Machine-Level Programming V: Advanced Topics

15-213/15-513: Introduction to Computer Systems
8th Lecture, June 1, 2023

Instructors:

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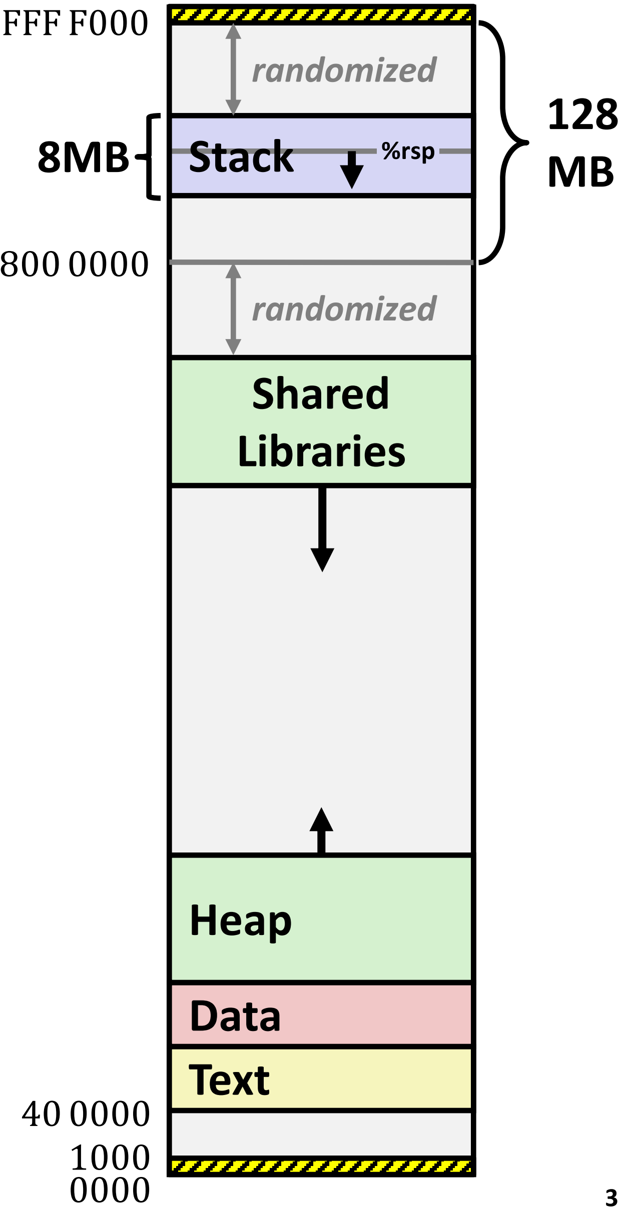
Today

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

x86-64 Linux Memory Layout

not drawn to scale

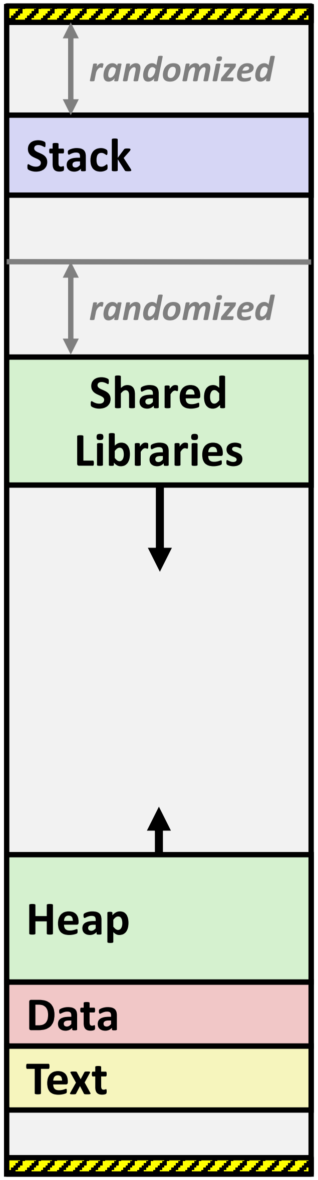
- **Stack**
  - Runtime stack (8MB limit)
  - e.g., local variables
- **Heap**
  - Dynamically allocated as needed
  - When call **`malloc()`**, **`calloc()`**, **`new()`**
- **Data**
  - Statically allocated data
  - e.g., global vars, **`static`** vars, string constants
- **Text / Shared Libraries**
  - 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 ... */
}
```

not drawn to scale



Where does everything go?

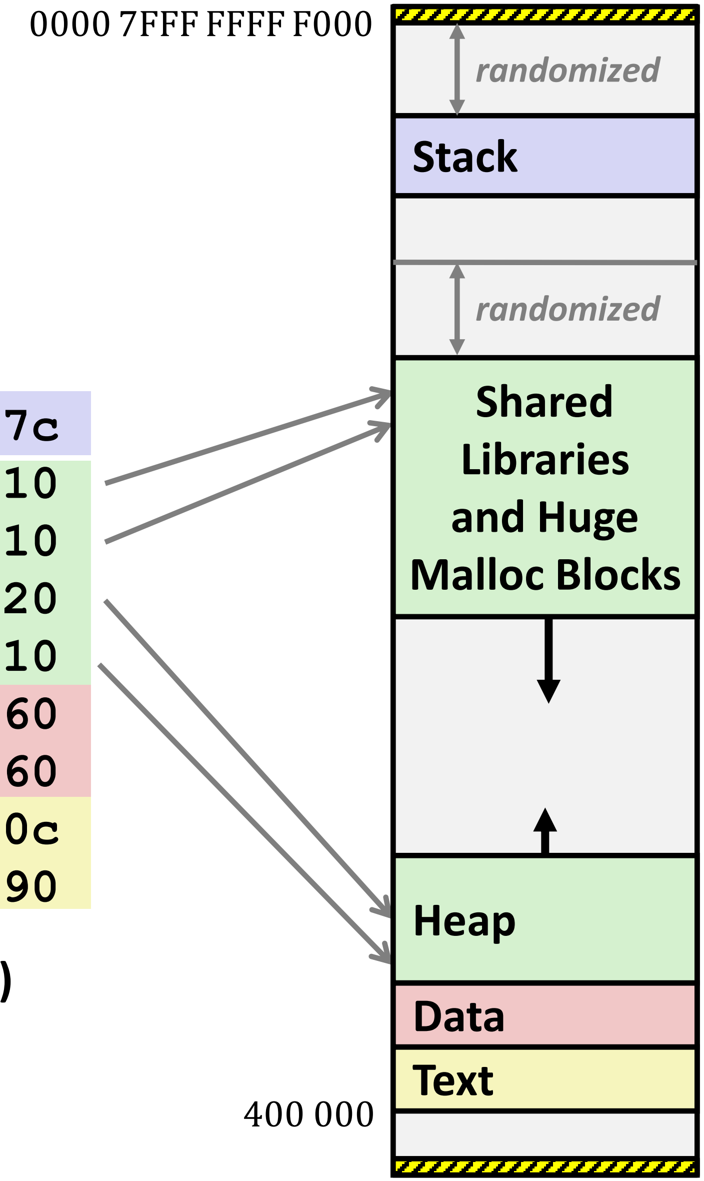
x86-64 Example Addresses

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)

not drawn to scale



Today

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

https://canvas.cmu.edu/courses/34989/assignments/596855

Do parts 1 and 2 of the activity (getting started, gets())

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
```

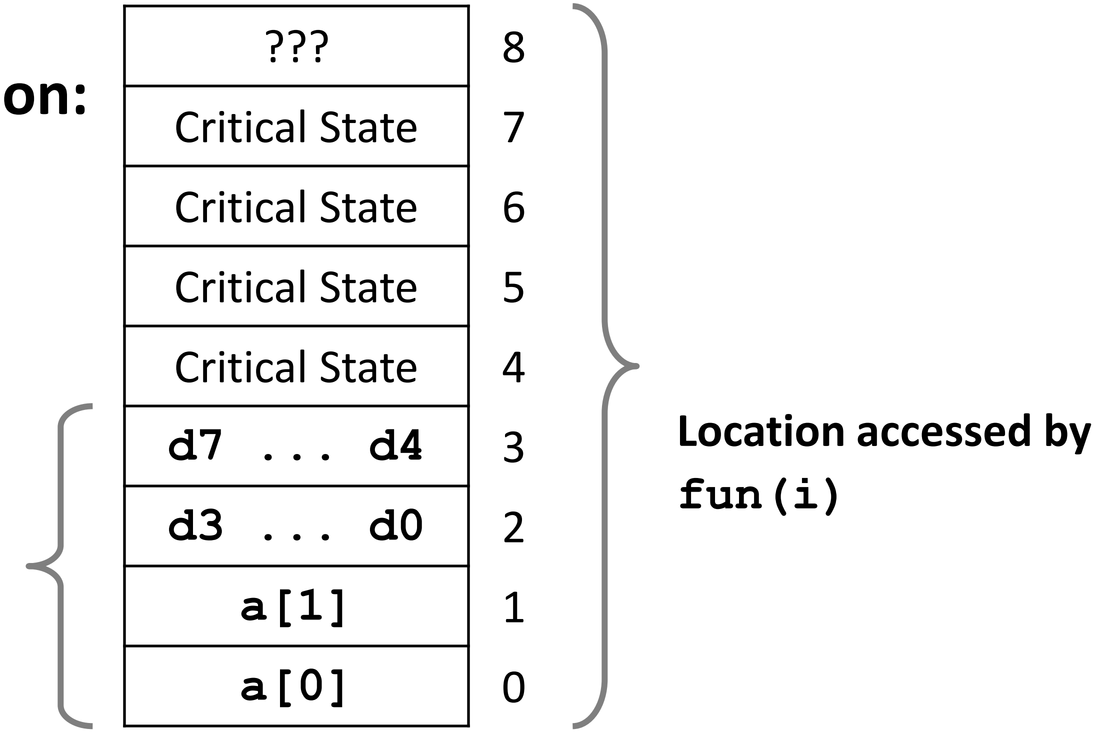
- Result is system specific

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
d7 ... d4	3
d3 ... d0	2
a[1]	1
a[0]	0

`struct_t`

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:01234567890123456789012
01234567890123456789012
```

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

Buffer Overflow Disassembly

echo:

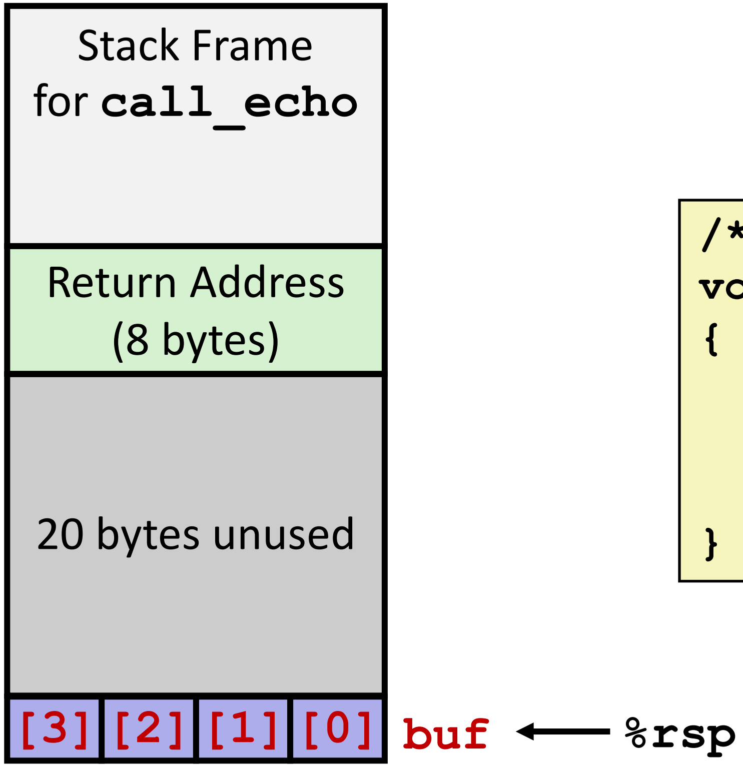
```
000000000040069c <echo>:
 40069c:  48 83 ec 18                 sub    $0x18,%rsp
 4006a0:  48 89 e7                    mov    %rsp,%rdi
 4006a3:  e8 a5 ff ff ff              callq  40064d <gets>
 4006a8:  48 89 e7                    mov    %rsp,%rdi
 4006ab:  e8 50 fe ff ff              callq  400500 <puts@plt>
 4006b0:  48 83 c4 18                 add    $0x18,%rsp
 4006b4:  c3                          retq
```

call_echo:

```
 4006b5:  48 83 ec 08                 sub    $0x8,%rsp
 4006b9:  b8 00 00 00 00              mov    $0x0,%eax
 4006be:  e8 d9 ff ff ff              callq  40069c <echo>
 4006c3:  48 83 c4 08                 add    $0x8,%rsp
 4006c7:  c3                          retq
```

Buffer Overflow Stack Example

Before call to gets

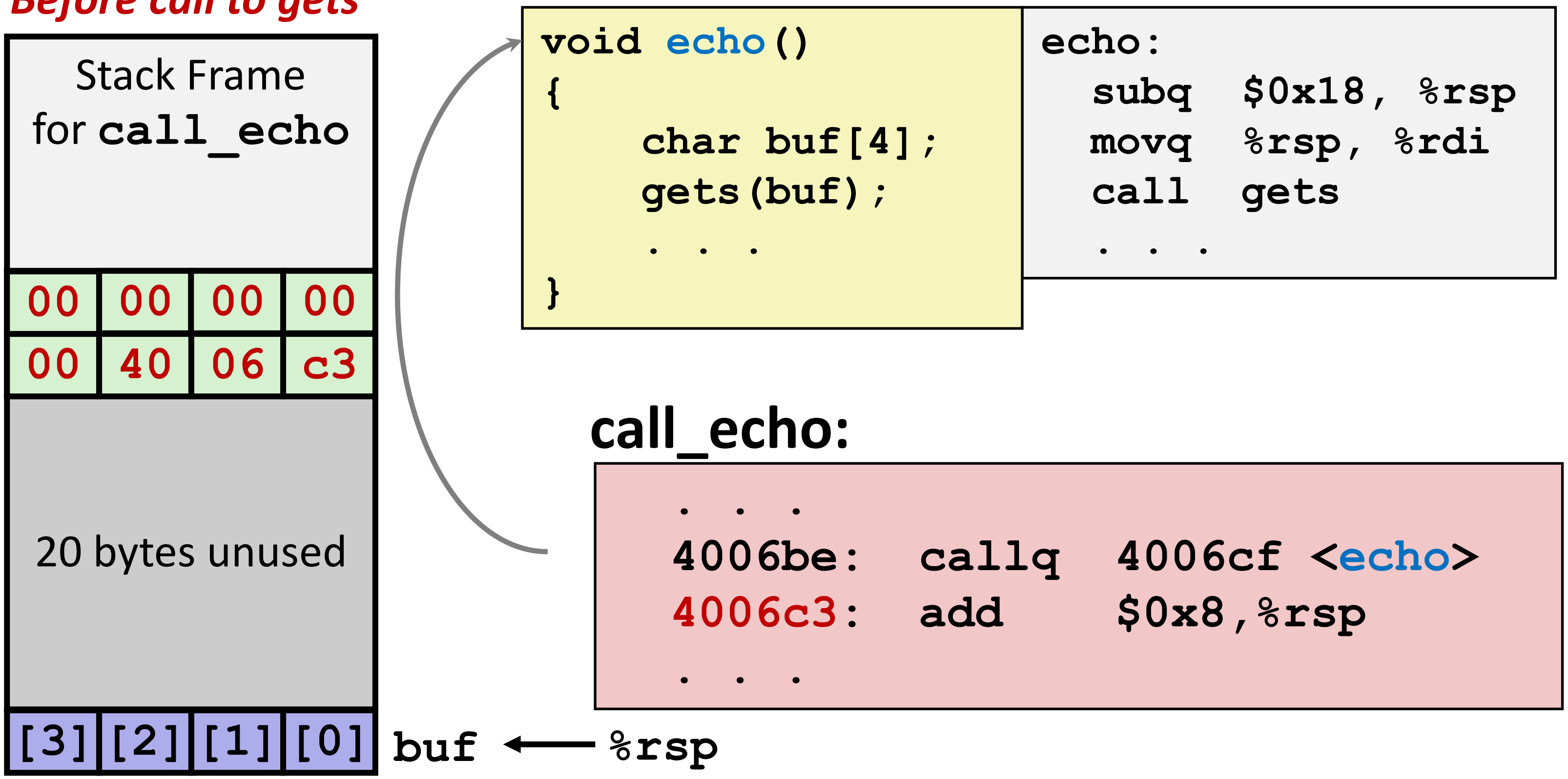


```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
  subq $0x18, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

Buffer Overflow Stack Example

Before call to gets



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

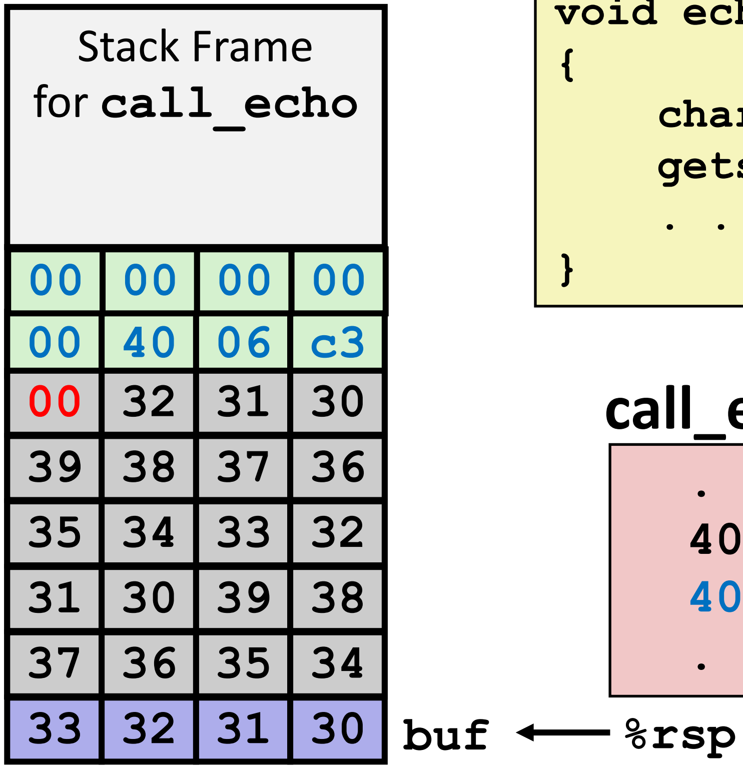
```
echo:
  subq  $0x18, %rsp
  movq  %rsp, %rdi
  call  gets
  . . .
```

call_echo:

```
 . . .
 4006be:  callq  4006cf <echo>
 4006c3:  add    $0x8,%rsp
 . . .
```

Buffer Overflow Stack Example #1

After call to gets



Stack Frame for `call_echo`

00	00	00	00
00	40	06	c3
00	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

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

```
echo:
  subq   $0x18, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

call_echo:

```
  . . .
  4006be:   callq   4006cf <echo>
  4006c3:   add     $0x8,%rsp
  . . .
```

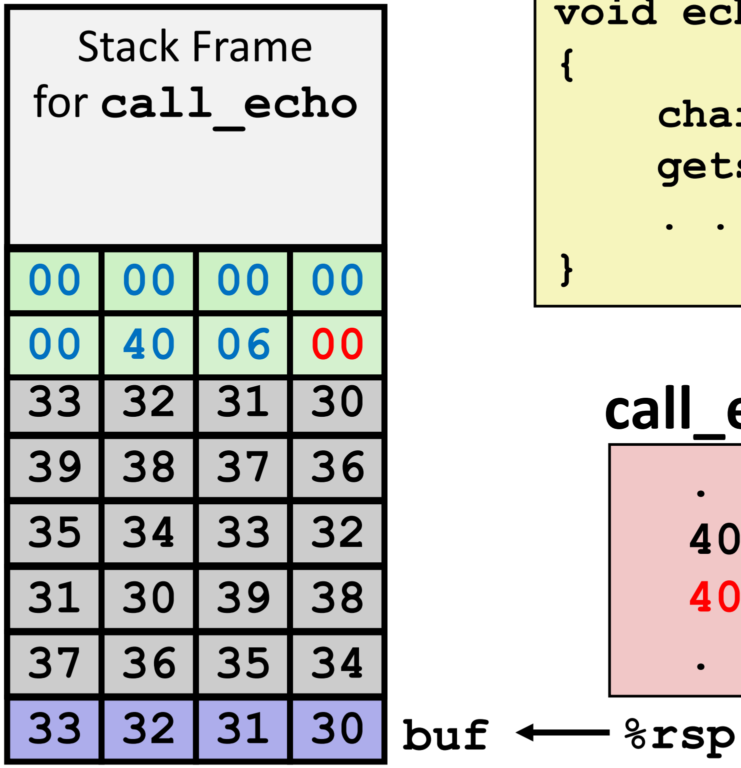
```
unix>./bufdemo-nsp
Type a string:01234567890123456789012
01234567890123456789012
```

"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

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

```
echo:
  subq   $0x18, %rsp
  movq   %rsp, %rdi
  call   gets
  . . .
```

call_echo:

```
   . . .
  4006be:  callq  4006cf <echo>
  4006c3:  add    $0x8,%rsp
   . . .
```

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

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

Stack Smashing Attacks

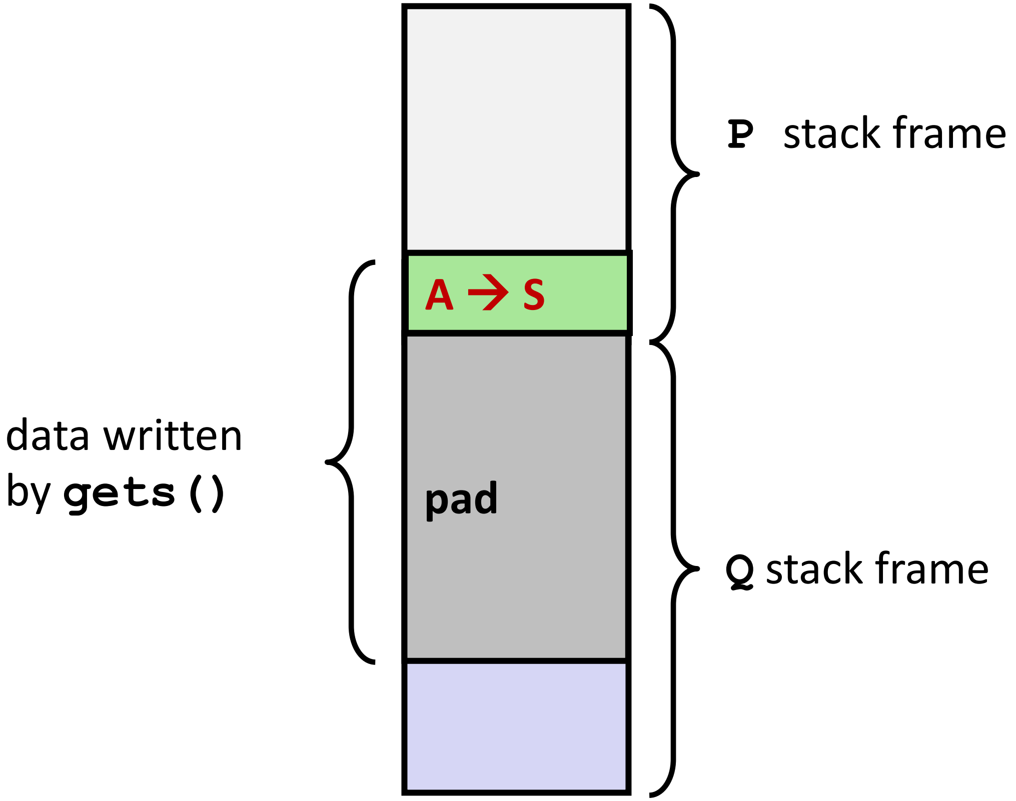
```
void P(){
   Q();
   ...
}
```

return address A

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

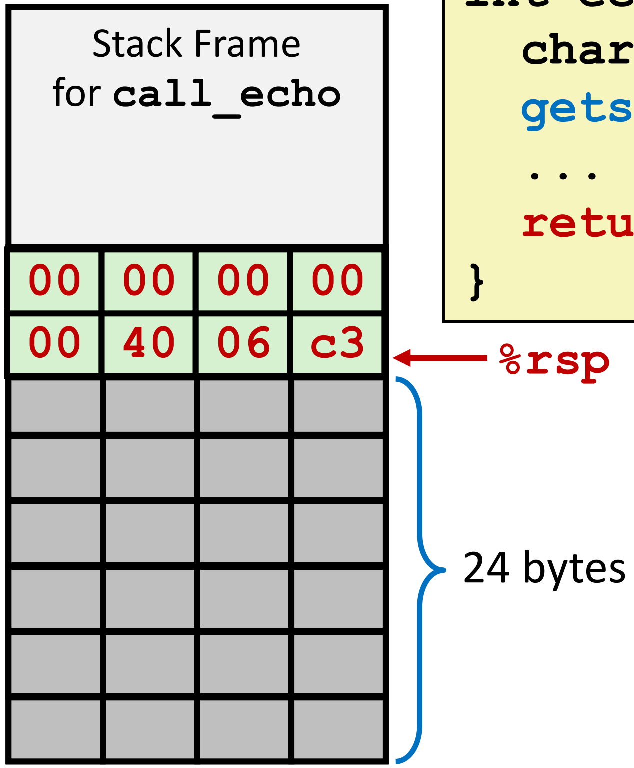
```
void S(){
/* Something
   unexpected */
   ...
}
```

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

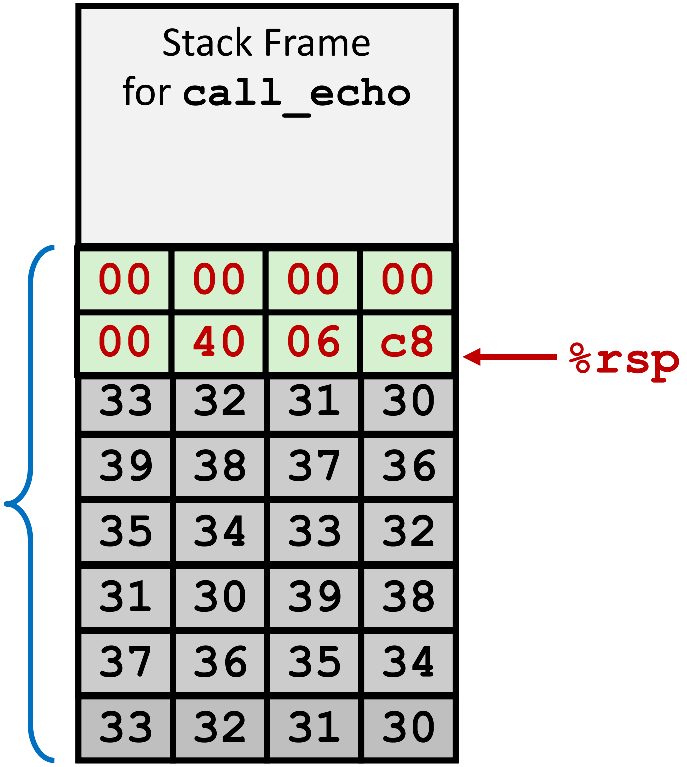
```
void smash() {
   printf("I've been smashed!\n");
   exit(0);
}
```

```
00000000004006c8 <smash>:
  4006c8:         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
c8 06 40 00 00 00 00 00
```

Smashing String Effect



Stack Frame
for `call_echo`

00	00	00	00
00	40	06	c8
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);
}
```

```
00000000004006c8 <smash>:
  4006c8:       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
c8 06 40 00 00 00 00 00
```

Performing Stack Smash

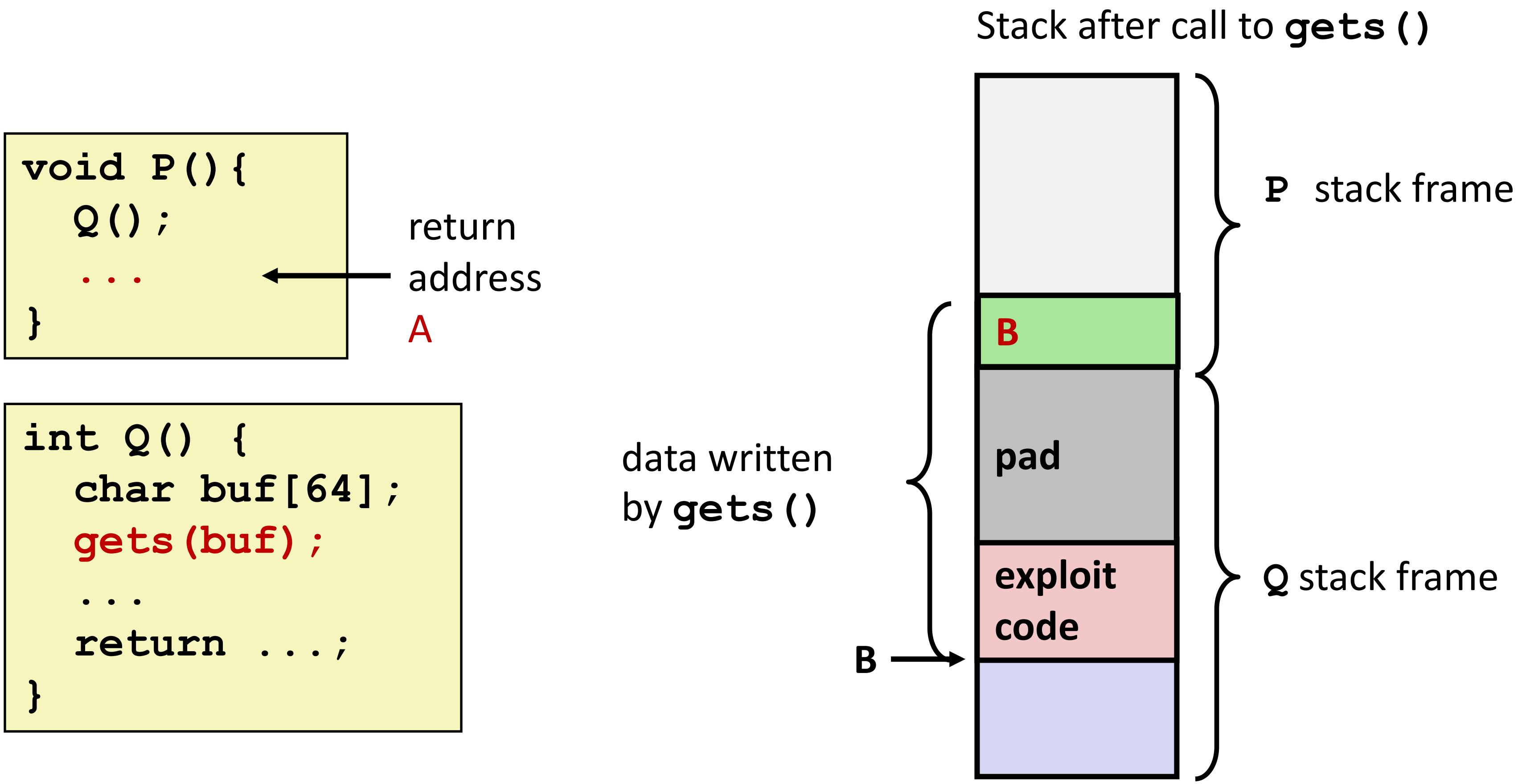
```
linux> cat smash-hex.txt
30 31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 37 38 39 30 31 32 33 c8 06 40 00 00 00 00 00
linux> cat smash-hex.txt | ./hexify | ./bufdemo-nsp
Type a string:012345678901234567890123?@
I've been smashed!
```

- **Put hex sequence in file smash-hex.txt**
- **Use hexify program to convert hex digits to characters**
  - Some of them are non-printing
- **Provide as input to vulnerable program**

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

```
30 31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 37 38 39 30 31 32 33
c8 06 40 00 00 00 00 00
```

Code Injection Attacks



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

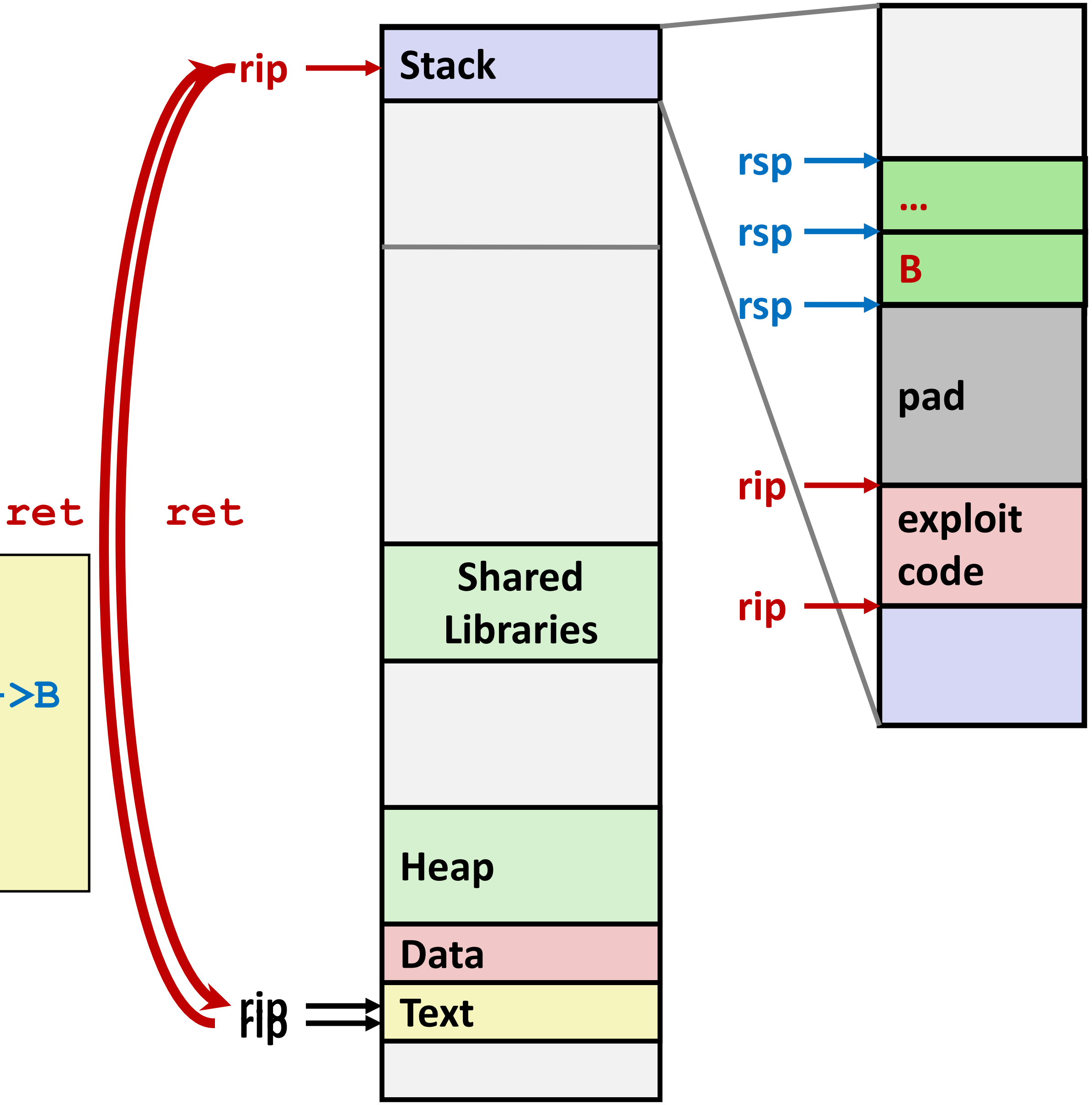
```
int Q() {
  char buf[64];
  gets(buf);
  ...
  return ...;
}
```

- 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 ...;
}
```



Today

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

https://canvas.cmu.edu/courses/34989/assignments/596855

Do parts 3 and 4 now

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);
}
```

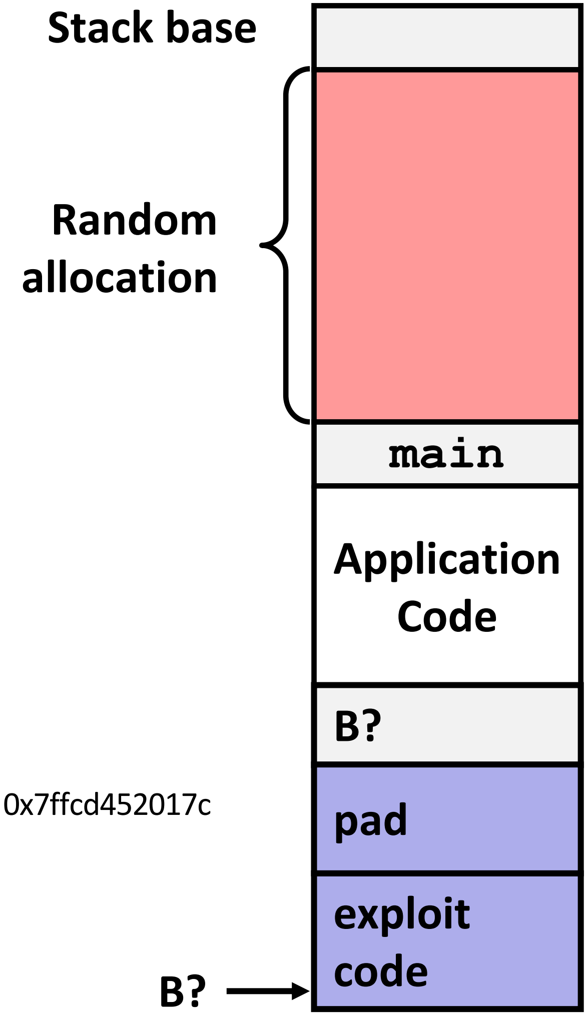
- **For example, use library routines that limit string lengths**
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
  - Don’t use `scanf` with `%s` conversion specification
    - Use `fgets` to read the string
    - Or use `%ns` where `n` is a suitable integer

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

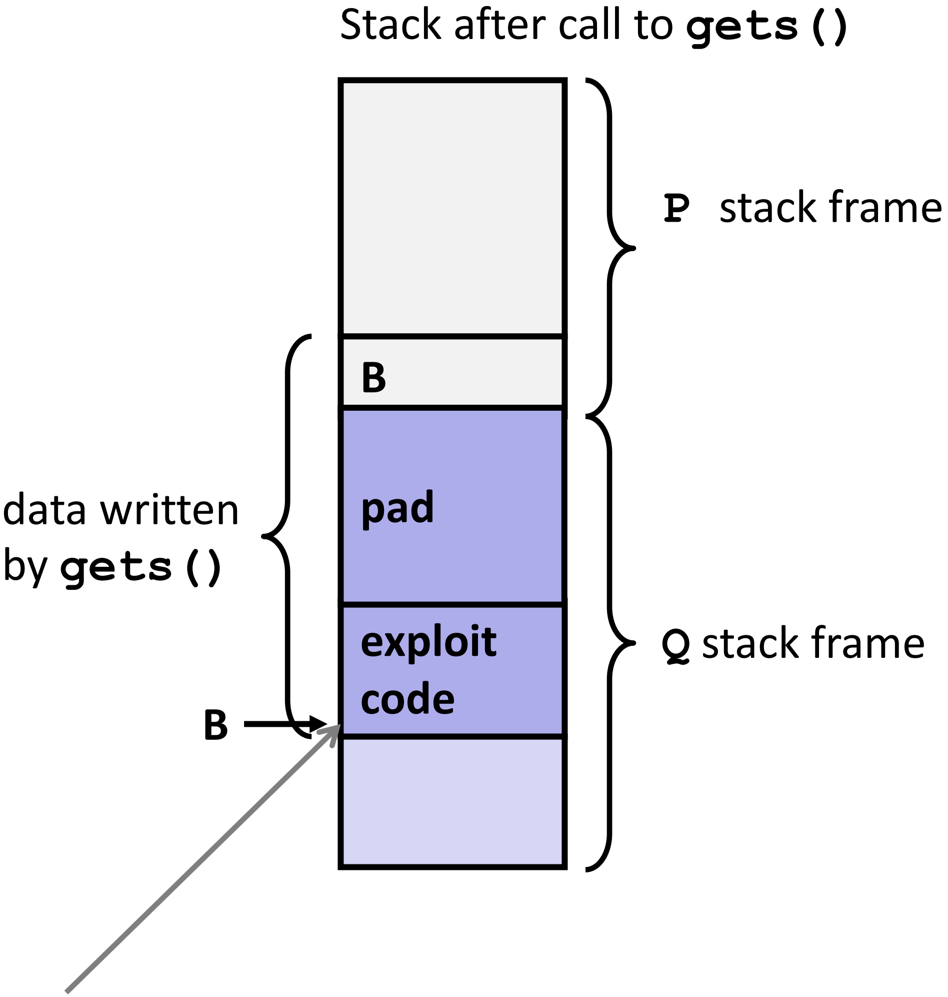
local	0x7ffe4d3be87c	0x7fff75a4f9fc	0x7ffeadb7c80c	0x7ffeaea2fdac	0x7ffcd452017c

  - 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:0123456
0123456
```

```
unix>./bufdemo-sp
Type a string:012345678
*** stack smashing detected ***
```

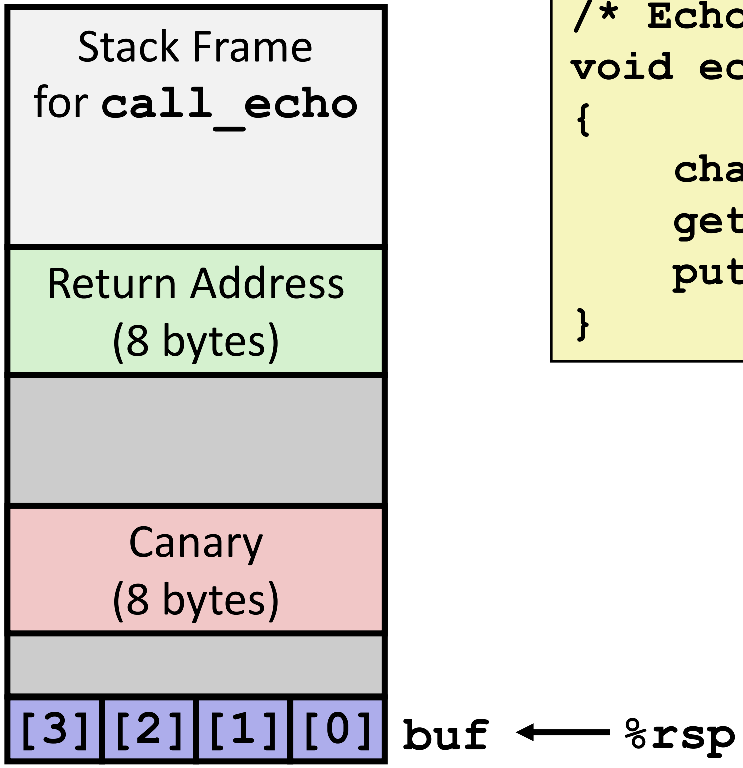
Protected Buffer Disassembly

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

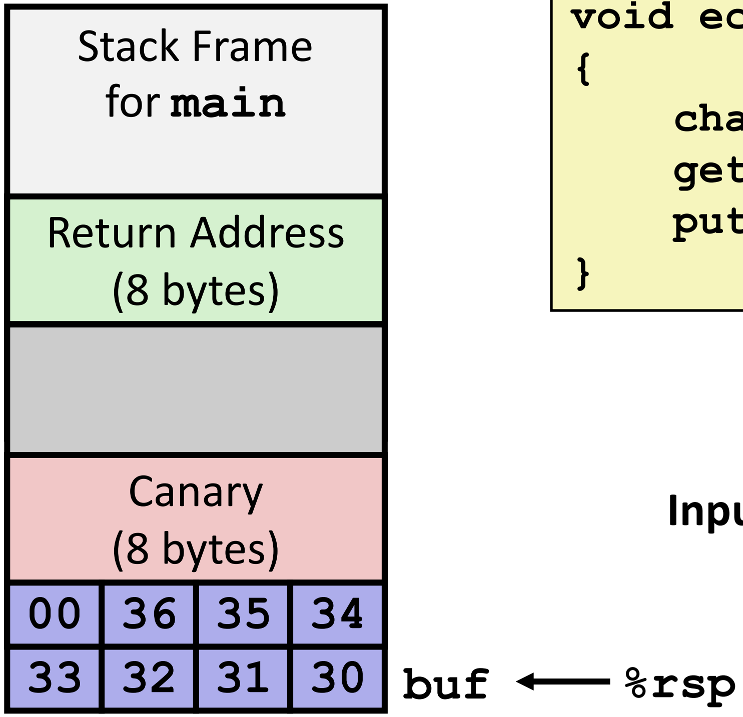


```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    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: ***0123456***

Some systems:
LSB of canary is 0x00
Allows input 01234567

```
echo:
    . . .
    mov     0x8(%rsp),%rax     # Retrieve from stack
    xor     %fs:0x28,%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 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
```

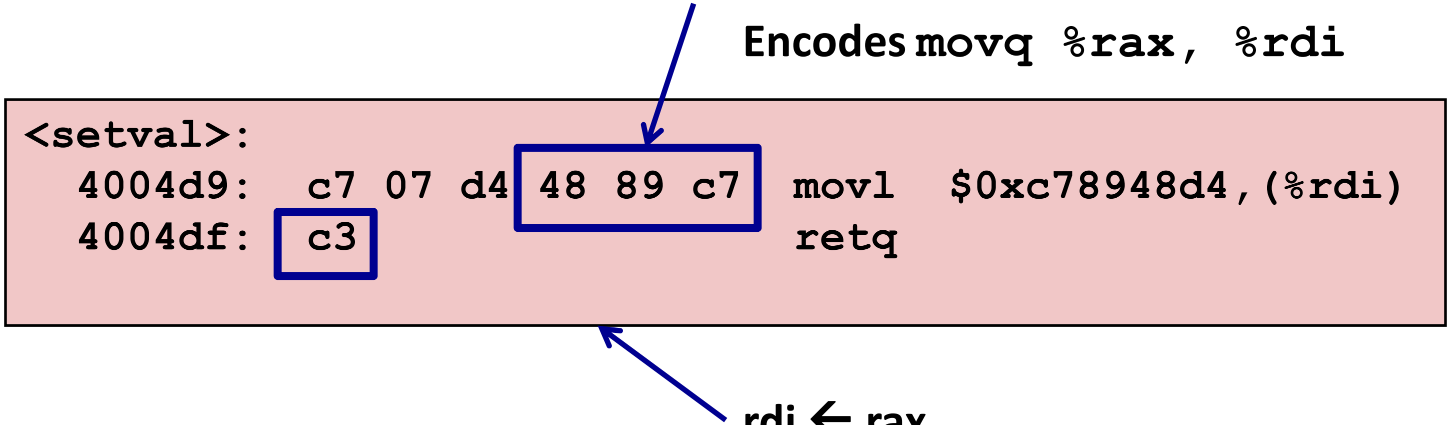
rax ← rdi + rdx

Gadget address = 0x4004d4

- Use tail end of existing functions

Gadget Example #2

```
void setval(unsigned *p) {
    *p = 3347663060u;
}
```



Encodes `movq %rax, %rdi`

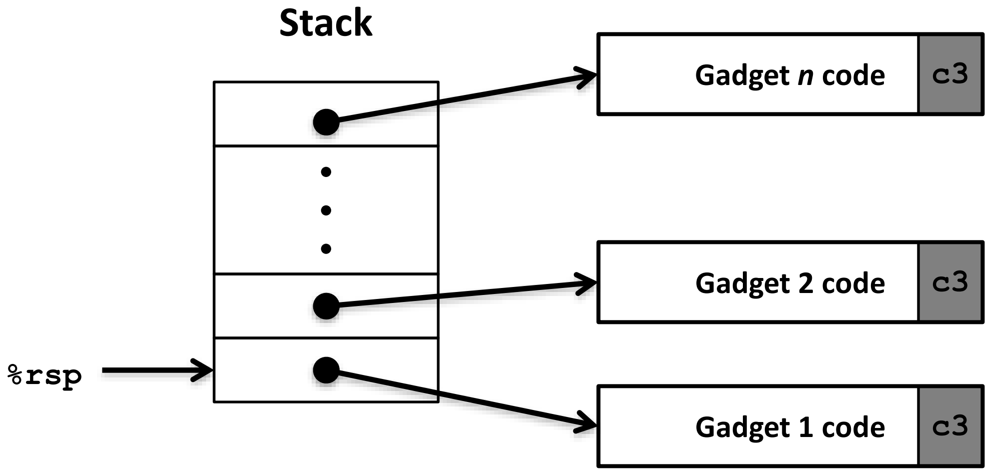
```
<setval>:
  4004d9:  c7 07 d4 48 89 c7  movl  $0xc78948d4,(%rdi)
  4004df:  c3                 retq
```

rdi ← rax

Gadget address = `0x4004dc`

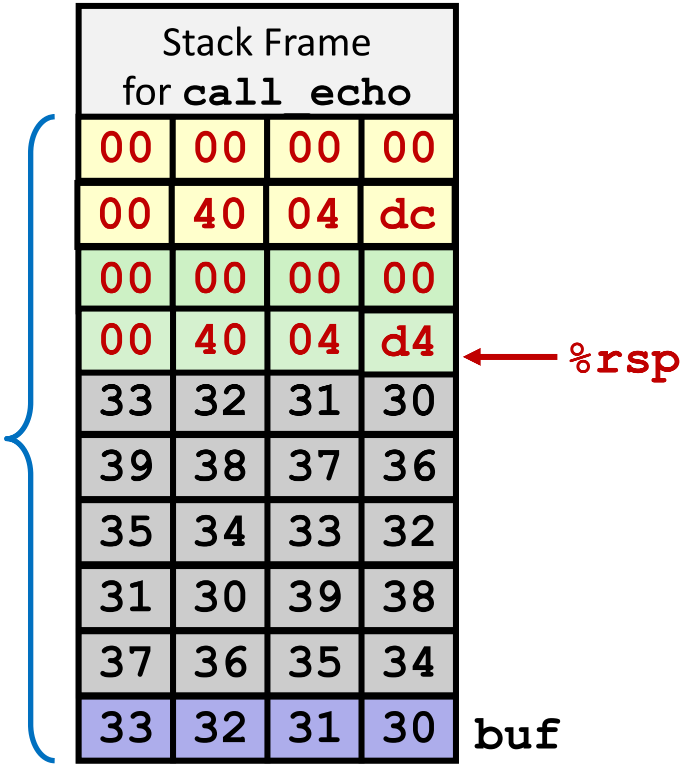
- **Repurpose byte codes**

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



Stack Frame for `call_echo`			
00	00	00	00
00	40	04	dc
00	00	00	00
00	40	04	d4
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

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

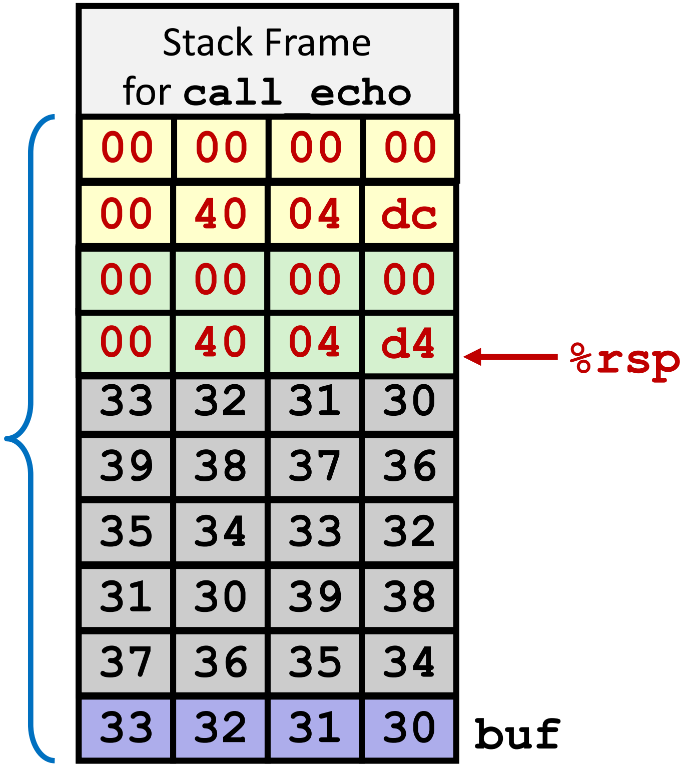
  rdi ← rdi + rdx

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?



00	00	00	00
00	40	04	dc
00	00	00	00
00	40	04	d4
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

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

Today

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

Today

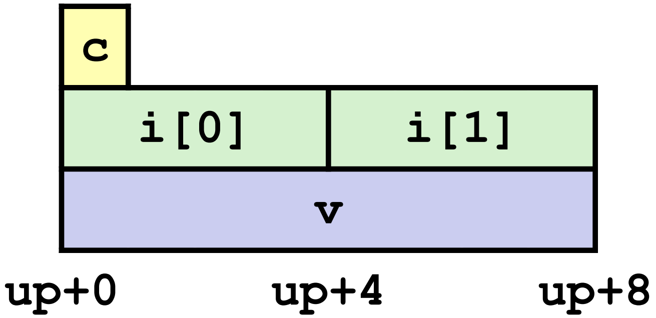
- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection
  - Bypassing Protection
- **Unions**

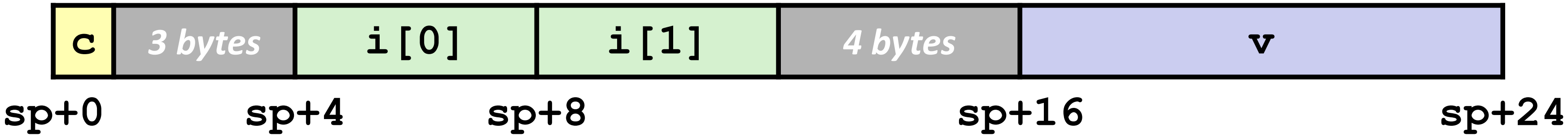
Union Allocation

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

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

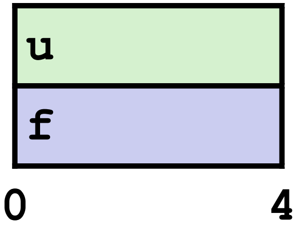
```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```





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;
}
```

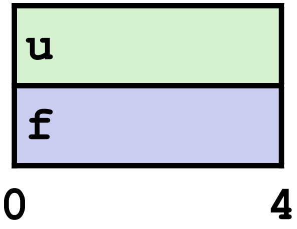
```
unsigned float2bit(float f)
{
  bit_float_t arg;
  arg.f = f;
  return arg.u;
}
```

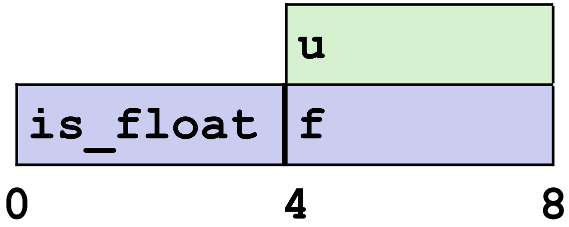
Same as `(float) u` ?

Same as `(unsigned) f` ?

Using Unions as Sum Types

```
typedef union {
  float f;
  unsigned u;
} num_t;

typedef struct {
  bool is_float;
  num_t val;
} value_t;
```





(technically is_float only takes 1 byte and then there's 3 bytes of padding)

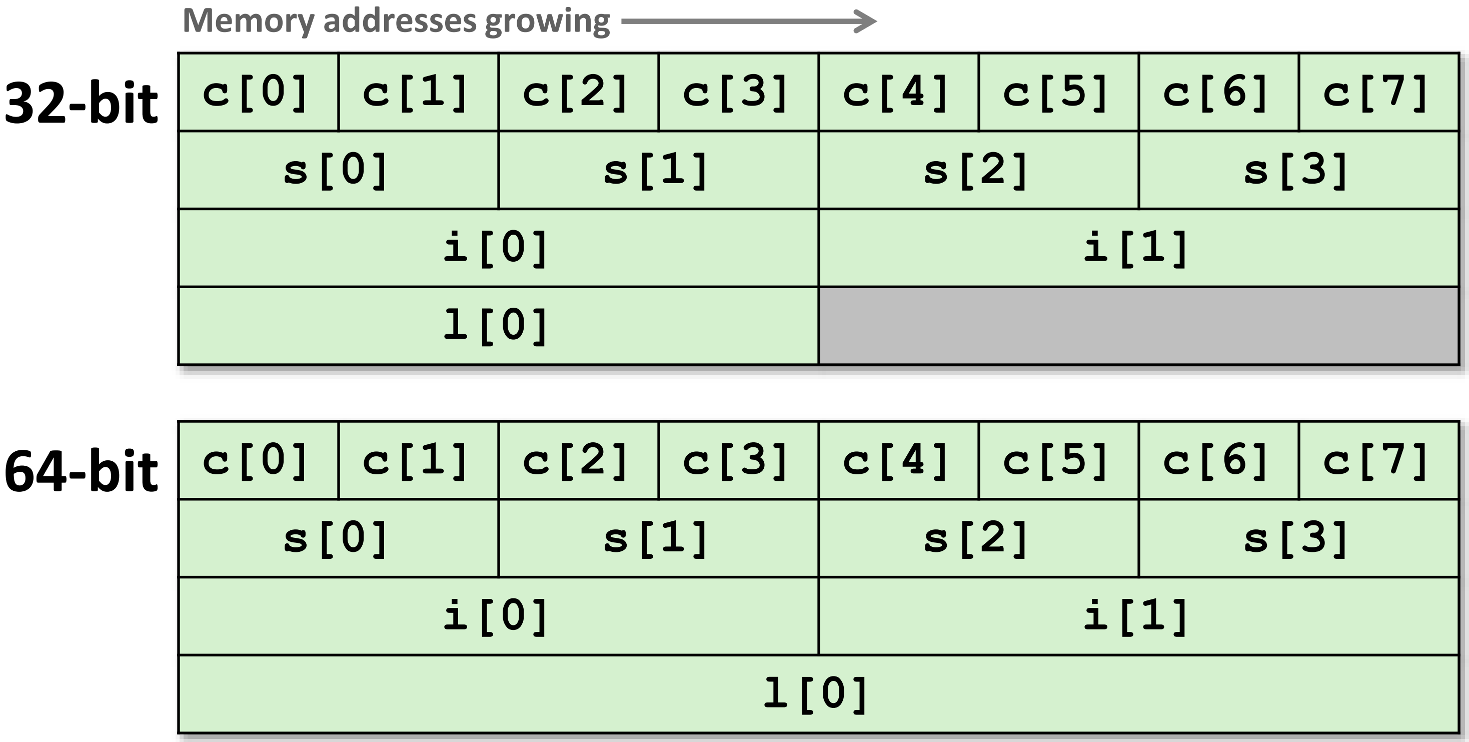
Byte Ordering Revisited

- **Idea**
  - Short/long/quad words stored in memory as 2/4/8 consecutive bytes
  - Which byte is most (least) significant?
  - Can cause problems when exchanging binary data between machines
- **Big Endian**
  - Most significant byte has lowest address
  - Sparc, *Internet*
- **Little Endian**
  - Least significant byte has lowest address
  - Intel x86, ARM Android and IOS
- **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?



Memory addresses growing →

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

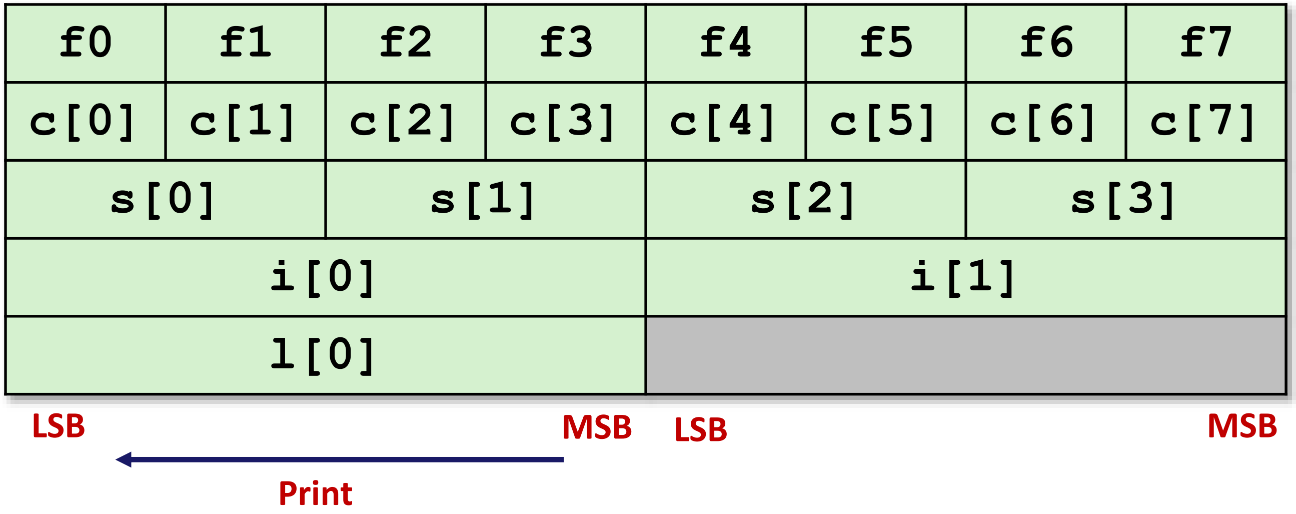
<table>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">i[0]</td><td colspan="4">i[1]</td></tr>
<tr><td colspan="8">l[0]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



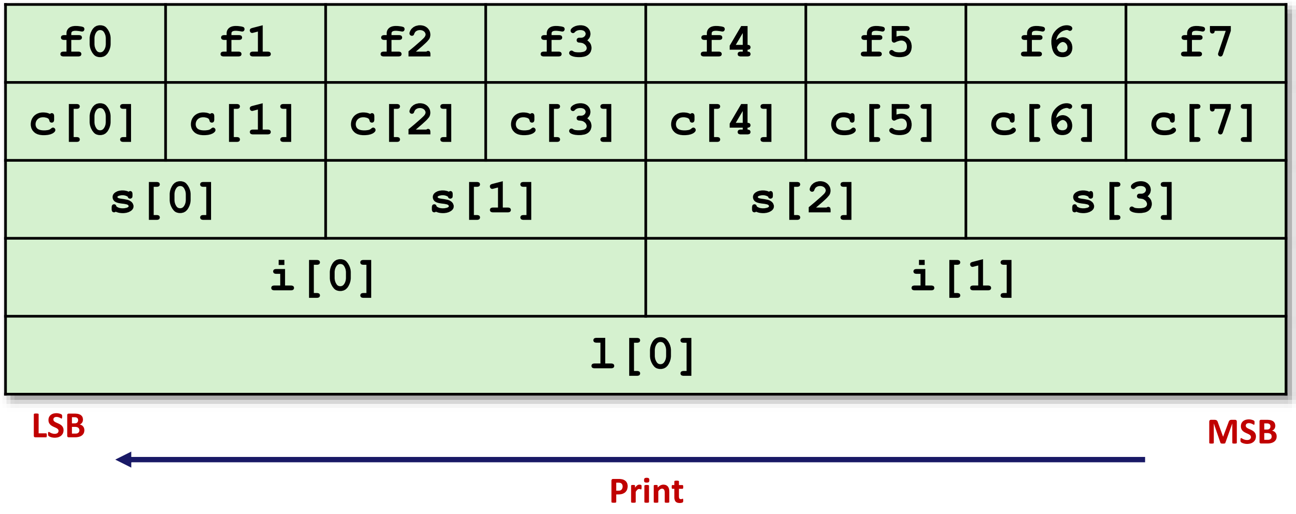
f0	f1	f2	f3	f4	f5	f6	f7
c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

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 x86-64

Little Endian



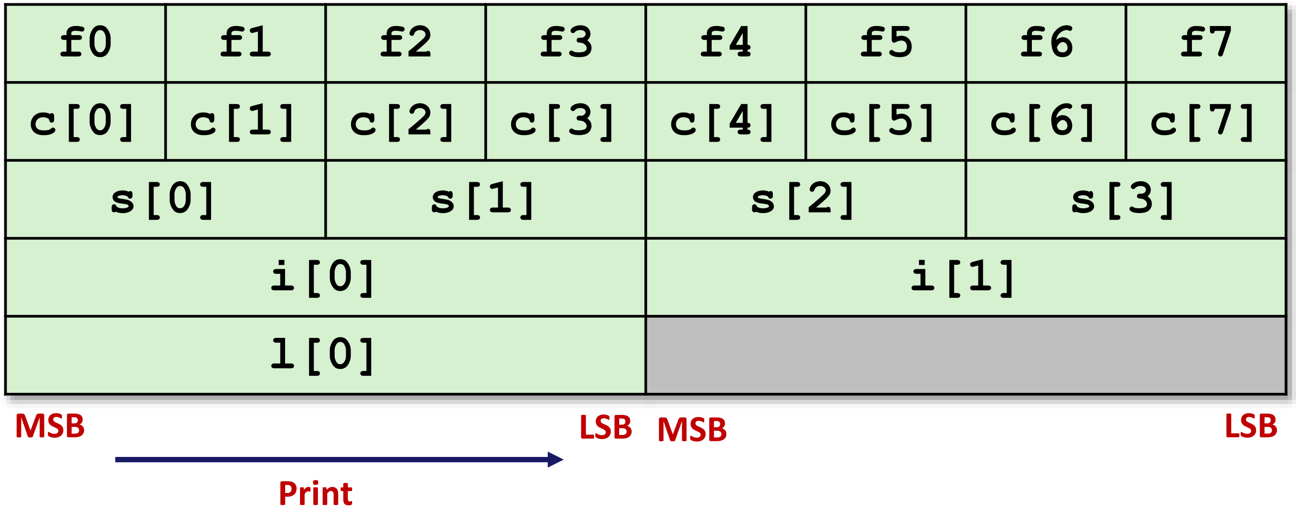
<table>
<tr><td>f0</td><td>f1</td><td>f2</td><td>f3</td><td>f4</td><td>f5</td><td>f6</td><td>f7</td></tr>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td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

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]
```

Byte Ordering on Sun

Big 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>

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]
```