Buffer overflows

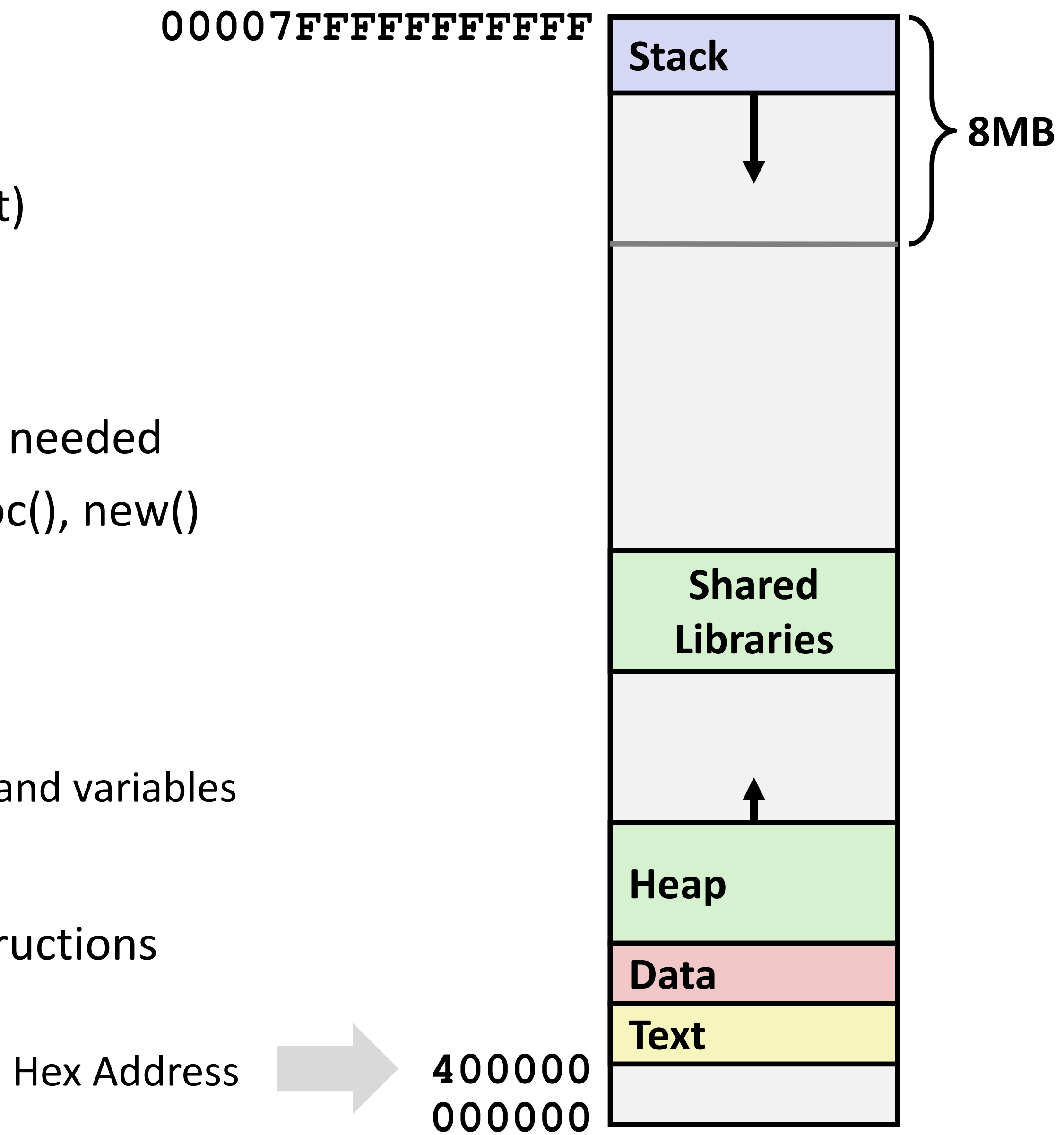
- **Buffer overflows are possible because C does not check array boundaries**
- **Buffer overflows are dangerous because buffers for user input are often stored on the stack**

- **Topics for Today:**
  - Address space layout
  - Input buffers on the stack
  - Overflowing buffers and injecting code
  - Defenses against buffer overflows

x86-64 Linux Memory Layout

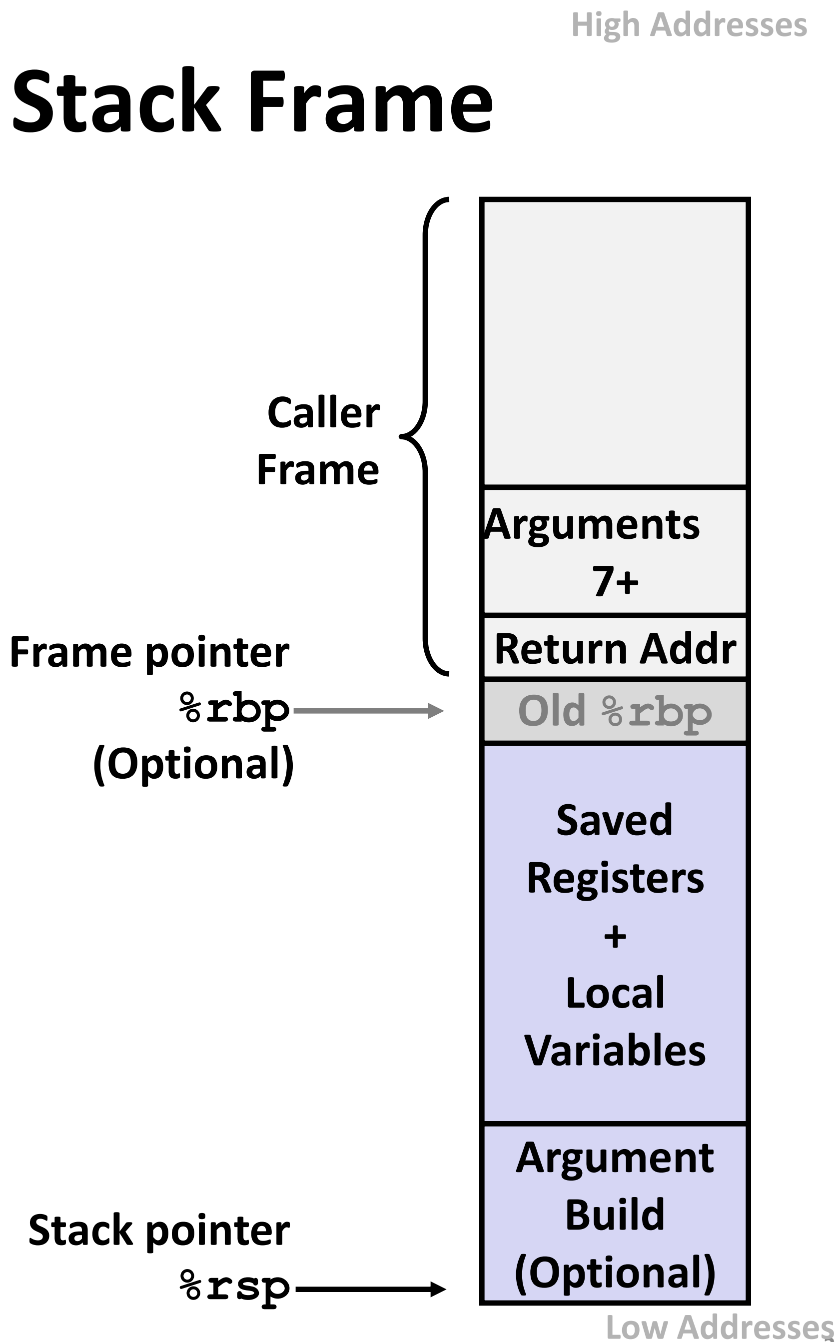
not drawn to scale

- **Stack**
  - Runtime stack (8MB limit)
  - E. g., local variables
- **Heap**
  - Dynamically allocated as needed
  - When call malloc(), calloc(), new()
- **Data**
  - Statically allocated data
    - Read-only: string literals
    - Read/write: global arrays and variables
- **Text / Shared Libraries**
  - Executable machine instructions
  - Read-only



Reminder: x86-64/Linux Stack Frame

- **Caller's Stack Frame**
  - Arguments (if > 6 args) for this call
  - Return address
    - Pushed by **`call`** instruction
- **Current/ Callee Stack Frame**
  - 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)



not drawn to scale

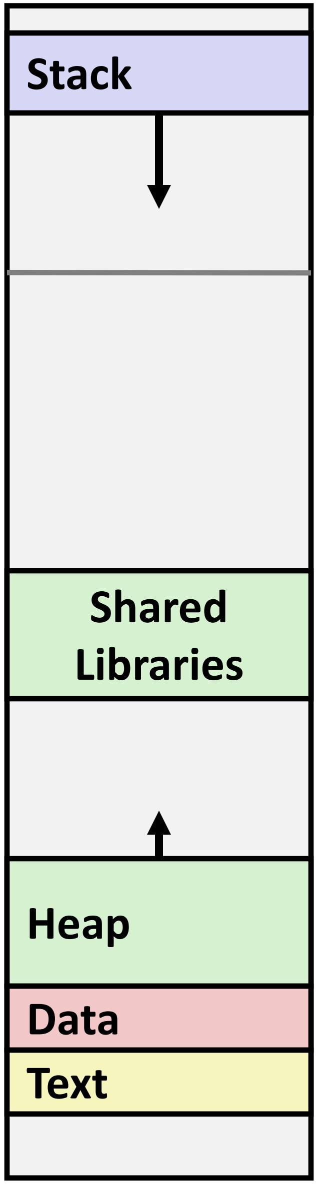
Memory Allocation Example

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



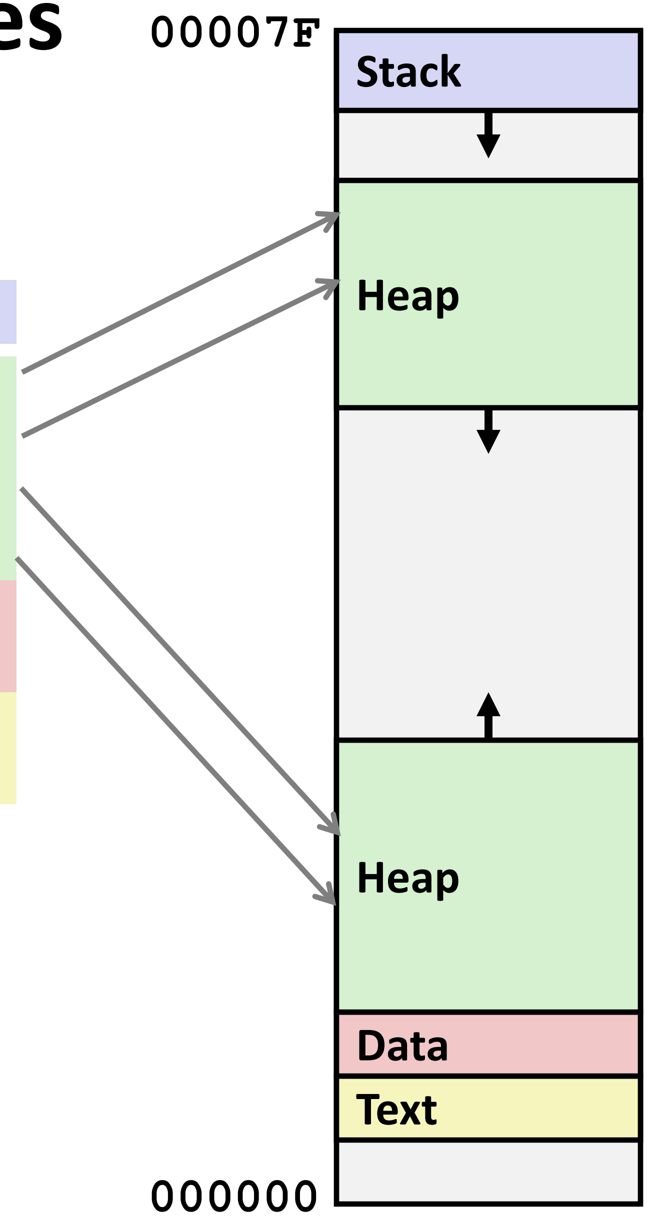
Where does everything go?

x86-64 Example Addresses

address range ~2^{47}

not drawn to scale

`&local`	`0x00007ffe4d3be87c`
`p1`	`0x00007f7262a1e010`
`p3`	`0x00007f7162a1d010`
`p4`	`0x000000008359d120`
`p2`	`0x000000008359d010`
`&big_array[0]`	`0x0000000080601060`
`huge_array`	`0x0000000000601060`
`main()`	`0x000000000040060c`
`useless()`	`0x0000000000400590`



What is approximate &p1?

Today

- Memory Layout
- **Buffer Overflow**
  - Vulnerability
  - Protection

Internet Worm

- **These 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

- **November, 1988**
  - Internet Worm attacks thousands of Internet hosts.
  - How did it happen?

- ***Stack buffer overflow* exploits!**

Buffer Overflow in a nutshell

- **Many classic Unix/Linux/C functions do not check argument sizes**
- **C does not check array bounds**
- **Allows overflowing (writing past the end of) buffers (arrays)**
- **Overflows of buffers on the stack overwrite interesting data**
- **Attackers just choose the right inputs**
- **Why a big deal?**
  - It’s the #1 technical cause of security vulnerabilities
    - #1 overall cause is social engineering / user ignorance
- **Most common form**
  - Unchecked lengths on string inputs
  - Particularly for bounded character arrays on the stack
    - sometimes referred to as stack smashing

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 dest
  - **`scanf`, `fscanf`, `sscanf`,** when given **`%s`** conversion specification

Vulnerable Buffer Code

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

```
unix>./bufdemo-nsp
Type a string:012345678901234567890123
012345678901234567890123
```

```
unix>./bufdemo-nsp
Type a string:0123456789012345678901234
Segmentation Fault
```

Buffer Overflow Disassembly

echo:

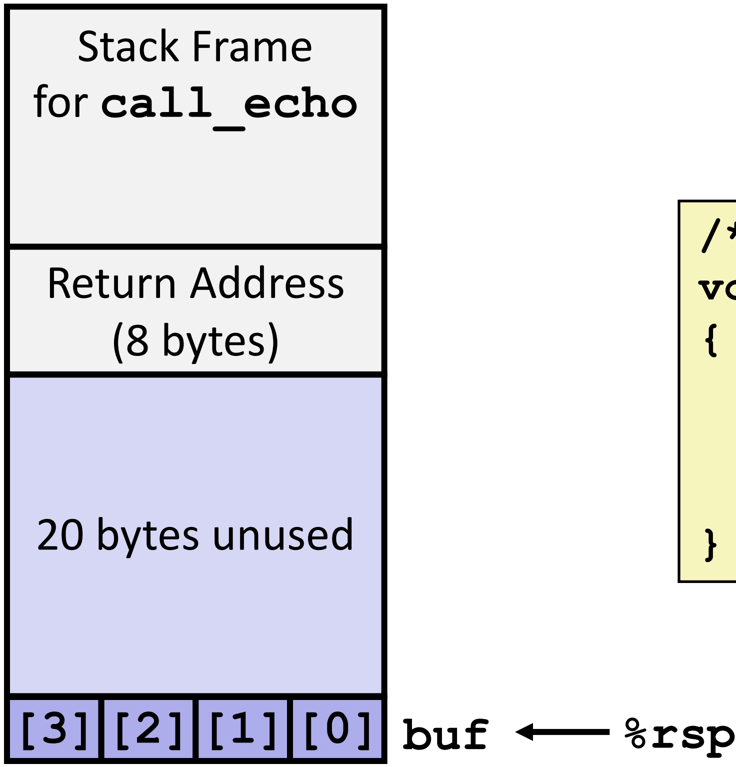
```
0000000004006cf <echo>:
 4006cf:  48 83 ec 18              sub    $0x18,%rsp
 4006d3:  48 89 e7                 mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff           callq  400680 <gets>
 4006db:  48 89 e7                 mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff           callq  400520 <puts@plt>
 4006e3:  48 83 c4 18              add    $0x18,%rsp
 4006e7:  c3                       retq
```

call_echo:

```
4006e8:   48 83 ec 08              sub    $0x8,%rsp
 4006ec:  b8 00 00 00 00           mov    $0x0,%eax
 4006f1:  e8 d9 ff ff ff           callq  4006cf <echo>
 4006f6:  48 83 c4 08              add    $0x8,%rsp
 4006fa:  c3                       retq
```

Buffer Overflow Stack

Before call to gets

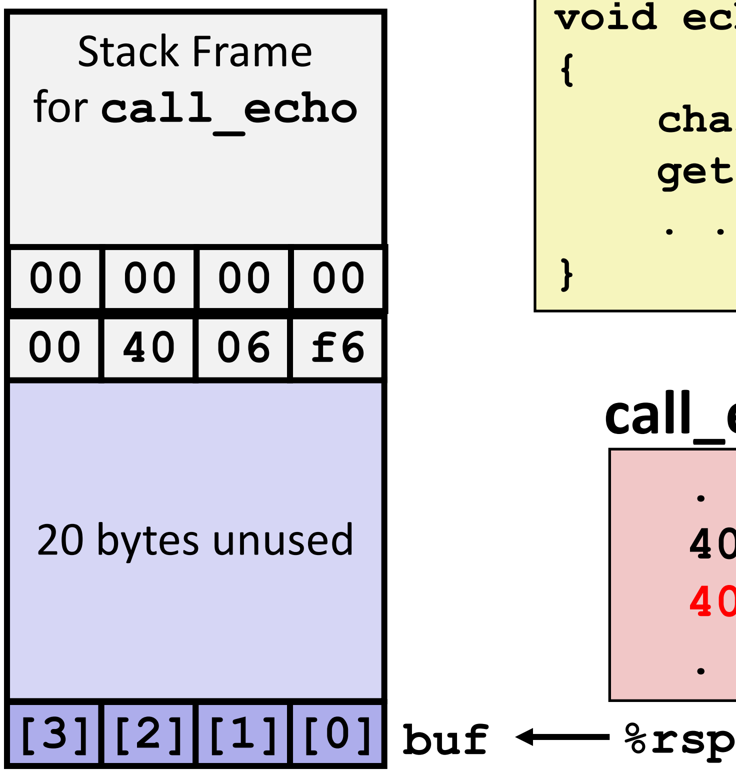



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

Buffer Overflow Stack Example

Before call to gets




```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

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

call_echo:

```
 . . .
 4006f1:  callq  4006cf <echo>
 4006f6:  add    $0x8,%rsp
 . . .
```

Buffer Overflow Stack Example #1

After call to gets

Stack Frame for `call_echo`

00	00	00	00
00	40	06	f6
00	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

buf ← %rsp

```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

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

call_echo:

```
  . . .
  4006f1:  callq   4006cf <echo>
  4006f6:  add     $0x8,%rsp
  . . .
```

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012
01234567890123456789012
```

Overflowed buffer, but did not corrupt state

Buffer Overflow Stack Example #2

After call to gets

Stack Frame for `call_echo`

00	00	00	00
00	40	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	30

buf ← %rsp

```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

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

call_echo:

```
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $0x8,%rsp
  . . .
```

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012345678901234
Segmentation Fault
```

Overflowed buffer and corrupted return pointer

Buffer Overflow Stack Example #3

After call to gets

Stack Frame
for `call_echo`

00	00	00	00
00	40	06	00
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

`buf` ⟵ `%rsp`

```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

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

call_echo:

```
. . .
4006f1:  callq   4006cf <echo>
4006f6:  add     $0x8,%rsp
. . .
```

```
unix>./bufdemo-nsp
Type a string:012345678901234567890123
012345678901234567890123
```

Overflowed buffer, corrupted return pointer, but program seems to work!

Buffer Overflow Stack Example #3 Explained

After call to gets

Stack Frame for `call_echo`			
00	00	00	00
00	40	06	00
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

`buf` ⟵ `%rsp`

register_tm_clones:

```
  . . .
  400600:  mov     %rsp,%rbp
  400603:  mov     %rax,%rdx
  400606:  shr     $0x3f,%rdx
  40060a:  add     %rdx,%rax
  40060d:  sar     %rax
  400610:  jne     400614
  400612:  pop     %rbp
  400613:  retq
```

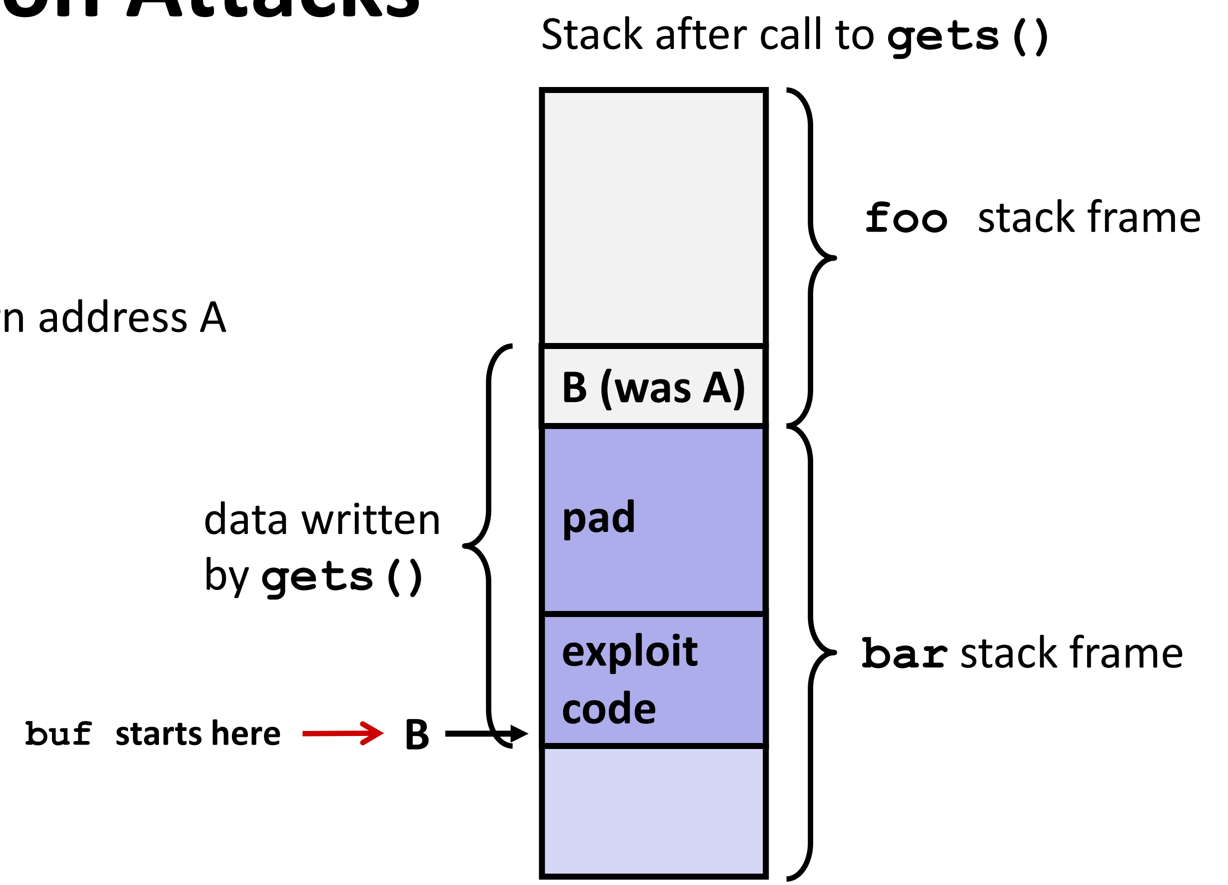
"Returns" to unrelated code
Lots of things happen, without modifying critical state
Eventually executes `retq` back to `main`

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

Exploits Based on Buffer Overflows

- ***Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines***
- **Distressingly common in real progams**
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- **Examples across the decades**
  - Original “Internet worm” (1988)
  - “IM wars” (1999)
  - Twilight hack on Wii (2000s)
  - … and many, many more
- **You will learn some of the tricks in lab 3**
  - Hopefully to convince you to never leave such holes in your programs!!

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 by sending phony argument:
    - ***`finger "exploit-code padding new-return-address"`***
    - exploit code: executed a root shell on the victim machine with a direct TCP connection to the attacker.
- **Once on a machine, 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…

What to do about buffer overflow attacks…

1. Avoid overflow vulnerabilities

2. Employ system-level protections

3. Have compiler use “stack canaries”

- Lets talk about each…

1. Avoid Overflow Vulnerabilities in Code (!)

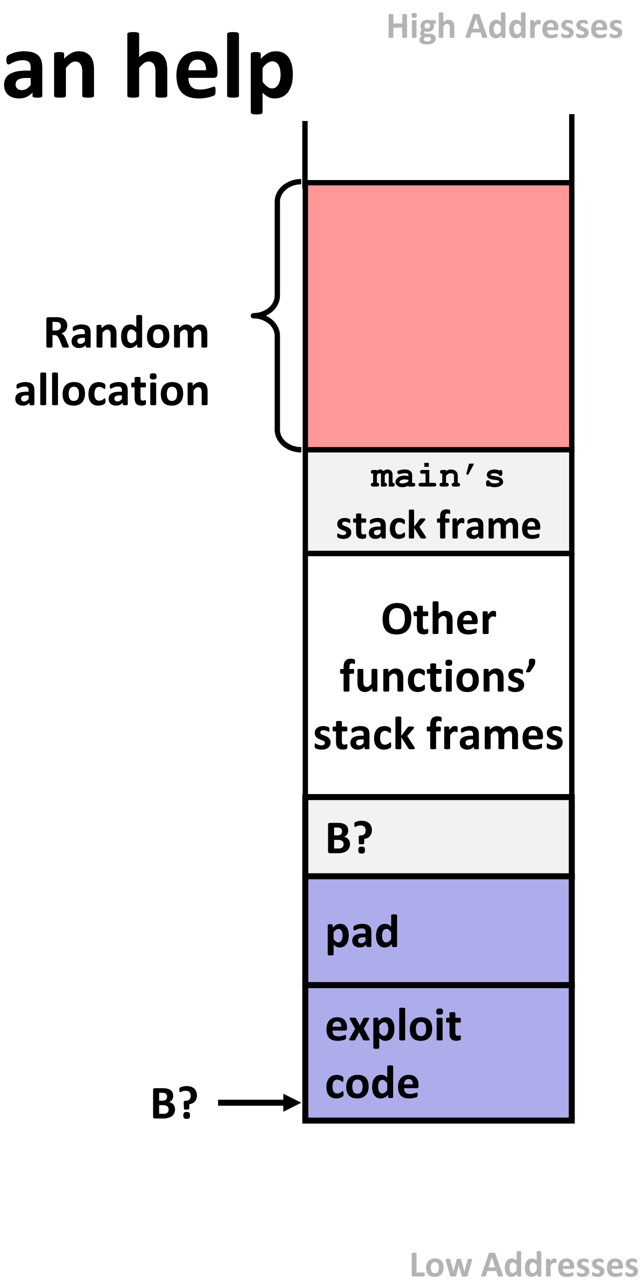
```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

- **Use library routines that limit string lengths**
  - **`fgets`** instead of **`gets`** (second 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 can help

Randomized stack offsets

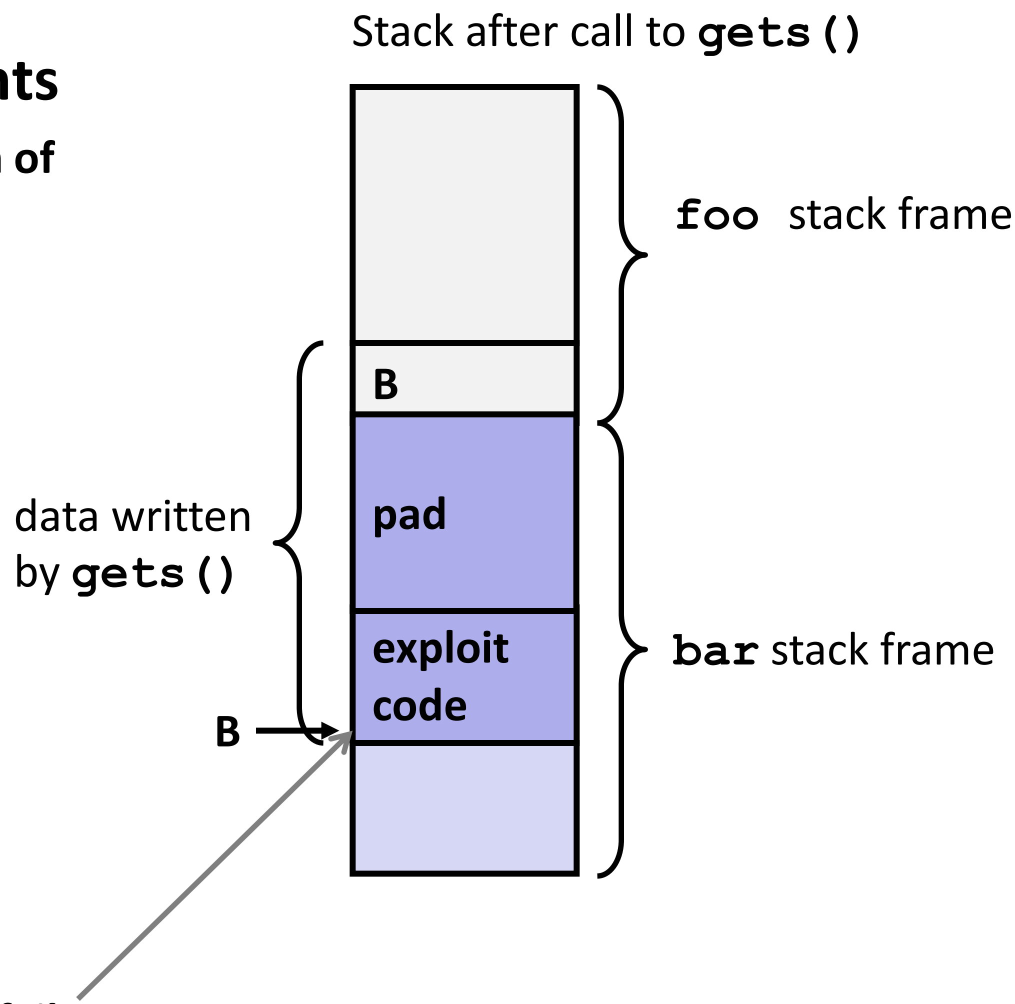
- At start of program, allocate random amount of space on stack
- Shifts stack addresses for entire program
  - Addresses will vary from one run to another
- Makes it difficult for hacker to predict beginning of inserted code
- E.g.: 5 executions of memory allocation code from slide 4, address of variable `local` changes each time:
  - `0x7ffe4d3be87c`
  - `0x7fff75a4f9fc`
  - `0x7ffeadb7c80c`
  - `0x7ffeaea2fdac`
  - `0x7ffcd452017c`
  - Stack repositioned each time program executes



2. System-Level Protections can help

Nonexecutable 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, data, or heap regions
  - Hardware support needed



Any attempt to execute this code will fail

3. Stack Canaries can help

- **Idea**
  - Place special value (“canary”) on stack just beyond buffer
    - “After” buffer but before return address
  - Check for corruption before exiting function
- **GCC Implementation**
  - **`-fstack-protector`**
  - Now the default for gcc
  - Code back on slide 12 (./*`bufdemo-nsp)`* compiled without this option

```
unix>./bufdemo-sp
Type a string:0123456
0123456
```

```
unix>./bufdemo-sp
Type a string:01234567
*** stack smashing detected ***
```

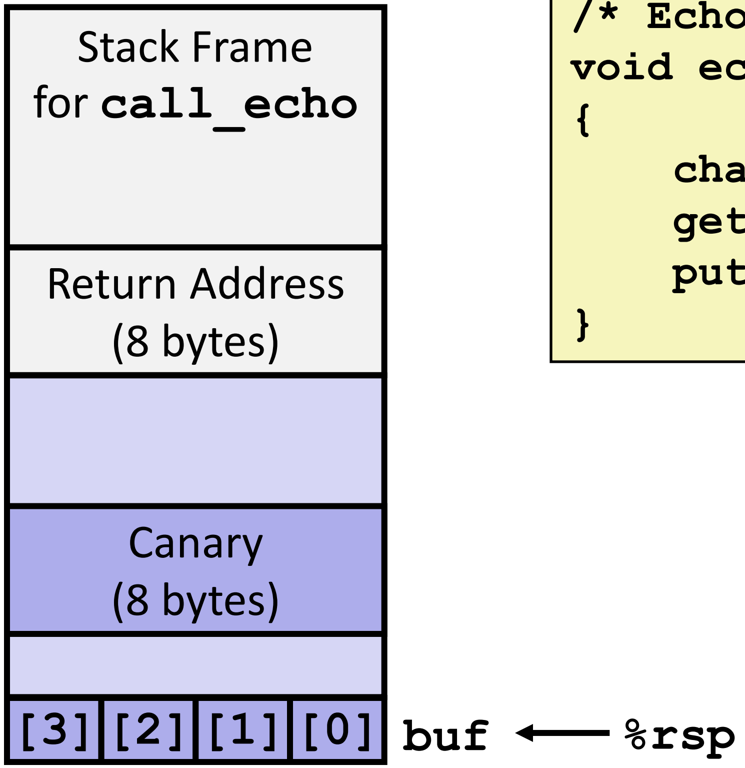
Protected Buffer Disassembly

echo:

```
40072f:  sub    $0x18,%rsp
400733:  mov    %fs:0x28,%rax
40073c:  mov    %rax,0x8(%rsp)
400741:  xor    %eax,%eax
400743:  mov    %rsp,%rdi
400746:  callq  4006e0 <gets>
40074b:  mov    %rsp,%rdi
40074e:  callq  400570 <puts@plt>
400753:  mov    0x8(%rsp),%rax
400758:  xor    %fs:0x28,%rax
400761:  je     400768 <echo+0x39>
400763:  callq  400580 <__stack_chk_fail@plt>
400768:  add    $0x18,%rsp
40076c:  retq
```

Setting Up Canary

Before call to gets

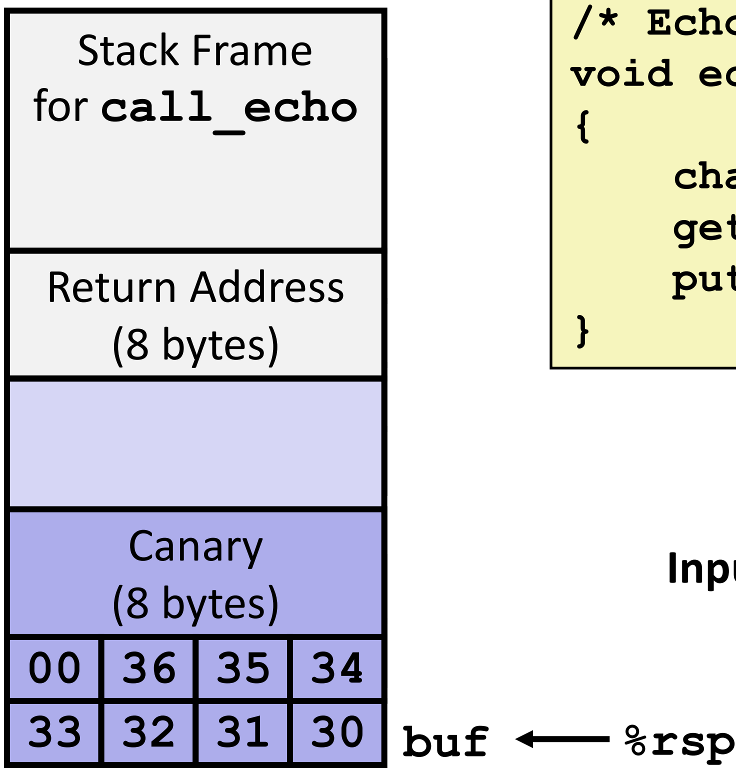



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

Input: ***0123456***

```
echo:
    . . .
    movq    8(%rsp), %rax       # Retrieve from stack
    xorq    %fs:40, %rax        # Compare to canary
    je      .L6                 # If same, OK
    call    __stack_chk_fail    # FAIL
.L6:        . . .
```

Summary: Avoiding buffer overflow attacks

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"**