CSC 405
Computer Security

Control Hijacking Attacks

Alexandros Kapravelos
akaprav@ncsu.edu

Attacker's mindset

- Take control of the victim's machine
  - Hijack the execution flow of a running program
  - Execute arbitrary code
- Requirements
  - Inject attack code or attack parameters
  - Abuse vulnerability and modify memory such that control flow is redirected
- Change of control flow
  - alter a code pointer (i.e., value that influences program counter)
  - change memory region that should not be accessed

Buffer Overflows

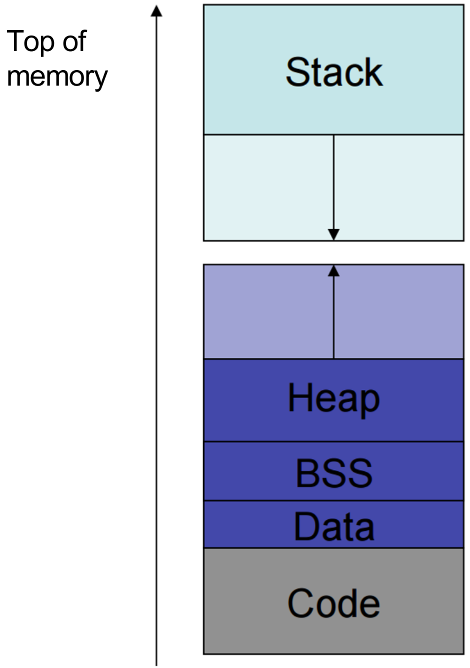
- Result from mistakes done while writing code
  - coding flaws because of
    - unfamiliarity with language
    - ignorance about security issues
    - unwillingness to take extra effort
- Often related to particular programming language
- Buffer overflows
  - mostly relevant for C / C++ programs
  - not in languages with automatic memory management
    - dynamic bounds checks (e.g., Java)
    - automatic resizing of buffers (e.g., Perl)

Buffer Overflows

- One of the most used attack techniques
- Advantages
  - very effective
    - attack code runs with privileges of exploited process
  - can be exploited locally and remotely
    - interesting for network services
- Disadvantages
  - architecture dependent
    - directly inject assembler code
  - operating system dependent
    - use of system calls
  - some guesswork involved (correct addresses)

Process memory regions

- Stack segment
  - local variables
  - procedure calls
- Data segment
  - global initialized variables (data)
  - global uninitialized variables (bss)
  - dynamic variables (heap)
- Code (Text) segment
  - program instructions
  - usually read-only



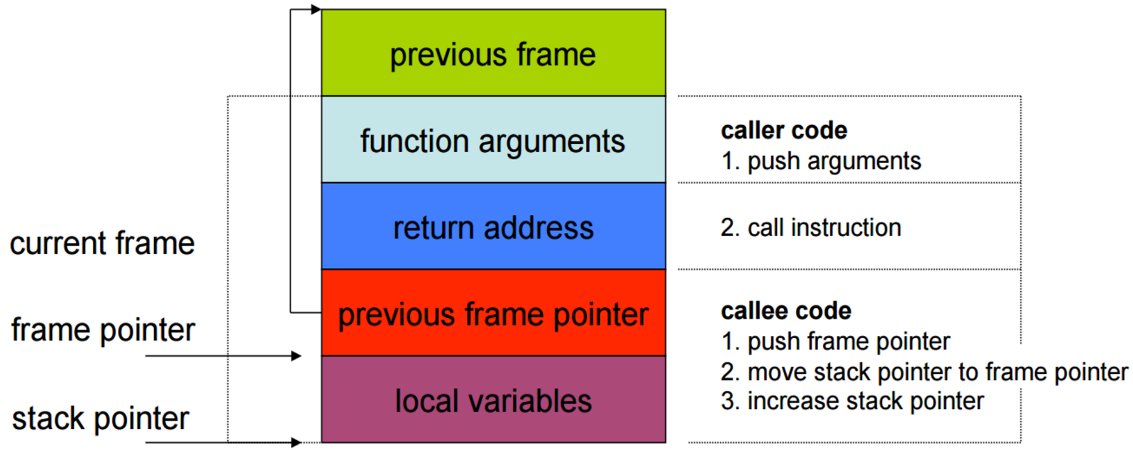
Overflow types

- Overflow memory region on the stack
  - overflow function return address
  - overflow function frame (base) pointer
  - overflow longjmp buffer
- Overflow (dynamically allocated) memory region on the heap
- Overflow function pointers
  - stack, heap, BSS

Stack

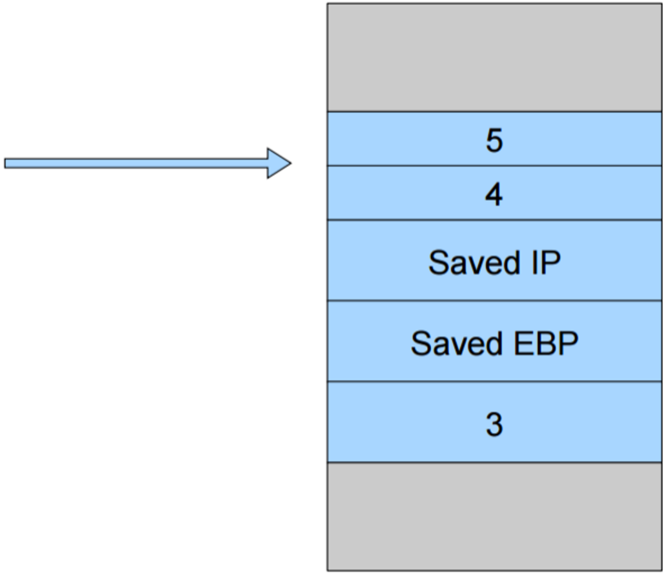
- Usually grows towards smaller memory addresses
  - Intel, Motorola, SPARC, MIPS
- Processor register points to top of stack
  - stack pointer – SP
  - points to last stack element or first free slot
- Composed of frames
  - pushed on top of stack as consequence of function calls
  - address of current frame stored in processor register
    - frame/base pointer – FP
  - used to conveniently reference local variables

Stack


previous frame
function arguments
return address
previous frame pointer
local variables
current frame
frame pointer
stack pointer
caller code
1. push arguments
2. call instruction
callee code
1. push frame pointer
2. move stack pointer to frame pointer
3. increase stack pointer

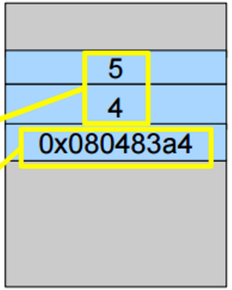
Procedure Call

```
int foo(int a, int b)
{
   int i = 3;

   return (a + b) * i;
}

int main()
{
   int e = 0;
   e = foo(4, 5);
   printf("%d", e);
}
```



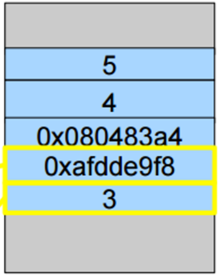
A Closer Look

```
(gdb) disas main
Dump of assembler code for function main:
0x0804836d <main+0>:    push   %ebp
0x0804836e <main+1>:    mov    %esp,%ebp
0x08048370 <main+3>:    sub    $0x18,%esp
0x08048373 <main+6>:    and    $0xfffffff0,%esp
0x08048376 <main+9>:    mov    $0x0,%eax
0x0804837b <main+14>:   add    $0xf,%eax
0x0804837e <main+17>:   add    $0xf,%eax
0x08048381 <main+20>:   shr    $0x4,%eax
0x08048384 <main+23>:   shl    $0x4,%eax
0x08048387 <main+26>:   sub    %eax,%esp
0x08048389 <main+28>:   movl   $0x0,0xfffffffc(%ebp)
0x08048390 <main+35>:   movl   $0x5,0x4(%esp)
0x08048398 <main+43>:   movl   $0x4,(%esp)
0x0804839f <main+50>:   call   0x8048354 <foo>
0x080483a4 <main+55>:   mov    %eax,0xfffffffc(%ebp)
```



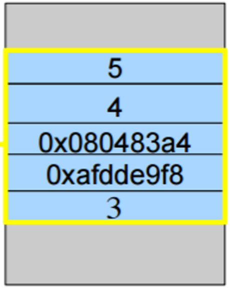
A Closer Look

```
(gdb) breakpoint foo
Breakpoint 1 at 0x804835a
(gdb) run
Starting program: ./test1
Breakpoint 1, 0x0804835a in foo ()
(gdb) disas
Dump of assembler code for function foo:
0x08048354 <foo+0>:     push   %ebp
0x08048355 <foo+1>:     mov    %esp,%ebp
0x08048357 <foo+3>:     sub    $0x10,%esp
0x0804835a <foo+6>:     movl   $0x3,0xfffffffc(%ebp)
0x08048361 <foo+13>:    mov    0xc(%ebp),%eax
0x08048364 <foo+16>:    add    0x8(%ebp),%eax
0x08048367 <foo+19>:    imul   0xfffffffc(%ebp),%eax
0x0804836b <foo+23>:    leave
0x0804836c <foo+24>:    ret
End of assembler dump.
(gdb)
```



The foo Frame

```
(gdb) stepi
0x08048361 in foo ()
(gdb) x/12wx $ebp-16
0xaf9d3cc8:  0xaf9d3cd8  0x080482de  0xa7faf360   0x00000003
0xaf9d3cd8:  0xafdde9f8  0x080483a4  0x00000004   0x00000005
0xaf9d3ce8:  0xaf9d3d08  0x080483df  0xa7fadff4   0x08048430
```



Taking Control of a Program with a Buffer Overflow

Buffer Overflow

- Main problem of buffer overflows:
  - program accepts more input than there is space allocated
- This happens when an array (or buffer) has not enough space, more bytes are provided, and no checks are made
  - especially easy with C strings (character arrays)
  - plenty of vulnerable library functions

`strcpy, strcat, gets, fgets, sprintf ..`

- Input spills to adjacent regions and modifies
  - code pointer or application data
    - all the overflow possibilities that we have enumerated before
  - normally, this just crashes the program (e.g., sigsegv)

Example

```c
// Test2.c
#include <stdio.h>
#include <string.h>

int vulnerable(char* param) {
    char buffer[100];
    strcpy(buffer, param);
}

int main(int argc, char* argv[]) {
    vulnerable(argv[1]);
    printf("Everything's fine\n");
}
```

Buffer that can contain 100 bytes

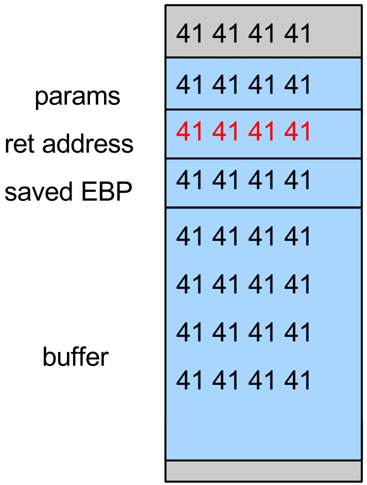
Copy an arbitrary number of characters from param to buffer

Let's Crash

```
> ./test2 hello
Everything's fine

> ./test2 AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Segmentation fault

>
```

What Happened?

```
> gdb ./test2

(gdb) run hello
Starting program: ./test2
Everything's fine


(gdb)  run  AAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAA

Starting program: ./test2 AAAAAAAAA...
Program received signal SIGSEGV,
Segmentation fault.
0x41414141 in ?? ()
```



Choosing Where to Jump

- Address inside a buffer of which the attacker controls the content
  - works for remote attacks
  - the attacker need to know the address of the buffer
  - the memory page containing the buffer must be executable
- Address of an environment variable
  - easy to implement, works even with tiny buffers
  - only for local exploits
  - some programs clean the environment
  - the stack must be executable
- Address of a function inside the program
  - works for remote attacks, does not require an executable stack
  - need to find the right code
  - one or more fake frames must be put on the stack

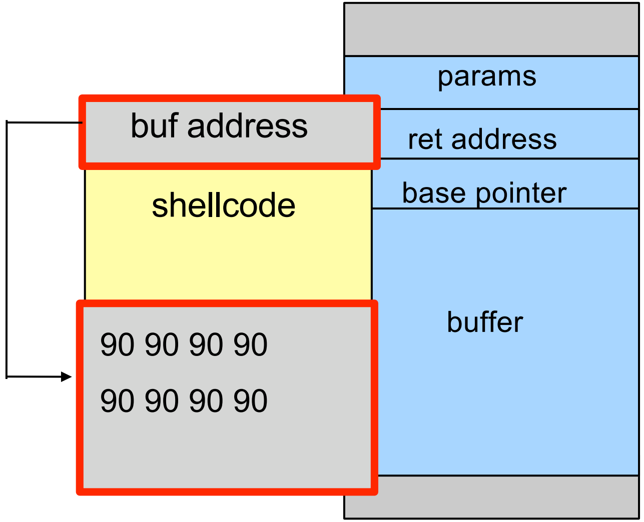
Jumping into the Buffer

- The buffer that we are overflowing is usually a good place to put the malicious code (`shellcode`) that we want to execute
- The buffer is somewhere on the stack, but in most cases the exact address is unknown
  - The address must be **precise**: jumping one byte before or after would just make the application crash
  - On the local system, it is possible to calculate the address with a debugger, but it is very unlikely to be the same address on a different machine
  - Any change to the environment variables affect the stack position

Solution: The NOP Sled

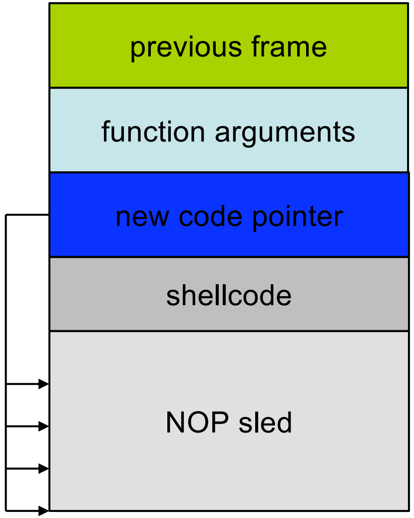
- A sled is a "landing area" that is put in front of the shellcode
- Must be created in a way such that wherever the program jump into it..
  - .. it always finds a valid instruction
  - .. it always reaches the end of the sled and the beginning of the shellcode
- The simplest sled is a sequence of no operation (NOP) instructions
  - single byte instruction (`0x90`) that does not do anything
  - more complex sleds possible (ADMmutate)
- It mitigates the problem of finding the exact address to the buffer by increasing the size of the target are area

Assembling the Malicious Buffer



Code Pointer

Any return address into
the NOP sled succeeds



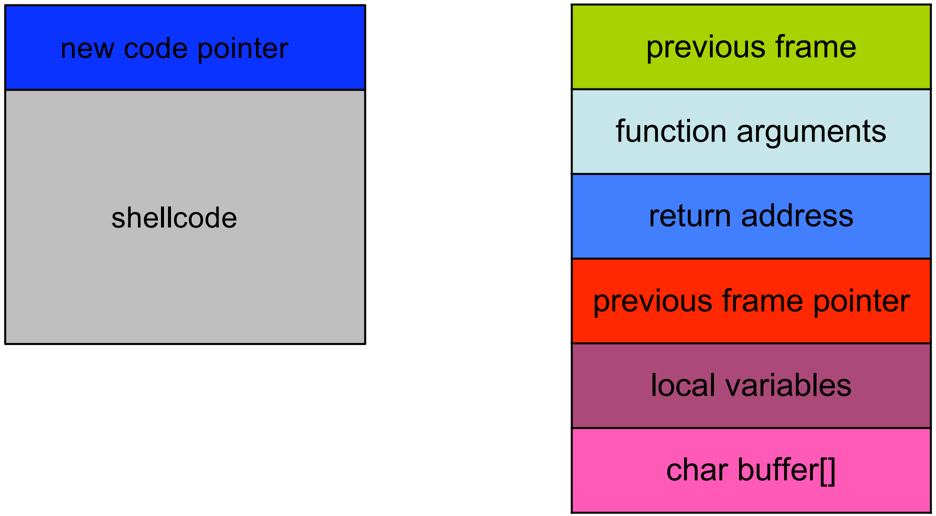
Solution: Jump using a Register

- Find a register that points to the buffer (or somewhere into it)
  - ESP
  - EAX (return value of a function call)
- Locate an instruction that jump/call using that register
  - can also be in one of the libraries
  - does not even need to be a real instruction, just look for the right sequence of bytes
  - you can search for a pattern with gdb find

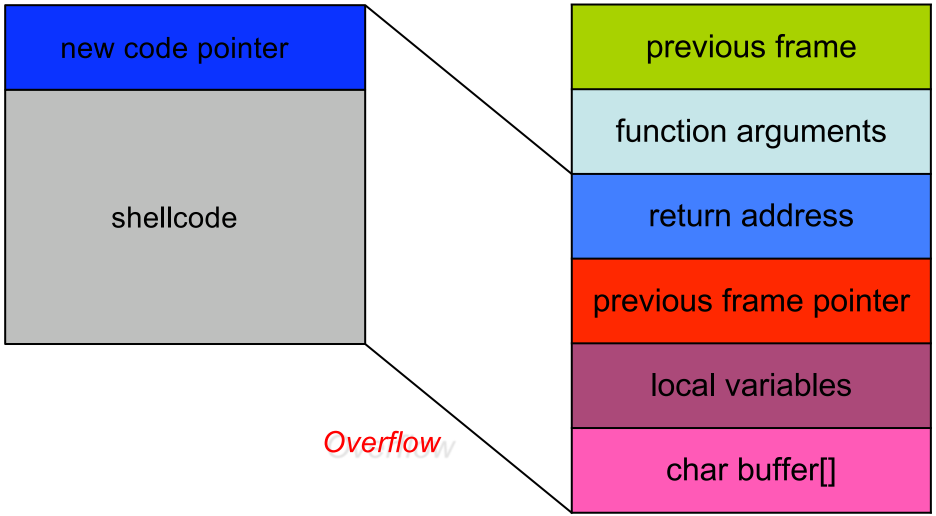
```
jmp ESP        =       0xFF 0xE4
```

- Overwrite the return address with the address of that instruction

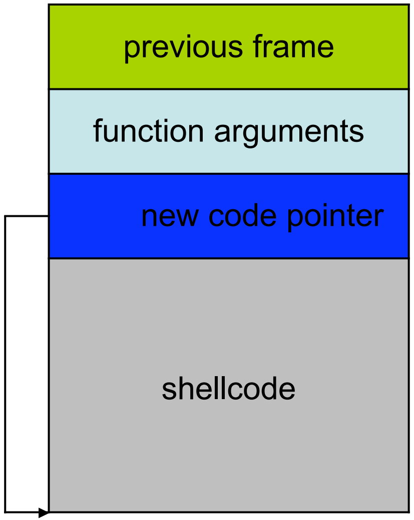
Pulling It All Together



Pulling It All Together



Pulling It All Together



Small Buffers

- Buffer can be too small to hold exploit code
- Store exploit code in environmental variable
  - environment stored on stack
  - return address has to be redirected to environment variable

- Advantage
  - exploit code can be arbitrary long
- Disadvantage
  - access to environment needed

Format String Vulnerabilities

Format String Vulnerability

- Problem of user supplied input that is used with `*printf()`
  - `printf(“Hello world\n“);  // is ok`
  - `printf(user_input);  // vulnerable`
- `*printf()`
  - function with variable number of arguments

    `int        printf(const char *format, ...)`
  - as usual, arguments are fetched from the stack
- `const char *format` is called format string
  - used to specify type of arguments
    - %d or %x for numbers
    - %s for strings

Format string

parameter	output	passed as
%d	decimal (int)	value
%u	unsigned decimal (unsigned int)	value
%x	hexadecimal (unsigned int)	value
%s	string ((const) (unsigned) char *)	reference
%n	number of bytes written so far, (* int)	reference

The stack and its role at format strings

```
printf("Number %d has no address, number %d has: %08x\n", i, a, &a);
```

stack top
...
&a
a
i
A
...
stack bottom

A	address of the format string
i	value of the variable i
a	value of the variable a
&a	address of the variable a

Format String Vulnerability

```c
#include <stdio.h>

int main(int argc, char **argv) {
   char buf[128];
   int x = 1;

   snprintf(buf, sizeof(buf), argv[1]);
   buf[sizeof(buf) - 1] = '\0';

   printf("buffer (%d): %s\n", strlen(buf), buf);
   printf("x is %d/%#x (@ %p)\n", x, x, &x);
   return 0;
}
```

Format String Vulnerability

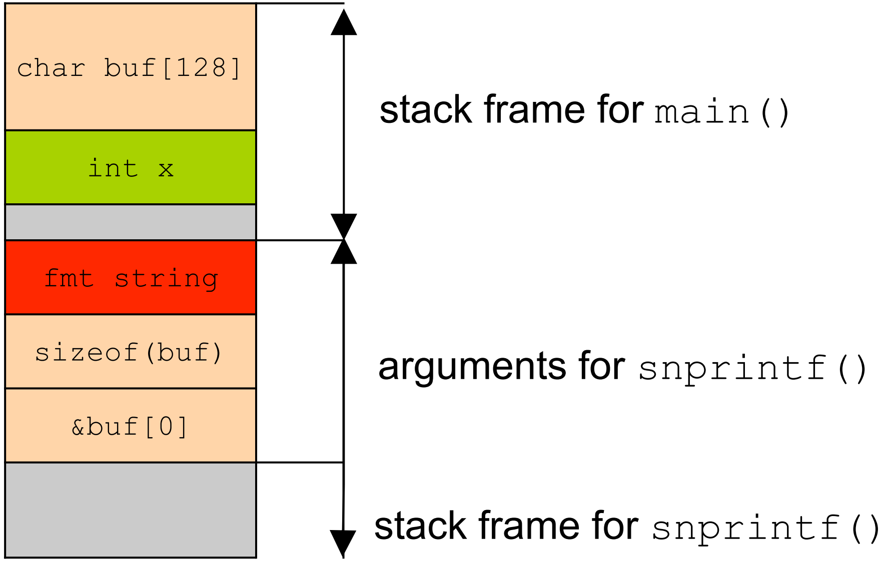
```
$ ./vul "AAAA %x %x %x %x"
buffer (28): AAAA 40017000 1 bffff680 4000a32c
x is 1/0x1 (@ 0xbffff638)

$ ./vul "AAAA %x %x %x %x %x"
buffer (35): AAAA 40017000 1 bffff680 4000a32c 1
x is 1/0x1 (@ 0xbffff638)

$ ./vul "AAAA %x %x %x %x %x %x"
buffer (44): AAAA 40017000 1 bffff680 4000a32c 1 41414141
x is 1/0x1 (@ 0xbffff638)
```

We are pointing to our format string itself!

What happens when a format string does not have a corresponding variable on the stack?

Format String Vulnerability

Stack Layout



Format String Vulnerability

```
$ ./vul $(python -c ‘print “\x38\xf6\xff\xbf %x %x %x %x %x %x“')
buffer (44): 8öÿ¿ 40017000 1 bffff680 4000a32c 1 bffff638
x is 1/0x1 (@ 0xbffff638)

$ ./vul $(python -c ‘print "\x38\xf6\xff\xbf %x %x %x %x %x%n“')
buffer (35): 8öÿ¿ 40017000 1 bffff680 4000a32c 1
x is 35/0x2f (@ 0xbffff638)
```

Format String Vulnerability

- **%n**

  The number of characters written so far is stored into the integer indicated by the int*(or variant) pointer argument

- One can use width modifier to write arbitrary values
  - for example, %.500d
  - even in case of truncation, the values that would have been written are used for %n
- More resources
  - https://crypto.stanford.edu/cs155old/cs155-spring08/papers/formatstring-1.2.pdf
  - https://www.exploit-db.com/docs/english/28476-linux-format-string-exploitation.pdf