Introduction to Computer Systems

15-213, fall 2009

9th Lecture, Sep. 28th

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Last Time:

- **Structures**

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

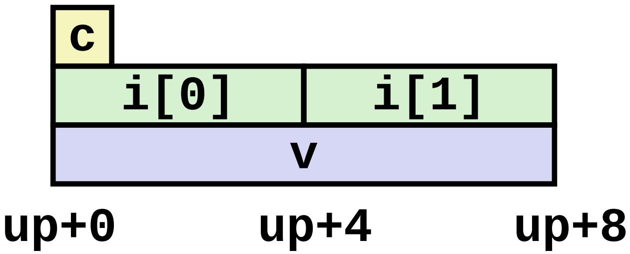
Memory Layout

- **Alignment**

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

- **Unions**

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



Summary

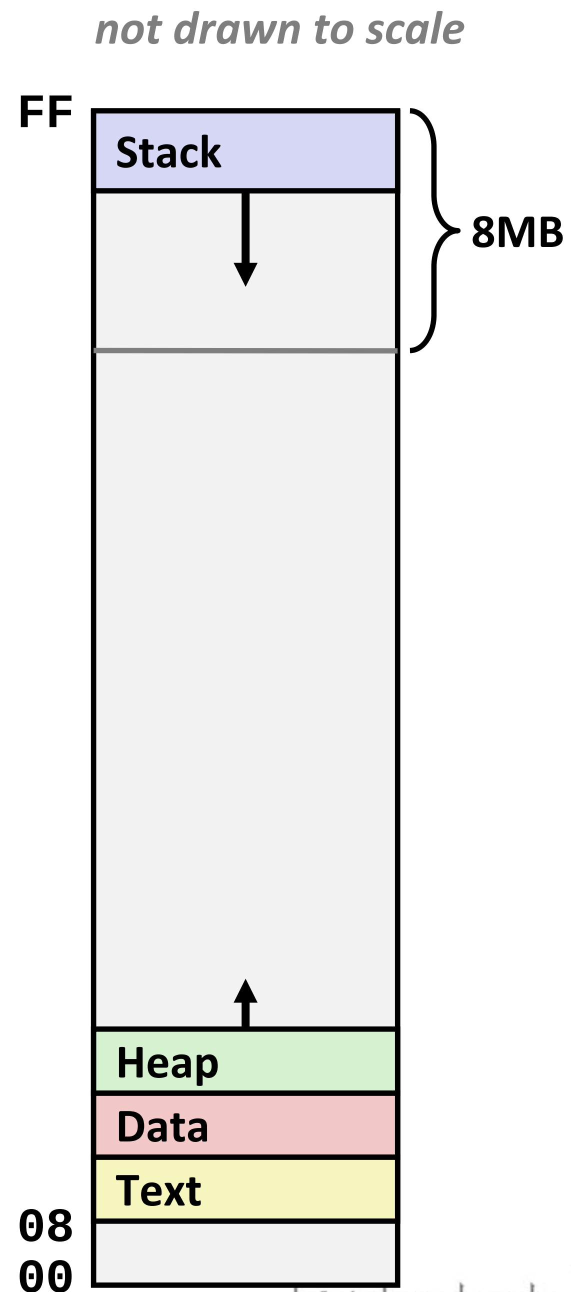
- **Arrays in C**
  - Contiguous allocation of memory
  - Aligned to satisfy every element's alignment requirement
  - Pointer to first element
  - No bounds checking
- **Structures**
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment
- **Unions**
  - Overlay declarations
  - Way to circumvent type system

Today

- **Memory layout**
- Buffer overflow, worms, and viruses

IA32 Linux Memory Layout

- **Stack**
  - Runtime stack (8MB limit)
- **Heap**
  - Dynamically allocated storage
  - When call **`malloc(), calloc(), new()`**
- **Data**
  - Statically allocated data
  - E.g., arrays & strings declared in code
- **Text**
  - Executable machine instructions
  - Read-only



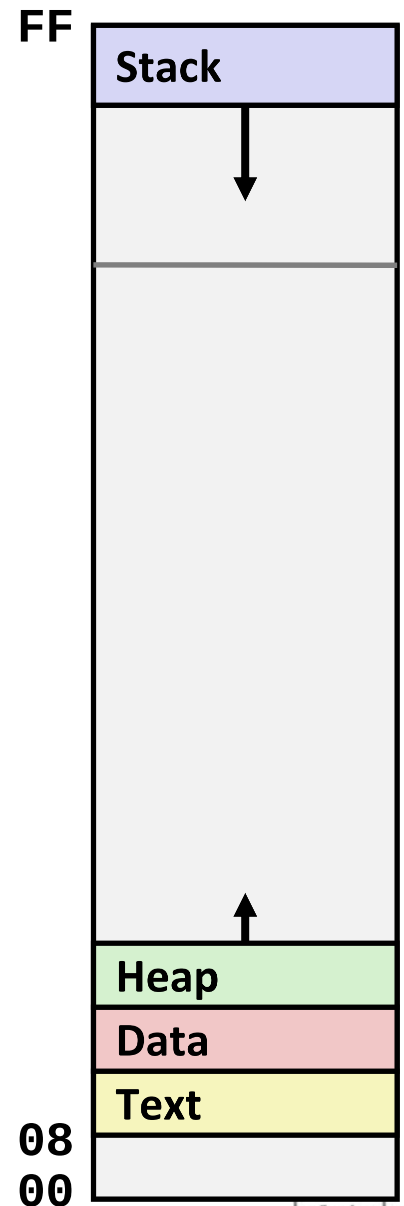
Upper 2 hex digits
= 8 bits of address

Memory Allocation Example

```
char big_array[1<<24];  /*  16 MB */
char huge_array[1<<28]; /* 256 MB */

int beyond;
char *p1, *p2, *p3, *p4;

int useless() {  return 0; }

int main()
{
 p1 = malloc(1 <<28);  /* 256 MB */
 p2 = malloc(1 << 8);  /* 256 B  */
 p3 = malloc(1 <<28);  /* 256 MB */
 p4 = malloc(1 << 8);  /* 256 B  */
 /* Some print statements ... */
}
```

Where does everything go?

not drawn to scale



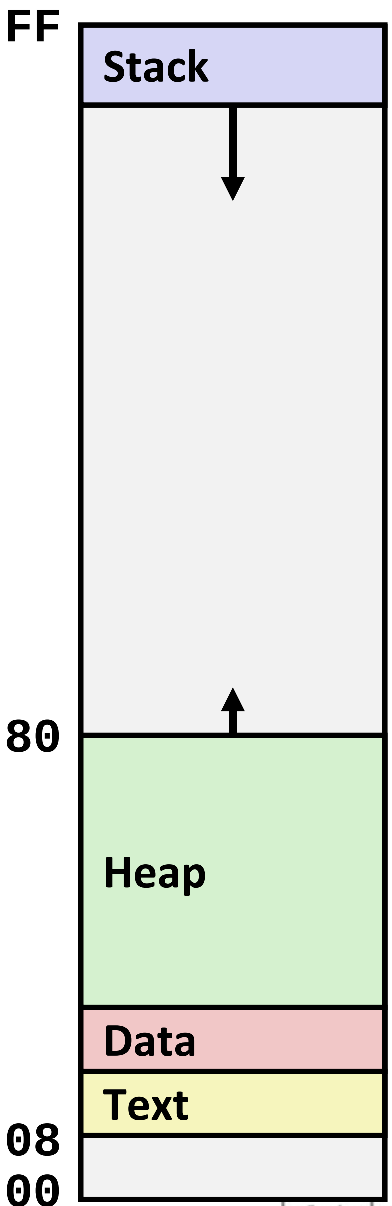
IA32 Example Addresses

address range ~2^{32}

`$esp`	`0xffffbcd0`
`p3`	`0x65586008`
`p1`	`0x55585008`
`p4`	`0x1904a110`
`p2`	`0x1904a008`
`&p2`	`0x18049760`
`beyond`	`0x08049744`
`big_array`	`0x18049780`
`huge_array`	`0x08049760`
`main()`	`0x080483c6`
`useless()`	`0x08049744`
final `malloc()`	`0x006be166`

`malloc()` is dynamically linked
address determined at runtime

not drawn to scale



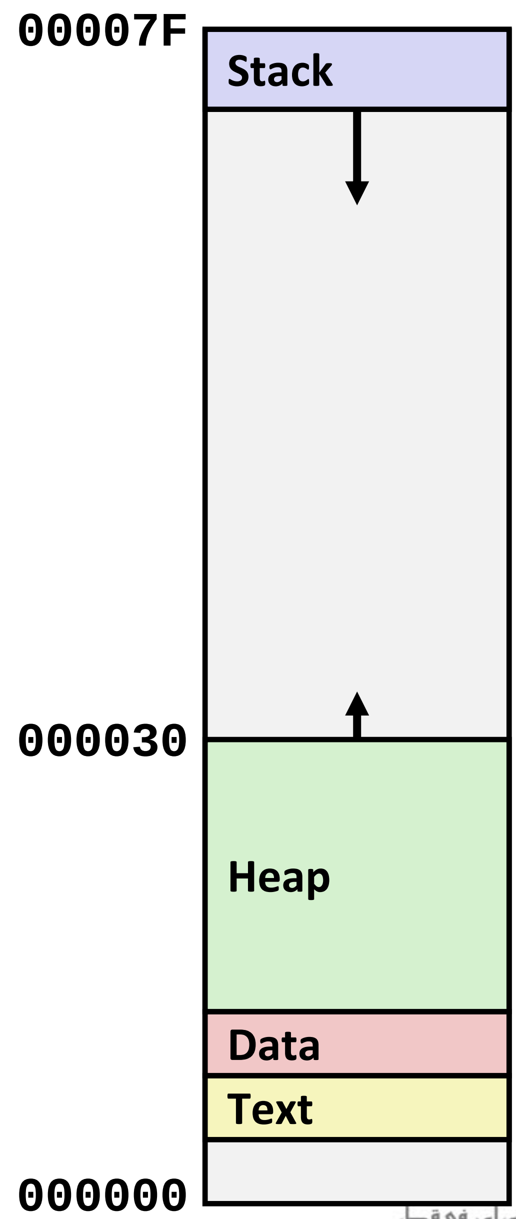
x86-64 Example Addresses

address range ~2^{47}

`$rsp`	`0x7ffffff8d1f8`
`p3`	`0x2aaabaadd010`
`p1`	`0x2aaaaaadc010`
`p4`	`0x000011501120`
`p2`	`0x000011501010`
`&p2`	`0x000010500a60`
`beyond`	`0x000000500a44`
`big_array`	`0x000010500a80`
`huge_array`	`0x000000500a50`
`main()`	`0x000000400510`
`useless()`	`0x000000400500`
final `malloc()`	`0x00386ae6a170`

`malloc()` is dynamically linked
address determined at runtime

not drawn to scale



C operators

<table>
<tr><th>Operators</th><th>Associativity</th></tr>
<tr><td>() [] -> .</td><td>left to right</td></tr>
<tr><td>! ~ ++ -- + - * & (type) sizeof</td><td>right to left</td></tr>
<tr><td>* / %</td><td>left to right</td></tr>
<tr><td>+ -</td><td>left to right</td></tr>
<tr><td><< >></td><td>left to right</td></tr>
<tr><td>< <= > >=</td><td>left to right</td></tr>
<tr><td>== !=</td><td>left to right</td></tr>
<tr><td>&</td><td>left to right</td></tr>
<tr><td>^</td><td>left to right</td></tr>
<tr><td>|</td><td>left to right</td></tr>
<tr><td>&&</td><td>left to right</td></tr>
<tr><td>||</td><td>left to right</td></tr>
<tr><td>?:</td><td>right to left</td></tr>
<tr><td>= += -= *= /= %= &= ^= != <<= >>=</td><td>right to left</td></tr>
<tr><td>,</td><td>left to right</td></tr>
</table>

- -> has very high precedence
- ( ) has very high precedence
- monadic * just below

C Pointer Declarations: Test Yourself!

`int *p`	p is a pointer to int
`int *p[13]`	
`int *(p[13])`	
`int **p`	p is a pointer to a pointer to an int
`int (*p)[13]`	
`int *f()`	f is a function returning a pointer to int
`int (*f)()`	f is a pointer to a function returning int
`int (*(*f())[13])()`	
`int (*(*x[3])())[5]`	x is an array[3] of pointers to functions returning pointers to array[5] of ints

C Pointer Declarations (Check out guide)

`int *p`	p is a pointer to int
`int *p[13]`	p is an array[13] of pointer to int
`int *(p[13])`	p is an array[13] of pointer to int
`int **p`	p is a pointer to a pointer to an int
`int (*p)[13]`	p is a pointer to an array[13] of int
`int *f()`	f is a function returning a pointer to int
`int (*f)()`	f is a pointer to a function returning int
`int (*(*f())[13])()`	f is a function returning ptr to an array[13] of pointers to functions returning int
`int (*(*x[3])())[5]`	x is an array[3] of pointers to functions returning pointers to array[5] of ints

Avoiding Complex Declarations

- Use `typedef` to build up the declaration

- Instead of `int (*(*x[3])())[5]` :

```
typedef int fiveints[5];
typedef fiveints* p5i;
typedef p5i (*f_of_p5is)();
f_of_p5is x[3];
```

- `x` is an array of 3 elements, each of which is a pointer to a function returning an array of 5 ints

Today

- Memory layout
- **Buffer overflow, worms, and viruses**

Internet Worm and IM War

- **November, 1988**
  - Internet Worm attacks thousands of Internet hosts.
  - How did it happen?

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 Unix functions**
  - **`strcpy`**: Copies string 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);
}
```

```
int main()
{
  printf("Type a string:");
  echo();
  return 0;
}
```

```
unix>./bufdemo
Type a string:1234567
1234567
```

```
unix>./bufdemo
Type a string:12345678
Segmentation Fault
```

```
unix>./bufdemo
Type a string:123456789ABC
Segmentation Fault
```

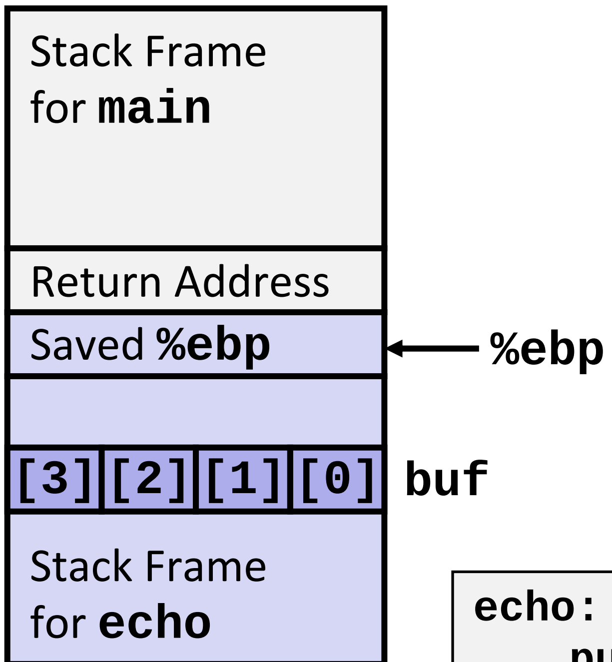
Buffer Overflow Disassembly

```
080484f0 <echo>:
 80484f0:  55                push   %ebp
 80484f1:  89 e5             mov    %esp,%ebp
 80484f3:  53                push   %ebx
 80484f4:  8d 5d f8          lea    0xfffffff8(%ebp),%ebx
 80484f7:  83 ec 14          sub    $0x14,%esp
 80484fa:  89 1c 24          mov    %ebx,(%esp)
 80484fd:  e8 ae ff ff ff    call   80484b0 <gets>
 8048502:  89 1c 24          mov    %ebx,(%esp)
 8048505:  e8 8a fe ff ff    call   8048394 <puts@plt>
 804850a:  83 c4 14          add    $0x14,%esp
 804850d:  5b                pop    %ebx
 804850e:  c9                leave
 804850f:  c3                ret
```

```
 80485f2:  e8 f9 fe ff ff    call   80484f0 <echo>
 80485f7:  8b 5d fc          mov 0xfffffffc(%ebp),%ebx
 80485fa:  c9                leave
 80485fb:  31 c0             xor    %eax,%eax
 80485fd:  c3                ret
```

Buffer Overflow Stack

Before call to gets



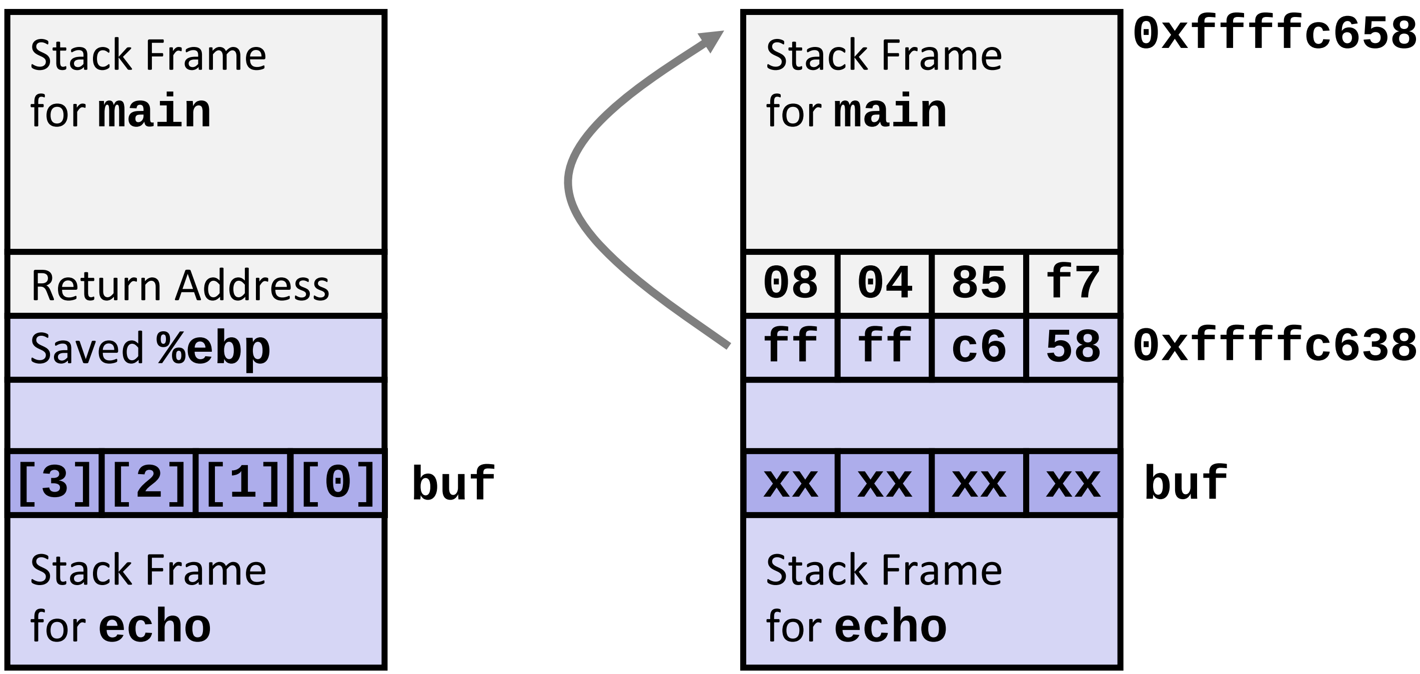

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    pushl %ebp              # Save %ebp on stack
    movl  %esp, %ebp
    pushl %ebx              # Save %ebx
    leal  -8(%ebp),%ebx     # Compute buf as %ebp-8
    subl  $20, %esp         # Allocate stack space
    movl  %ebx, (%esp)      # Push buf on stack
    call  gets              # Call gets
    . . .
```

Buffer Overflow Stack Example

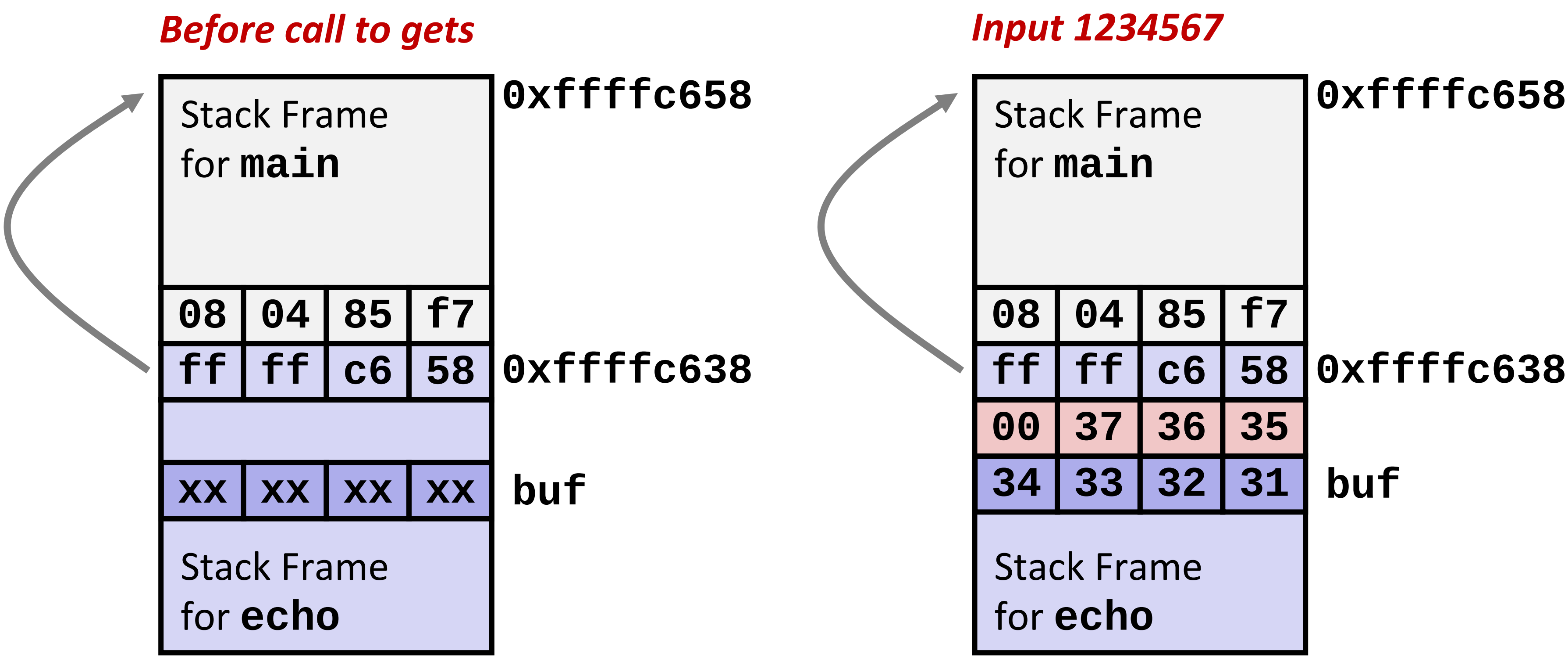
```
unix> gdb bufdemo
(gdb) break echo
Breakpoint 1 at 0x8048583
(gdb) run
Breakpoint 1, 0x8048583 in echo ()
(gdb) print /x $ebp
$1 = 0xffffc638
(gdb) print /x *(unsigned *)$ebp
$2 = 0xffffc658
(gdb) print /x *((unsigned *)$ebp + 1)
$3 = 0x80485f7
```

Before call to gets *Before call to gets*




```
80485f2: call 80484f0 <echo>
80485f7: mov  0xfffffffc(%ebp),%ebx # Return Point
```

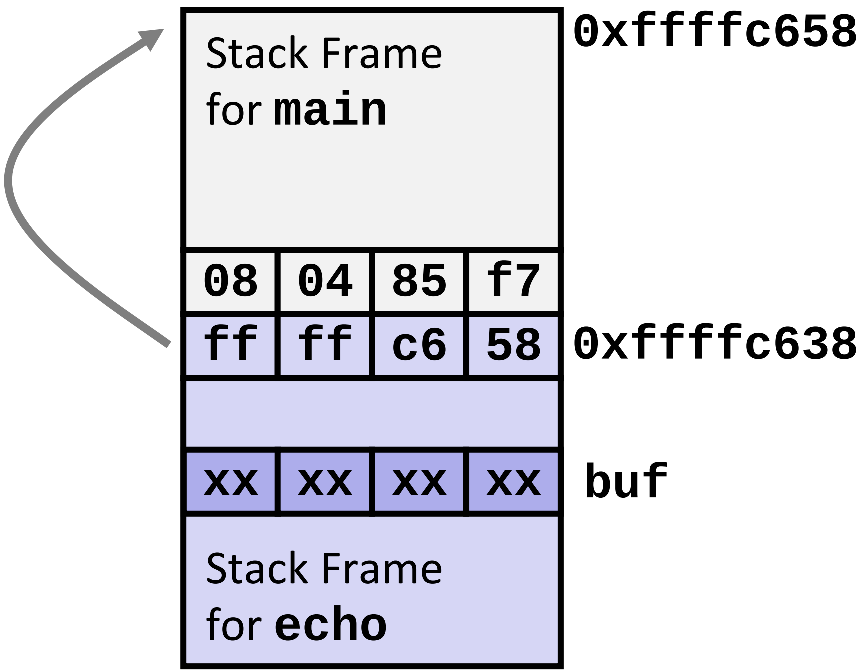
Buffer Overflow Example #1



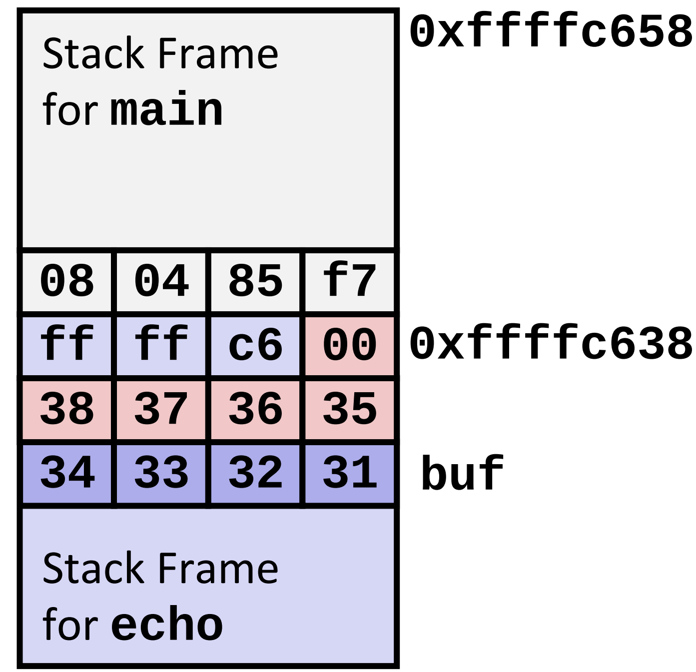
Overflow buf, but no problem

Buffer Overflow Example #2

Before call to gets



Input 12345678

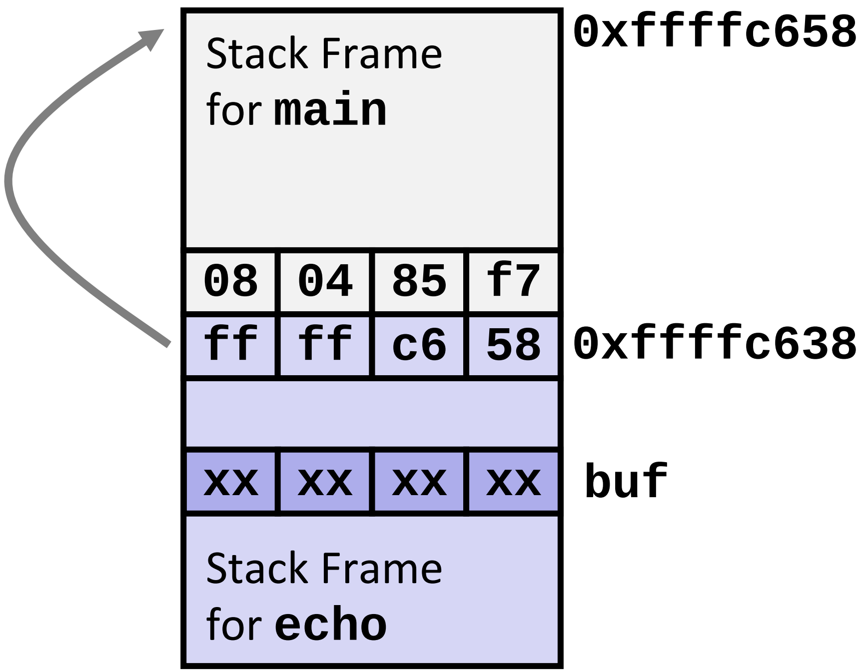


Base pointer corrupted

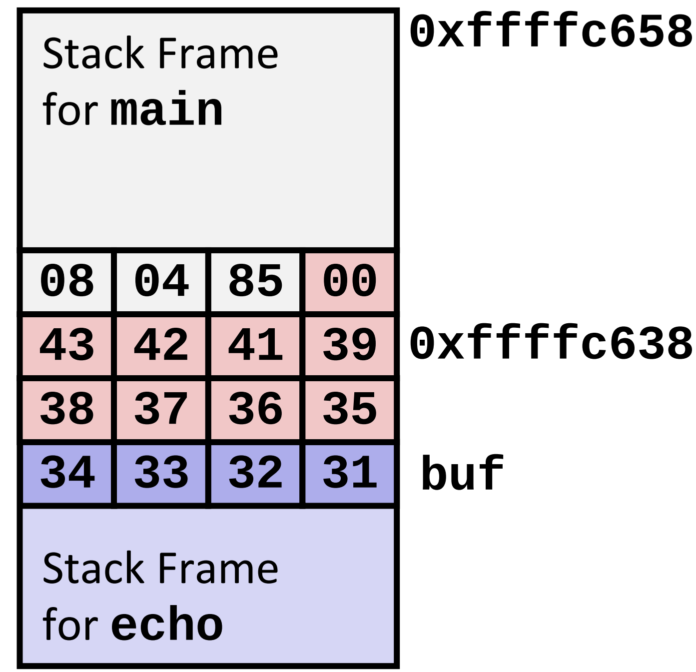
```
. . .
804850a:  83 c4 14   add    $0x14,%esp   # deallocate space
804850d:  5b         pop    %ebx         # restore %ebx
804850e:  c9         leave               # movl %ebp, %esp; popl %ebp
804850f:  c3         ret                 # Return
```

Buffer Overflow Example #3

Before call to gets



Input 12345678



Return address corrupted

```
80485f2:  call 80484f0 <echo>
80485f7:  mov  0xfffffffc(%ebp),%ebx # Return Point
```

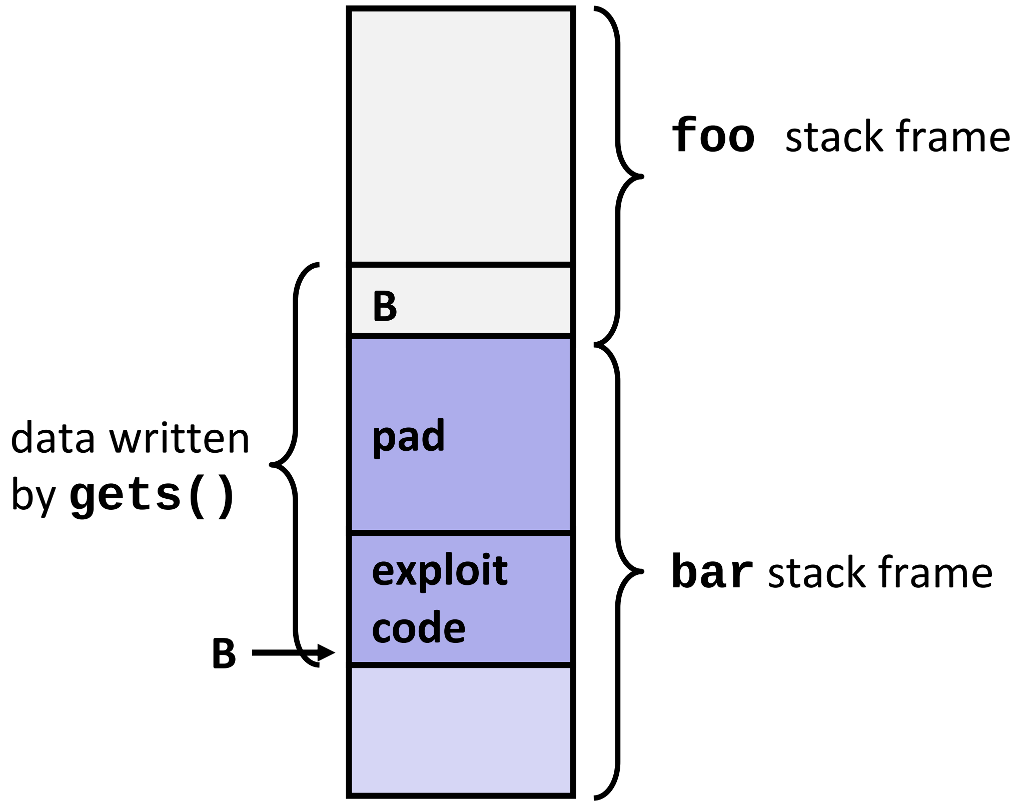
Malicious Use of Buffer Overflow

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

return address A

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

Stack after call to **gets()**



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

Exploits Based on Buffer Overflows

- ***Buffer overflow bugs allow remote machines to execute arbitrary code on victim machines***
- **Internet worm**
  - Early versions of the finger server (fingerd) used **`gets()`** to read the argument sent by the client:
    - **`finger droh@cs.cmu.edu`**
  - 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.

Avoiding Overflow Vulnerability

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

- **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

System-Level Protections

- **Randomized stack offsets**
  - At start of program, allocate random amount of space on stack
  - Makes it difficult for hacker to predict beginning of inserted code

- **Nonexecutable code segments**
  - In traditional x86, can mark region of memory as either “read-only” or “writeable”
    - Can execute anything readable
  - Add explicit “execute” permission

```
unix> gdb bufdemo
(gdb) break echo

(gdb) run
(gdb) print /x $ebp
$1 = 0xffffc638

(gdb) run
(gdb) print /x $ebp
$2 = 0xffffbb08

(gdb) run
(gdb) print /x $ebp
$3 = 0xffffc6a8
```

Worms and Viruses

- **Worm: A program that**
  - Can run by itself
  - Can propagate a fully working version of itself to other computers

- **Virus: Code that**
  - Add itself to other programs
  - Cannot run independently

- **Both are (usually) designed to spread among computers and to wreak havoc**