CSED211 : Microprocessor & Assembly Programming

Lecture 8: Advanced Topics

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*Disclaimer:
Most slides are taken from author’s lecture slides.

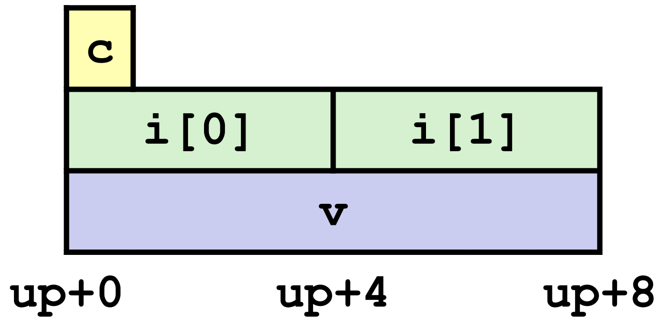
Today

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

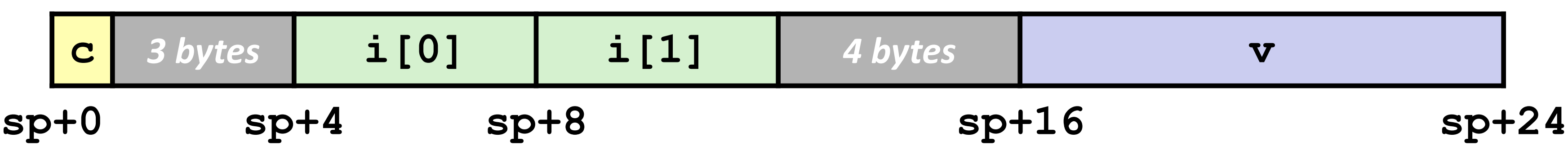
Union Allocation

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

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

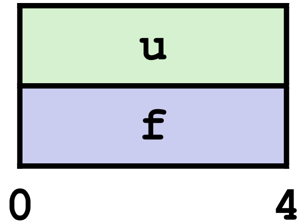



```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```



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 is most (least) significant?
  - Can cause problems when exchanging binary data between machines
- Big Endian
  - Most significant byte has lowest address
  - SPARC
- Little Endian
  - Least significant byte has lowest address
  - Intel x86
- Bi Endian
  - 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?

32-bit

<table>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">i[0]</td><td colspan="4">i[1]</td></tr>
<tr><td colspan="4">l[0]</td><td colspan="4"></td></tr>
</table>

64-bit

<table>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">i[0]</td><td colspan="4">i[1]</td></tr>
<tr><td colspan="8">l[0]</td></tr>
</table>

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

<table>
<tr><td>f0</td><td>f1</td><td>f2</td><td>f3</td><td>f4</td><td>f5</td><td>f6</td><td>f7</td></tr>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">i[0]</td><td colspan="4">i[1]</td></tr>
<tr><td colspan="4">l[0]</td><td colspan="4"></td></tr>
</table>

LSB MSB LSB MSB

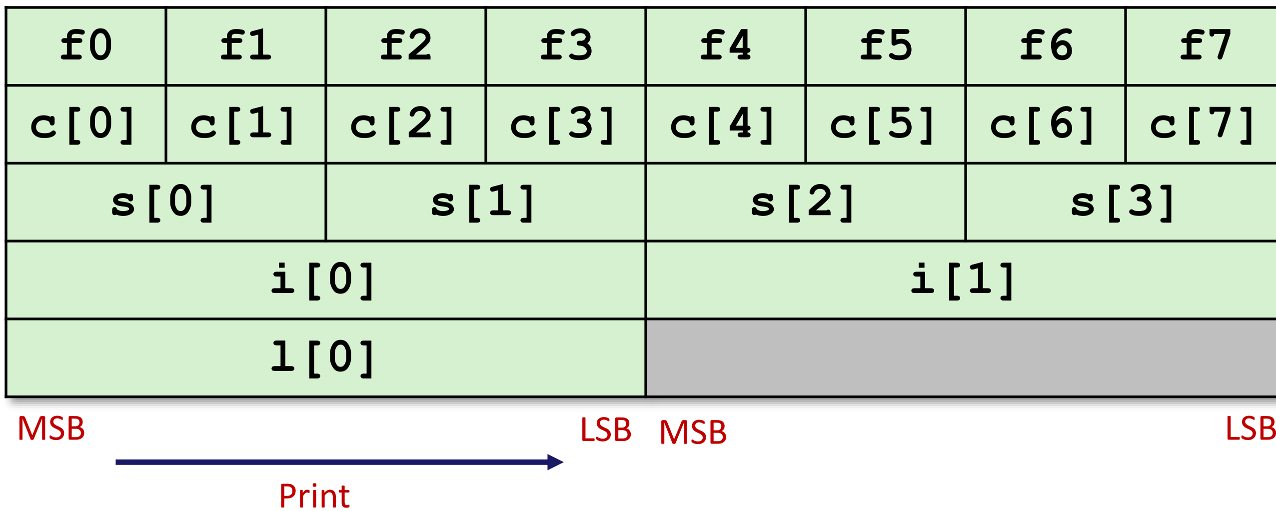
Print

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 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]
```

Byte Ordering on x86-64

Little Endian

<table>
<tr><td>f0</td><td>f1</td><td>f2</td><td>f3</td><td>f4</td><td>f5</td><td>f6</td><td>f7</td></tr>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">i[0]</td><td colspan="4">i[1]</td></tr>
<tr><td colspan="8">l[0]</td></tr>
</table>

LSB ← Print — MSB

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]
```

Summary

- Arrays in C
  - 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

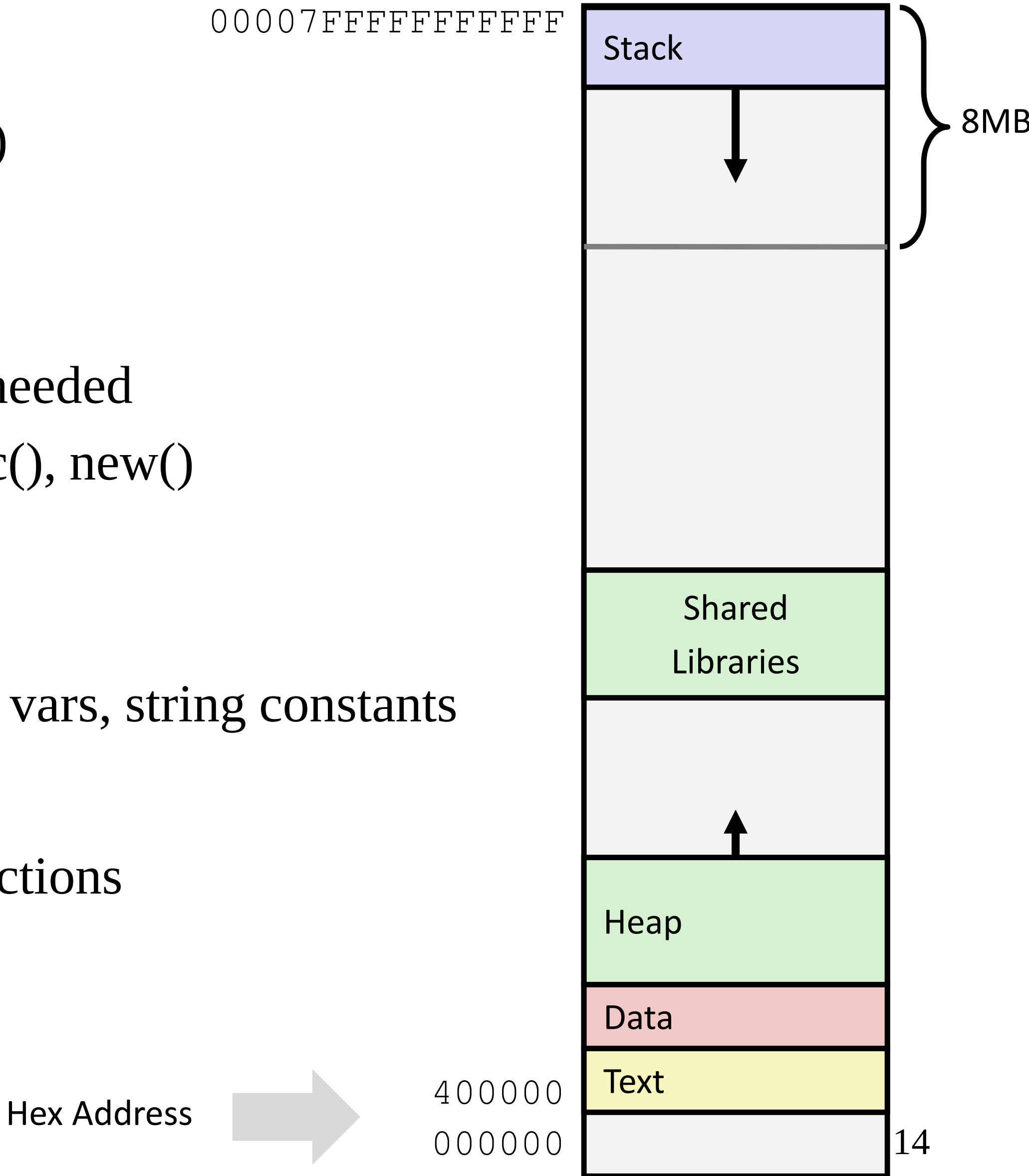
Today

- Unions
- 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

not drawn to scale

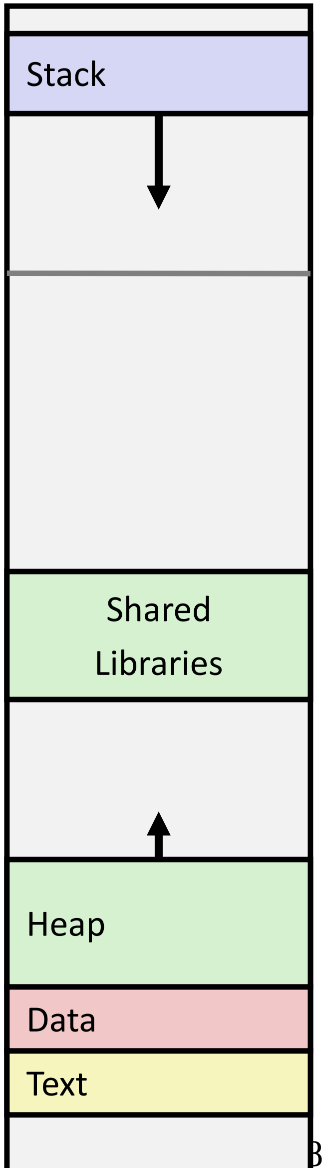
```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

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

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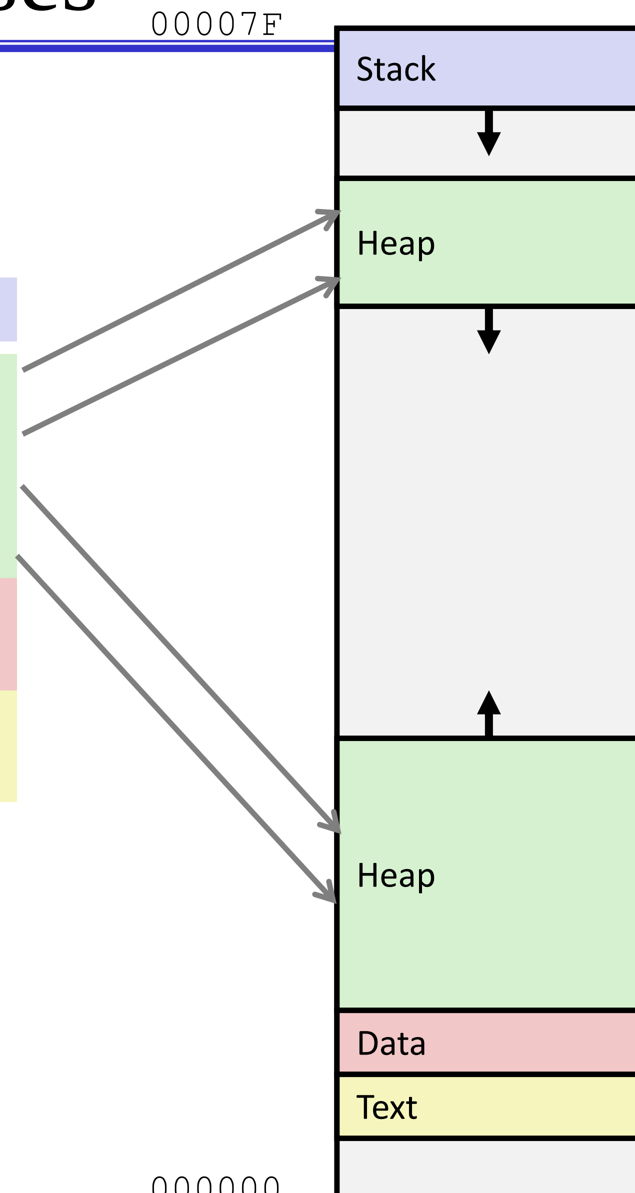
address range ~2^{47}

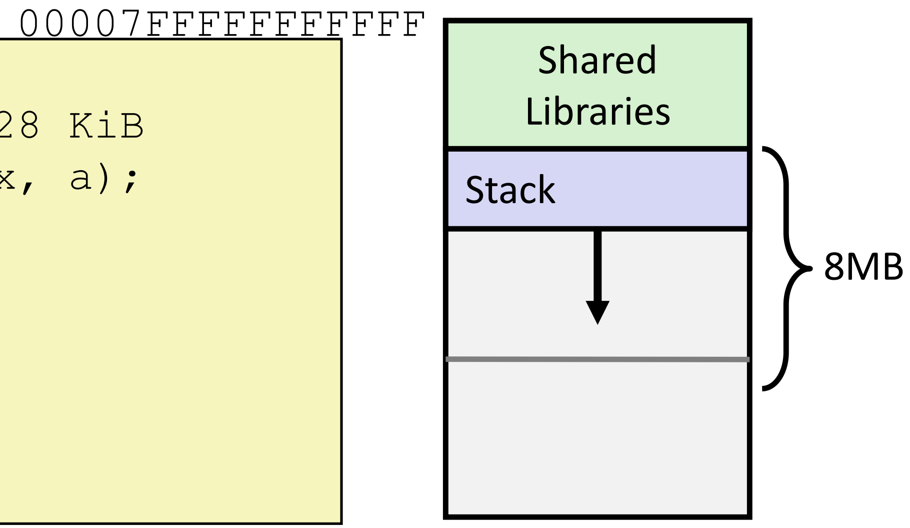
local	0x00007ffe4d3be87c
p1	0x00007f7262a1e010
p3	0x00007f7162a1d010
p4	0x000000008359d120
p2	0x000000008359d010
big_array	0x0000000080601060
huge_array	0x0000000000601060
main()	0x000000000040060c
useless()	0x0000000000400590



not drawn to scale

Runaway Stack Example

```
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

- Unions
- 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:

	Critical State	6
	?	5
	?	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
Type a string:012345678901234567890123
012345678901234567890123
```

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

Buffer Overflow Disassembly

echo:

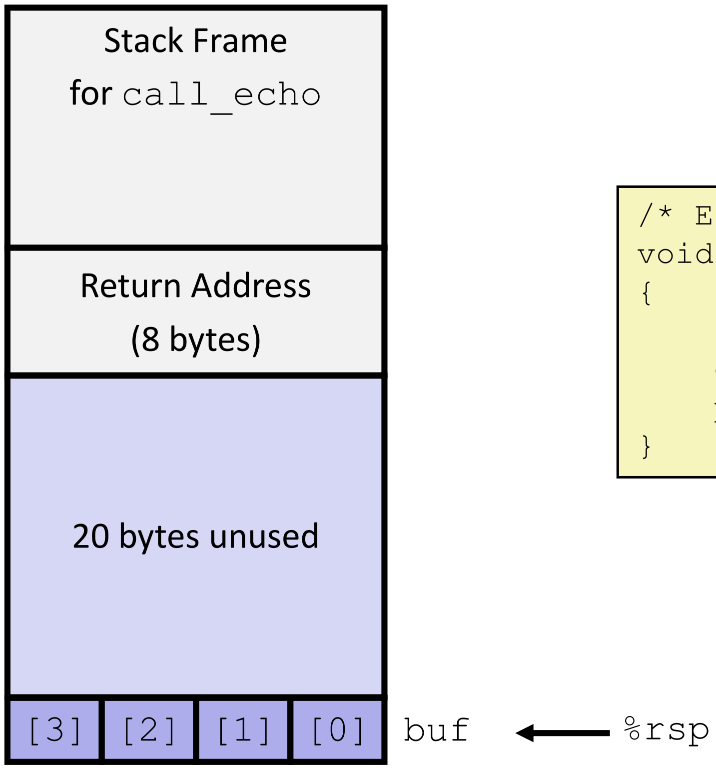
```
0000000000004006cf <echo>:
 4006cf:      48 83 ec 18                 sub    $0x18,%rsp
 4006d3:      48 89 e7                    mov    %rsp,%rdi
 4006d6:      e8 a5 ff ff ff              callq  400680 <gets>
 4006db:      48 89 e7                    mov    %rsp,%rdi
 4006de:      e8 3d fe ff ff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

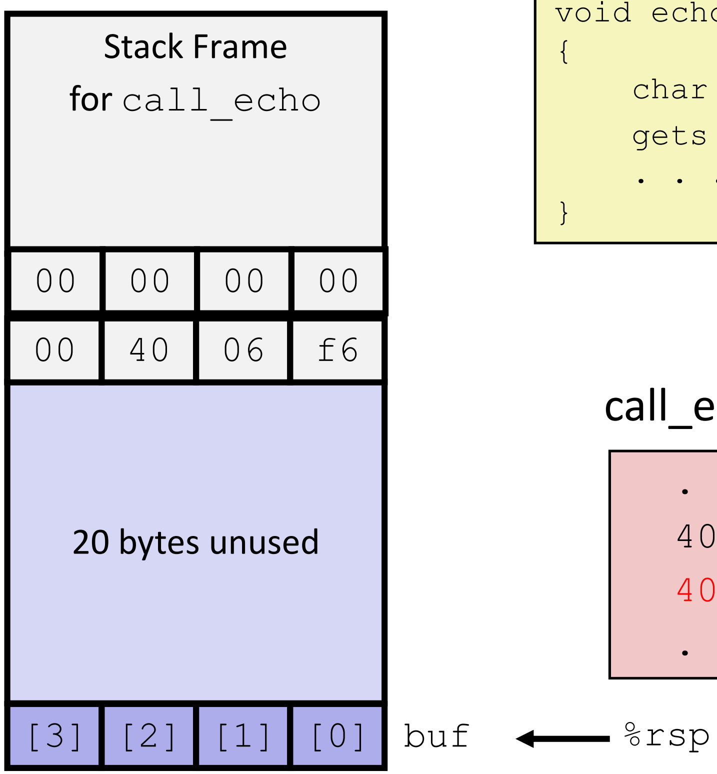



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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
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	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:

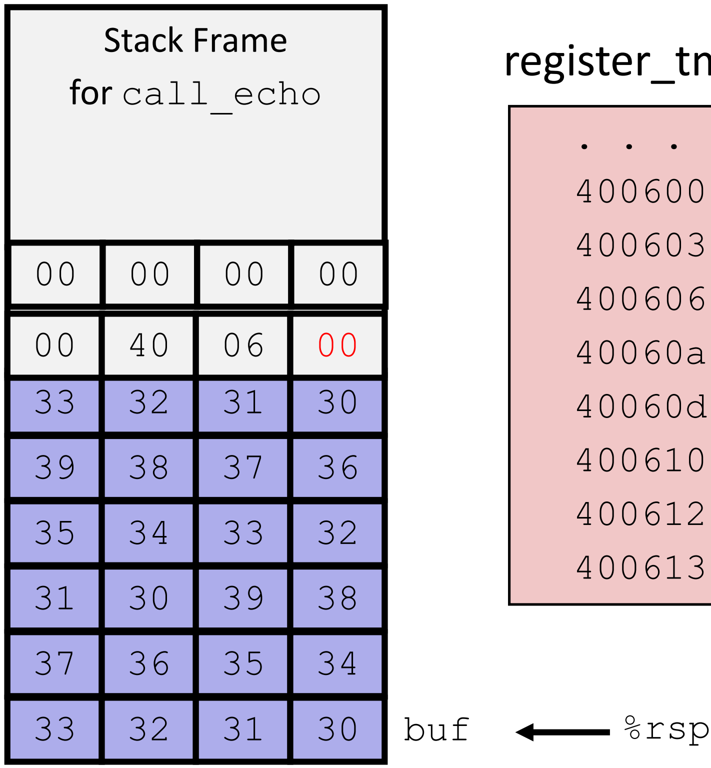
```
  . . .
  4006f1:     callq   4006cf <echo>
  4006f6:     add     $0x8,%rsp
  . . .
```

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

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

Buffer Overflow Stack Example #3 Explained

After call to gets



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`

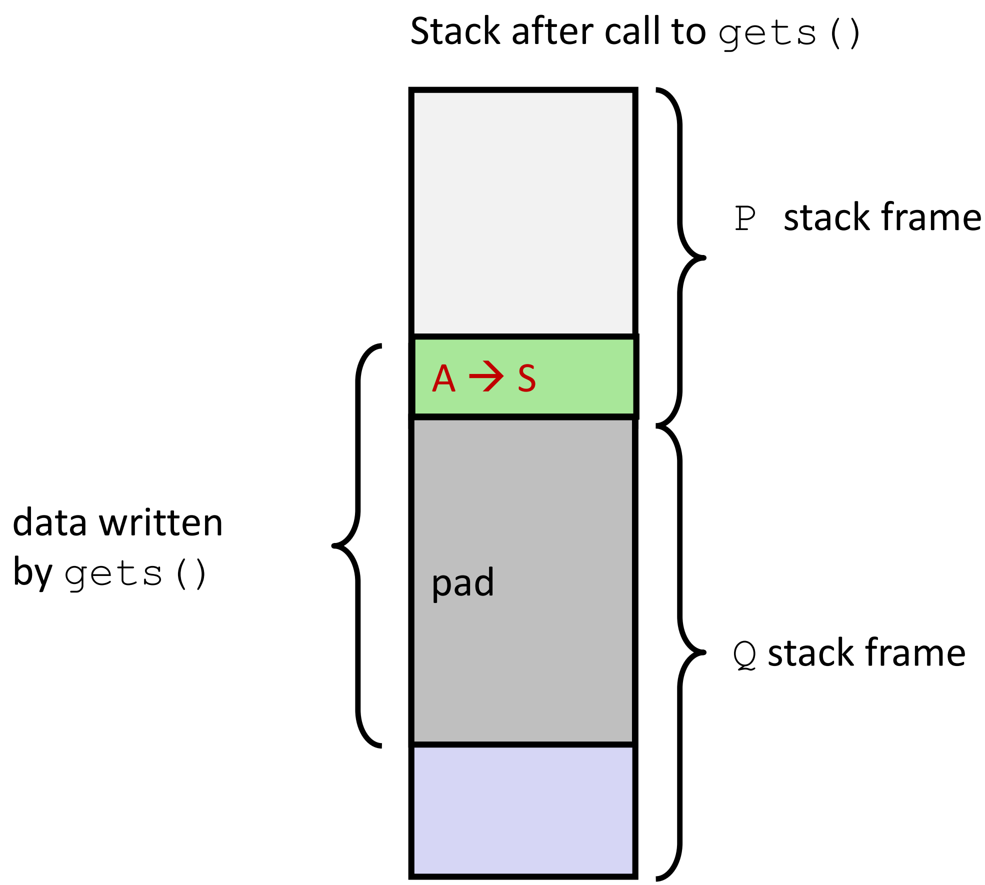
Stack Smashing Attacks

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

return address A

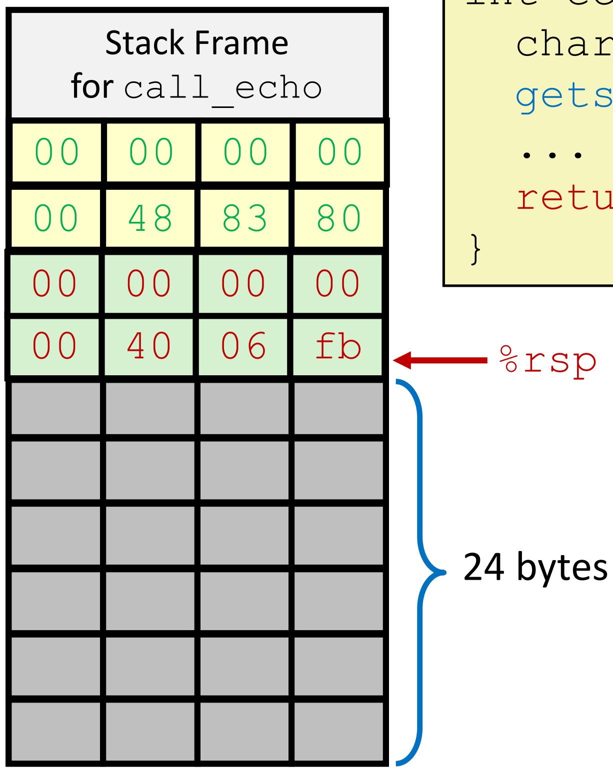
```
int Q() {
  char buf[64];
  gets(buf);
  ...
  return ...;
}
```

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



- 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
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

%rsp

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
```

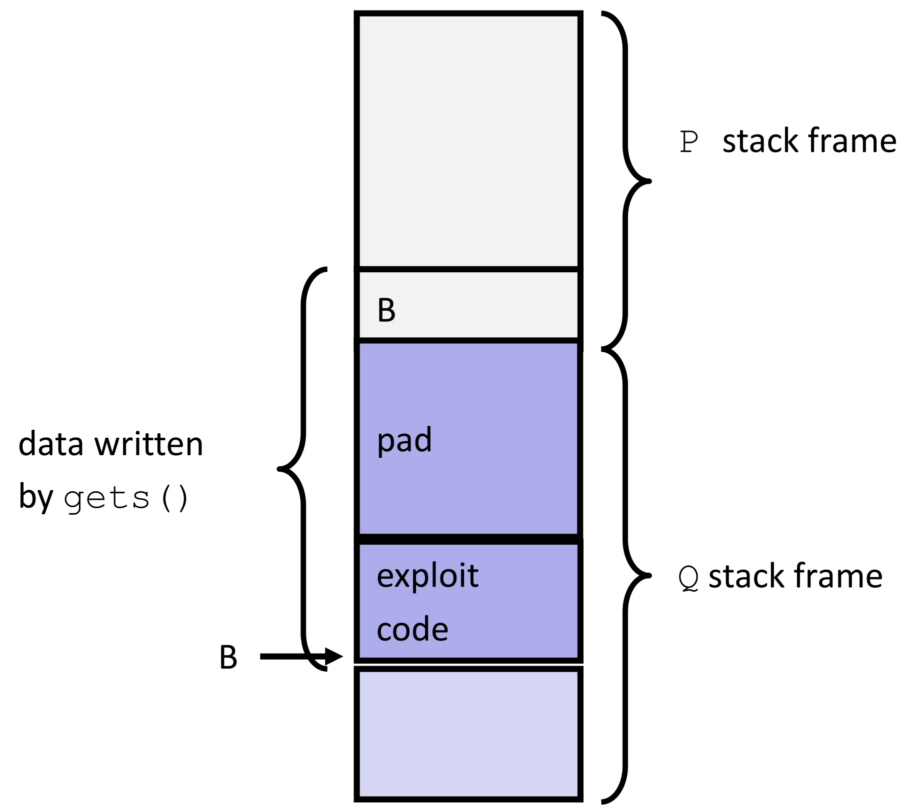
Code Injection Attacks

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

return address A

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

Stack after call to `gets()`

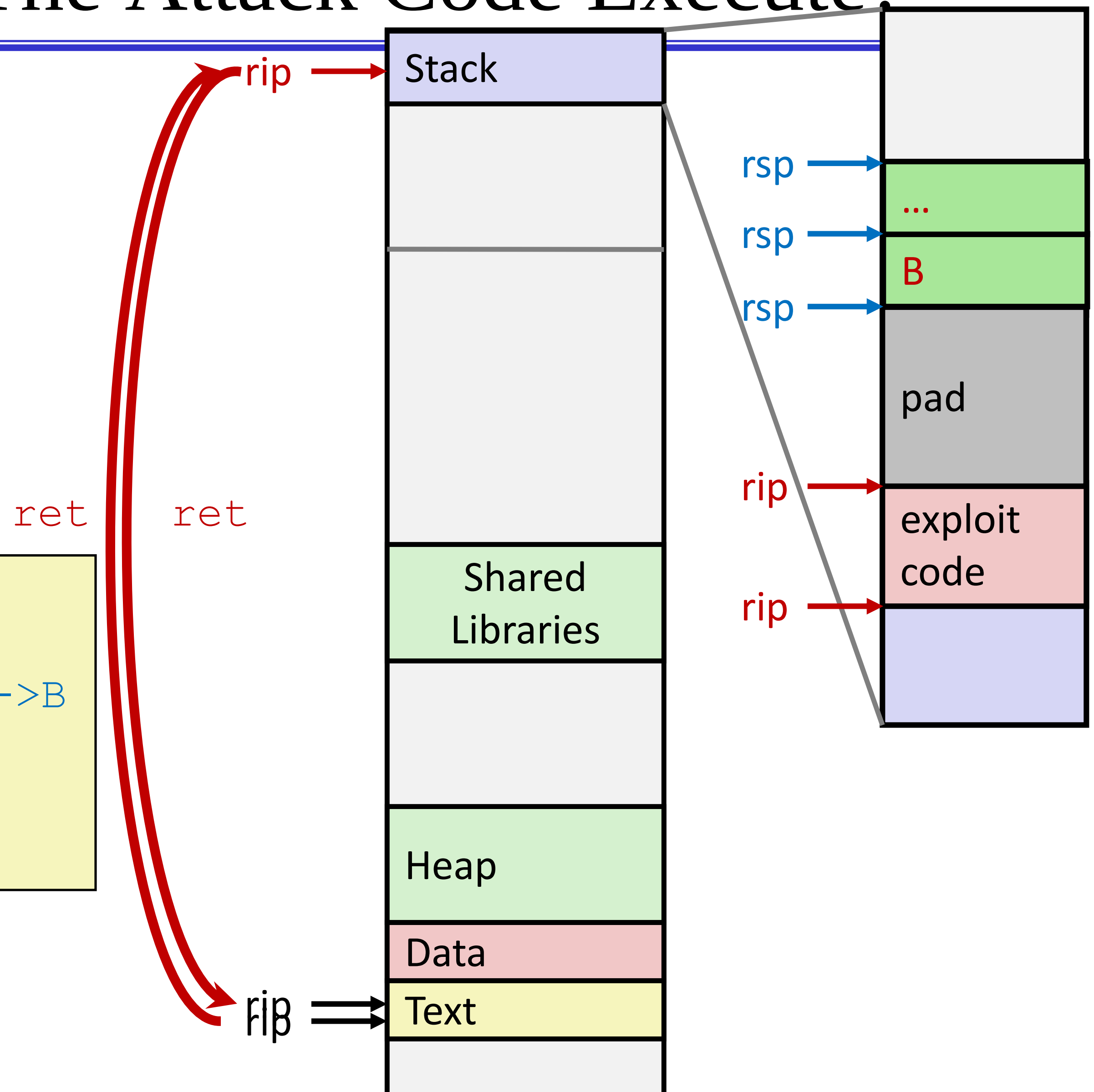


- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer B
- When `Q()` executes `ret`, will jump to exploit code

How Does The Attack Code Execute?

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

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



Exploits Based on Buffer Overflows

- *Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines*
- Distressingly common in real progams
  - 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!!

OK, 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);
}
```

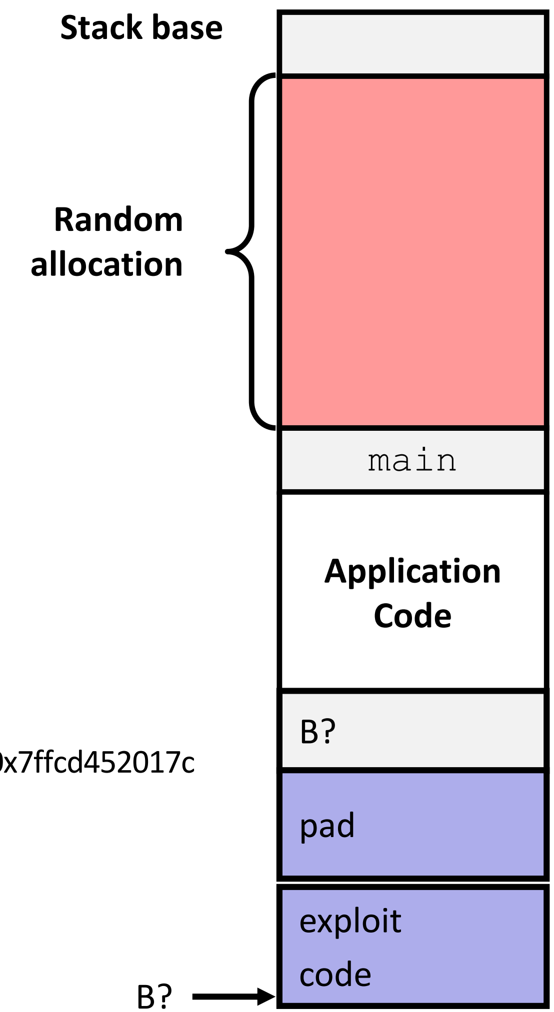
- For example, use library routines that limit string lengths
  - **`fgets`** instead of **`gets`**
  - **`strncpy`** instead of **`strcpy`**
  - Don't use **`scanf`** with **`%s`** conversion specification
    - Use **`fgets`** to read the string
    - Or use **`%ns`** where **`n`** is a suitable integer

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

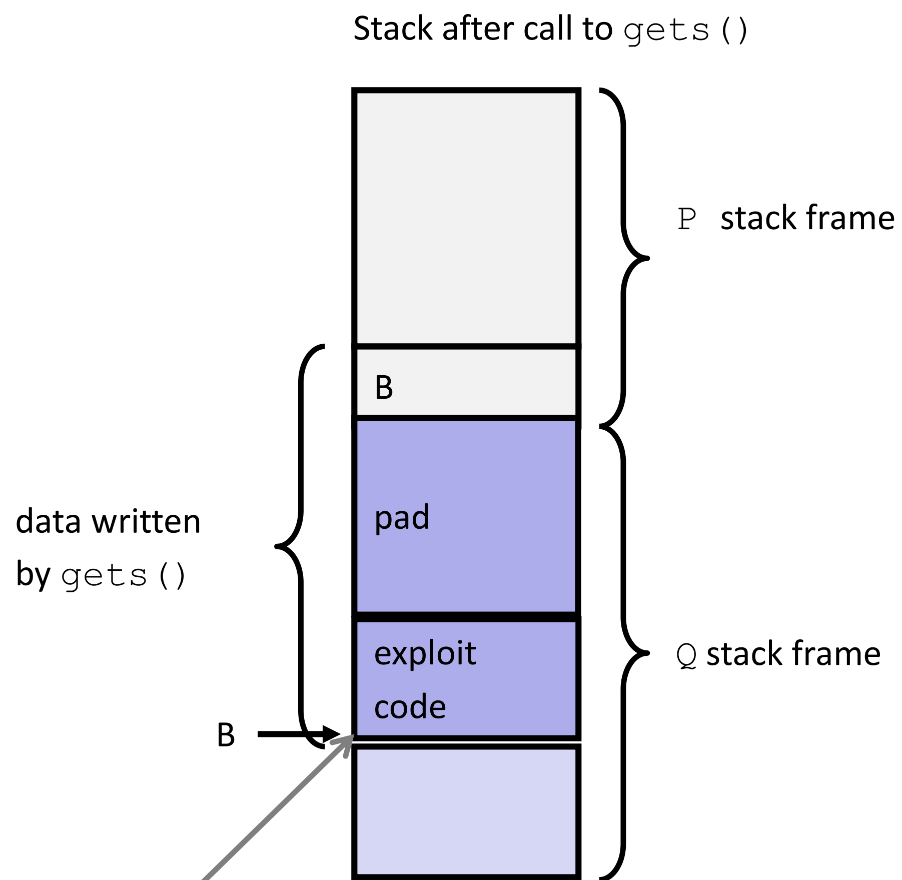
local	0x7ffe4d3be87c	0x7fff75a4f9fc	0x7ffeadb7c80c	0x7ffeaea2fdac	0x7ffcd452017c

  - 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-protected
Type a string:0123456
0123456
```

```
unix>./bufdemo-protected
Type a string:01234567
*** stack smashing detected ***
```

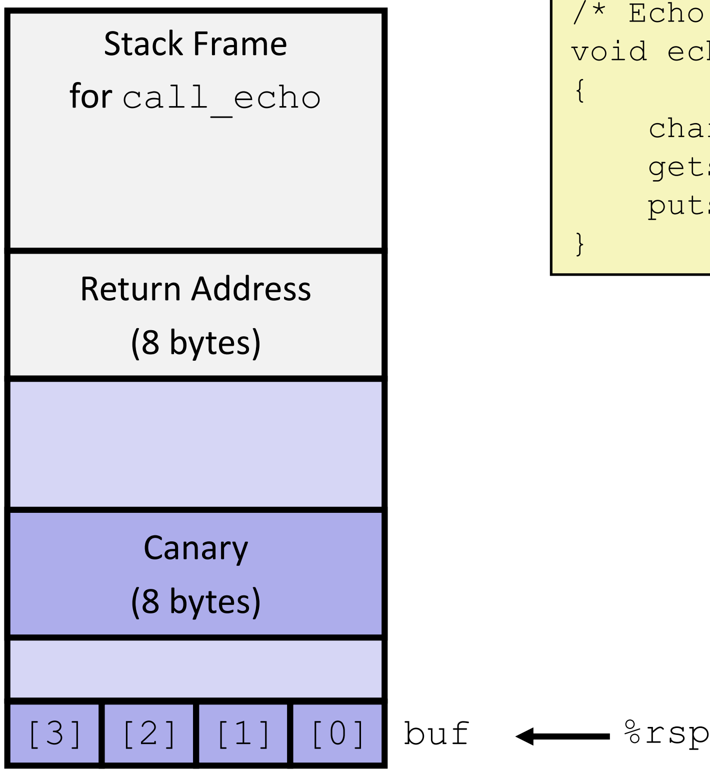
Protected Buffer Disassembly

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

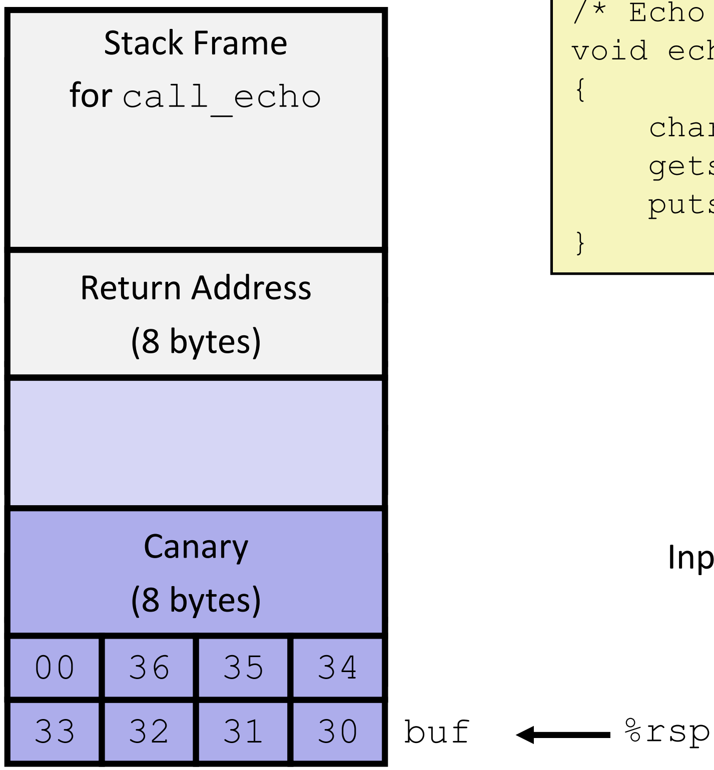



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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



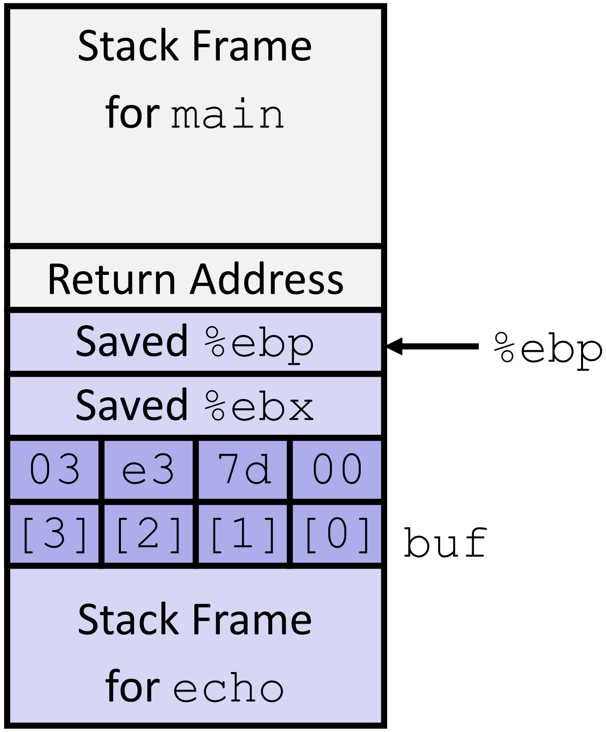

```
/* Echo Line */
void echo()
{
    char buf[4];   /* Way too small! */
    gets(buf);
    puts(buf);
}
```

Input: *0123456*

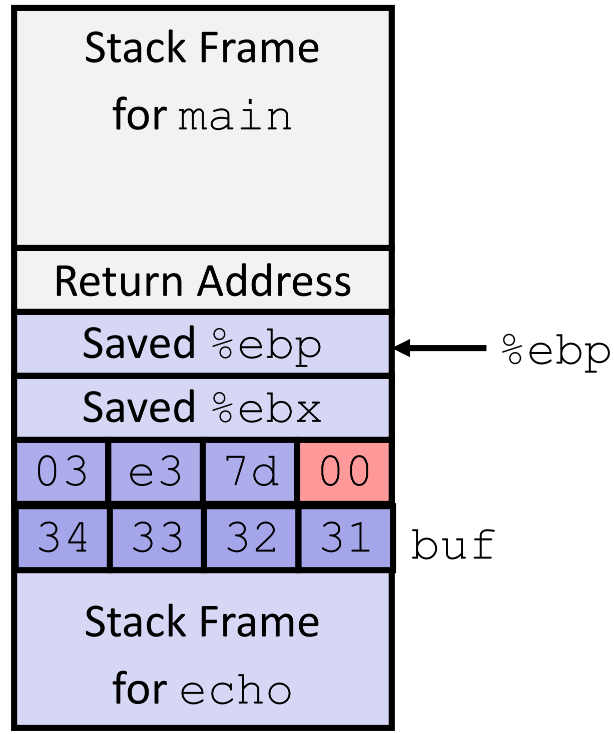
```
echo:
    . . .
    movq        8(%rsp), %rax      # Retrieve from stack
    xorq        %fs:40, %rax       # Compare to canary
    je          .L6                # If same, OK
    call        __stack_chk_fail   # FAIL
.L6: . . .
```

Canary Example

Before call to gets



Input 1234




```
(gdb) break echo
(gdb) run
(gdb) stepi 3
(gdb) print /x *((unsigned *) $ebp - 2)
$1 = 0x3e37d00
```

Benign corruption!

(allows programmers to make silent off-by-one errors)

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`

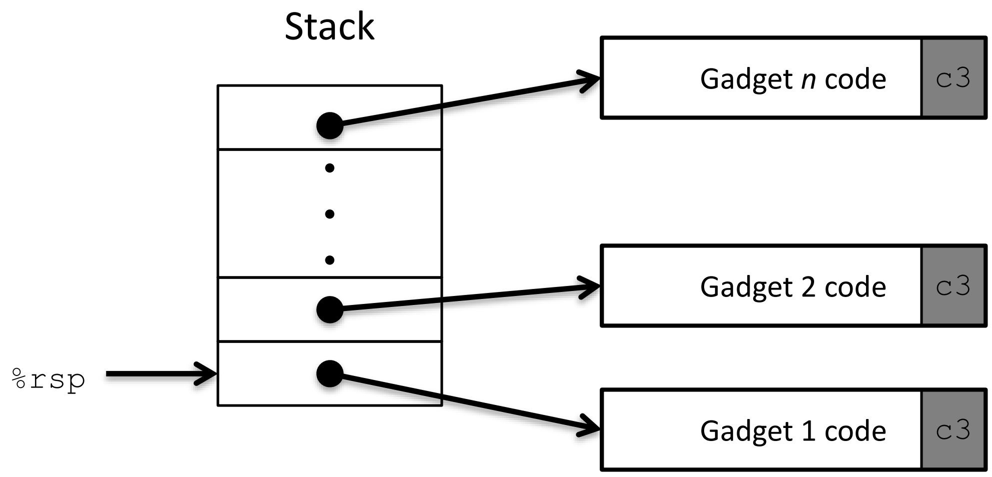
```
<setval>:
  4004d9:  c7 07 d4 48 89 c7  movl   $0xc78948d4,(%rdi)
  4004df:  c3                 retq
```

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