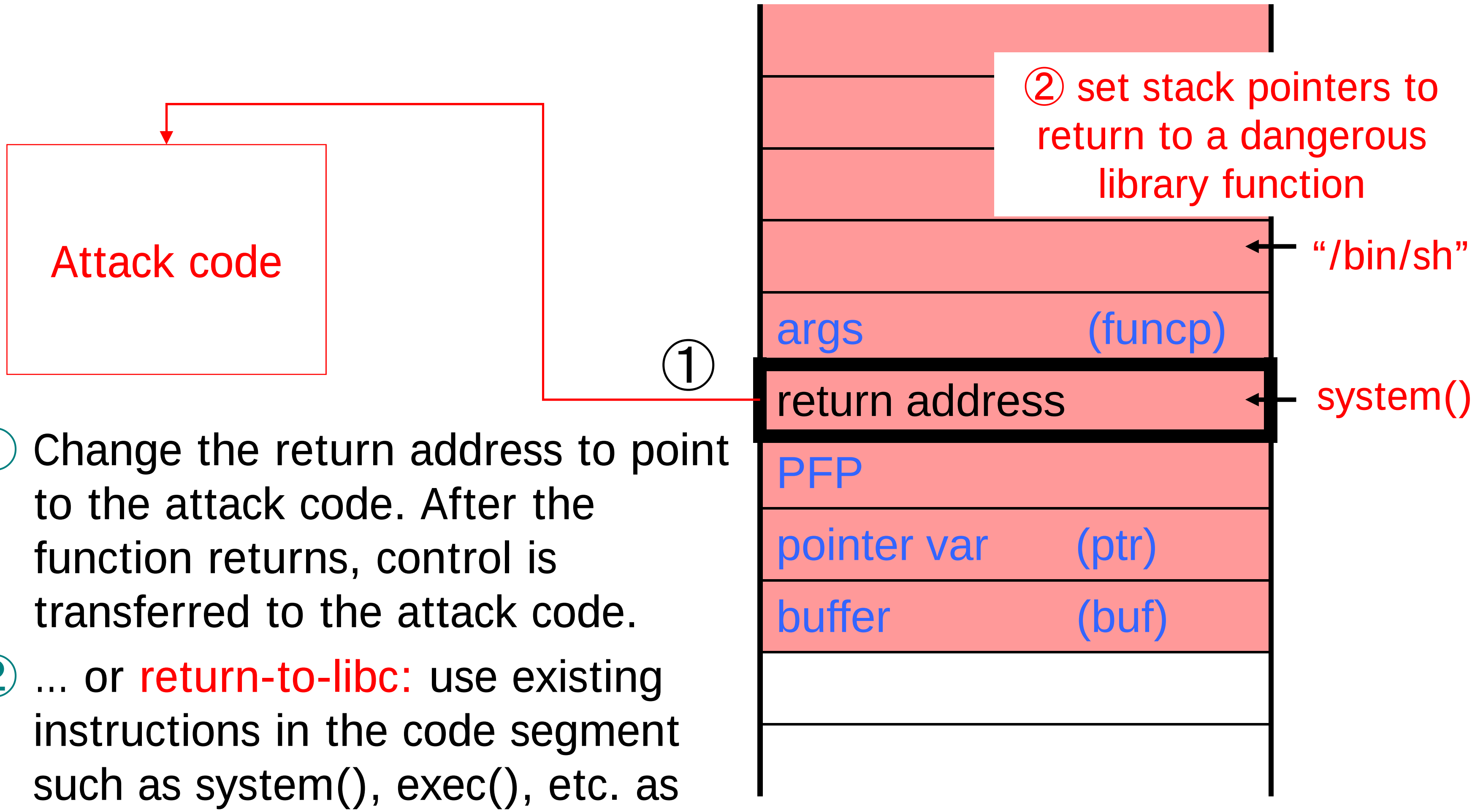
- Basic exploit: executable attack code is stored on stack, in the buffer containing attacker's string
  - Stack memory usually contains only data, but...
- For the basic exploit, overflow portion of the buffer must contain correct address of attack code in the RET position
  - The value in the RET position must point to the beginning of attack assembly code in the buffer
    - Otherwise application will crash with segmentation violation
  - Attacker must correctly guess in which stack position his buffer will be when the function is called

Stack Corruption: General View

```
int bar (int val1) {
   int  val2;
   foo (a_function_pointer);
}

int foo (void (*funcp)()) {
   char* ptr = point_to_an_array;
   char buf[128];
   gets (buf);
   strncpy(ptr, buf, 8);
   (*funcp)();
}
```



Attack #1: Return Address



① Change the return address to point to the attack code. After the function returns, control is transferred to the attack code.

② ... or return-to-libc: use existing instructions in the code segment such as system(), exec(), etc. as the attack code.

Problem: No Range 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 Range 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")

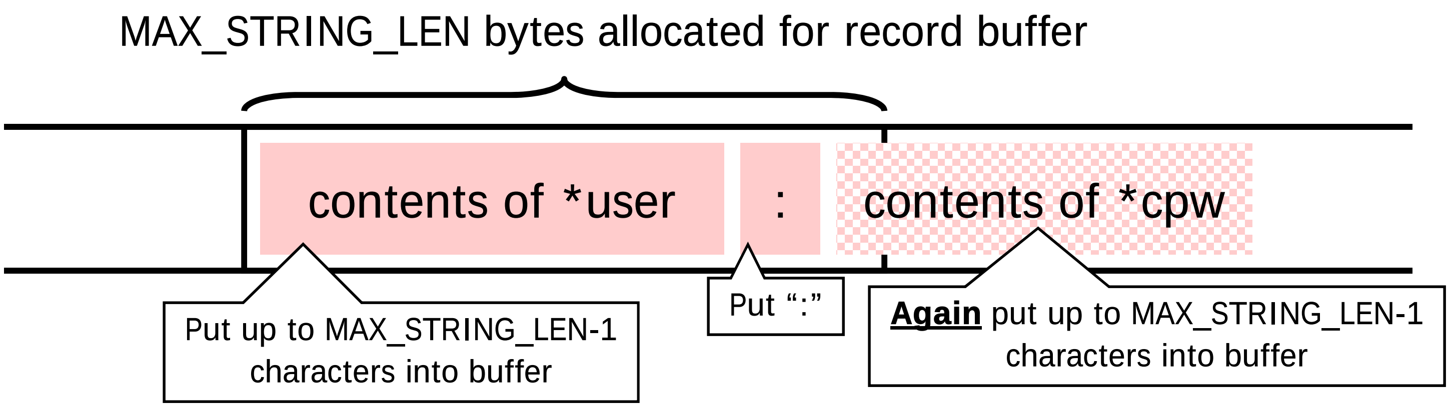
- Published "fix" (do you see the problem?)

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

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); …
```



Off-By-One Overflow

◆ Home-brewed range-checking string copy

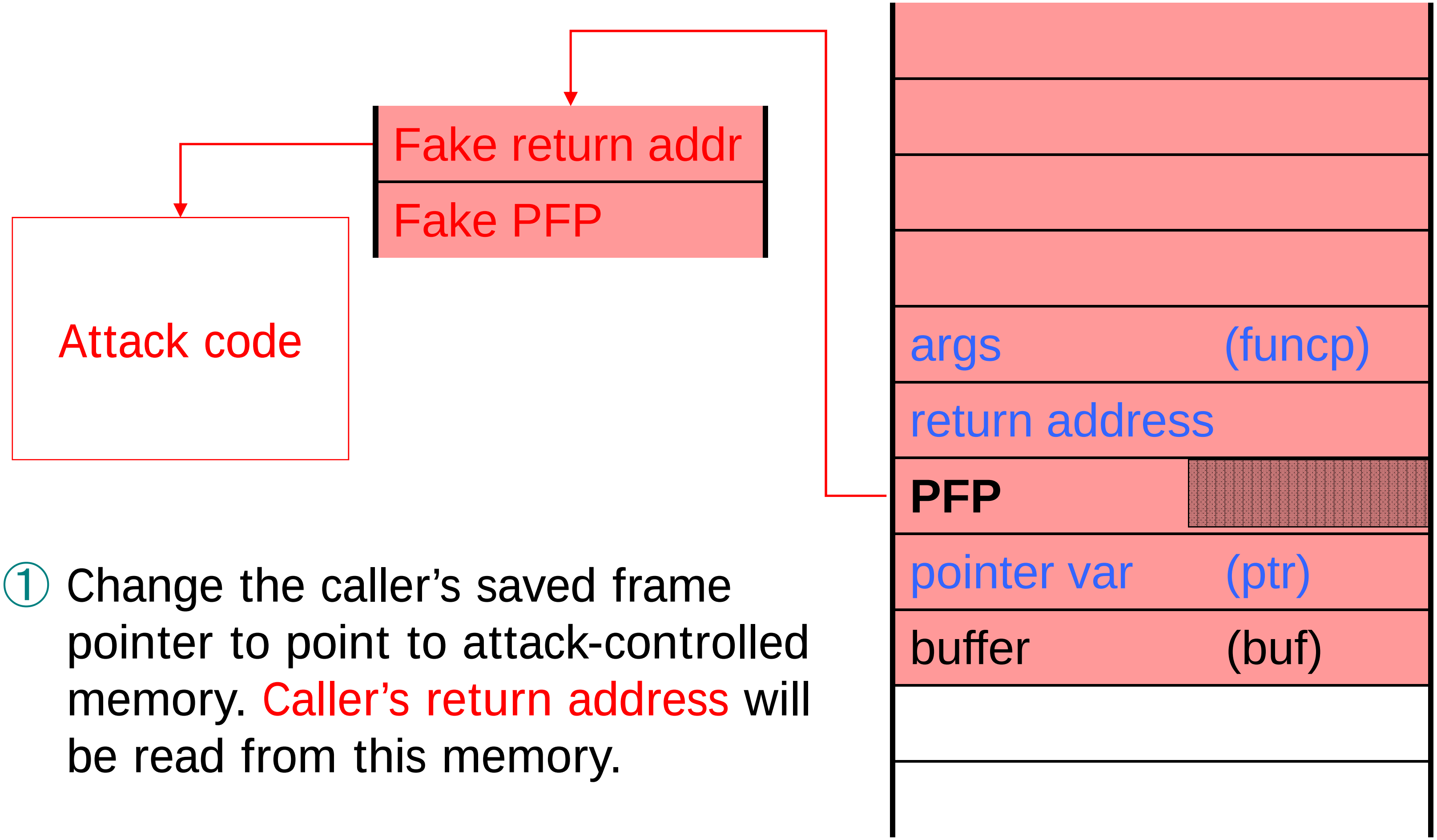
```
void notSoSafeCopy(char *input) {
        char buffer[512]; int i;

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

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

◆ 1-byte overflow: can't change RET, but can change pointer to <u>previous</u> stack frame

- On little-endian architecture, make it point into buffer
- RET for <u>previous</u> function will be read from buffer!

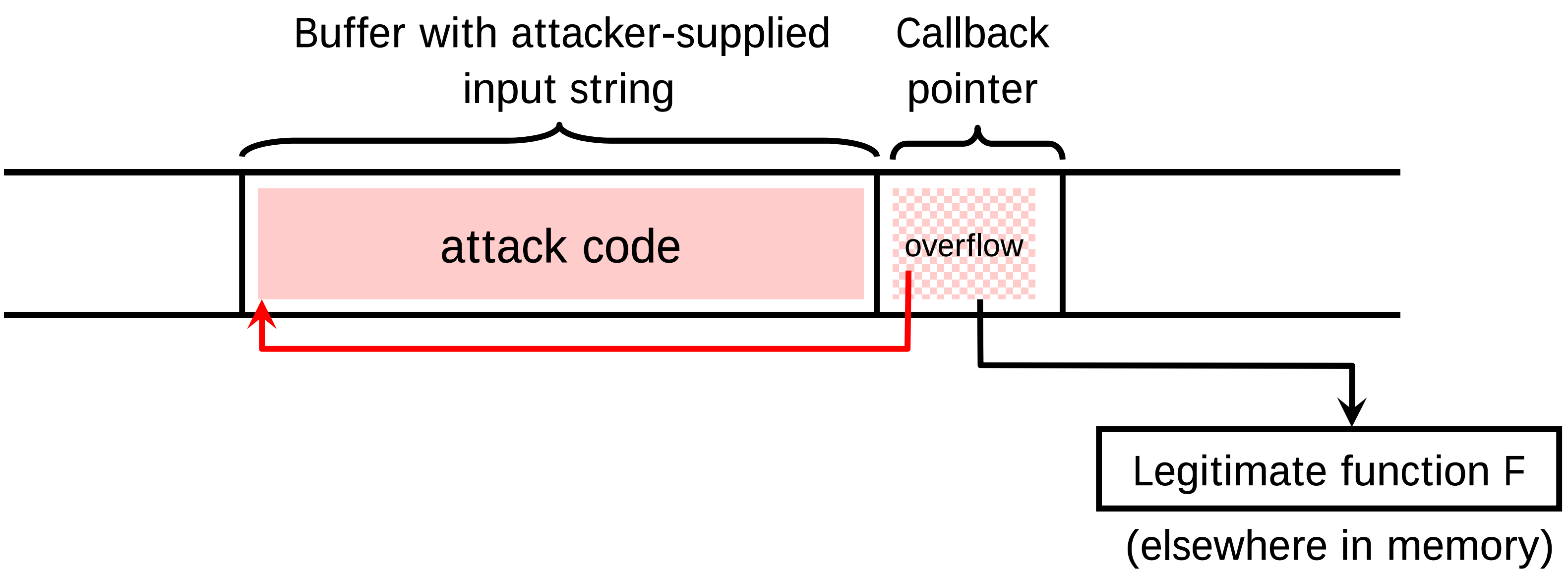
Attack #2: Frame Pointer



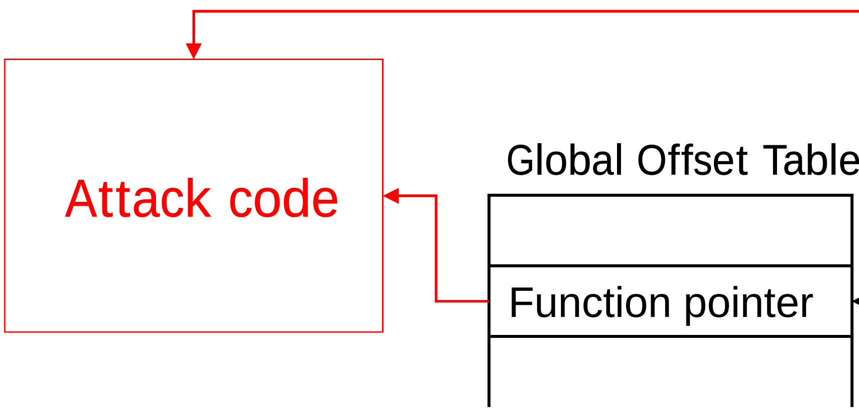
① Change the caller's saved frame pointer to point to attack-controlled memory. Caller's return address will be read from this memory.

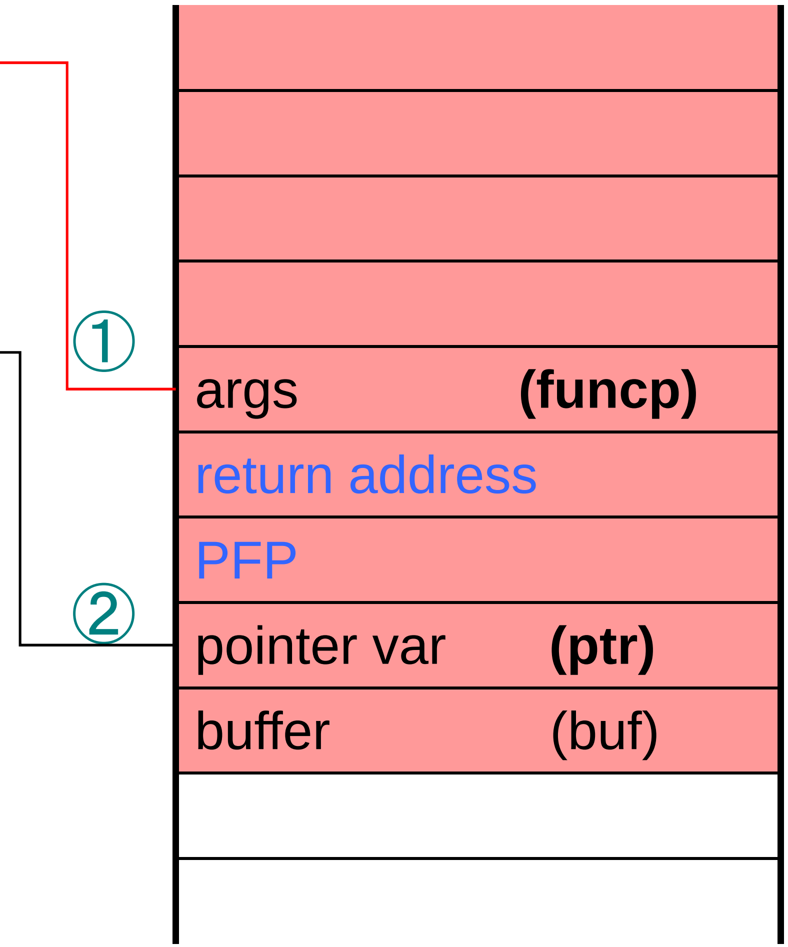
Function Pointer Overflow

- 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)(...)



Attack #3: Pointer Variables





① Change a function pointer to point to the attack code.

② Any memory, even outside the stack, can be modified by the statement that stores a value into the compromised pointer.

```
strncpy(ptr, buf, 8);
*ptr = 0;
```

Heap Overflow

- Overflowing buffers on heap can change pointers that point to important data
  - Sometimes can also transfer execution to attack code
  - Can cause program to crash by forcing it to read from an invalid address (segmentation violation)
- Illegitimate privilege elevation: if program with overflow has sysadm/root rights, attacker can use it to write into a normally inaccessible file
  - For example, replace a filename pointer with a pointer into buffer location containing name of a system file
    - Instead of temporary file, write into AUTOEXEC.BAT

Start Thinking About a Project

- A few ideas are on the course website
- Several ways to go about it
  - Build a tool that improves software security
    - Analysis, verification, attack detection, attack containment
  - Apply an existing tool to a real-world system
  - Demonstrate feasibility of some attack
  - Do a substantial theoretical study
  - Invent something of your own
- Start forming teams and thinking about potential topics early on!

Some Ideas (More Later)

- Sandboxes and reference monitors
- Enforcing security policies with transactions
- E-commerce protocols
  - Micropayment schemes, secure electronic transactions
- Wireless security
  - Ad-hoc routing, WiFi security, location security
- Enforcing legally mandated privacy policies
- Security for voice-over-IP
- Choose something that interests you!

Reading Assignment

- Read "Smashing the Stack for Fun and Profit" and "Blended Attacks"
  - Links on the course website
- For better understanding, read other reference materials on buffer overflow on the course site
  - Sotirov and Dowd's "Bypassing Browser Memory Protections"
  - This will help when we talk about defenses later on