



# 计算机系统基础09

## Machine-Level Programming V: Advanced Topics

# Today

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

# x86-64 Linux Memory Layout

*not drawn to scale*

## ■ Stack

- Runtime stack (8MB limit)
- E. g., local variables

## ■ Heap

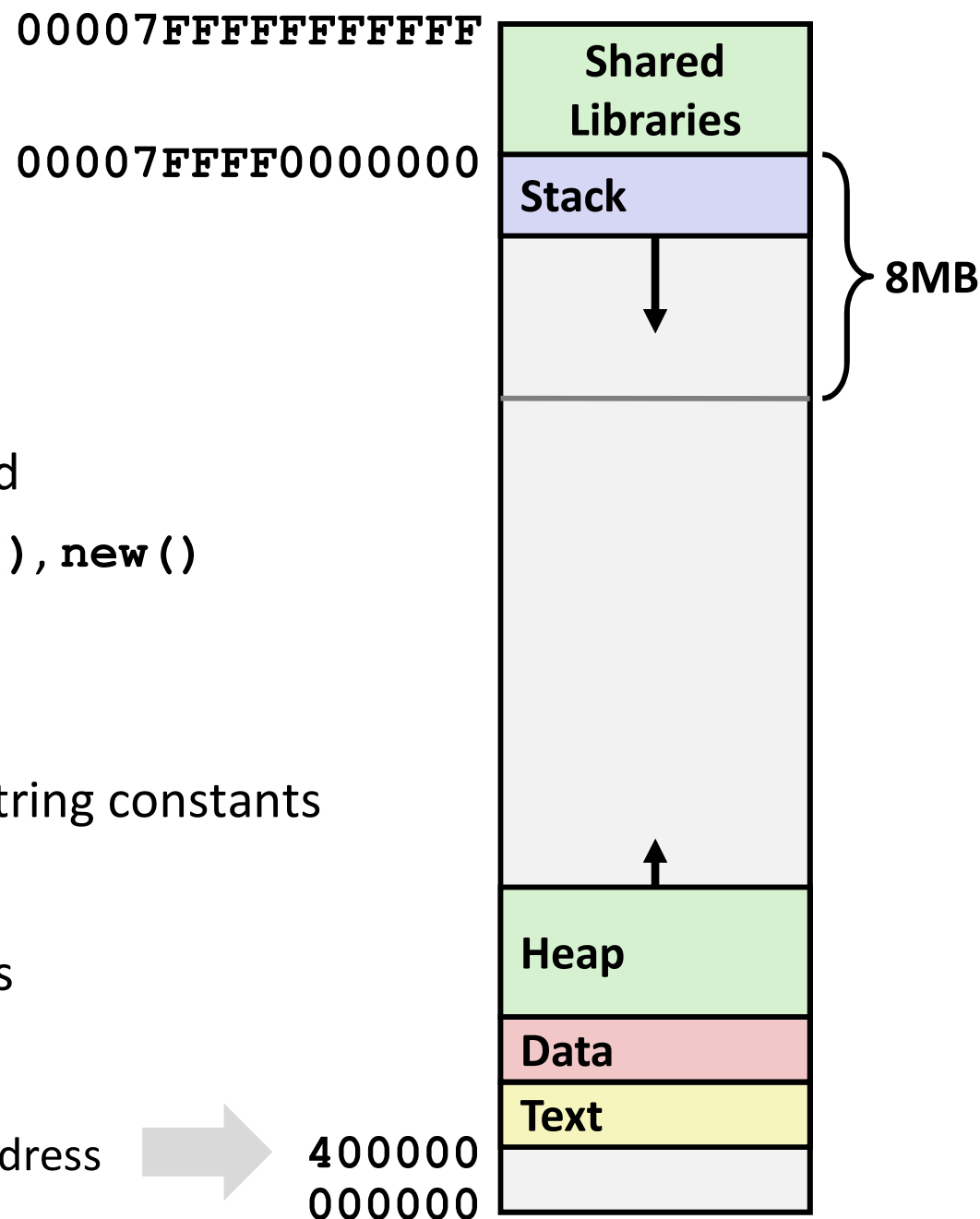
- Dynamically allocated as needed
- When call `malloc()`, `calloc()`, `new()`

## ■ Data

- Statically allocated data
- E.g., global vars, `static` vars, string constants

## ■ Text / Shared Libraries

- Executable machine instructions
- Read-only



*not drawn to scale*

# Memory Allocation Example

00007FFFFFFFFFFFFFFF

```

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

*address range  $\sim 2^{47}$*

```

local
p1
p3
p4
p2
big_array
huge_array
main()
useless()

```

0x00007ffe4d3be87c

0x00007f7262a1e010

0x00007f7162a1d010

0x000000008359d120

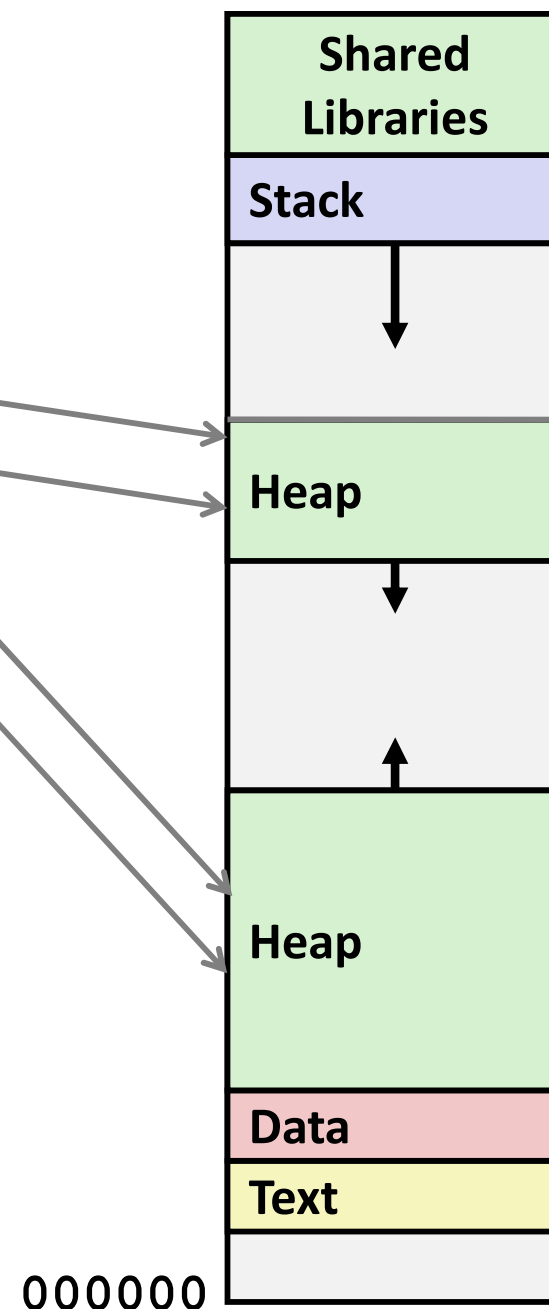
0x000000008359d010

0x0000000080601060

0x0000000000601060

0x000000000040060c

0x0000000000400590



(Exact values can vary)

*not drawn to scale*

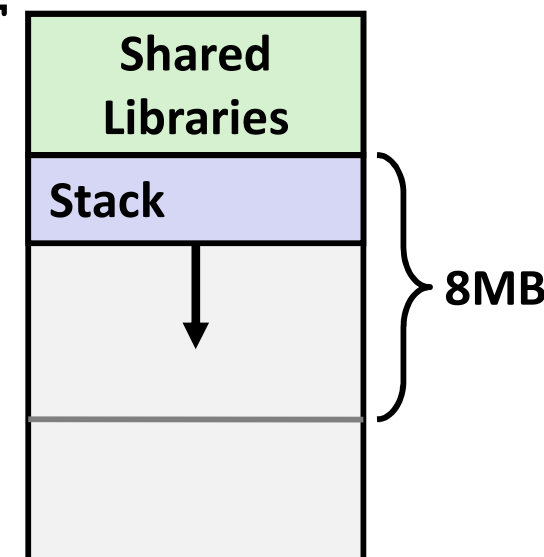
# Runaway Stack Example

00007FFFFFFFFFFFFFFF

```

int recurse(int x) {
    int a[1<<15]; // 4*2^15 = 128 KiB
    printf("x = %d.  a at %p\n", x, a);
    a[0] = (2<<13)-1;
    a[a[0]] = x-1;
    if (a[a[0]] == 0)
        return -1;
    return recurse(a[a[0]]) - 1;
}

```



- Functions store local data on in stack frame
- Recursive functions cause deep nesting of frames

```

./runaway 48
x = 48.  a at 0x7fffd43e45d0
x = 47.  a at 0x7fffd43a45c0
x = 46.  a at 0x7fffd43645b0
x = 45.  a at 0x7fffd43245a0
. . .
x = 4.   a at 0x7fffd38e4310
x = 3.   a at 0x7fffd38a4300
x = 2.   a at 0x7fffd38642f0
Segmentation fault

```

# Today

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

# 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(4) | -> | Segmentation fault |
| fun(8) | -> | 3.1400000000       |

- Result is system specific

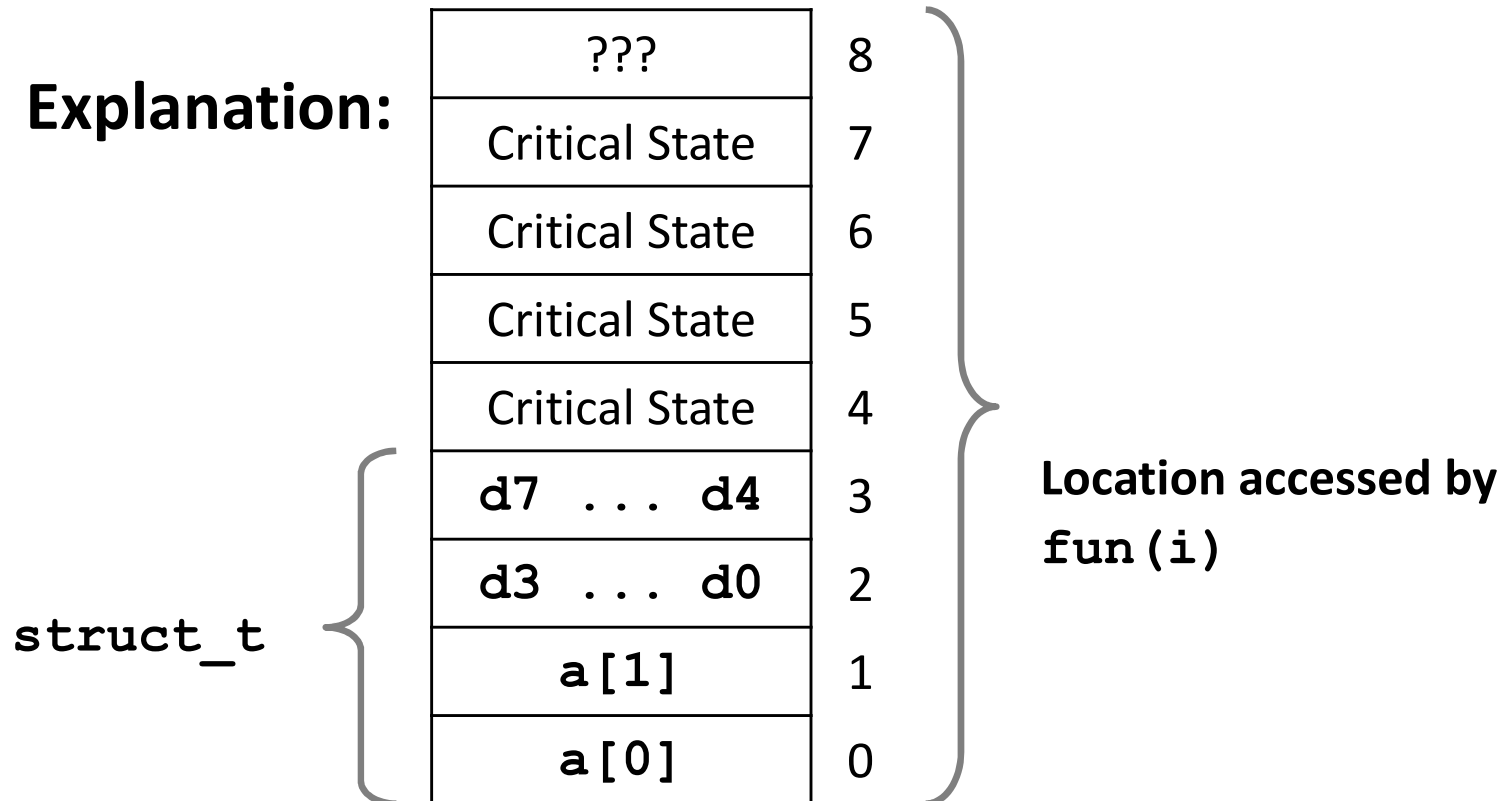


# Memory Referencing Bug Example

```
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:

00000000004006cf <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

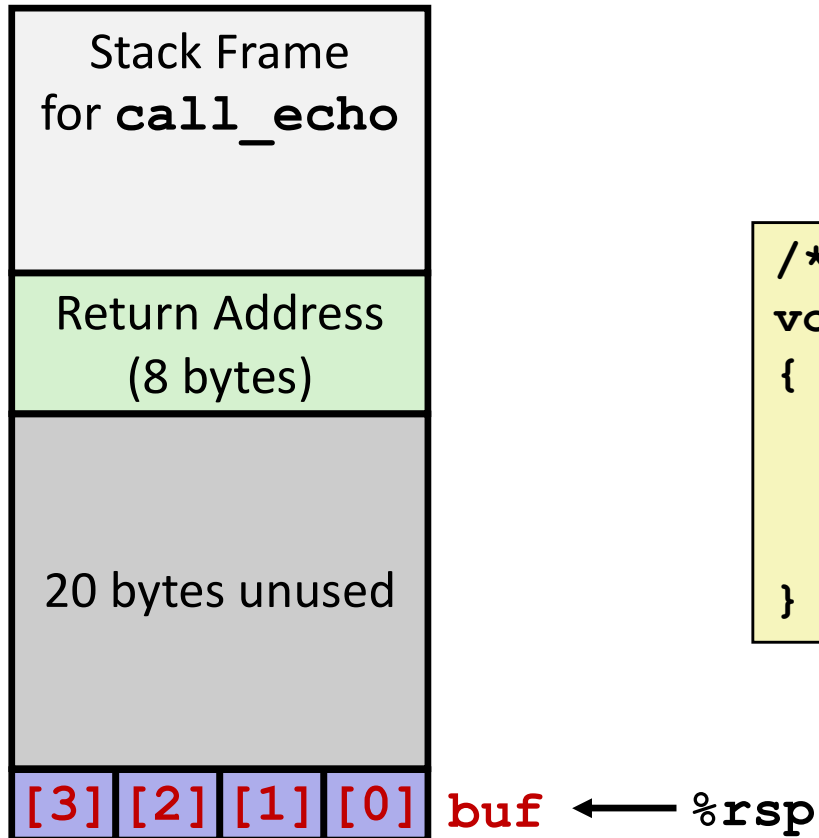
add \$0x8,%rsp

4006fa: c3

retq

# Buffer Overflow Stack

*Before call to gets*

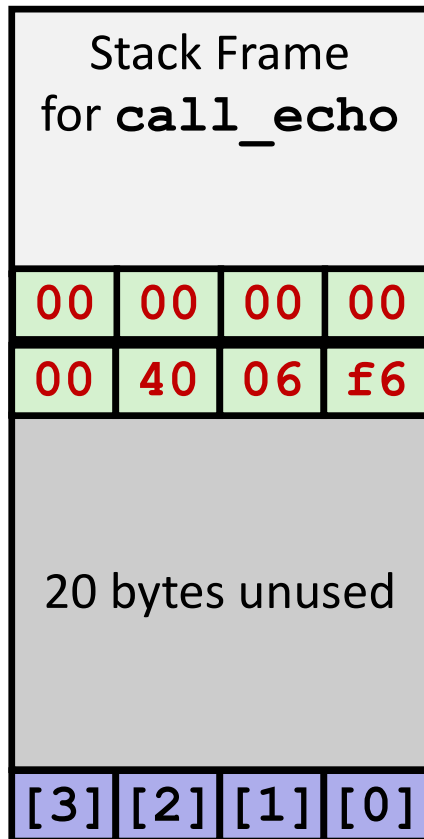


```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    subq    $0x18, %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<br>for <code>call_echo</code> |    |    |    |
|---|----|----|----|
| 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
```

```
"01234567890123456789012\0"
```

**Overflowed buffer, but did not corrupt state**



# Buffer Overflow Stack Example #2

*After call to gets*

| Stack Frame<br>for <code>call_echo</code> |    |    |    |
|---|----|----|----|
| 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
    . . .
```

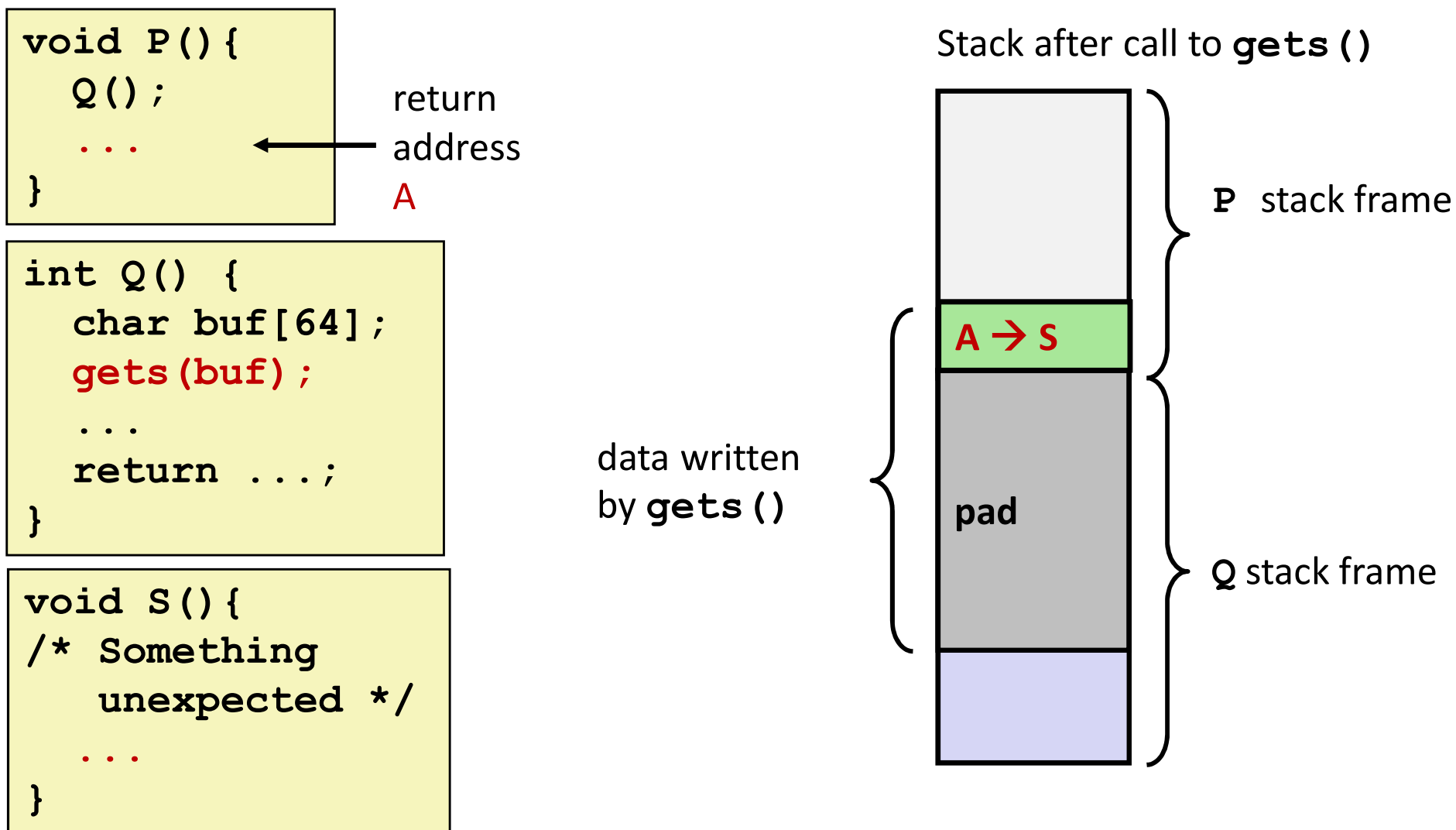
`call_echo:`

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

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

**Program “returned” to 0x0400600, and then crashed.**

# Stack Smashing Attacks



- Overwrite normal return address **A** with address of some other code **S**
- When **Q** executes `ret`, will jump to other code

# Crafting Smashing String

| Stack Frame<br>for call echo |    |    |    |
|------------------------------|----|----|----|
| 00                           | 00 | 00 | 00 |
| 00                           | 48 | 83 | 80 |
| 00                           | 00 | 00 | 00 |
| 00                           | 40 | 06 | fb |
|                              |    |    |    |
|                              |    |    |    |
|                              |    |    |    |
|                              |    |    |    |
|                              |    |    |    |
|                              |    |    |    |
|                              |    |    |    |

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

← %rsp

24 bytes

*Target Code*

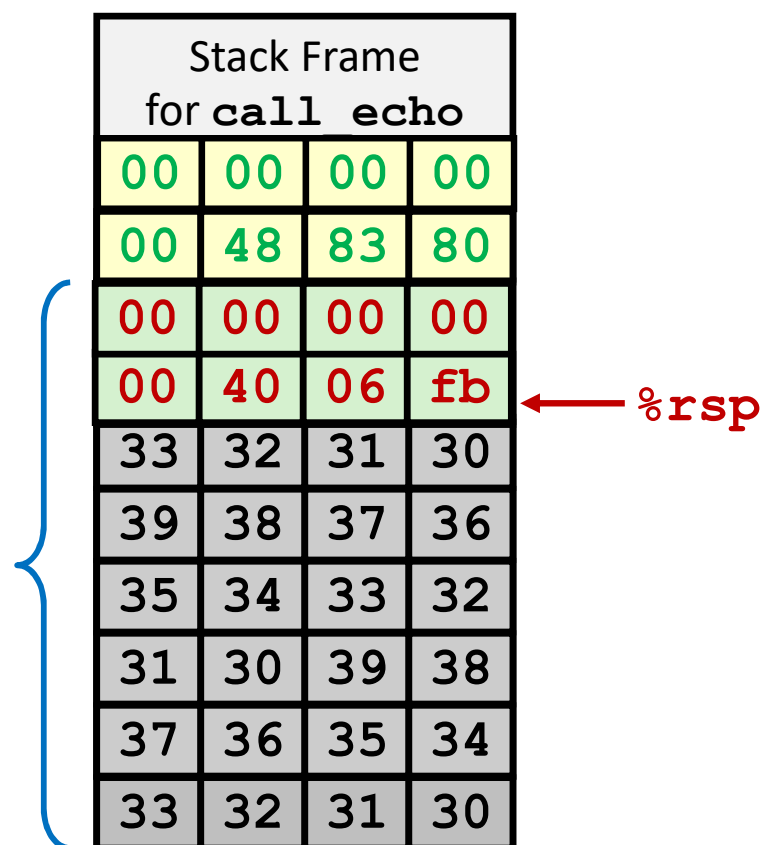
```
void smash() {
    printf("I've been smashed!\n");
    exit(0);
}
```

```
00000000004006fb <smash>:
4006fb:          48 83 ec 08
```

*Attack String (Hex)*

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

# Smashing String Effect



## Target Code

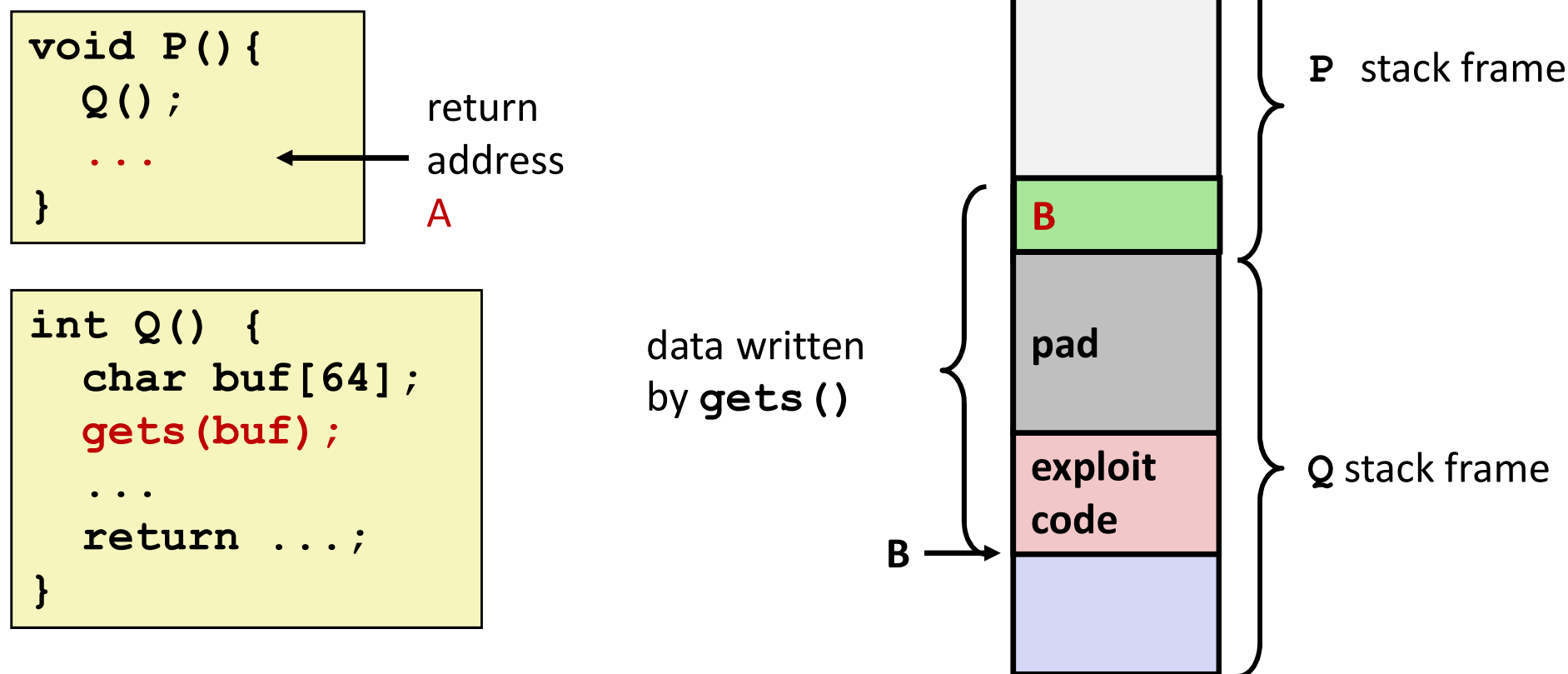
```
void smash() {
    printf("I've been smashed!\n");
    exit(0);
}
```

```
00000000004006fb <smash>:
4006fb:          48 83 ec 08
```

## Attack String (Hex)

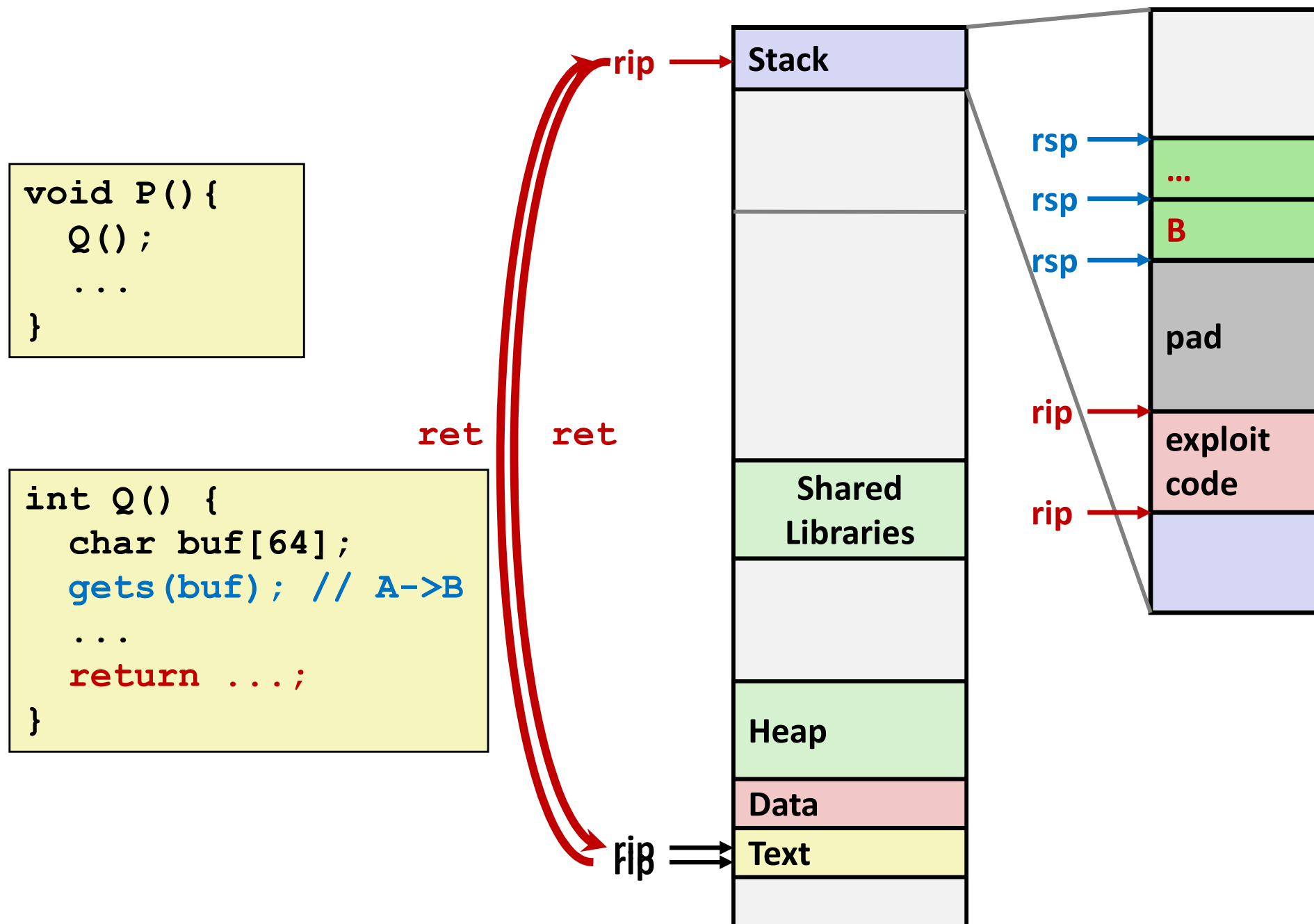
```
30 31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 37 38 39 30 31 32 33
fb 06 40 00 00 00 00 00 00
```

# Code Injection Attacks



- 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?



# 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]; /* Way too small! */  
    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



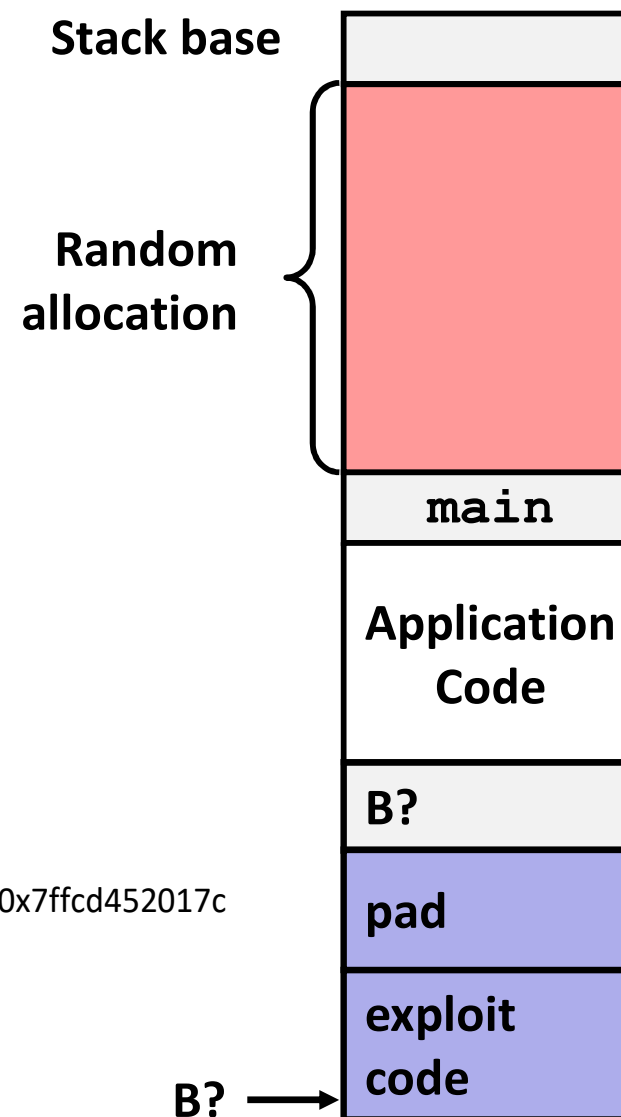
## 2. System-Level Protections can help?

### ■ 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



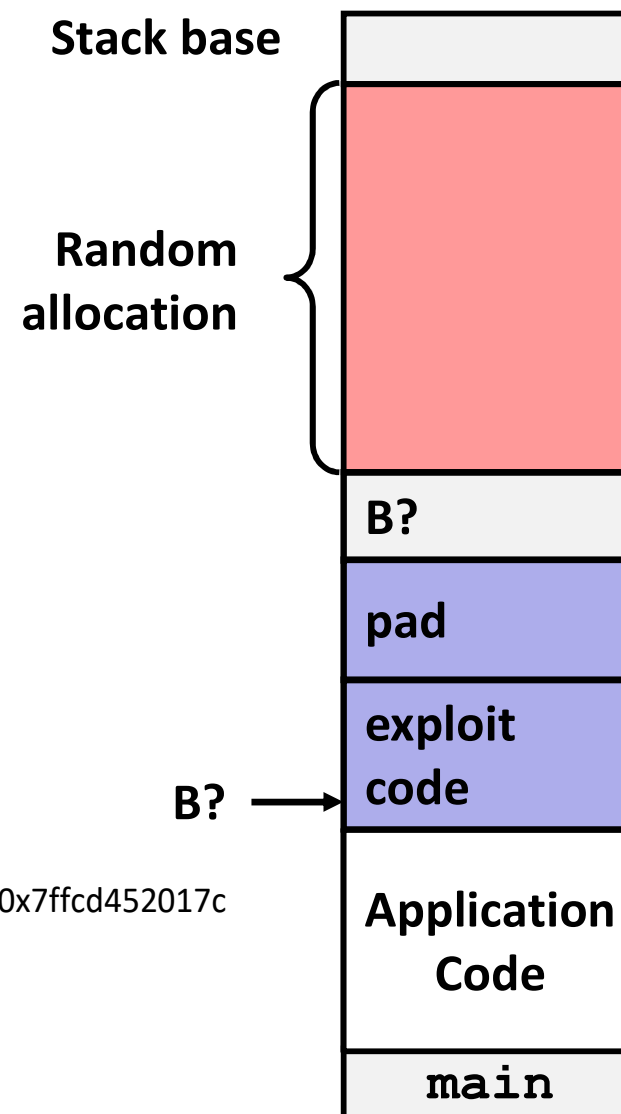
## 2. System-Level Protections can help 修改

### ■ 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

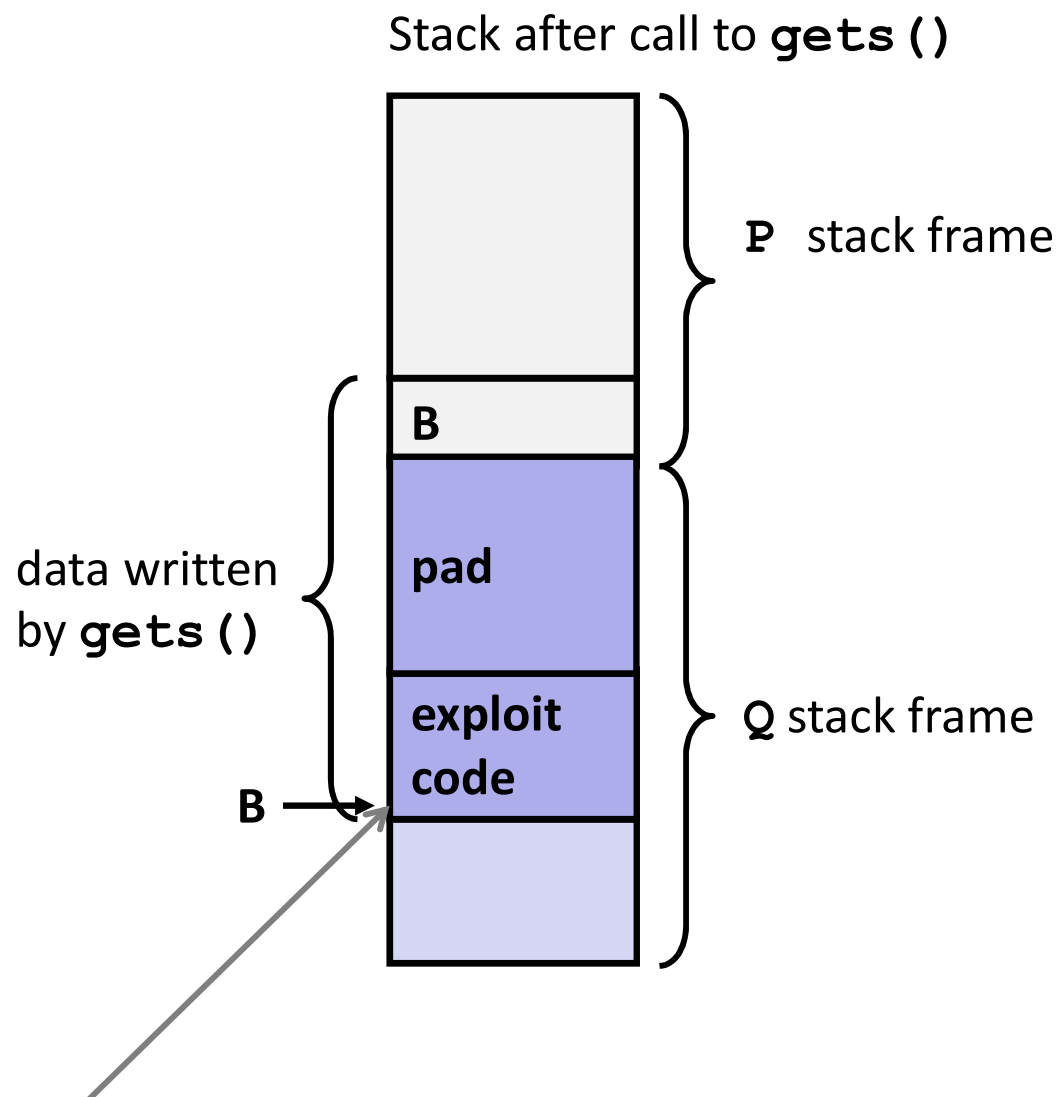
- Stack repositioned each time program executes



## 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: 01234567  
*** stack smashing detected ***
```

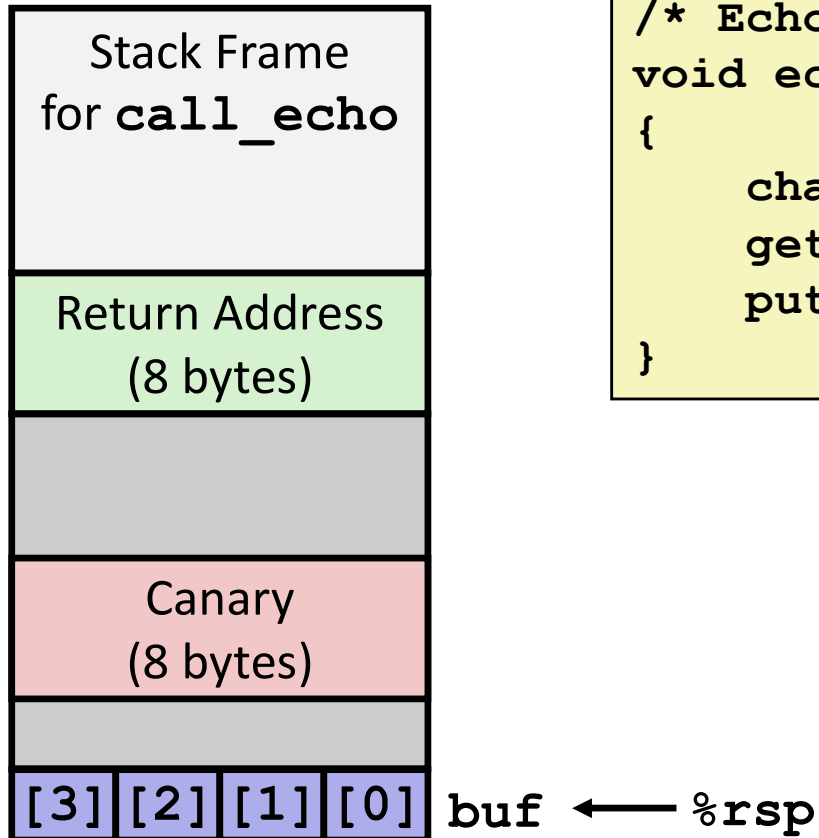
# Protected Buffer Disassembly

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*



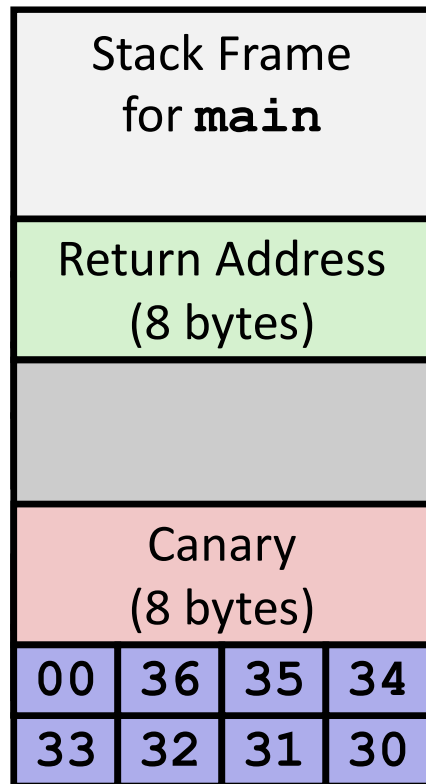
```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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*



**buf** ← **%rsp**

```
/* 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
```

# 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
```

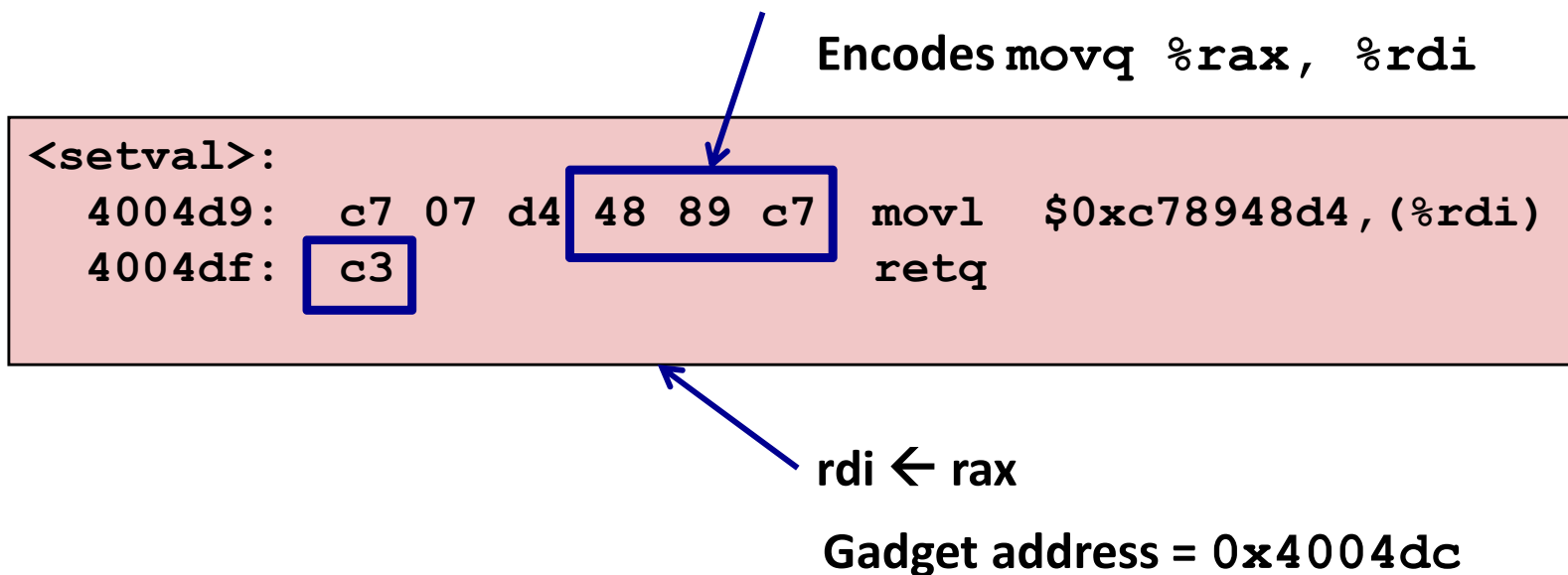
$\text{rax} \leftarrow \text{rdi} + \text{rdx}$

Gadget address = 0x4004d4

- Use tail end of existing functions

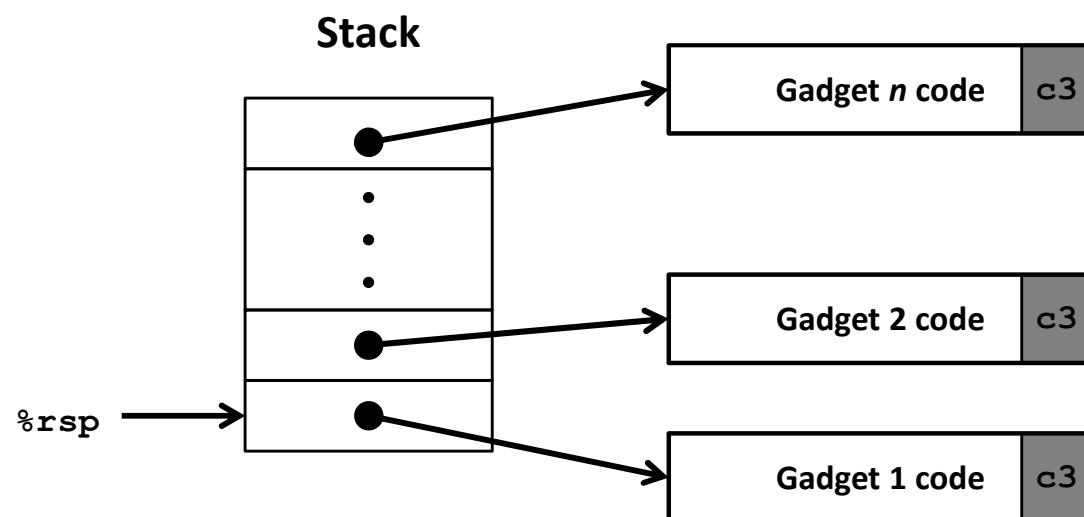
# Gadget Example #2

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



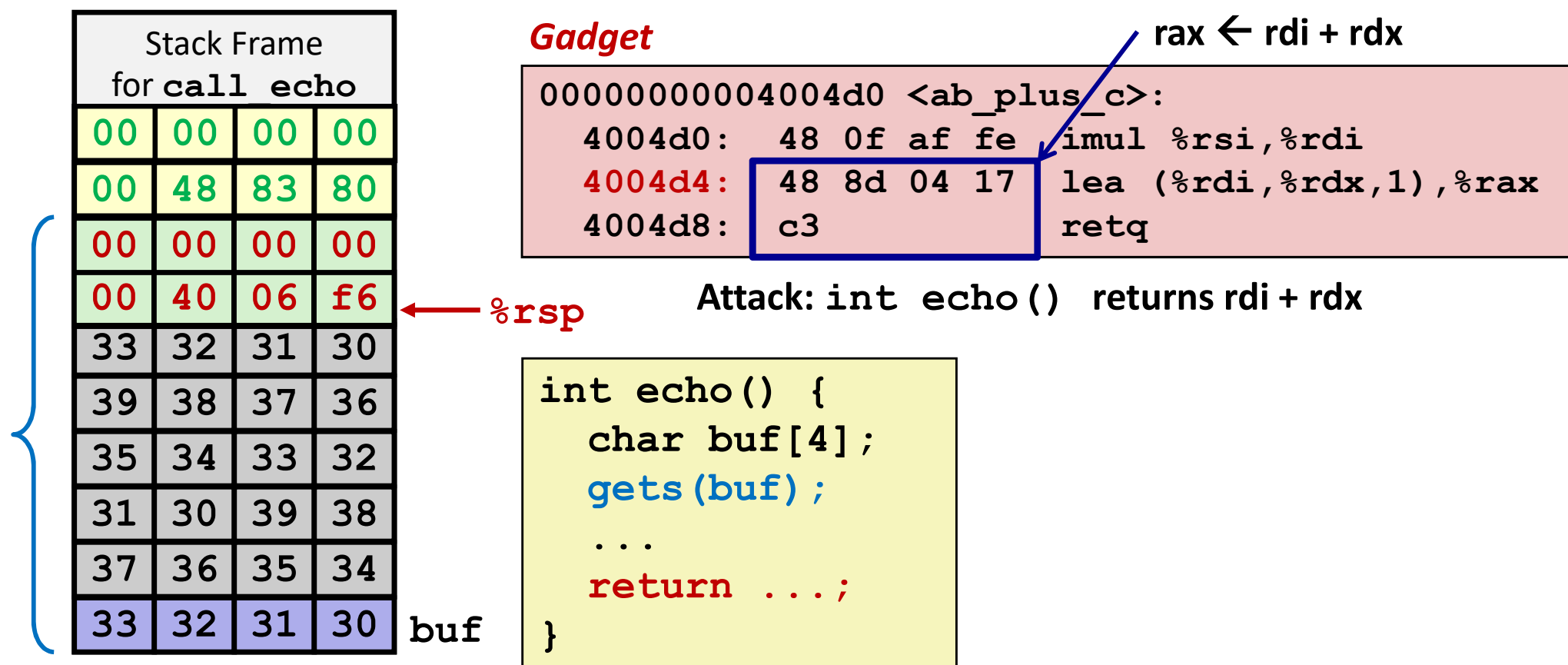
## ■ Repurpose byte codes

# ROP Execution



- Trigger with `ret` instruction
  - Will start executing Gadget 1
- Final `ret` in each gadget will start next one

# Crafting an ROB Attack String



## Attack String (Hex)

```

30 31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 37 38 39 30 31 32 33
d4 04 40 00 00 00 00 00
  
```

Multiple gadgets will corrupt stack upwards

# Today

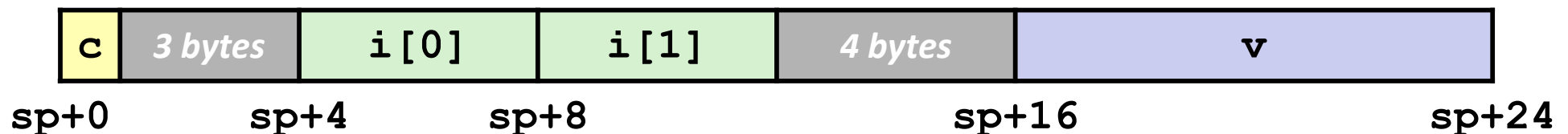
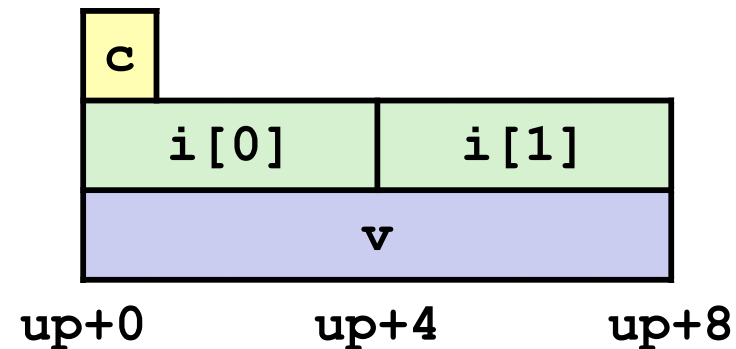
- **Memory Layout**
- **Buffer Overflow**
  - Vulnerability
  - Protection
- **Unions**

# Union Allocation

- Allocate according to largest element
- Can only use one field at a time

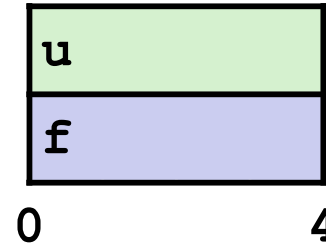
```
union U1 {
    char c;
    int i[2];
    double v;
} *up;
```

```
struct S1 {
    char c;
    int i[2];
    double v;
} *sp;
```



# Using Union to Access Bit Patterns

```
typedef union {  
    float f;  
    unsigned u;  
} bit_float_t;
```



```
float bit2float(unsigned u)  
{  
    bit_float_t arg;  
    arg.u = u;  
    return arg.f;  
}
```

Same as (float) u?

```
unsigned float2bit(float f)  
{  
    bit_float_t arg;  
    arg.f = f;  
    return arg.u;  
}
```

Same as (unsigned) f?

# Byte Ordering Revisited

## ■ Idea

- Short/long/quad words stored in memory as 2/4/8 consecutive bytes
- Which byte is most (least) significant?
- Can cause problems when exchanging binary data between machines

## ■ Big Endian

- Most significant byte has lowest address
- Sparc, *Internet*

## ■ Little Endian

- Least significant byte has lowest address
- Intel x86, ARM Android and IOS

## ■ Bi Endian

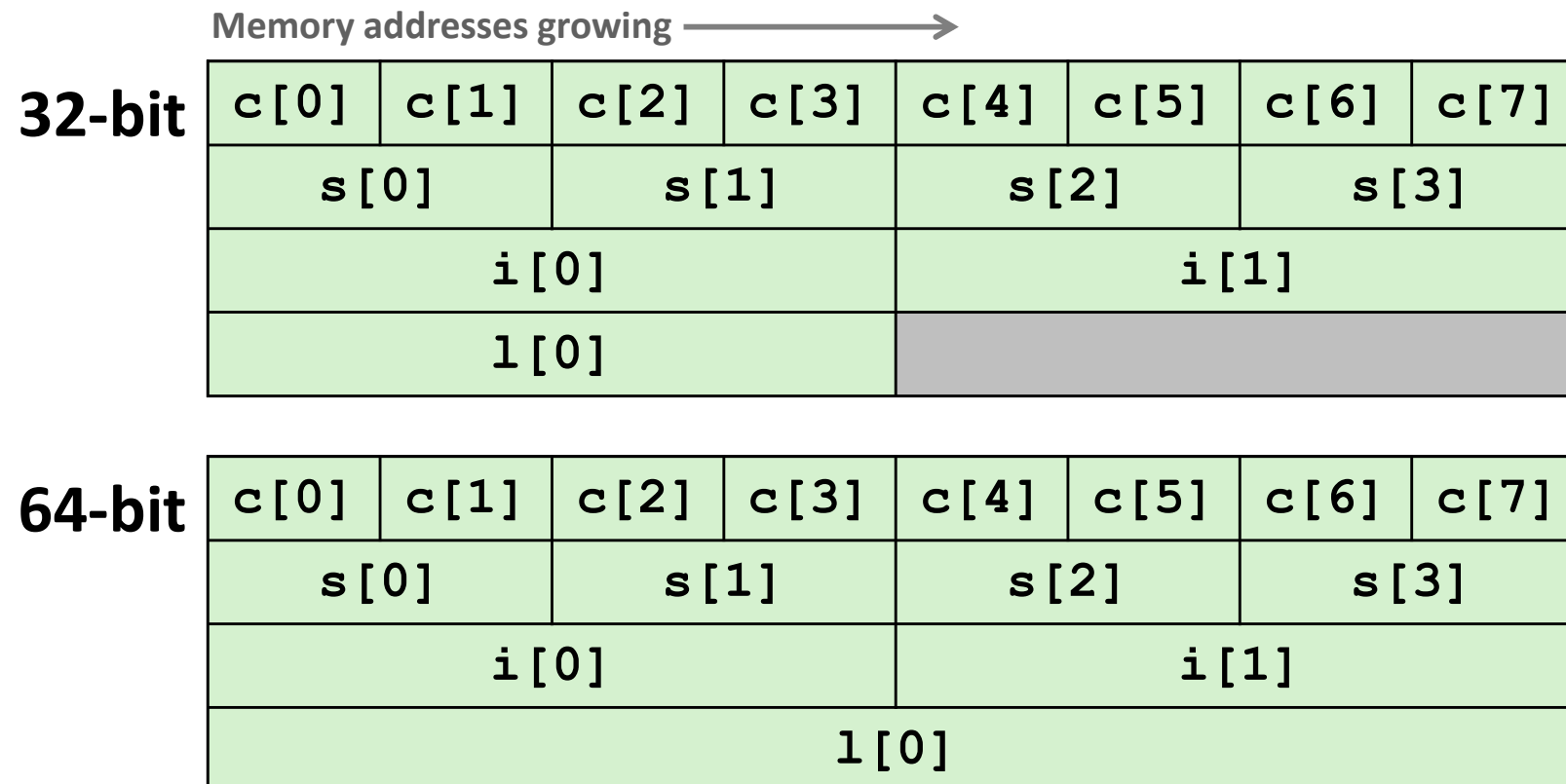
- Can be configured either way
- ARM



# Byte Ordering Example

```
union {
    unsigned char c[8];
    unsigned short s[4];
    unsigned int i[2];
    unsigned long l[1];
} dw;
```

**How are the bytes inside short/int/long stored?**



# Byte Ordering Example (Cont).

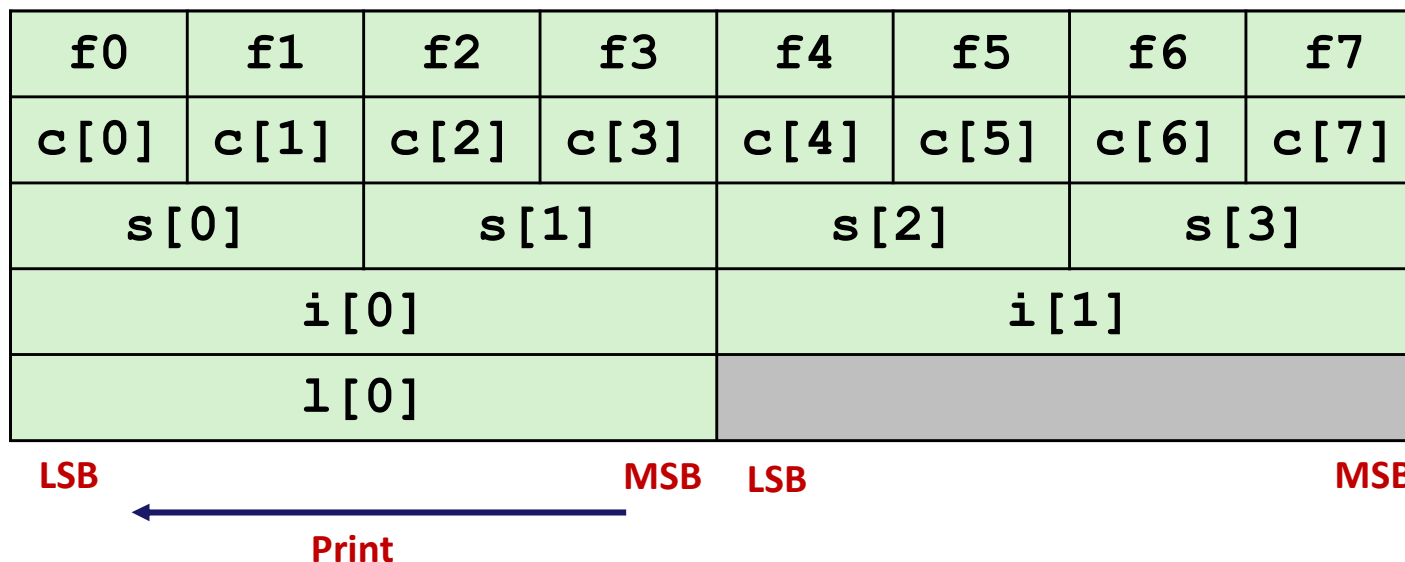
```
int j;
for (j = 0; j < 8; j++)
    dw.c[j] = 0xf0 + j;

printf("Characters 0-7 ==
[0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x] \n",
    dw.c[0], dw.c[1], dw.c[2], dw.c[3],
    dw.c[4], dw.c[5], dw.c[6], dw.c[7]);

printf("Shorts 0-3 == [0x%x,0x%x,0x%x,0x%x] \n",
    dw.s[0], dw.s[1], dw.s[2], dw.s[3]);

printf("Ints 0-1 == [0x%x,0x%x] \n",
    dw.i[0], dw.i[1]);

printf("Long 0 == [0x%lx] \n",
    dw.l[0]);
```



## Output:

**Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]**

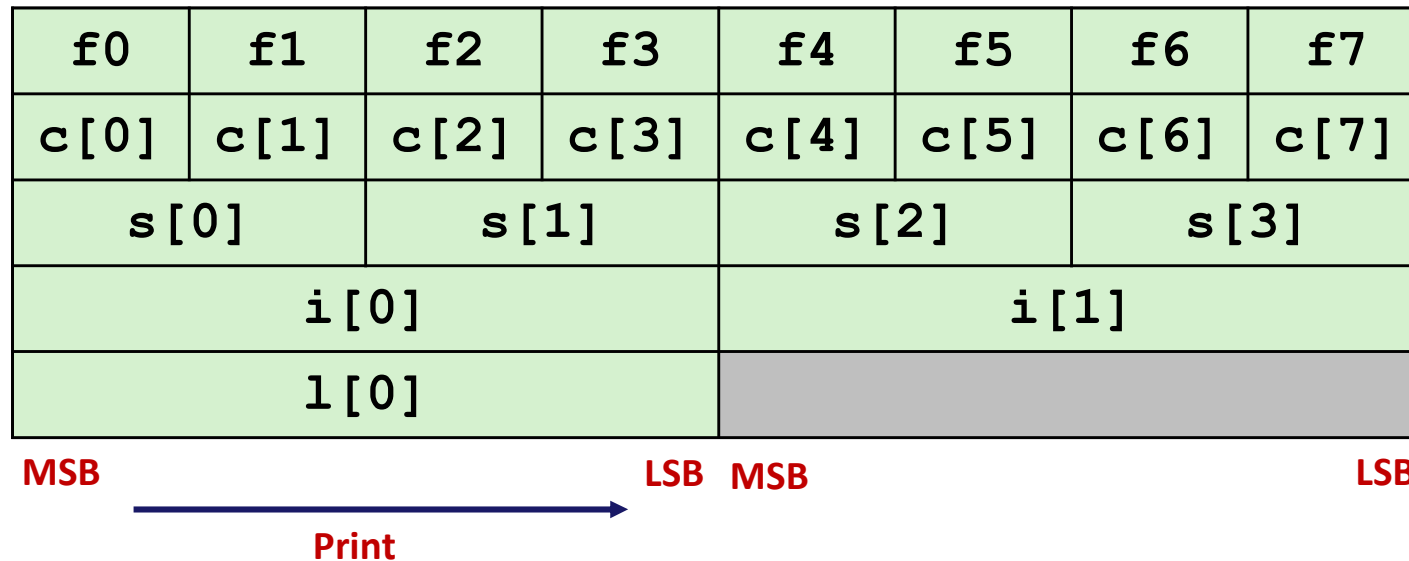
**Shorts**      0-3 == [0xf1f0,0xf3f2,0xf5f4,0xf7f6]

```
Ints      0-1 == [0xf3f2f1f0,0xf7f6f5f4]
```

```
Long      0      == [0xf3f2f1f0]
```

# Byte Ordering on Sun

## Big Endian



## Output on Sun:

Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]

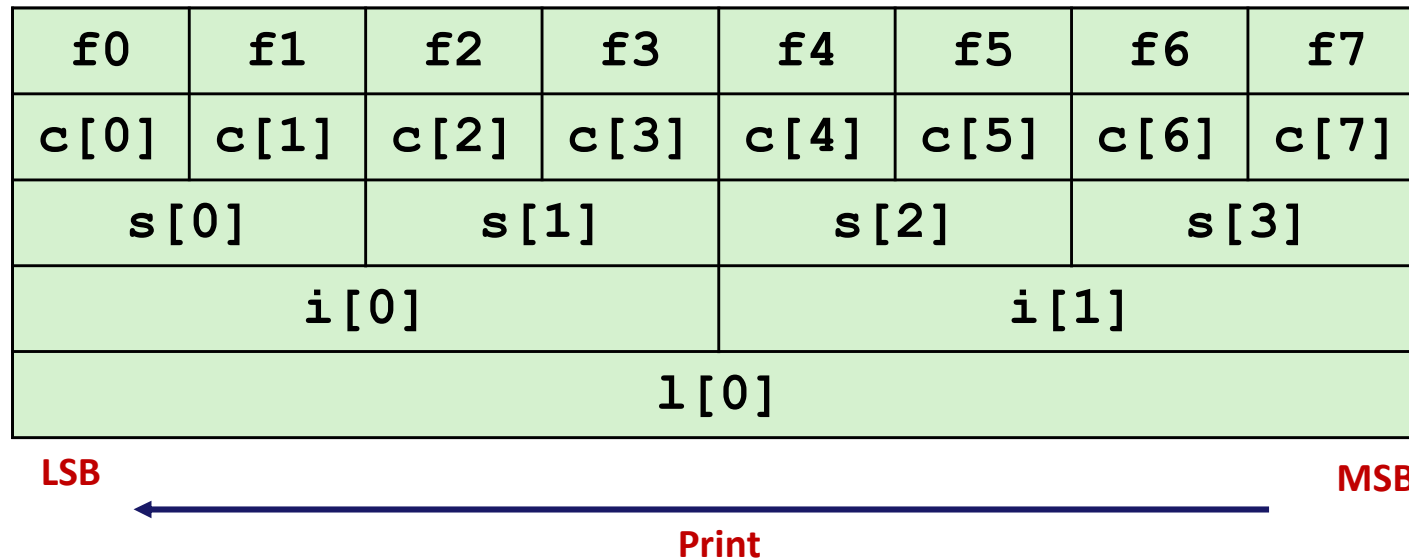
Shorts 0-3 == [0xf0f1,0xf2f3,0xf4f5,0xf6f7]

Ints 0-1 == [0xf0f1f2f3,0xf4f5f6f7]

Long 0 == [0xf0f1f2f3]

# Byte Ordering on x86-64

## Little Endian



## Output on x86-64:

Characters 0-7 == [0xf0, 0xf1, 0xf2, 0xf3, 0xf4, 0xf5, 0xf6, 0xf7]  
 Shorts 0-3 == [0xf1f0, 0xf3f2, 0xf5f4, 0xf7f6]  
 Ints 0-1 == [0xf3f2f1f0, 0xf7f6f5f4]  
 Long 0 == [0xf7f6f5f4f3f2f1f0]

# Summary of Compound Types in C

## ■ Arrays

- Contiguous allocation of memory
- Aligned to satisfy every element's alignment requirement
- Pointer to first element
- No bounds checking

## ■ Structures

- Allocate bytes in order declared
- Pad in middle and at end to satisfy alignment

## ■ Unions

- Overlay declarations
- Way to circumvent type system

# Summary

- **Memory Layout**
- **Buffer Overflow**
  - Vulnerability
  - Protection
  - Code Injection Attack
  - Return Oriented Programming
- **Unions**

# 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)
  - “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.

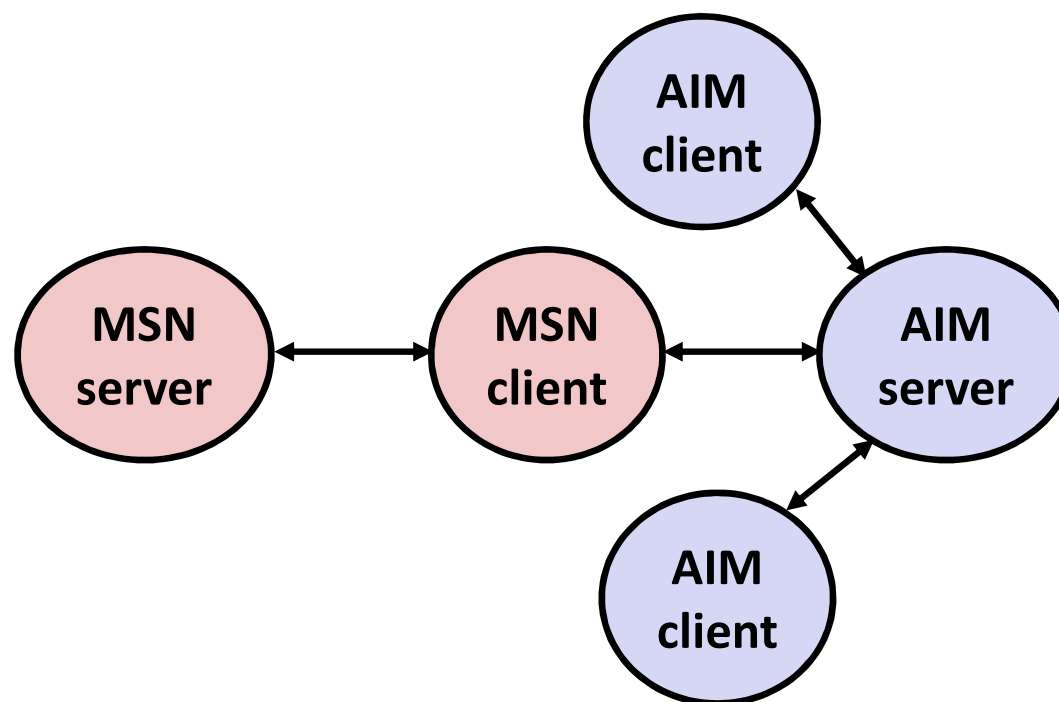
## ■ Once on a machine, scanned for other machines to attack

- 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**

# 教材阅读

## ■ 第3章 3.10、3.9.2