Buffer Overflows
CSE 351 Spring 2019

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http://xkcd.com/804/
Administrivia

- Homework 3 due Wednesday (5/8)
- Mid-quarter survey due Thursday (5/9)
- Lab 3 released today, due Wednesday (5/15)

- Midterm Grading in progress, grades coming soon
  - Solutions posted on website
  - Rubric and grades will be found on Gradescope
  - Regrade requests will be open for a short time after grade release via Gradescope
Buffer Overflows

- Address space layout (more details!)
- Input buffers on the stack
- Overflowing buffers and injecting code
- Defenses against buffer overflows
Review: General Memory Layout

- **Stack**
  - Local variables (procedure context)

- **Heap**
  - Dynamically allocated as needed
  - `malloc()`, `calloc()`, `new`, ...

- **Statically allocated Data**
  - Read/write: global variables (Static Data)
  - Read-only: string literals (Literals)

- **Code/Instructions**
  - Executable machine instructions
  - Read-only
x86-64 Linux Memory Layout

- **Stack**
  - Runtime stack has 8 MiB limit

- **Heap**
  - Dynamically allocated as needed
  - `malloc()`, `calloc()`, `new`, ...

- **Statically allocated data (Data)**
  - Read-only: string literals
  - Read/write: global arrays and variables

- **Code / Shared Libraries**
  - Executable machine instructions
  - Read-only

Hex Address: 0x00007FFFFFFFFFFF
Memory Allocation Example

```c
char big_array[1L<<24]; /* 16 MB */
char huge_array[1L<<31]; /* 2 GB */

int global = 0;

int useless() { return 0; }

int main()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8); /* 256 B */
    p3 = malloc(1L << 32); /* 4 GB */
    p4 = malloc(1L << 8); /* 256 B */
    /* Some print statements ... */
}
```

Where does everything go?
**Memory Allocation Example**

```c
char big_array[1L<<24]; /* 16 MB */
char huge_array[1L<<31]; /* 2 GB */

int global = 0;

int useless() { return 0; }

int main()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8); /* 256 B */
    p3 = malloc(1L << 32); /* 4 GB */
    p4 = malloc(1L << 8); /* 256 B */
    /* Some print statements ... */
}
```

Where does everything go?
Reminder: x86-64/Linux Stack Frame

- **Caller’s Stack Frame**
  - Arguments (if > 6 args) for this call

- **Current/ Callee Stack Frame**
  - Return address
    - Pushed by `call` instruction
  - Old frame pointer (optional)
  - Saved register context (when reusing registers)
  - Local variables (if can’t be kept in registers)
  - “Argument build” area (If callee needs to call another function -parameters for function about to call, if needed)
Buffer Overflow in a Nutshell

- Characteristics of the traditional Linux memory layout provide opportunities for malicious programs
  - Stack grows “backwards” in memory
  - Data and instructions both stored in the same memory

- C does not check array bounds
  - Many Unix/Linux/C functions don’t check argument sizes
  - Allows overflowing (writing past the end) of buffers (arrays)
Buffer Overflow in a Nutshell

- Buffer overflows on the stack can overwrite “interesting” data
  - Attackers just choose the right inputs

- Simplest form (sometimes called “stack smashing”)
  - Unchecked length on string input into bounded array causes overwriting of stack data
  - Try to change the return address of the current procedure

- Why is this a big deal?
  - It is (was?) the #1 technical cause of security vulnerabilities
    - #1 overall cause is social engineering / user ignorance
String Library Code

- Implementation of Unix function `gets()`

```c
/* Get string from stdin */
char* gets(char* dest) {
    int c = getchar();
    char* p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

- What could go wrong in this code?
String Library Code

- Implementation of Unix function `gets()`

```c
/* Get string from stdin */
char* gets(char* dest) {
    int c = getchar();
    char* p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

- No way to specify `limit` on number of characters to read

- Similar problems with other Unix functions:
  - `strcpy`: Copies string of arbitrary length to a `dst`
  - `scanf`, `fscanf`, `sscanf`, when given `%s` specifier
Vulnerable Buffer Code

```c
/* Echo Line */
void echo() {
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}

void call_echo() {
    echo();
}
```

```
unix> ./buf-nsp
Enter string: 12345678901234567890123
12345678901234567890123
unix> ./buf-nsp
Enter string: 123456789012345678901234
Segmentation Fault
```
Buffer Overflow Disassembly (buf-nsp)

**echo:**

```
00000000004005c6 <echo>:
  4005c6:  48 83 ec 18
  ...                             ... calls printf ...
  4005d9:  48 89 e7
  4005dc:  e8 dd ff ff ff
  4005e1:  48 89 e7
  4005e4:  e8 95 fe ff ff
  4005e9:  48 83 c4 18
  4005ed:  c3
```

**call_echo:**

```
00000000004005ee <call_echo>:
  4005ee:  48 83 ec 08
  4005f2:  b8 00 00 00 00 00
  4005f7:  e8 ca ff ff ff
  4005fc:  48 83 c4 08
  400600:  c3
```

The return address is indicated by the purple arrow.
Buffer Overflow Stack

Before call to gets

Stack frame for call_echo

Return address (8 bytes)

16 bytes unused

[3] [2] [1] [0]

Note: addresses increasing right-to-left, bottom-to-top

/* Echo Line */
void echo()
{
    char buf[8]; /* Way too small! */
    gets(buf);
    puts(buf);
}

echo:
    subq $24, %rsp
    ...
    movq %rsp, %rdi
    call gets
    ...

buf ← %rsp
Buffer Overflow Example

**Before call to gets**

```c
void echo() {
    char buf[8];
    gets(buf);
    ...  
}
```

Stack frame for `call_echo`

```
00 00 00 00
00 40 05 fc
```

16 bytes unused

```assembly
buf ← %rsp
```

echo:

```
subq $24, %rsp
... 
movq %rsp, %rdi
call gets
... 
```

call_echo:

```
...  
4005f7: callq 4005c6 <echo>
4005fc: add $0x8,%rsp
... 
```
Buffer Overflow Example #1

After call to gets

Stack frame for call_echo

<table>
<thead>
<tr>
<th>00</th>
<th>00</th>
<th>00</th>
<th>00</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>40</td>
<td>05</td>
<td>fc</td>
</tr>
<tr>
<td>00</td>
<td>33</td>
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<td>34</td>
<td>33</td>
<td>32</td>
<td>31</td>
</tr>
</tbody>
</table>

Note: Digit “N” is just 0x3N in ASCII!

void echo()
{
    char buf[8];
    gets(buf);
    ...
}

call_echo:

... 4005f7: callq 4005c6 <echo>
    4005fc: add $0x8,%rsp
    ...

buf ← %rsp

Note: Digit “N” is just 0x3N in ASCII!

unix> ./buf-nsp
Enter string: 12345678901234567890123
12345678901234567890123

Overflowed buffer, but did not corrupt state
Buffer Overflow Example #2

**After call to gets**

```c
void echo()
{
    char buf[8];
    gets(buf);
    ... 
}
```

```markdown
After call to gets
```

Stack frame for `call_echo`

<table>
<thead>
<tr>
<th>00</th>
<th>00</th>
<th>00</th>
<th>00</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>40</td>
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<td>34</td>
<td>33</td>
<td>32</td>
<td>31</td>
</tr>
</tbody>
</table>

```markdown
```
buf ← %rsp
```

```c
unix> ./buf-nsp
```
```
Enter string: 123456789012345678901234
```
```
Segmentation Fault
```

Overflowed buffer and corrupted return pointer
Buffer Overflow Example #2 Explained

After return from echo

Stack frame for call_echo

| 00 | 00 | 00 | 00 |
|    |    |    |    |
| 00 | 40 | 05 | 00 |
| 34 | 33 | 32 | 31 |
| 30 | 39 | 38 | 37 |
| 36 | 35 | 34 | 33 |
| 32 | 31 | 30 | 39 |
| 38 | 37 | 36 | 35 |
| 34 | 33 | 32 | 31 |

buf⟵%rsp

```assembly
0000000000400500 <deregister_tm_clones>:
  400500:  mov   $0x60104f,%eax
  400505:  push  %rbp
  400506:  sub   $0x601048,%rax
  40050c:  cmp   $0xe,%rax
  400510:  mov   %rsp,%rbp
  400513:  jbe   400530
  400515:  mov   $0x0,%eax
  40051a:  test  %rax,%rax
  40051d:  je    400530
  40051f:  pop   %rbp
  400520:  mov   $0x601048,%edi
  400525:  jmpq  *%rax
  400527:  nopw  0x0(%rax,%rax,1)
  40052e:  nop
  400530:  pop   %rbp
  400531:  retq
```

“Returns” to unrelated code, but continues!
Eventually segfaults on retq of deregister_tm_clones.
Malicious Use of Buffer Overflow: Code Injection Attacks

- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When `bar()` executes `ret`, will jump to exploit code

```c
int bar() {
    char buf[64];
    gets(buf);
    ...
    return ...;
}
```

```c
void foo(){
    bar();
    A: ...
}
```
Peer Instruction Question

- `smash_me` is vulnerable to stack smashing!
- What is the minimum number of characters that `gets` must read in order for us to change the return address to a stack address (in Linux)?
  - Talk to your neighbor!

```asm
smash_me:
    subq $0x30, %rsp
    ...
    movq %rsp, %rdi
    call gets
    ...
```

A. 33  
B. 36  
C. 51  
D. 54  
E. We’re lost...
Exploits Based on Buffer Overflows

- **Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines**

- Distressingly common in real programs
  - Programmers keep making the same mistakes 😞
  - Recent measures make these attacks much more difficult

- Examples across the decades
  - Original “Internet worm” (1988)
  - *Still happens!!*
    - Heartbleed (2014, affected 17% of servers)
    - Cloudbleed (2017)
  - **Fun**: Nintendo hacks
    - Using glitches to rewrite code: [https://www.youtube.com/watch?v=TqK-2jUQBUY](https://www.youtube.com/watch?v=TqK-2jUQBUY)
    - FlappyBird in Mario: [https://www.youtube.com/watch?v=hB6eY73sLV0](https://www.youtube.com/watch?v=hB6eY73sLV0)
Example: the original Internet worm (1988)

- Exploited a few vulnerabilities to spread
  - Early versions of the finger server (fingerd) used `gets()` to read the argument sent by the client:
    - `finger droh@cs.cmu.edu`
  - Worm attacked `fingerd` server with phony argument:
    - `finger "exploit-code padding new-return-addr"`
    - Exploit code: executed a root shell on the victim machine with a direct TCP connection to the attacker

- Scanned for other machines to attack
  - Invaded ~6000 computers in hours (10% of the Internet)
    - see June 1989 article in *Comm. of the ACM*
  - The young author of the worm was prosecuted...
Heartbleed (2014)

- Buffer over-read in OpenSSL
  - Open source security library
  - Bug in a small range of versions
- “Heartbeat” packet
  - Specifies length of message
  - Server echoes it back
  - Library just “trusted” this length
  - Allowed attackers to read contents of memory anywhere they wanted
- Est. 17% of Internet affected
  - “Catastrophic”
  - Github, Yahoo, Stack Overflow, Amazon AWS, ...
Dealing with buffer overflow attacks

1. Avoid overflow vulnerabilities
2. Employ system-level protections
3. Have compiler use “stack canaries”
1) Avoid Overflow Vulnerabilities in Code

/* Echo Line */
void echo()
{
    char buf[8]; /* Way too small! */
    fgets(buf, 8, stdin);
    puts(buf);
}

- Use library routines that limit string lengths
  - `fgets` instead of `gets` (2\textsuperscript{nd} argument to `fgets` sets limit)
  - `strncpy` instead of `strcpy`
  - Don’t use `scanf` with `%s` conversion specification
    - Use `fgets` to read the string
    - Or use `%ns` where `n` is a suitable integer
2) System-Level Protections

- **Randomized stack offsets**
  - At start of program, allocate *random* amount of space on stack
  - Shifts stack addresses for entire program
    - Addresses will vary from one run to another
  - Makes it difficult for hacker to predict beginning of inserted code

- **Example**: Code from Slide 6 executed 5 times; address of variable `local` =
  - 0x7fffd19d3f8ac
  - 0x7ffe8a462c2c
  - 0x7ffe927c905c
  - 0x7ffefd5c27dc
  - 0x7fffa0175afc

- Stack repositioned each time program executes
2) System-Level Protections

- **Non-executable code segments**
  - In traditional x86, can mark region of memory as either “read-only” or “writeable”
    - Can execute anything readable
  - x86-64 added explicit “execute” permission
  - **Stack marked as non-executable**
    - Do *NOT* execute code in Stack, Static Data, or Heap regions
    - Hardware support needed

Any attempt to execute this code will fail
3) Stack Canaries

- Basic Idea: place special value ("canary") on stack just beyond buffer
  - Secret value known only to compiler
  - "After" buffer but before return address
  - Check for corruption before exiting function

- GCC implementation (now default)
  - -fstack-protector
  - Code back on Slide 14 (buf-nsp) compiled with -fno-stack-protector flag

```
unix> ./buf
Enter string: 12345678
12345678

unix> ./buf
Enter string: 123456789
*** stack smashing detected ***
```
Protected Buffer Disassembly (buf)

echo:

```assembly
400638:  sub $0x18,%rsp
40063c:  mov %fs:0x28,%rax
400645:  mov %rax,0x8(%rsp)
40064a:  xor %eax,%eax
...
...
... call printf ...
400656:  mov %rsp,%rdi
400659:  callq 400530 <gets@plt>
40065e:  mov %rsp,%rdi
400661:  callq 4004e0 <puts@plt>
400666:  mov 0x8(%rsp),%rax
40066b:  xor %fs:0x28,%rax
400674:  je 40067b <echo+0x43>
400676:  callq 4004f0 <__stack_chk_fail@plt>
40067b:  add $0x18,%rsp
40067f:  retq
```

This is extra (non-testable) material
Setting Up Canary

Before call to gets

/* Echo Line */
void echo()
{
    char buf[8]; /* Way too small! */
    gets(buf);
    puts(buf);
}

Segment register (don’t worry about it)

buf ← %rsp
Checking Canary

After call to `gets`

Stack frame for `call_echo`

Return address (8 bytes)

Canary (8 bytes)

```
/* Echo Line */
void echo()
{
    char buf[8]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

echo:

```
...  
movq 8(%rsp), %rax  # retrieve from Stack
xorq %fs:40, %rax  # compare to canary
je .L2             # if same, OK
  call __stack_chk_fail  # else, FAIL
.L6:    ...
```

buf ← %rsp

Input: 1234567
Summary

1) Avoid overflow vulnerabilities
   - Use library routines that limit string lengths

2) Employ system-level protections
   - Randomized Stack offsets
   - Code on the Stack is not executable

3) Have compiler use “stack canaries”