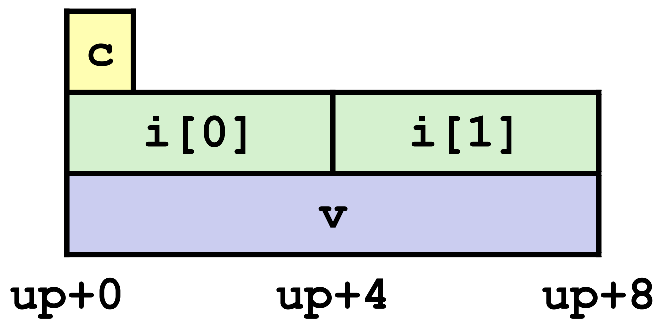
Compound Types in C

- **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

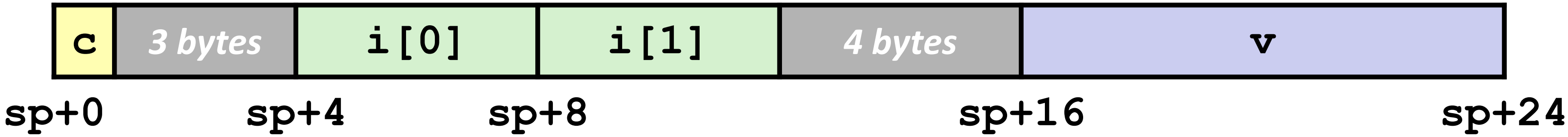
Union Allocation

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

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

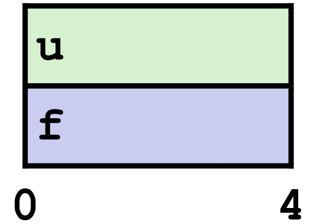



```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```



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` ?

Machine-Level Programming V: Advanced Topics

15-213: Introduction to Computer Systems
9th Lecture, February 14

Instructors:

Seth C. Goldstein, Brandon Lucia, Franz Franchetti, and Brian Railing

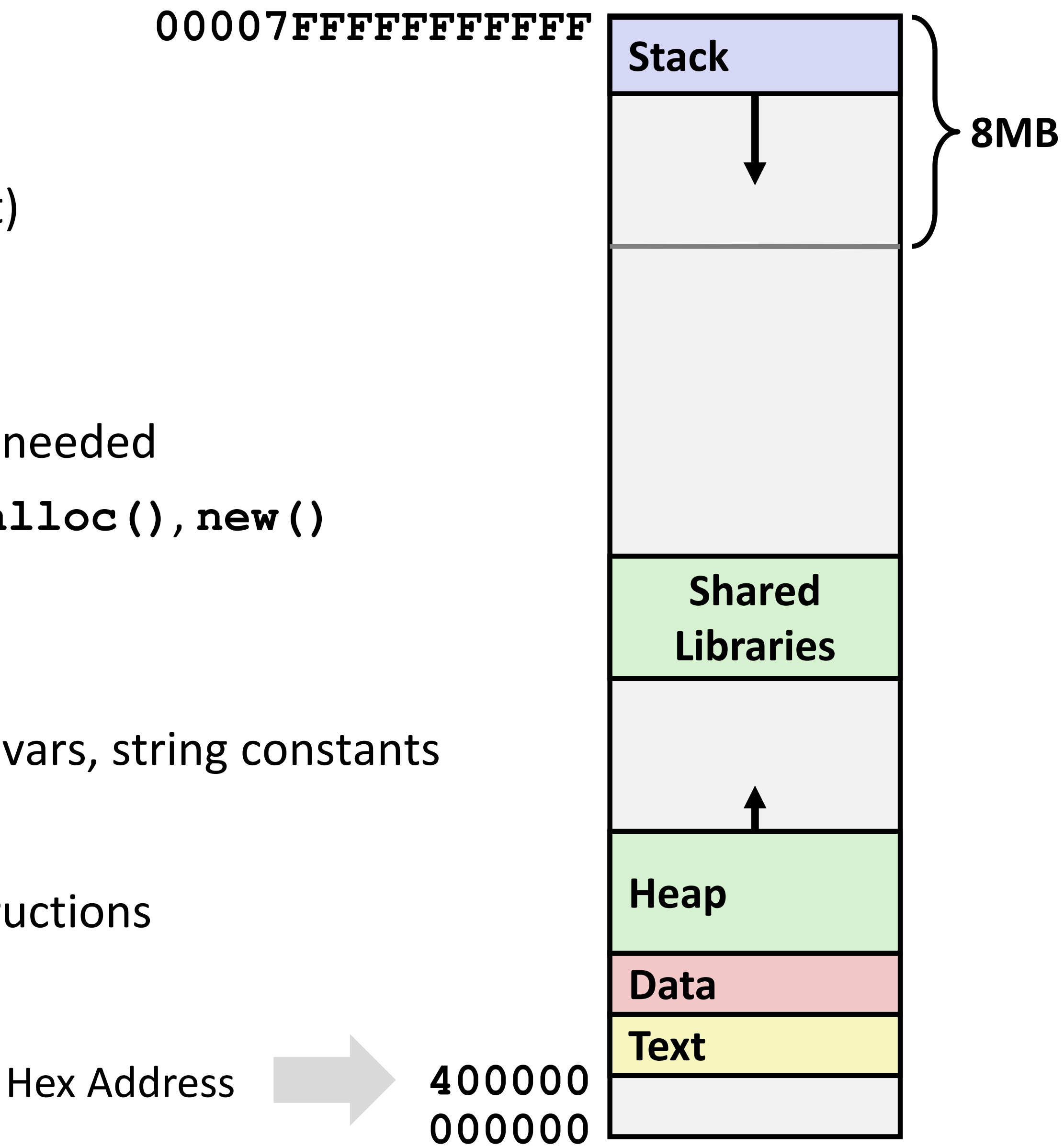
Today

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

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



not drawn to scale

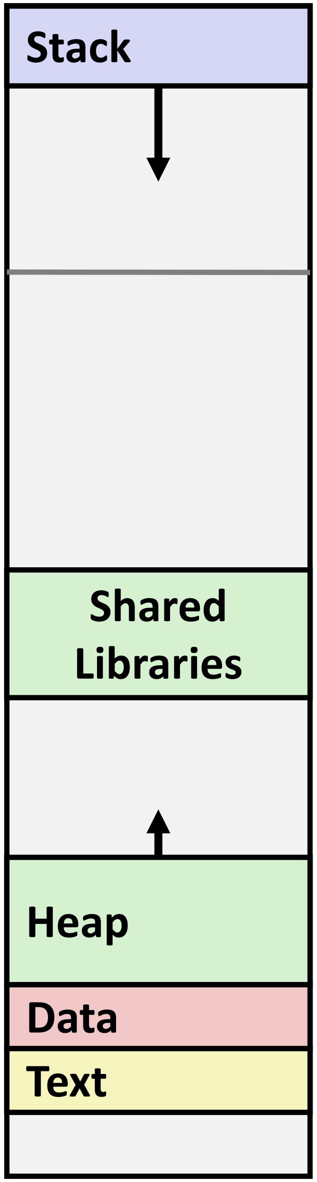
Memory Allocation Example

```
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 ... */
}
```



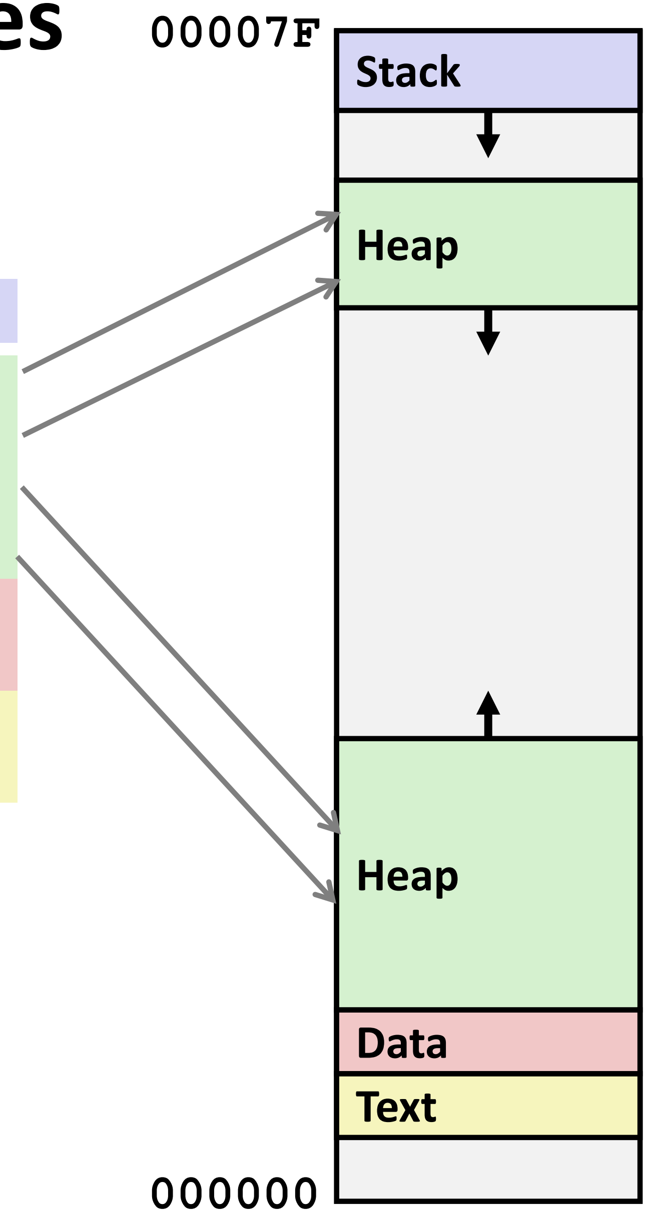
Where does everything go?

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`



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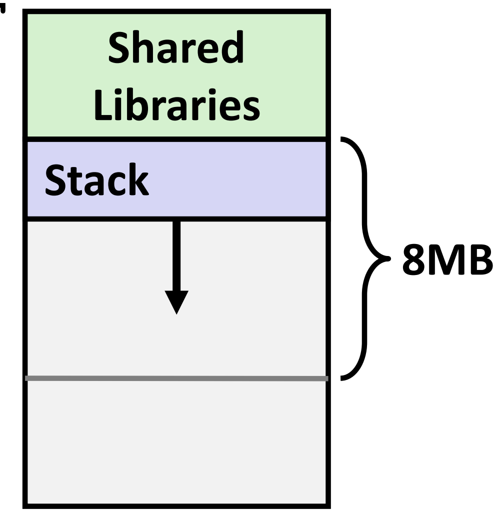
Runaway Stack Example

00007FFFFFFFFFFF




```
int recurse(int x) {
    int a[2<<15];  /* 2~17 =  128 KiB */
    printf("x = %d.  a at %p\n", x, a);
    a[0] = (2<<13)-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 48
x = 48.  a at 0x7fffd43e45d0
x = 47.  a at 0x7fffd43a45c0
x = 46.  a at 0x7fffd43645b0
x = 45.  a at 0x7fffd43245a0
. . .
x = 4.  a at 0x7fffd38e4310
x = 3.  a at 0x7fffd38a4300
x = 2.  a at 0x7fffd38642f0
Segmentation fault
```

Today

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

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
```

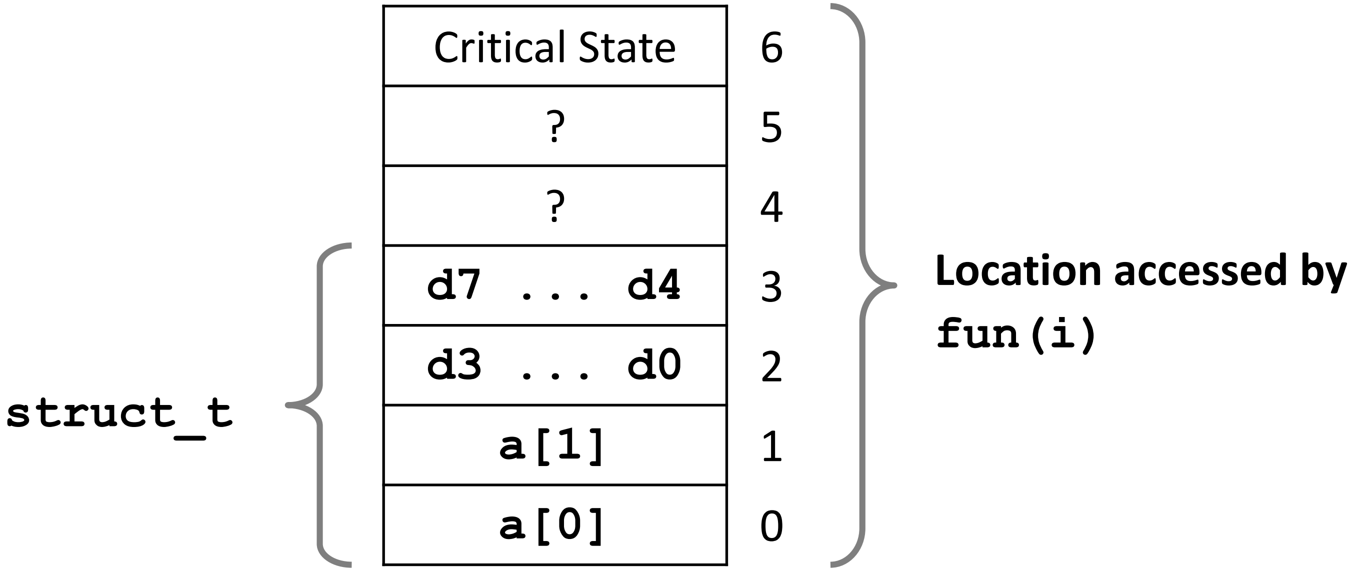
- Result is system specific

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);
}
```

← btw, how big is big enough?

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

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

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

Buffer Overflow Disassembly

echo:

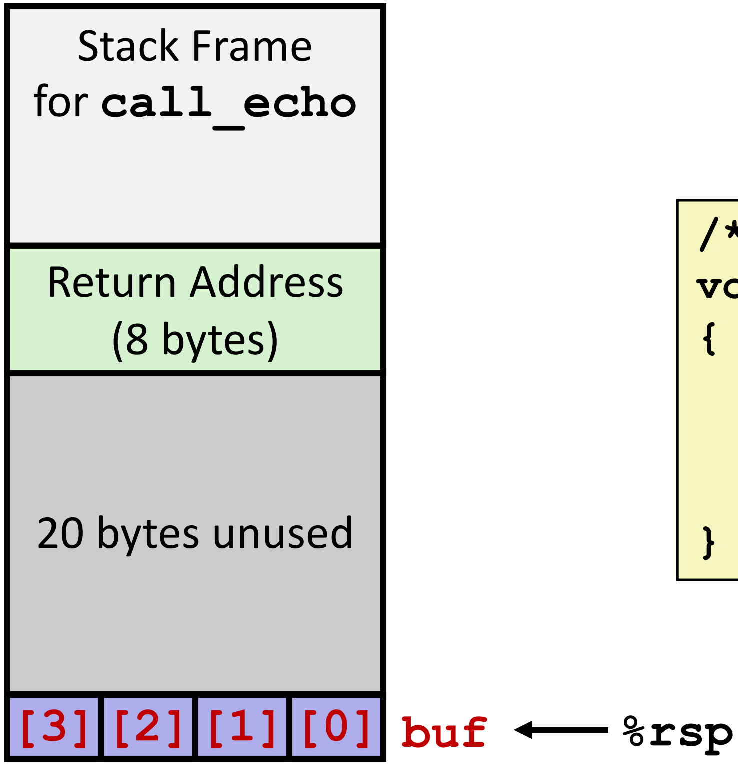
```
0000000004006cf <echo>:
 4006cf:  48 83 ec 18          sub    $0x18,%rsp
 4006d3:  48 89 e7             mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff       callq  400680 <gets>
 4006db:  48 89 e7             mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff       callq  400520 <puts@plt>
 4006e3:  48 83 c4 18          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

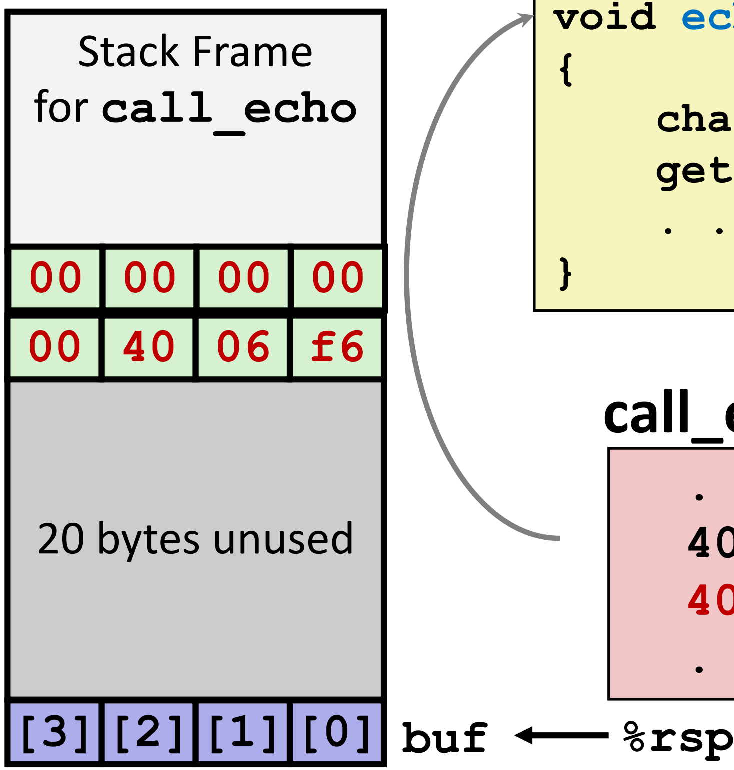



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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   $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
  . . .
```

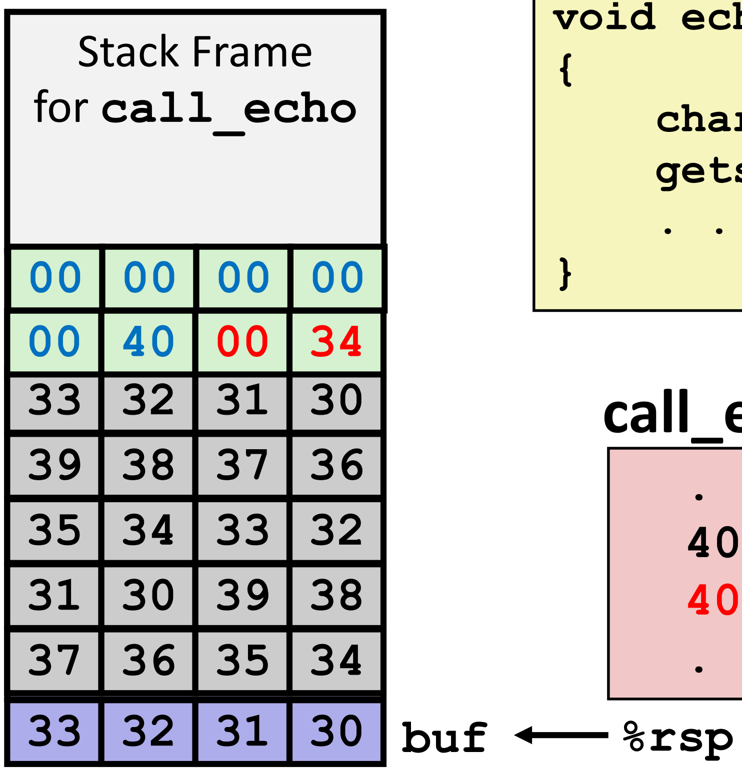
```
unix>./bufdemo-nsp
Type a string:01234567890123456789012
01234567890123456789012
```

"01234567890123456789012\0"

Overflowed buffer, but did not corrupt state

Buffer Overflow Stack Example #2

After 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
. . .
```

```
unix>./bufdemo-nsp
Type a string:012345678901234567890123
4
Segmentation Fault
```

"012345678901234567890123\0"

Overflowed buffer and corrupted return pointer

Stack Smashing Attacks

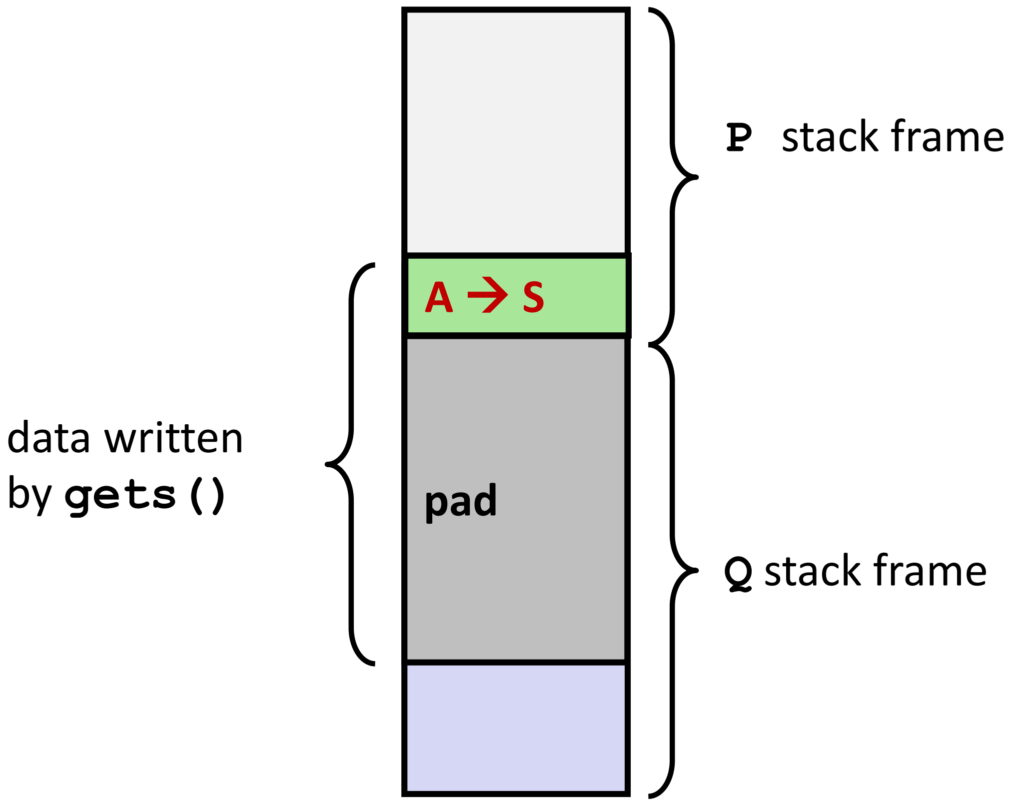
```
void P(){
  Q();
  ...
}
```

return address A

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

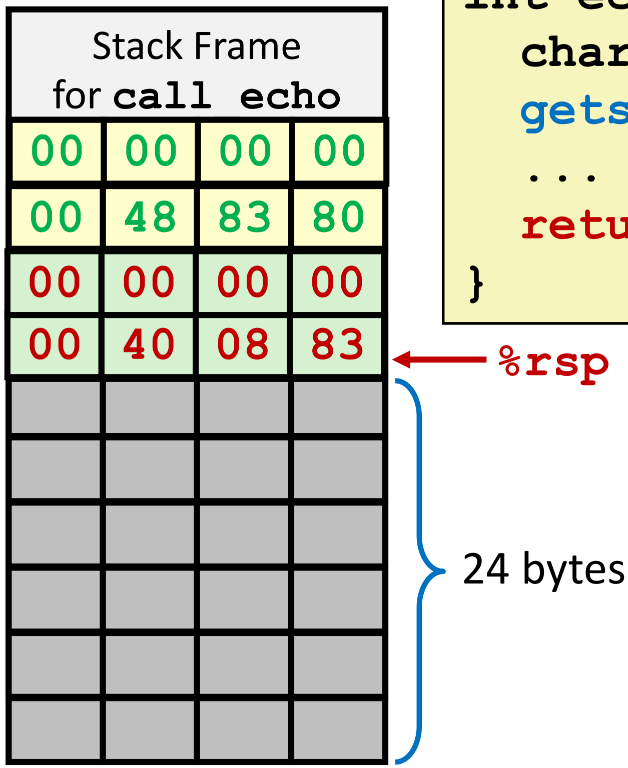
```
void S(){
/* Something
   unexpected */
  ...
}
```

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

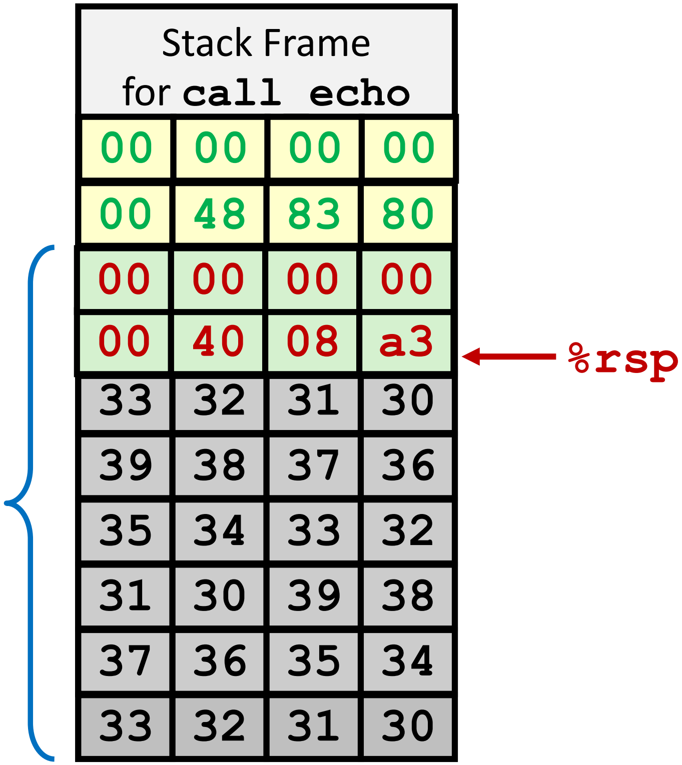
```
void smash() {
   printf("I've been smashed!\n");
   exit(0);
}
```

```
00000000004008a3 <smash>:
  4008a3:         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
a3 08 40 00 00 00 00 00
```

Smashing String Effect



Target Code

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

```
00000000004008a3 <smash>:
  4008a3:        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
a3 08 40 00 00 00 00 00
```

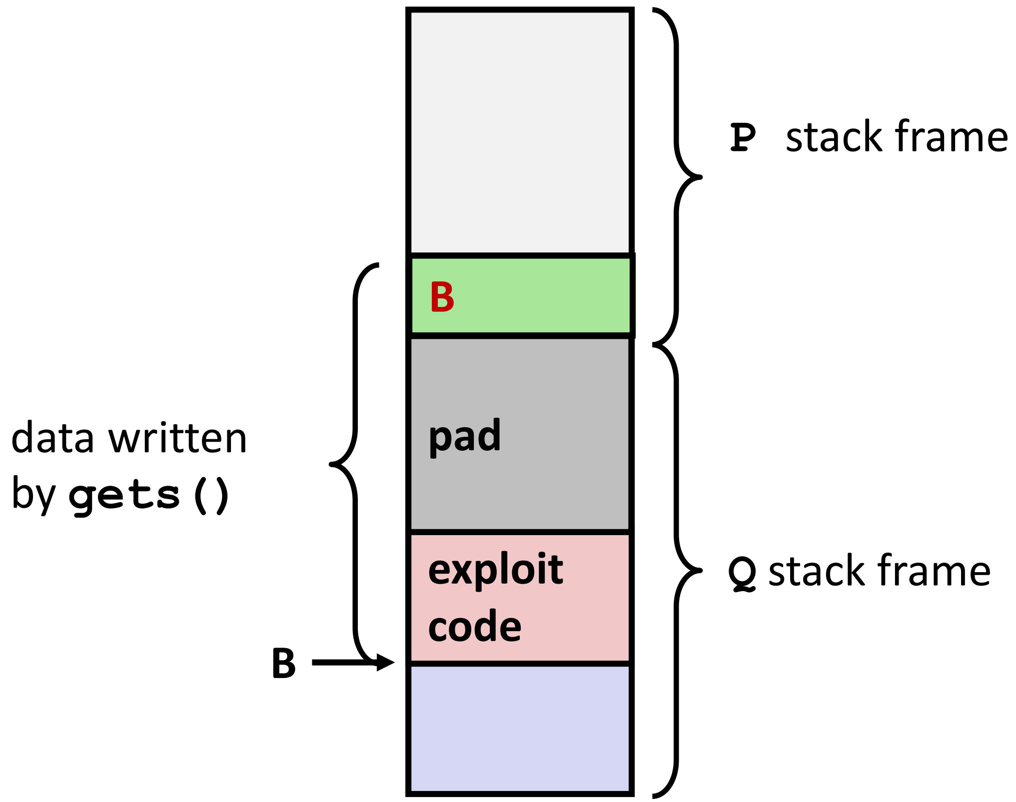
Code Injection Attacks

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

return address A

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

Stack after call to **gets()**

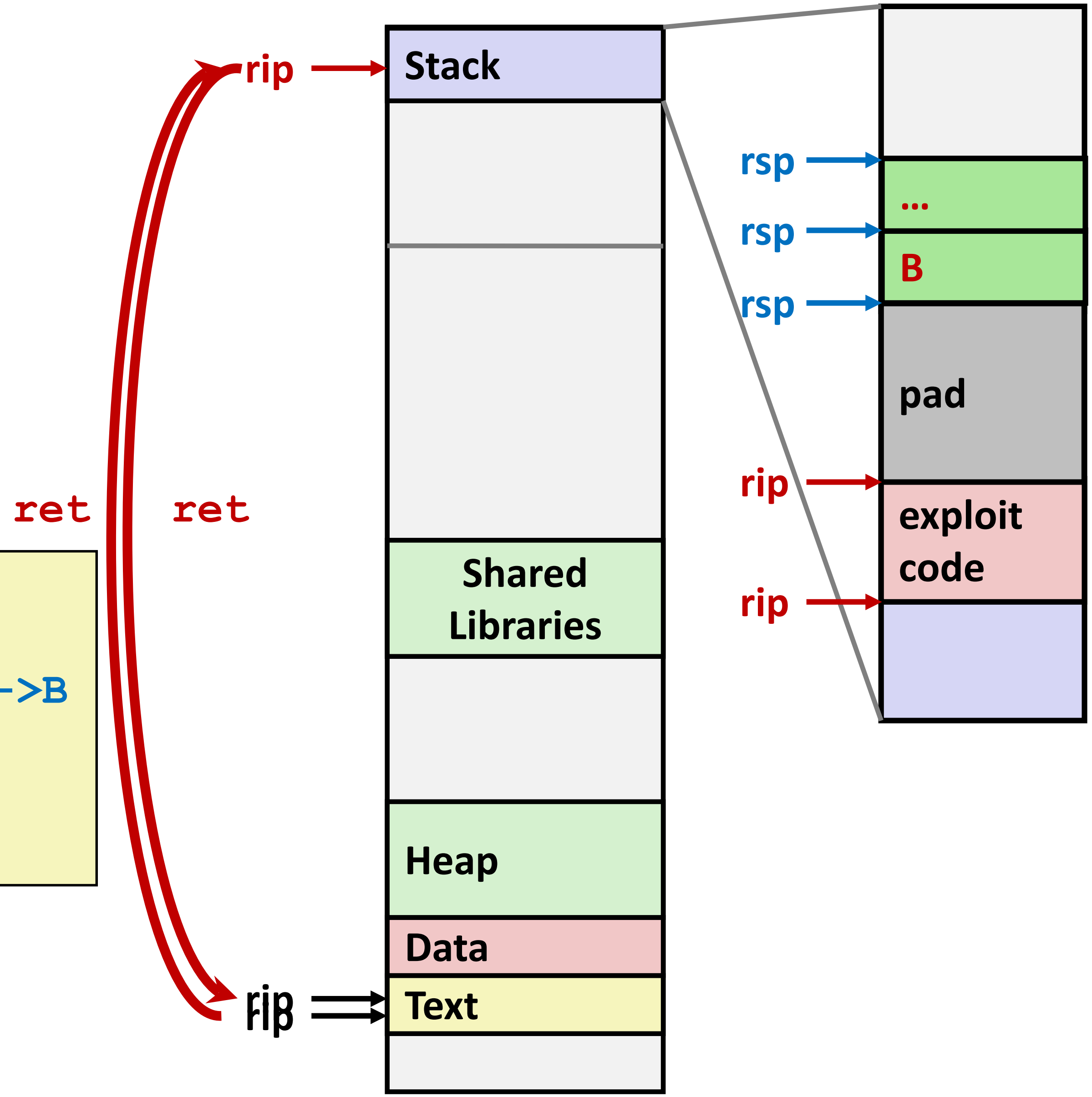


- **Input string contains byte representation of executable code**
- **Overwrite return address A with address of buffer B**
- **When Q executes `ret`, will jump to exploit code**

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);
}
```

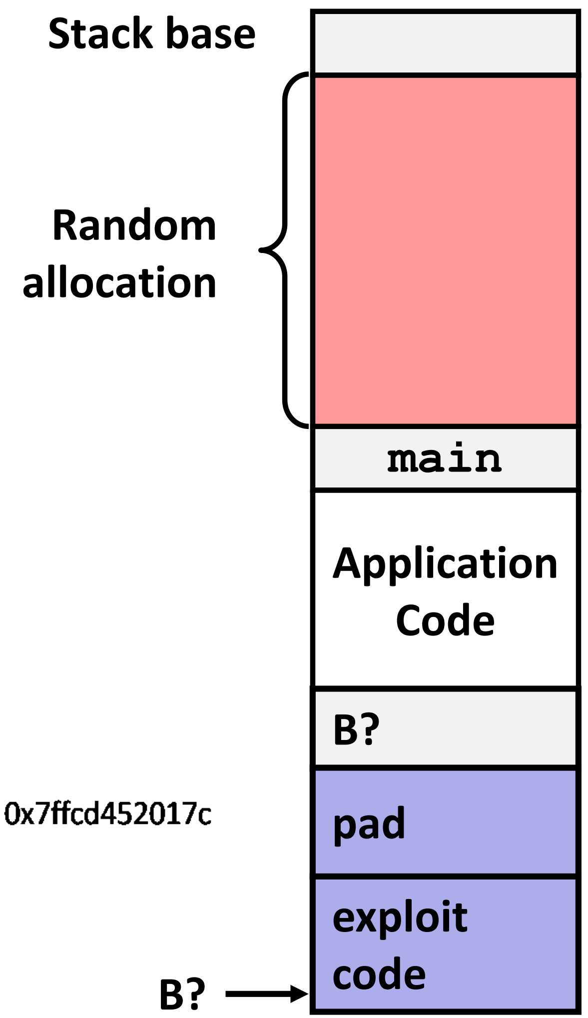
- **For example, use library routines that limit string lengths**
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
  - Don't use `scanf` with `%s` conversion specification
    - Use `fgets` to read the string
    - Or use `%ns` where `n` is a suitable integer

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

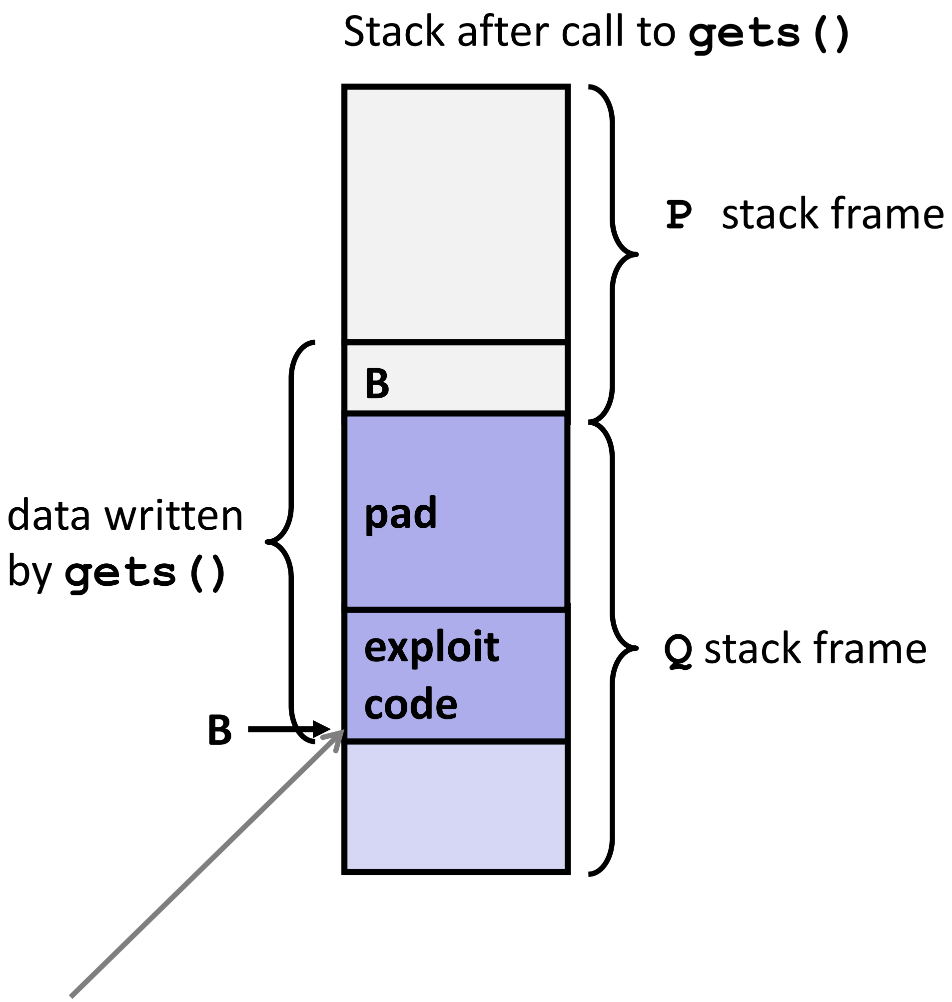
local	0x7ffe4d3be87c	0x7fff75a4f9fc	0x7ffeadb7c80c	0x7ffeaea2fdac	0x7ffcd452017c

  - 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 ***
```

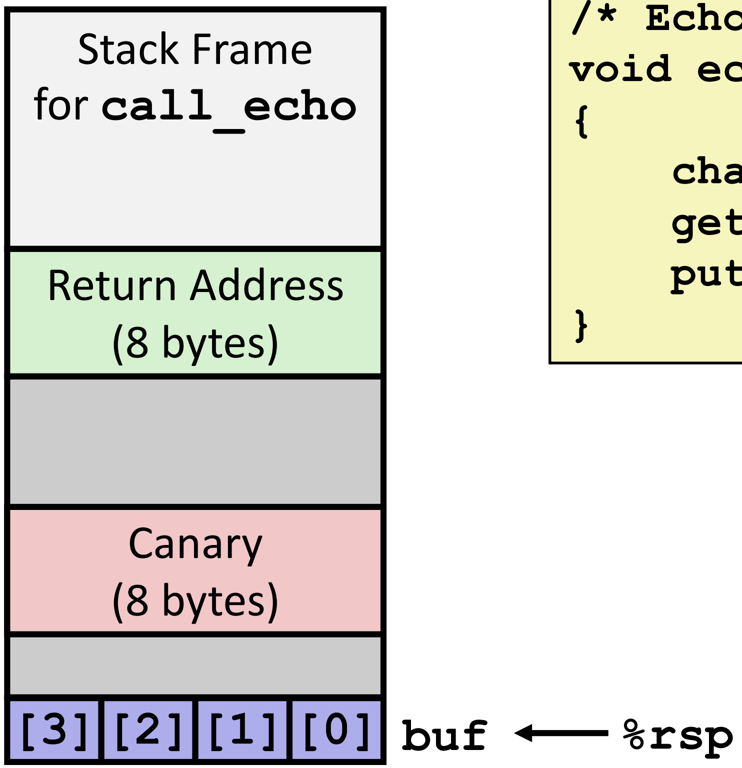
Protected Buffer Disassembly

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

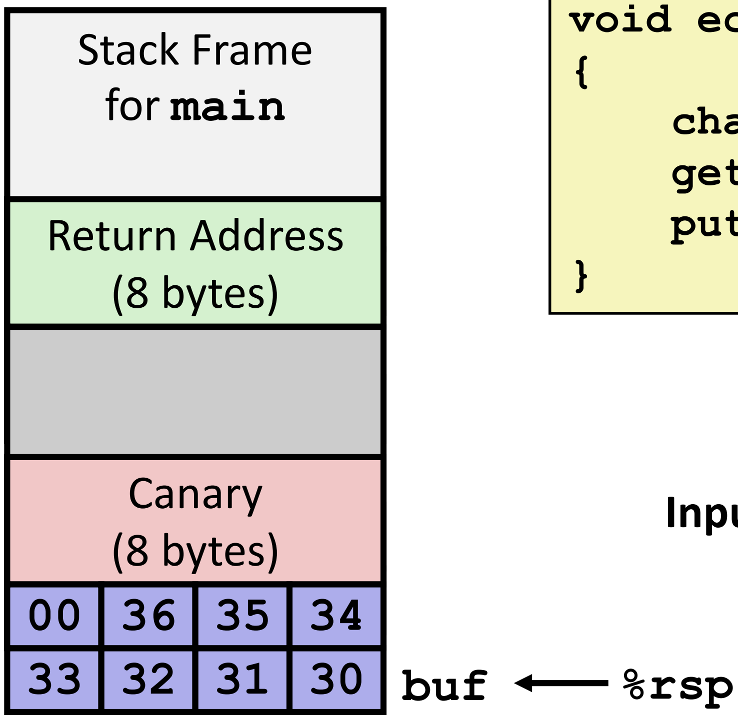



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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




```
/* 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`

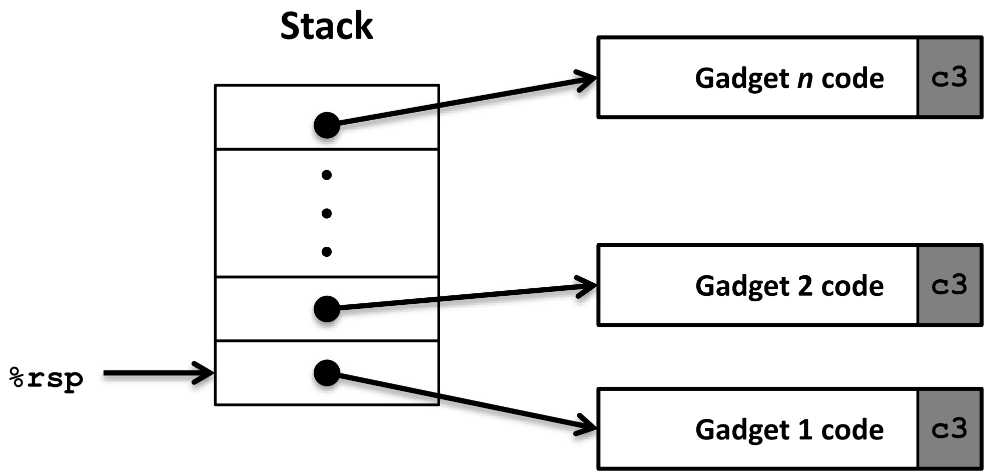
```
<setval>:
  4004d9:  c7 07 d4 48 89 c7  movl  $0xc78948d4,(%rdi)
  4004df:  c3                 retq
```

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

Stack Frame for `call echo`				
00	00	00	00	
00	48	83	80	
00	00	00	00	
00	40	06	f6	← %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	buf

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