Buffer overflows

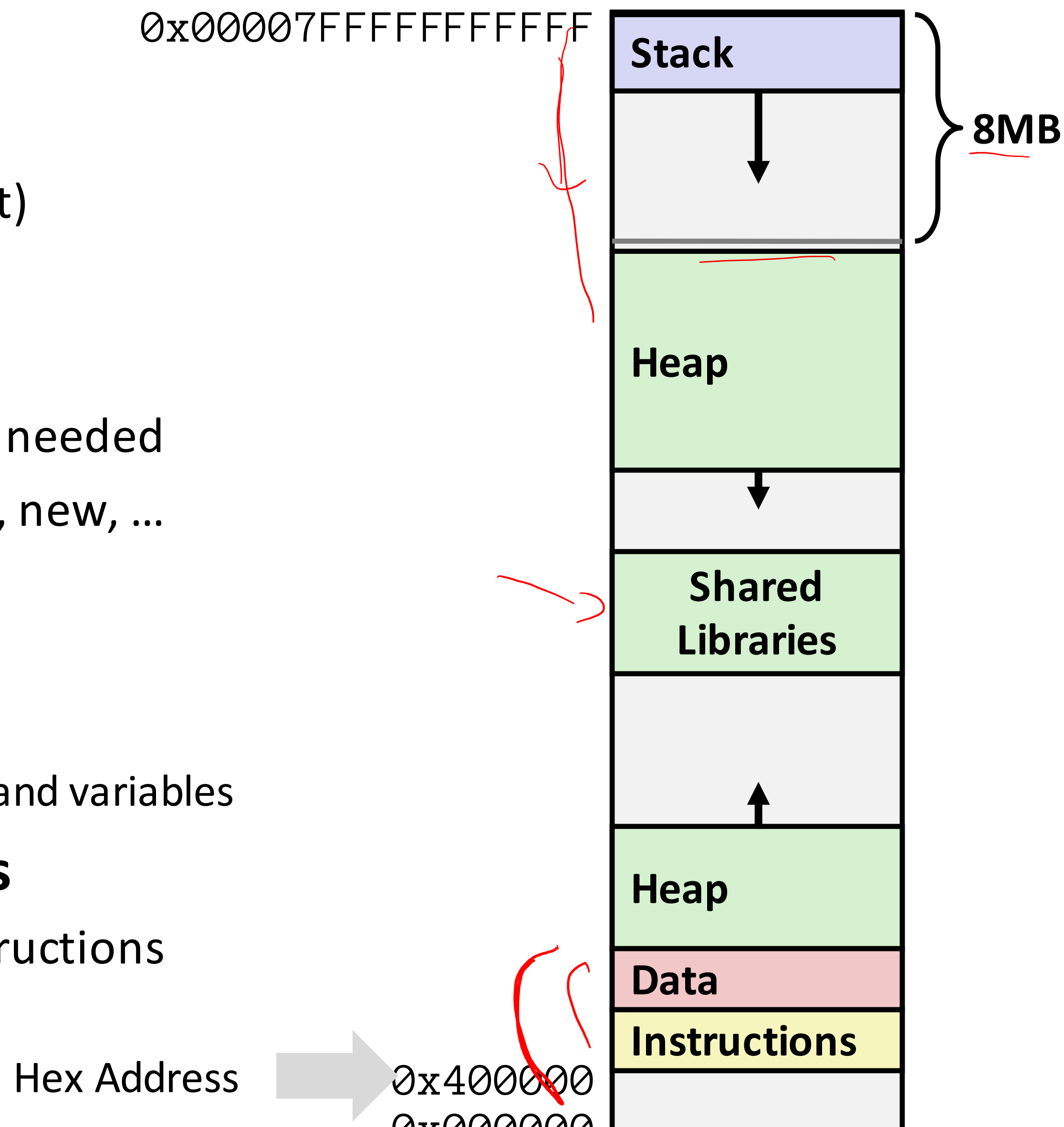
- **Buffer overflows are possible because C does not check array boundaries**
- **Buffer overflows are dangerous because buffers for user input are often stored on the stack**

- **Specific topics:**
  - Address space layout
  - Input buffers on the stack
  - Overflowing buffers and injecting code
  - Defenses against buffer overflows

x86-64 Linux Memory Layout

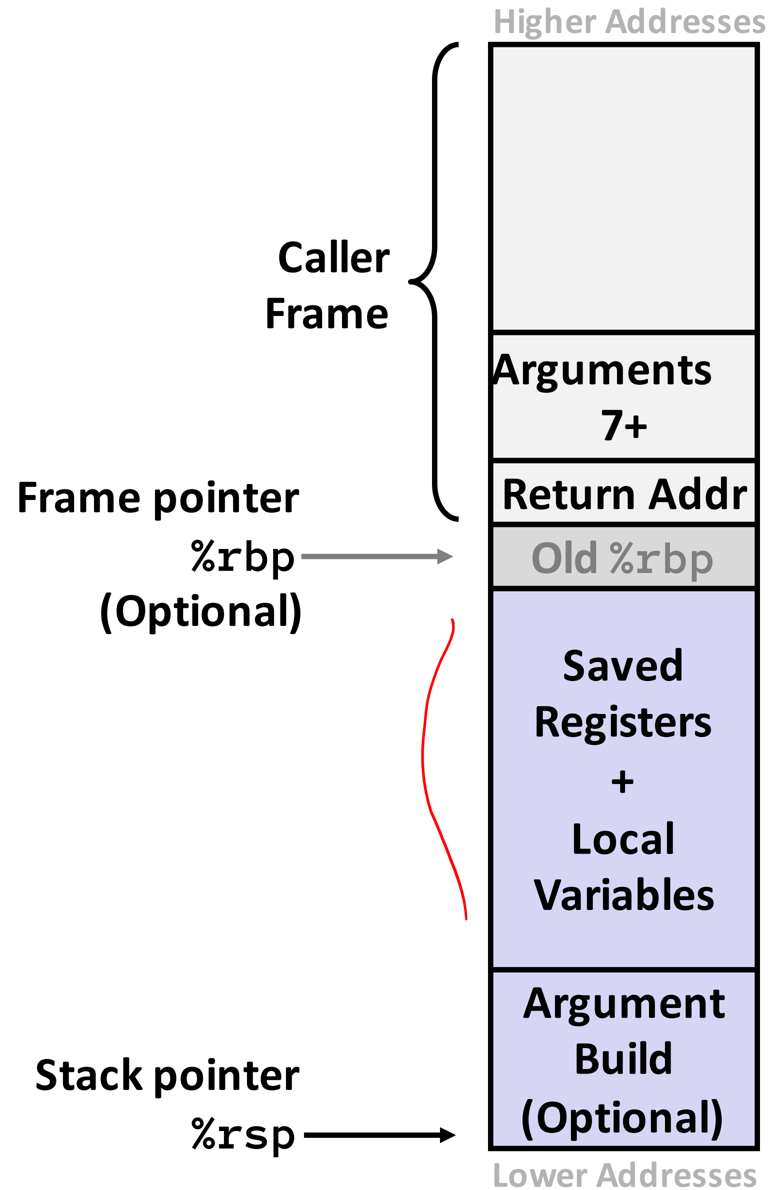
not drawn to scale

- **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
- **Code / 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)



Memory Allocation Example

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

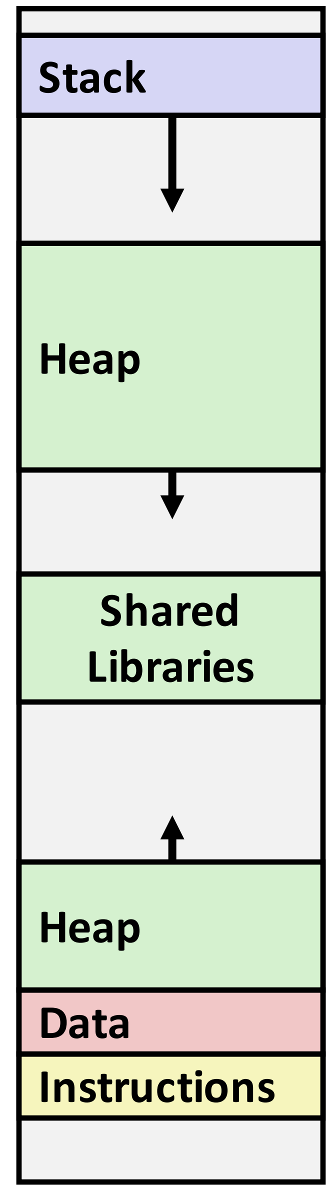
int global = 0;

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



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Memory Allocation Example

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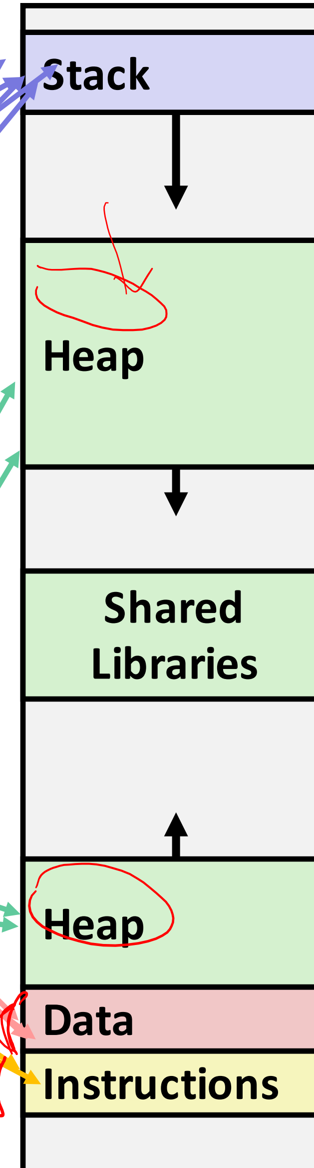
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8);  /* 256  B */
    p3 = malloc(1L << 32); /*   4 GB */
    p4 = malloc(1L << 8);  /* 256  B */
    /* Some print statements ... */
}
```



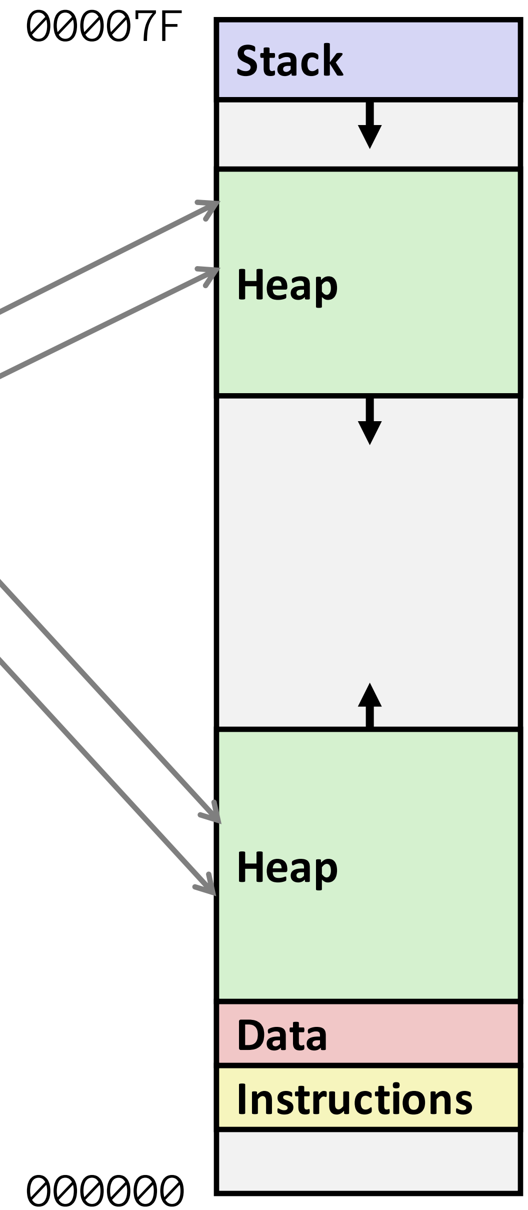
Where does everything go?

not drawn to scale

x86-64 Example Addresses

address range ~2^{47}

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



What is &p1? (approximately)

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 is (was?) the #1 *technical* cause of security vulnerabilities
    - #1 *overall* cause is social engineering / user ignorance
- **Simplest 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:

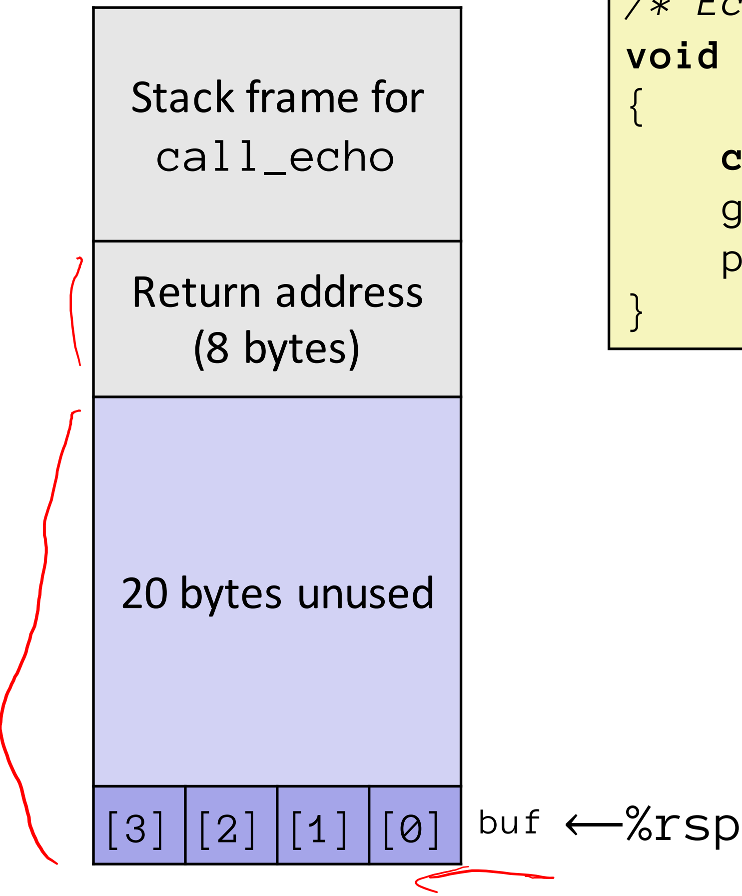
```
00000000004006cf <echo>:
 4006cf:   48 83 ec 18          sub    $0x24,%rsp
 4006d3:   48 89 e7             mov    %rsp,%rdi
 4006d6:   e8 a5 ff ff ff       callq  400680 <gets>
 4006db:   48 89 e7             mov    %rsp,%rdi
 4006de:   e8 3d fe ff ff       callq  400520 <puts@plt>
 4006e3:   48 83 c4 18          add    $0x24,%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

Stack frame for call_echo			
00	00	00	00
00	40	06	f6
20 bytes unused			
[3]	[2]	[1]	[0]

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
. . .
```

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: 0123456789012345678901234
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
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

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`

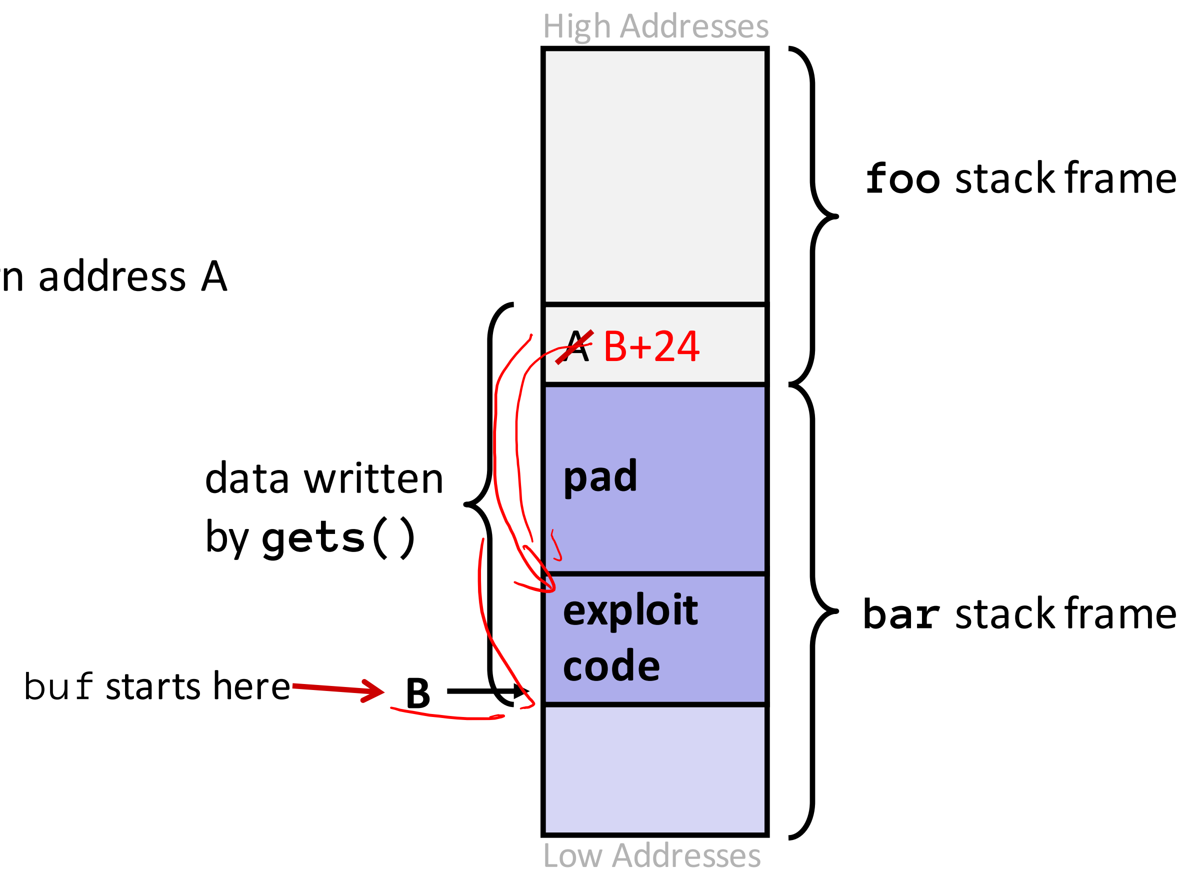
Malicious Use of Buffer Overflow: Code Injection Attacks

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

return address A

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

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**

Exploits Based on Buffer Overflows

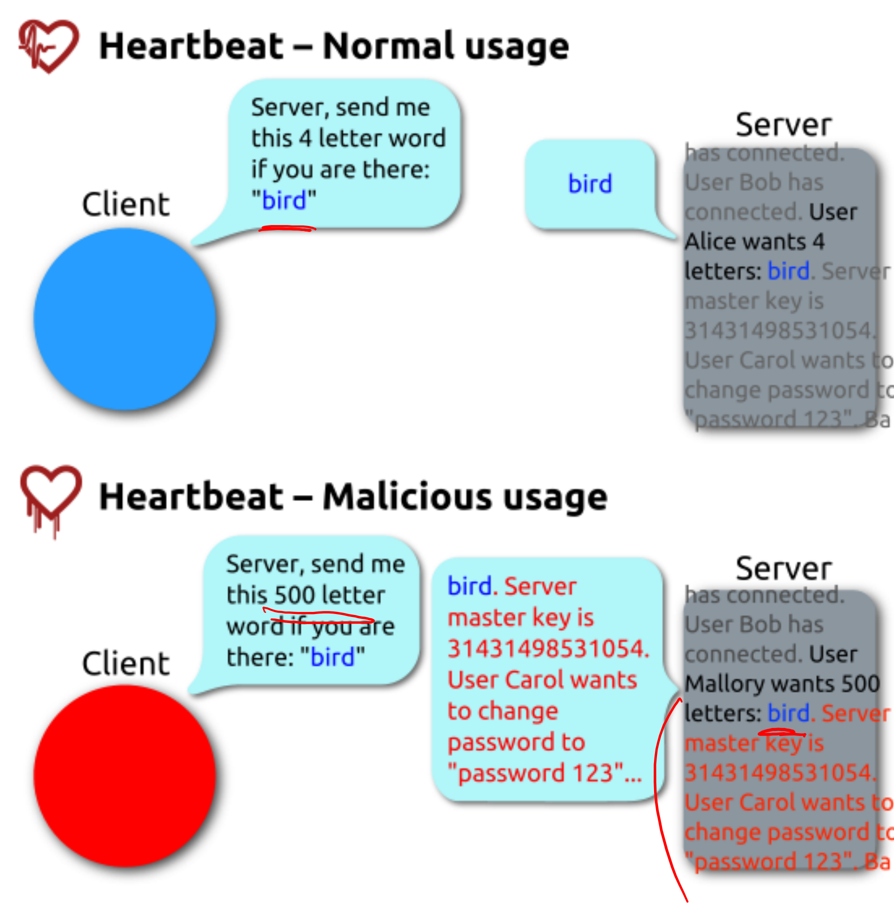
- ***Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines***
- **Distressingly common in real programs**
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- **Examples across the decades**
  - Original "Internet worm" (1988)
  - *Still happens!!* Heartbleed (2014, affected 17% of servers)
  - *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
  - … 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…

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, ...



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 (!)

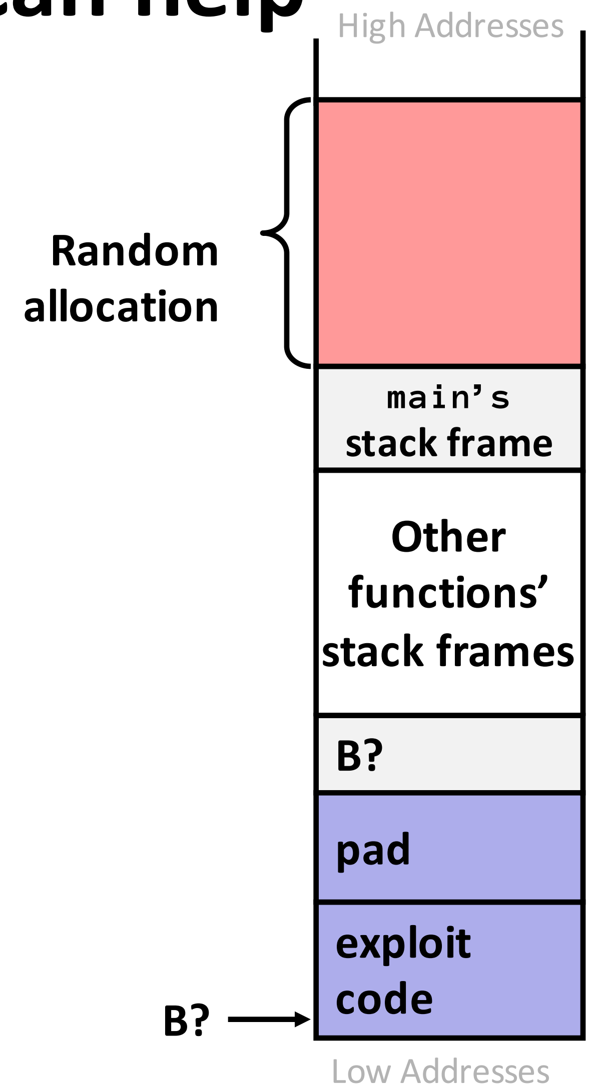
```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

- **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

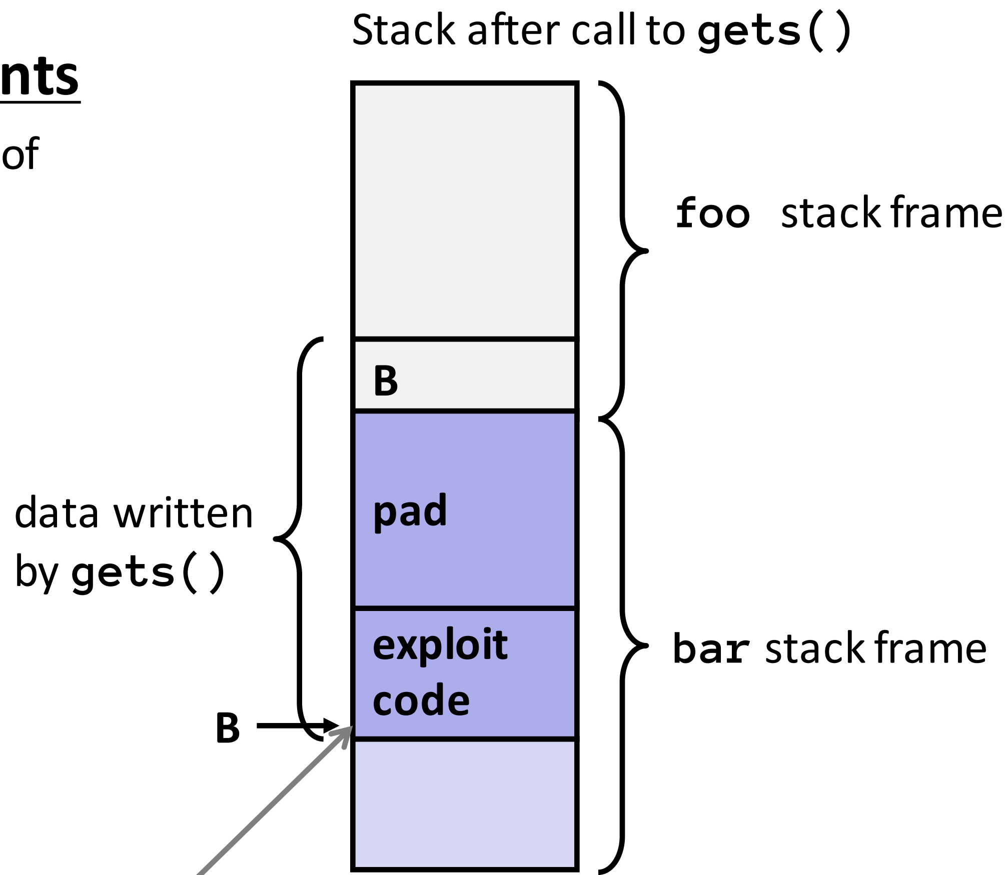
- At start of program, allocate random amount of space on stack
- Shifts stack addresses for entire program
  - Addresses will vary from one run to another
- Makes it difficult for hacker to predict beginning of inserted code
- E.g.: 5 executions of memory allocation code from slide 4, address of variable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



2. System-Level Protections can help

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, 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
    - *Secret* value known only to compiler
    - "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 ***
```

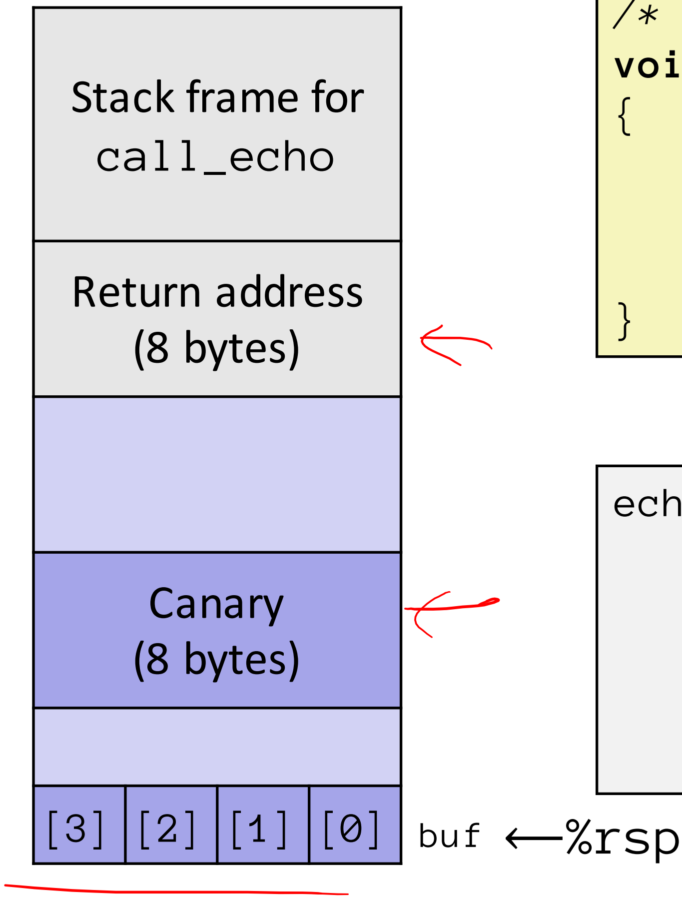
Protected Buffer Disassembly

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



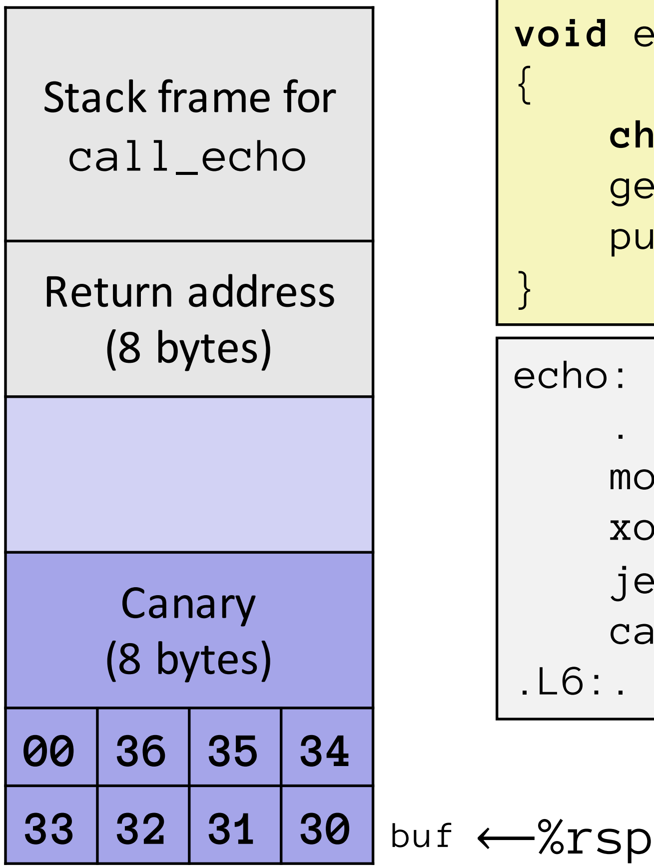

```c
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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




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

```
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:. . .
```

Input: *0123456*

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"**