Buffer Overflows

CSE 351 Summer 2018

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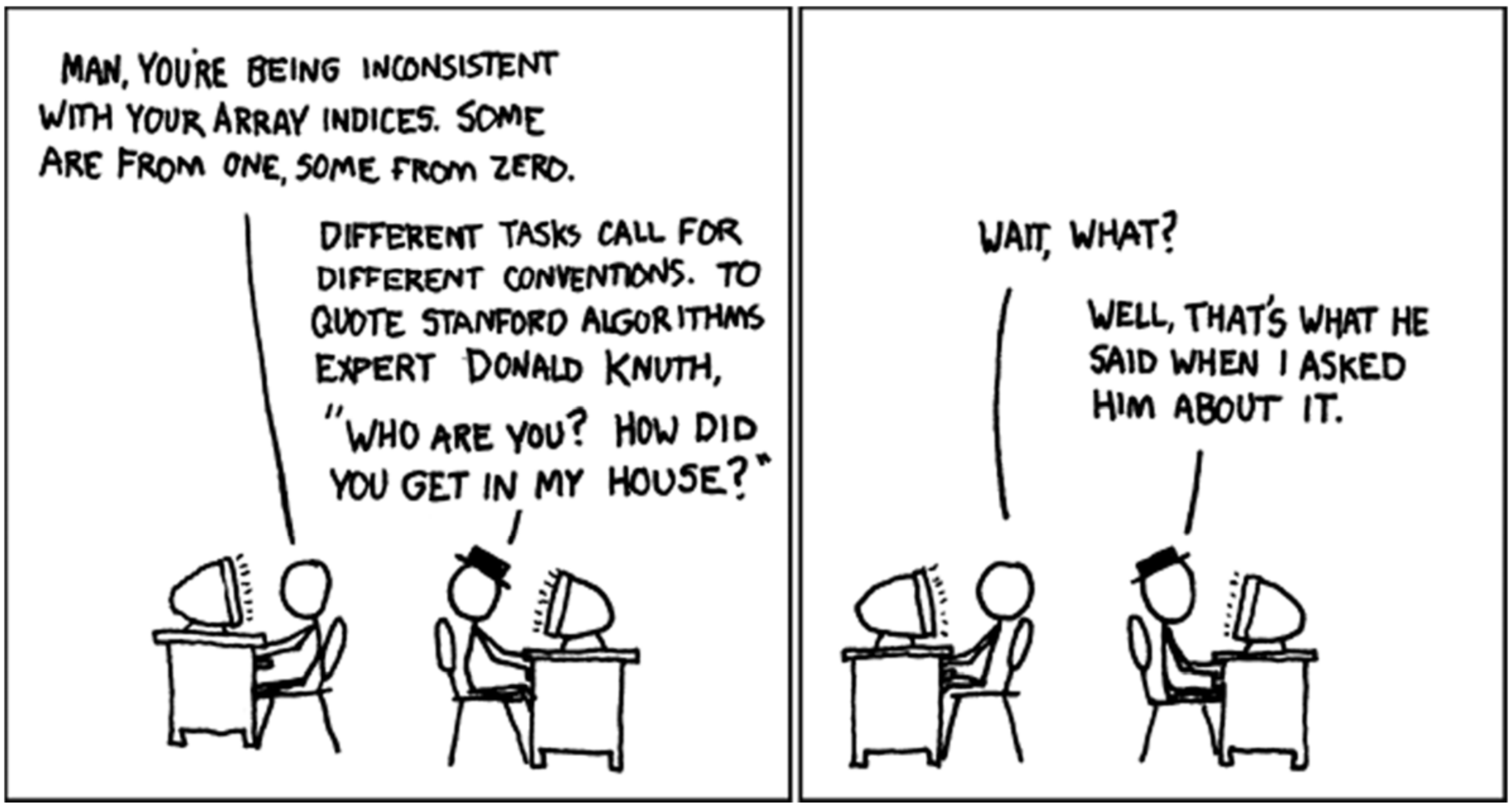


http://xkcd.com/163/

Administrivia

- Mid-quarter survey due tonight (7/20)
- Homework 3 due Monday (7/23)
- Lab 3 due next Friday (7/27)

- Midterm grades (out of 100) released
  - Solutions posted on website
  - Rubric and grades found on Gradescope
  - Regrade requests will be open until Sunday (7/22) @ 5 pm
    - Must include reason based on solutions and rubric

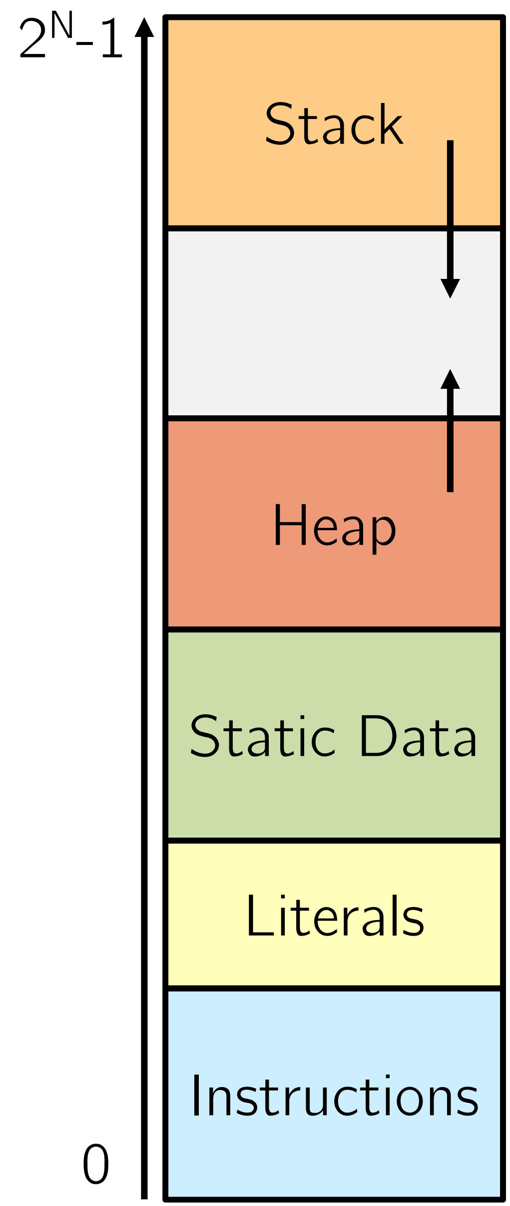
Buffer Overflows

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

not drawn to scale

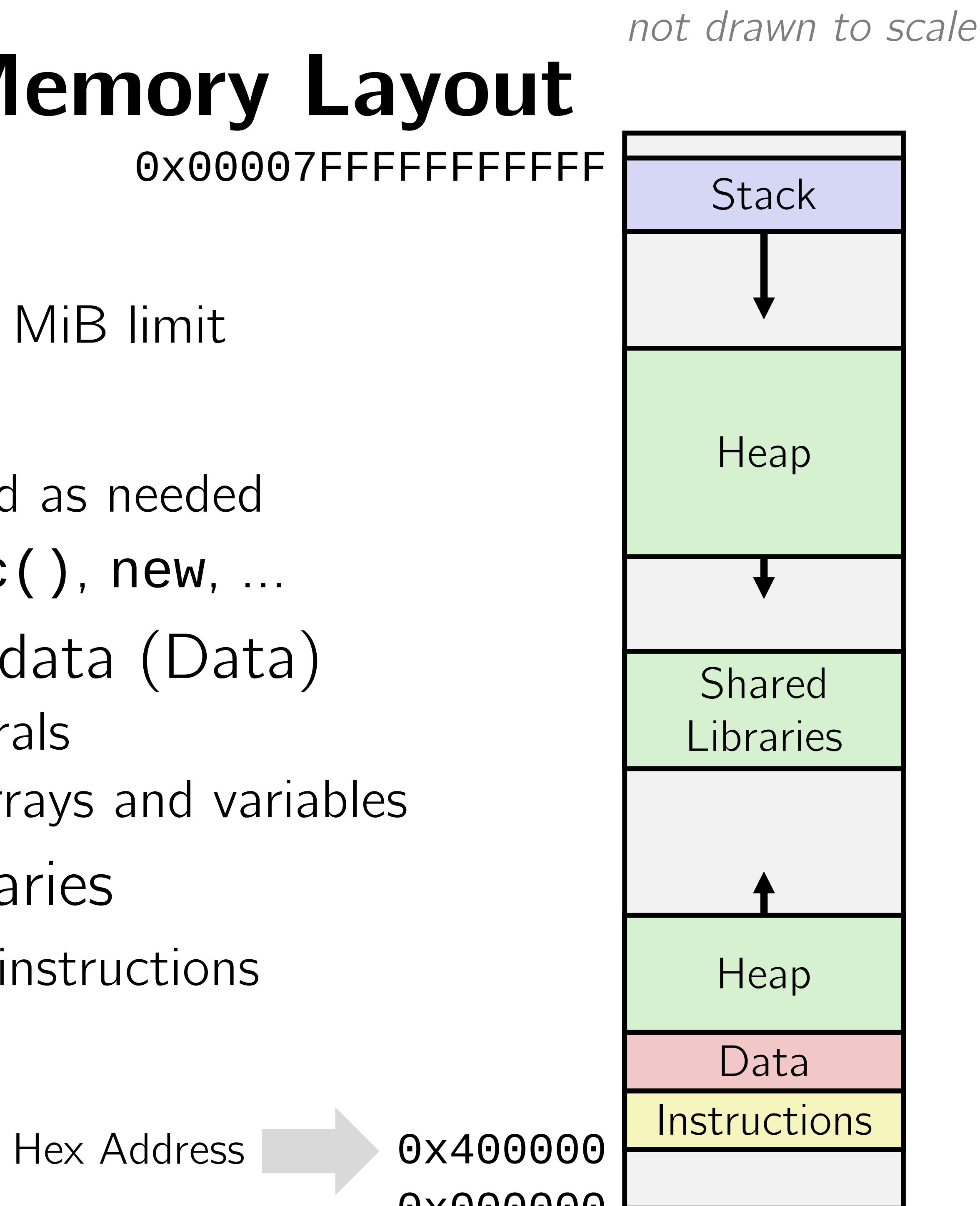
Review: General Memory Layout

- 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



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



Memory Allocation Example

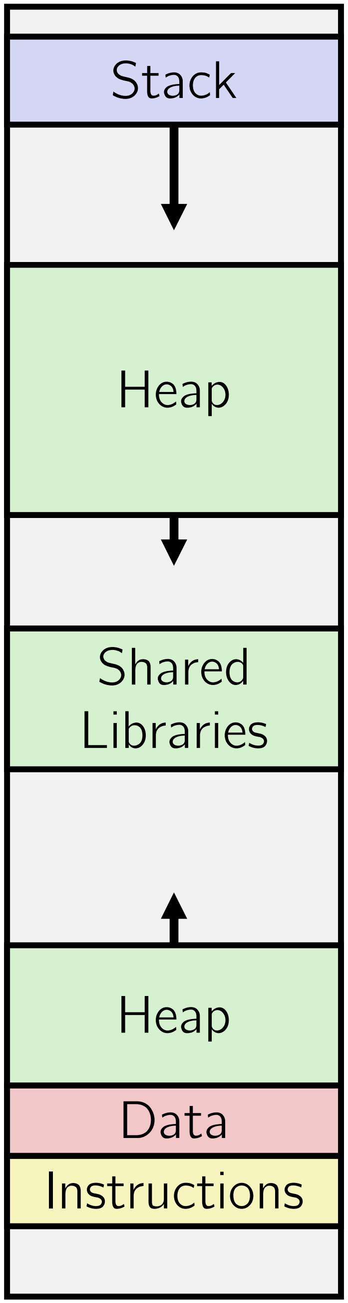
not drawn to scale

```
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 */
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 */
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    p4 = malloc(1L << 8);  /* 256  B */
    /* Some print statements ... */
}
```
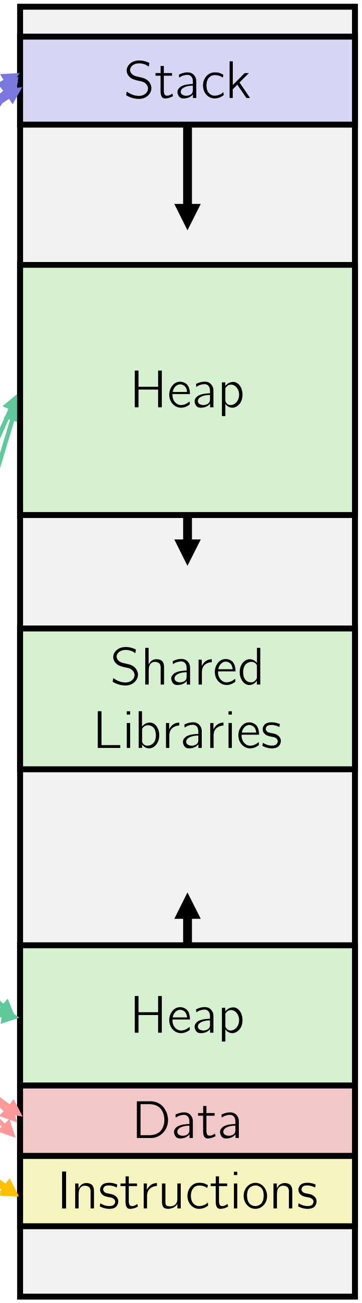
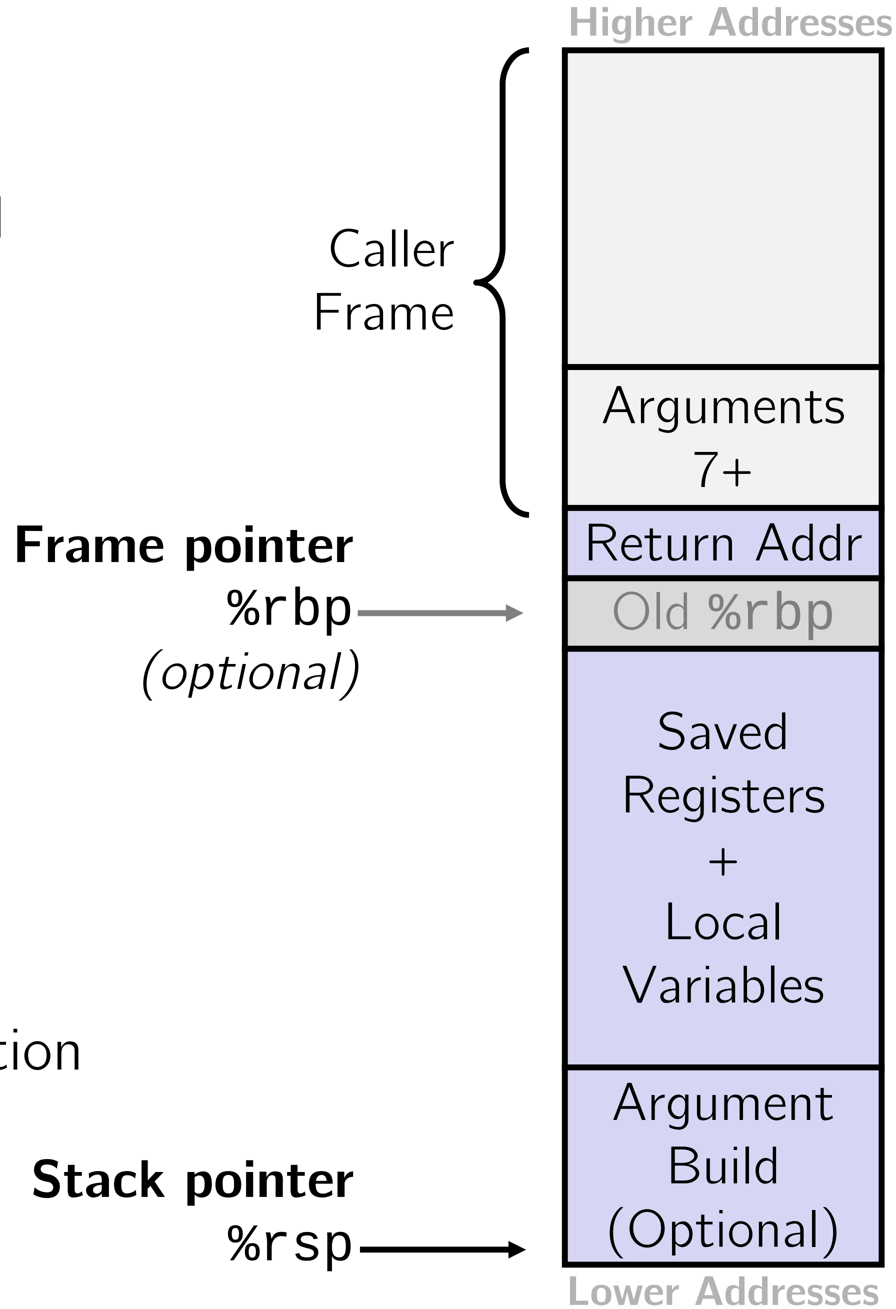



Where does everything go?

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 be called, 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
```

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
```

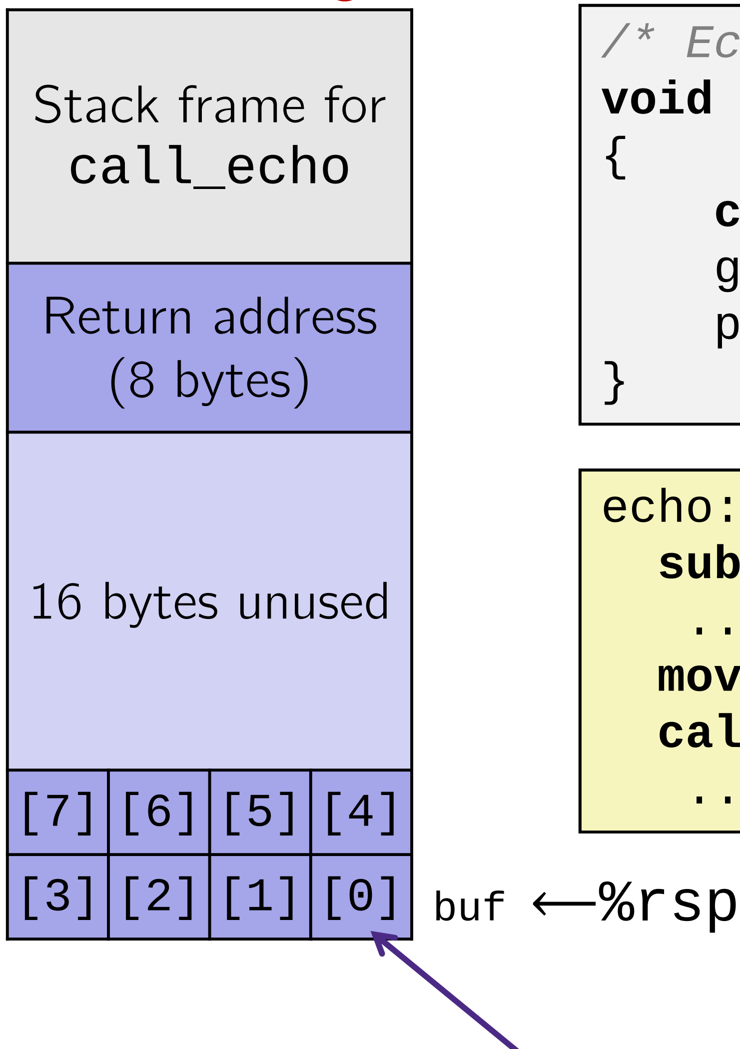
call_echo:

```
00000000004005ee <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 (4005fc)

Buffer Overflow Stack

Before call to gets



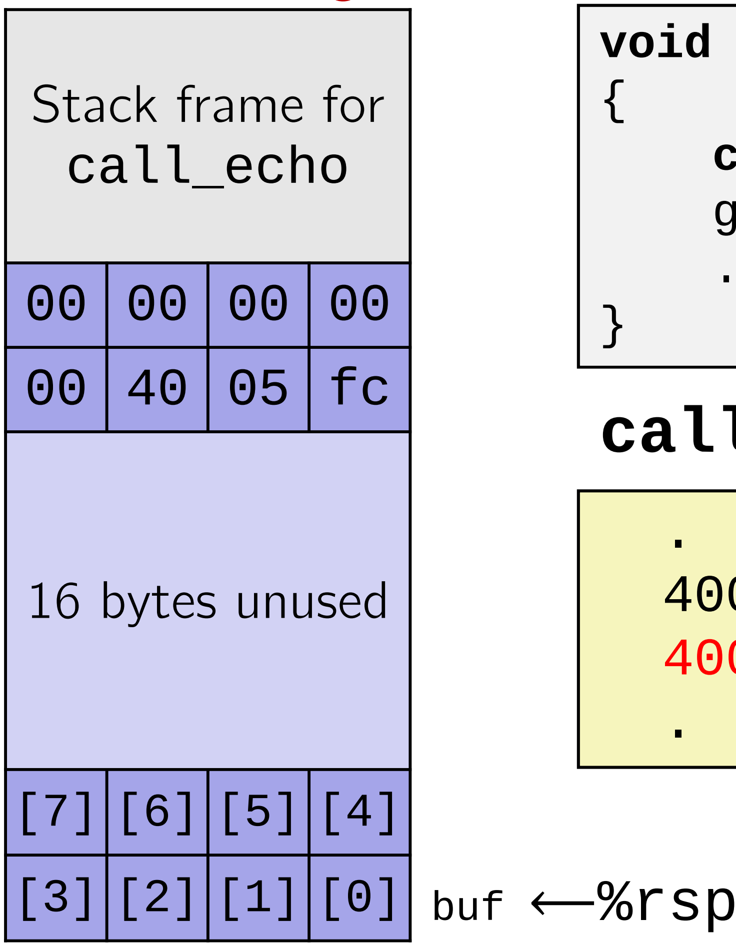

```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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: 123456789012345678901234
Segmentation Fault
```

Overflowed buffer and corrupted return pointer

Buffer Overflow Example #2

After return from echo

Stack frame for `call_echo`				←%rsp
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

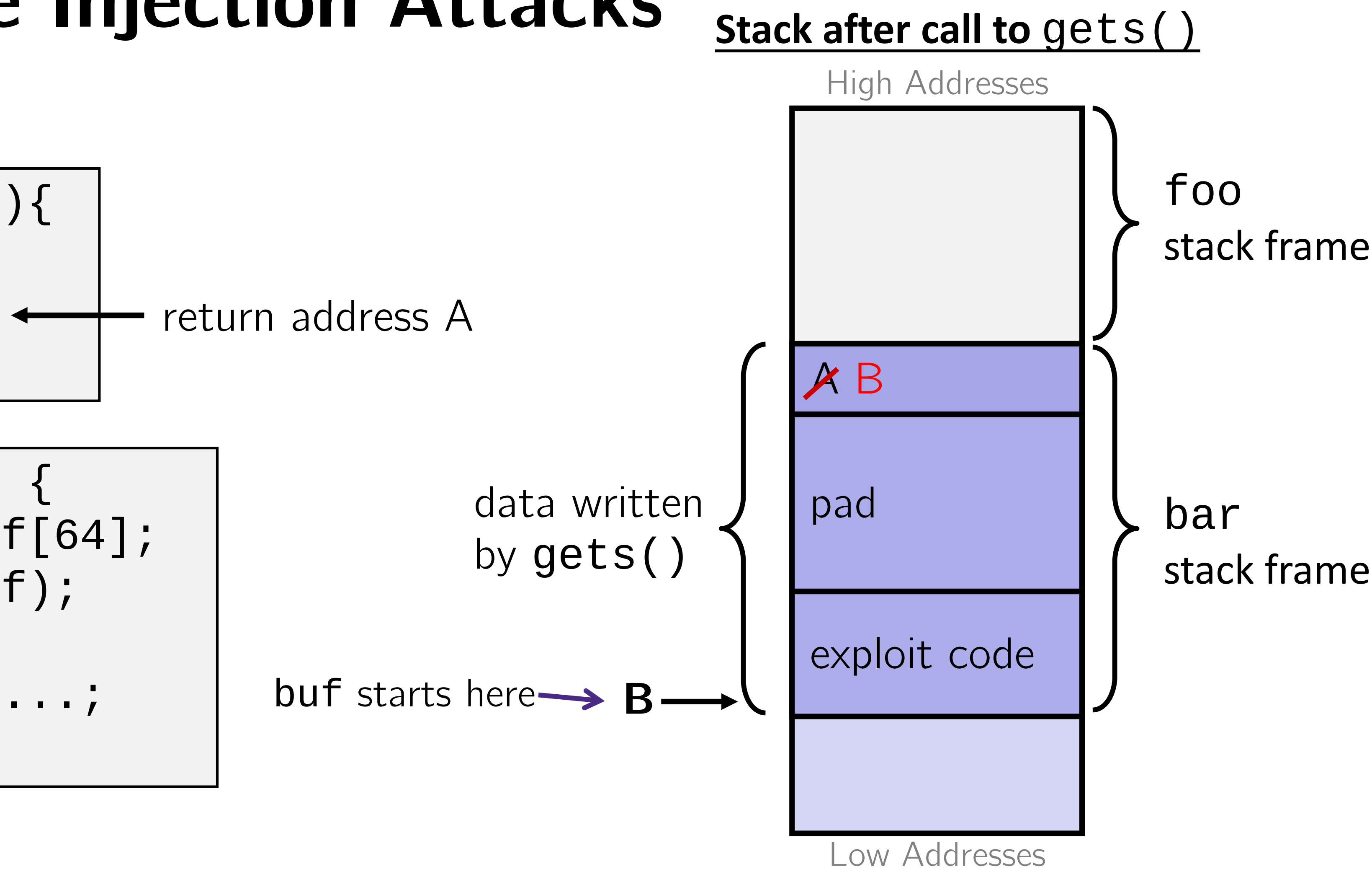
```
0000000000400500 <deregister_tm_clones>:
  400500:   mov    $0x60104f,%eax
  400505:   push   %rbp
  400506:   sub    $0x601048,%rax
  40050c:   cmp    $0xe,%rax
  400510:   mov    %rsp,%rbp
  400513:   jbe    400530
  400515:   mov    $0x0,%eax
  40051a:   test   %rax,%rax
  40051d:   je     400530
  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:...
}
```

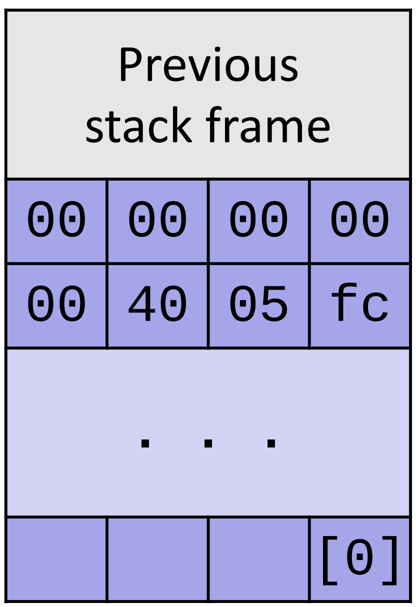
```
int bar() {
  char buf[64];
  gets(buf);
  ...
  return ...;
}
```



- 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)?
  - Vote at http://PollEv.com/justinh




```
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

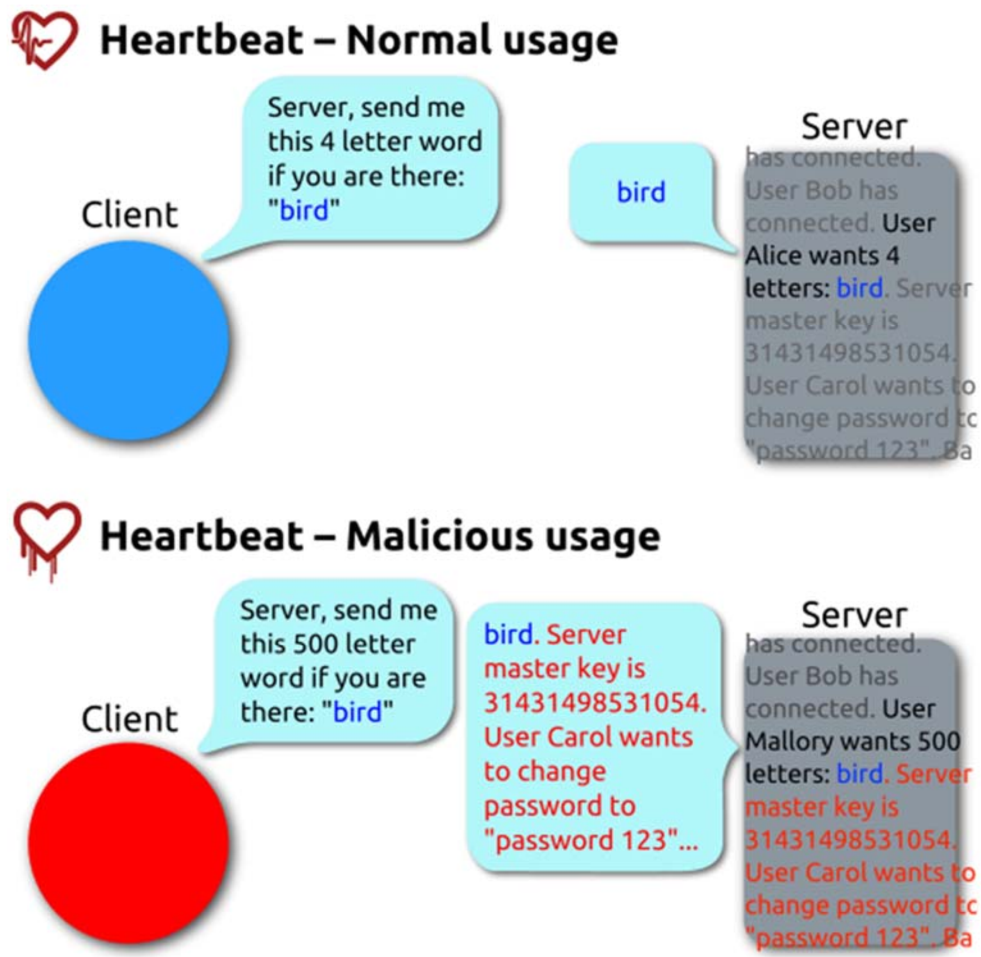
- *Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines*
- Distressingly common in real programs
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original "Internet worm"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

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"

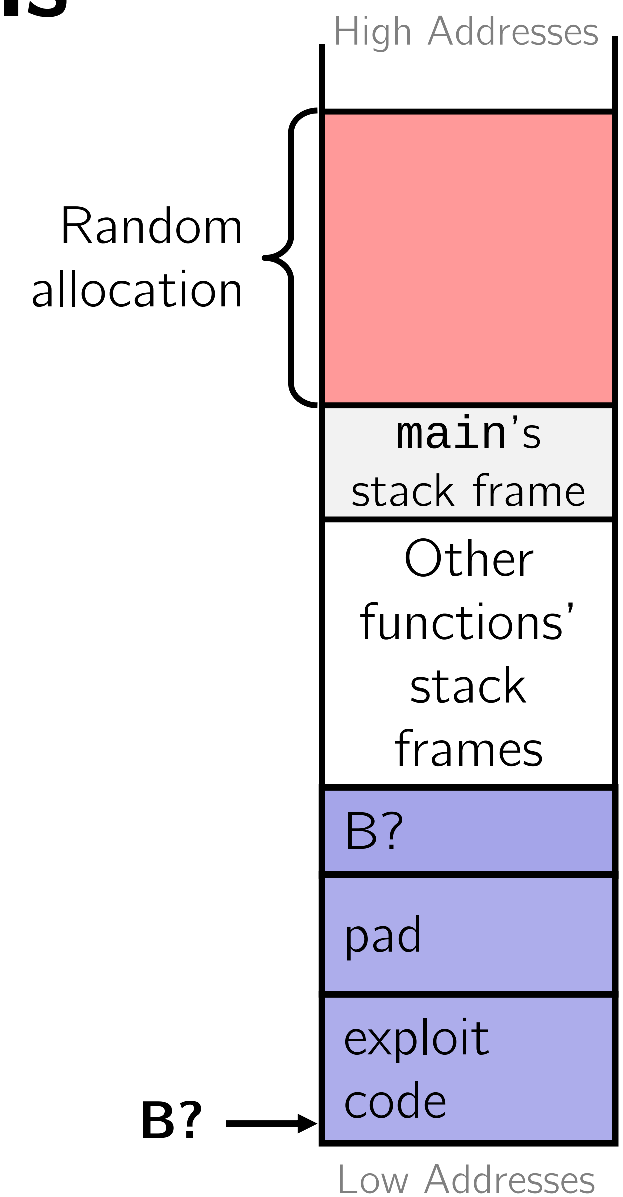
1) Avoid Overflow Vulnerabilities

```
/* 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

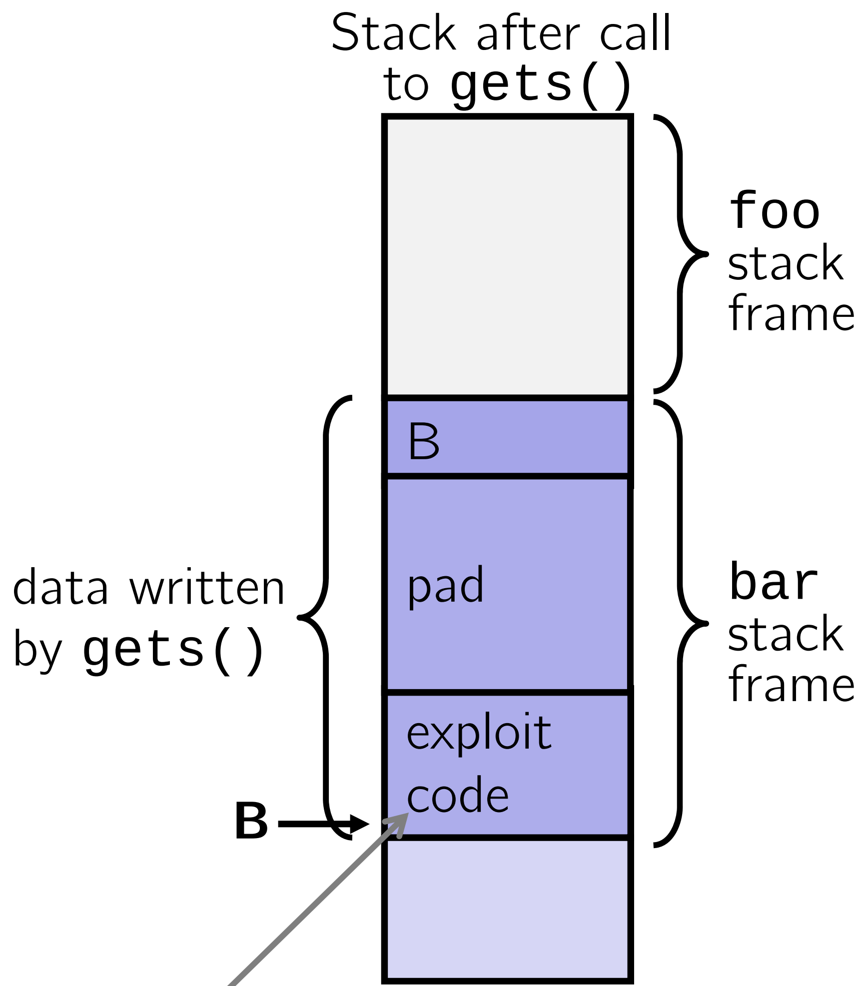
2) System-Level Protections

- **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 the 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 Disassembly (buf)

This is extra (non-testable) material

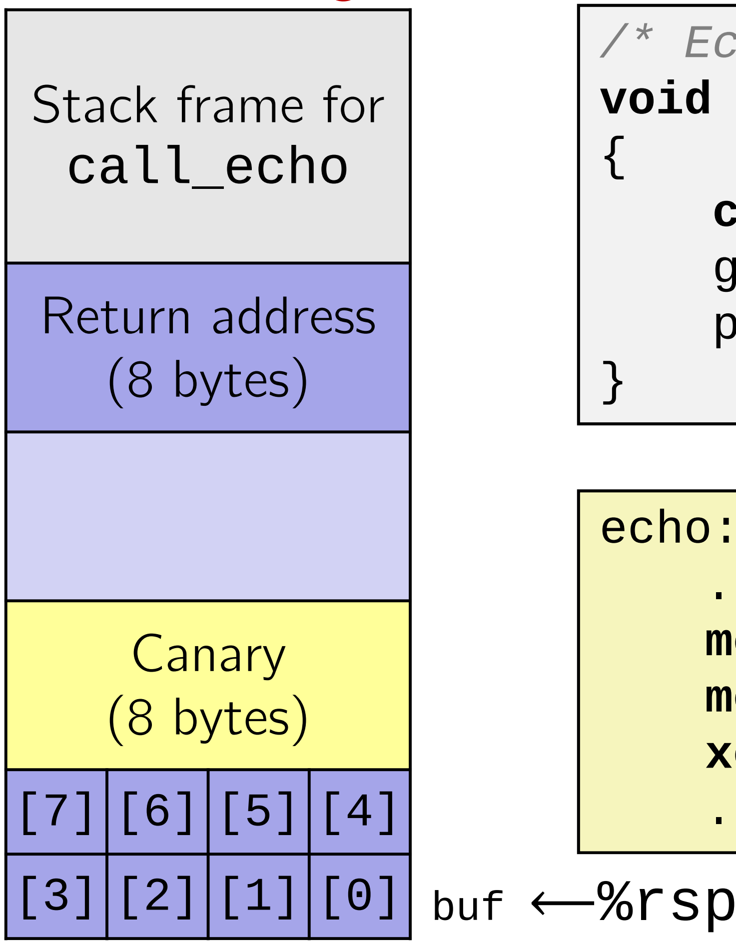
echo:

```
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

This is extra (non-testable) material

Before call to gets




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

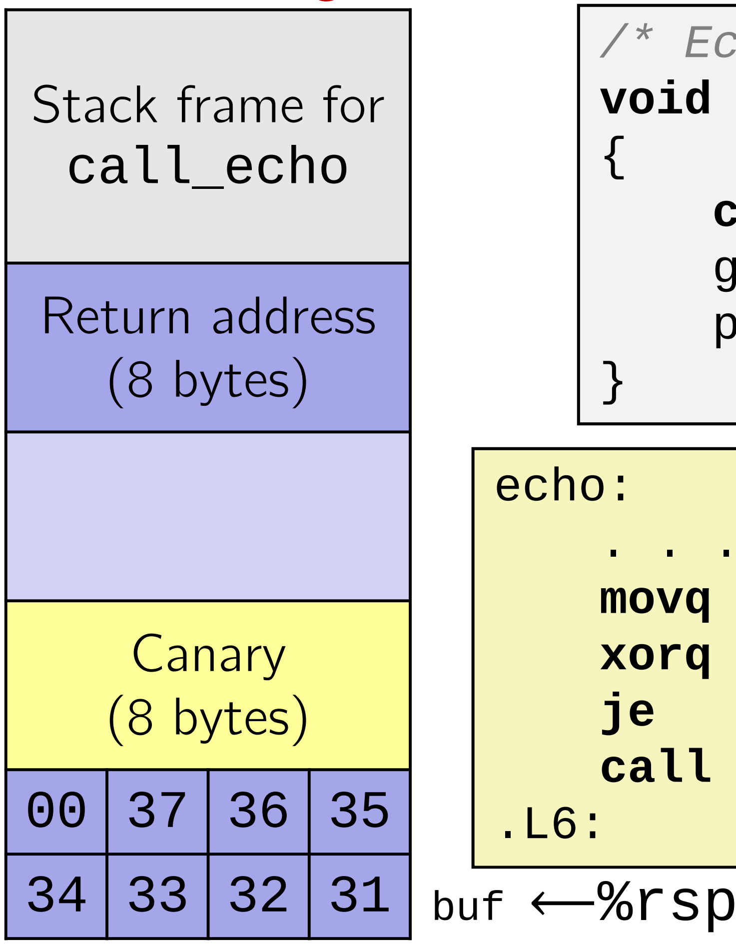
Segment register *(don't worry about it)*

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

Checking Canary

This is extra (non-testable) material

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***

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 10

OS X Yosemite

Computer system:

Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Aside: Units and Prefixes

- Here focusing on large numbers (exponents > 0)
- Note that $10^3 \approx 2^{10}$
- SI prefixes are *ambiguous* if base 10 or 2
- IEC prefixes are *unambiguously* base 2

SIZE PREFIXES (10^x for Disk, Communication; 2^x for Memory)

SI Size	Prefix	Symbol	IEC Size	Prefix	Symbol
10^3	Kilo-	K	2^{10}	Kibi-	Ki
10^6	Mega-	M	2^{20}	Mebi-	Mi
10^9	Giga-	G	2^{30}	Gibi-	Gi
10^{12}	Tera-	T	2^{40}	Tebi-	Ti
10^{15}	Peta-	P	2^{50}	Pebi-	Pi
10^{18}	Exa-	E	2^{60}	Exbi-	Ei
10^{21}	Zetta-	Z	2^{70}	Zebi-	Zi
10^{24}	Yotta-	Y	2^{80}	Yobi-	Yi

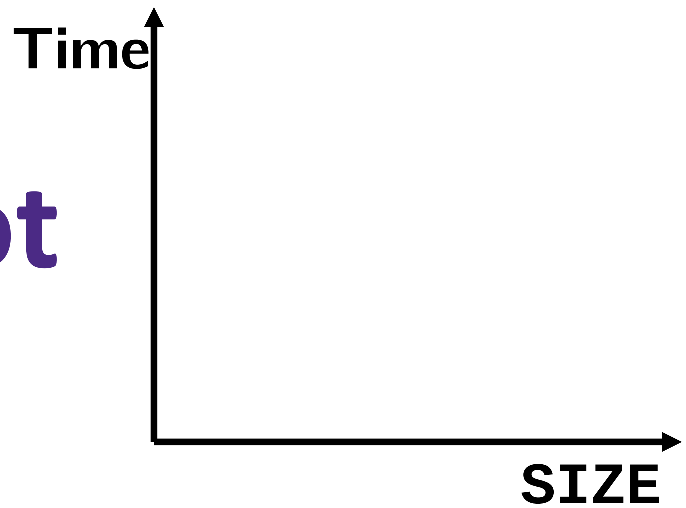
How to Remember?

- Will be given to you on Final reference sheet
- Mnemonics
  - There unfortunately isn't one well-accepted mnemonic
    - But that shouldn't stop you from trying to come with one!
  - **K**iller **M**echanical **G**iraffe **T**eaches **P**et, **E**xtinct **Z**ebra to **Y**odel
  - **K**irby **M**issed **G**anondorf **T**erribly, **P**otentially **E**xterminating **Z**elda and **Y**oshi
  - xkcd: **K**arl **M**arx **G**ave **T**he **P**roletariat **E**leven **Z**eppelins, **Y**o
    - https://xkcd.com/992/
  - Post your best on Piazza!

How does execution time grow with SIZE?

```
int array[SIZE];
int sum = 0;

for (int i = 0; i < 200000; i++) {
  for (int j = 0; j < SIZE; j++) {
    sum += array[j];
  }
}
```

Plot



Actual Data