Buffer Overflows

CSE 351 Autumn 2018

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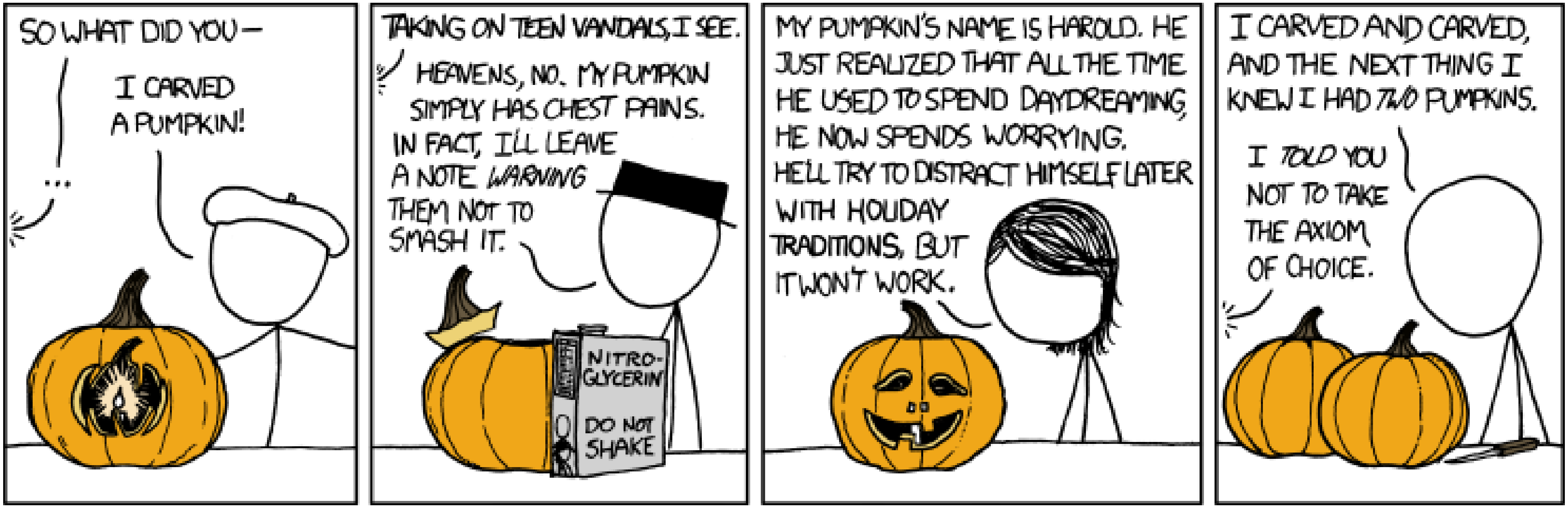


http://xkcd.com/804/

Administrivia

- Mid-quarter survey due tomorrow (11/1)
- Homework 3 due Friday (11/2)
- Lab 3 released today, due next Friday (11/9)

- Midterm grades (out of 100) to be released by Friday
  - Solutions posted on website
  - Rubric and grades will be found on Gradescope
  - Regrade requests will be open for a short time after grade release

Peer Instruction Question

Vote on sizeof(**struct old**): http://PollEv.com/justinh

- Minimize the size of the struct by re-ordering the vars

K
4
2
8
4
$K_{max} = 8$

```
struct old {
   int i;

   short s[3];

   char *c;

   float f;
};
```

```
struct new {
   int     i;

   float   f   ;

   char *  c   ;

   short   s[3] ;
};
```

could also switch these (internal vs. external frag)

- What are the old and new sizes of the struct?

sizeof(struct old) = 32 B

sizeof(struct new) = 24 B

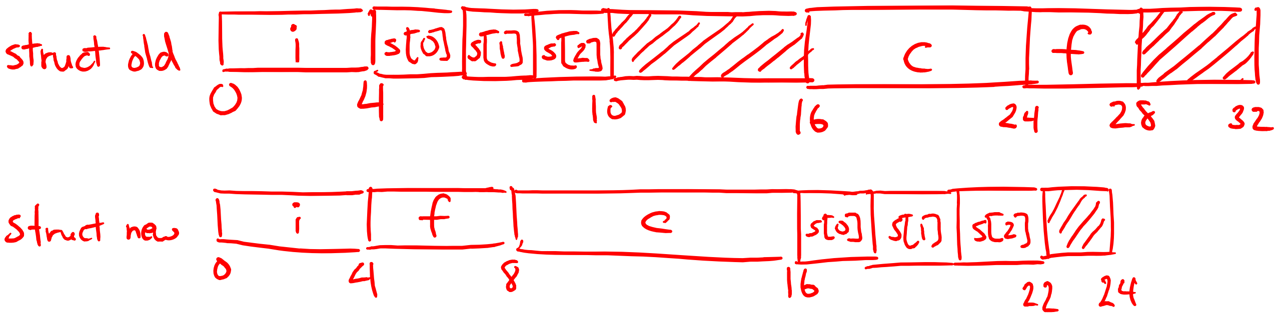
A. 16 bytes

B. 22 bytes

C. 28 bytes

[✓ D. 32 bytes]

E. We're lost…



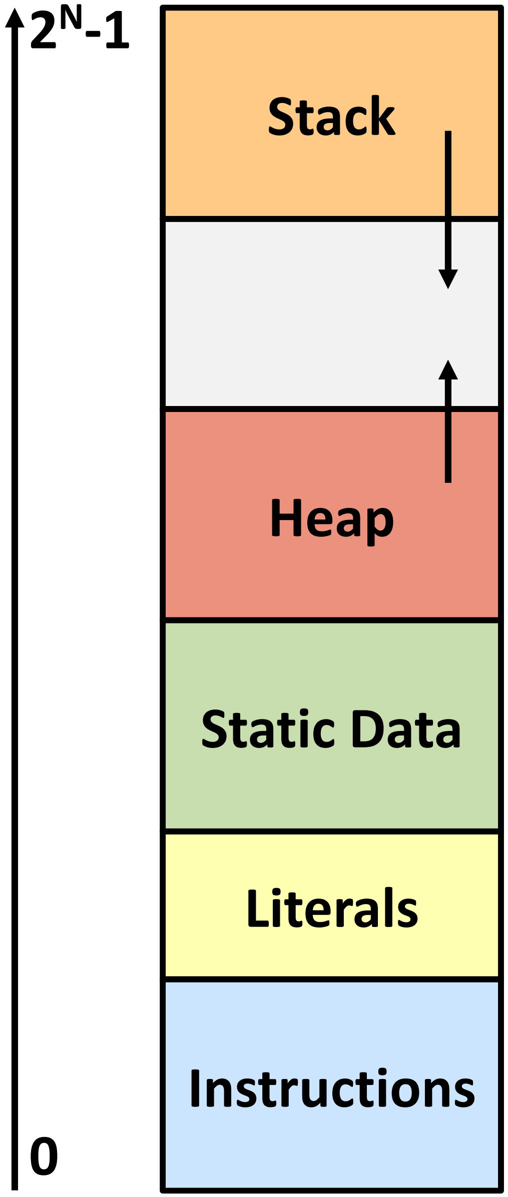
Buffer Overflows

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

not drawn to scale

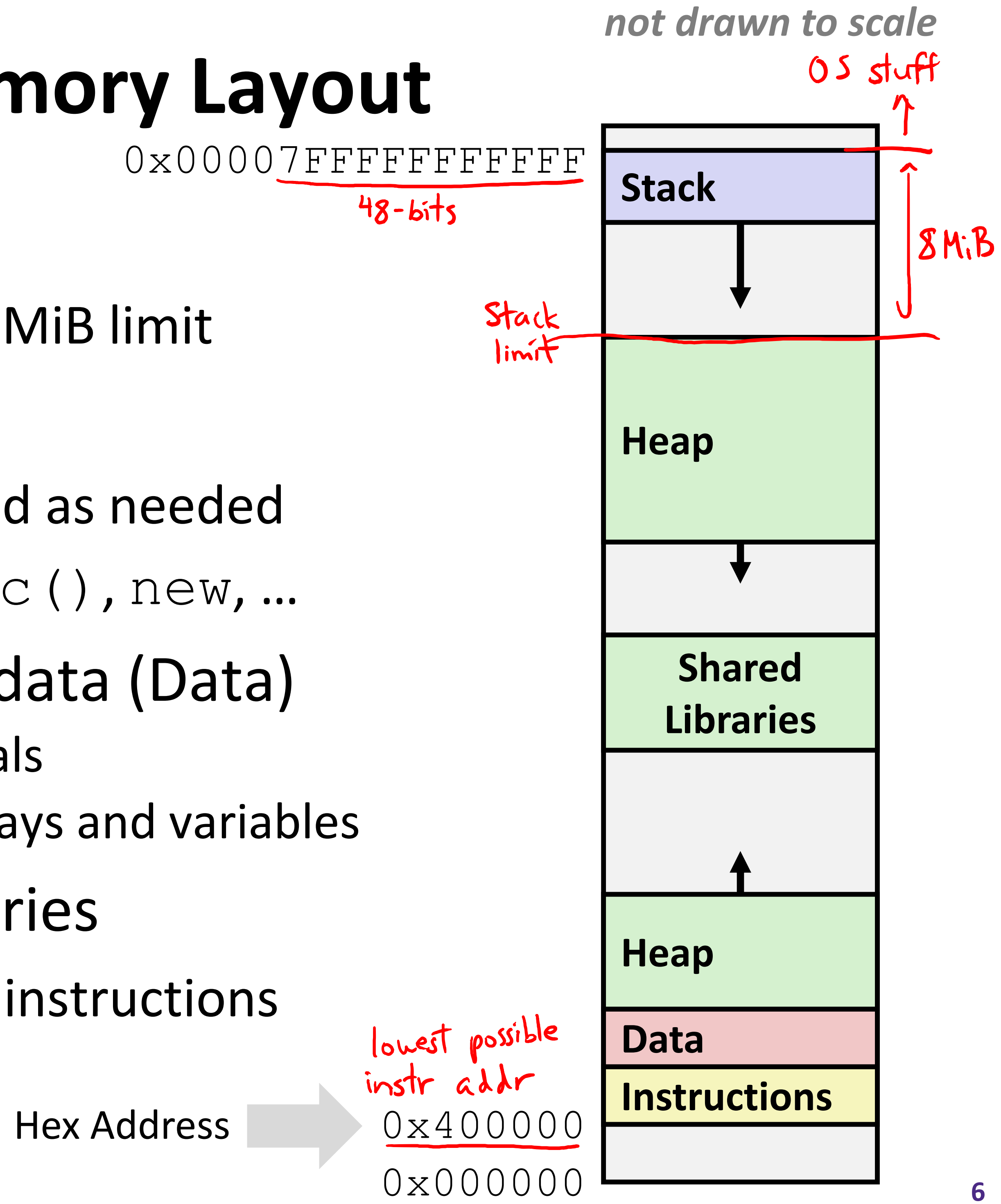
Review: General Memory Layout

- 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

```
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 ... */
}
```

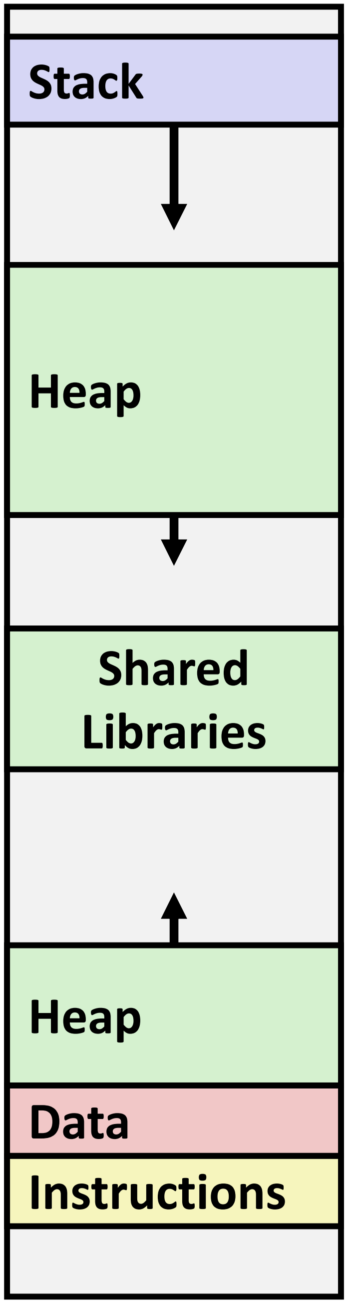
global (Data)

labels in code

local (Stack)

dynamically-allocated memory (Heap)

not drawn to scale

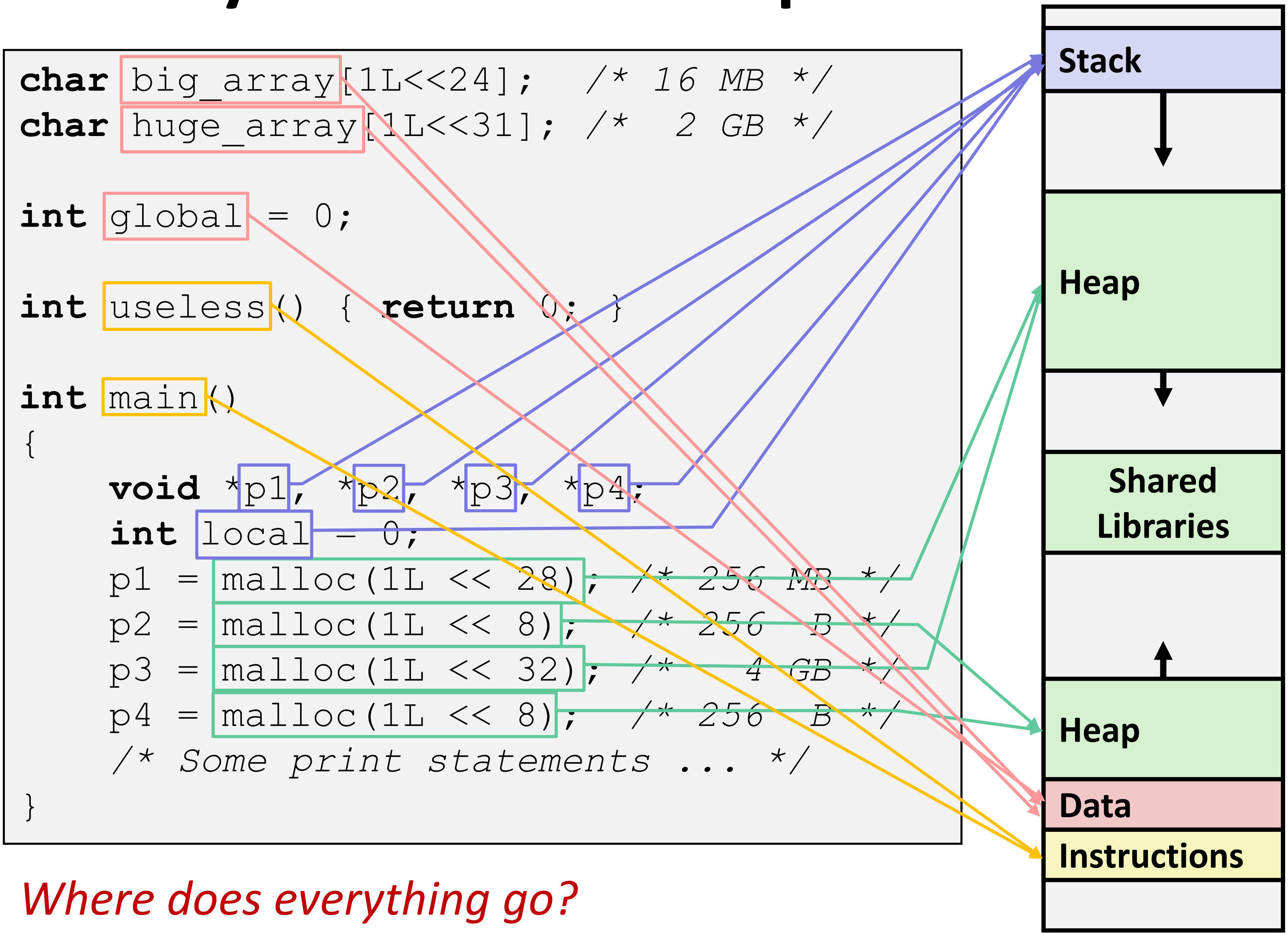


Where does everything go?

p1 → stack address
*p1 → heap address

not drawn to scale

Memory Allocation Example

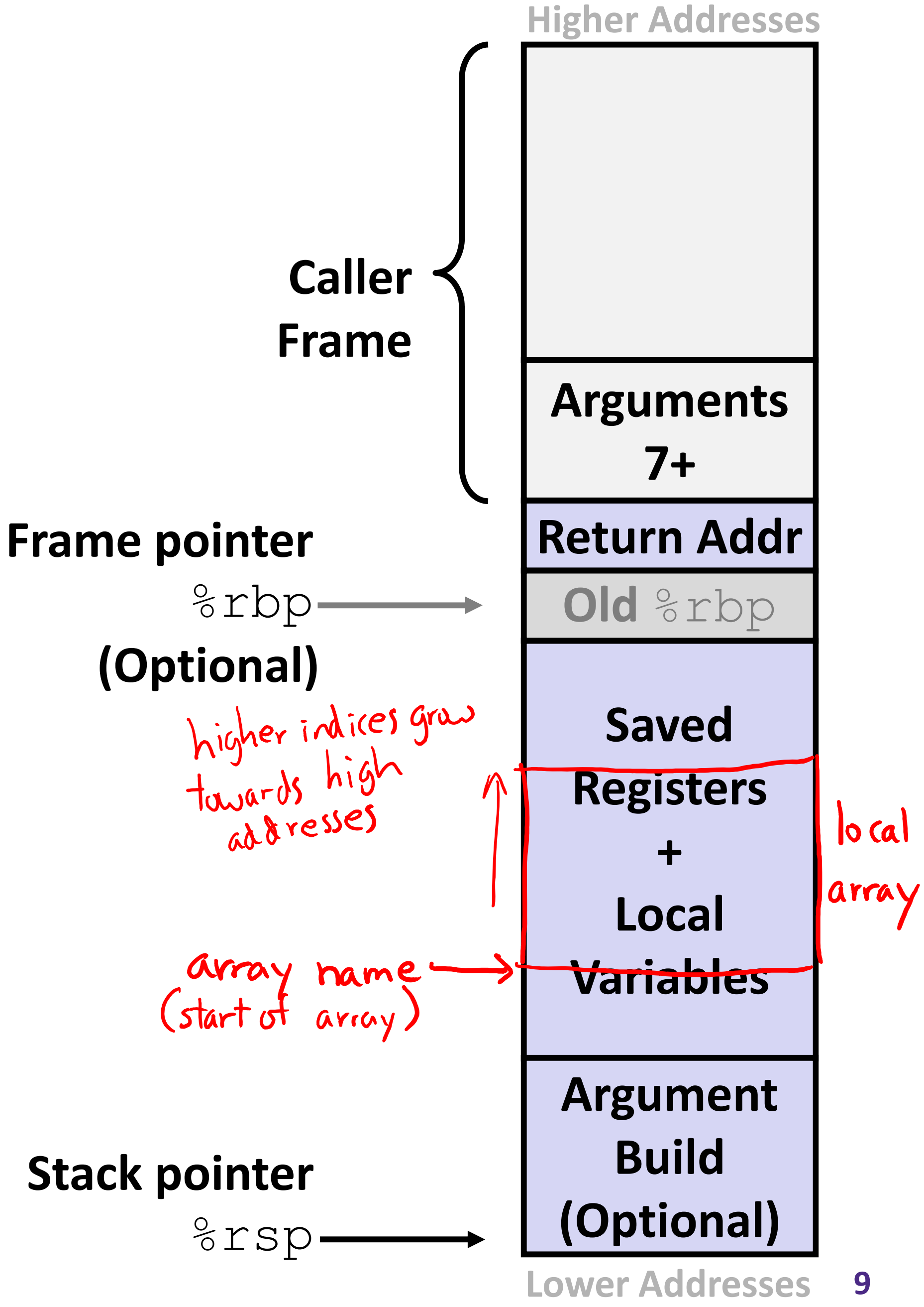


```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

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 */
    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)



Higher Addresses

Caller Frame

Arguments 7+

Return Addr

Frame pointer `%rbp` **(Optional)**

Old `%rbp`

Saved Registers + Local Variables

higher indices grow towards high addresses

local array

array name (start of array)

Argument Build (Optional)

Stack pointer `%rsp`

Lower Addresses

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;
}
```

end of file

newline

reads character from input stream

pointer to start of an array (don't know size!)

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

    ↖ stop condition looking for special characters

- 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);
}
```

input buffer

read input into buffer

print output from buffer

```
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:

24

```
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 fe ff ff           callq  400480 <gets@plt>
  4005b4:  48 89 7c 24 08           lea    0x8(%rsp),%rdi
  4005b9:  e8 b2 fe ff ff           callq  4004a0 <puts@plt>
  4005be:  48 83 c4 18              add    $0x18,%rsp
  4005c2:  c3                       retq
```

compiler choice

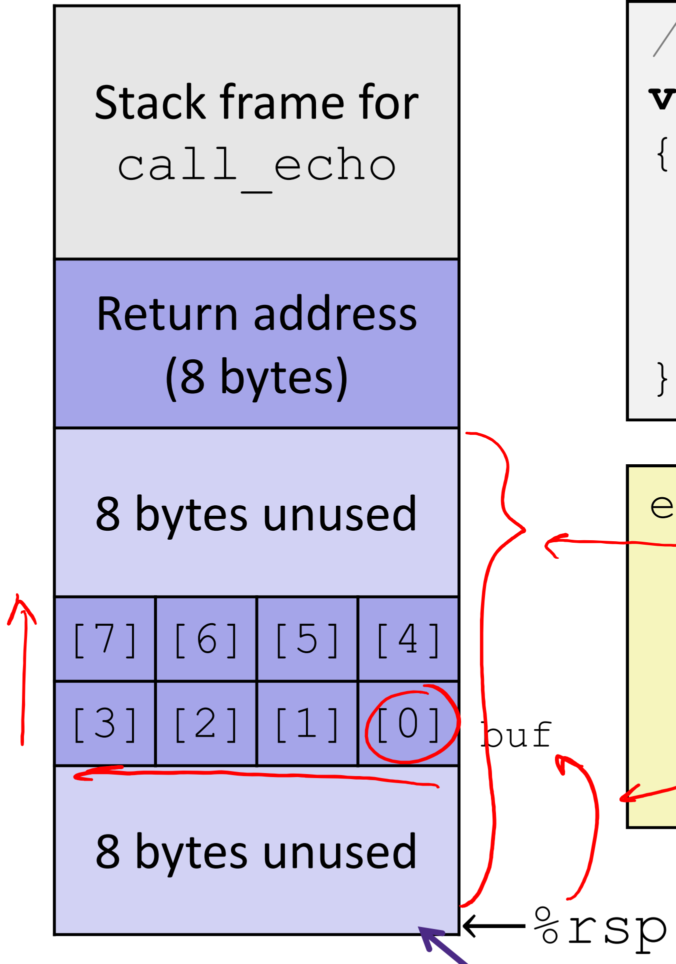
call_echo:

```
0000000004005c3 <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
```

return address placed on stack

Buffer Overflow Stack

Before call to gets



Stack frame for `call_echo`

Return address (8 bytes)

8 bytes unused

[7]	[6]	[5]	[4]
[3]	[2]	[1]	[0]

buf

8 bytes unused

%rsp

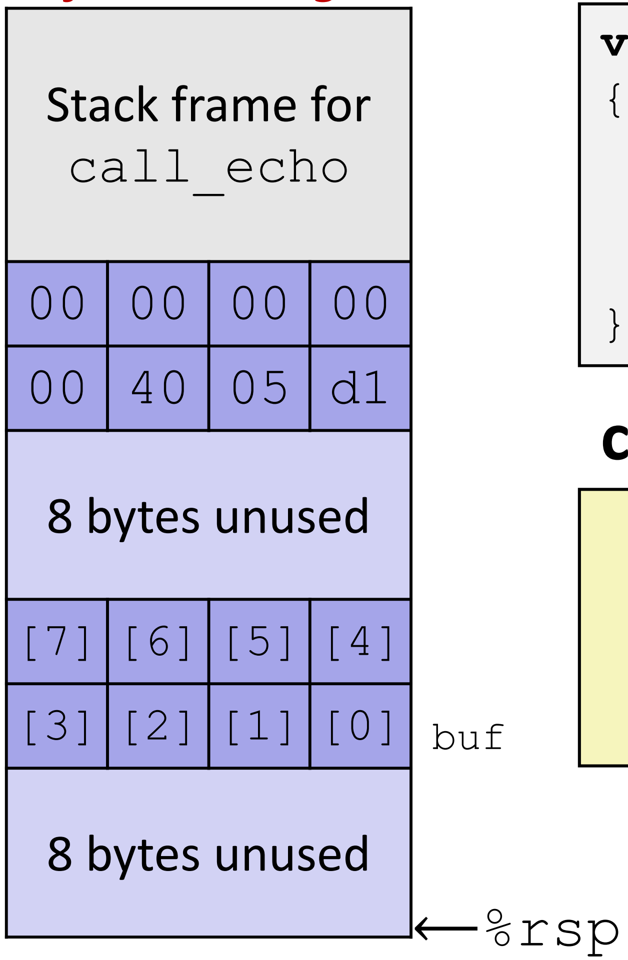
```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

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

Buffer Overflow Example

Before call to gets



Stack frame for `call_echo`

`00 00 00 00`

`00 40 05 d1`

8 bytes unused

`[7] [6] [5] [4]`

`[3] [2] [1] [0]` `buf`

8 bytes unused

← `%rsp`

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

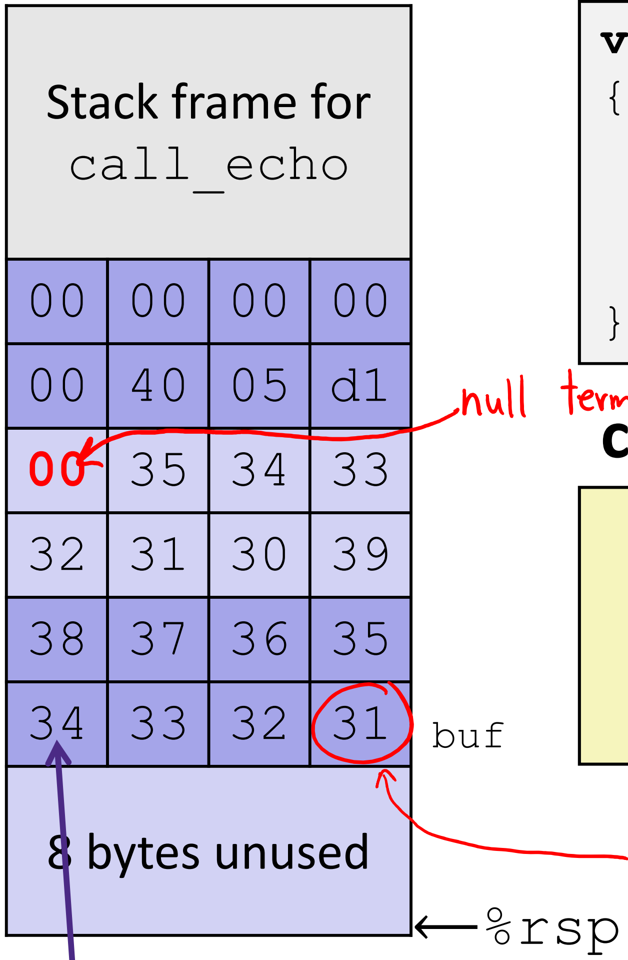
```
echo:
  subq   $24, %rsp
   ...
  leaq   8(%rsp), %rdi
  call   gets
   ...
```

call_echo:

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

Buffer Overflow Example #1

After call to gets



null terminator

0x31 = '1'

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

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

call_echo:

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

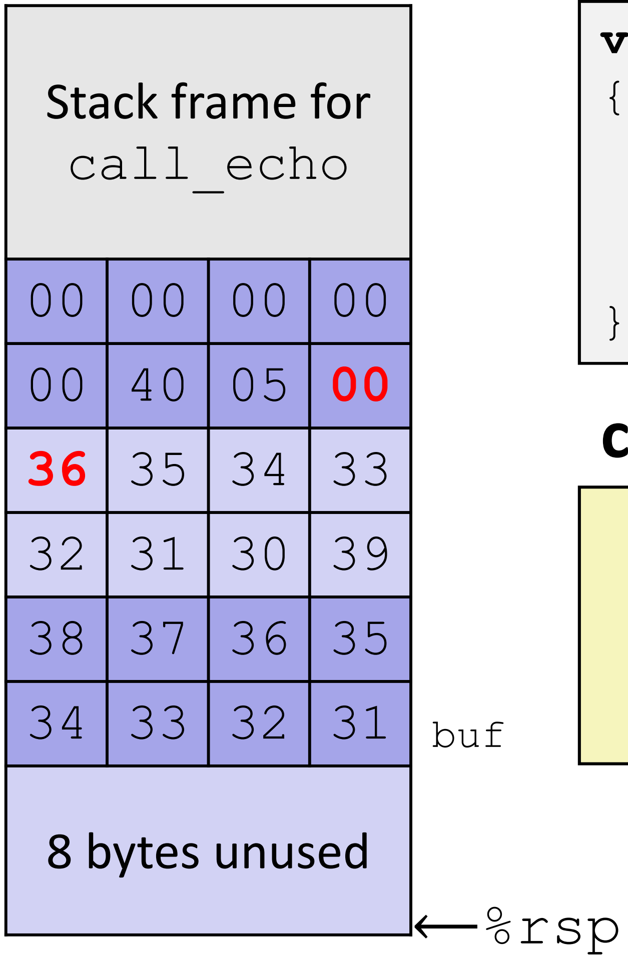
```
unix> ./buf-nsp
Enter string: 123456789012345
123456789012345
```

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

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
36	35	34	33
32	31	30	39
38	37	36	35
34	33	32	31

8 bytes unused

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

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

call_echo:

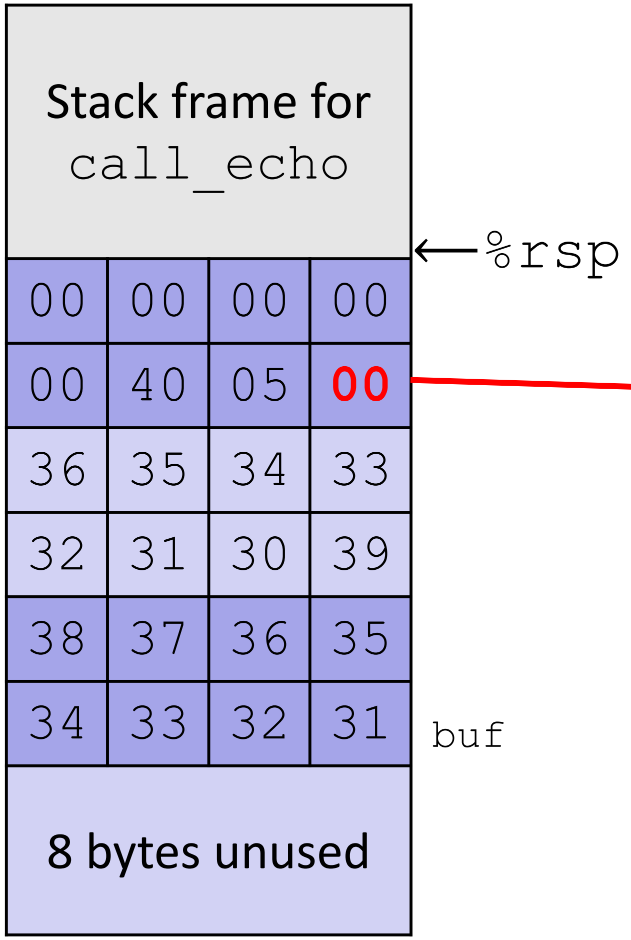
```
   . . .
   4005cc:   callq   400597 <echo>
   4005d1:   add     $0x8,%rsp
   . . .
```

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

Overflowed buffer and corrupted return pointer

Buffer Overflow Example #2 Explained

After return from 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

```
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
```

2nd byte of this instruction

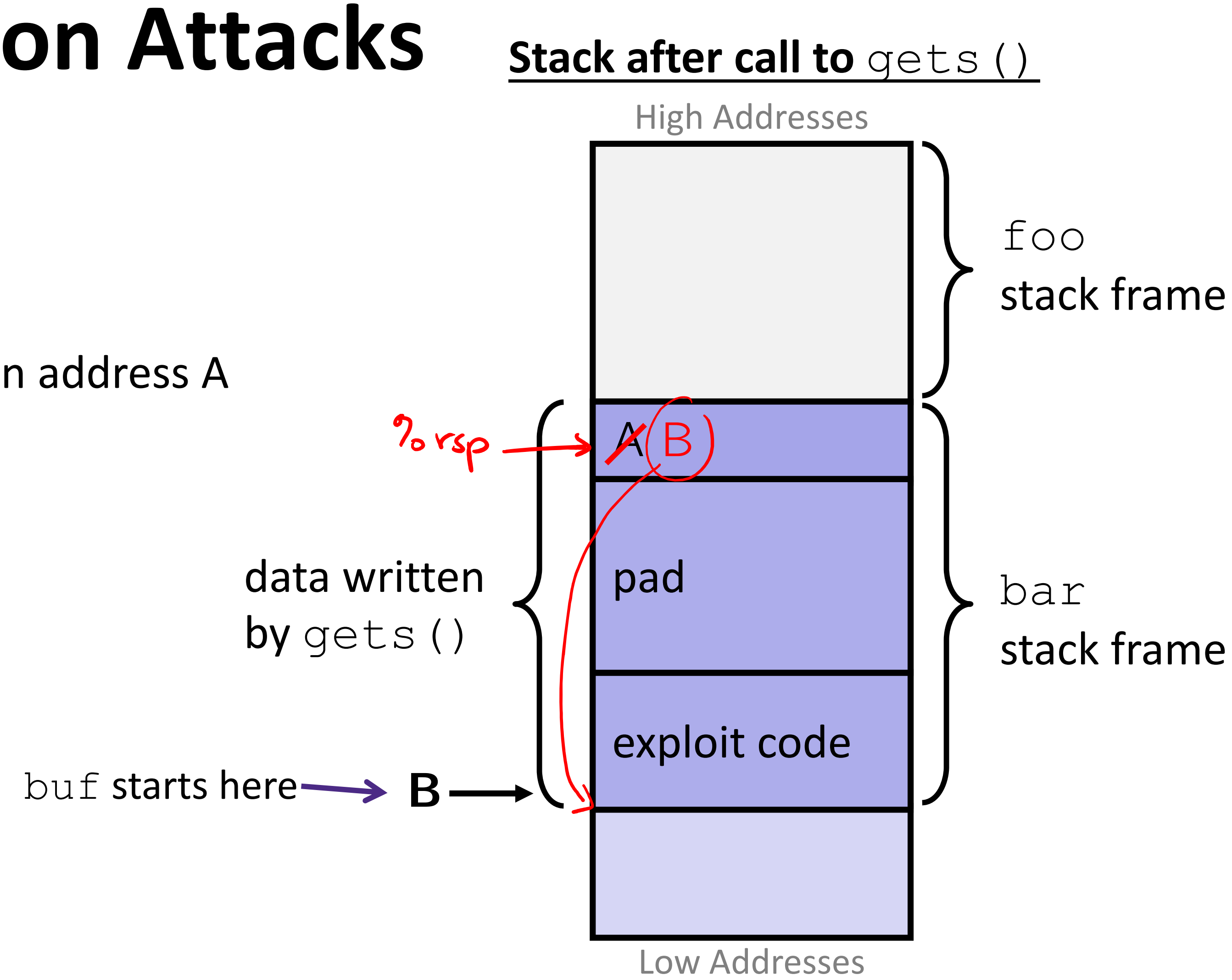
"Returns" to a byte that is not the beginning of an instruction, so program signals `SIGILL, Illegal instruction`

Malicious Use of Buffer Overflow: Code Injection Attacks

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

return address 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 x86-64 Linux)?
  - Vote at http://PollEv.com/justinh

0x 00 00 7f ff ?? ?? ?? ??

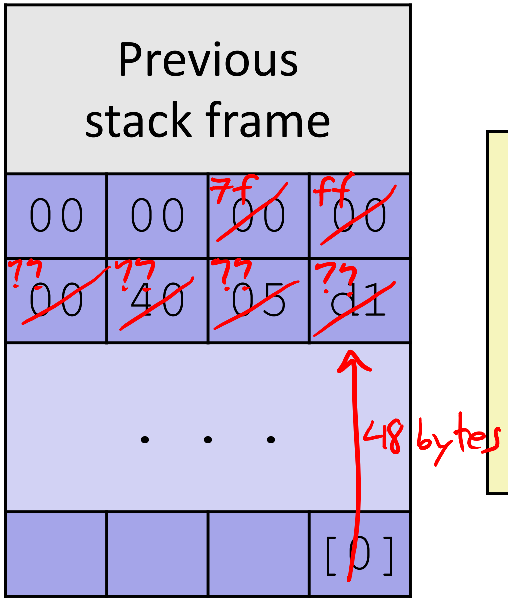
always 0's

6 bytes of data

get to ret addr

64 bytes − 16 + 6

overwrite ret addr



```
smash_me:
   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

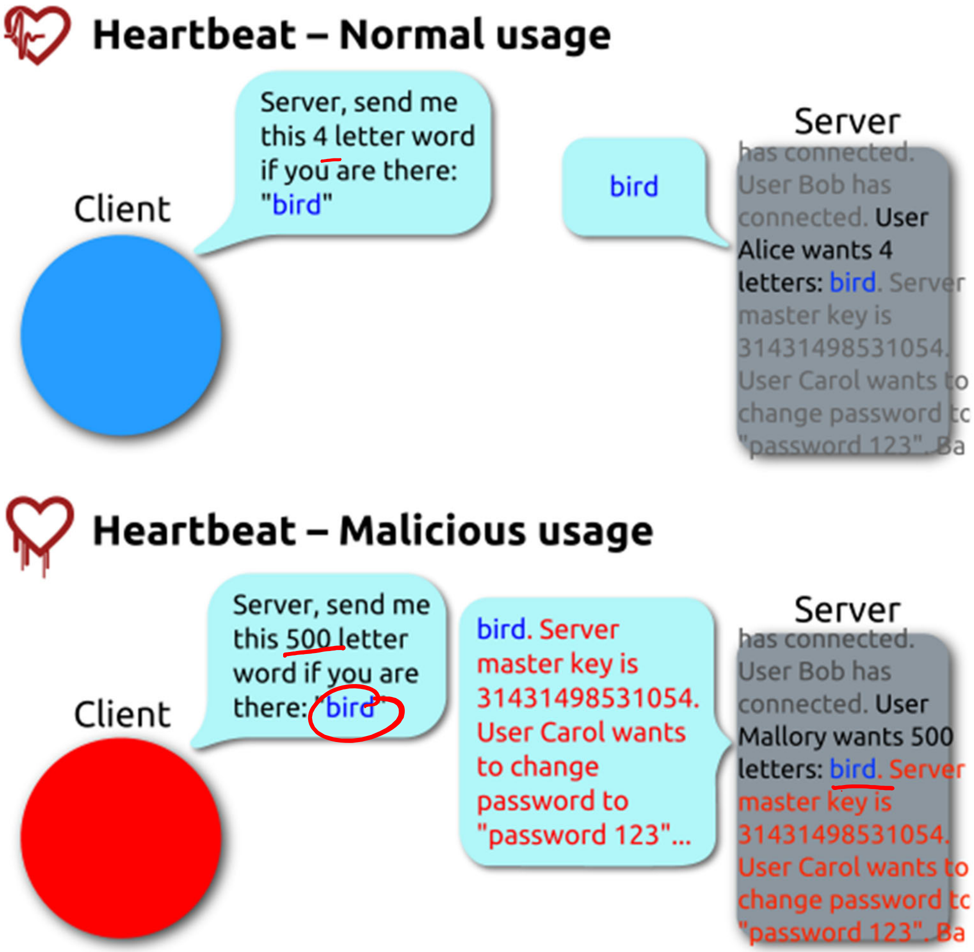
- *Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines*
- Distressingly common in real programs
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original "Internet worm"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



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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

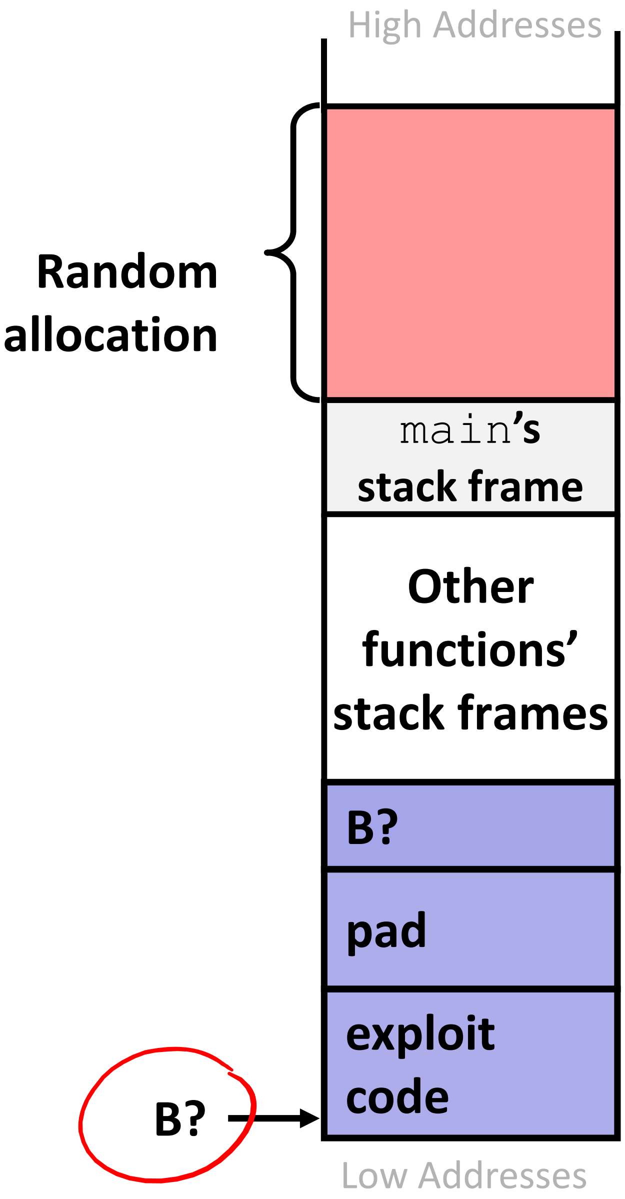
```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    fgets(buf, 8, stdin);
    puts(buf);
}
```

character read limit

- 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

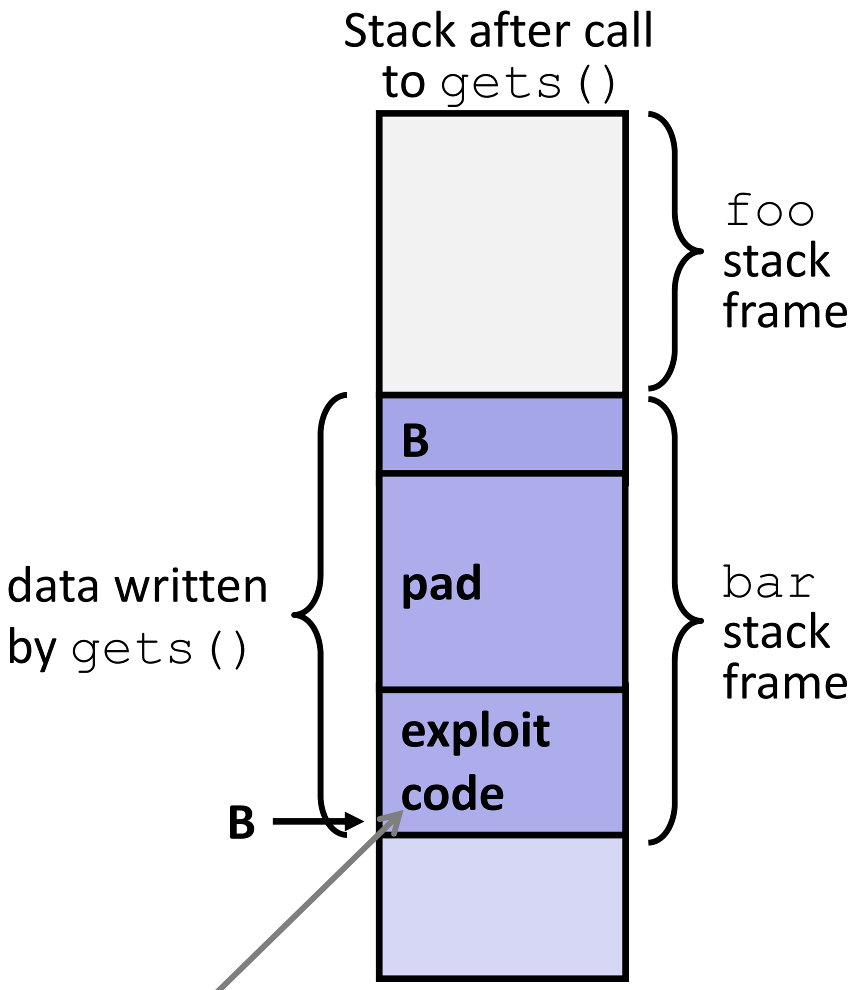
2) System-Level Protections

- **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:

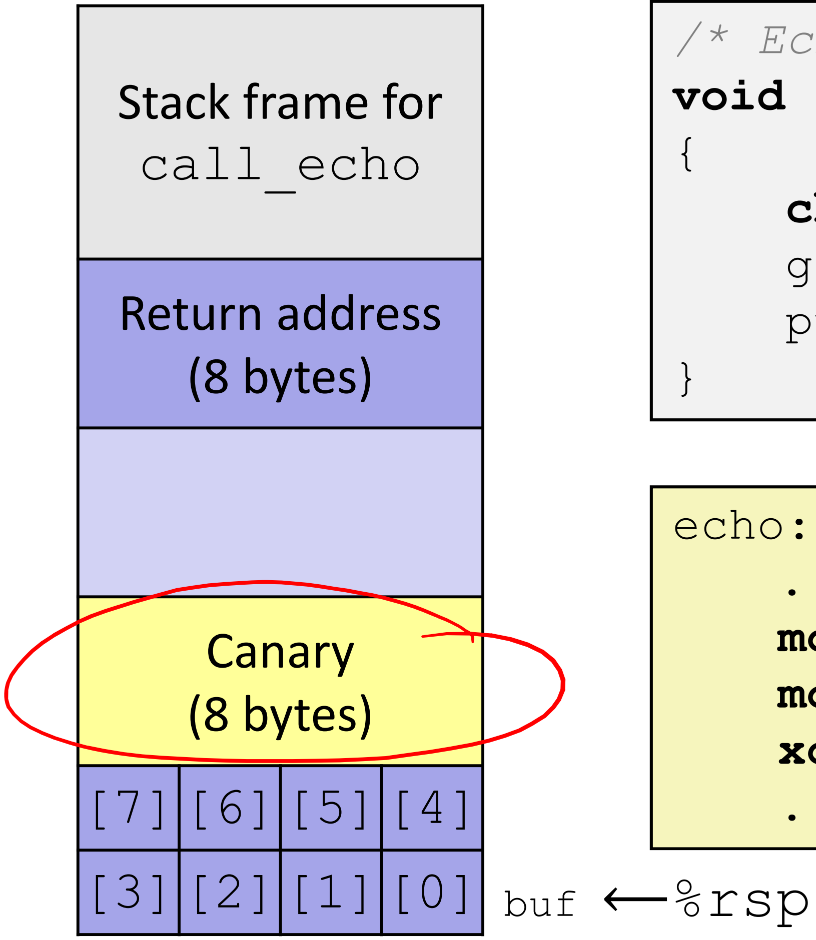
```
400607:  sub    $0x18,%rsp
40060b:  mov    %fs:0x28,%rax    # read canary value
400614:  mov    %rax,0x8(%rsp)   # store canary on Stack
400619:  xor    %eax,%eax        # erase canary from register
  ...    ... call printf ...
400625:  mov    %rsp,%rdi
400628:  callq  400510 <gets@plt>
40062d:  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
```

try: diff buf-nsp.s buf.s

Setting Up Canary

This is extra (non-testable) material

Before call to gets



Stack frame for `call_echo`

Return address (8 bytes)

Canary (8 bytes)

[7] [6] [5] [4]

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

buf ⟵%rsp

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

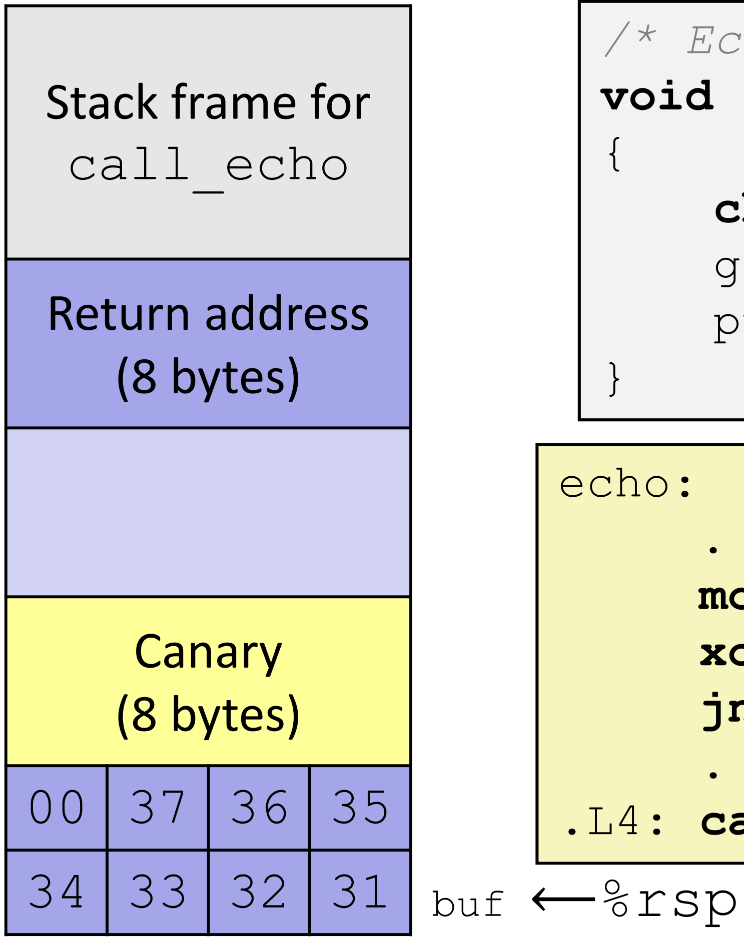
Segment register *(don't worry about it)*

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

Checking Canary

This is extra (non-testable) material

After call to gets



Stack frame for `call_echo`

Return address (8 bytes)

Canary (8 bytes)

00	37	36	35
34	33	32	31

`buf` ←`%rsp`

```
/* 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
    jne    .L4               # if not same, FAIL
    . . .
.L4: call   __stack_chk_fail
```

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”