

Machine-Level Programming V: Advanced Topics

15-213/18-213/15-513/18-613: Introduction to Computer Systems
9th Lecture, February 11, 2020

Today

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

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

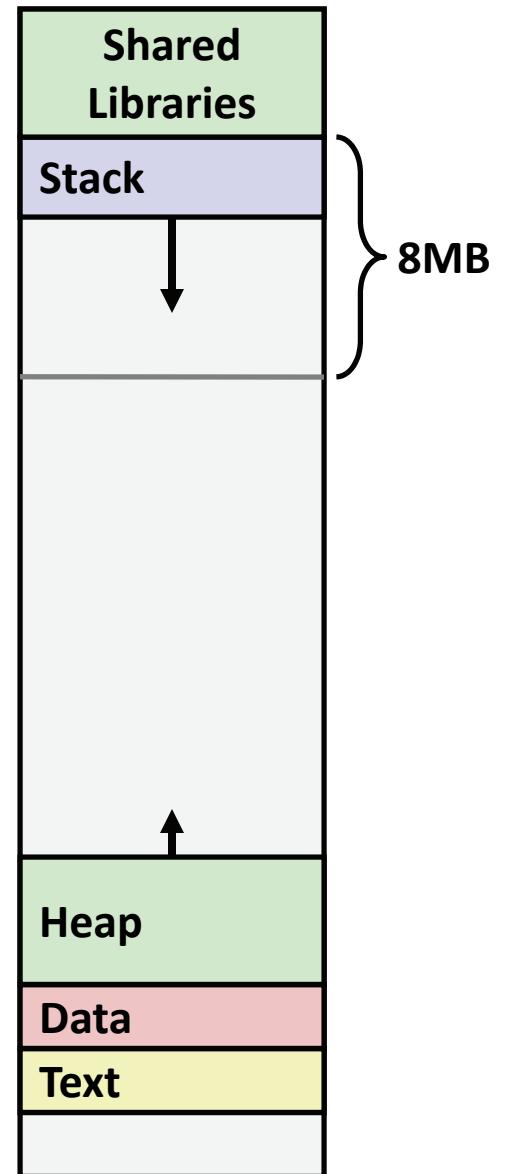
Hex Address

400000
000000



not drawn to scale

00007FFFFFFFFF
(= $2^{47}-1$)
00007FFF0000000



not drawn to scale

Memory Allocation Example

00007FFFFFFFFF

```

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

int global = 0;

int useless() { return 0; }

int main ()
{
    void *phuge1, *psmall2, *phuge3, *psmall4;
    int local = 0;
    phuge1 = malloc(1L << 28); /* 256 MB */
    psmall2 = malloc(1L << 8); /* 256 B */
    phuge3 = malloc(1L << 32); /* 4 GB */
    psmall4 = malloc(1L << 8); /* 256 B */
    /* Some print statements ... */
}

```



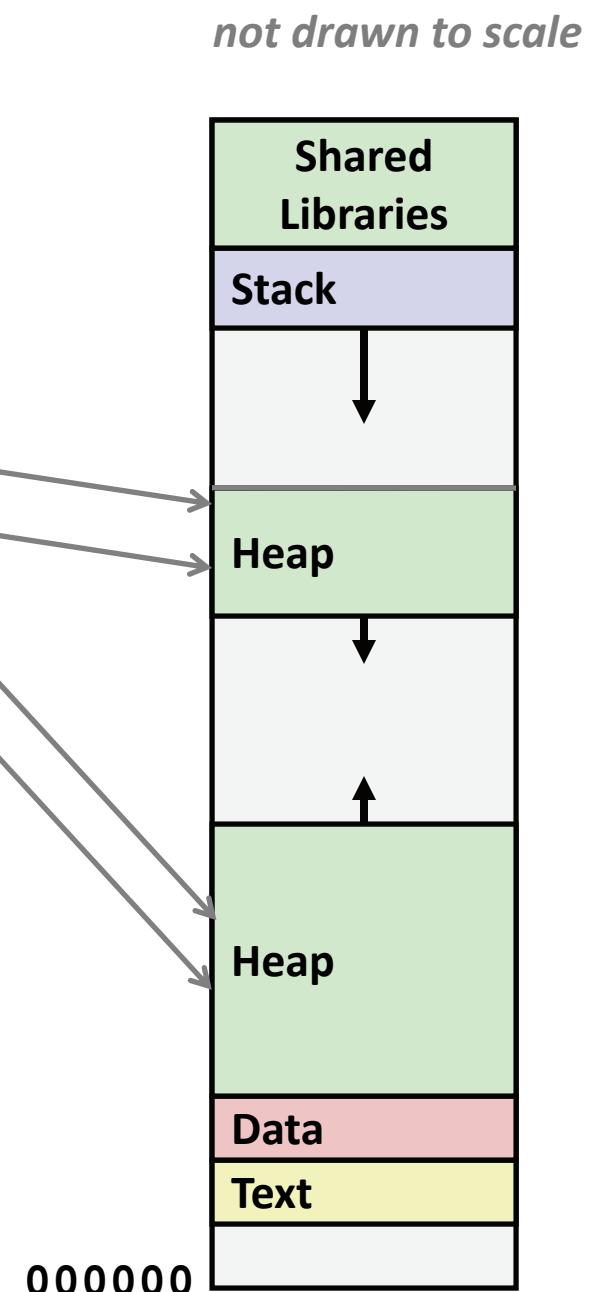
Where does everything go?

x86-64 Example Addresses

address range $\sim 2^{47}$

local	0x00007ffe4d3be87c
phuge1	0x00007f7262a1e010
phuge3	0x00007f7162a1d010
psmall4	0x000000008359d120
psmall2	0x000000008359d010
big_array	0x0000000080601060
huge_array	0x0000000000601060
main()	0x000000000040060c
useless()	0x0000000000400590

(Exact values can vary)

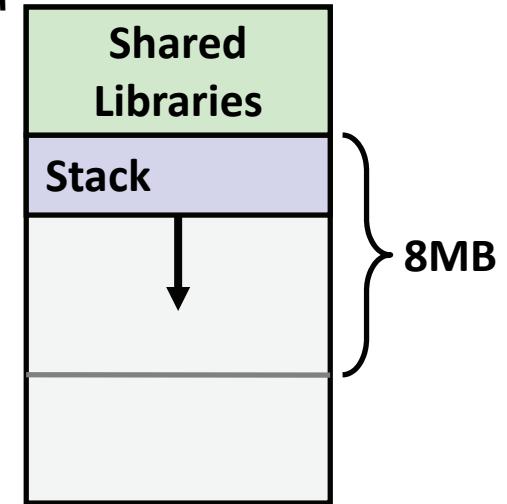


not drawn to scale

Runaway Stack Example

00007FFFFFFFFFFFFF

```
int recurse(int x) {
    int a[1<<15]; // 4*2^15 = 128 KiB
    printf("x = %d. a at %p\n", x, a);
    a[0] = (1<<14)-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 67
x = 67. a at 0x7ffd18aba930
x = 66. a at 0x7ffd18a9a920
x = 65. a at 0x7ffd18a7a910
x = 64. a at 0x7ffd18a5a900
. . .
x = 4. a at 0x7ffd182da540
x = 3. a at 0x7ffd182ba530
x = 2. a at 0x7ffd1829a520
Segmentation fault (core dumped)
```

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(6)  ->  Stack smashing detected
fun(8)  ->  Segmentation fault
```

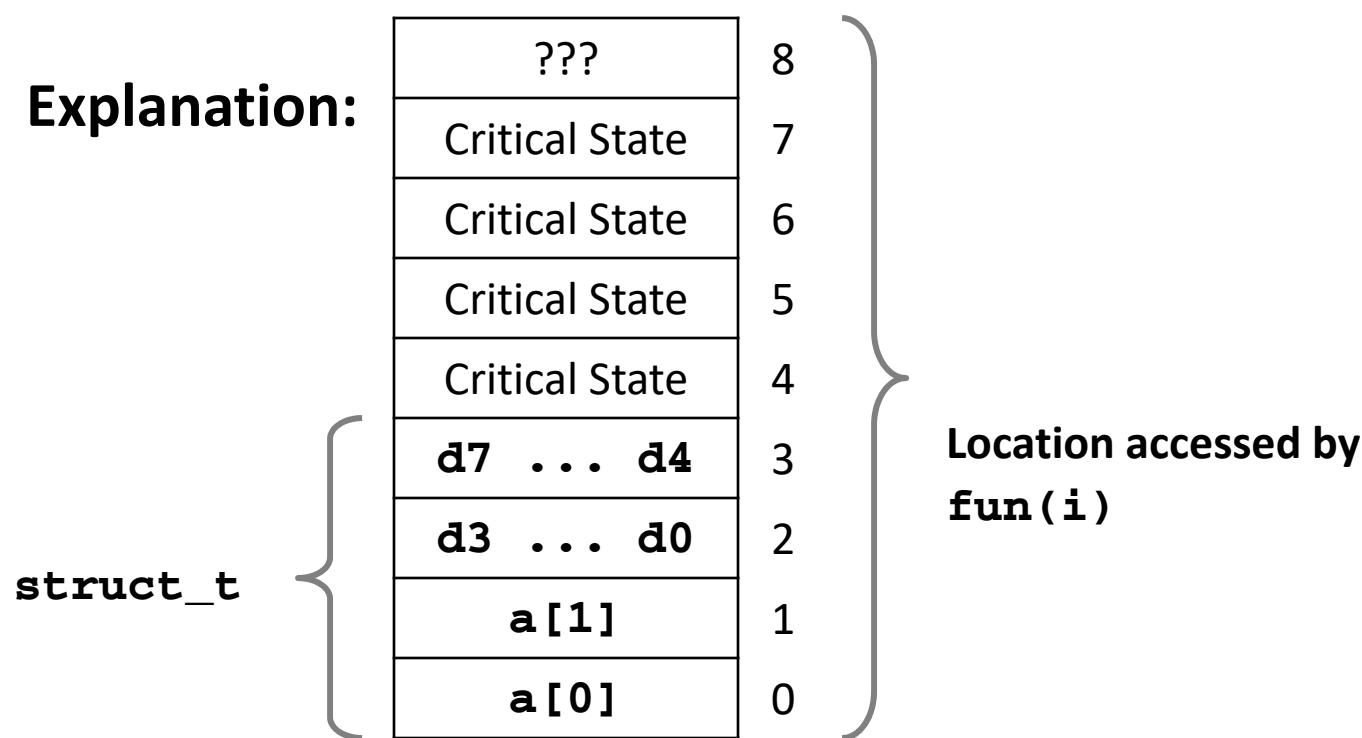
- Result is system specific

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);
}
```

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

← BTW, how big
is big enough?

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

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

Buffer Overflow Disassembly

echo:

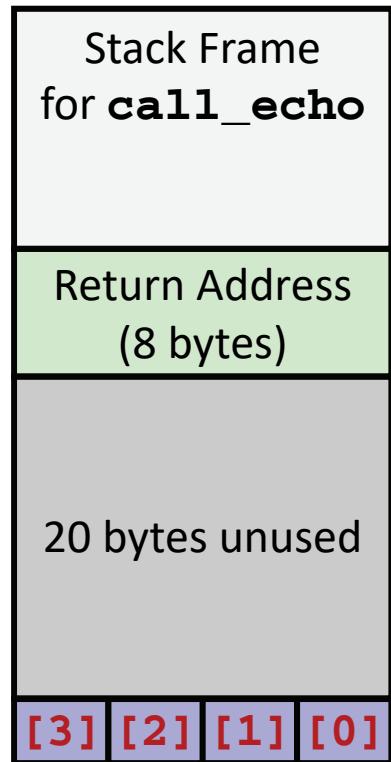
```
00000000040069c <echo>:  
40069c: 48 83 ec 18          sub    $0x18,%rsp  
4006a0: 48 89 e7          mov    %rsp,%rdi  
4006a3: e8 a5 ff ff ff    callq  40064d <gets>  
4006a8: 48 89 e7          mov    %rsp,%rdi  
4006ab: e8 50 fe ff ff    callq  400500 <puts@plt>  
4006b0: 48 83 c4 18          add    $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

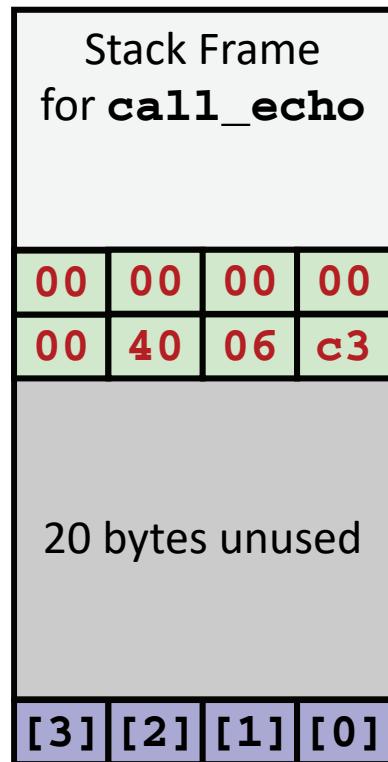


```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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 $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 <code>call_echo</code>			
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

```
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
...
```

`buf ← %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	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

```
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
. . .
```

`buf` ← `%rsp`

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

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

Stack Smashing Attacks

```

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

```

return address
A


```

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

```

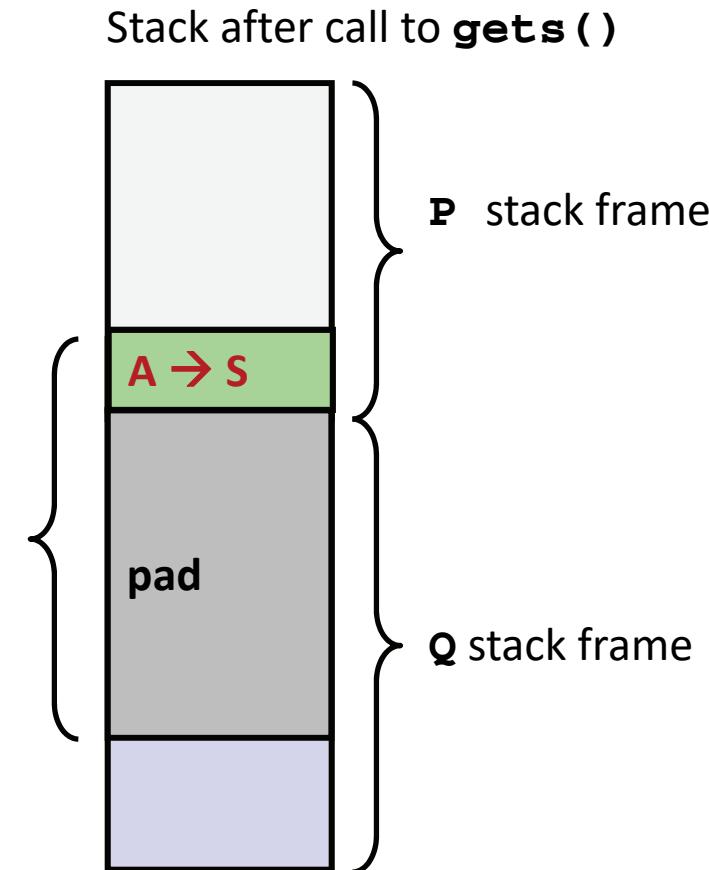


```

void S() {
    /* Something
       unexpected */
    ...
}

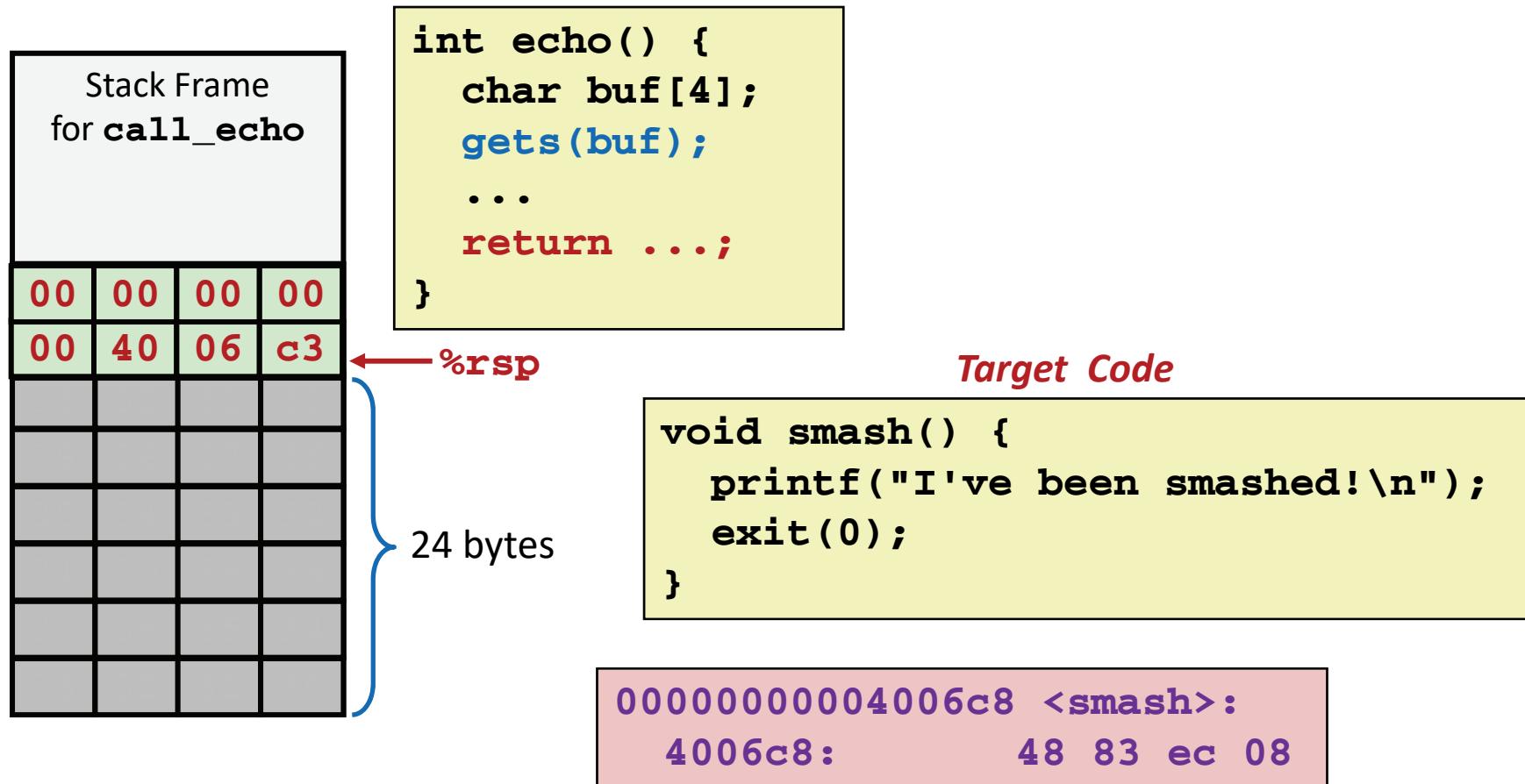
```

data written by **gets()**



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

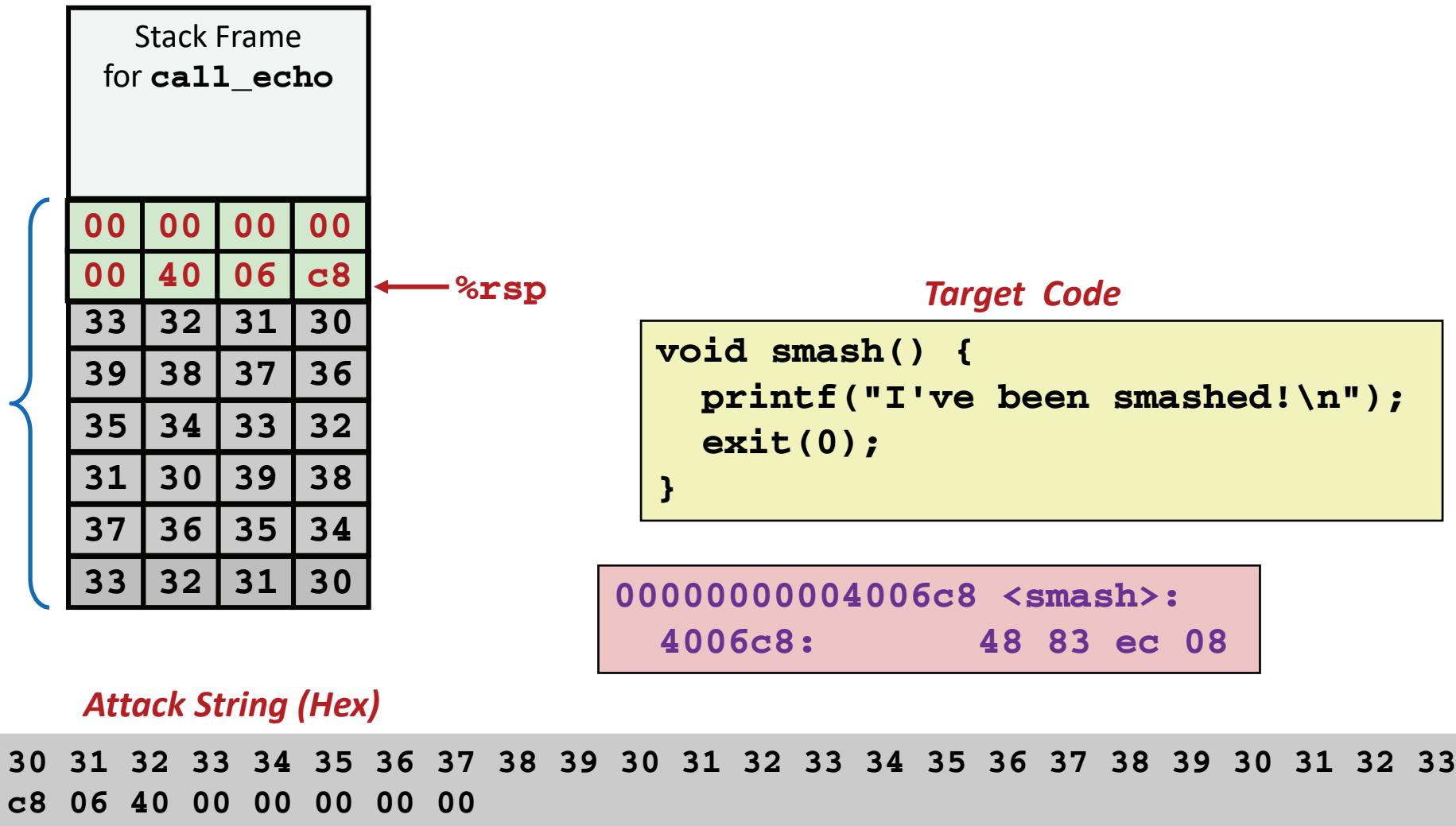
Crafting Smashing String



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
c8 06 40 00 00 00 00 00

Smashing String Effect



Performing Stack Smash

```
linux> cat smash-hex.txt
30 31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 37 38 39 30 31 32 33 c8 06 40 00 00 00 00 00
linux> cat smash-hex.txt | ./hexify | ./bufdemo-nsp
Type a string:012345678901234567890123?@
I've been smashed!
```

- Put hex sequence in file `smash-hex.txt`
- Use `hexify` program to convert hex digits to characters
 - Some of them are non-printing
- Provide as input to vulnerable program

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

```
30 31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 37 38 39 30 31 32 33
c8 06 40 00 00 00 00 00 00 00
```

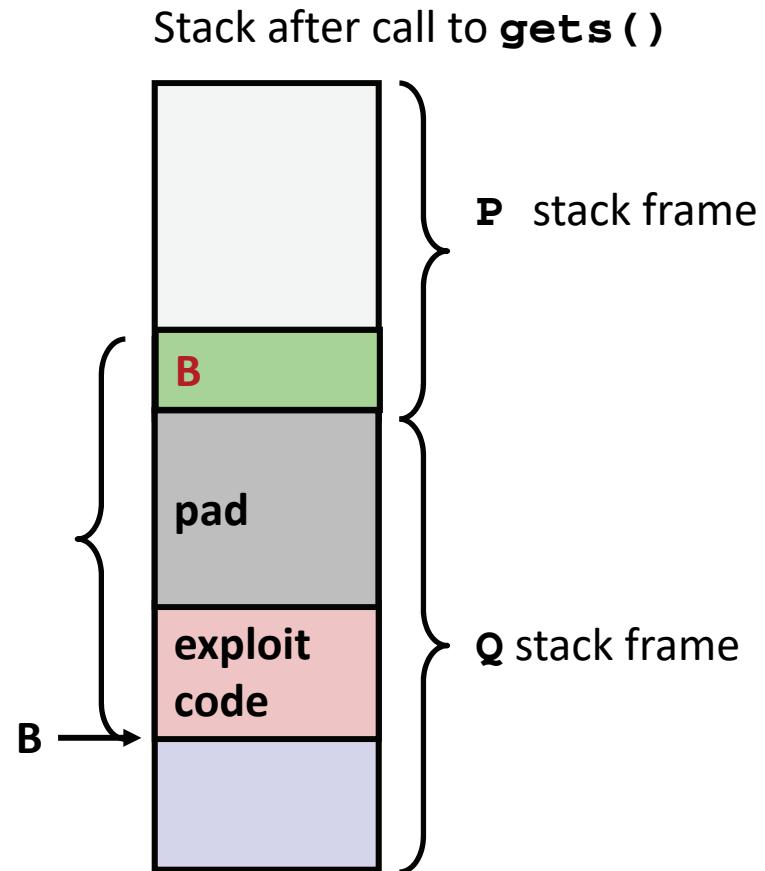
Code Injection Attacks

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

return address
A

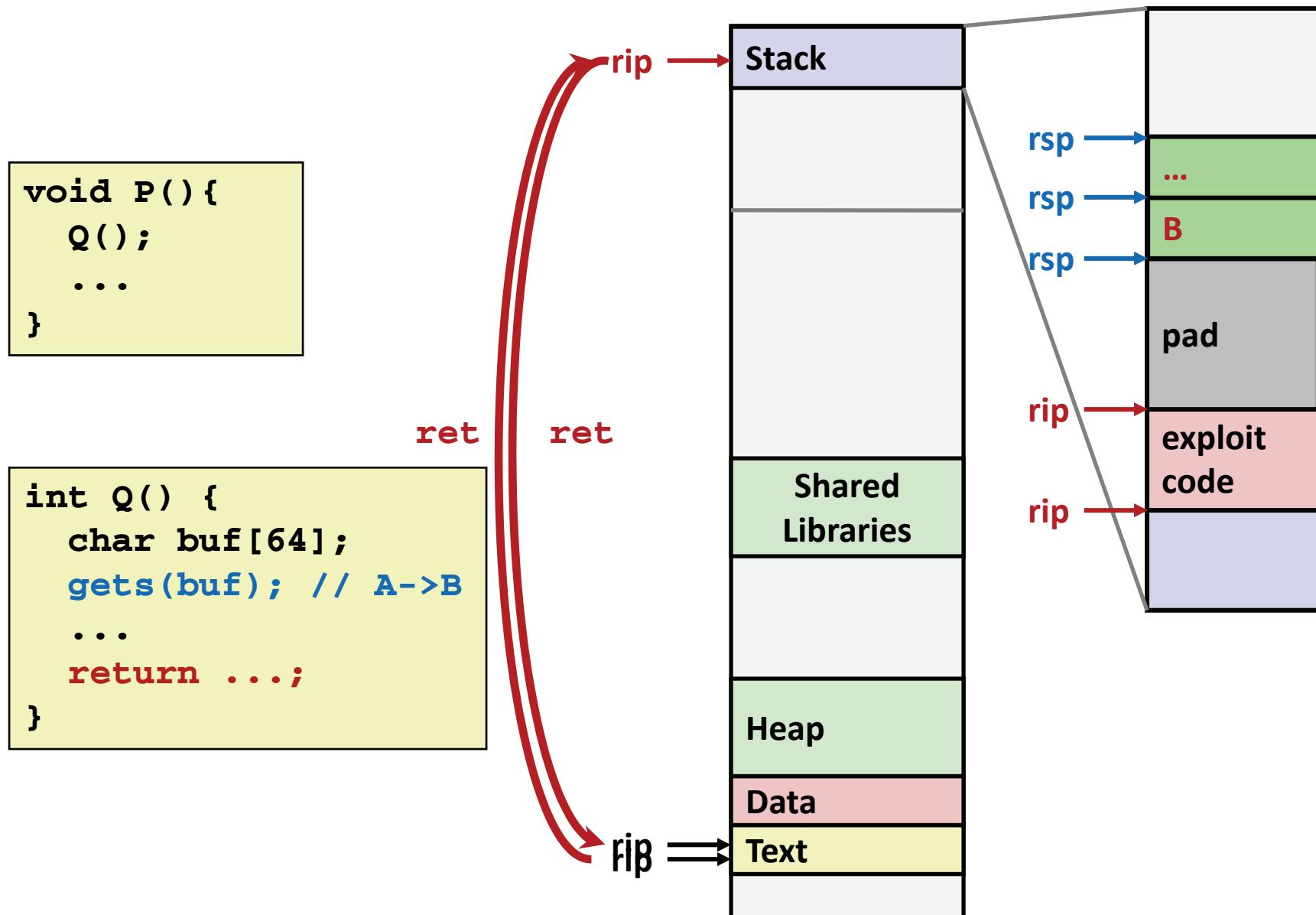
```
int Q() {
    char buf[64];
    gets(buf);
    ...
    return ...;
}
```

data written by **gets()**



- 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];
    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

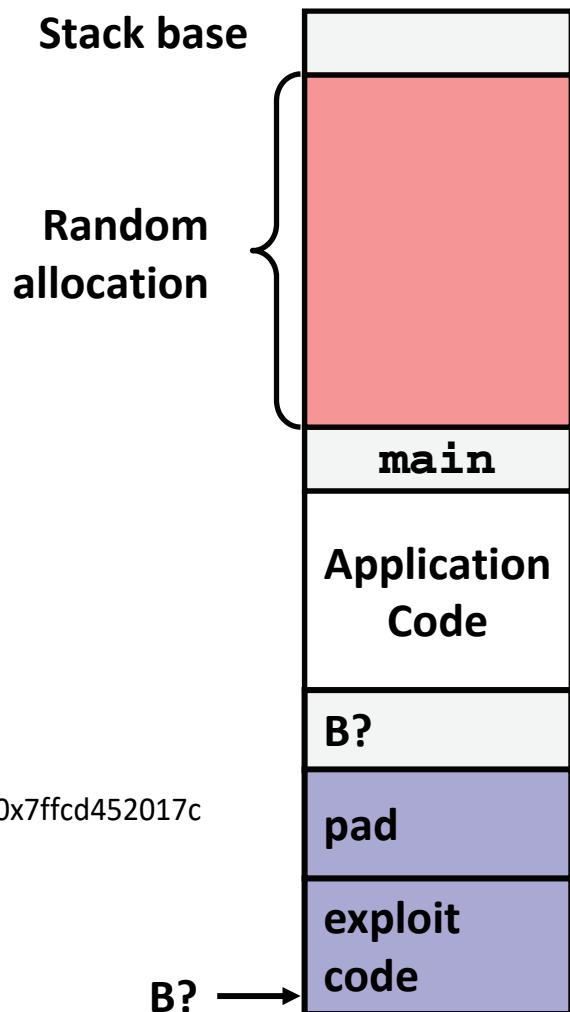
■ Randomized stack offsets

- 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

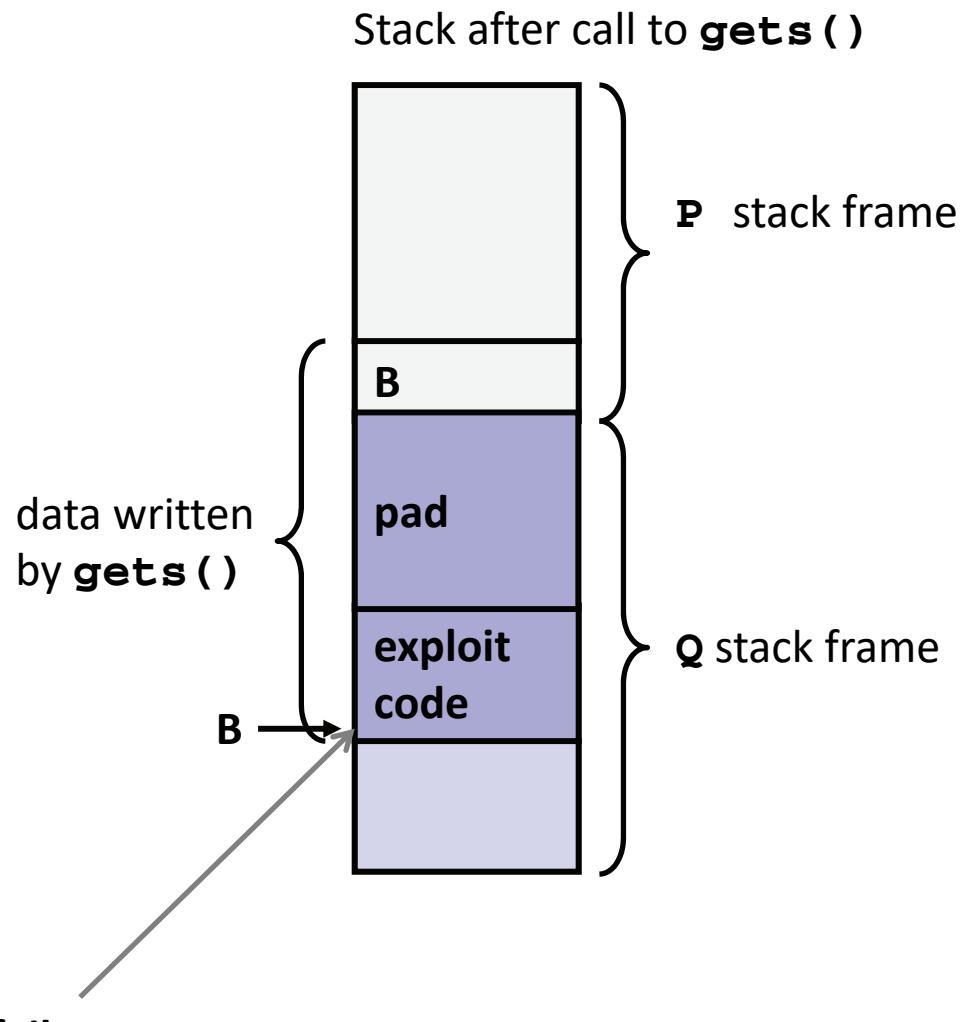
- Stack repositioned each time program executes



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



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:

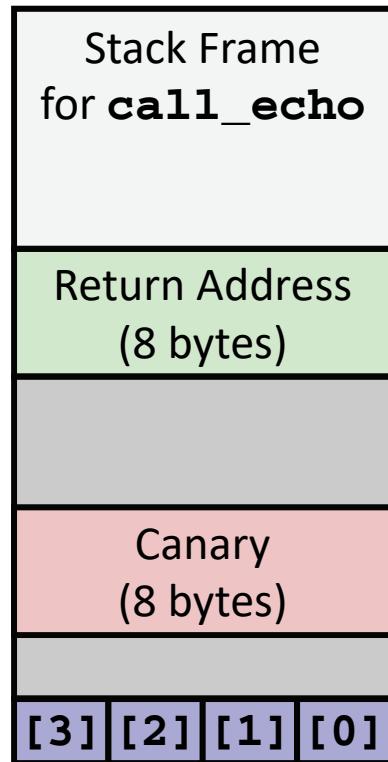
```
40072f: sub    $0x18,%rsp
400733: mov    %fs:0x28,%rax
40073c: mov    %rax,0x8(%rsp)
400741: xor    %eax,%eax
400743: mov    %rsp,%rdi
400746: callq  4006e0 <gets>
40074b: mov    %rsp,%rdi
40074e: callq  400570 <puts@plt>
400753: mov    0x8(%rsp),%rax
400758: xor    %fs:0x28,%rax
400761: je     400768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

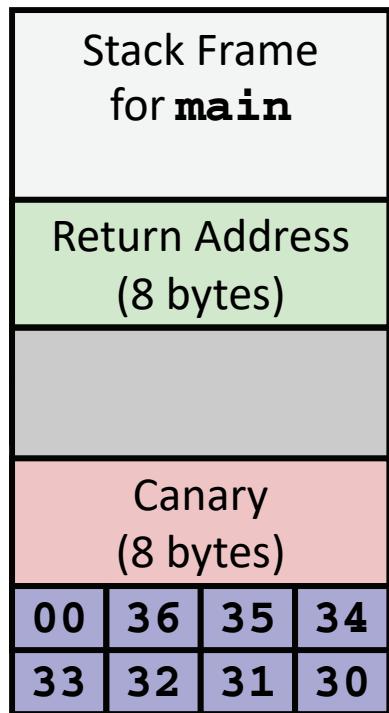


```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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



```
/* 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
```

Quiz Time!

Check out:

<https://canvas.cmu.edu/courses/13182/quizzes/31653>

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
```

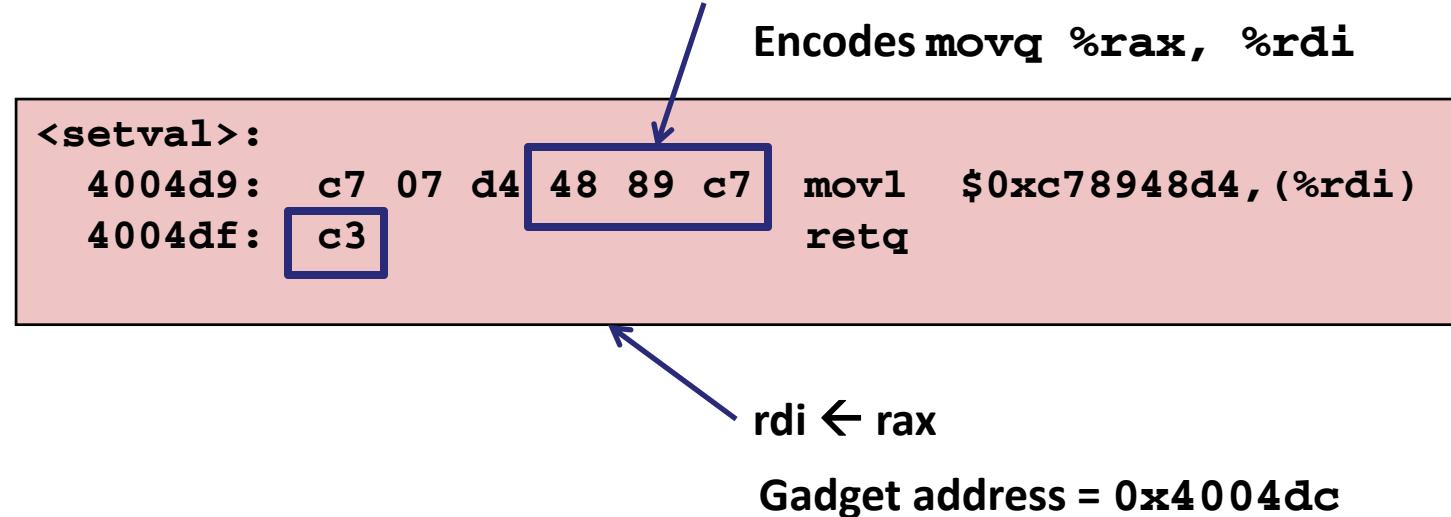
$\text{rax} \leftarrow \text{rdi} + \text{rdx}$

Gadget address = 0x4004d4

- Use tail end of existing functions

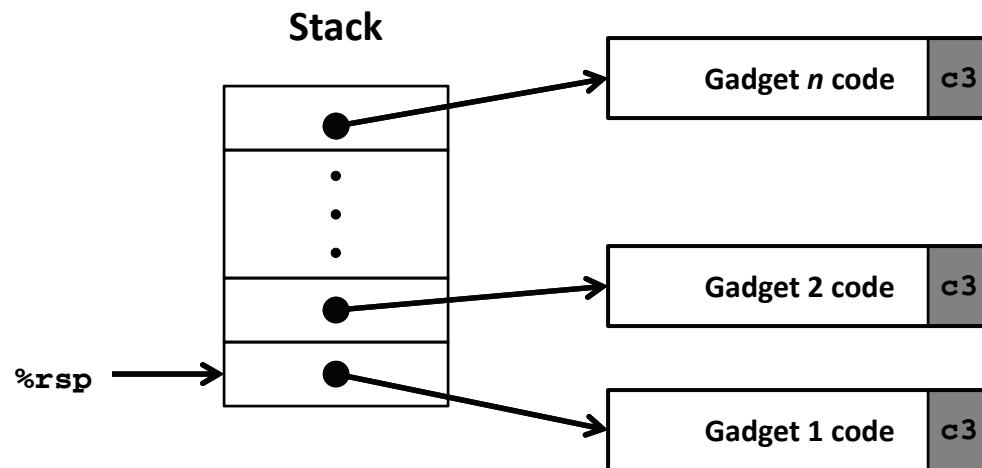
Gadget Example #2

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



■ Repurpose byte codes

ROP Execution



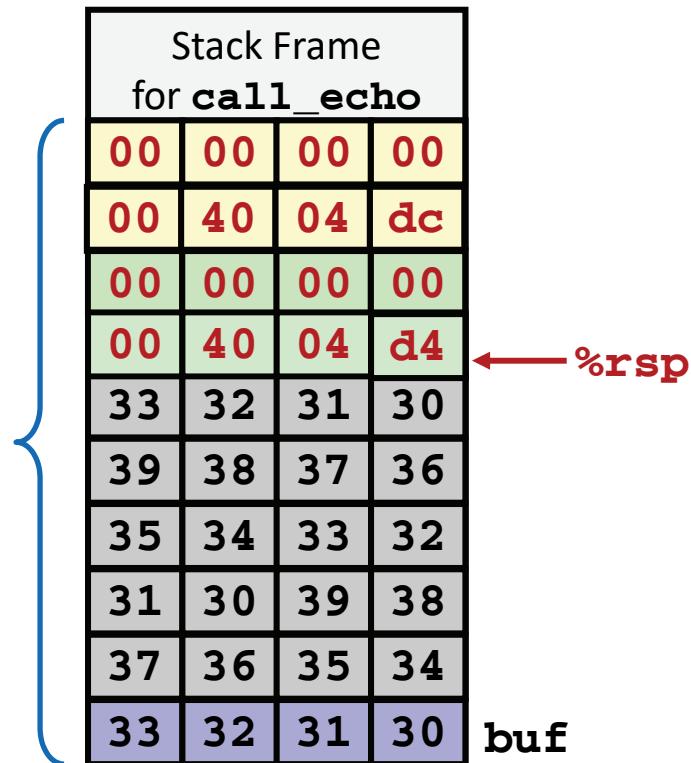
■ Trigger with `ret` instruction

- Will start executing Gadget 1

■ Final `ret` in each gadget will start next one

- `ret`: pop address from stack and jump to that address

Crafting an ROP Attack String



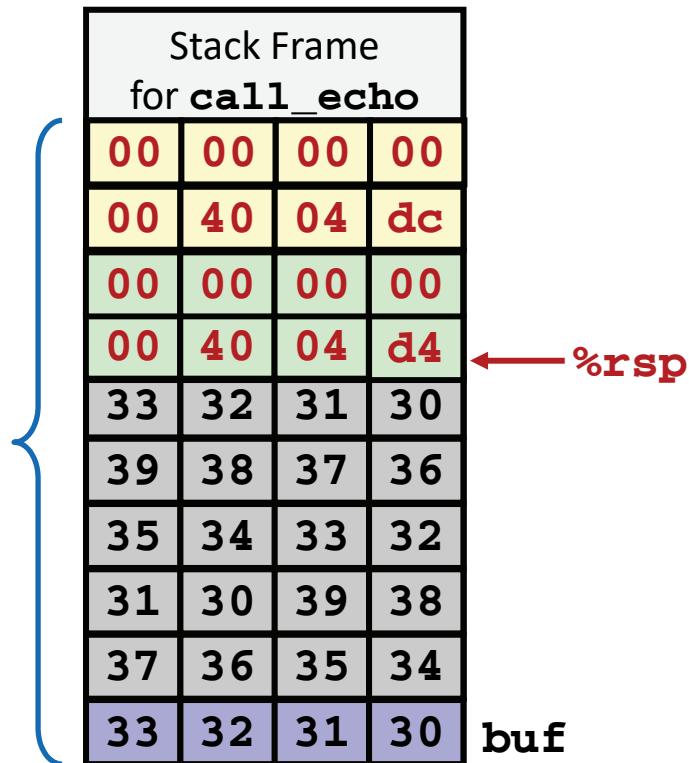
- **Gadget #1**
 - `0x4004d4` $\text{rax} \leftarrow \text{rdi} + \text{rdx}$
- **Gadget #2**
 - `0x4004dc` $\text{rdi} \leftarrow \text{rax}$
- **Combination**
 - $\text{rdi} \leftarrow \text{rdi} + \text{rdx}$

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	dc	04	40	00	00	00	00	00	00	00	00	00	00	00	00	00

Multiple gadgets will corrupt stack upwards

What Happens When echo Returns?



1. **Echo executes `ret`**
 - Starts Gadget #1
2. **Gadget #1 executes `ret`**
 - Starts Gadget #2
3. **Gadget #2 executes `ret`**
 - Goes off somewhere ...

Multiple gadgets will corrupt stack upwards

Today

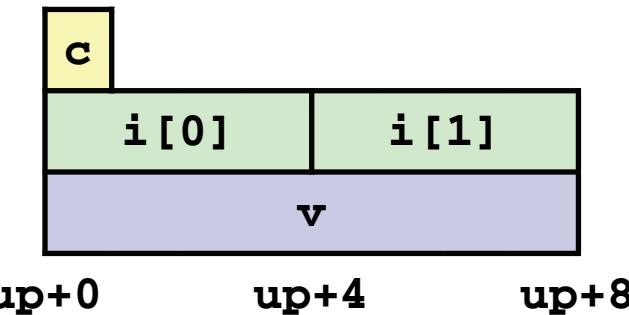
- Memory Layout
- Buffer Overflow
 - Vulnerability
 - Protection
- Unions

Union Allocation

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

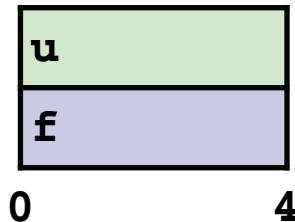
```
union U1 {  
    char c;  
    int i[2];  
    double v;  
} *up;
```

```
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

■ BigEndian

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

■ LittleEndian

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

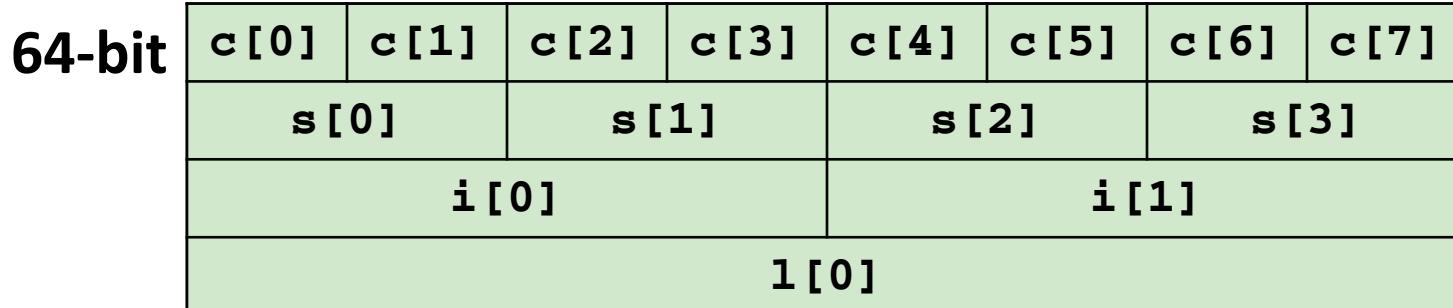
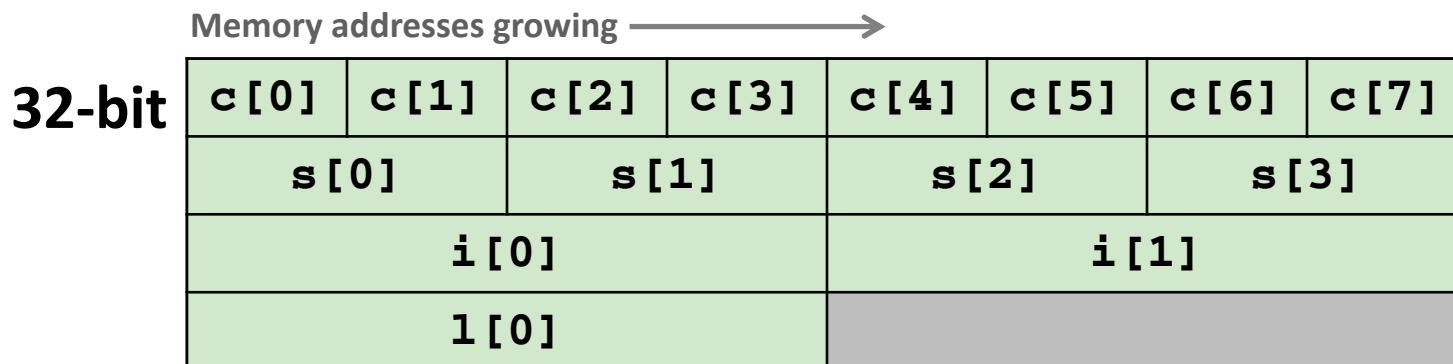
■ BiEndian

- 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]);

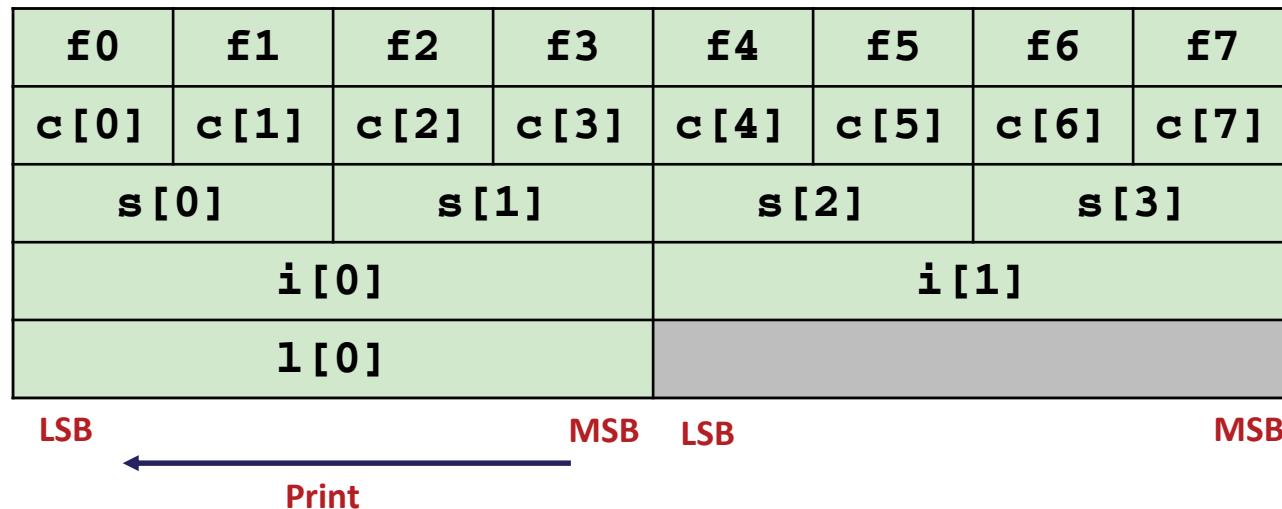
printf("Shorts 0-3 == [0x%x, 0x%x, 0x%x, 0x%x] \n",
       dw.s[0], dw.s[1], dw.s[2], dw.s[3]);

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

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

Byte Ordering on IA32

Little Endian



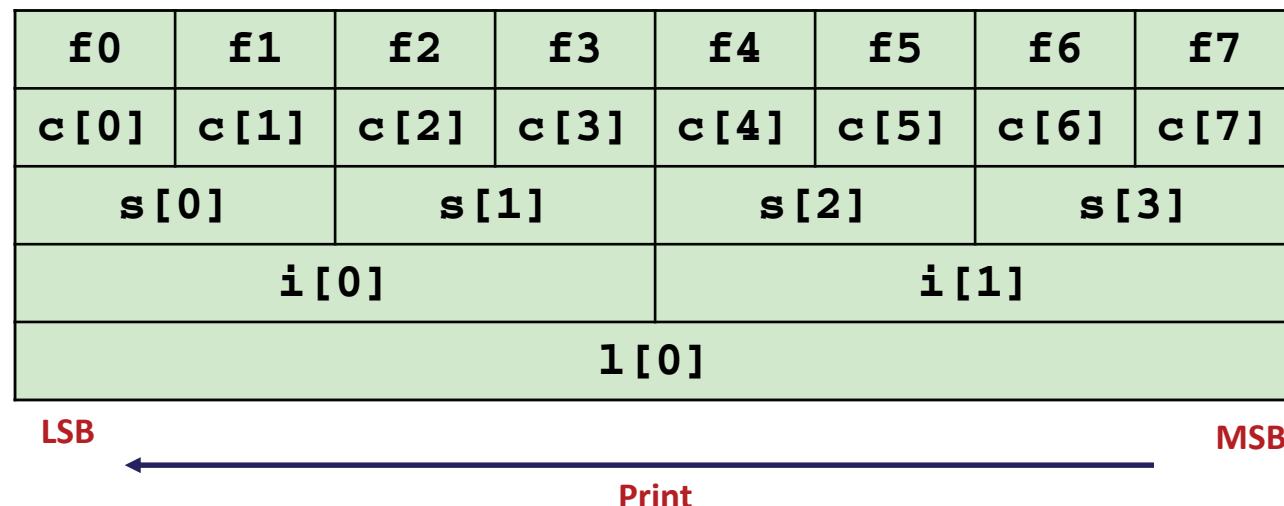
Output:

```

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 x86-64

Little Endian

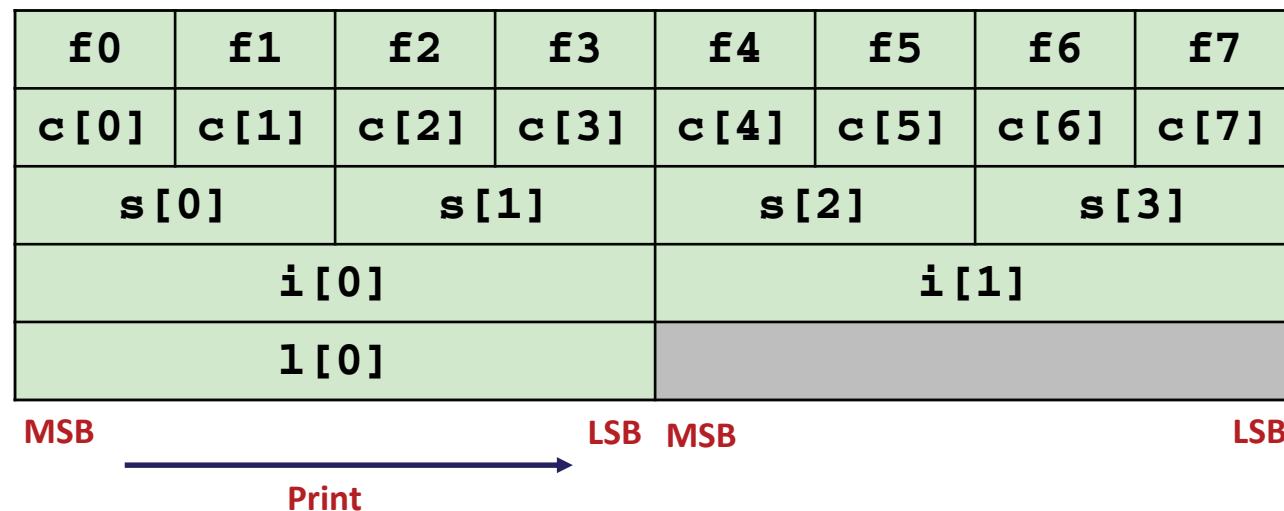


Output on x86-64:

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]

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]

```

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.

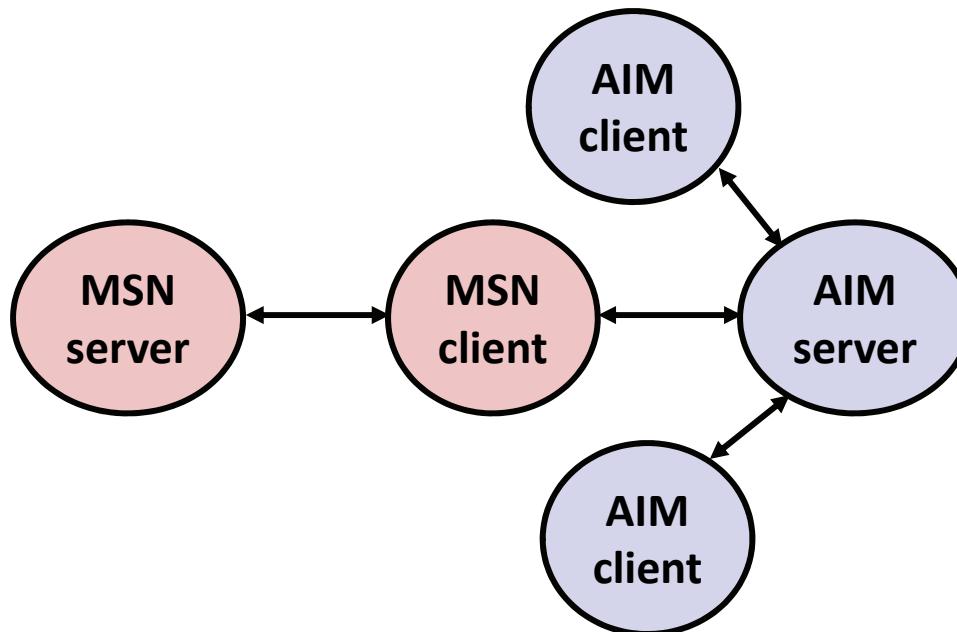
■ Once on a machine, scanned for other machines to attack

- 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