Machine-Level Programming V: Advanced Topics

COMP400727: Introduction to Computer Systems

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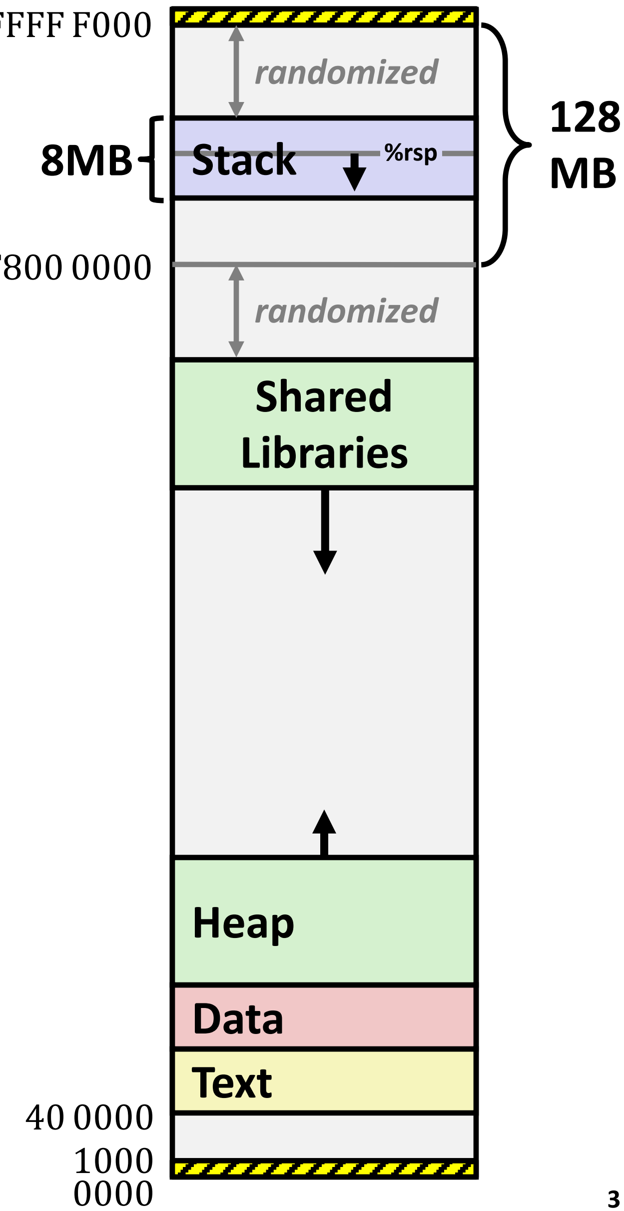
Today

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

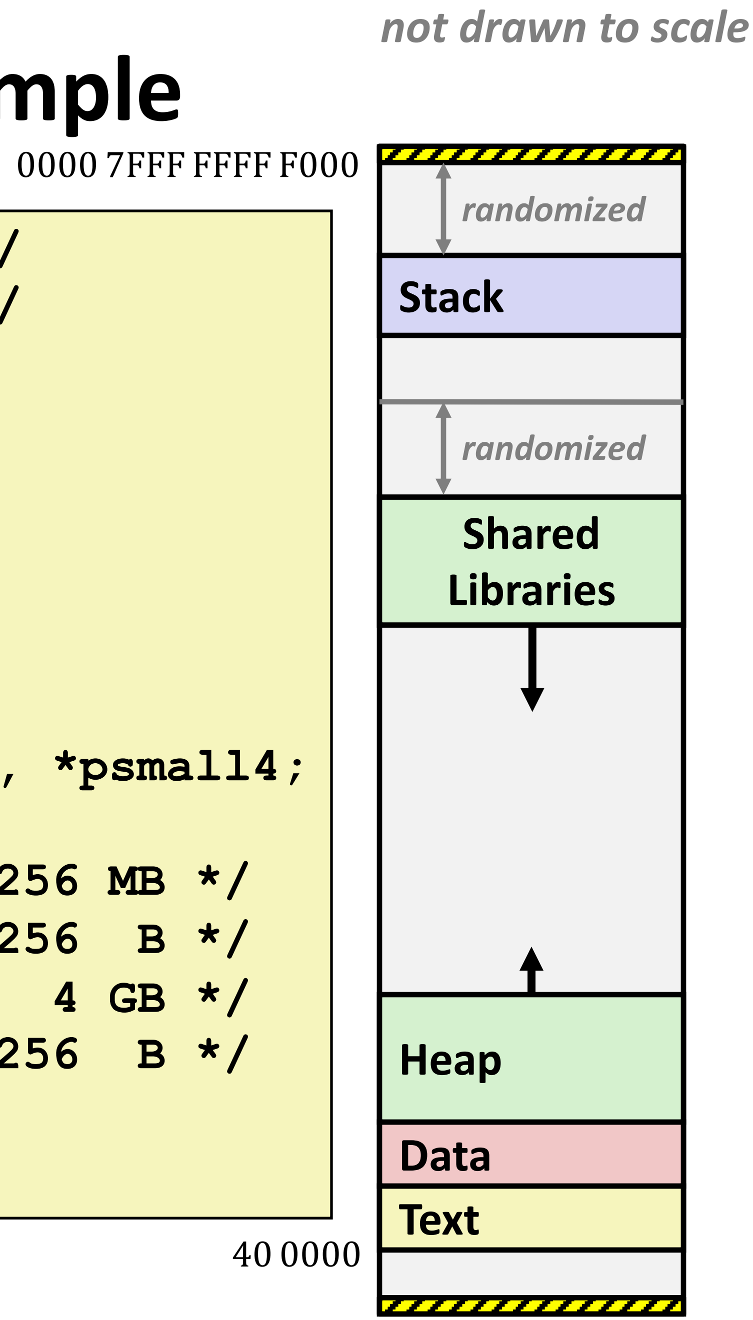
```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

int global = 0;

int useless() { return 0; }

int main ()
{
    void *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?



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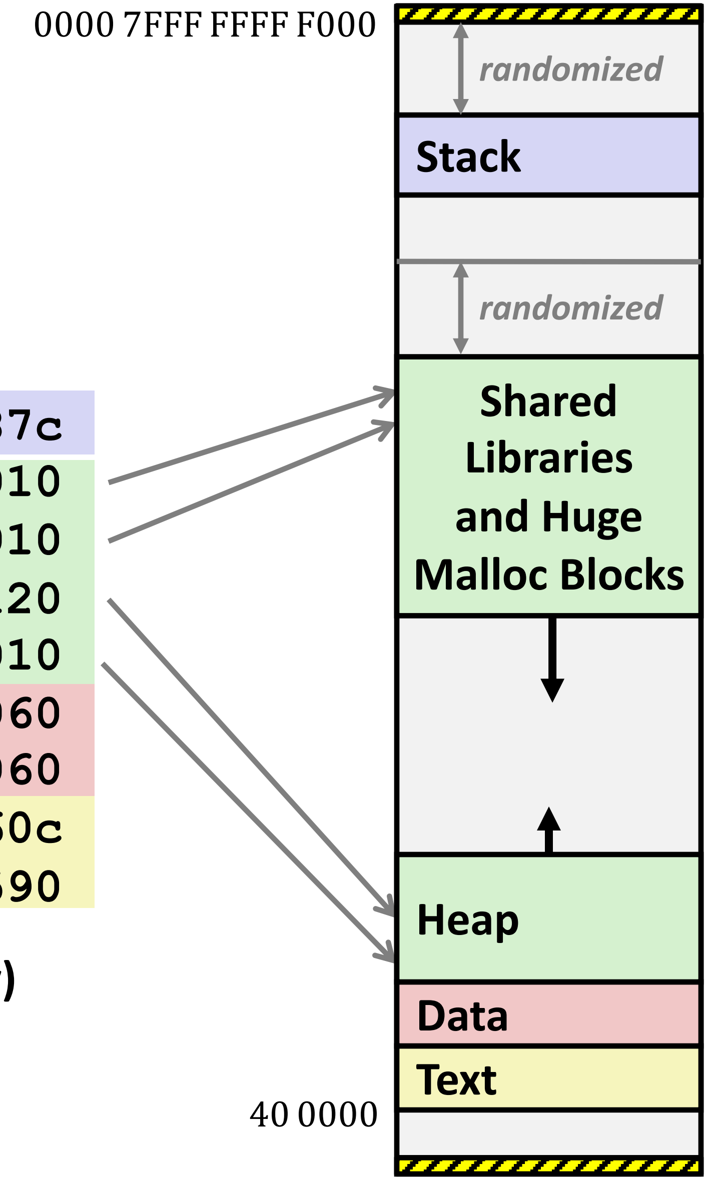
x86-64 Example Addresses

address range ~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)



Today

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

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)  ->   Segmentation fault
fun(8)  ->   3.1400000000
```

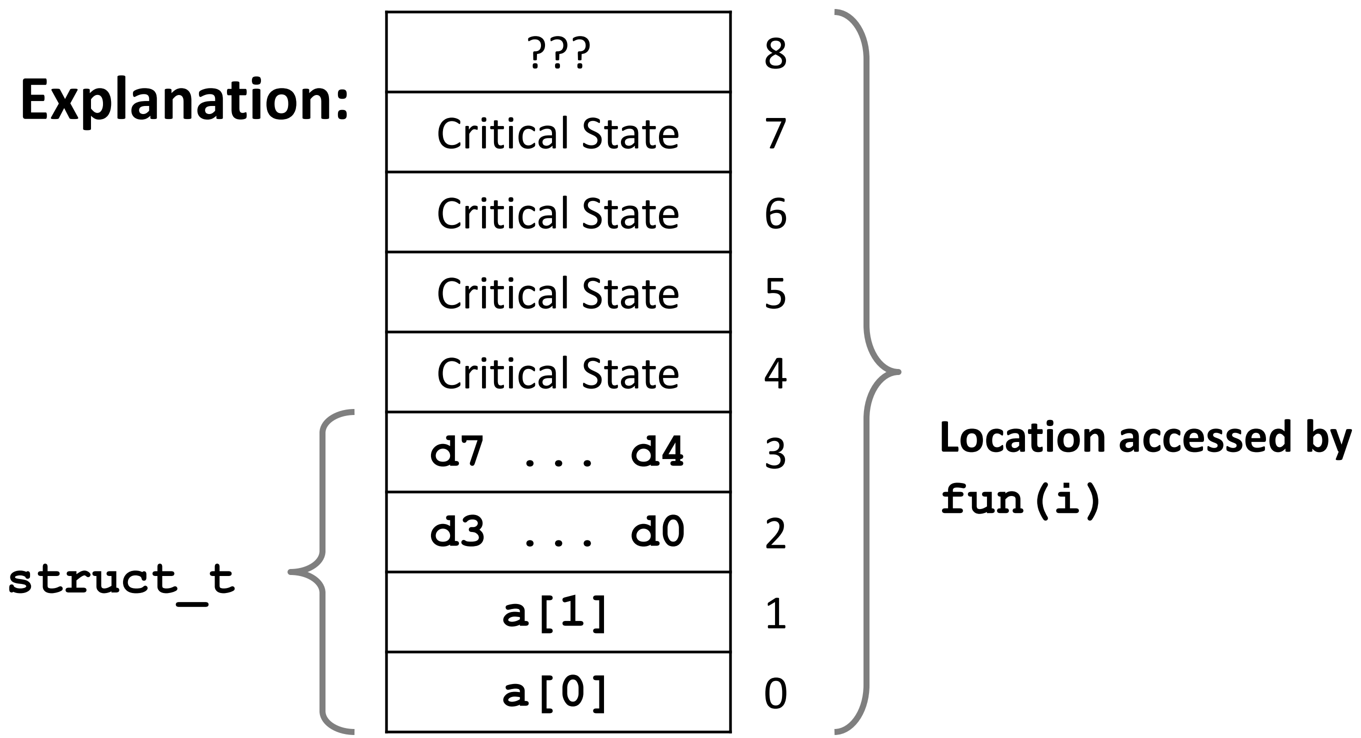
- Result is system specific

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(6)  ->   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
- **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();
}
```

```
unix>./bufdemo-nsp
Type a string: 01234567890
01234567890
```

```
unix>./bufdemo-nsp
Type a string: 012345678901
012345678901
Segmentation Fault
```

Buffer Overflow Disassembly

echo:

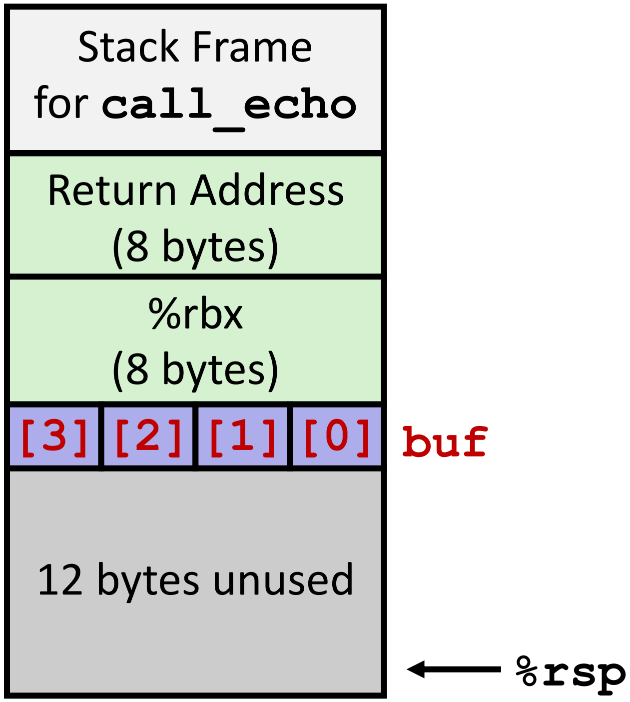
```
0000000000001159 <echo>:
    1159: 53                     push   %rbx
    115a: 48 83 ec 10            sub    $0x10,%rsp
    115e: 48 8d 5c 24 0c         lea    0xc(%rsp),%rbx
    1163: 48 89 df               mov    %rbx,%rdi
    1166: b8 00 00 00 00         mov    $0x0,%eax
    116b: e8 d0 fe ff ff         call   1040 <gets@plt>
    1170: 48 89 df               mov    %rbx,%rdi
    1173: e8 b8 fe ff ff         call   1030 <puts@plt>
    1178: 48 83 c4 10            add    $0x10,%rsp
    117c: 5b                     pop    %rbx
    117d: c3                     ret
```

call_echo:

```
  117e:    48 83 ec 08           sub    $0x8,%rsp
  1182:    b8 00 00 00 00        mov    $0x0,%eax
  1187:    e8 c5 ff ff ff        callq  1189 <echo>
  118c:    48 83 c4 08           add    $0x8,%rsp
  1190:    c3                    ret
```

Buffer Overflow Stack Example

Before call to gets

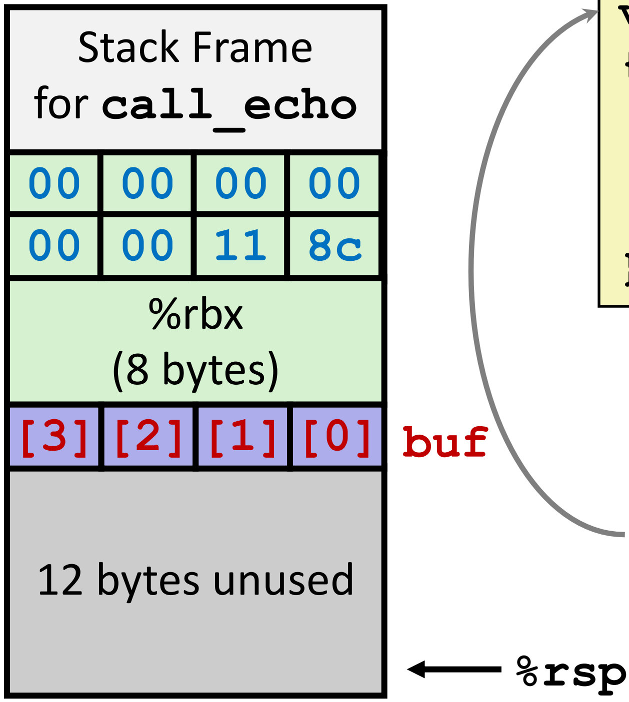



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
  push  %rbx
  subq  $0x10, %rsp
  lea   0xc(%rsp),%rbx
  mov   %rbx,%rdi
  mov    $0x0,%eax
  call  gets
  . . .
```

Buffer Overflow Stack Example

Before call to gets




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

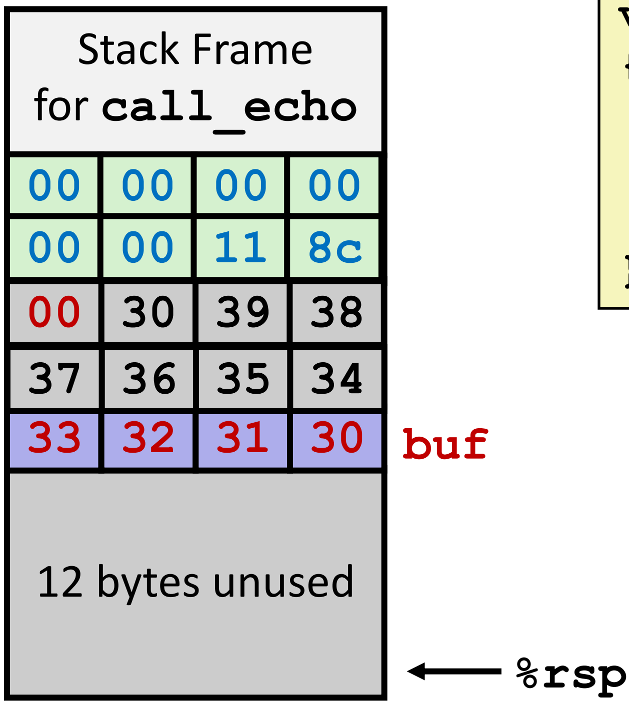
```
echo:
  push  %rbx
  subq  $0x10, %rsp
  lea   0xc(%rsp),%rbx
  mov   %rbx,%rdi
  mov    $0x0,%eax
  call  gets
  . . .
```

call_echo:

```
 . . .
 1187:    callq  4006cf <echo>
 118c:    add    $0x8,%rsp
 . . .
```

Buffer Overflow Stack Example #1

After call to gets




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

```
echo:
   push   %rbx
   subq   $0x10, %rsp
   lea    0xc(%rsp),%rbx
   mov    %rbx,%rdi
   mov     $0x0,%eax
   call   gets
   . . .
```

call_echo:

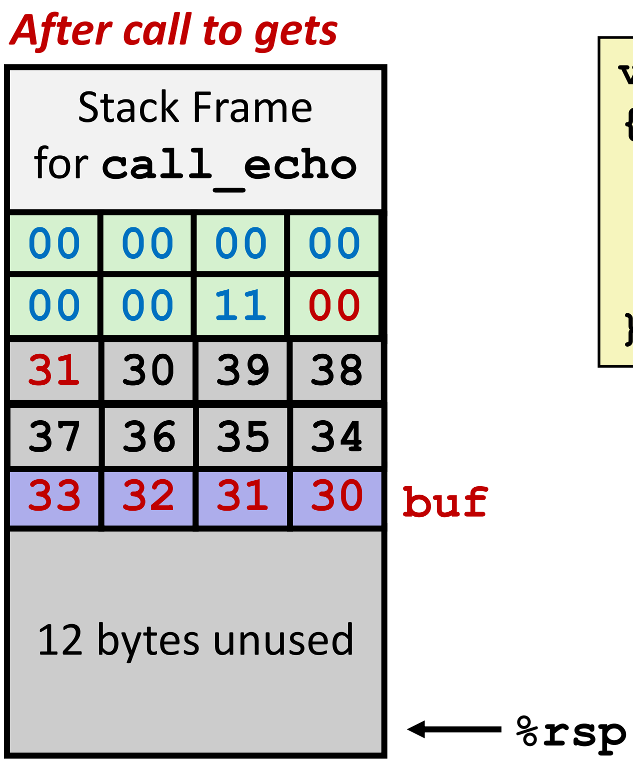
```
 . . .
 1187:     callq   4006cf <echo>
 118c:     add     $0x8,%rsp
 . . .
```

```
unix>./bufdemo-nsp
Type a string:01234567890
01234567890
```

```
"01234567890\0"
```

Overflowed buffer, but did not corrupt state

Buffer Overflow Stack Example #1




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

```
echo:
   push   %rbx
   subq   $0x10, %rsp
   lea    0xc(%rsp),%rbx
   mov    %rbx,%rdi
   mov     $0x0,%eax
   call   gets
   . . .
```

call_echo:

```
   . . .
   1187:     callq   4006cf <echo>
   118c:     add     $0x8,%rsp
   . . .
```

```
unix>./bufdemo-nsp
Type a string:012345678901
012345678901
segmentation fault
```

Program “returned” to 0x1100, and then crashed.

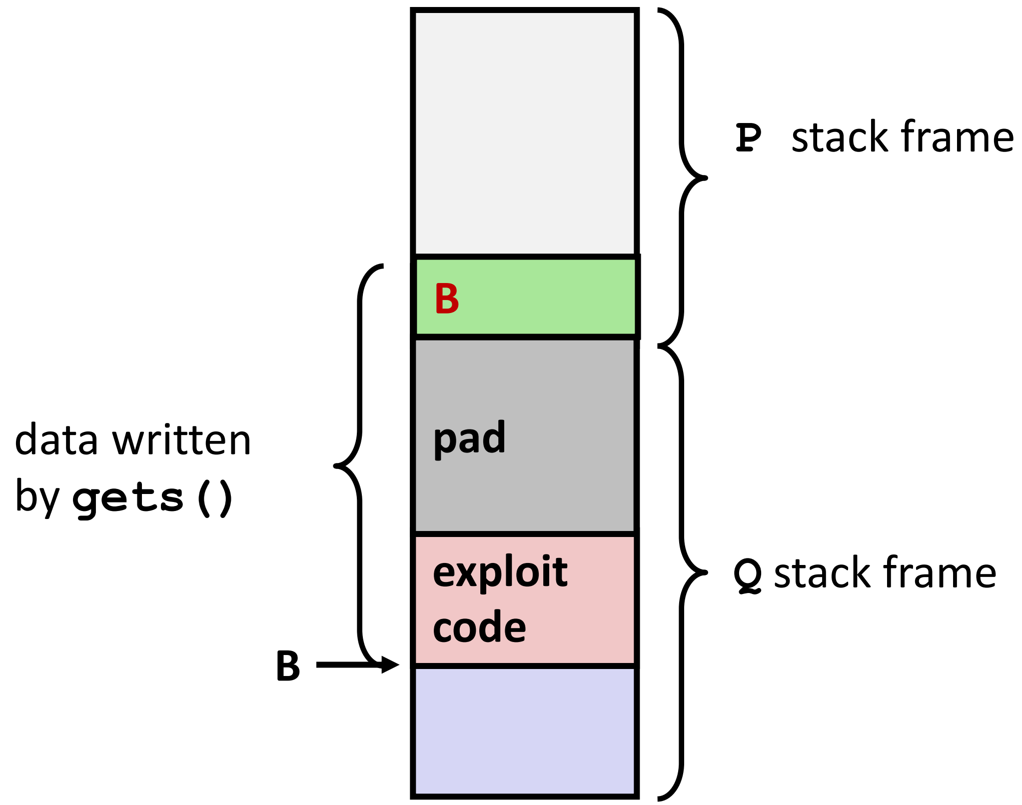
Code Injection Attacks

```
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

Exploits Based on Buffer Overflows

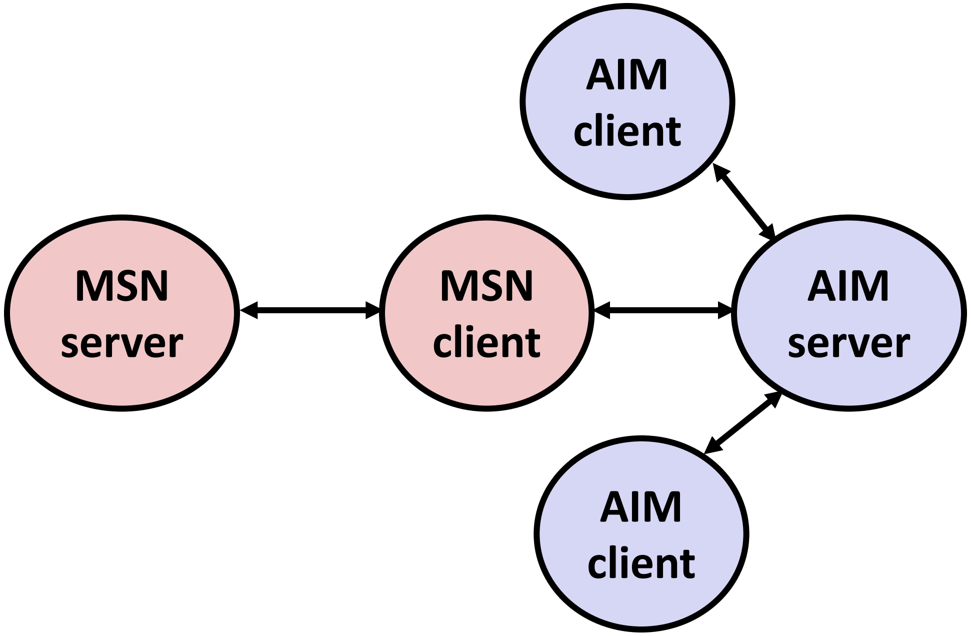
- ***Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines***
- **Distressingly common in real programs**
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- **Examples across the decades**
  - Original "Internet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

Today

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

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);
}
```

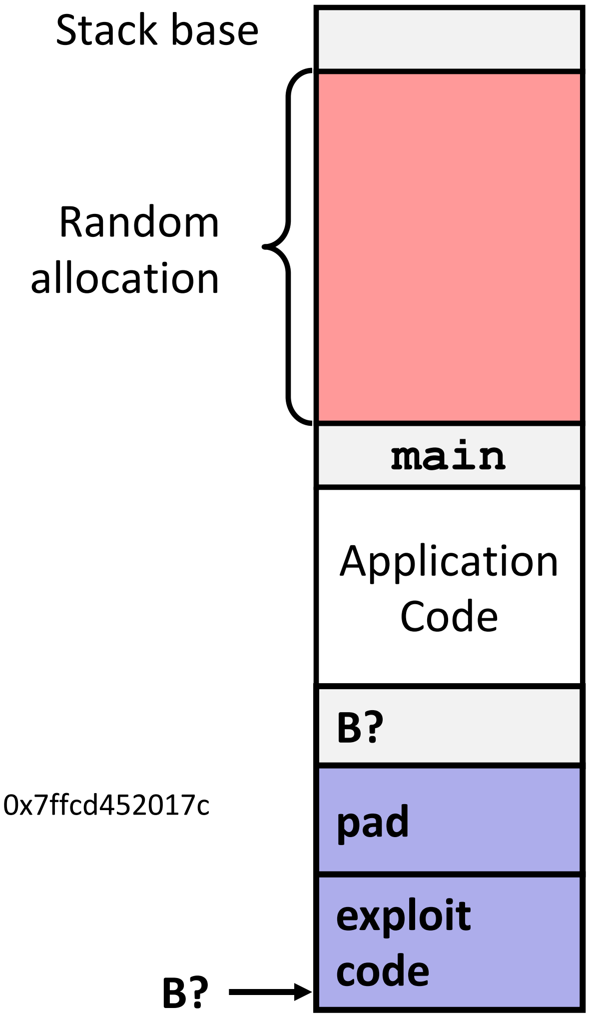
- **For example, use library routines that limit string lengths**
  - **fgets** instead of **gets**
  - **strncpy** instead of **strcpy**
  - Don't use **scanf** with **%s** conversion specification
    - Use **fgets** to read the string
    - Or use **%ns** where **n** is a suitable integer

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

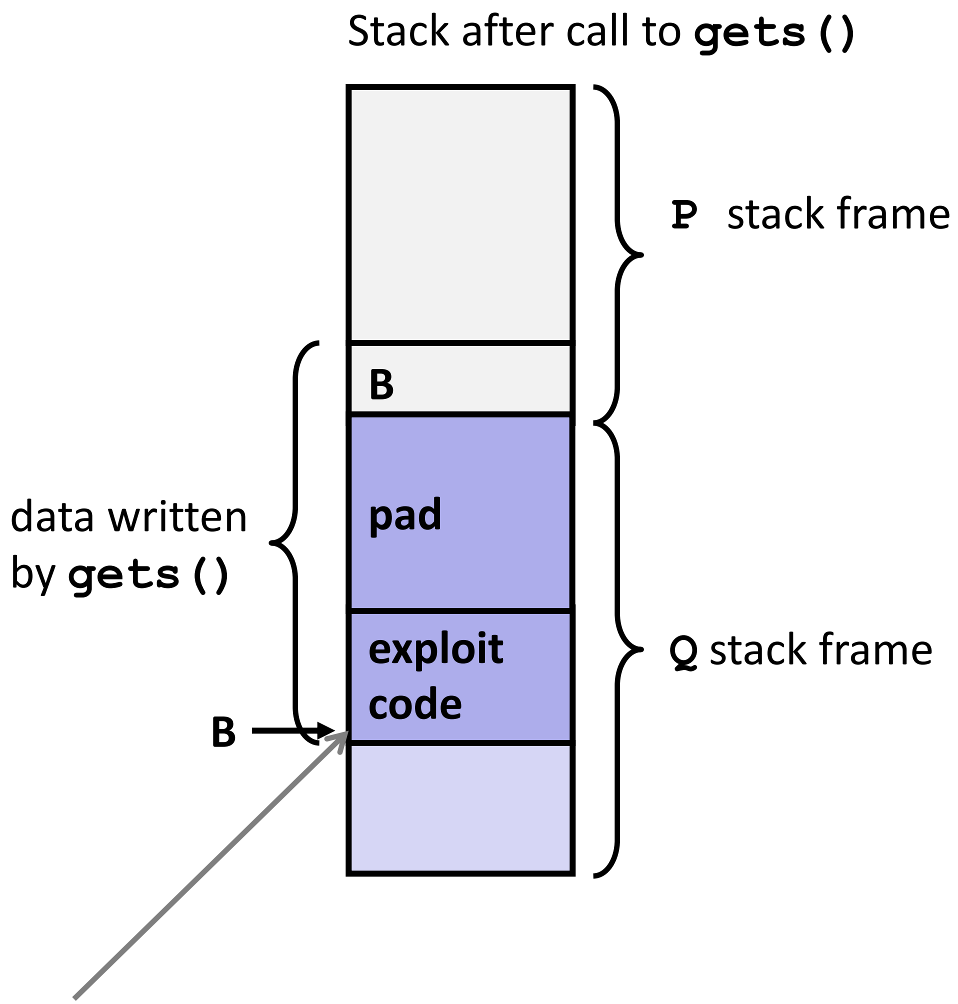
local 0x7ffe4d3be87c 0x7fff75a4f9fc 0x7ffeadb7c80c 0x7ffeaea2fdac 0x7ffcd452017c

- Stack repositioned each time program executes



2. System-Level Protections Can Help

- **Non-executable memory**
  - Older x86 CPUs would execute machine code from any readable address
  - x86-64 added a way to mark regions of memory as *not executable*
  - Immediate crash on jumping into any such region
  - Current Linux and Windows mark the stack this way



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:0123
0123456
```

```
unix>./bufdemo-sp
Type a string:01234
*** stack smashing detected ***
```

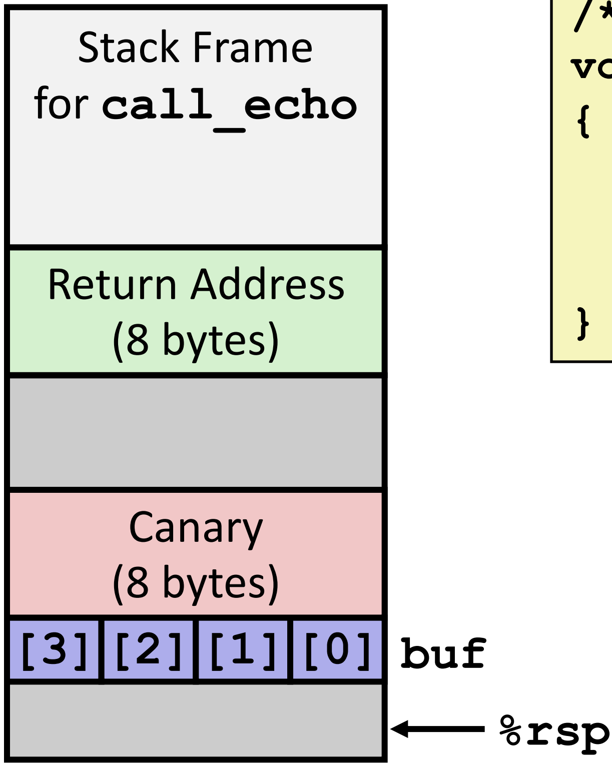
Protected Buffer Disassembly

echo:

```
1169:    push   %rbx
116a:    sub    $0x10,%rsp
116e:    mov    %fs:0x28,%rax
1177:    mov    %rax,0x8(%rsp)
117c:    xor    %eax,%eax
117e:    lea    0x4(%rsp),%rbx
1183:    mov    %rbx,%rdi
1186:    callq 1050 <gets@plt>
118b:    mov    %rbx,%rdi
118e:    call   1030 <puts@plt>
1193:    mov    0x8(%rsp),%rax
1198:    sub    %fs:0x28,%rax
11a1:    jne    11a9 <echo+0x40>
11a3:    add    $0x10,%rsp
11a7:    pop    %rbx
11a8:    ret
11a9:    call   1040 <__stack_chk_fail@plt>
```

Setting Up Canary

Before call to gets

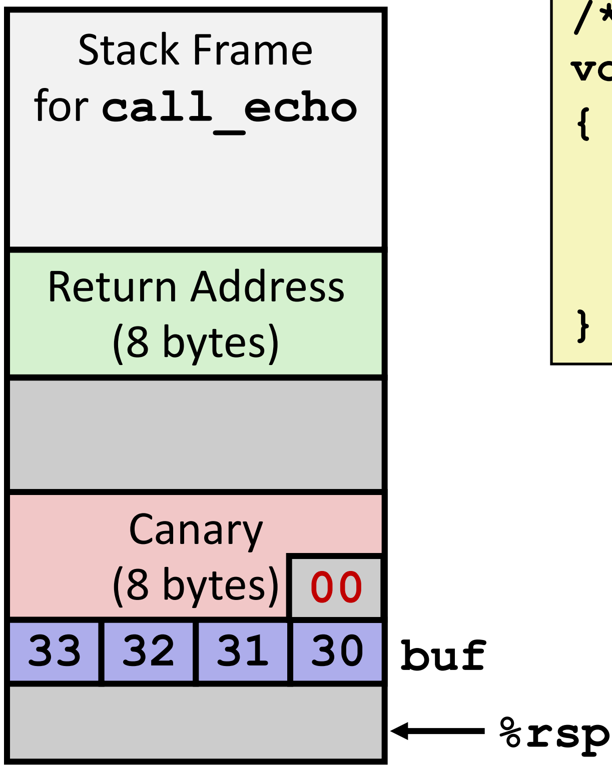



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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: ***0123***

LSB of canary is 0x00

```
echo:
. . .
1193    mov    0x8(%rsp),%rax     # Retrieve from stack
1198    sub    %fs:0x28,%rax      # Compare to canary
11a1    jne    11a9 <echo+0x40>   # If not same, error
. . .
11a9    call   __stack_chk_fail   # FAIL
```

Return-Oriented Programming Attacks

- **Challenge (for hackers)**
  - Stack randomization makes it hard to predict buffer location
  - Marking stack non-executable makes it hard to insert binary code
- **Alternative Strategy**
  - Use existing code
    - Part of the program or the C library
  - 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`

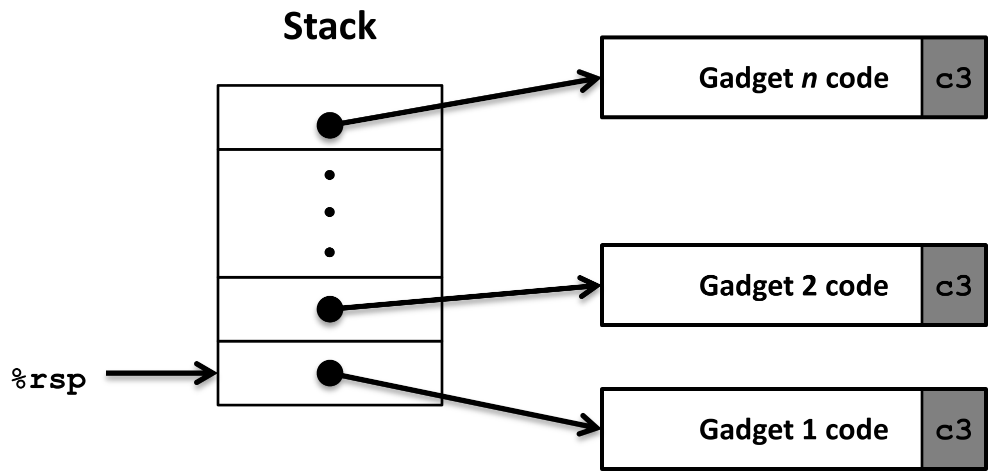
```
<setval>:
  4004d9:  c7 07 d4 48 89 c7   movl  $0xc78948d4,(%rdi)
  4004df:  c3                  retq
```

rdi ← rax

Gadget address = `0x4004dc`

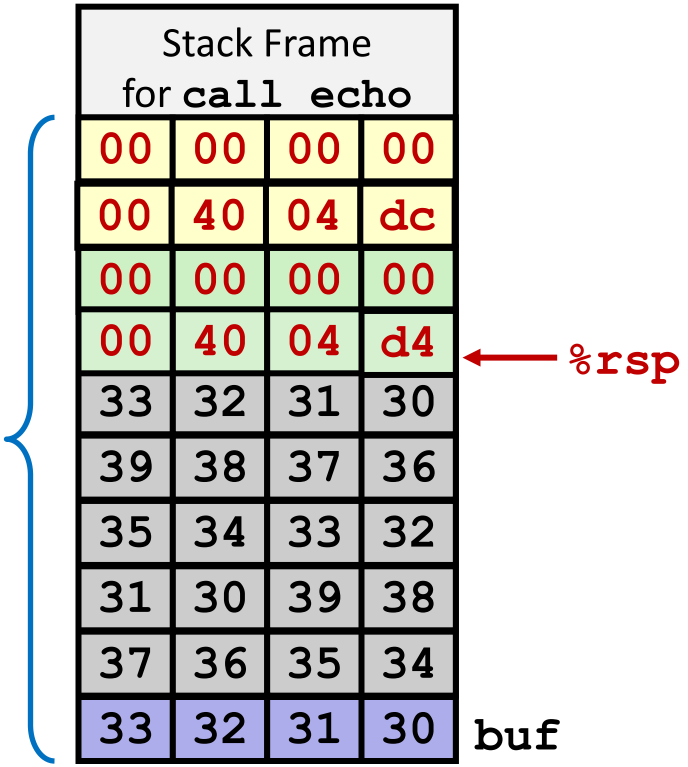
- Repurpose byte codes

ROP Execution



- **Trigger with `ret` instruction**
  - Will start executing Gadget 1
- **Final `ret` in each gadget will start next one**
  - **`ret`**: pop address from stack and jump to that address

Crafting an ROP Attack String



- **Gadget #1**
  - `0x4004d4` rax ← rdi + rdx
- **Gadget #2**
  - `0x4004dc` rdi ← rax
- **Combination**

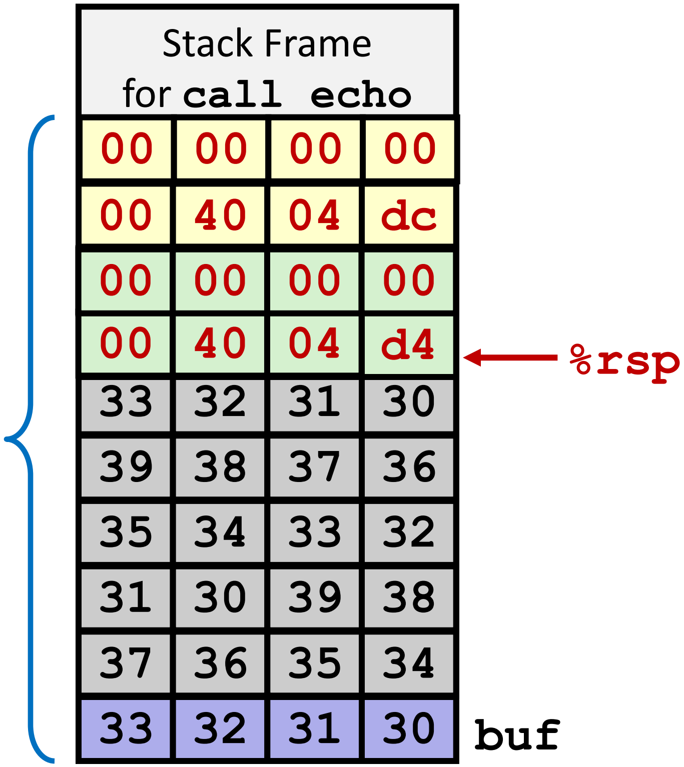
  rdi ← rdi + rdx

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
```

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

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  - Bypassing Protection