Buffer Overflows

CSE 351 Spring 2019

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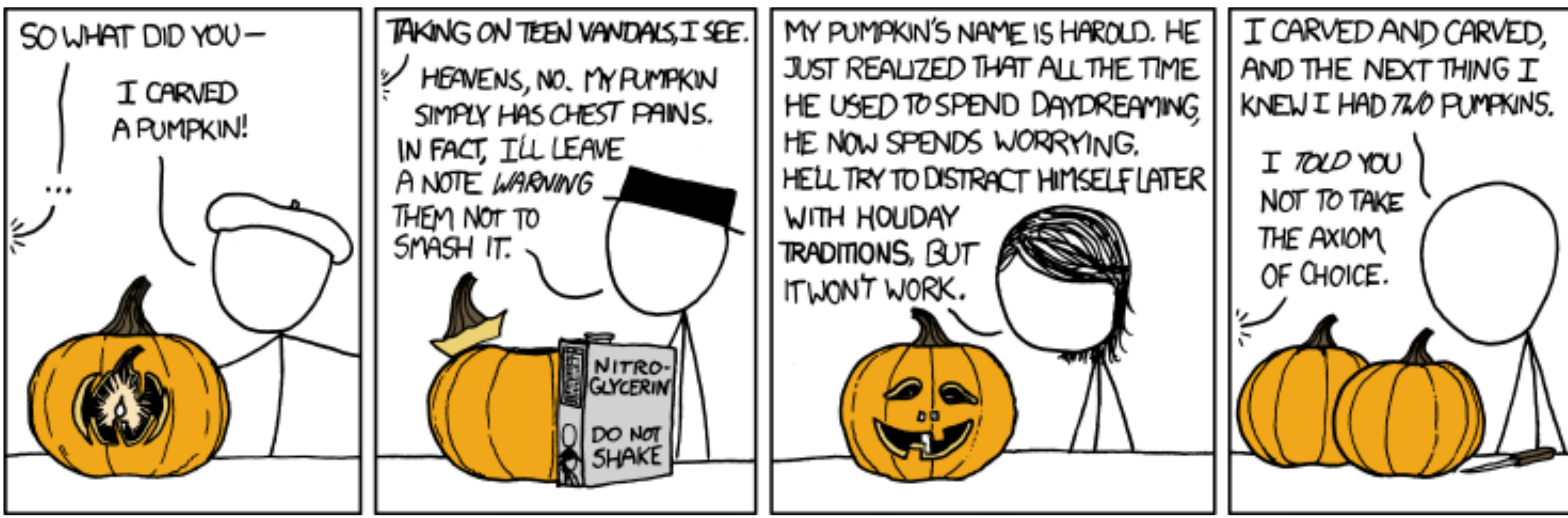


http://xkcd.com/804/

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

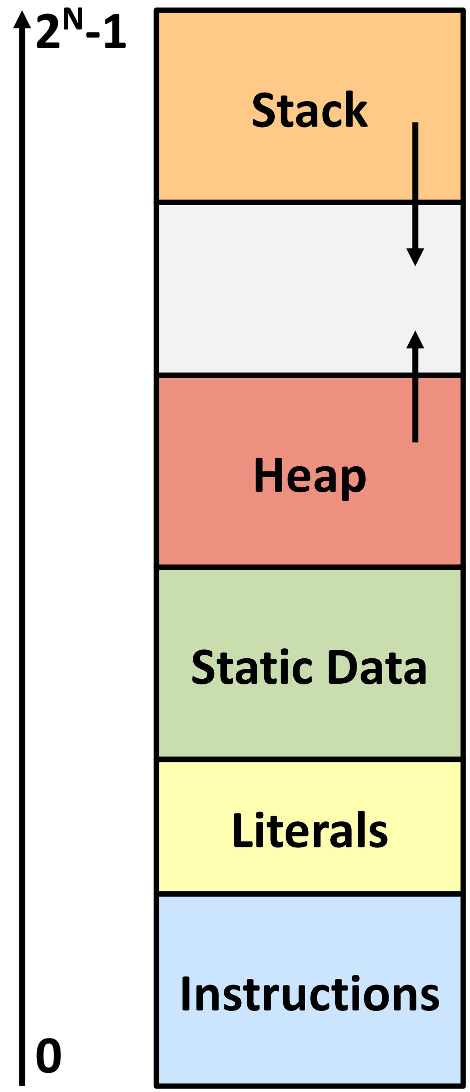
Buffer Overflows

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

not drawn to scale

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



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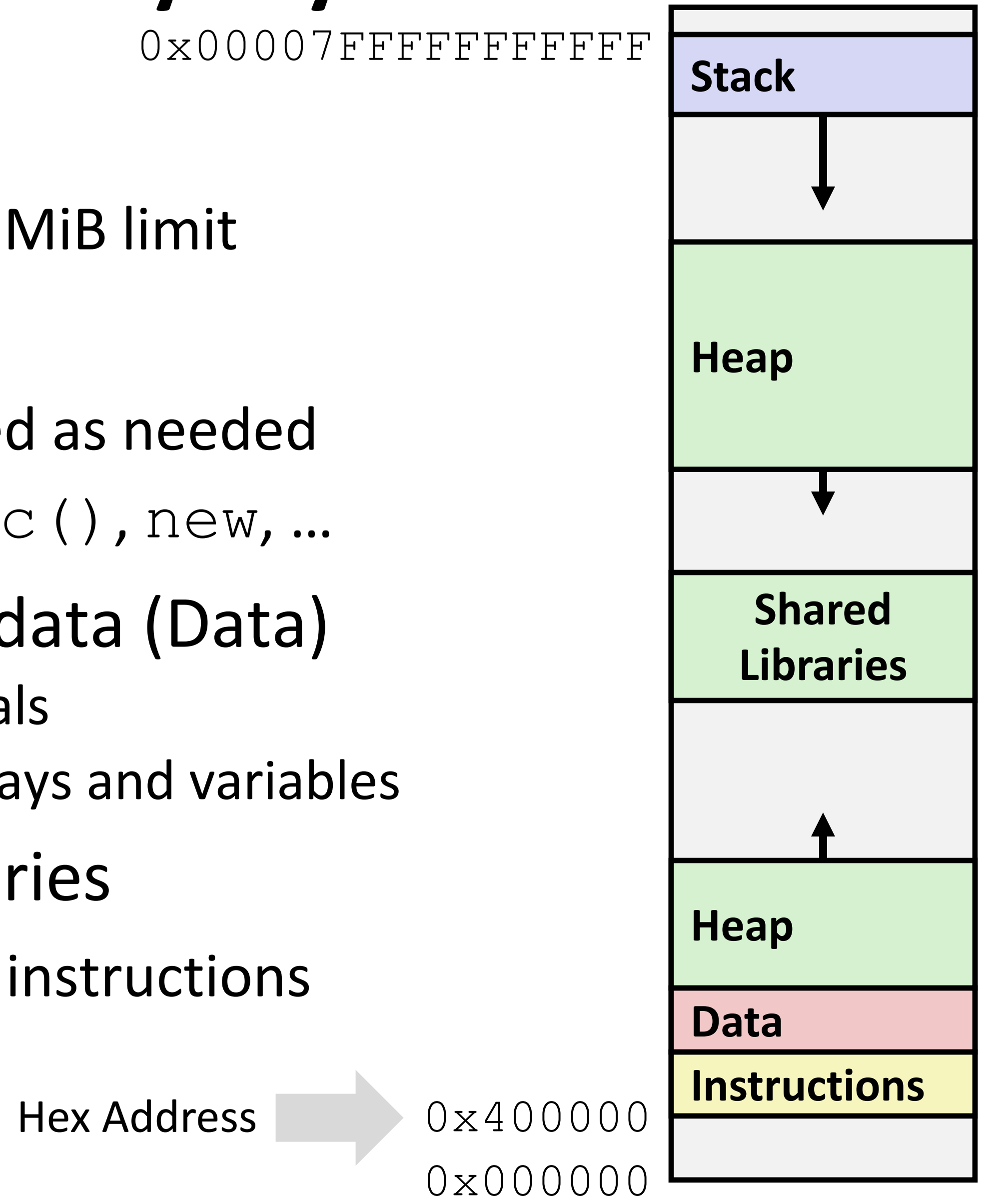
x86-64 Linux Memory Layout

- 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



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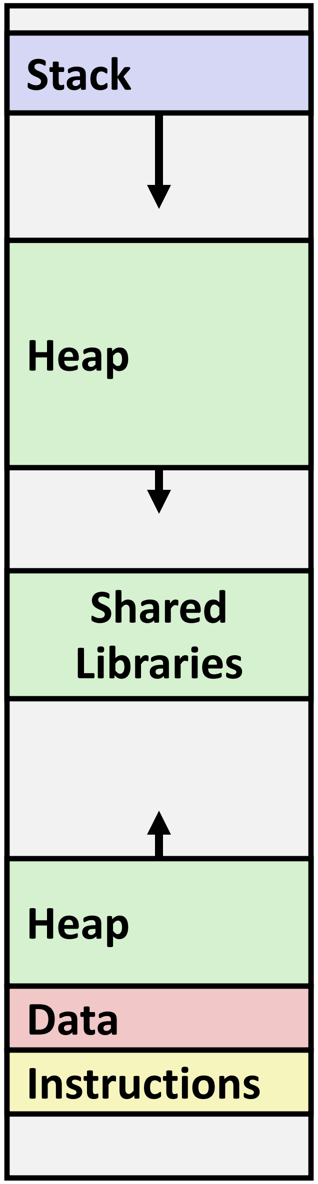
Memory Allocation Example

```
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?

not drawn to scale

Memory Allocation Example

```
char big_array[1L<<24];  /* 16 MB */
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    p4 = malloc(1L << 8);  /* 256  B */
    /* Some print statements ... */
}
```
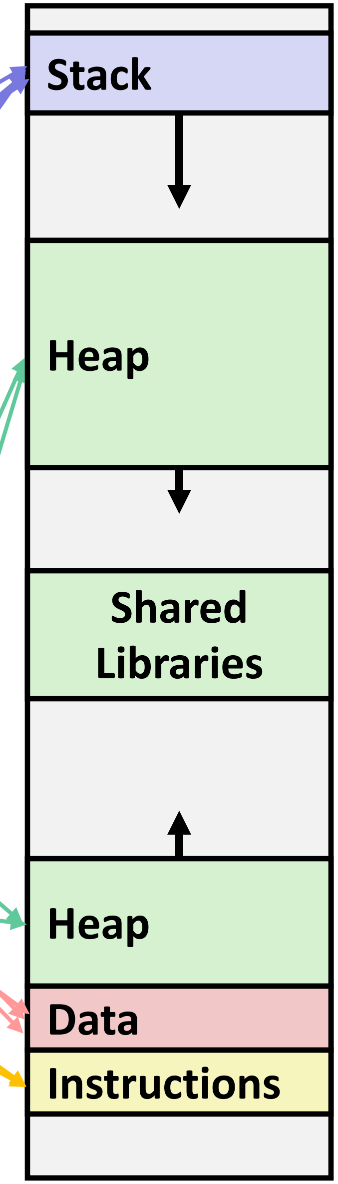
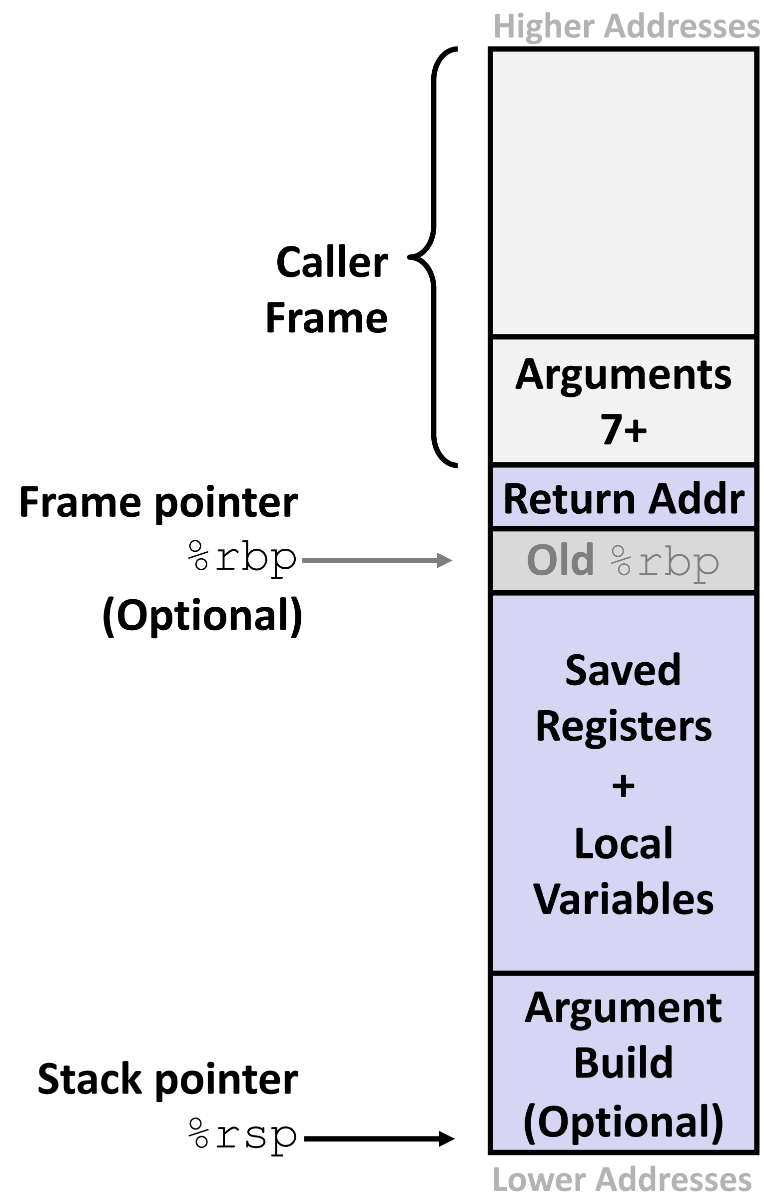



Where does everything go?

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()`

```
/* 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;
}
```

pointer to start of an array

same as:

```
*p = c;
p++;
```

  - What could go wrong in this code?

String Library Code

- Implementation of Unix function `gets()`

```
/* 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

```
/* 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:

```
0000000004005c6 <echo>:
 4005c6:  48 83 ec 18          sub    $0x18,%rsp
   ...                          ... calls printf ...
 4005d9:  48 89 e7             mov    %rsp,%rdi
 4005dc:  e8 dd fe ff ff       callq  4004c0 <gets@plt>
 4005e1:  48 89 e7             mov    %rsp,%rdi
 4005e4:  e8 95 fe ff ff       callq  400480 <puts@plt>
 4005e9:  48 83 c4 18          add    $0x18,%rsp
 4005ed:  c3                   retq
```

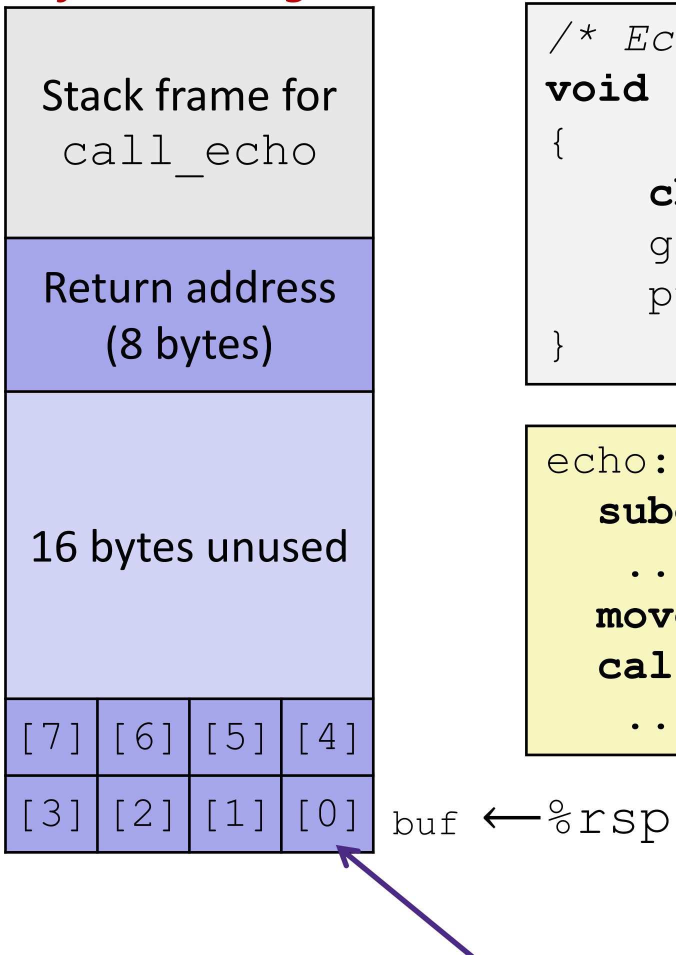
call_echo:

```
0000000004005ee <call_echo>:
 4005ee:  48 83 ec 08          sub    $0x8,%rsp
 4005f2:  b8 00 00 00 00       mov    $0x0,%eax
 4005f7:  e8 ca ff ff ff       callq  4005c6 <echo>
 4005fc:  48 83 c4 08          add    $0x8,%rsp
 400600:  c3                   retq
```

return address

Buffer Overflow Stack

Before call to gets



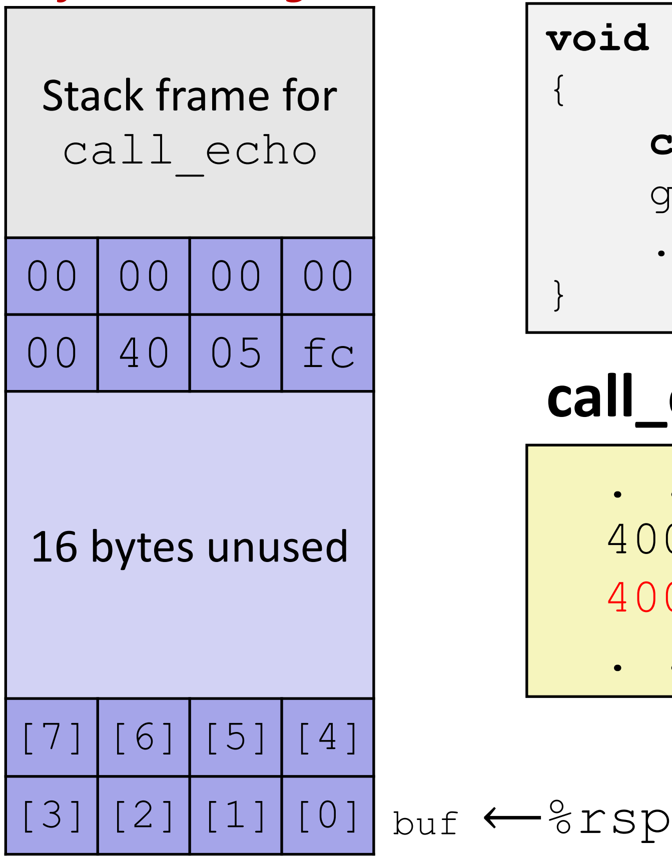

```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

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

Buffer Overflow Example

Before call to gets




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

```
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`

00	00	00	00
00	40	05	fc
00	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

Note: Digit "*N*" is just 0x3*N* in ASCII!

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

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

call_echo:

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

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

Overflowed buffer, but did not corrupt state

Buffer Overflow Example #2

After call to gets

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

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

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

call_echo:

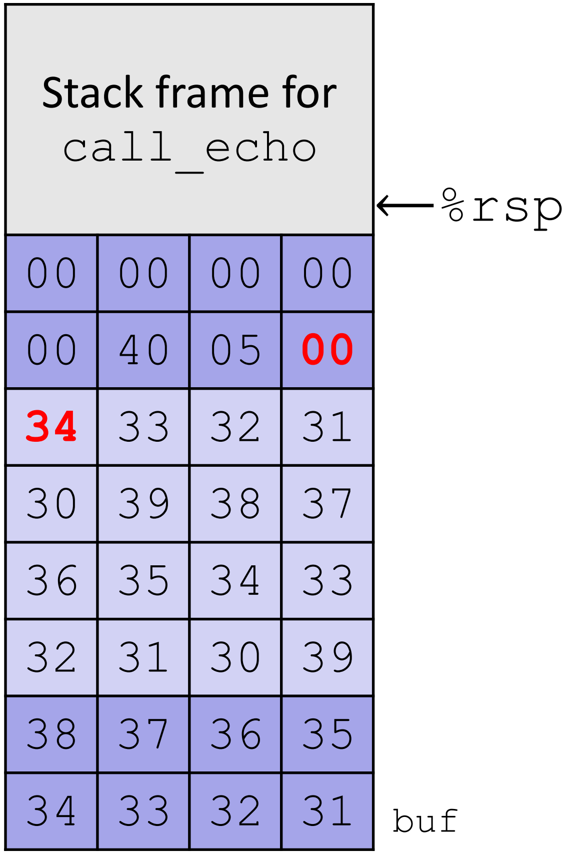
```
   . . .
   4005f7:  callq   4005c8 <echo>
   4005fc:  add     $0x8,%rsp
   . . .
```

```
unix> ./buf-nsp
Enter string: 12345678901234567890123**4**
Segmentation Fault
```

Overflowed buffer and corrupted return pointer

Buffer Overflow Example #2 Explained

After return from echo




```
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`.

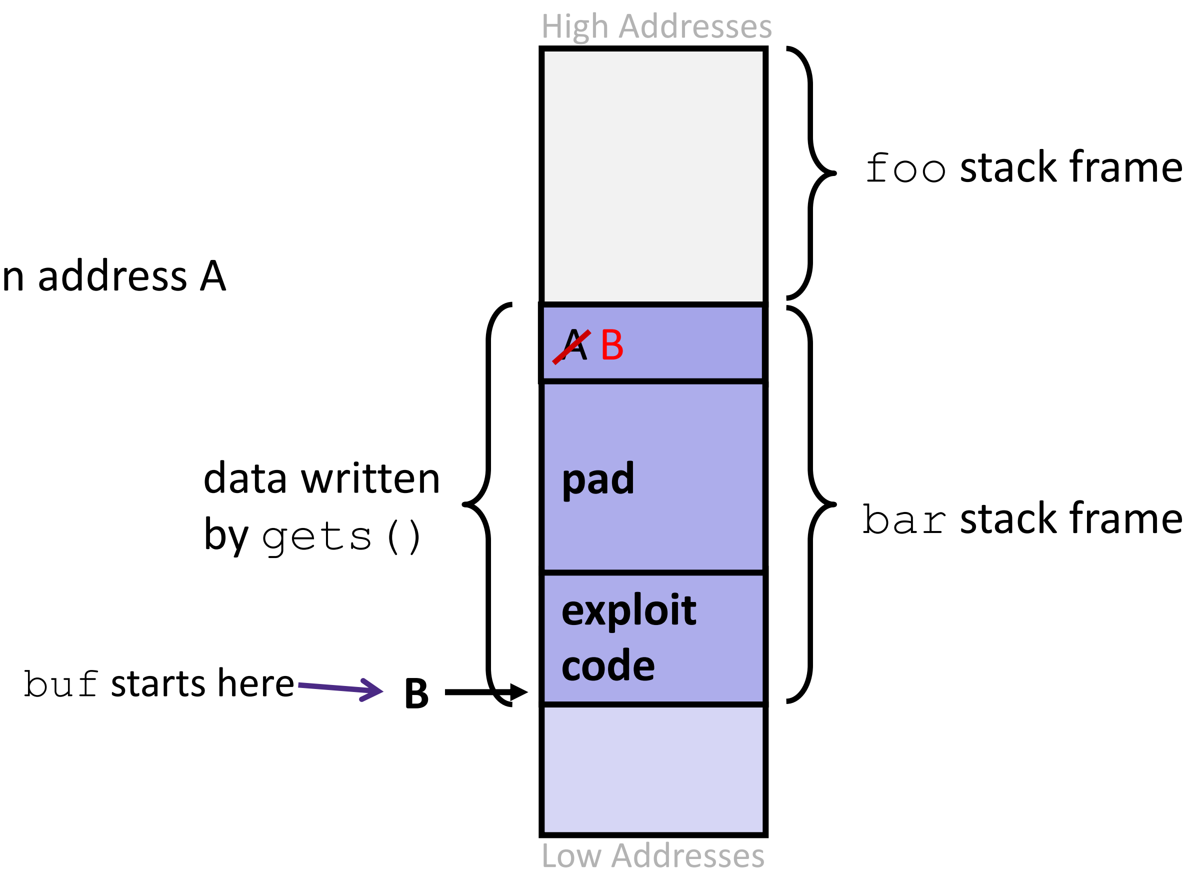
Malicious Use of Buffer Overflow: Code Injection Attacks

```
void foo(){
  bar();
A:...
}
```

return address A

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

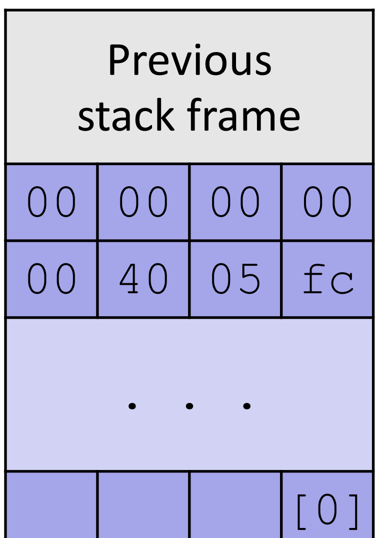
Stack after call to gets()



- 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

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!




```
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

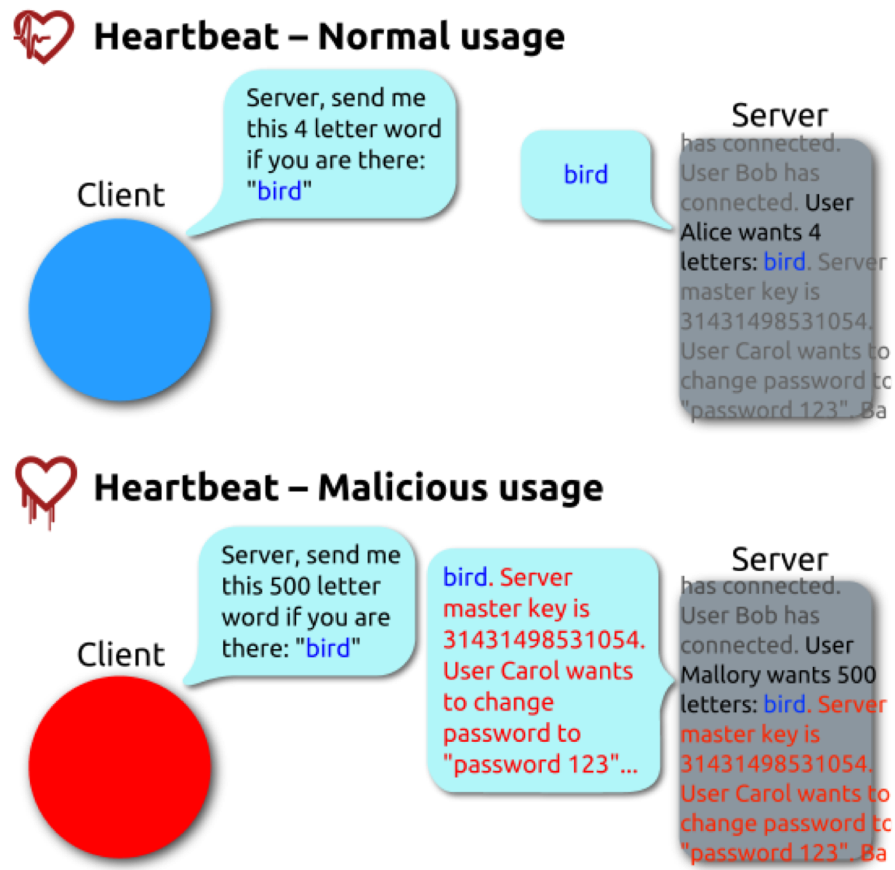
- *Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines*
- Distressingly common in real programs
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original “Internet worm” (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
    - FlappyBird in Mario: 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”

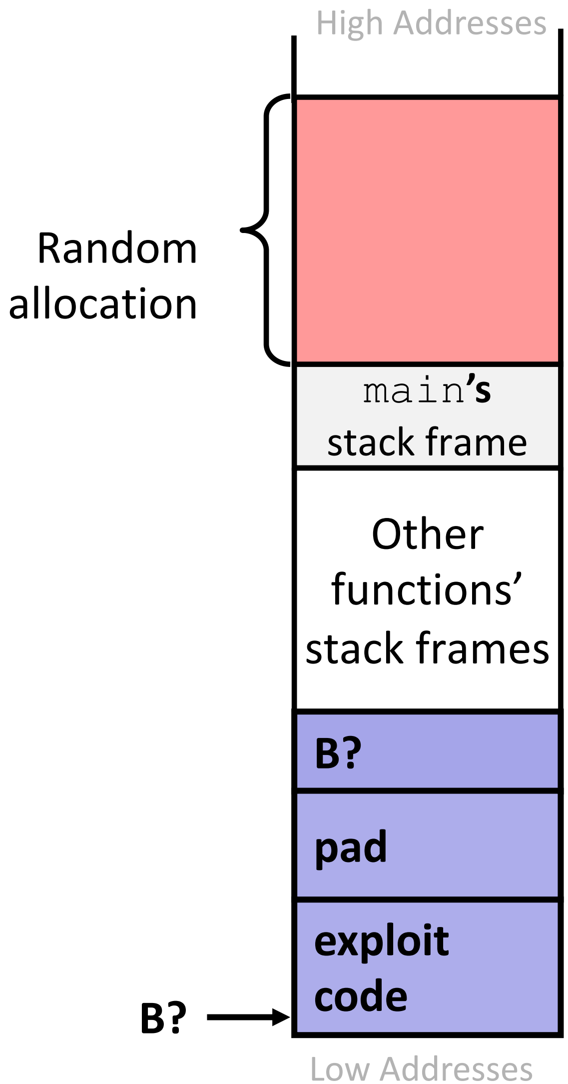
1) Avoid Overflow Vulnerabilities in Code

```
/* 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` (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

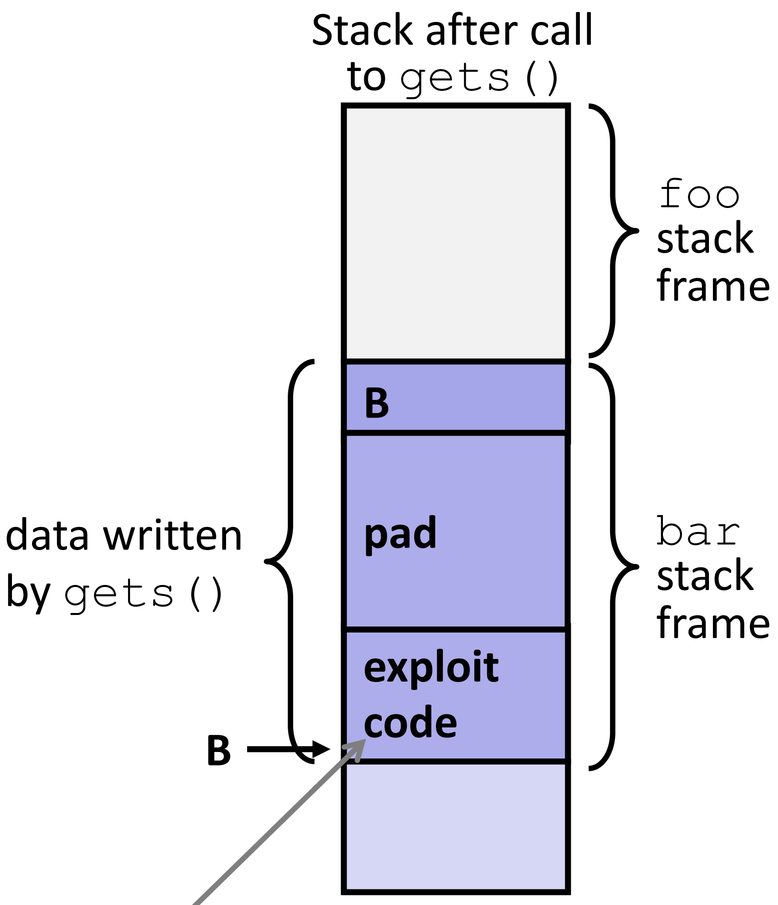
2) System-Level Protections

- **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) 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)

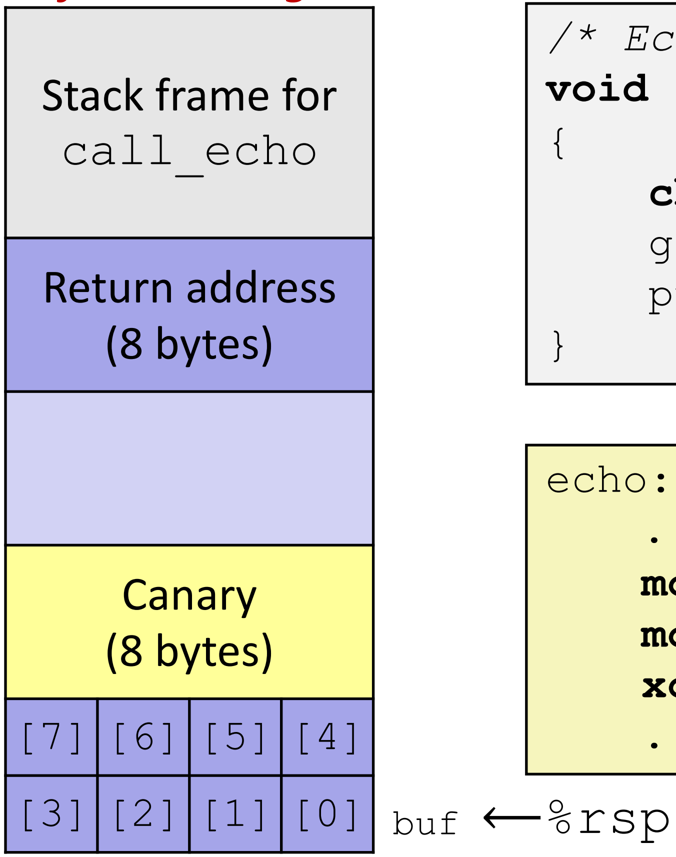
This is extra (non-testable) material

echo:

```
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
```

Setting Up Canary

Before call to gets



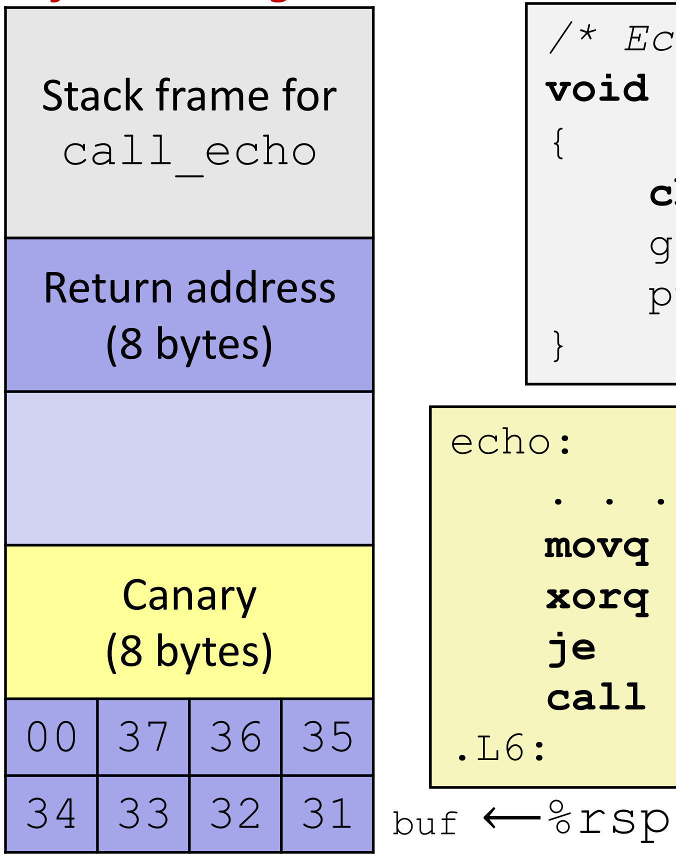

```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

Segment register
(don't worry about it)

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

Checking Canary

After call to gets




```
/* 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:        . . .
```

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"