# Machine-level Programming V: Advanced Topics

’20H2

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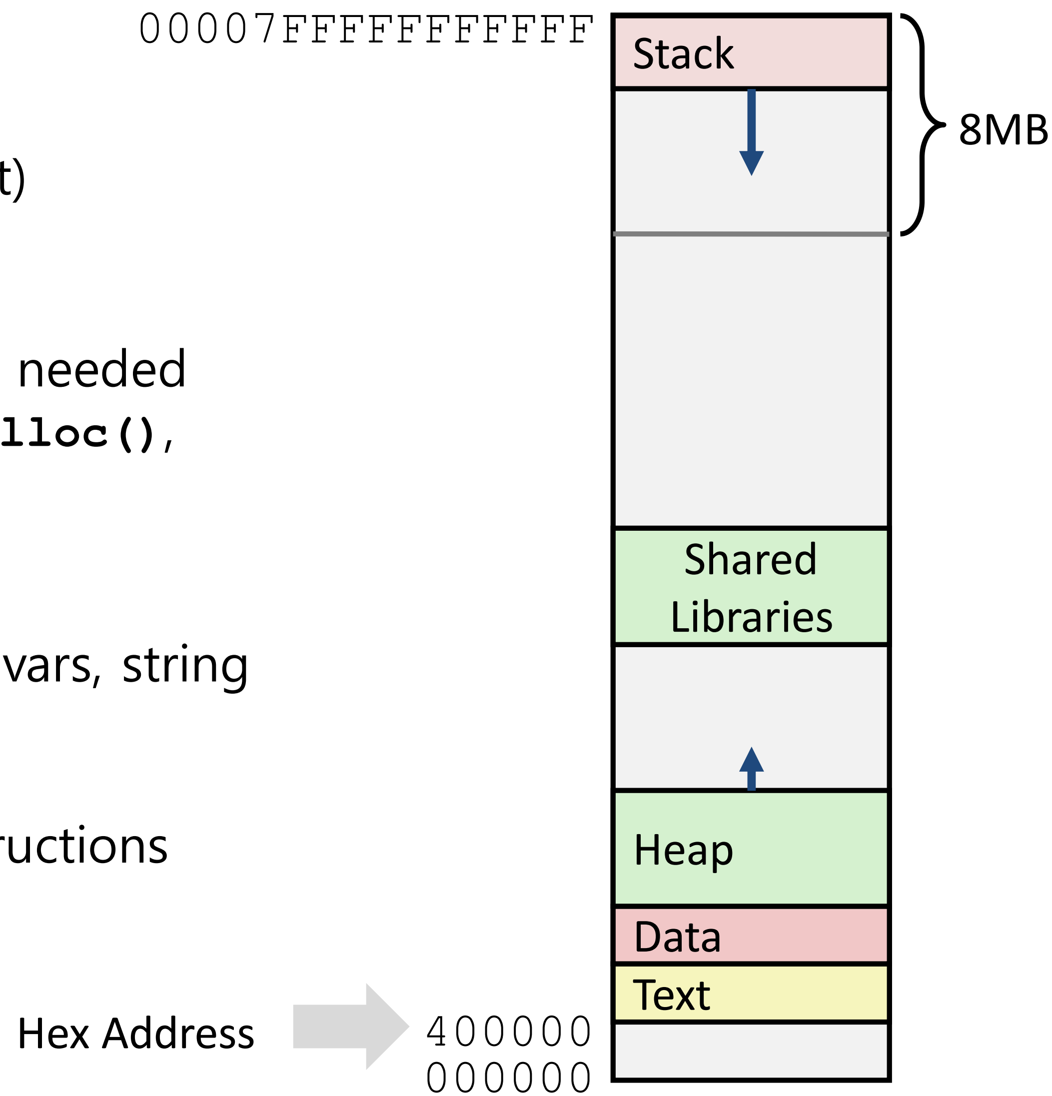
# Outline

- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection

# x86-64 Linux Memory Layout

- Stack
  - Runtime stack (8MB limit)
  - e.g., local variables
- Heap
  - Dynamically allocated as needed
  - When call **`malloc()`**, **`calloc()`**, **`new()`**
- Data
  - Statically allocated data
  - e.g., global vars, **`static`** vars, string constants
- Text / Shared Libraries
  - Executable machine instructions
  - Read-only

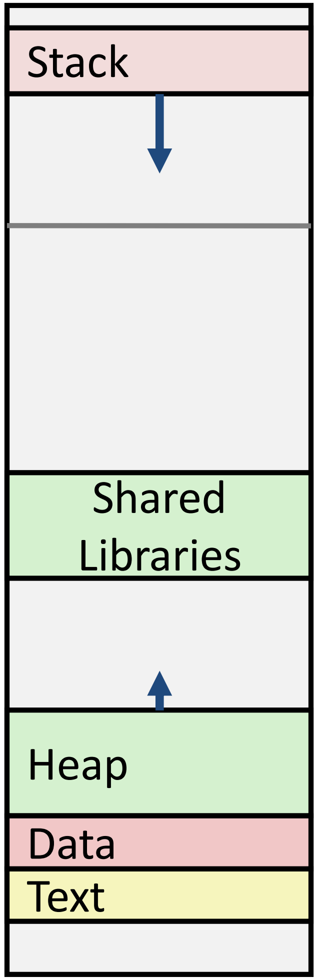


# Memory Allocation Example

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

*Where does everything go?*

*not drawn to scale*

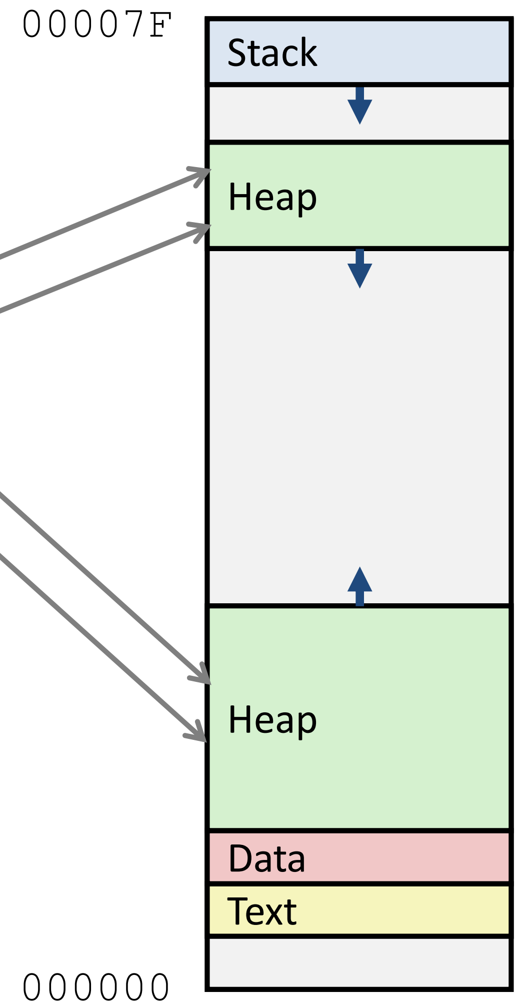


# x86-64 Example Addresses

*not drawn to scale*

*address range ~$2^{47}$*

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



# Outline

- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection

# Recall: Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;

double fun(int i) {
  volatile struct_t s;
  s.d = 3.14;
  s.a[i] = 1073741824; /* Possibly out of bounds */
  return s.d;
}
```

```
fun(0)  ->     3.1400000000
fun(1)  ->     3.1400000000
fun(2)  ->     3.1399998665
fun(3)  ->     2.0000006104
fun(6)  ->     Stack smashing detected
fun(8)  ->     Segmentation fault
```

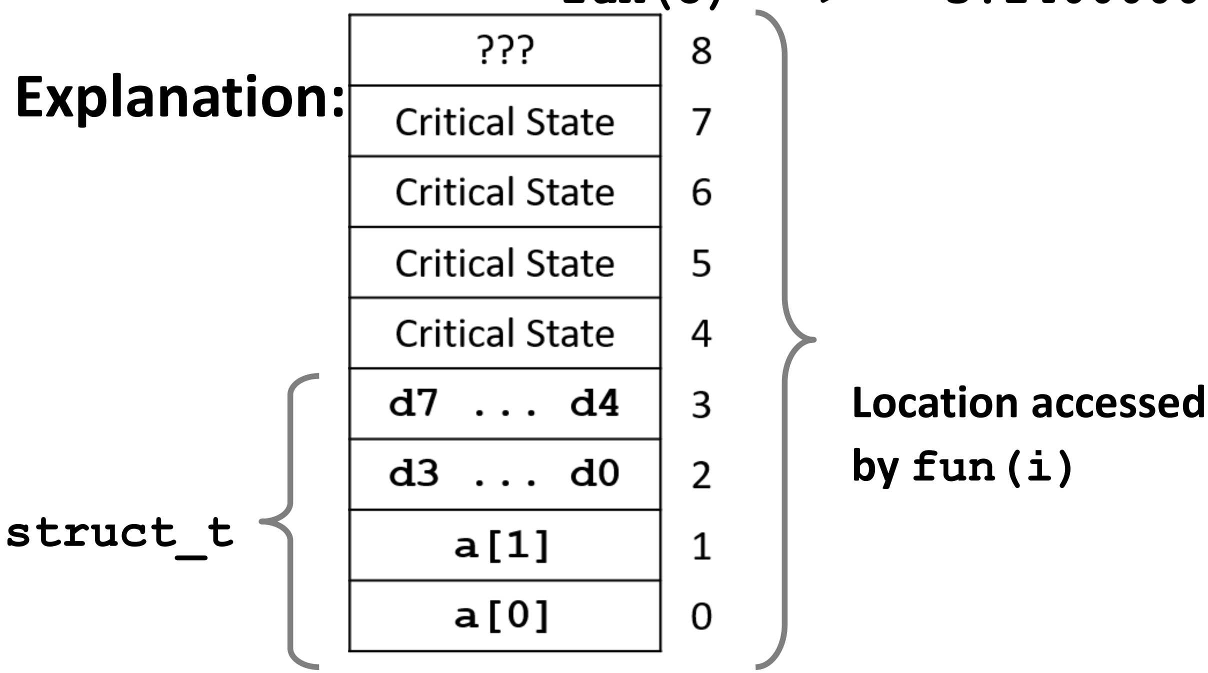
- Result is system specific

# Memory Referencing Bug Example

```
typedef struct
{
  int a[2];
  double d;
} struct_t;
```

| | | |
|---|---|---|
| `fun(0)` | `->` | `3.1400000000` |
| `fun(1)` | `->` | `3.1400000000` |
| `fun(2)` | `->` | `3.1399998665` |
| `fun(3)` | `->` | `2.0000006104` |
| `fun(4)` | `->` | **Segmentation fault** |
| `fun(8)` | `->` | `3.1400000000` |

**Explanation:**



# Such Problems are a BIG Deal

- Generally called a “buffer overflow”
  - When exceeding the memory size allocated for an array
- 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;
}
```

  – No way to specify limit on number of characters to read
- Similar problems with other library functions
  – **strcpy**, **strcat**: Copy strings of arbitrary length
  – **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);
}
```

← **BTW, how big is big enough?**

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

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

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

# Buffer Overflow Disassembly

**echo:**

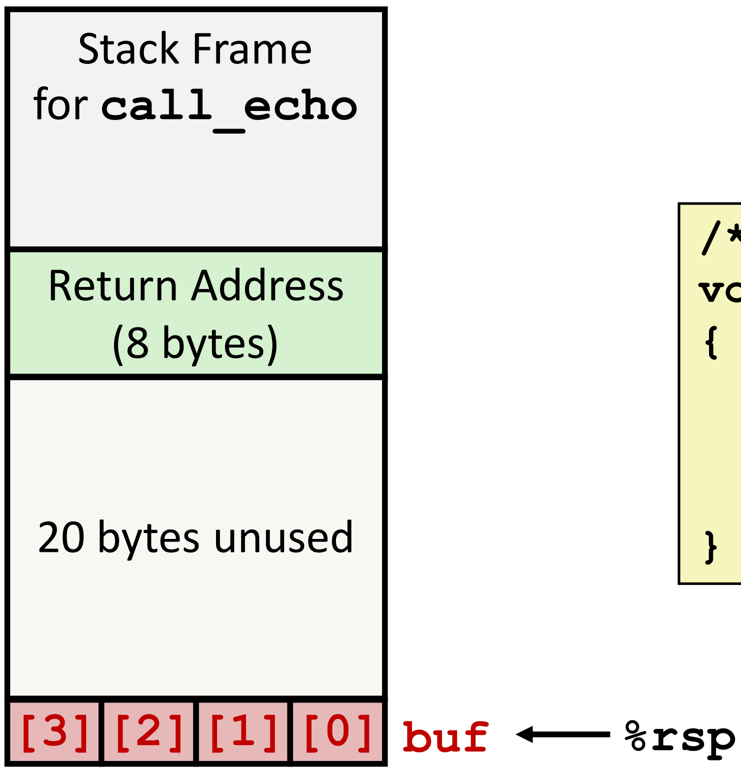
```
0000000000040069c <echo>:
 40069c:  48 83 ec 18              sub    $0x18,%rsp
 4006a0:  48 89 e7                 mov    %rsp,%rdi
 4006a3:  e8 a5 ff ff ff           callq  40064d <gets>
 4006a8:  48 89 e7                 mov    %rsp,%rdi
 4006ab:  e8 50 fe ff ff           callq  400500 <puts@plt>
 4006b0:  48 83 c4 18              add    $0x18,%rsp
 4006b4:  c3                       retq
```

**call_echo:**

```
 4006b5:  48 83 ec 08              sub    $0x8,%rsp
 4006b9:  b8 00 00 00 00           mov    $0x0,%eax
 4006be:  e8 d9 ff ff ff           callq  40069c <echo>
 4006c3:  48 83 c4 08              add    $0x8,%rsp
 4006c7:  c3                       retq
```

# Buffer Overflow Stack Example

***Before call to gets***

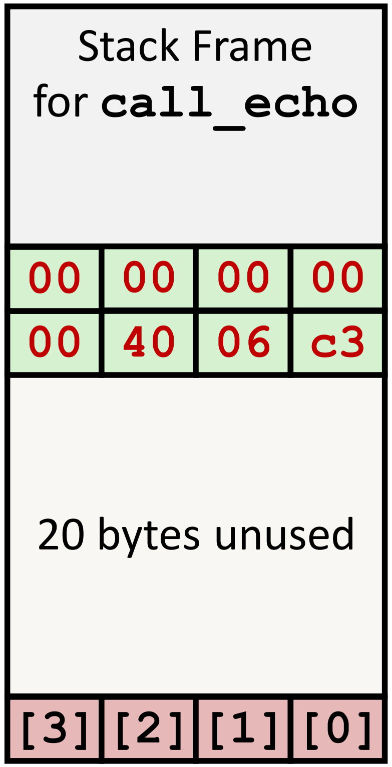



```c
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
  subq $0x18, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

# Buffer Overflow Stack Example

***Before call to gets***




buf ← %rsp

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

```
echo:
  subq   $0x18, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

**call_echo:**

```
   . . .
  4006be:   callq   4006cf <echo>
  4006c3:   add     $0x8,%rsp
   . . .
```

# Buffer Overflow Stack Example #1

***After call to gets***

| Stack Frame for `call_echo` | | | |
|---|---|---|---|
| 00 | 00 | 00 | 00 |
| 00 | 40 | 06 | c3 |
| 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  $0x18, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

**call_echo:**

```
  . . .
  4006be:   callq  4006cf <echo>
  4006c3:   add    $0x8,%rsp
  . . .
```

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

`"01234567890123456789012\0"`

**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   $0x18, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

**call_echo:**

```
  . . .
  4006be:    callq  4006cf <echo>
  4006c3:    add    $0x8,%rsp
  . . .
```

```
unix>./bufdemo-nsp
Type a string:012345678901234567890123 4
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   $0x18, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

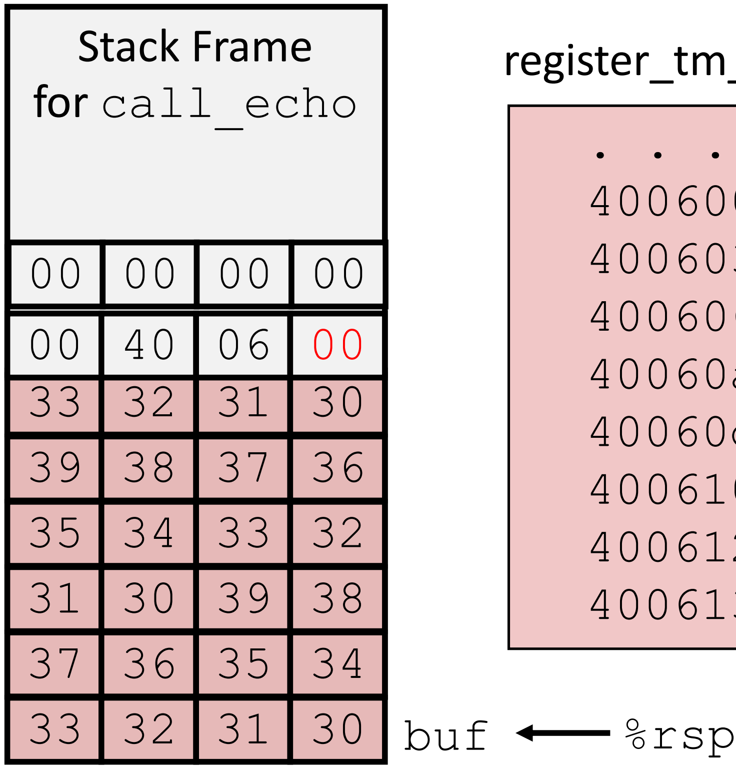
## call_echo:

```
  . . .
  4006be:    callq   4006cf <echo>
  4006c3:    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




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
```

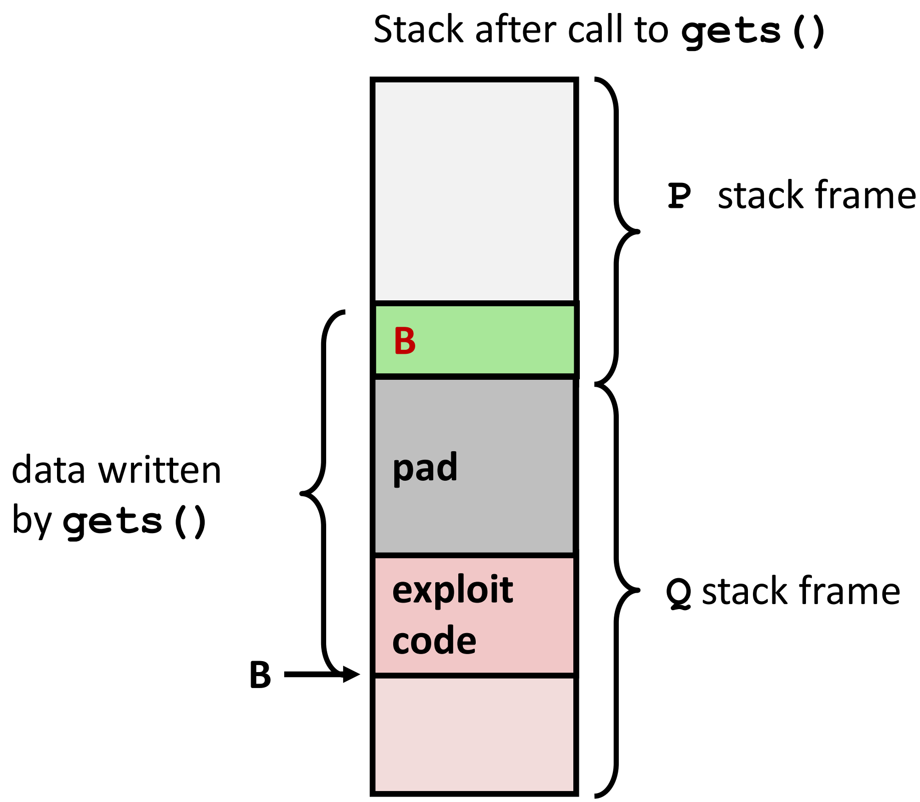
"Returns" to unrelated code
Lots of things happen, without modifying critical state
Eventually executes `retq` back to `main`

# Code Injection Attacks

```
void P(){
  Q();
  ...
}
```

return address A

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

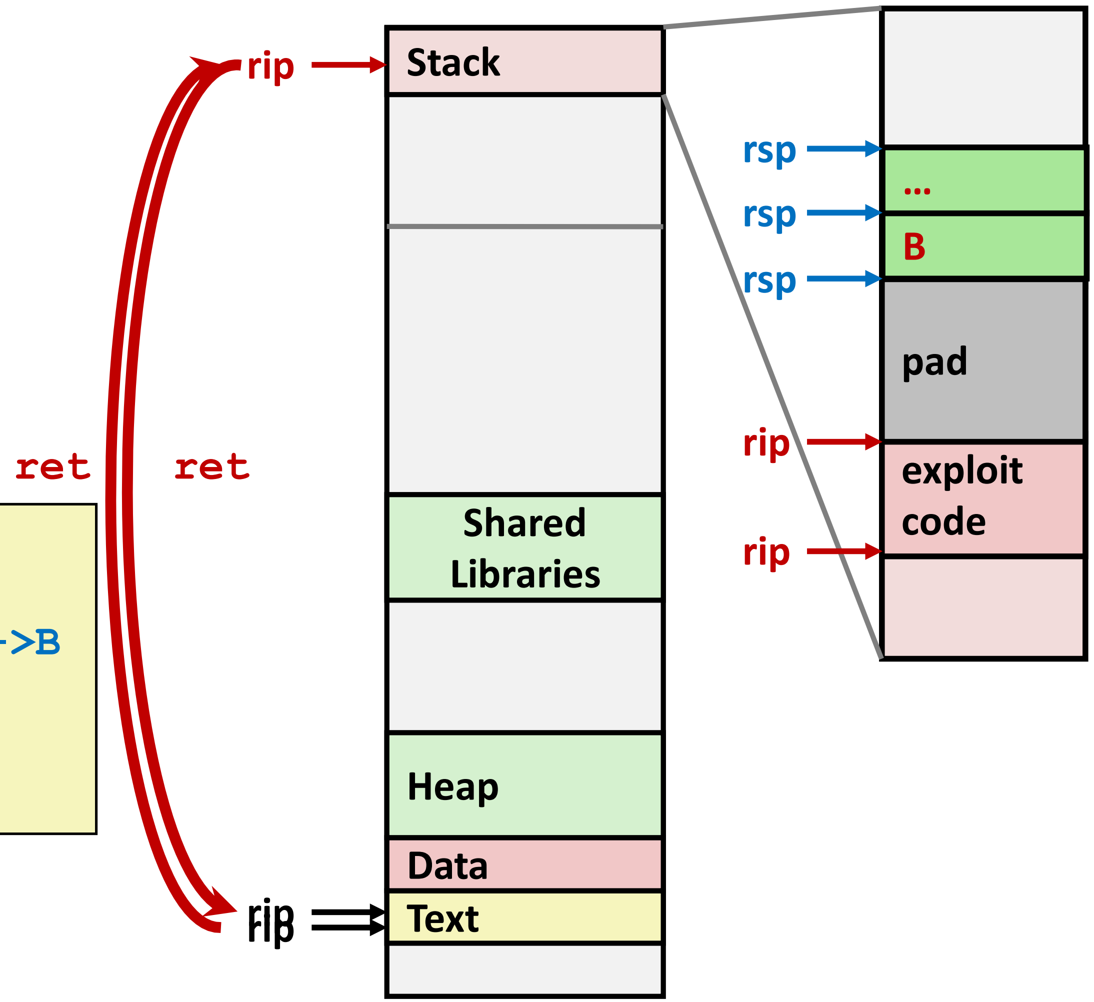



- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When `Q` executes `ret`, will jump to exploit code

# How Does The Attack Code Execute?

```
void P(){
  Q();
  ...
}
```

```
int Q() {
  char buf[64];
  gets(buf); // A->B
  ...
  return ...;
}
```



# Exploits Based on Buffer Overflows

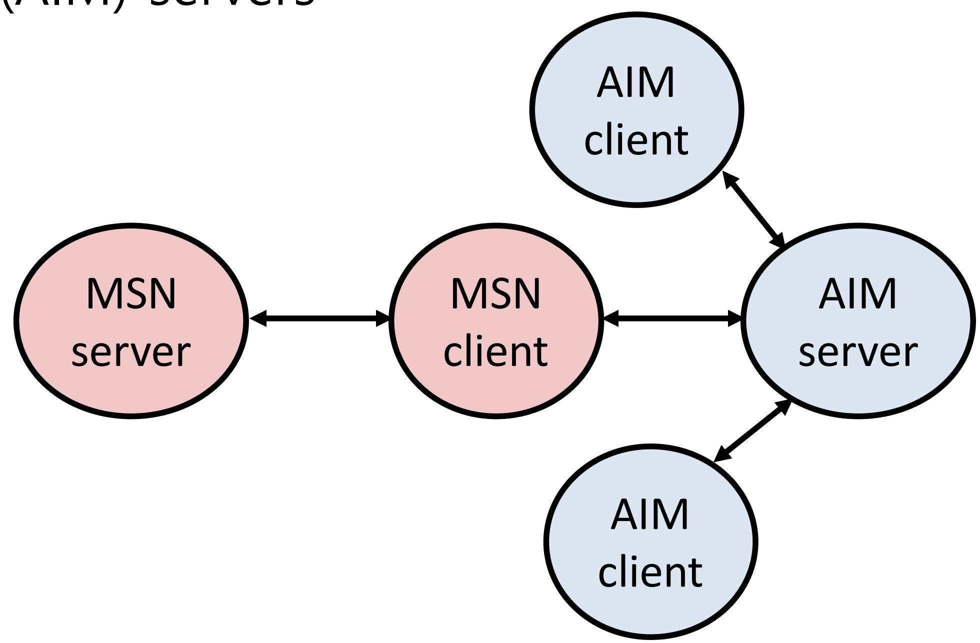
- *Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines*
- Distressingly common in real progams
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original "Internet worm" (1988)
  - "IM wars" (1999)
  - Twilight hack on Wii (2000s)
  - … and many, many more
- You will learn some of the tricks in attacklab
  - 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…
  - and CERT was formed… still homed at CMU

# Example 2: IM War

- July, 1999
  - Microsoft launches MSN Messenger (instant messaging system).
  - Messenger clients can access popular AOL Instant Messaging Service (AIM) servers



# IM War (cont.)

- August 1999
  - Mysteriously, Messenger clients can no longer access AIM servers
  - Microsoft and AOL begin the IM war:
    - AOL changes server to disallow Messenger clients
    - Microsoft makes changes to clients to defeat AOL changes
    - At least 13 such skirmishes
  - What was really happening?
    - AOL had discovered a buffer overflow bug in their own AIM clients
    - They exploited it to detect and block Microsoft: the exploit code returned a 4-byte signature (the bytes at some location in the AIM client) to server
    - When Microsoft changed code to match signature, AOL changed signature location

```
Date: Wed, 11 Aug 1999 11:30:57 -0700 (PDT)
From: Phil Bucking <philbucking@yahoo.com>
Subject: AOL exploiting buffer overrun bug in their own software!
To: rms@pharlap.com

Mr. Smith,

I am writing you because I have discovered something that I think you
might find interesting because you are an Internet security expert with
experience in this area. I have also tried to contact AOL but received
no response.

I am a developer who has been working on a revolutionary new instant
messaging client that should be released later this year.
...
It appears that the AIM client has a buffer overrun bug. By itself
this might not be the end of the world, as MS surely has had its share.
But AOL is now *exploiting their own buffer overrun bug* to help in
its efforts to block MS Instant Messenger.
....
Since you have significant credibility with the press I hope that you
can use this information to help inform people that behind AOL's
friendly exterior they are nefariously compromising peoples' security.

Sincerely,
Phil Bucking
Founder, Bucking Consulting
philbucking@yahoo.com
```

*It was later determined that this email originated from within Microsoft!*

# Aside: Worms and Viruses

- Worm: A program that
  - Can run by itself
  - Can propagate a fully working version of itself to other computers

- Virus: Code that
  - Adds itself to other programs
  - Does not run independently

- Both are (usually) designed to spread among computers and to wreak havoc

# Ok, What to Do About Buffer Overflow Attacks

- Avoid overflow vulnerabilities
- Employ system-level protections
- Have compiler use “stack canaries”

- Lets talk about each…

# 1. Avoid Overflow Vulnerabilities in Code (!)

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

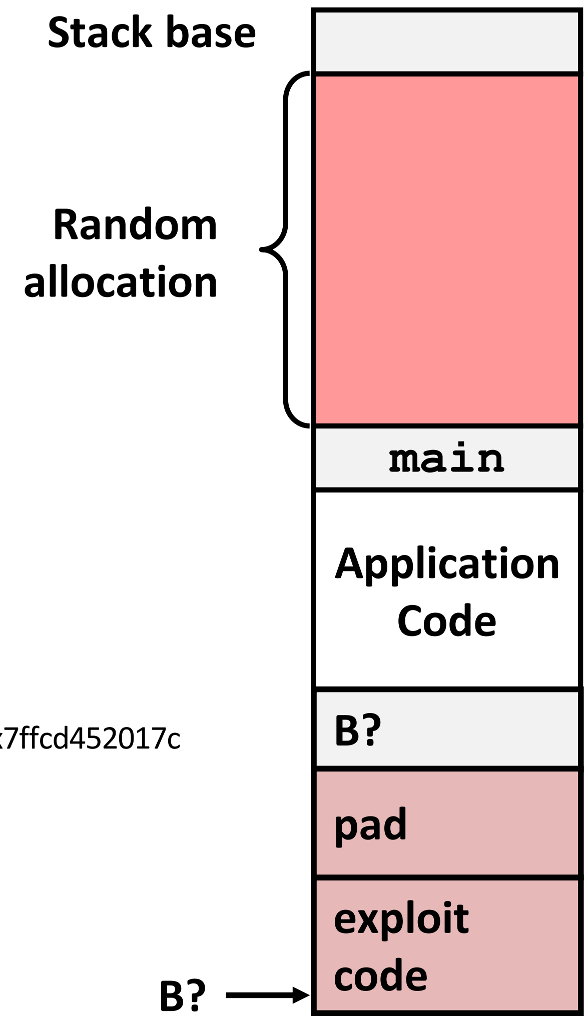
- For example, use library routines that limit string lengths
  - **`fgets`** instead of **`gets`**
  - **`strncpy`** instead of **`strcpy`**
  - Don't use **`scanf`** with **`%s`** conversion specification
    - Use **`fgets`** to read the string
    - Or use **`%ns`** where **`n`** is a suitable integer

# 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
  - Makes it difficult for hacker to predict beginning of inserted code
  - e.g., 5 executions of memory allocation code

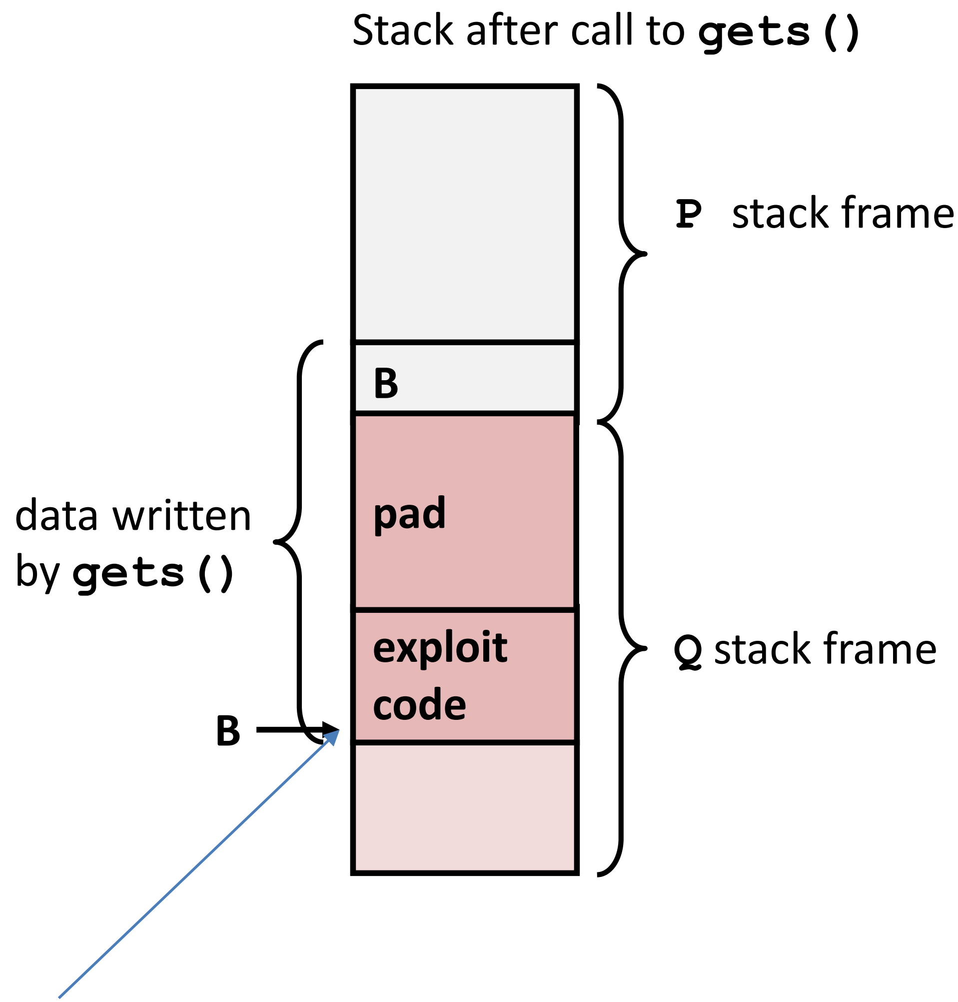
| | | | | | |
|---|---|---|---|---|---|
| local | 0x7ffe4d3be87c | 0x7fff75a4f9fc | 0x7ffeadb7c80c | 0x7ffeaea2fdac | 0x7ffcd452017c |

    - 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




**Any attempt to execute this code will fail**

# 3. Stack Canaries Can Help

- Idea
  - Place special value ("canary") on stack just beyond buffer
  - Check for corruption before exiting function
- GCC Implementation
  - `-fstack-protector`
  - Now the default (disabled earlier)

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

```
unix>./bufdemo-sp
Type a string:012345678
*** stack smashing detected ***
```

# Protected Buffer Disassembly

**echo:**

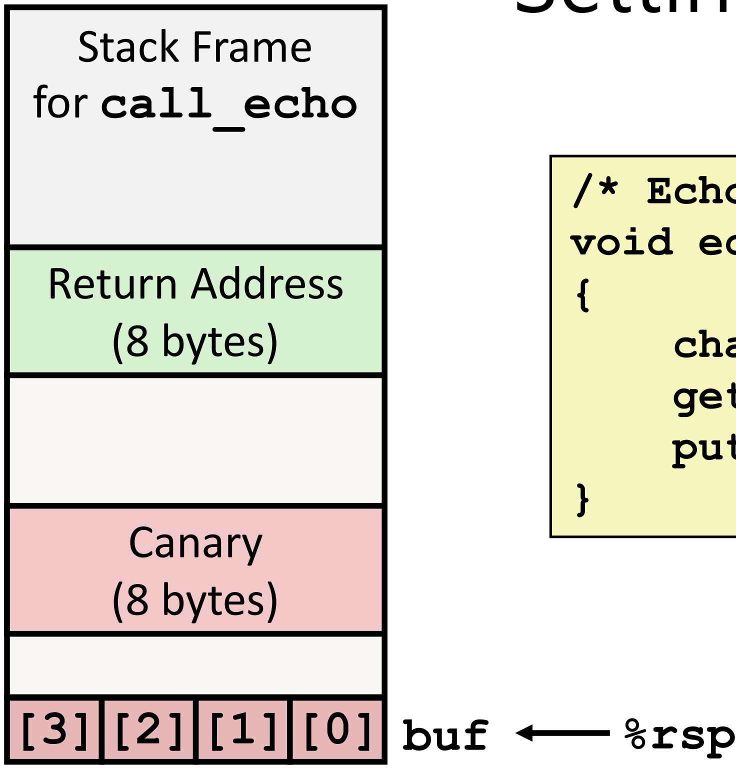
```
40072f:  sub    $0x18,%rsp
400733:  mov    %fs:0x28,%rax
40073c:  mov    %rax,0x8(%rsp)
400741:  xor    %eax,%eax
400743:  mov    %rsp,%rdi
400746:  callq  4006e0 <gets>
40074b:  mov    %rsp,%rdi
40074e:  callq  400570 <puts@plt>
400753:  mov    0x8(%rsp),%rax
400758:  xor    %fs:0x28,%rax
400761: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

**Aside: `%fs:0x28`**

- **Read from memory using segmented addressing**
- **Segment is read-only**
- **Value generated randomly every time program runs**

# Setting Up Canary

*Before call to gets*

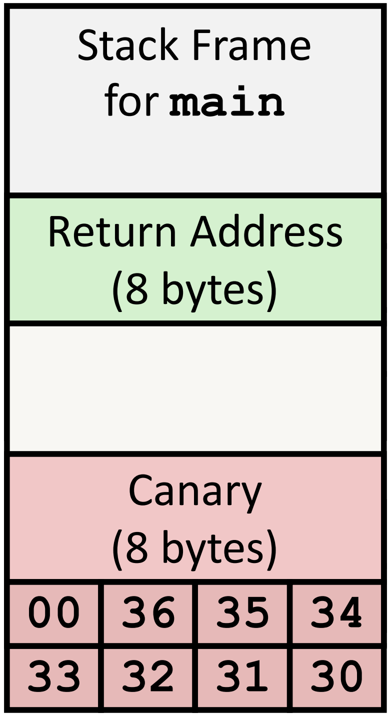



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    mov     %fs:0x28, %rax   # Get canary
    mov     %rax, 0x8(%rsp)  # Place on stack
    xor     %eax, %eax       # Erase register
    . . .
```

# Checking Canary

*After call to gets*




buf ⟵ %rsp

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

**Input:** ***0123456***

***Some systems:***
***LSB of canary is 0x00***
***Allows input 01234567***

```
echo:
    . . .
    mov     0x8(%rsp),%rax      # Retrieve from stack
    xor     %fs:0x28,%rax       # Compare to canary
    je      .L6                 # If same, OK
    call    __stack_chk_fail    # FAIL
```

# Return-Oriented Programming Attacks

- Challenge (for hackers)
  - Stack randomization makes it hard to predict buffer location
  - Marking stack nonexecutable makes it hard to insert binary code
- Alternative Strategy
  - Use existing code
    - e.g., library code from stdlib
  - String together fragments to achieve overall desired outcome
  - *Does not overcome stack canaries*
- Construct program from *gadgets*
  - Sequence of instructions ending in **`ret`**
    - Encoded by single byte **`0xc3`**
  - Code positions fixed from run to run
  - Code is executable

# Gadget Example #1

```
long ab_plus_c
  (long a, long b, long c)
{
    return a*b + c;
}
```

```
00000000004004d0 <ab_plus_c>:
  4004d0:  48 0f af fe  imul %rsi,%rdi
  4004d4:  48 8d 04 17  lea (%rdi,%rdx,1),%rax
  4004d8:  c3           retq
```

**rax ← rdi + rdx**

**Gadget address = `0x4004d4`**

- Use tail end of existing functions

# Gadget Example #2

```
void setval(unsigned *p) {
    *p = 3347663060u;
}
```

**Encodes `movq %rax, %rdi`**

```
<setval>:
  4004d9:  c7 07 d4 48 89 c7  movl  $0xc78948d4,(%rdi)
  4004df:  c3                 retq
```

**rdi ← rax**

**Gadget address = `0x4004dc`**

- Repurpose byte codes

# Questions?