Machine-Level Programming V: Advanced Topics

CENG331 - Computer Organization

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Adapted from slides of the textbook: http://csapp.cs.cmu.edu/

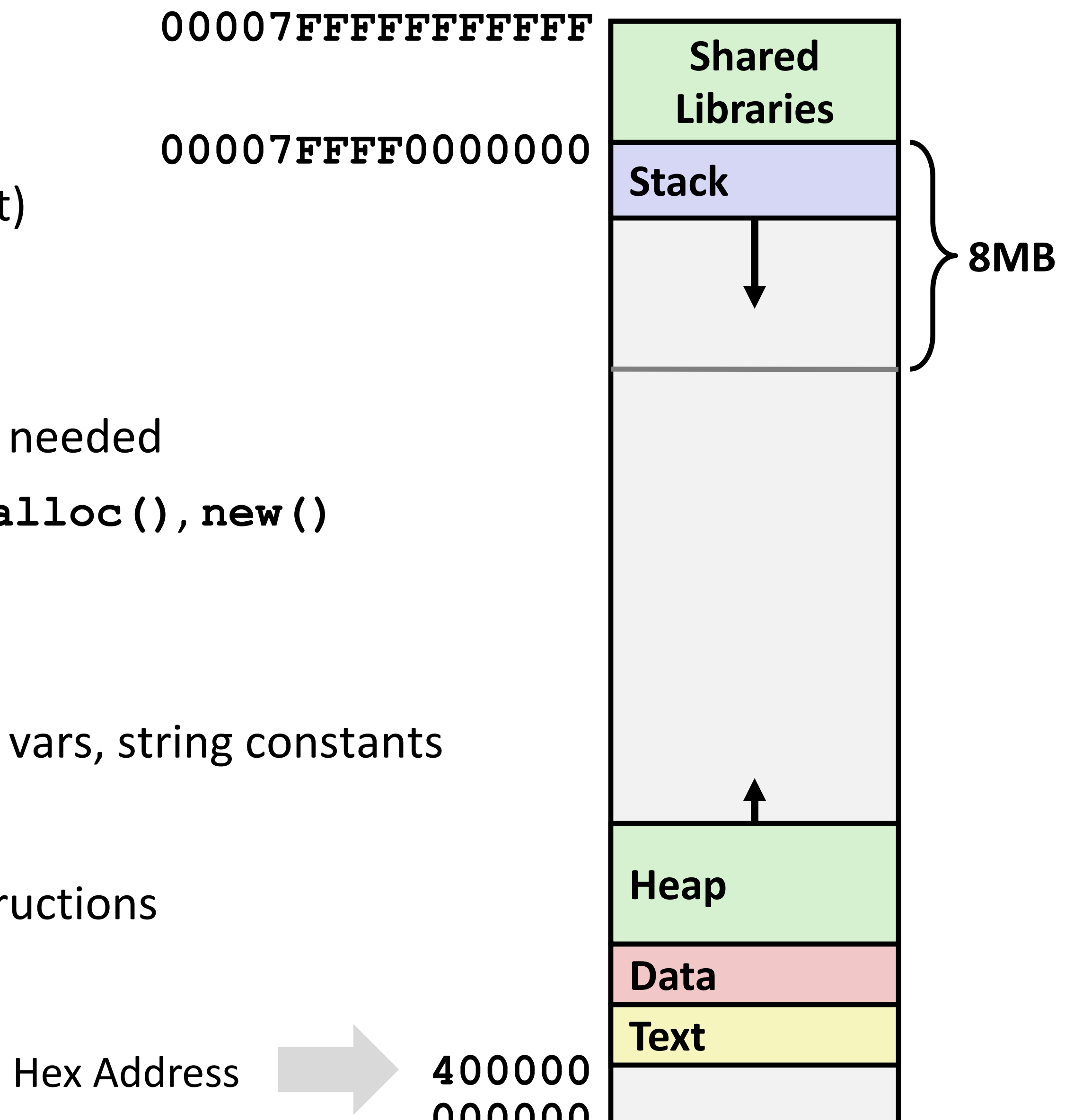
Today

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

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



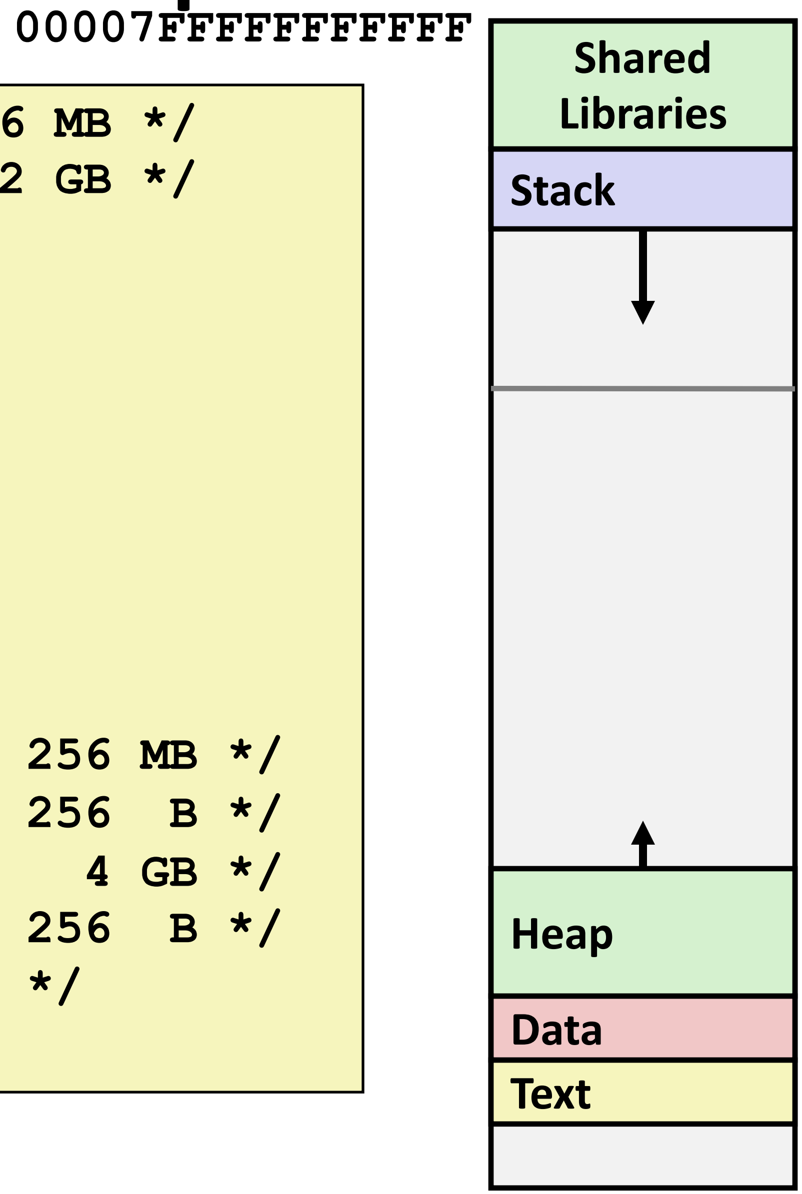
Memory Allocation Example

```
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 ~2^{47}

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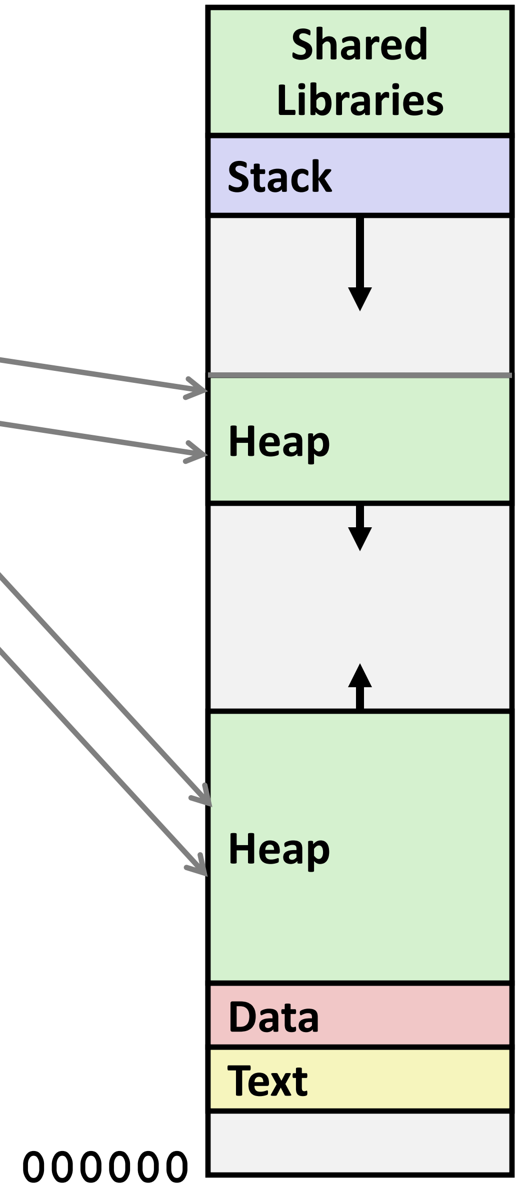
`local`	`0x00007ffe4d3be87c`
`p1`	`0x00007f7262a1e010`
`p3`	`0x00007f7162a1d010`
`p4`	`0x000000008359d120`
`p2`	`0x000000008359d010`
`big_array`	`0x0000000080601060`
`huge_array`	`0x0000000000601060`
`main()`	`0x000000000040060c`
`useless()`	`0x0000000000400590`



Runaway Stack Example

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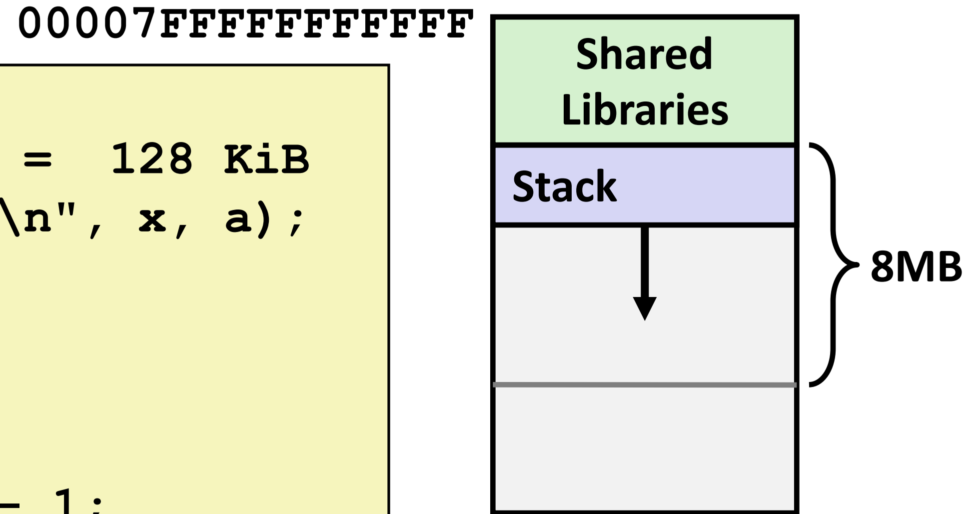
```
int recurse(int x) {
    int a[1<<15];  // 4*2^15 =  128 KiB
    printf("x = %d.  a at %p\n", x, a);
    a[0] = (1<<14)-1;
    a[a[0]] = x-1;
    if (a[a[0]] == 0)
        return -1;
    return recurse(a[a[0]]) - 1;
}
```



- **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:

	???	8
	Critical State	7
	Critical State	6
	Critical State	5
	Critical State	4
struct_t	d7 ... d4	3
struct_t	d3 ... d0	2
struct_t	a[1]	1
struct_t	a[0]	0

Location accessed by `fun(i)`

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:012345678901234567890123
012345678901234567890123
Segmentation Fault
```

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

Buffer Overflow Disassembly

echo:

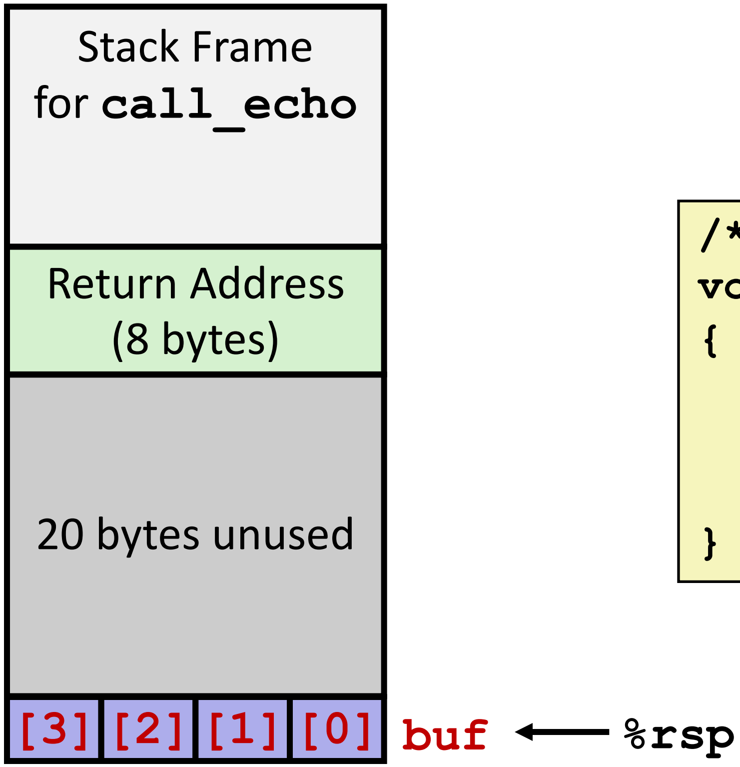
```
0000000004006cf <echo>:
 4006cf:  48 83 ec 18             sub    $0x18,%rsp
 4006d3:  48 89 e7                mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff          callq  400680 <gets>
 4006db:  48 89 e7                mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff          callq  400520 <puts@plt>
 4006e3:  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

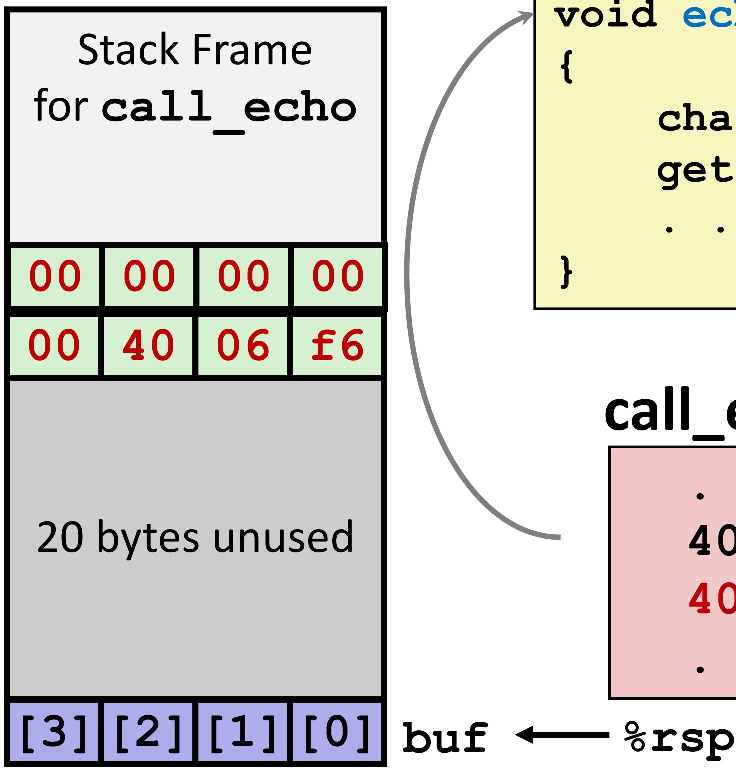



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

call_echo:

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

Buffer Overflow Stack Example #1

After call to gets

Stack Frame for `call_echo`			
00	00	00	00
00	40	06	f6
00	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

buf ⟵ %rsp

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

```
echo:
  subq   $0x18, %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 `call_echo`			
00	00	00	00
00	40	06	00
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

buf ← %rsp

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

```
echo:
   subq   $24, %rsp
   movq   %rsp, %rdi
   call   gets
   . . .
```

call_echo:

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

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

Program "returned" to 0x0400600, and then crashed.

Stack Smashing Attacks

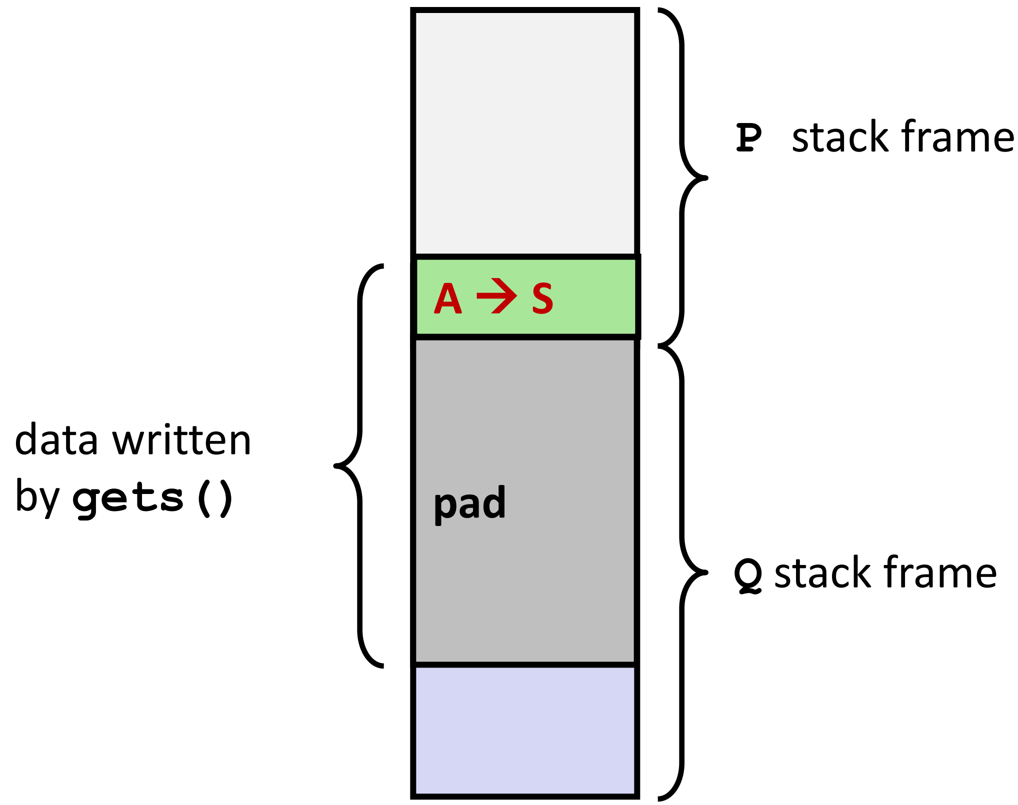
```
void P(){
  Q();
  ...
}
```

return address A

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

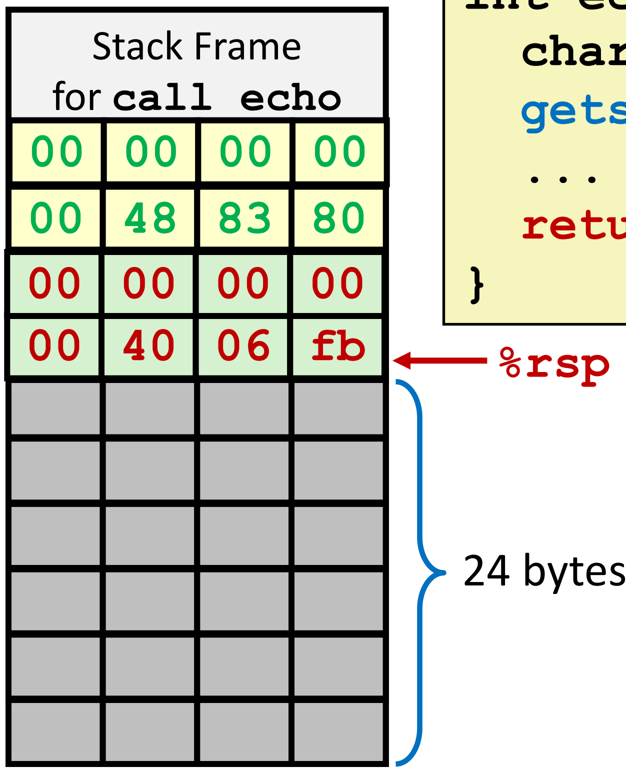
```
void S(){
/* Something
   unexpected */
  ...
}
```

Stack after call to **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




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

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

Stack Frame for `call echo`				
00	00	00	00	
00	48	83	80	
00	00	00	00	
00	40	06	fb	← `%rsp`
33	32	31	30	
39	38	37	36	
35	34	33	32	
31	30	39	38	
37	36	35	34	
33	32	31	30	

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
```

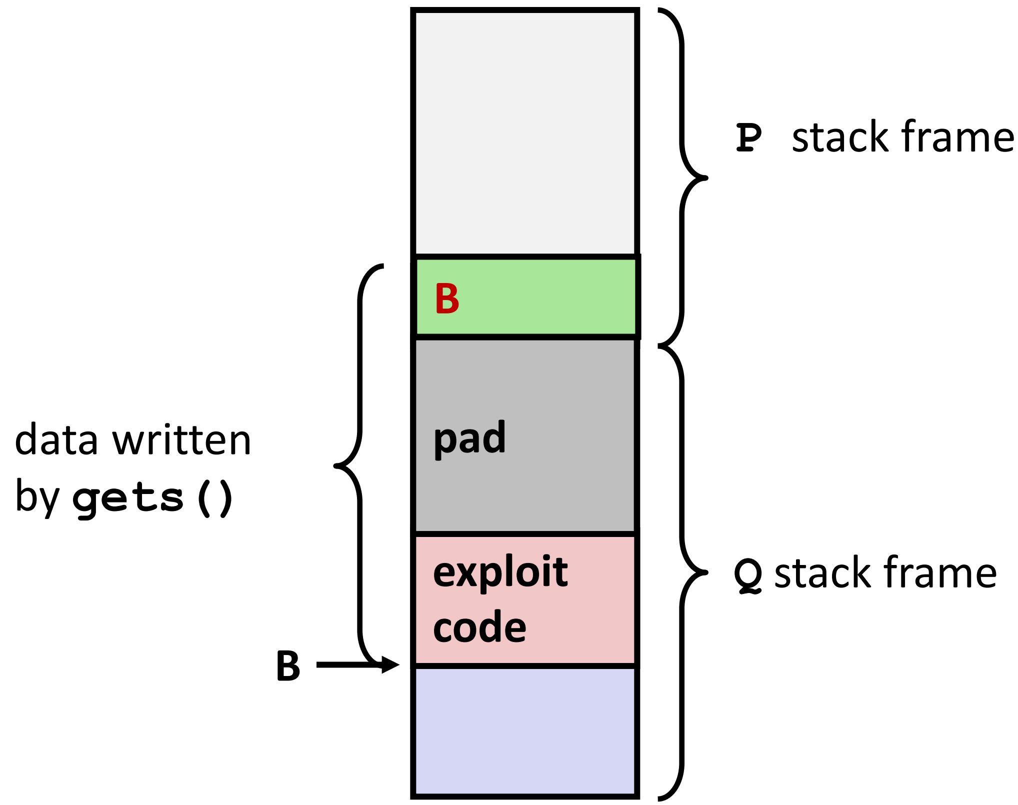
Code Injection Attacks

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

return address A

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

Stack after call to gets()

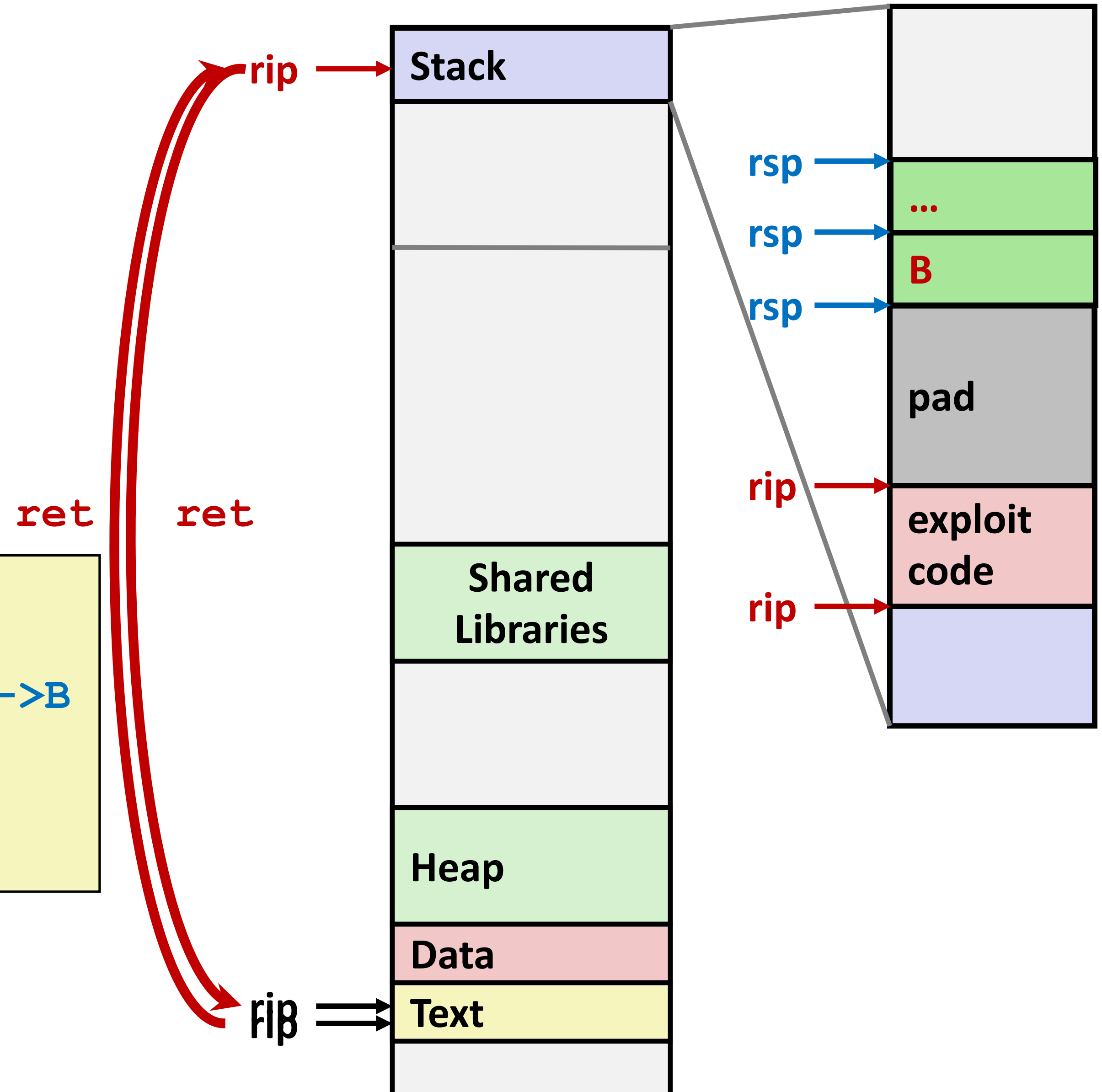


- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When Q executes `ret`, will jump to exploit code

How Does The Attack Code Execute?

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

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



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);
}
```

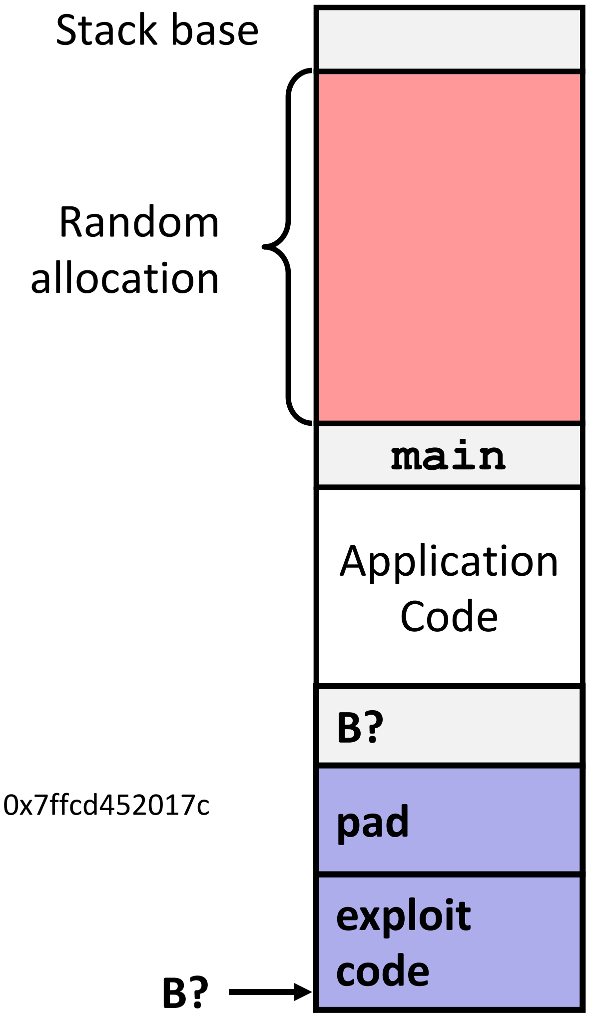
- **For example, use library routines that limit string lengths**
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
  - Don't use `scanf` with `%s` conversion specification
    - Use `fgets` to read the string
    - Or use `%ns` where `n` is a suitable integer

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

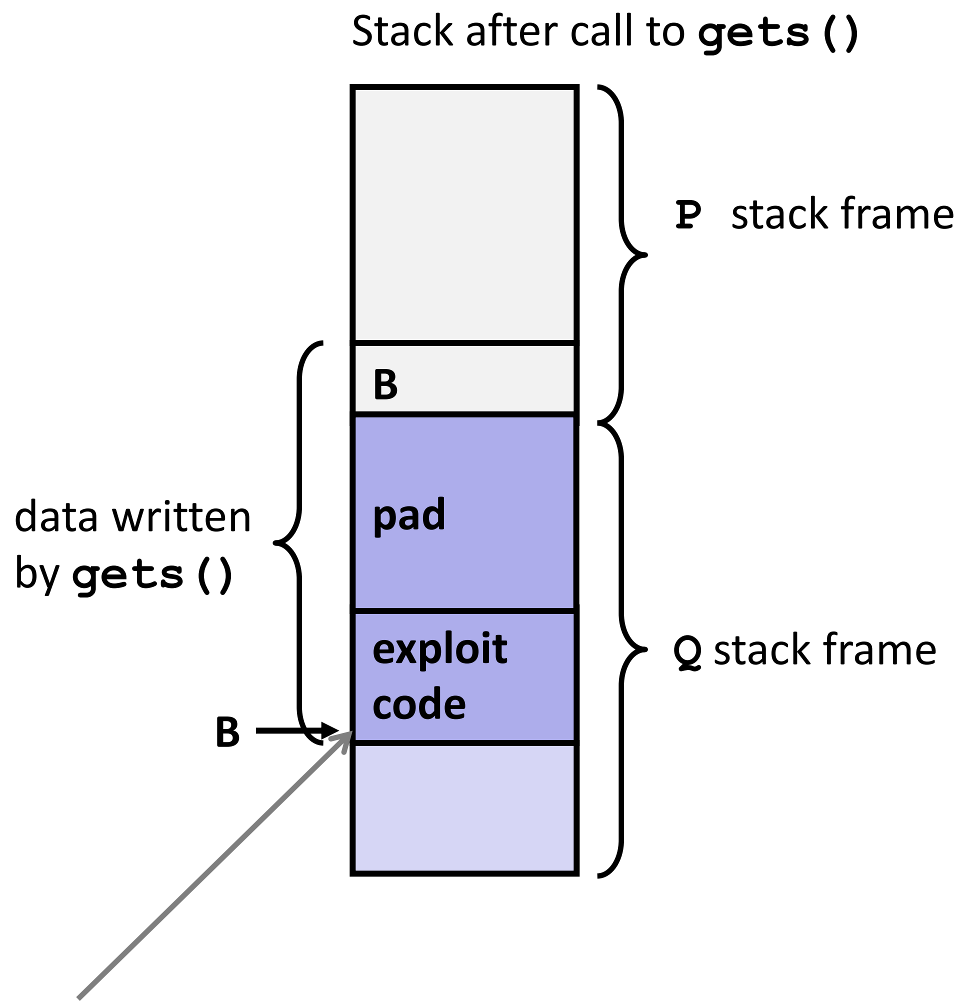
local	0x7ffe4d3be87c	0x7fff75a4f9fc	0x7ffeadb7c80c	0x7ffeaea2fdac	0x7ffcd452017c

  - Stack repositioned each time program executes



2. System-Level Protections can help

- **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 ***
```

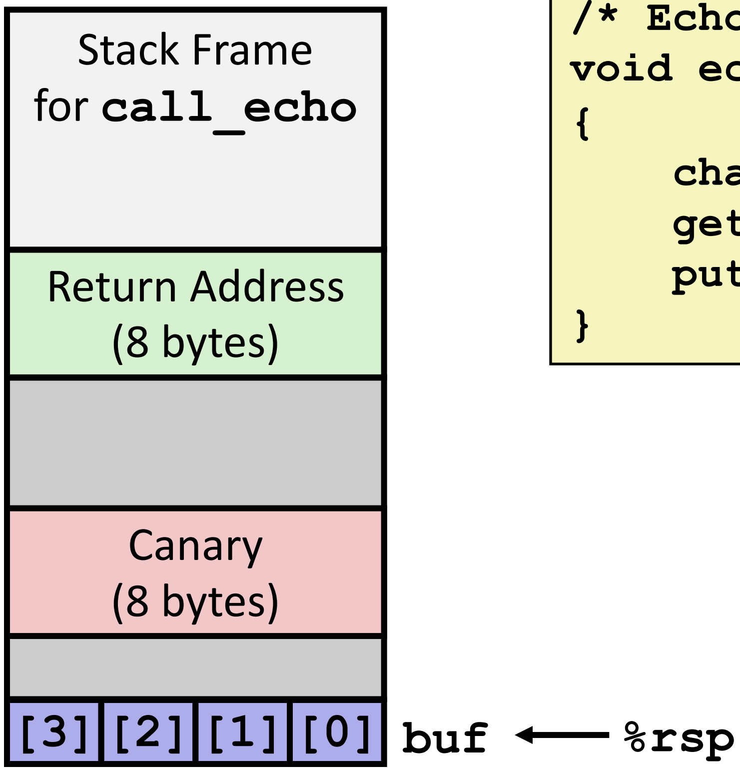
Protected Buffer Disassembly

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

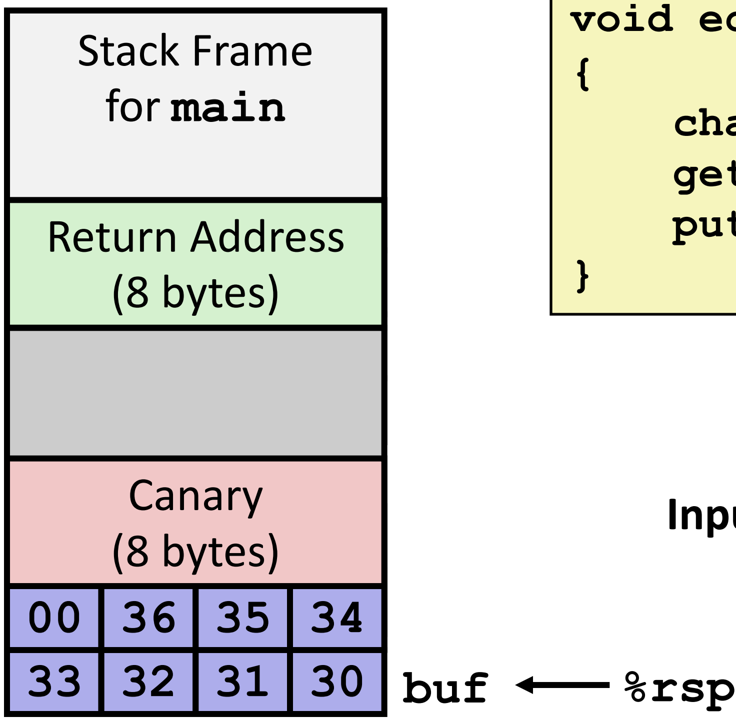



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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




```c
/* 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
```

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`

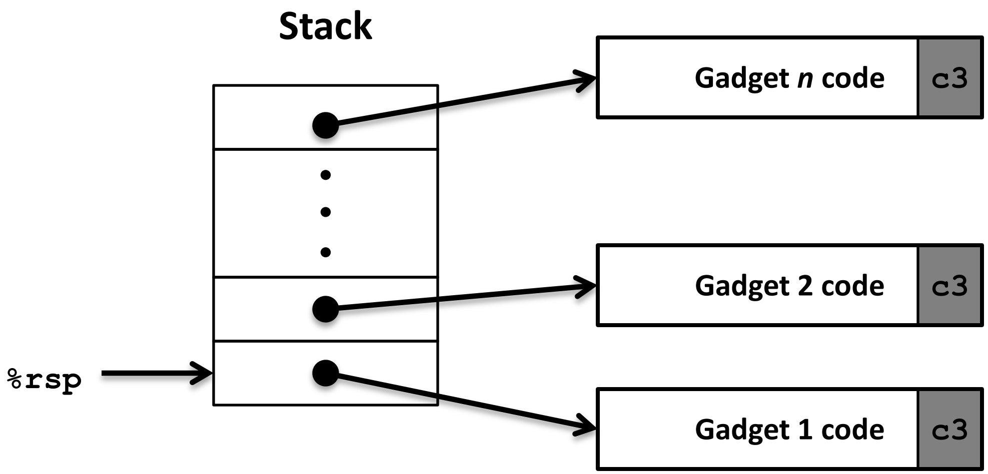
```
<setval>:
  4004d9:  c7 07 d4 48 89 c7  movl  $0xc78948d4,(%rdi)
  4004df:  c3                 retq
```

rdi ← rax

Gadget address = `0x4004dc`

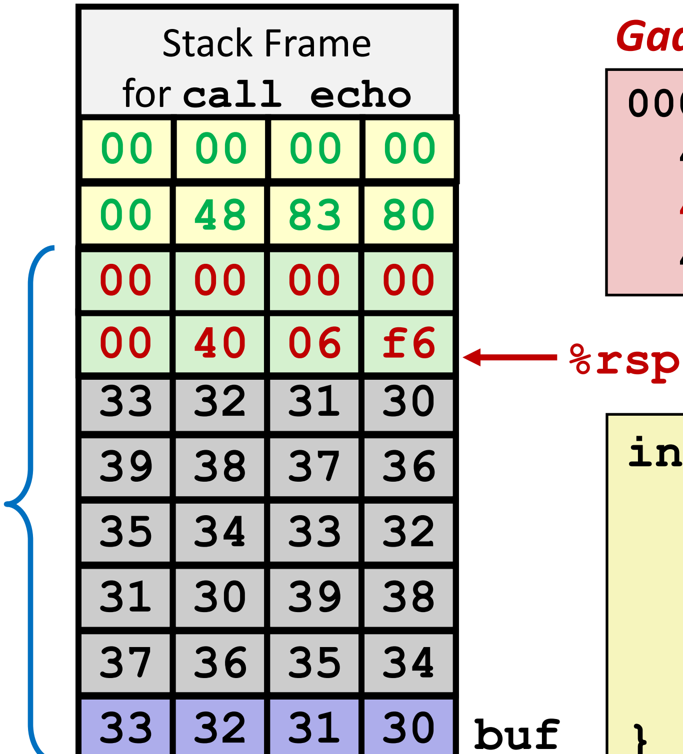
- **Repurpose byte codes**

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



Gadget

rax ← rdi + rdx

```
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
```

Attack: `int echo()` returns rdi + rdx

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

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

Summary

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

Exploits Based on Buffer Overflows

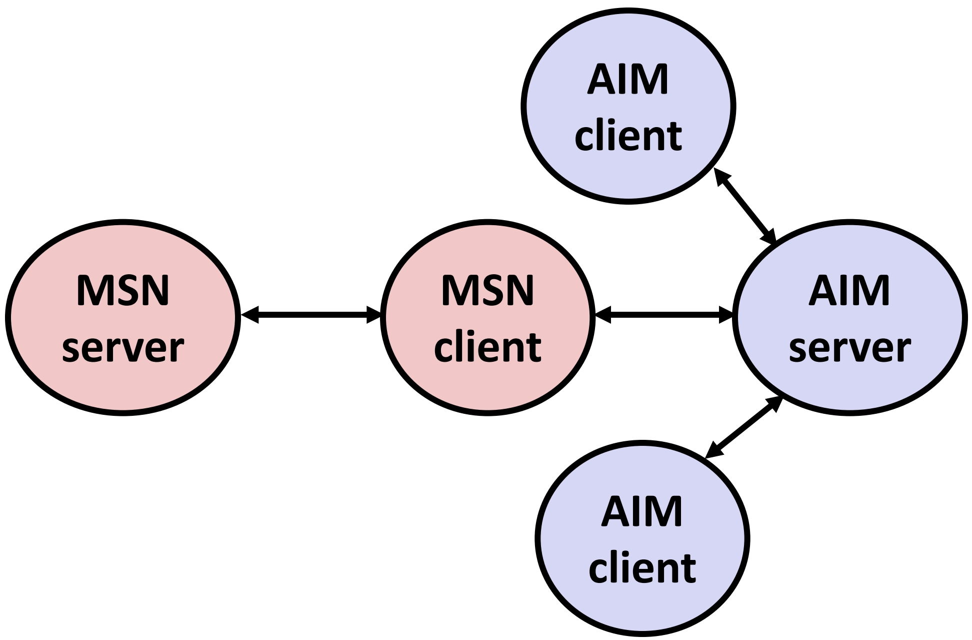
- ***Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines***
- **Distressingly common in real programs**
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- **Examples across the decades**
  - Original “Internet 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

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**