

Machine-Level Programming V: Advanced Topics

15-213: Introduction to Computer Systems
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Today

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

x86-64 Linux Memory Layout

not drawn to scale

00007FFFFFFF

■ 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

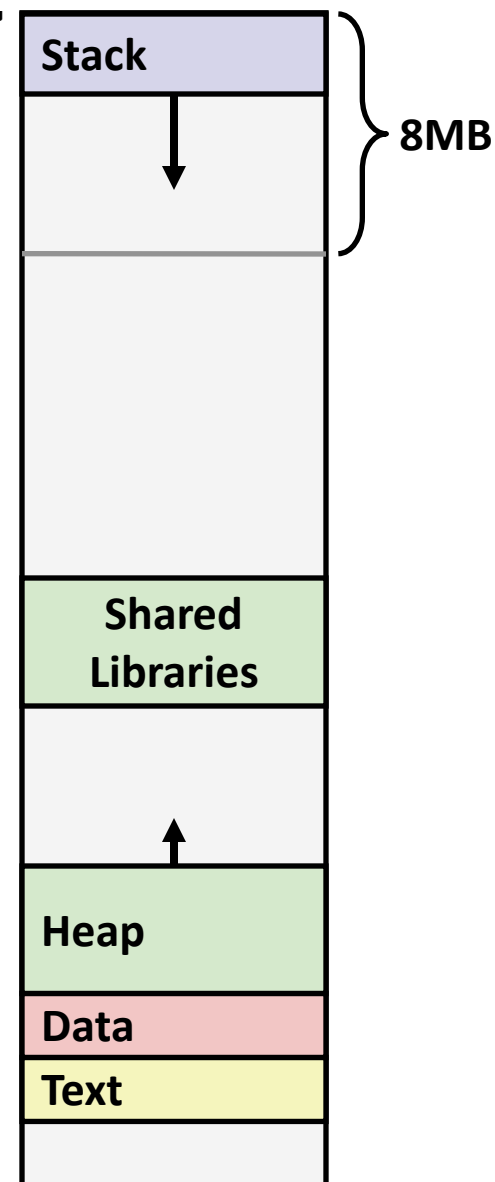
■ Text / Shared Libraries

- Executable machine instructions
- Read-only

Hex Address



400000
000000



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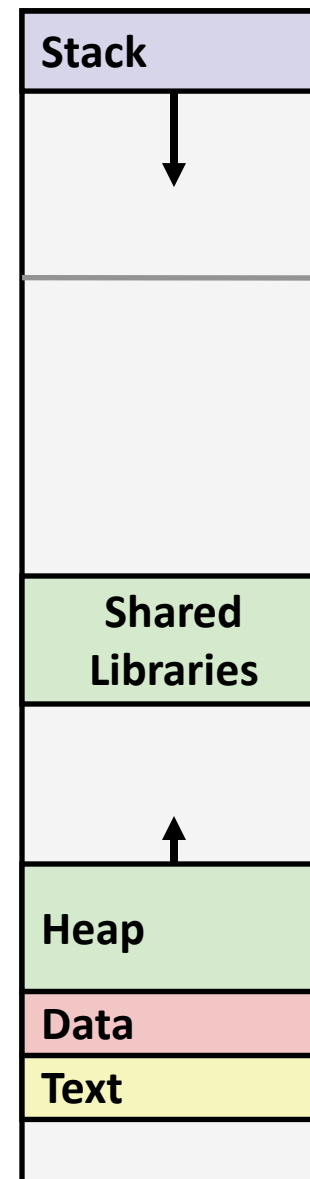
Memory Allocation Example

```
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 $\sim 2^{47}$

```

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

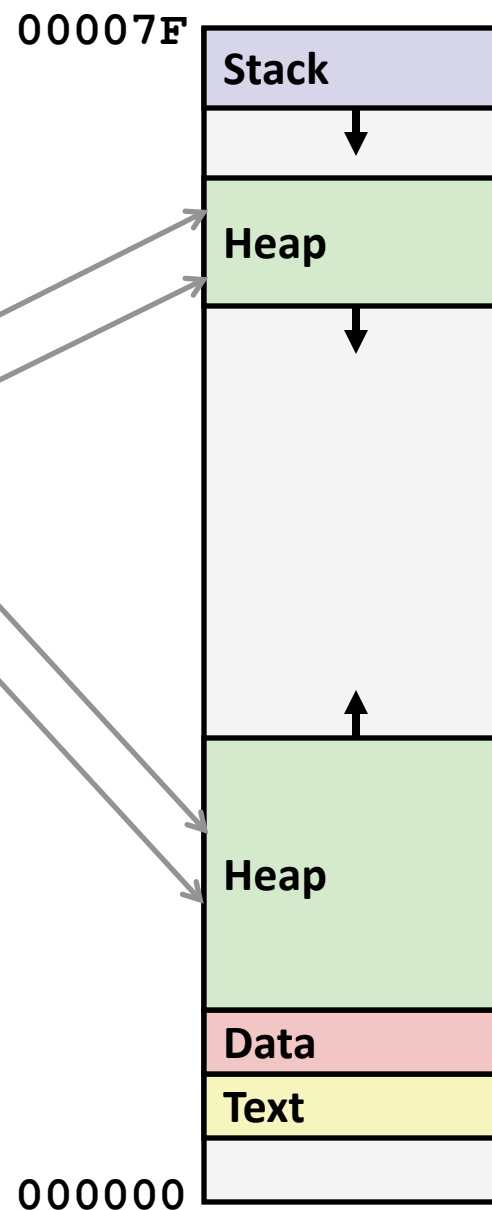
```

```

0x00007ffe4d3be87c
0x00007f7262a1e010
0x00007f7162a1d010
0x000000008359d120
0x000000008359d010
0x0000000080601060
0x0000000000601060
0x000000000040060c
0x0000000000400590

```

not drawn to scale



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)	->	3.14
fun(1)	->	3.14
fun(2)	->	3.1399998664856
fun(3)	->	2.00000061035156
fun(4)	->	3.14
fun(6)	->	Segmentation fault

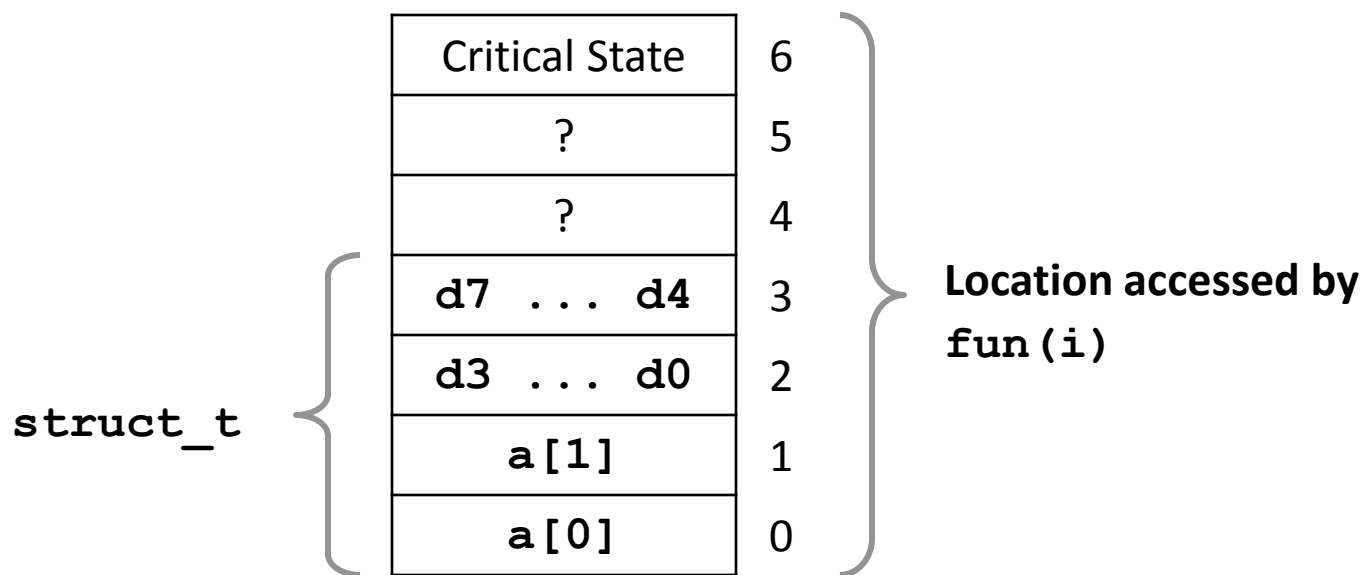
- Result is system specific

Memory Referencing Bug Example

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

fun(0)	->	3.14
fun(1)	->	3.14
fun(2)	->	3.1399998664856
fun(3)	->	2.00000061035156
fun(4)	->	3.14
fun(6)	->	Segmentation fault

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);  
}
```

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

← btw, how big
is big enough?

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

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

Buffer Overflow Disassembly

echo:

00000000004006cf <echo>:

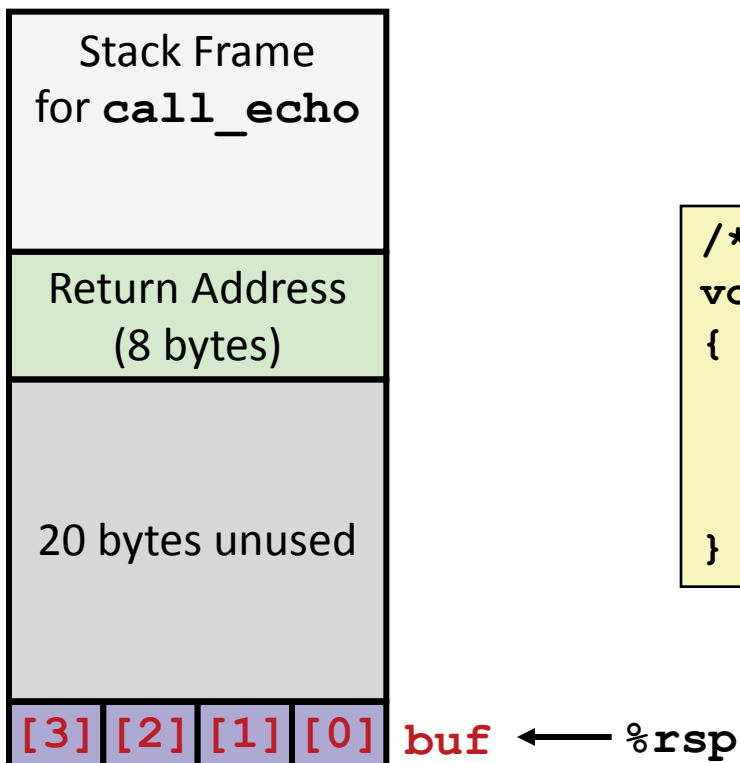
4006cf:	48 83 ec 18	sub	\$0x18 , %rsp
4006d3:	48 89 e7	mov	%rsp , %rdi
4006d6:	e8 a5 ff ff ff	callq	400680 <gets>
4006db:	48 89 e7	mov	%rsp, %rdi
4006de:	e8 3d fe ff ff	callq	400520 <puts@plt>
4006e3:	48 83 c4 18	add	\$0x18, %rsp
4006e7:	c3	retq	

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

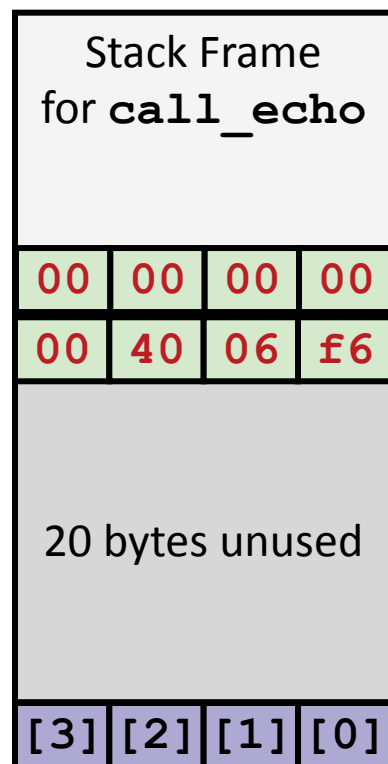


```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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 <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 for <code>call_echo</code>			
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

```
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
. . .
```

`buf ← %rsp`

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

```
"0123456789012345678901234\0"
```

Overflowed buffer and corrupted return pointer

Buffer Overflow Stack Example #3

After call to gets

Stack Frame 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
```

```
"012345678901234567890123\0"
```

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

Buffer Overflow Stack Example #3 Explained

After call to gets

Stack Frame for <code>call_echo</code>			
00	00	00	00
00	48	83	80
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

```

```

void call_echo() {
    echo();
}

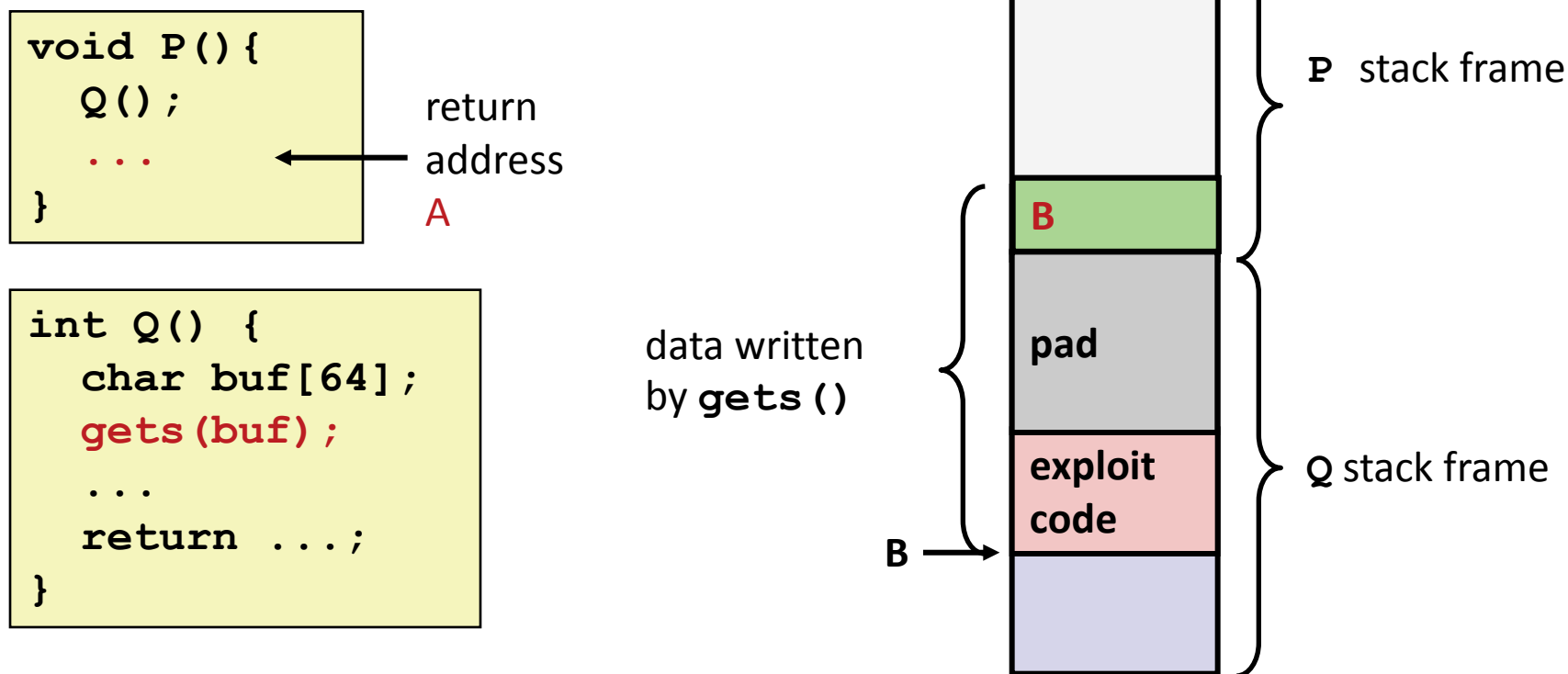
```

“Returns” to unrelated code

Lots of things happen, without modifying critical state

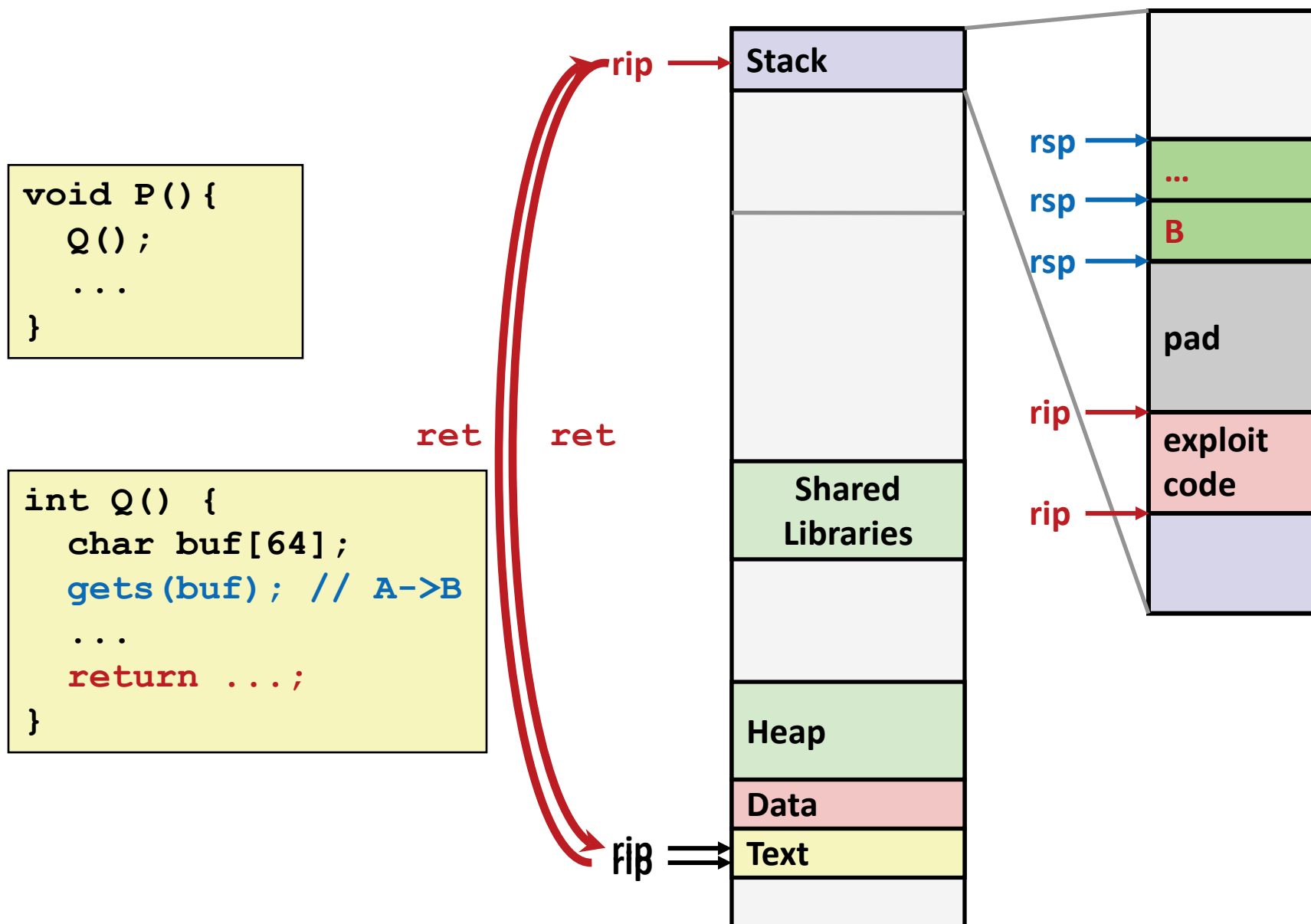
Eventually executes `retq` back to main – `call_echo` has no local variables

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?



Crafting an Injection Attack String

Stack Frame for <code>call echo</code>			
00	00	00	00
00	48	83	80
00	00	00	00
00	40	06	f6
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	C3	00
00	00	00	B8

Injected Code

```
B8 00 00 00 00    mov    $0x0,%eax
C3                retq
```

Attack: `int echo()` always returns 0

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

`buf = 00007FFFFFFFAB80`

Attack String

```
"\xB8\0\0\0\C3678901234567890123\x80\xAB\xFF\xFF\xFF\x07\0\0"
```

Cannot have '\n' or EOF in attack string

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 **%**n**s** where **n** is a suitable integer

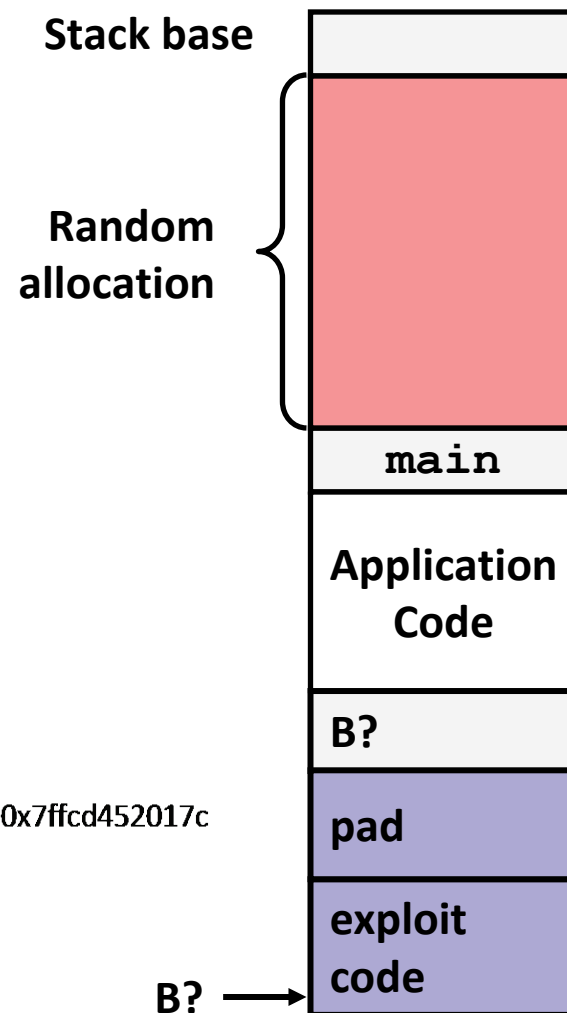
2. System-Level Protections can help

■ 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

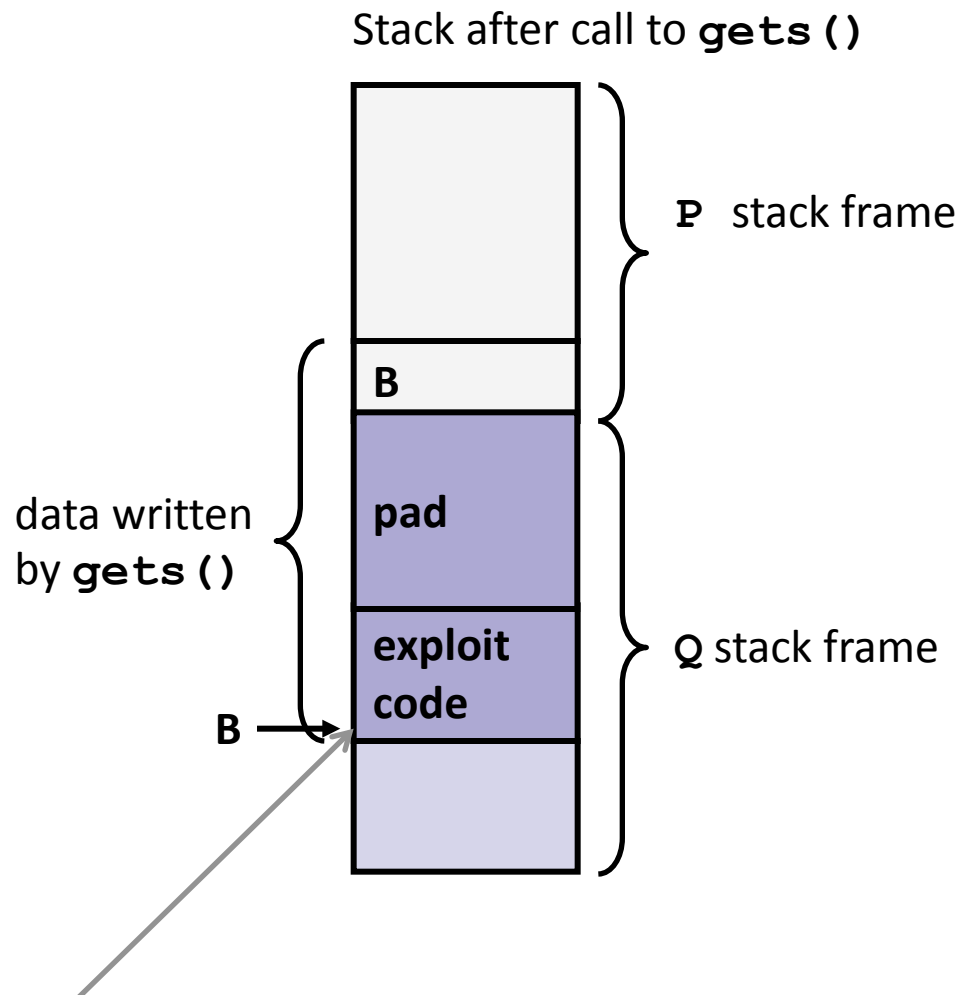
- Stack repositioned each time program executes



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

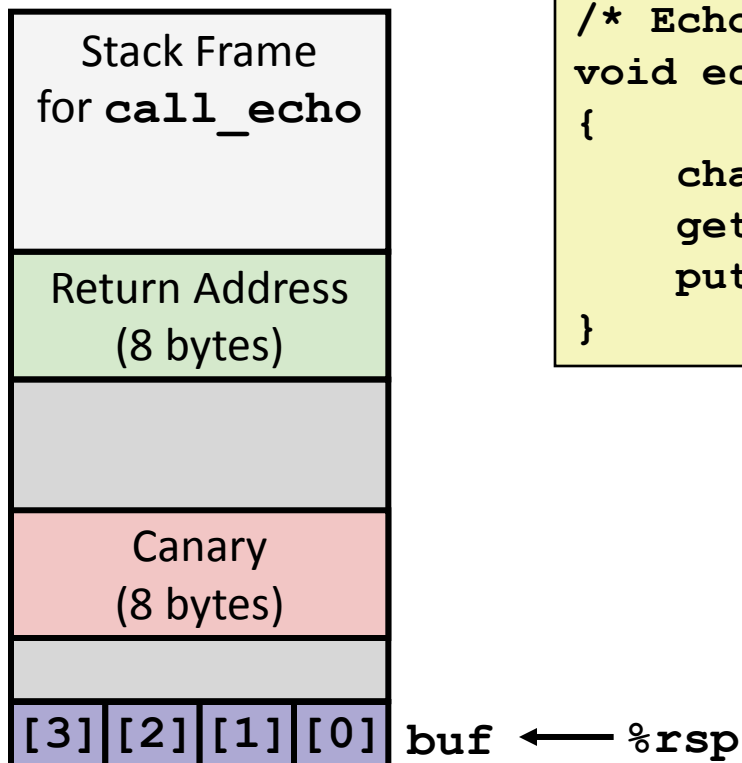
Protected Buffer Disassembly

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



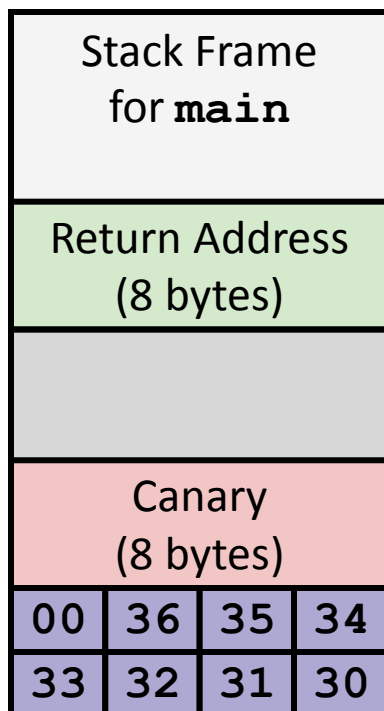
```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

`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
```

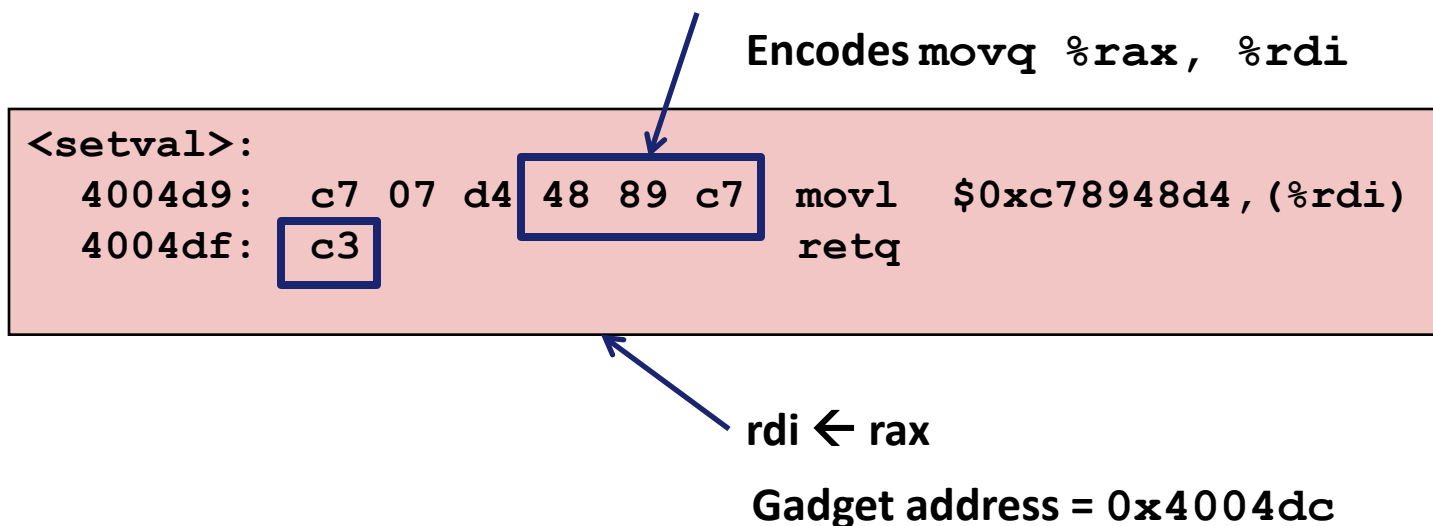
$\text{rax} \leftarrow \text{rdi} + \text{rdx}$

Gadget address = 0x4004d4

- Use tail end of existing functions

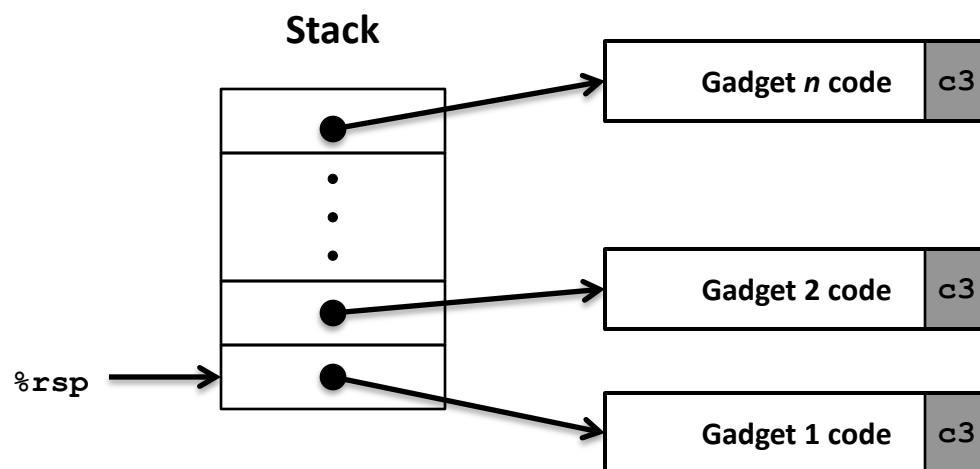
Gadget Example #2

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



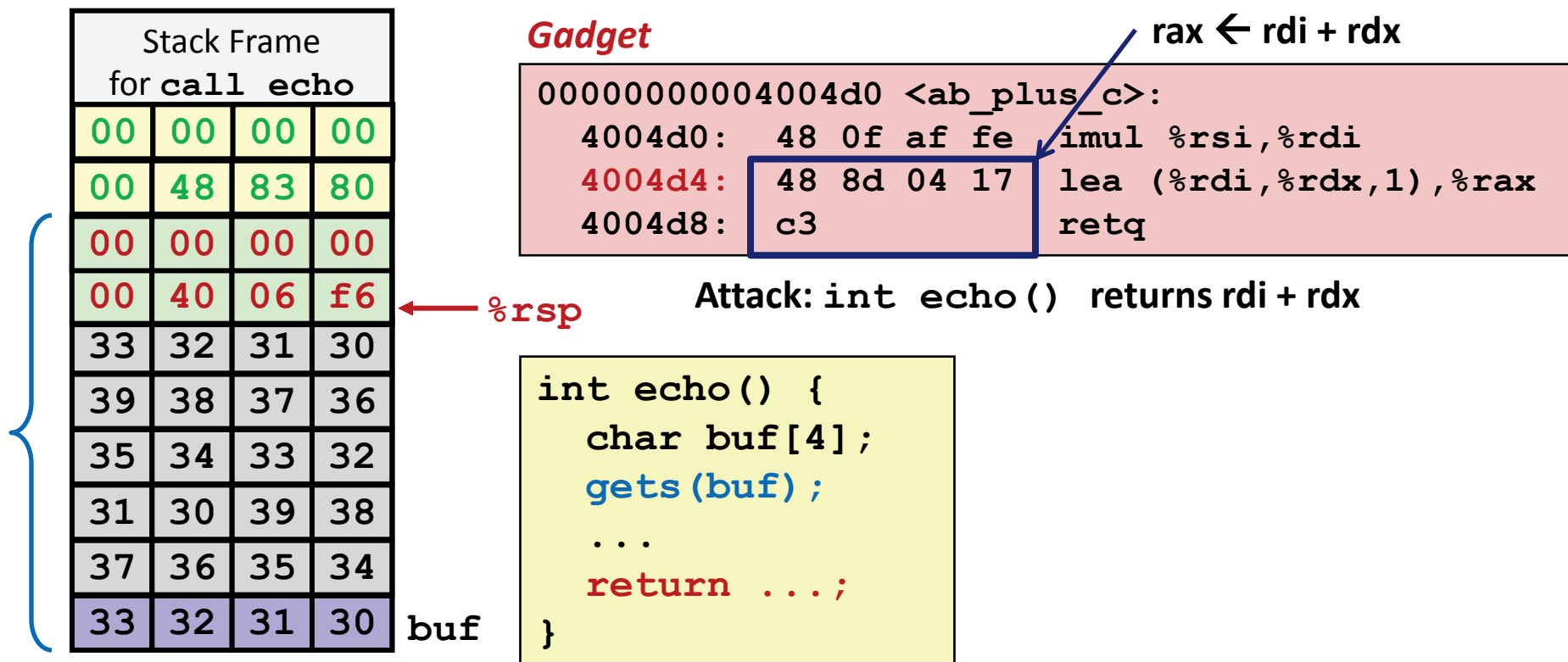
■ Repurpose byte codes

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

```
"012345678901234567890123\xd4\x04\x40\0\0\0\0\0"
```

Multiple gadgets will corrupt stack upwards

Craft Your Own Attack

Stack Frame for <code>call echo</code>			
00	00	00	00
00	48	83	80
00	00	00	00
00	40	04	dc
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

Gadget

```

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

```

Encodes `movq %rax, %rdi`

← `%rsp`

Gadget address = `0x4004dc`

Attack: invoke `movq %rax, %rdi`

Attack String

```
"012345678901234567890123\xdc\x04\x40\0\0\0\0\0"
```

Today

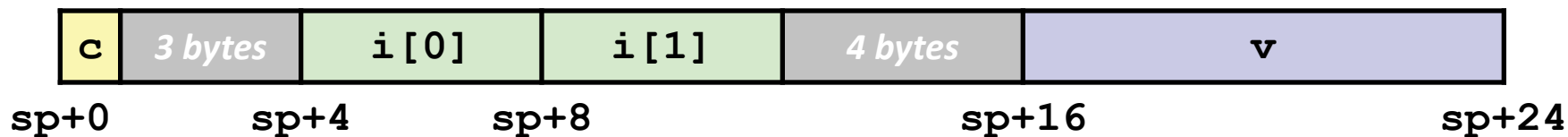
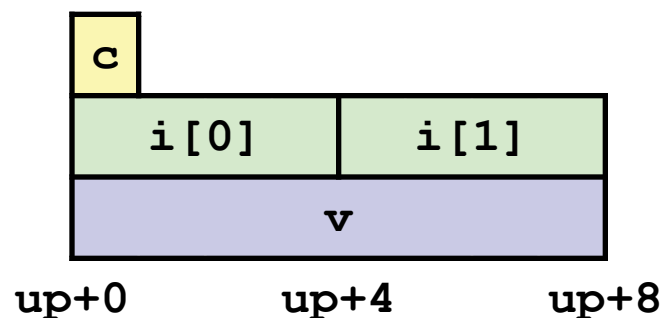
- Memory Layout
- Buffer Overflow
 - Vulnerability
 - Protection
- **Unions**

Union Allocation

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

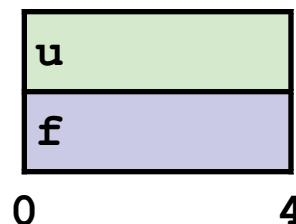
```
union U1 {
    char c;
    int i[2];
    double v;
} *up;
```

```
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;  
}
```

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

Same as (float) 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?

Memory addresses growing →

32-bit

c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

64-bit

c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

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]);
```

f0	f1	f2	f3	f4	f5	f6	f7
c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

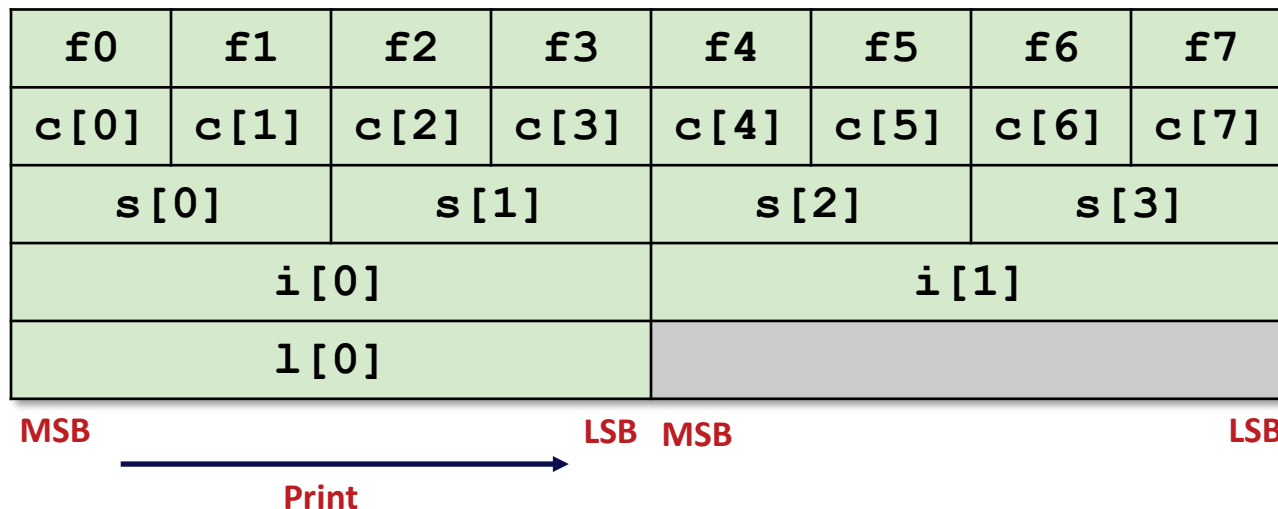
LSB
MSB
LSB
MSB

←
Print

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

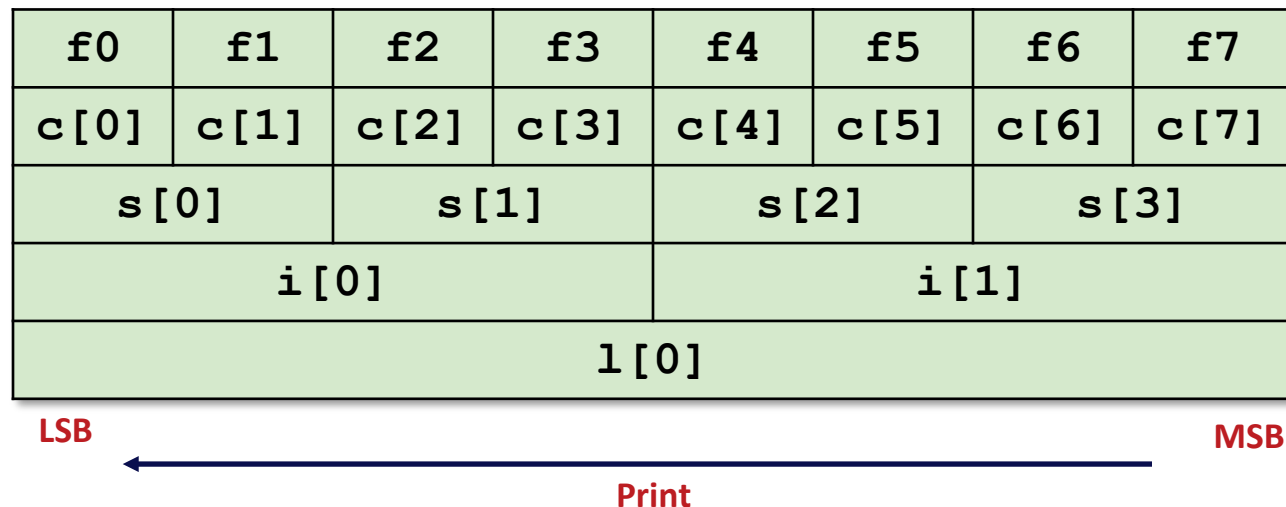


Output on Sun:

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.

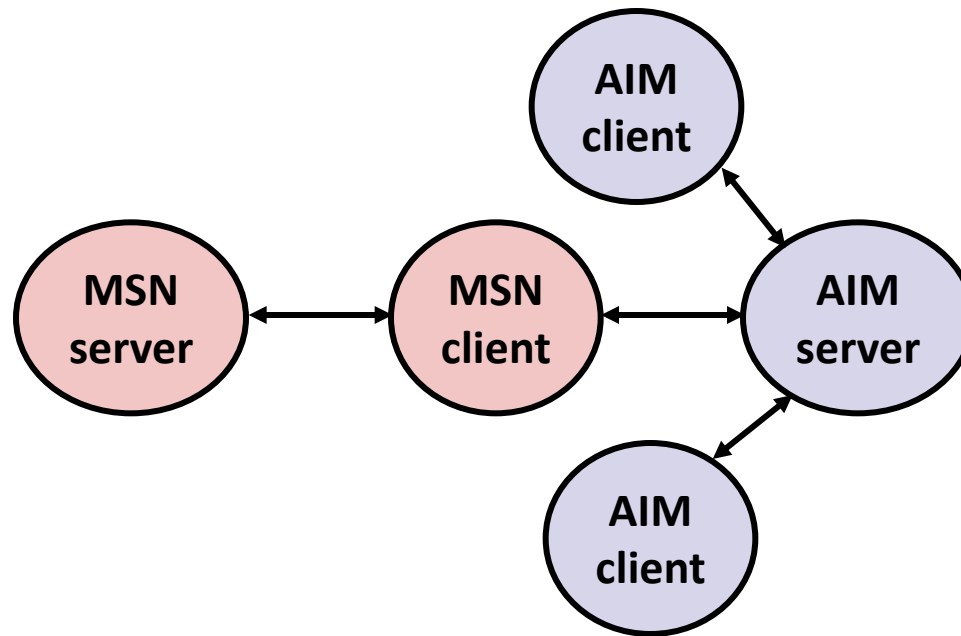
■ Once on a machine, scanned for other machines to attack

- 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**