Buffer Overflows
CSE 351 Summer 2020

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http://xkcd.com/2291/
Administrivia

- Questions doc: [https://tinyurl.com/CSE351-7-22](https://tinyurl.com/CSE351-7-22)

- No hw due Friday!
- hw13 due Monday (7/27) – 10:30am
- Lab 2 due tonight (7/22)
  - Extra Credit portion – make sure you also submit to the Lab 2 Extra Credit assignment on Gradescope
- Lab 3 released later this afternoon
  - Today’s lecture on buffer overflow.
  - You get to write some buffer overflow exploits!
Nested Array Example

```c
int sea[4][5] = {
    { 9, 8, 1, 9, 5 },
    { 9, 8, 1, 0, 5 },
    { 9, 8, 1, 0, 3 },
    { 9, 8, 1, 1, 5 }
};
```

- “Row-major” ordering of all elements
- Elements in the same row are contiguous
- Guaranteed (in C)
Nested Array Row Access Code

```c
int* get_sea_zip(int index)
{
    return sea[index];
}
```

```
int sea[4][5] =
{
    { 9, 8, 1, 9, 5 },
    { 9, 8, 1, 0, 5 },
    { 9, 8, 1, 0, 3 },
    { 9, 8, 1, 1, 5 }};
```

- **Row Vector**
  - `sea[index]` is array of 5 ints
  - Starting address = `sea + 20 * index`

- **Assembly Code**
  - Computes and returns address
  - Compute as: `sea+4*(index+4*index) = sea+20*index`
Nested Array Element Access Code

```c
int get_sea_digit(int index, int digit)
{
    return sea[index][digit];
}
```

```c
int sea[4][5] =
    {{ 9, 8, 1, 9, 5 },
     { 9, 8, 1, 0, 5 },
     { 9, 8, 1, 0, 3 },
     { 9, 8, 1, 1, 5 }};
```

---

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>leaq %rdi,%rdi,4, %rax</td>
<td># 5*index</td>
</tr>
<tr>
<td>addl %rax, %rsi</td>
<td># 5*index+digit</td>
</tr>
<tr>
<td>movl sea(,%rsi,4), %eax</td>
<td># <em>(sea + 4</em>(5*index+digit))</td>
</tr>
</tbody>
</table>

- **Array Elements**
  - `sea[index][digit]` is an `int` (`sizeof(int)=4`)
  - Address = `sea + 5*4*index + 4*digit`

- **Assembly Code**
  - Computes address as: `sea + ((index+4*index) + digit)*4`
  - `movl` performs memory reference **only once!**
Multidimensional Referencing Examples

```
int sea[4][5];
```

<table>
<thead>
<tr>
<th>Reference</th>
<th>Address</th>
<th>Value</th>
<th>Guaranteed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>sea[3][3]</td>
<td>76<em>20</em>3+4*3 = 148</td>
<td>19</td>
<td>yes</td>
</tr>
<tr>
<td>sea[2][5]</td>
<td>76+20<em>2+4</em>5 = 136</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td>sea[2][-1]</td>
<td>76+20<em>2+4</em>-1 = 112</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td>sea[4][-1]</td>
<td>76+20<em>4+4</em>-1 = 152</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td>sea[0][19]</td>
<td>76+20<em>0+4</em>19 = 152</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td>sea[0][-1]</td>
<td>76+20<em>0+4</em>-1 = 72</td>
<td>??</td>
<td>no</td>
</tr>
</tbody>
</table>

- Code does not do any bounds checking
- Ordering of elements within array guaranteed
Polling Question [Arrays - a]

Which of the following statements is **FALSE**?

- Answer posted on inked slides after class!

```c
int sea[4][5];
```

A. `sea[4][-2]` is a *valid* array reference

B. `sea[1][1]` makes *two* memory accesses

C. `sea[2][1]` will *always* be a higher address than `sea[1][2]`

D. `sea[2]` is calculated using *only* 1 element

E. We’re lost…
Data Structures in Assembly

- **Arrays**
  - One-dimensional
  - Multidimensional (nested)
  - Multilevel
    - We will go fast through this, more in section tomorrow!

- **Structs**
  - Alignment

- **Unions**
Multilevel Array Example

Multilevel Array Declaration(s):

```c
int cmu[5] = { 1, 5, 2, 1, 3 };
int uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
int* univ[3] = {uw, cmu, ucb};
```

Is a multilevel array the same thing as a 2D array? **NO**

2D Array Declaration:

```c
int univ2D[3][5] = {
    { 9, 8, 1, 9, 5 },
    { 1, 5, 2, 1, 3 },
    { 9, 4, 7, 2, 0 }
};
```

One array declaration = one contiguous block of memory
Multilevel Array Example

Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 8 bytes each
- Each pointer points to array of `ints`

```
int cmu[5] = { 1, 5, 2, 1, 3 };
int uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };

int* univ[3] = {uw, cmu, ucb};
```

Note: this is how Java represents multidimensional arrays
Element Access in **Multilevel Array**

```c
int get_univ_digit(int index, int digit)
{
    return univ[index][digit];
}
```

**Computation**

- **Element access** `Mem[Mem[univ+8*index]+4*digit]`
- **Must do** two memory reads
  - First get pointer to row array
  - Then access element within array
- **But allows inner arrays to be different lengths (not in this example)**
# Array Element Accesses

## Multidimensional array

```c
int get_sea_digit (int index, int digit) {
    return sea[index][digit];
}
```

## Multilevel array

```c
int get_univ_digit (int index, int digit) {
    return univ[index][digit];
}
```

### Access looks the same, but it isn't:

- `Mem[sea+20*index+4*digit]`
- `Mem[Mem[univ+8*index]+4*digit]`
  - Two dereferences!
Multilevel Referencing Examples

<table>
<thead>
<tr>
<th>Reference</th>
<th>Address</th>
<th>Value</th>
<th>Guaranteed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>univ[2][3]</td>
<td>Mem[176] + 3*y = 60 + 12 = 72</td>
<td>2</td>
<td>yes</td>
</tr>
<tr>
<td>univ[1][5]</td>
<td>Mem[162] + 5*y = 16 + 20 = 36</td>
<td>9</td>
<td>no</td>
</tr>
<tr>
<td>univ[3][-1]</td>
<td>Mem[184] - 1<em>y = ?? - 1</em>y = ??</td>
<td>??</td>
<td>no</td>
</tr>
<tr>
<td>univ[1][12]</td>
<td>Mem[168] + 12*y = 16 + 48 = 64</td>
<td>4</td>
<td>no</td>
</tr>
</tbody>
</table>

- C code does not do any bounds checking
- Location of each lower-level array in memory is not guaranteed
Summary

- Contiguous allocations of memory
- **No bounds checking** (and no default initialization)
- Can usually be treated like a pointer to first element

```c
int a[4][5];  // array of arrays
- all levels in one contiguous block of memory
```

```c
int* b[4];  // array of pointers to arrays
- First level in one contiguous block of memory
- Each element in the first level points to another “sub” array
- Parts anywhere in memory```
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

This is extra (non-testable) material
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?

```
p1 = stack address
*p1 = heap address
```
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?
What Is a Buffer?

- A buffer is an array used to temporarily store data.
- You’ve probably seen “video buffering...”
  - The video is being written into a buffer before being played.
- Buffers can also store user input.
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)
  - Caller-saved pushed before setting up arguments for a function call
  - Callee-saved pushed before using long-term registers
  - Local variables (if can’t be kept in registers)
  - “Argument build” area (Need to call a function with >6 arguments? Put them here)
Buffer Overflow in a Nutshell

- 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” = Writing past the end of an array

- 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
Buffer Overflow in a Nutshell

- Stack grows down towards lower addresses
- Buffer grows up towards higher addresses
- If we write past the end of the array, we overload data on the stack!

Imagine local variable char buf[8];

Enter input: hello

No overflow 😊
Buffer Overflow in a Nutshell

- Stack grows down towards lower addresses
- Buffer grows up towards higher addresses
- If we write past the end of the array, we overwrite data on the stack!

Enter input: helloabcdef
Buffer Overflow in a Nutshell

- Stack grows down towards lower addresses
- Buffer grows up towards higher addresses
- If we write past the end of the array, we overwrite data on the stack!

Enter input: helloabcdef

Buffer overflow! 😞
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 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 \texttt{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 \textbf{limit} on number of characters to read

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

```c
/* Echo Line */
void echo() {
    char buf[8];  /* Way too small! */
    gets(buf);   /* read input into buffer */
    puts(buf);   /* print output from buffer */
}
```

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

```
unix> ./buf-nsp
Enter string: 123456789012345
123456789012345
unix> ./buf-nsp
Enter string: 1234567890123456
Illegal instruction
unix> ./buf-nsp
Enter string: 12345678901234567
Segmentation Fault
```
Buffer Overflow Disassembly (buf-nsp)

**echo:**

```
0000000000400597 <echo>:
400597:  48 83 ec 18  sub $0x18,%rsp
...                          ... calls printf ...
4005aa:  48 8d 7c 24 08  lea 0x8(%rsp),%rdi
4005af:  e8 d6 ff ff ff  callq 400480 <gets@plt>
4005b4:  48 89 7c 24 08  lea 0x8(%rsp),%rdi
4005b9:  e8 b2 ff ff ff  callq 4004a0 <puts@plt>
4005be:  48 83 c4 18     add $0x18,%rsp
4005c2:  c3               retq
```

**call_echo:**

```
00000000004005c3 <call_echo>:
4005c3:  48 83 ec 08  sub $0x8,%rsp
4005c7:  b8 00 00 00 00  mov $0x0,%eax
4005cc:  e8 c6 ff ff ff  callq 400597 <echo>
4005d1:  48 83 c4 08     add $0x8,%rsp
4005d5:  c3               retq
```

24 bytes allocated for local vars
Buffer Overflow Stack

**Before call to gets**

<table>
<thead>
<tr>
<th>Stack frame for call_echo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return address (8 bytes)</td>
</tr>
<tr>
<td>8 bytes unused</td>
</tr>
<tr>
<td>[3] [2] [1] [0]</td>
</tr>
<tr>
<td>8 bytes unused</td>
</tr>
</tbody>
</table>

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

**Note:** addresses increasing right-to-left, bottom-to-top
Buffer Overflow Example

**Before call to gets**

Stack frame for call_echo

<table>
<thead>
<tr>
<th>return address</th>
<th>00</th>
<th>00</th>
<th>00</th>
<th>00</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>00</td>
<td>40</td>
<td>05</td>
<td>d1</td>
</tr>
</tbody>
</table>

8 bytes unused

|-----|-----|-----|-----|

<table>
<thead>
<tr>
<th>[3]</th>
<th>[2]</th>
<th>[1]</th>
<th>[0]</th>
</tr>
</thead>
</table>

8 bytes unused

---

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

echo:

```
subq $24, %rsp
... leaq 8(%rsp), %rdi
call gets
...
```

call_echo:

```
... callq 400597 <echo>
4005d1: add $0x8, %rsp
...
```
Buffer Overflow Example #1

After call to `gets`

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

call_echo:

. . .

4005cc:  callq  400597 <echo>
4005d1:  add    $0x8,%rsp
. . .

echo:
    subq $24, %rsp
    ...  
    leaq 8(%rsp), %rdi
    call gets
    ...

Stack frame for call_echo

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>00</td>
<td>40</td>
<td>05</td>
<td>d1</td>
<td></td>
</tr>
<tr>
<td>00</td>
<td>35</td>
<td>34</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>31</td>
<td>30</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>37</td>
<td>36</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>33</td>
<td>32</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>

8 bytes unused

Note: Digit “N” is just 0x3N in ASCII!
0x31 = ‘1’
0x37 = ‘7’

unix> ./buf-nsp
Enter string: 123456789012345
123456789012345

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

**After call to gets**

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

### Stack frame for call_echo

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

8 bytes unused

```bash
unix> ./buf-nsp
Enter string: 1234567890123456
Illegal instruction
```

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

After return from echo

Stack frame for call_echo

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>00</td>
<td>40</td>
<td>05</td>
<td>00</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>35</td>
<td>34</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>31</td>
<td>30</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>37</td>
<td>36</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>33</td>
<td>32</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>

8 bytes unused

%rsp

buf

00000000004004f0 <deregister_tm_clones>:
4004f0: push %rbp
4004f1: mov $0x601040,%eax
4004f6: cmp $0x601040,%rax
4004fc: mov %rsp,%rbp
4004ff: je 400518
400501: mov $0x0,%eax
400506: test %rax,%rax
400509: je 400518
40050b: pop %rbp
40050c: mov $0x601040,%edi
400511: jmpq *%rax
400513: nopl 0x0(%rax,%rax,1)
400518: pop %rbp
400519: retq

“Returns” to a byte that is not the beginning of an instruction, so program signals SIGILL, Illegal instruction
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 $\text{bar}()$ executes $\text{ret}$, will jump to exploit code
Peer Instruction Question [Buf]

- **vulnerable** 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?

  - For example: (0x00 00 7f ff CA FE F0 0D)

<table>
<thead>
<tr>
<th>Previous stack frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>00 00 00 00</td>
</tr>
<tr>
<td>00 40 05 d1</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>[0]</td>
</tr>
</tbody>
</table>

For example:

```
subq $0x40, %rsp
...%
leaq 16(%rsp), %rdi
call gets
...%
```

A. 27  
B. 30  
C. 51  
D. 54  
E. We’re lost...
Exploits Based on Buffer Overflows

Buffer overflow bugs can allow attackers 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)
  - Heartbleed (2014, affected 17% of servers)
    - Similar issue in Cloudbleed (2017)
  - Hacking embedded devices
    - Cars, Smart homes, Planes
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 connection to the attacker

- Scanned for other machines to attack
  - Invaded ~6000 computers in hours (10% of the Internet)
    - see [June 1989 article](comm. of the ACM)
  - The author of the worm (Robert Morris*) was prosecuted...
Example: Heartbleed

HOW THE HEARTBLEED BUG WORKS:

SERVER, ARE YOU STILL THERE?
IF SO, REPLY "POTATO" (6 LETTERS).

User Meg wants these 6 letters: POTATO. User Ada wants pages about "irl games". Unlocking secure records with master key 5130985733435, user Charlie sends this message: "4538538374224".

POTATO
Example: Heartbleed

Server, are you still there? If so, reply "BIRD" (4 letters).

User Olivia from London wants pages about "bees in car why". Note: Files for IP 375.381.83.17 are in /tmp/files-3843. User Meg wants these 4 letters: BIRD. There are currently 34 connections open. User Brendan uploaded the file elf.png (contents: 834ba962e2c8b9ff09b3e5e8f).

Hmm...

BIRD
Example: Heartbleed

SERVER, ARE YOU STILL THERE? IF SO, REPLY "HAT" (500 LETTERS).

User Meg wants these 500 letters: HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about snakes but not too long. User Karen wants to change account password to "ColaBa$h".

HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about snakes but not too long. User Karen wants to change account password to "ColaBa$h".
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, ...

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Hacking Cars

- UW CSE research from 2010 demonstrated wirelessly hacking a car using buffer overflow
- Overwrote the onboard control system’s code
  - Disable brakes
  - Unlock doors
  - Turn engine on/off
Dealing with buffer overflow attacks

1) Employ system-level protections
2) Avoid overflow vulnerabilities
3) Have compiler use “stack canaries”
1) 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

Stack after call to `gets()`

Any attempt to execute this code will fail
1) System-Level Protections

- Non-executable code segments
  - Wait, doesn’t this fix everything?
  - Works well, but can’t always use it
  - Many embedded devices do not have this protection
    - Cars
    - Smart homes
    - Pacemakers
  - Some exploits still work!
    - Return-oriented programming
    - Return to libc attack
    - JIT-spray attack

Diagram:

Any attempt to execute this code will fail
1) 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` =
  - 0x7ffd19d3f8ac
  - 0x7ffe8a462c2c
  - 0x7ffe927c905c
  - 0x7ffefd5c27dc
  - 0x7fffa0175afc

- Stack repositioned each time program executes
2) Avoid Overflow Vulnerabilities in Code

```c
/* 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` (2nd 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) Avoid Overflow Vulnerabilities in Code

- Alternatively, don’t use C - use a language that does array index bounds check
  - Buffer overflow is impossible in Java
    - ArrayIndexOutOfBoundsException
  - Rust language was designed with security in mind
    - Panics on index out of bounds, plus more protections
3) Stack Canaries

- Basic Idea: place special value ("canary") on stack just beyond buffer
  - Secret value that is randomized before main()
  - Placed between buffer and return address
  - Check for corruption before exiting function

- GCC implementation
  - -fstack-protector
Protected Buffer Disassembly (buf)

echo:

```assembly
400607: sub $0x18,%rsp
40060b: mov %fs:0x28,%rax  # read canary value
400614: mov %rax,0x8(%rsp) # store canary on stack
400619: xor %eax,%eax    # erase canary from register
    ...          ... call printf ...
400625: mov %rsp,%rdi
400628: callq 400510 <gets@plt>
40062d: mov %rsp,%rdi
400630: callq 4004d0 <puts@plt>
400635: mov 0x8(%rsp),%rax # read current canary on stack
40063a: xor %fs:0x28,%rax # compare against original value
400643: jne 40064a <echo+0x43> # if unchanged, then return
400645: add $0x18,%rsp
400649: retq
40064a: callq 4004f0 <__stack_chk_fail@plt> # stack smashing detected
```

This is extra (non-testable) material

try: diff buf-nsps buf.s
Setting Up Canary

Before call to gets

Stack frame for call_echo

Return address (8 bytes)

Canary (8 bytes)

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

buf ← %rsp

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

Segment register (don’t worry about it)

echo:
...
    movq  %fs:40, %rax    # Get canary
    movq  %rax, 8(%rsp)  # Place on stack
    xorl  %eax, %eax     # Erase canary
...

This is extra (non-testable) material
Checking Canary

After call to `gets`

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

```
buf ← %rsp
```

Input: **1234567**

```
echo:            . . .
    movq 8(%rsp), %rax # retrieve from Stack
    xorq %fs:40, %rax # compare to canary
    jne .L4           # if not same, FAIL
    . . .
.L4: call __stack_chk_fail
```
Summary of Prevention Measures

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

2) Avoid overflow vulnerabilities
   - Use library routines that limit string lengths
   - Use a language that makes them impossible

3) Have compiler use “stack canaries”
Think this is cool?

- You’ll love Lab 3 😊
  - Check out the buffer overflow simulator!
- Take CSE 484 (Security)
  - Several different kinds of buffer overflow exploits
  - Many ways to counter them
- Nintendo fun!
  - Using glitches to rewrite code: https://www.youtube.com/watch?v=TqK-2jUQBUY
  - Flappy Bird in Mario: https://www.youtube.com/watch?v=hB6eY73sLV
Extra Notes about `%rbp`

- `%rbp` is used to store the frame pointer
  - Name comes from “base pointer”
- You can refer to a variable on the stack as `%rbp+offset`
- The base of the frame will never change, so each variable can be uniquely referred to with its offset
- The top of the stack (`%rsp`) may change, so referring to a variable as `%rsp-offset` is less reliable
  - For example, if you need save a variable for a function call, pushing it onto the stack changes `%rsp`
Hacking DNA Sequencing Tech

- Potential for malicious code to be encoded in DNA!
- Attacker can gain control of DNA sequencing machine when malicious DNA is read
- Ney et al. (2017)
  - https://dnasec.cs.washington.edu

Computer Security and...

Paul G. Allen School of Computer Science

There has been rapid improvement in the cost and time it takes to sequence a human genome. This was made possible by faster, massively parallel processing that can handle hundreds of millions of DNA strands simultaneously. The applications of DNA sequencing range from personalized medicine, ancestry, and...
# Where Is It?

<table>
<thead>
<tr>
<th>Variable/Label</th>
<th>Section of Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>big_array</td>
<td></td>
</tr>
<tr>
<td>global</td>
<td></td>
</tr>
<tr>
<td>huge_array</td>
<td></td>
</tr>
<tr>
<td>local</td>
<td></td>
</tr>
<tr>
<td>main</td>
<td></td>
</tr>
<tr>
<td>p1</td>
<td></td>
</tr>
<tr>
<td>*p1</td>
<td></td>
</tr>
<tr>
<td>useless</td>
<td></td>
</tr>
</tbody>
</table>
Notes Diagrams

1. Exploit code start of local array
2. Padding
3. Array addr

Higher Addresses

Caller’s Stack Frame

Return Addr

Old %rbp

Saved Registers

Local Variables

Stack smashing

start of local array %rsp

Lower Addresses

Higher Addresses

Caller’s Stack Frame

Saved Registers

Local Variables

1) exploit code

2) padding

3) array addr

Start of local array %rsp

Lower Addresses