Machine-Level Programming V: Buffer Overflows & Attacks

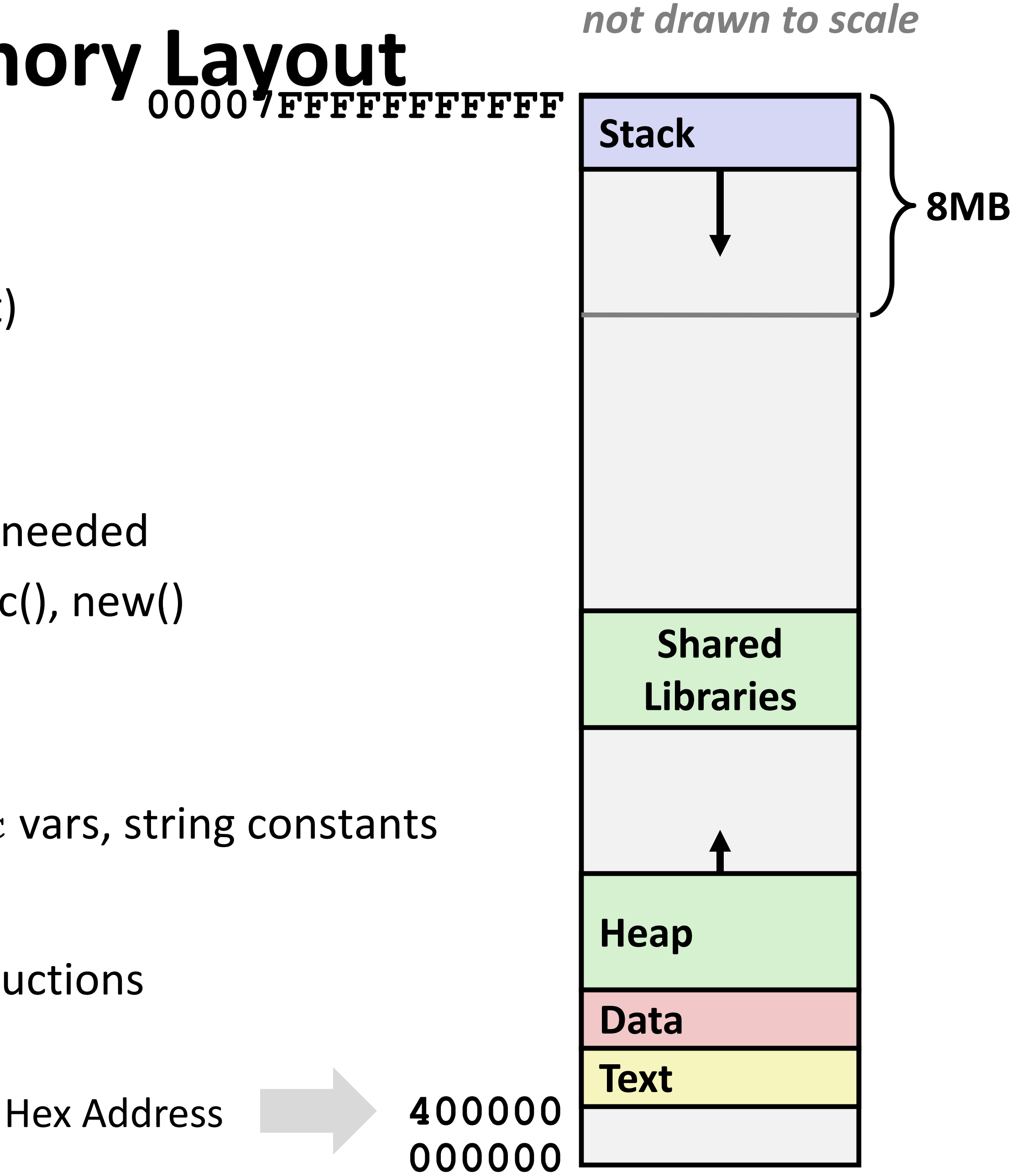
These slides adapted from materials provided by the textbook authors.

Machine-Level Programming V

- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection

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

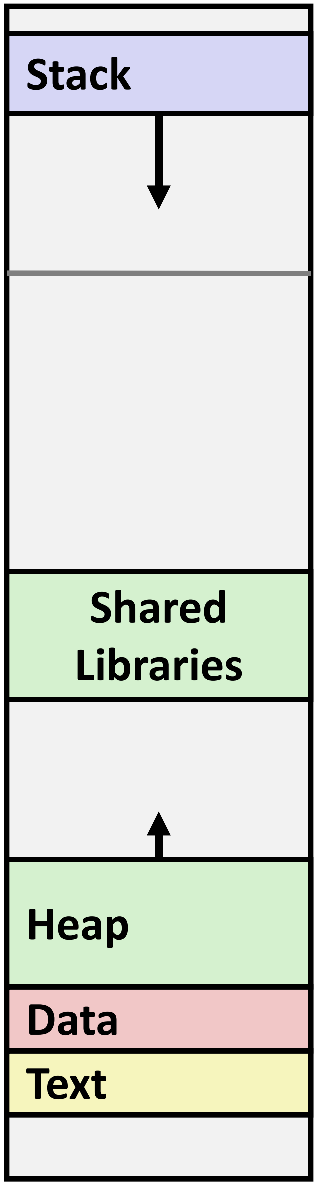


Memory Allocation Example

```
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?

not drawn to scale

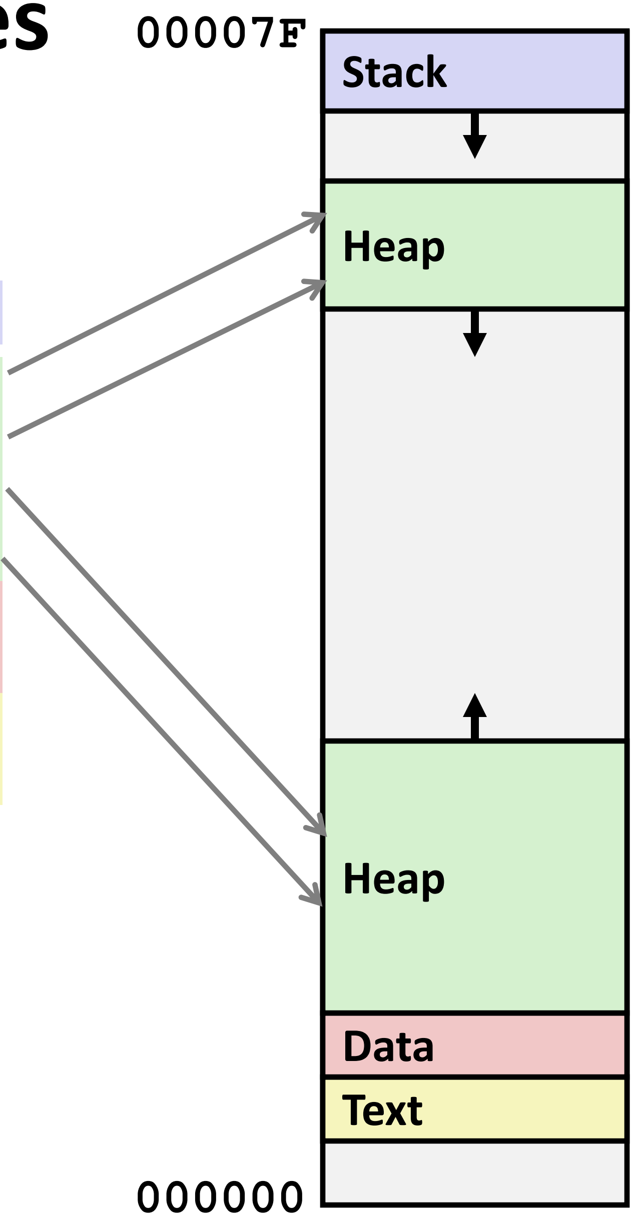


x86-64 Example Addresses

address range ~2^{47}

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

not drawn to scale



Machine-Level Programming V

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

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
```

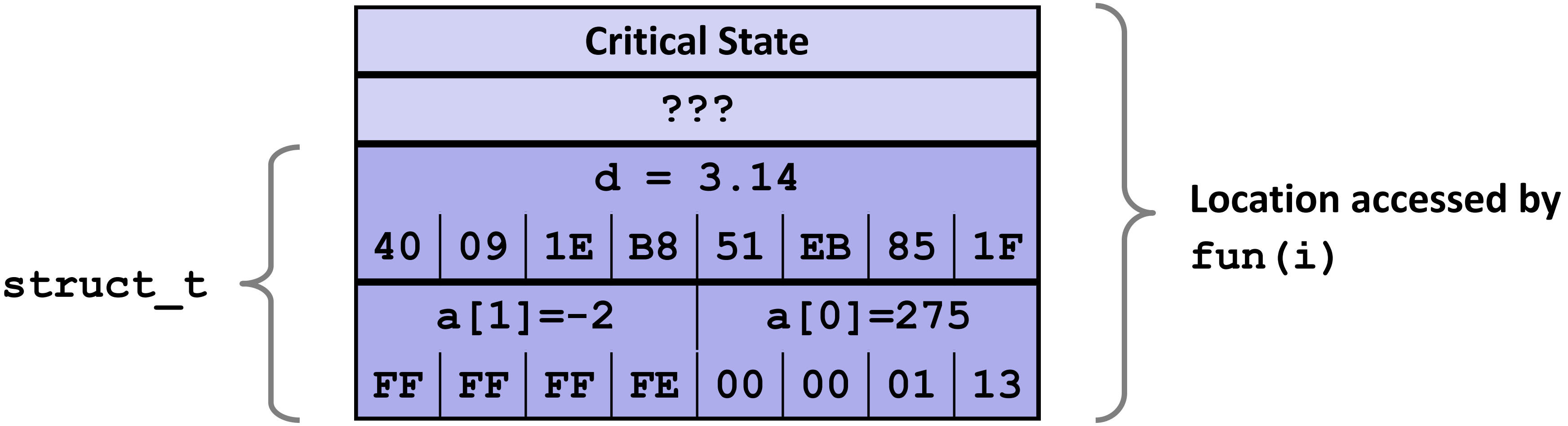
- Result is system specific

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
      See "Smashing the Stack for Fun and Profit"
      Phrack online hacking 'zine - http://phrack.org/issues/49/14.html

String Library Code

- **Implementation of Unix function `gets()`**

```c
/* 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);
}
```

← How big is big enough?

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

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

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

Buffer Overflow Disassembly

echo:

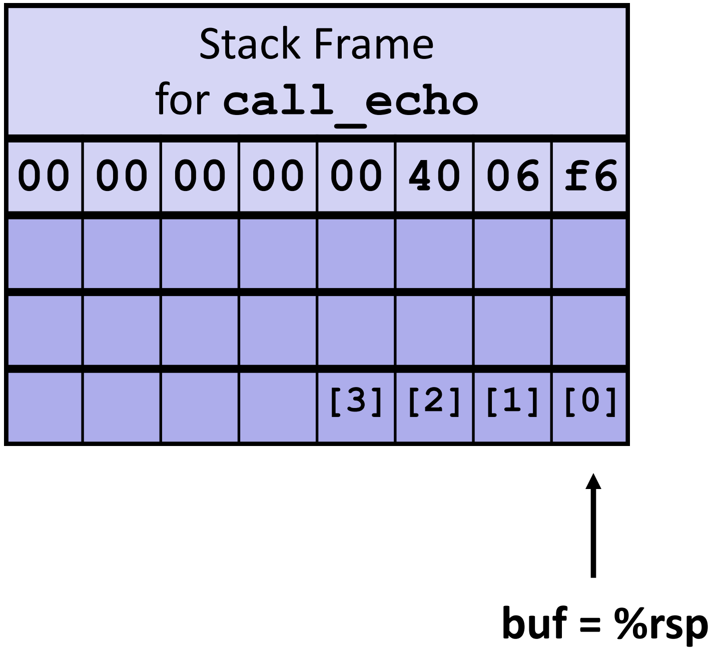
```
0000000000004006cf <echo>:
 4006cf:  48 83 ec 18           sub    $0x18,%rsp
 4006d3:  48 89 e7              mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff        callq  400680 <gets>
 4006db:  48 89 e7              mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff        callq  400520 <puts@plt>
 4006e3:  48 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



Stack Frame
for `call_echo`

00	00	00	00	00	40	06	f6
				[3]	[2]	[1]	[0]

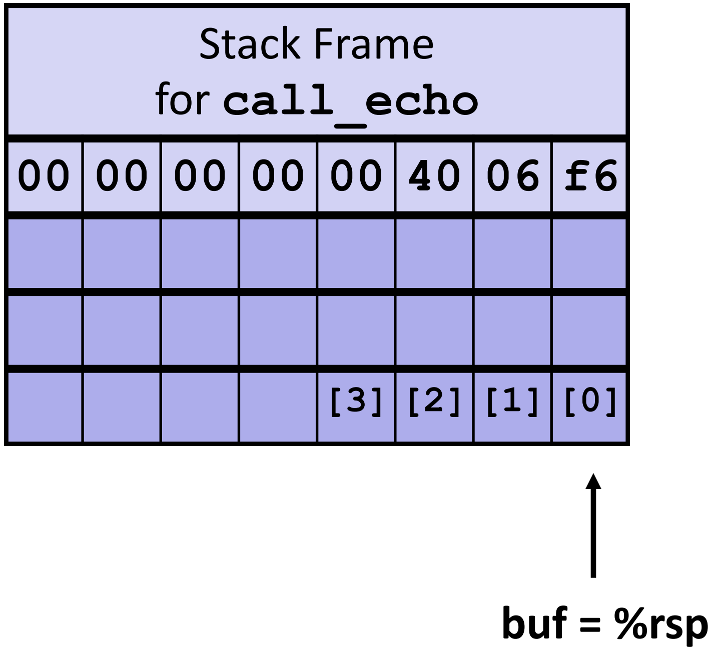
buf = %rsp

```
/* 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



Stack Frame for `call_echo`

00	00	00	00	00	40	06	f6
				[3]	[2]	[1]	[0]

buf = %rsp

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

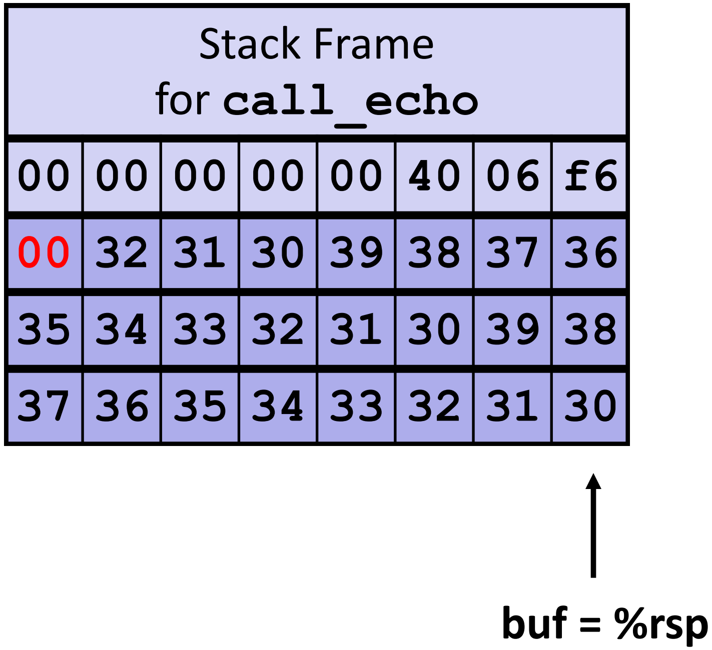
```
echo:
  subq  $24, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

call_echo:

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

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   $24, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

call_echo:

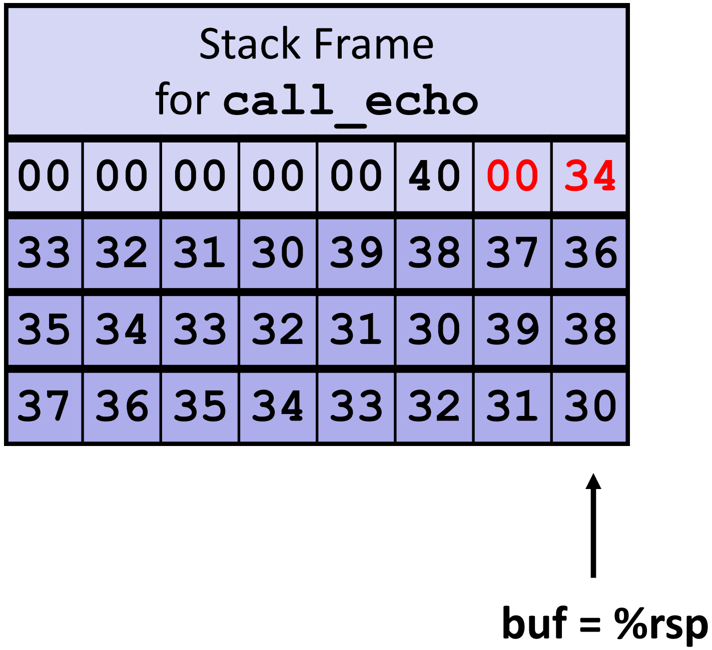
```
  . . .
  4006f1:  callq   4006cf <echo>
  4006f6:  add     $0x8,%rsp
  . . .
```

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

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	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

buf = %rsp

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

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

call_echo:

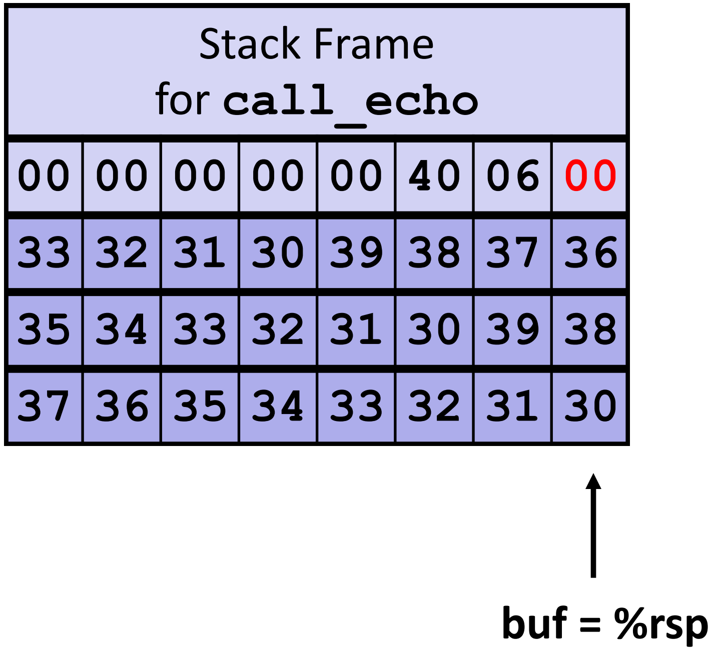
```
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $0x8,%rsp
  . . .
```

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

Overflowed buffer and corrupted return pointer

Buffer Overflow Stack Example #3

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:

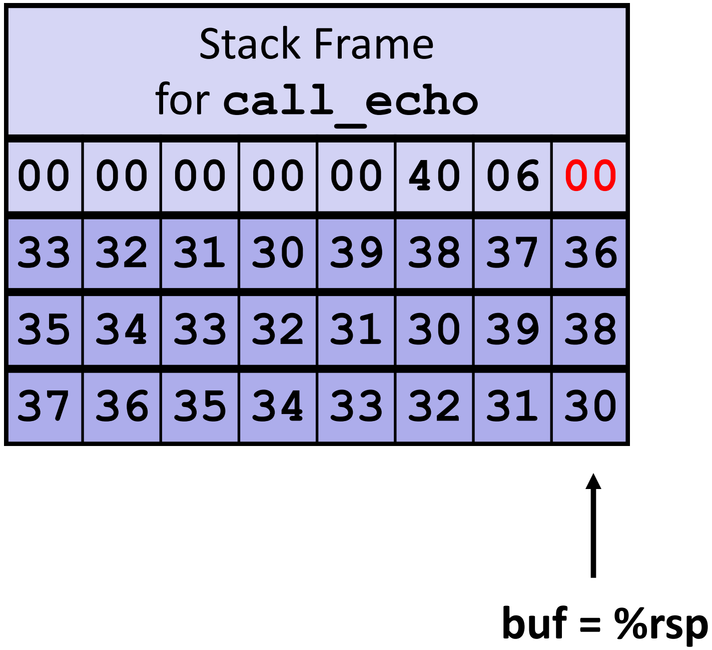
```
  . . .
  4006f1:  callq  4006cf <echo>
  4006f6:  add    $0x8,%rsp
  . . .
```

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

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

Buffer Overflow Stack Example #3 Explained

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

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
```

"Returns" to unrelated code

Lots of things happen, without modifying critical state

Eventually executes `retq` back to `main`

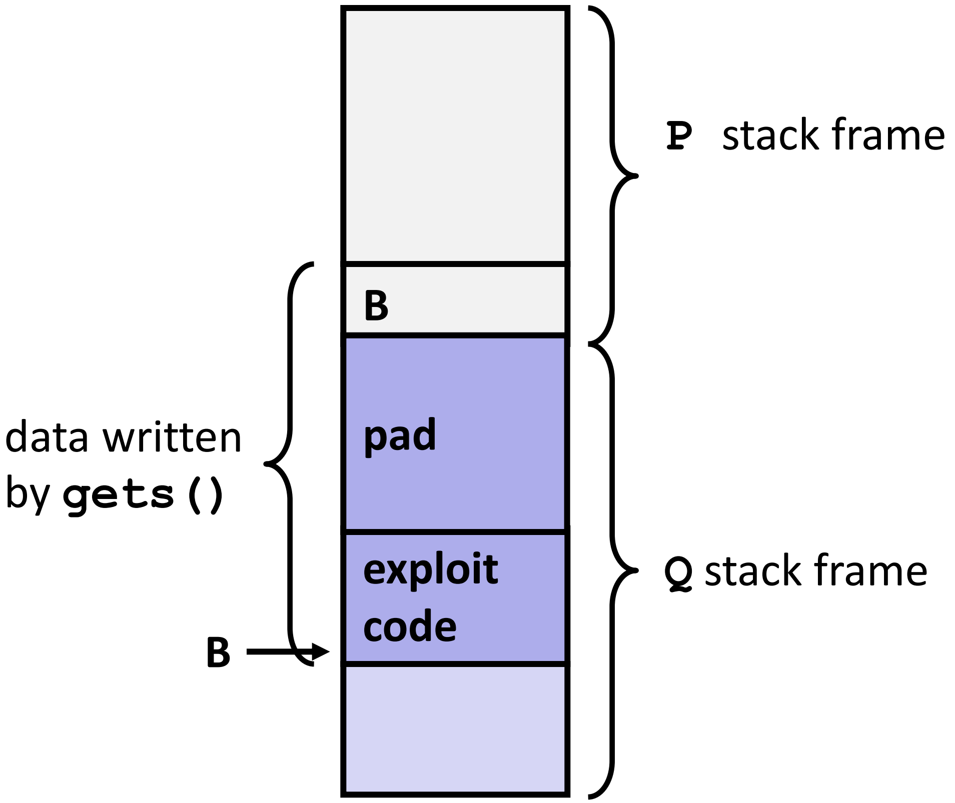
Code Injection Attacks

```
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**