Machine-Level Programming V: Advanced Topics

15-213 / 18-213: Introduction to Computer Systems
9th Lecture, Sep. 24, 2013

Instructors:

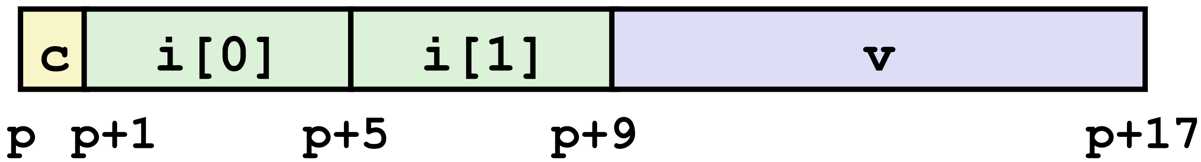
Randy Bryant, Dave O'Hallaron, and Greg Kesden

Today

- **Structures**
  - Alignment
- Unions
- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection

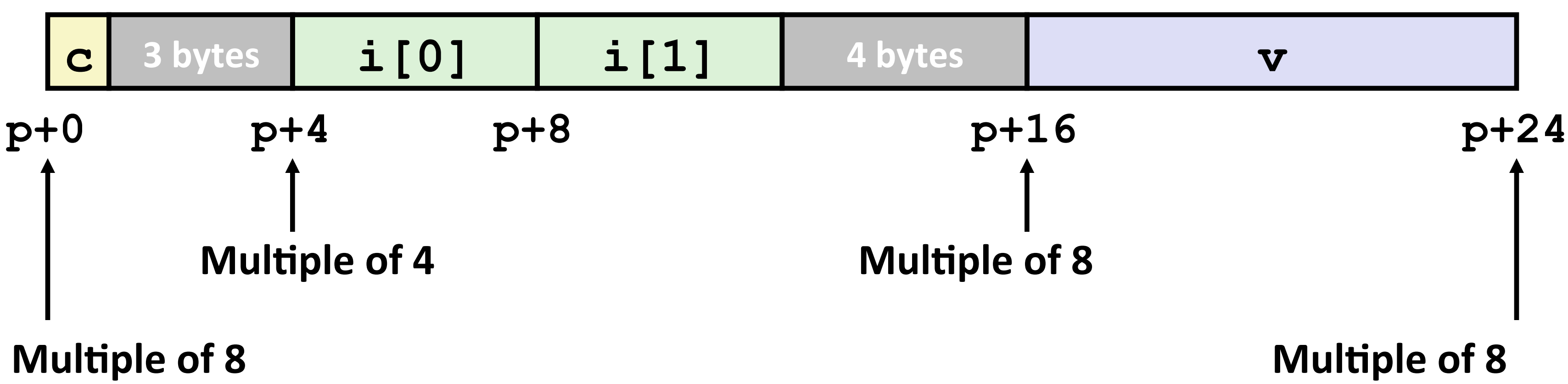
Structures & Alignment

- **Unaligned Data**




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

- **Aligned Data**
  - Primitive data type requires K bytes
  - Address must be multiple of K



Alignment Principles

- **Aligned Data**
  - Primitive data type requires K bytes
  - Address must be multiple of K
  - Required on some machines; advised on IA32
    - treated differently by IA32 Linux, x86-64 Linux, and Windows!
- **Motivation for Aligning Data**
  - Memory accessed by (aligned) chunks of 4 or 8 bytes (system dependent)
    - Inefficient to load or store datum that spans quad word boundaries
    - Virtual memory very tricky when datum spans 2 pages
- **Compiler**
  - Inserts gaps in structure to ensure correct alignment of fields

Specific Cases of Alignment (IA32)

- **1 byte: `char`, …**
  - no restrictions on address
- **2 bytes: `short`, …**
  - lowest 1 bit of address must be 0_2
- **4 bytes: `int`, `float`, `char *`, …**
  - lowest 2 bits of address must be 00_2
- **8 bytes: `double`, …**
  - Windows (and most other OS's & instruction sets):
    - lowest 3 bits of address must be 000_2
  - Linux:
    - lowest 2 bits of address must be 00_2
    - i.e., treated the same as a 4-byte primitive data type
- **12 bytes: `long double`**
  - Windows (GCC), Linux:
    - lowest 2 bits of address must be 00_2
    - i.e., treated the same as a 4-byte primitive data type

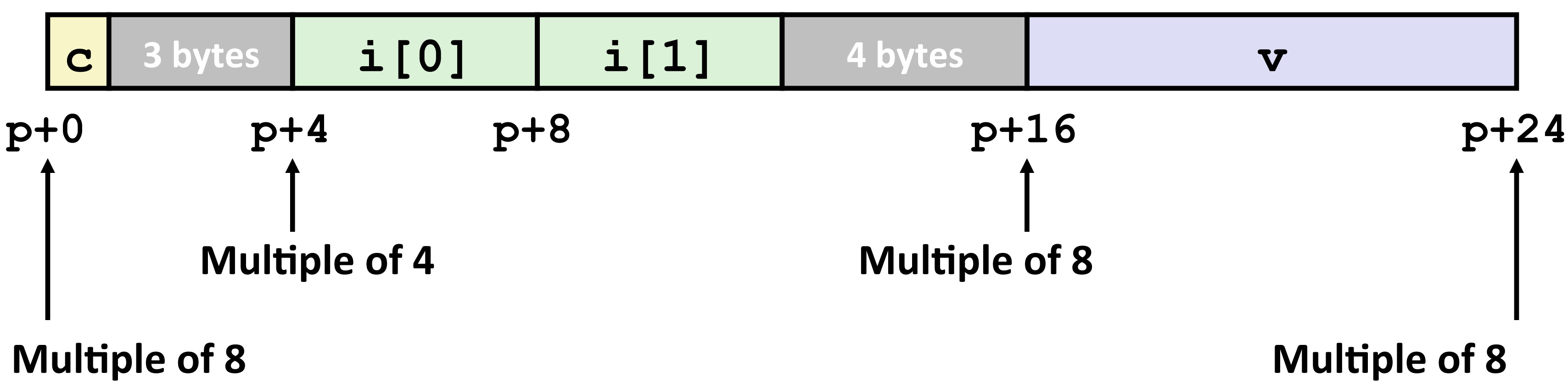
Specific Cases of Alignment (x86-64)

- **1 byte: `char`, …**
  - no restrictions on address
- **2 bytes: `short`, …**
  - lowest 1 bit of address must be 0_2
- **4 bytes: `int`, `float`, …**
  - lowest 2 bits of address must be 00_2
- **8 bytes: `double`, `long`, `char *`, …**
  - lowest 3 bits of address must be 000_2
- **16 bytes: `long double`** (GCC on Linux or Windows)
  - lowest 4 bits of address must be 0000_2

Satisfying Alignment with Structures

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

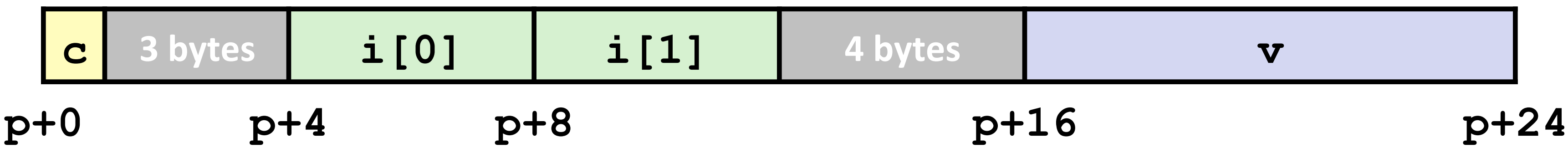
- **Within structure:**
  - Must satisfy each element's alignment requirement
- **Overall structure placement**
  - Each structure has alignment requirement K
    - K = Largest alignment of any element
  - Initial address & structure length must be multiples of K
- **Example (under Windows or x86-64):**
  - K = 8, due to `double` element



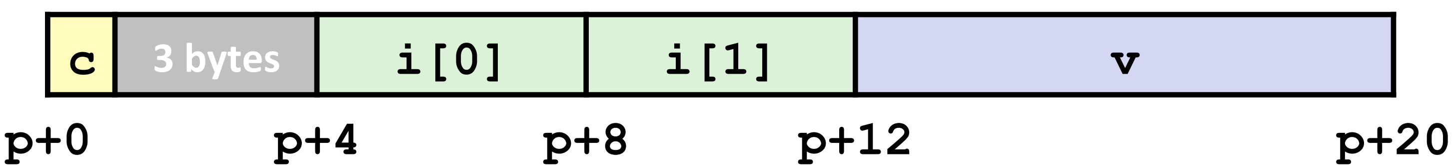
Different Alignment Conventions

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

- **Windows, x86-64**
  - K = 8, due to **`double`** element



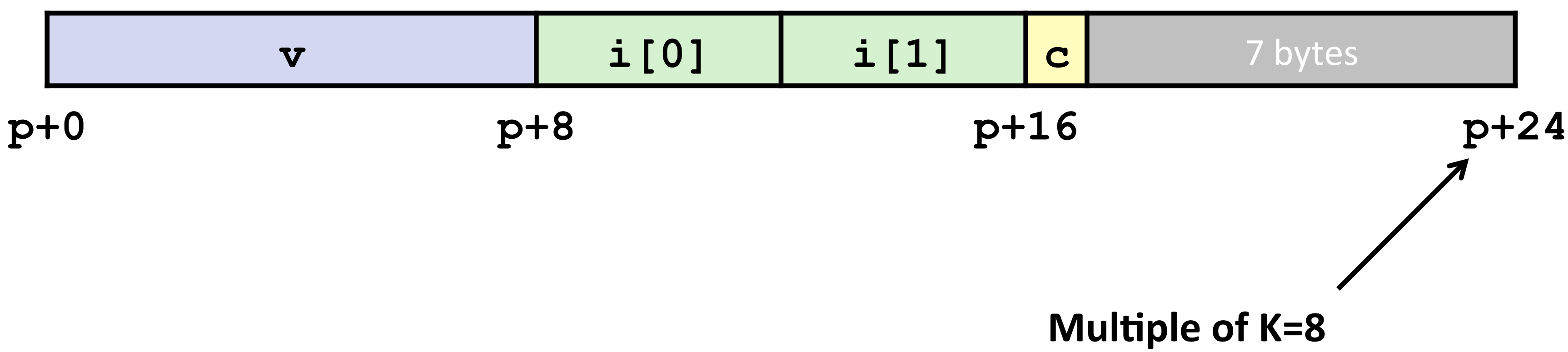
- **IA32 Linux**
  - K = 4; `double` treated like a 4-byte data type



Meeting Overall Alignment Requirement (Windows, x86-64)

- For largest alignment requirement K
- Overall structure must be multiple of K

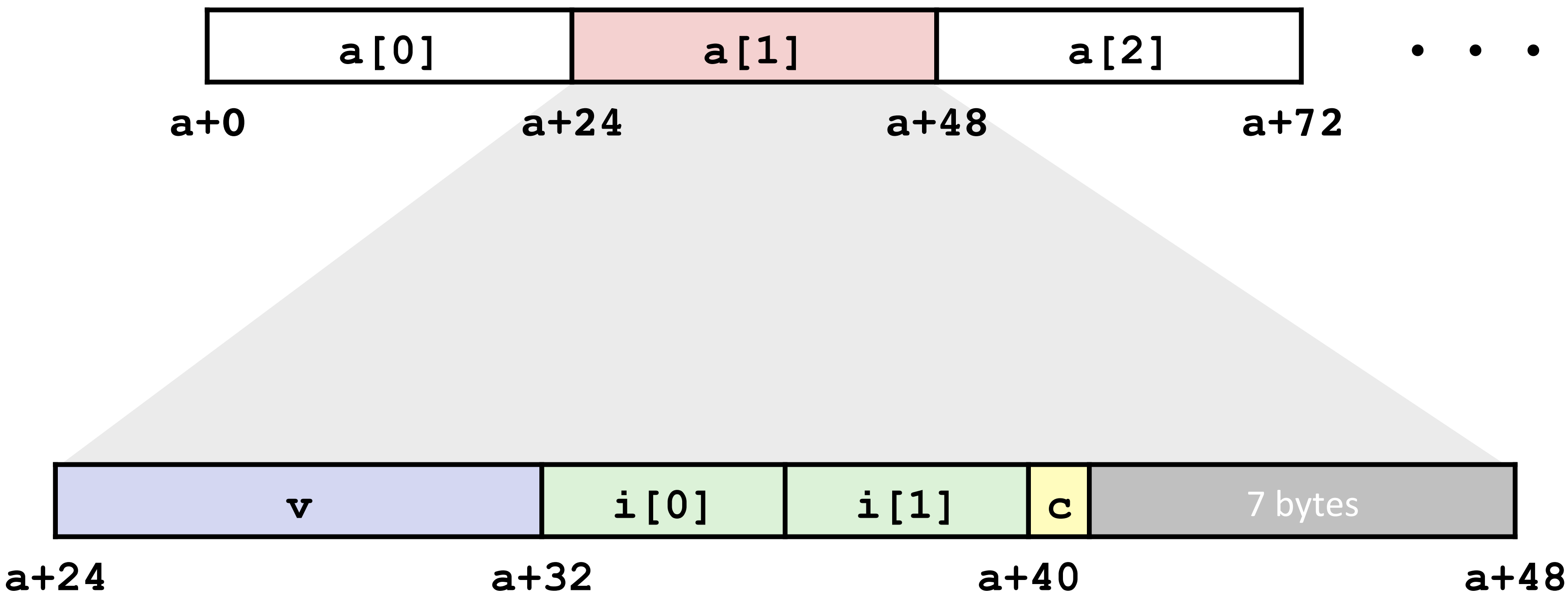
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures (Windows, x86-64)

- Overall structure length multiple of K
- Satisfy alignment requirement for every element

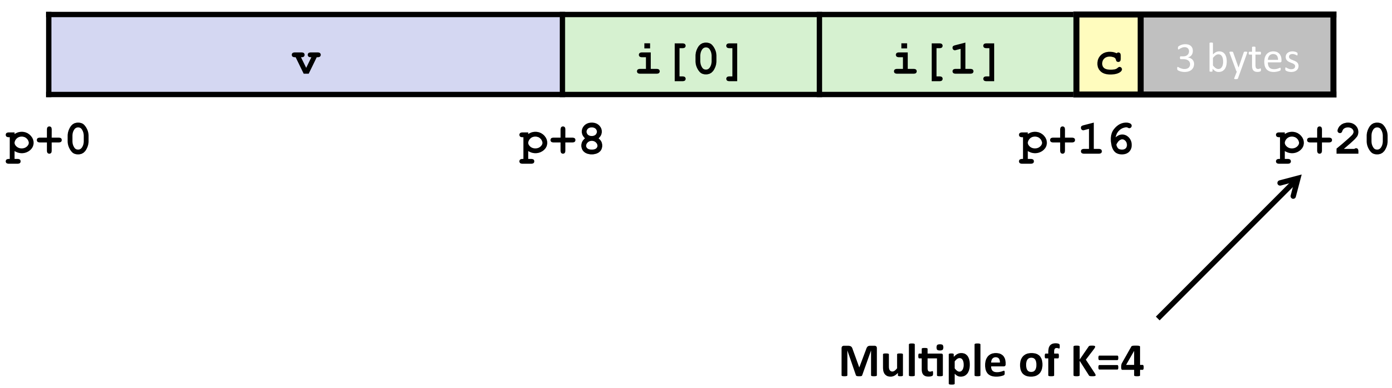
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Meeting Overall Alignment Requirement (IA32 Linux)

- **For largest alignment requirement K**
- **Overall structure must be multiple of K**
  - Up to maximum of K=4

```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures (IA32 Linux)

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```
struct S2 {
  double v;
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  char c;
} a[10];
```
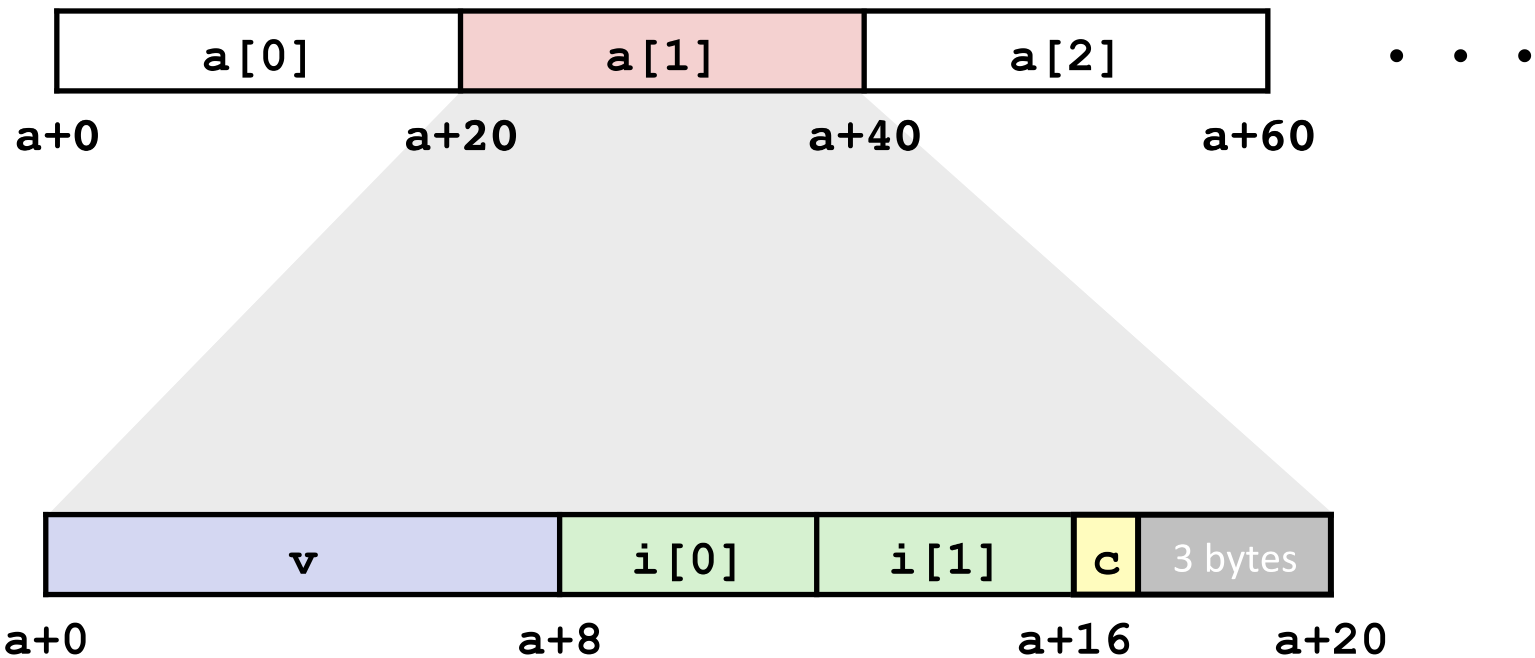
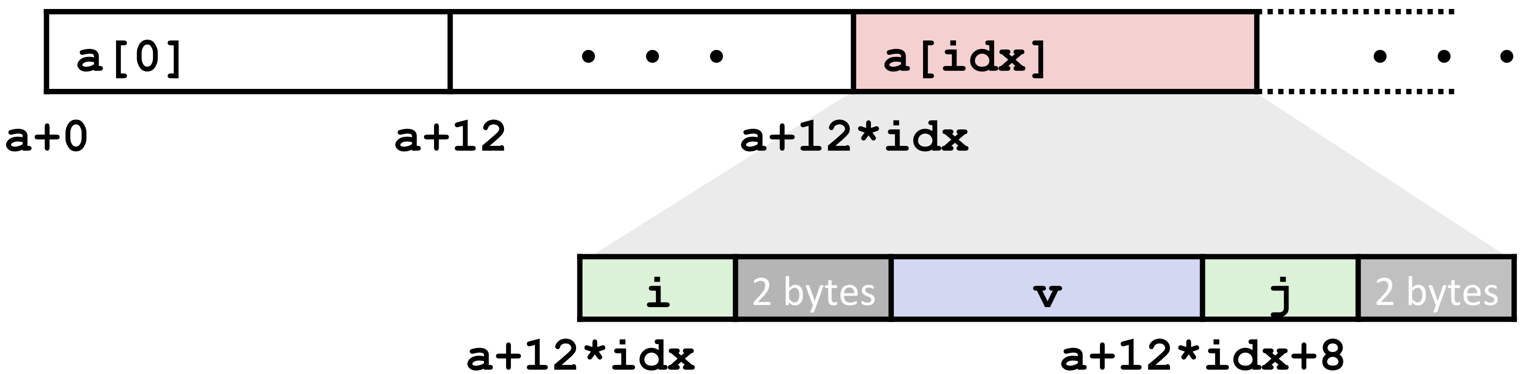



Accessing Array Elements

```
struct S3 {
  short i;
  float v;
  short j;
} a[10];
```

- **Compute array offset 12*idx**
  - `sizeof(S3)`, including alignment spacers
- **Element `j` is at offset 8 within structure**
- **Assembler gives offset `a+8`**
  - Resolved during linking




```
short get_j(int idx)
{
  return a[idx].j;
}
```

```
# %eax = idx
leal  (%eax,%eax,2),%eax # 3*idx
movswl  a+8(,%eax,4),%eax
```

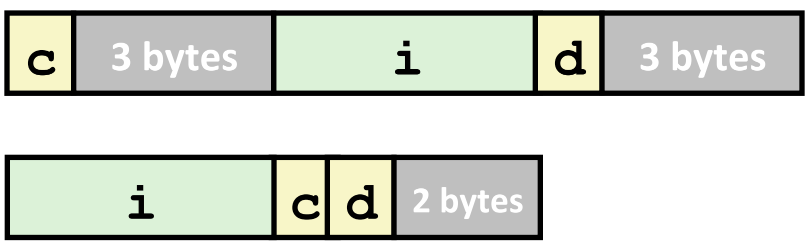
Saving Space

- Put large data types first

```
struct S4 {
  char c;
  int i;
  char d;
} *p;
```

```
struct S5 {
  int i;
  char c;
  char d;
} *p;
```

- Effect (K=4)



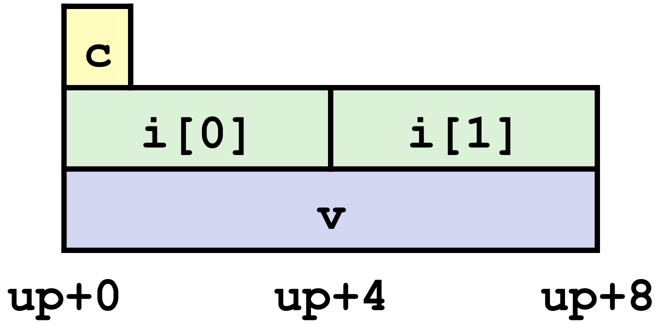
Today

- **Structures**
  - Alignment
- **Unions**
- **Memory Layout**
- **Buffer Overflow**
  - Vulnerability
  - Protection

Union Allocation

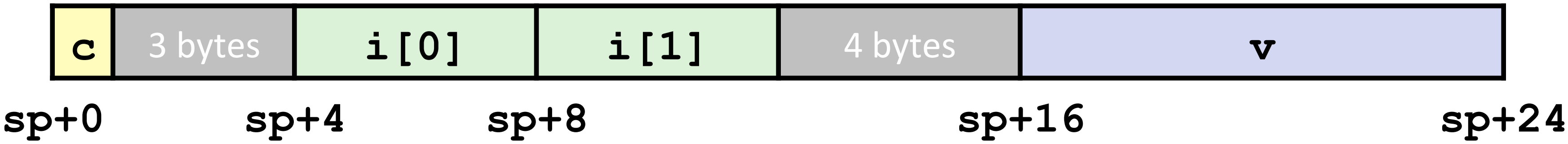
- Allocate according to largest element
- Can only use one field at a time

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



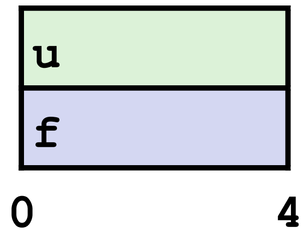

```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```

(Windows or x86-64)



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` ?

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
- **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

```c
union {
  unsigned char c[8];
  unsigned short s[4];
  unsigned int i[2];
  unsigned long l[1];
} dw;
```

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>
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<tr><td colspan="4">l[0]</td><td colspan="4"></td></tr>
</table>

LSB   MSB   LSB   MSB

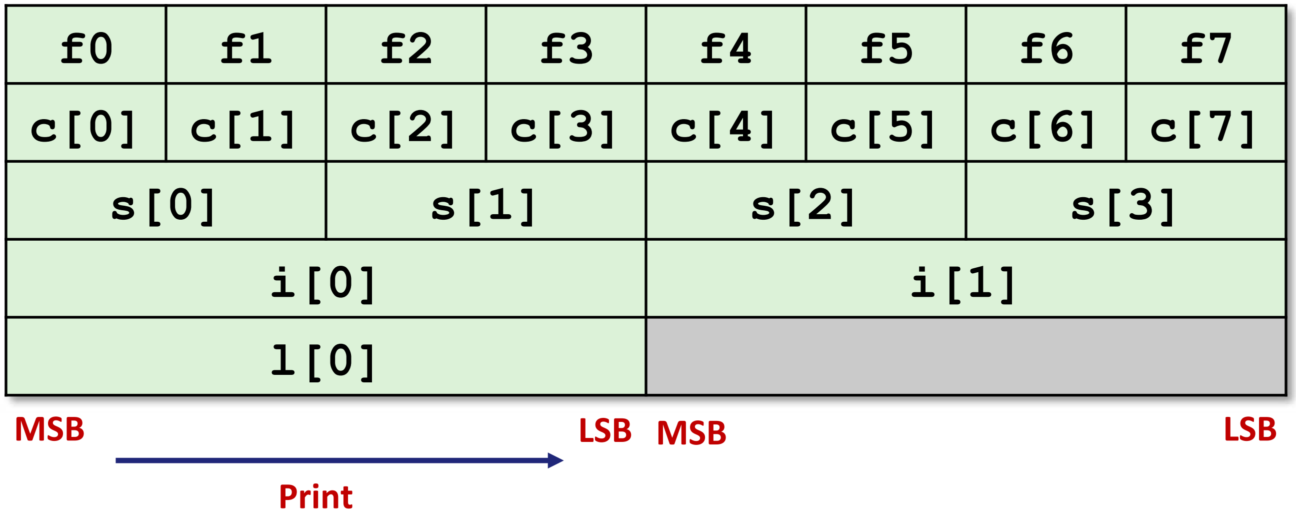
Print

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

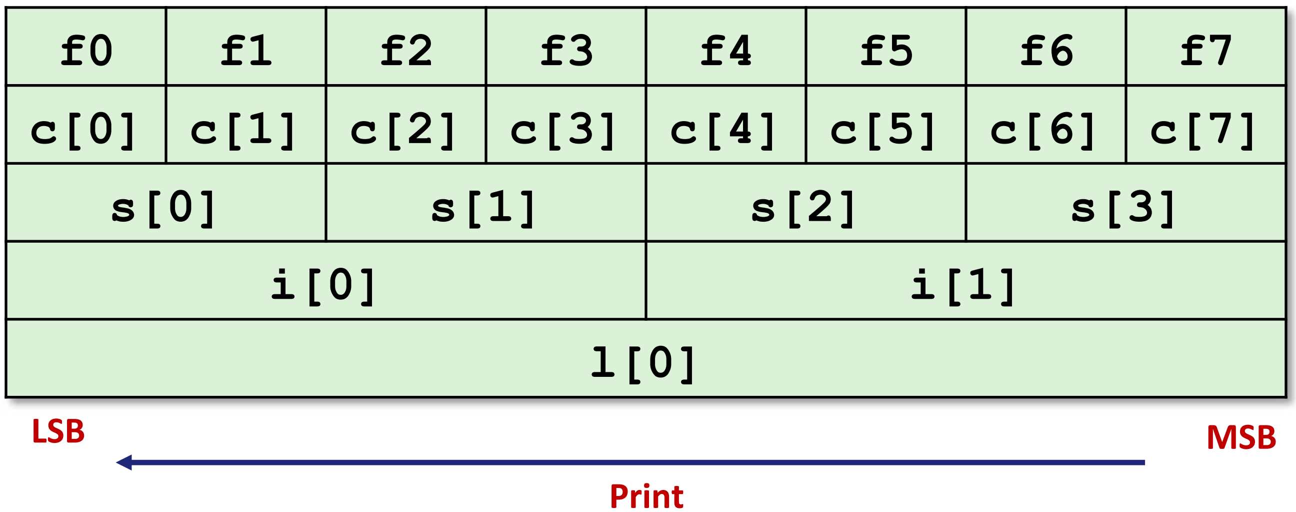


Output on Sun:

```
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



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
    - IA32 Linux unusual in only requiring 4-byte alignment for 8-byte data
  - 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

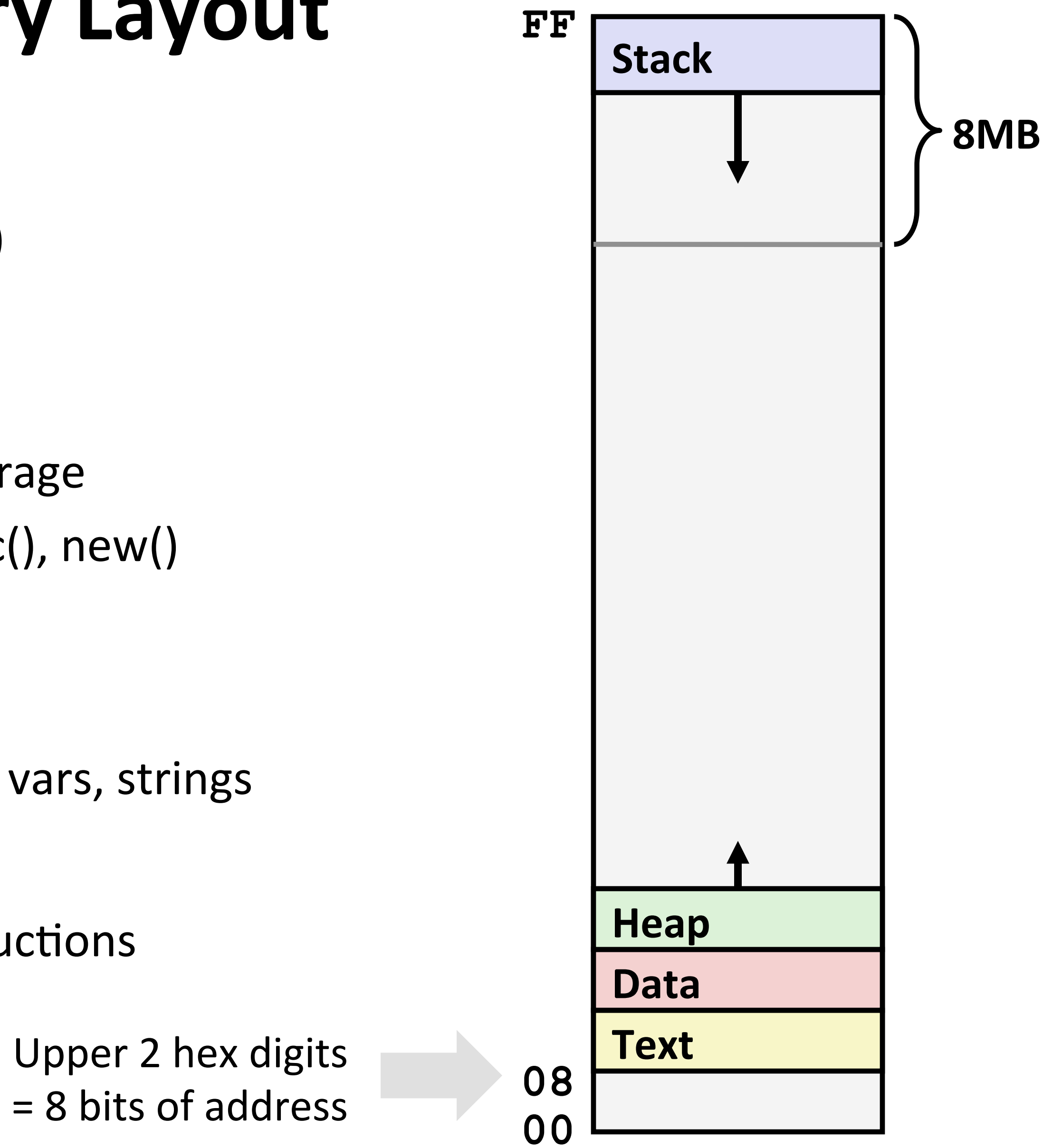
Today

- Structures
  - Alignment
- Unions
- **Memory Layout**
- Buffer Overflow
  - Vulnerability
  - Protection

IA32 Linux Memory Layout

- **Stack**
  - Runtime stack (8MB limit)
  - E. g., local variables
- **Heap**
  - Dynamically allocated storage
  - When call malloc(), calloc(), new()
- **Data**
  - Statically allocated data
  - E.g., global vars, `static` vars, strings
- **Text**
  - Executable machine instructions
  - Read-only

not drawn to scale



not drawn to scale

Memory Allocation Example

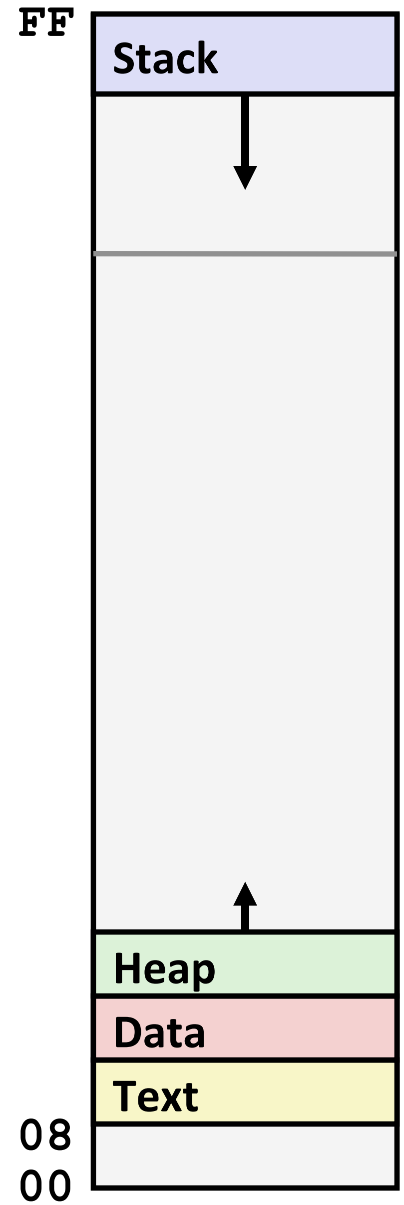
```
char big_array[1<<24];  /*  16 MB */
char huge_array[1<<28]; /* 256 MB */

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?



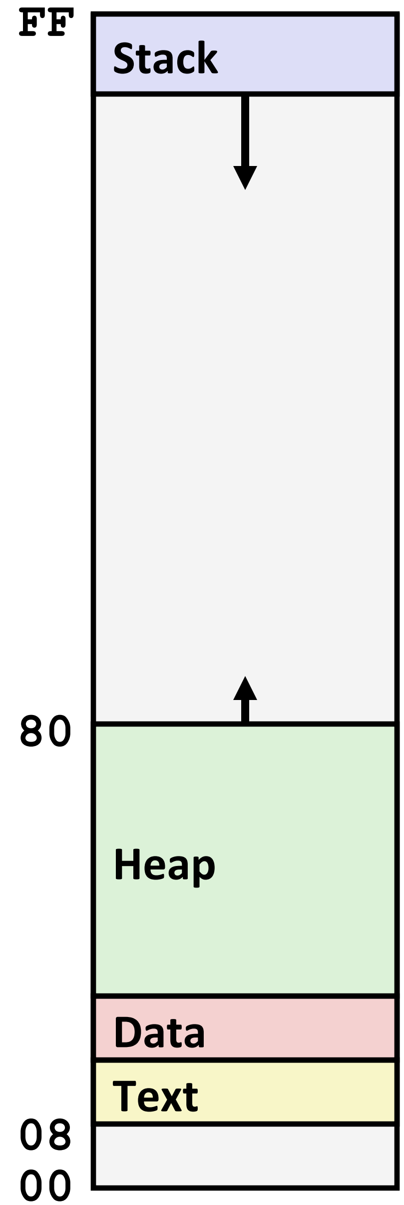
IA32 Example Addresses

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`	`0x00007ffffff8d1f8`
`p3`	`0x00002aaabaadd010`
`p1`	`0x00002aaaaaadc010`
`p4`	`0x0000000011501120`
`p2`	`0x0000000011501010`
`&p2`	`0x0000000010500a60`
`&beyond`	`0x0000000000500a44`
`big_array`	`0x0000000010500a80`
`huge_array`	`0x0000000000500a50`
`main()`	`0x0000000000400510`
`useless()`	`0x0000000000400500`
final `malloc()`	`0x000000386ae6a170`

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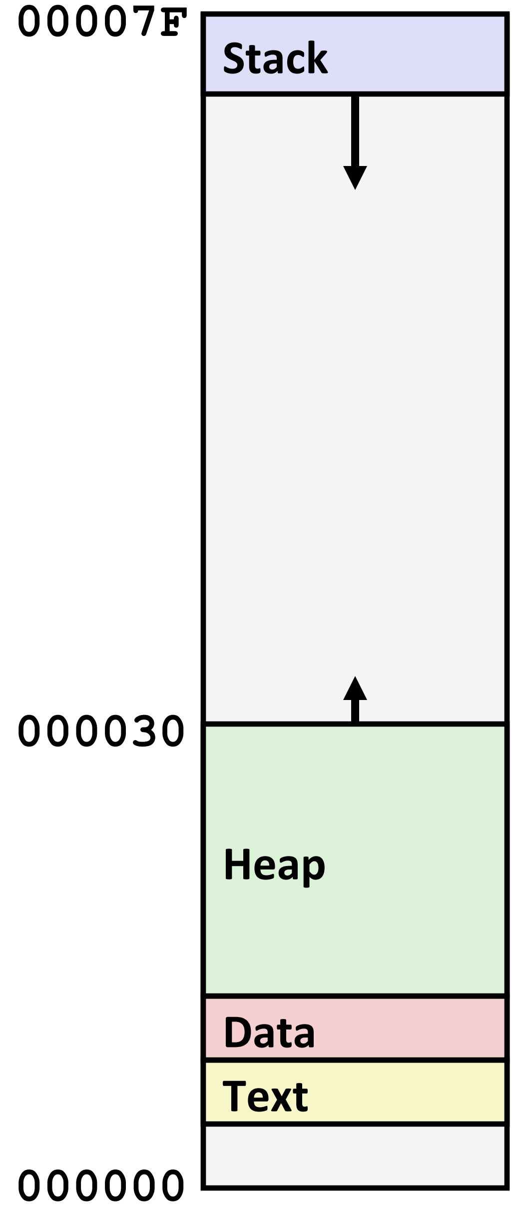

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- Structures
  - Alignment
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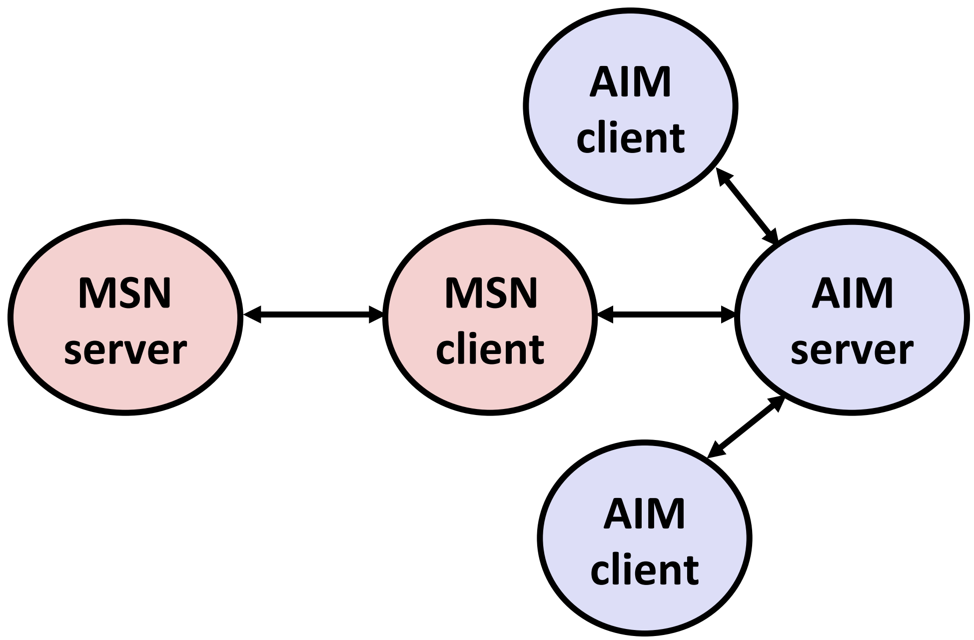
- **Buffer Overflow**
  - Vulnerability
  - Protection

Internet Worm and IM War

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

Internet Worm and IM War

- **July, 1999**
  - Microsoft launches MSN Messenger (instant messaging system).
  - Messenger clients can access popular AOL Instant Messaging Service (AIM) servers



Internet Worm and IM War (cont.)

- **August 1999**
  - Mysteriously, Messenger clients can no longer access AIM servers.
  - Microsoft and AOL begin the IM war:
    - AOL changes server to disallow Messenger clients
    - Microsoft makes changes to clients to defeat AOL changes.
    - At least 13 such skirmishes.
  - How did it happen?

Internet Worm and IM War (cont.)

- **The Internet Worm and AOL/Microsoft War were both based on *stack buffer overflow* exploits!**
  - many library functions do not check argument sizes.
  - allows target buffers to overflow.

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);
}
```

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

```
unix>./bufdemo
Type a string:0123456789a
0123456789a
```

```
unix>./bufdemo
Type a string:0123456789ab
Segmentation Fault
```

Buffer Overflow Disassembly

echo:

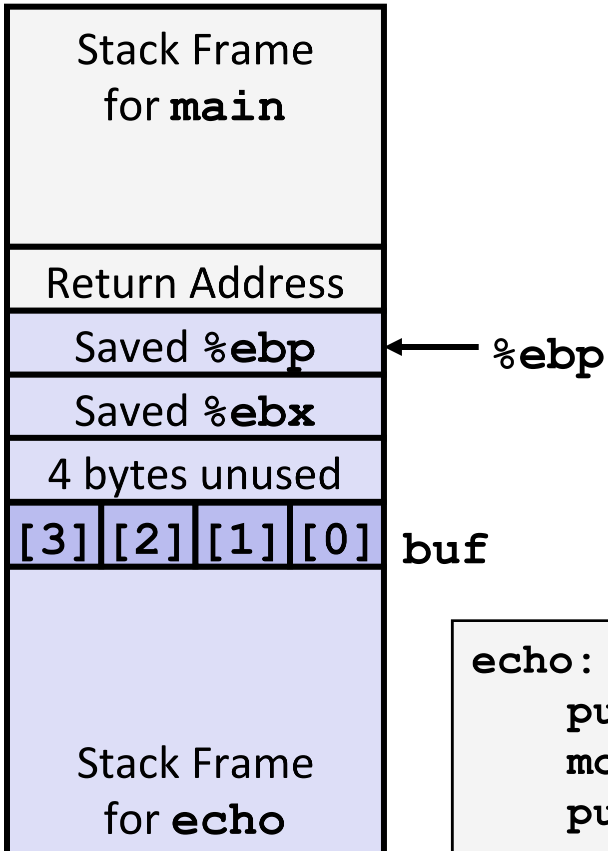
```
080485c3 <echo>:
80485c3:  55                    push   %ebp
80485c4:  89 e5                 mov    %esp,%ebp
80485c6:  53                    push   %ebx
80485c7:  83 ec 24              sub    $0x24,%esp
80485ca:  8d 5d f4              lea    -0xc(%ebp),%ebx
80485cd:  89 1c 24              mov    %ebx,(%esp)
80485d0:  e8 9e ff ff ff        call   8048573 <gets>
80485d5:  89 1c 24              mov    %ebx,(%esp)
80485d8:  e8 2f fe ff ff        call   804840c <puts@plt>
80485dd:  83 c4 24              add    $0x24,%esp
80485e0:  5b                    pop    %ebx
80485e1:  5d                    pop    %ebp
80485e2:  c3                    ret
```

call_echo:

```
 . . .
80485e9:  e8 d5 ff ff ff        call   80485c3 <echo>
80485ee:  c9                    leave
80485ef:  c3                    ret
```

Buffer Overflow Stack

Before call to gets



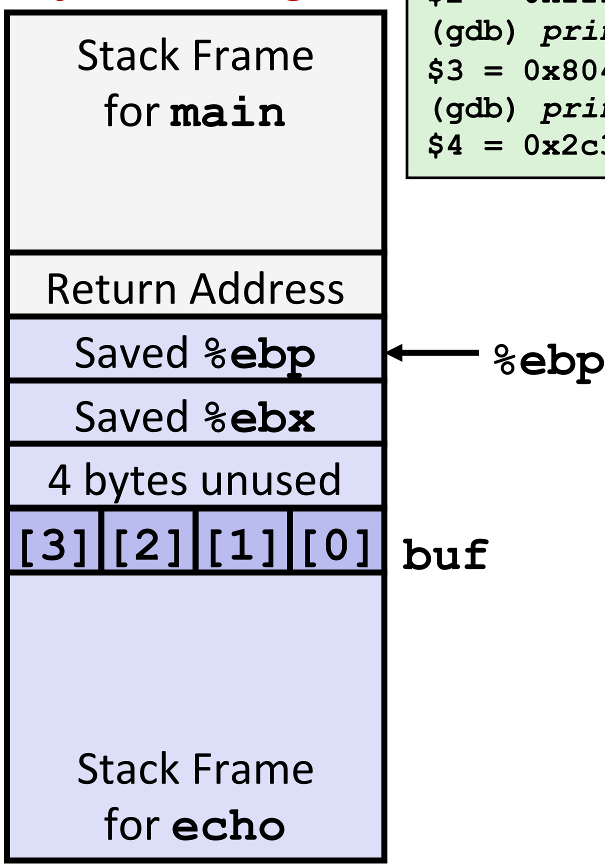

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    pushl %ebp              # Save %ebp on stack
    movl  %esp, %ebp
    pushl %ebx              # Save %ebx
    subl  $36, %esp         # Allocate stack space
    leal  -12(%ebp),%ebx    # Compute buf as %ebp-12
    movl  %ebx, (%esp)      # Push buf on stack
    call  gets              # Call gets
    . . .
```

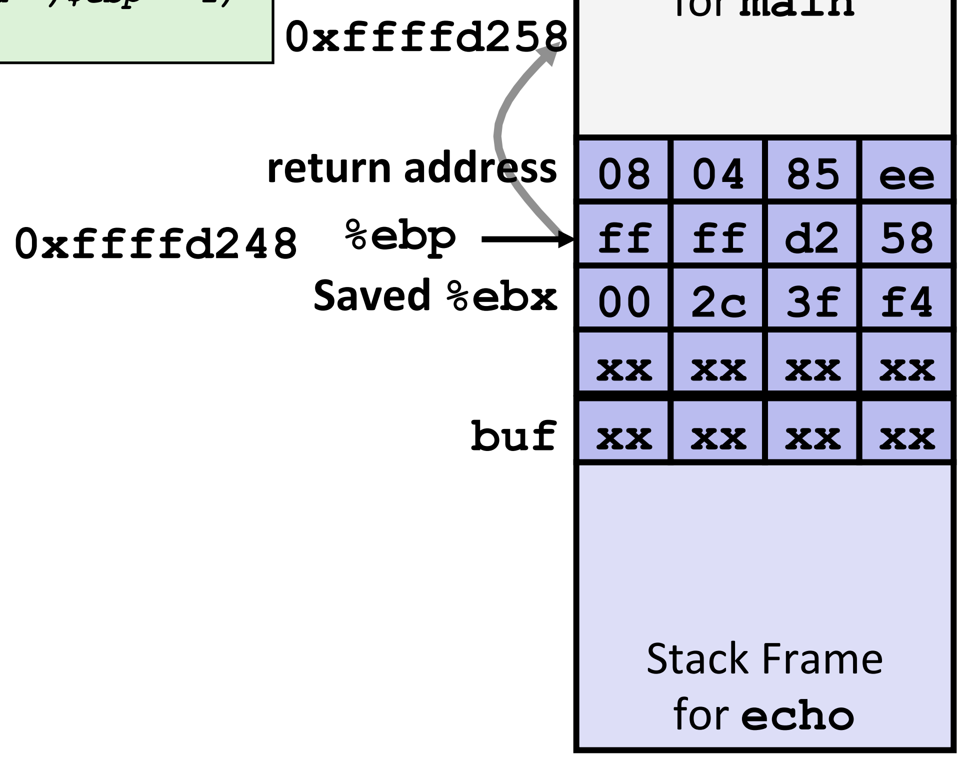
Buffer Overflow Stack Example

```
unix> gdb bufdemo
(gdb) break echo
Breakpoint 1 at 0x80485c9
(gdb) run
Breakpoint 1, 0x80485c9 in echo ()
(gdb) print /x $ebp
$1 = 0xffffd248
(gdb) print /x *(unsigned *)$ebp
$2 = 0xffffd258
(gdb) print /x *((unsigned *)$ebp + 1)
$3 = 0x80485ee
(gdb) print /x *((unsigned *)$ebp - 1)
$4 = 0x2c3ff4
```

Before call to gets



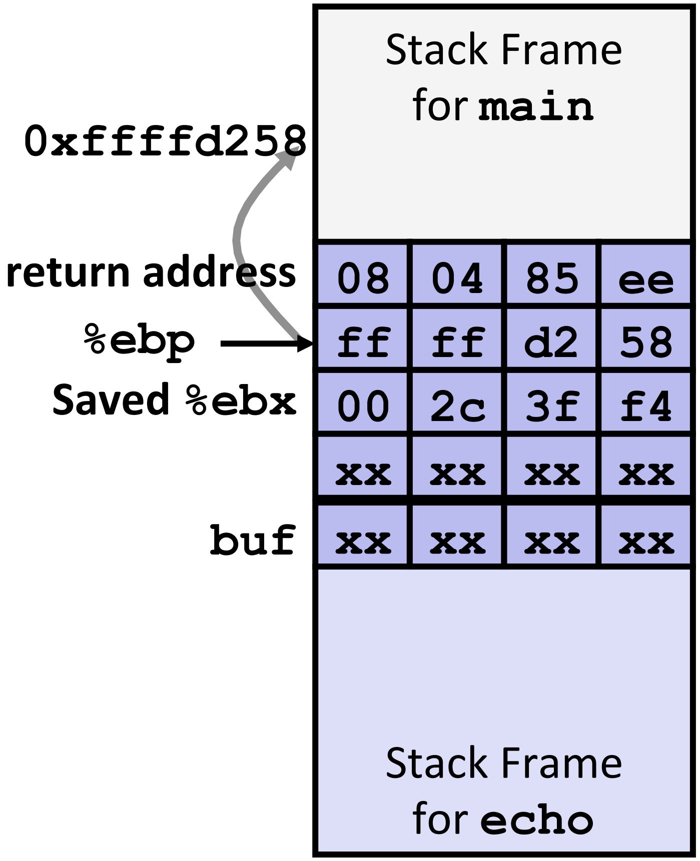
Before call to gets



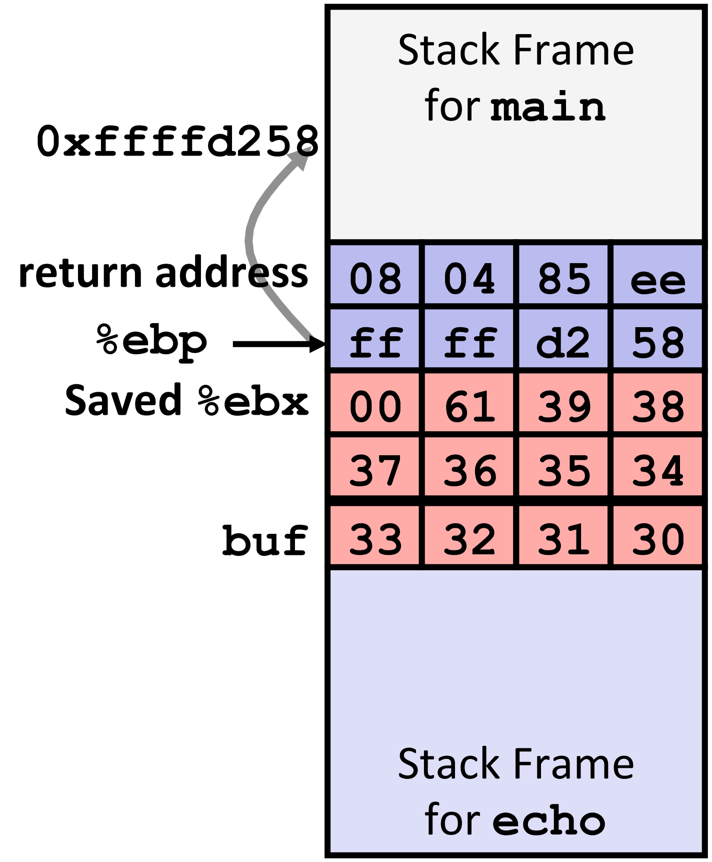

```
80485e9:   e8 d5 ff ff ff          call   80485c3 <echo>
80485ee:   c9                      leave
```

Buffer Overflow Example #1

Before call to gets



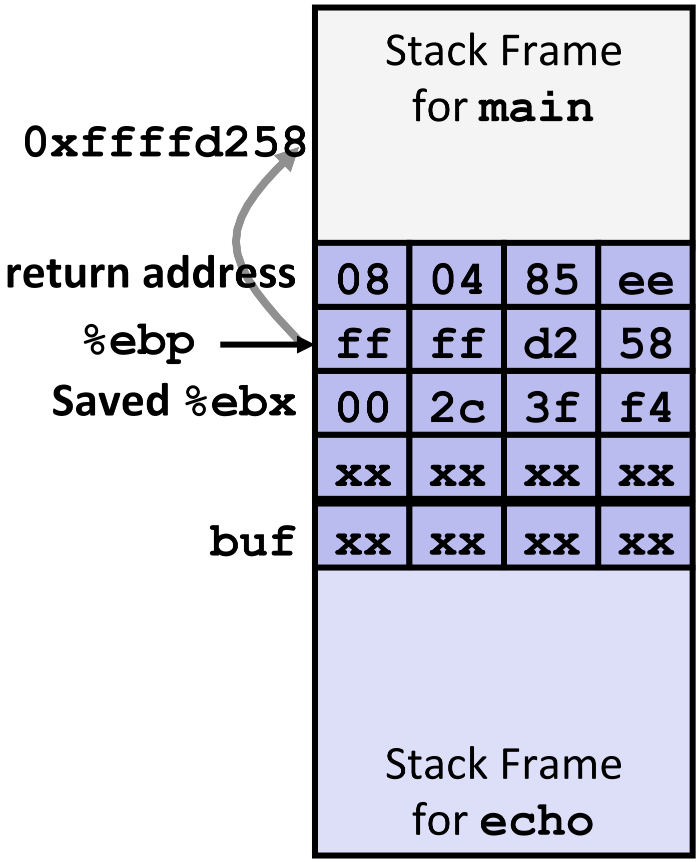
Input 0123456789a



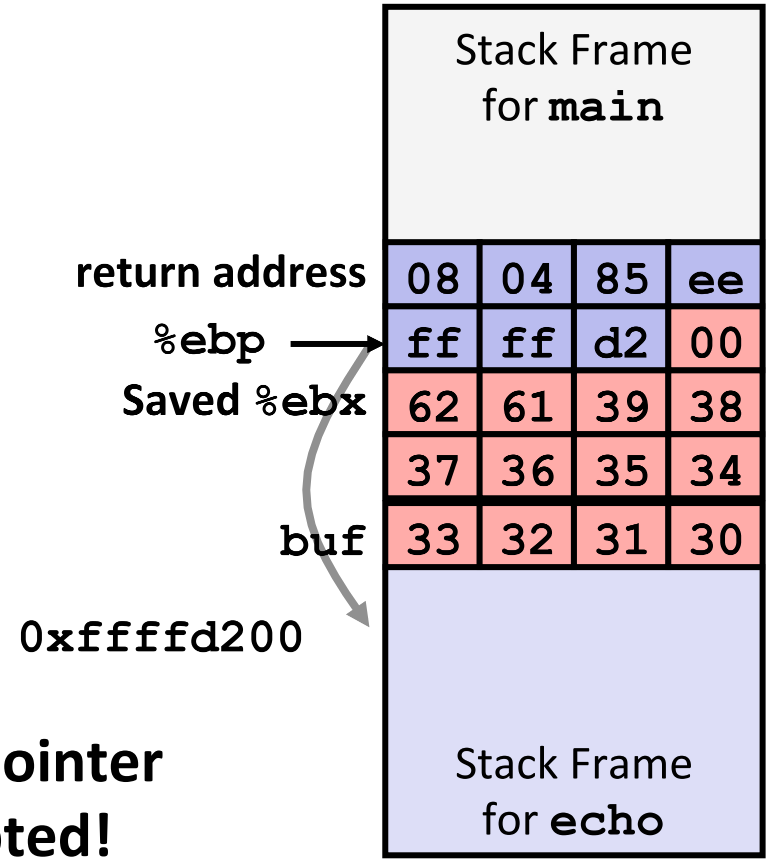
Overflow buf, and corrupt %ebx, but no adverse effects

Buffer Overflow Example #2

Before call to gets



Input 0123456789ab

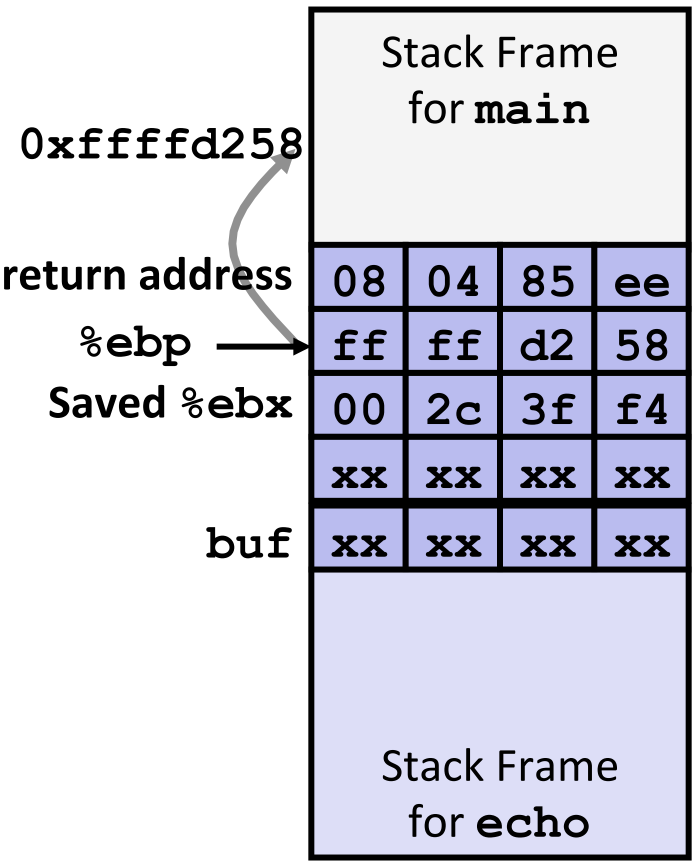


Base pointer corrupted!

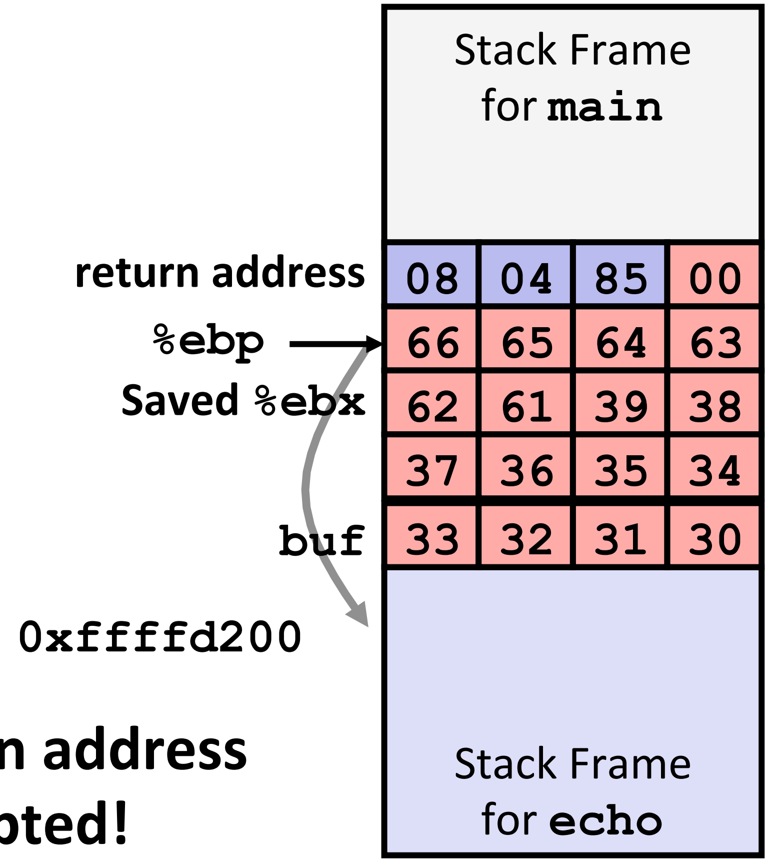
```
. . .
80485e9:   e8 d5 ff ff ff        call   80485c3 <echo>
80485ee:   c9                    leave  # Set %ebp to bad value
80485ef:   c3                    ret
```

Buffer Overflow Example #3

Before call to gets



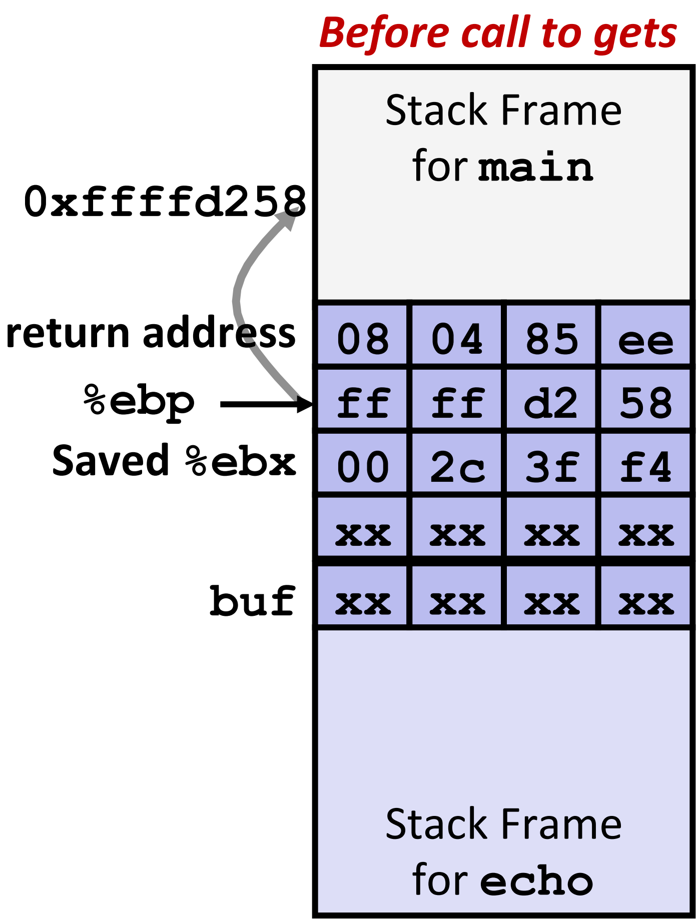
Input 0123456789abcdef



Return address corrupted!

```
. . .
80485e9:   e8 d5 ff ff ff          call   80485c3 <echo>
80485ee:   c9                      leave  # Desired return point
```

Buffer Overflow Example #4



- Can we trick program into calling a different function?

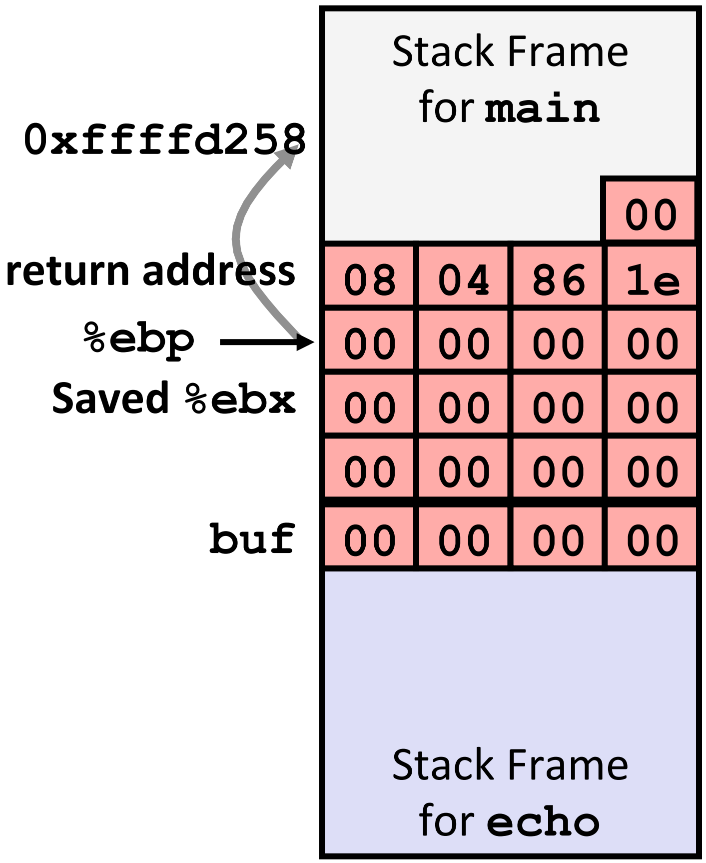
```
void gotcha() {
    printf(
"This function should not get called!\n"
           );
}
```

- Idea: Alter return address on stack

```
0804861e <gotcha>:
 804861e: 55   push   %ebp
  . . .
```

Buffer Overflow Example #4

Before call to gets



- **Alter return address on stack**

```
0804861e <gotcha>:
 804861e: 55  push   %ebp
  . . .
```

- **Exploit string:**

  00 00 00 00 00 00 00 00 (8X)

  00 00 00 00 00 00 00 00 (8X)

  1e 86 04 08 (Little Endian)

- **Must supply as raw bytes**
  - E.g., via tool hex2raw
  - See Buffer Lab

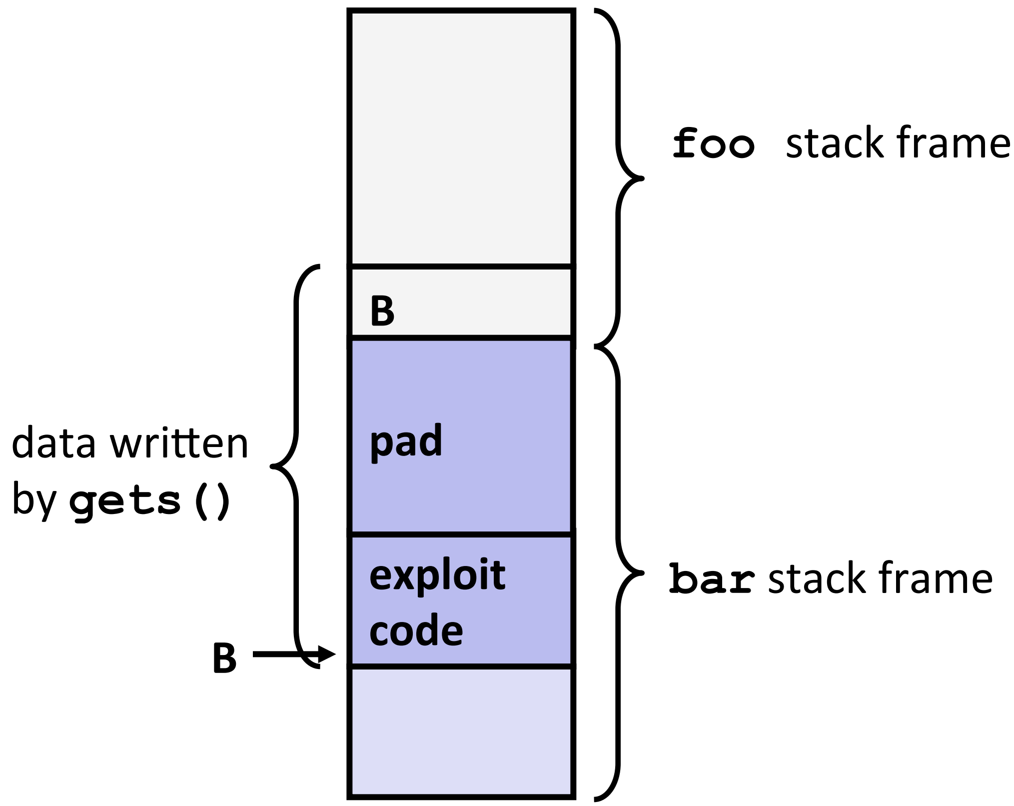
Malicious Use of Buffer Overflow

```
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 A with address of buffer B**
- **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.

Exploits Based on Buffer Overflows

- ***Buffer overflow bugs allow remote machines to execute arbitrary code on victim machines***
- **IM War**
  - AOL exploited existing buffer overflow bug in AIM clients
  - exploit code: returned 4-byte signature (the bytes at some location in the AIM client) to server.
  - When Microsoft changed code to match signature, AOL changed signature location.

```
Date: Wed, 11 Aug 1999 11:30:57 -0700 (PDT)
From: Phil Bucking <philbucking@yahoo.com>
Subject: AOL exploiting buffer overrun bug in their own software!
To: rms@pharlap.com

Mr. Smith,

I am writing you because I have discovered something that I think you
might find interesting because you are an Internet security expert with
experience in this area. I have also tried to contact AOL but received
no response.

I am a developer who has been working on a revolutionary new instant
messaging client that should be released later this year.
...
It appears that the AIM client has a buffer overrun bug. By itself
this might not be the end of the world, as MS surely has had its share.
But AOL is now *exploiting their own buffer overrun bug* to help in
its efforts to block MS Instant Messenger.
....
Since you have significant credibility with the press I hope that you
can use this information to help inform people that behind AOL's
friendly exterior they are nefariously compromising peoples' security.

Sincerely,
Phil Bucking
Founder, Bucking Consulting
philbucking@yahoo.com
```

It was later determined that this email originated from within Microsoft!

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
  - Currently disabled on shark machines

```
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
```

- **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 Canaries

- **Idea**
  - Place special value ("canary") on stack just beyond buffer
  - Check for corruption before exiting function
- **GCC Implementation**
  - `-fstack-protector`
  - `-fstack-protector-all`

```
unix>./bufdemo-protected
Type a string:123
123
```

```
unix>./bufdemo-protected
Type a string:1234
*** stack smashing detected ***
```

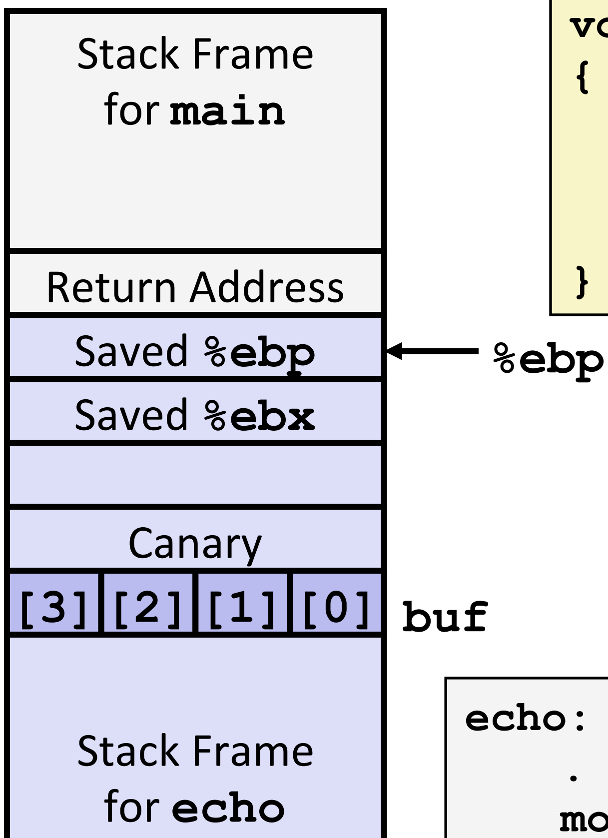
Protected Buffer Disassembly

echo:

```
804864b:   55                        push   %ebp
804864c:   89 e5                     mov    %esp,%ebp
804864e:   53                        push   %ebx
804864f:   83 ec 24                  sub    $0x24,%esp
8048652:   65 a1 14 00 00 00         mov    %gs:0x14,%eax
8048658:   89 45 f4                  mov    %eax,-0xc(%ebp)
804865b:   31 c0                     xor    %eax,%eax
804865d:   8d 5d f0                  lea    -0x10(%ebp),%ebx
8048660:   89 1c 24                  mov    %ebx,(%esp)
8048663:   e8 77 ff ff ff            call   80485df <gets>
8048668:   89 1c 24                  mov    %ebx,(%esp)
804866b:   e8 f0 fd ff ff            call   8048460 <puts@plt>
8048670:   8b 45 f4                  mov    -0xc(%ebp),%eax
8048673:   65 33 05 14 00 00 00      xor    %gs:0x14,%eax
804867a:   74 05                     je     8048681 <echo+0x36>
804867c:   e8 cf fd ff ff            call   8048450 <...fail...>
8048681:   83 c4 24                  add    $0x24,%esp
8048684:   5b                        pop    %ebx
8048685:   5d                        pop    %ebp
8048686:   c3                        ret
```

Setting Up Canary

Before call to gets

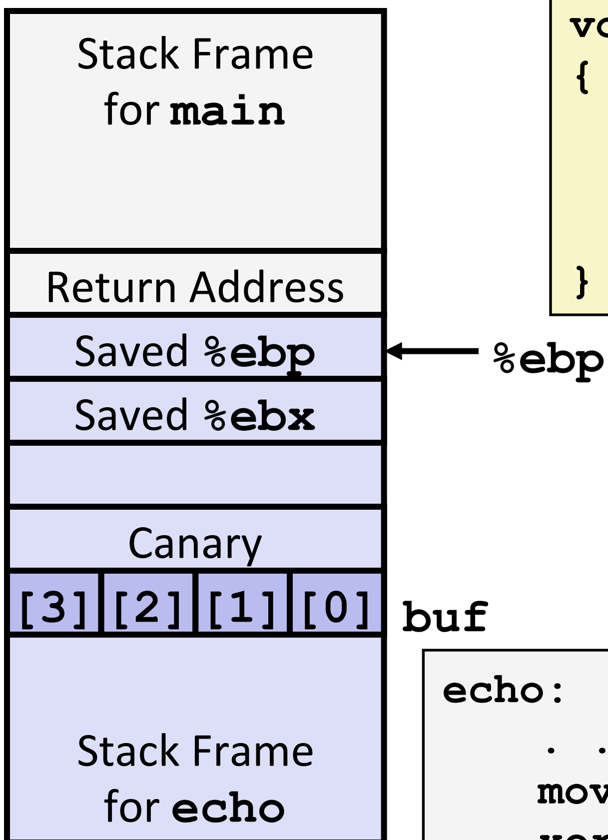



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movl    %gs:20, %eax      # Get canary
    movl    %eax, -12(%ebp)   # Put on stack
    xorl    %eax, %eax        # Erase canary
    . . .
```

Checking Canary

Before call to gets

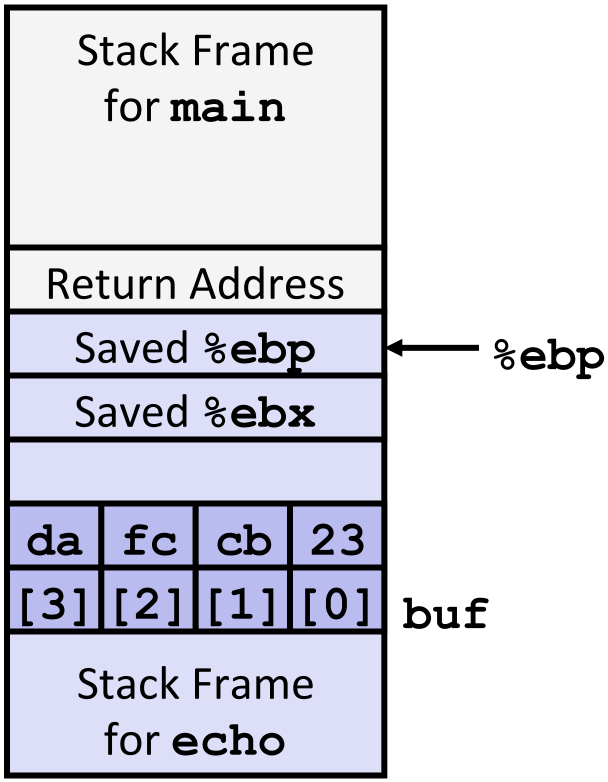



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

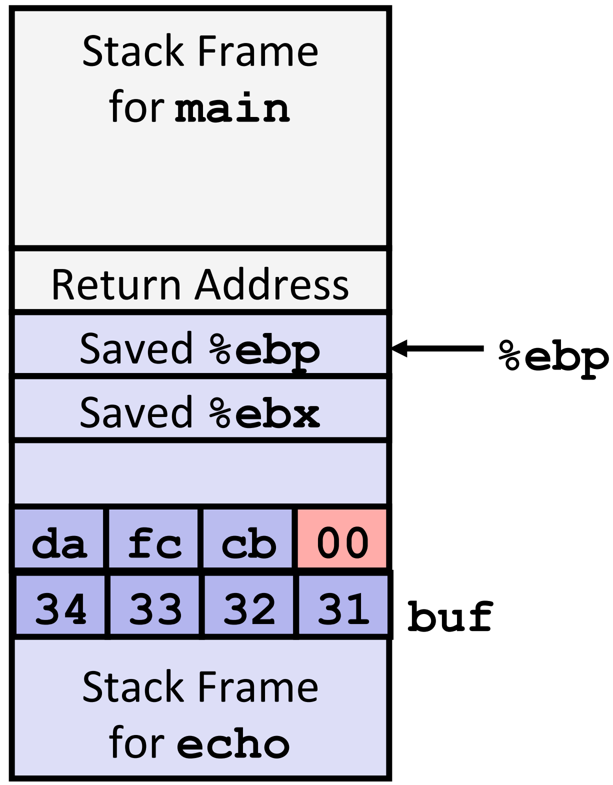
```
echo:
    . . .
    movl    -12(%ebp), %eax    # Retrieve from stack
    xorl    %gs:20, %eax       # Compare with Canary
    je      .L24               # Same: skip ahead
    call    __stack_chk_fail   # ERROR
.L24:
    . . .
```

Canary Example

Before call to gets



Input 1234




```
(gdb) break echo
(gdb) run
(gdb) stepi 3
(gdb) print /x *((unsigned *) $ebp - 3)
$1 = dafccb23
```

Canary corrupted

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**

Summary

- **Structures**
  - Alignment
- **Unions**
- **Memory Layout**
- **Buffer Overflow**
  - Vulnerability
  - Protection