

IF2130 – Organisasi dan Arsitektur Komputer

sumber: Greg Kesden, CMU 15-213, 2012

Machine-Level Programming: Struktur

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Today

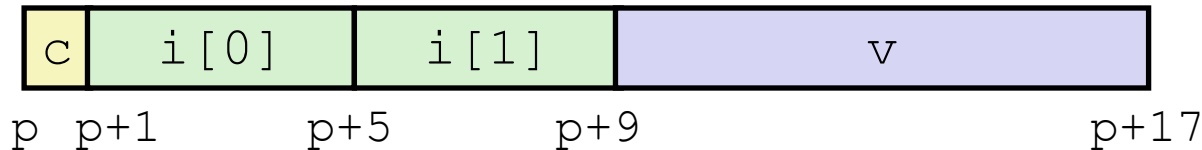
■ Structures

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



Structures & Alignment

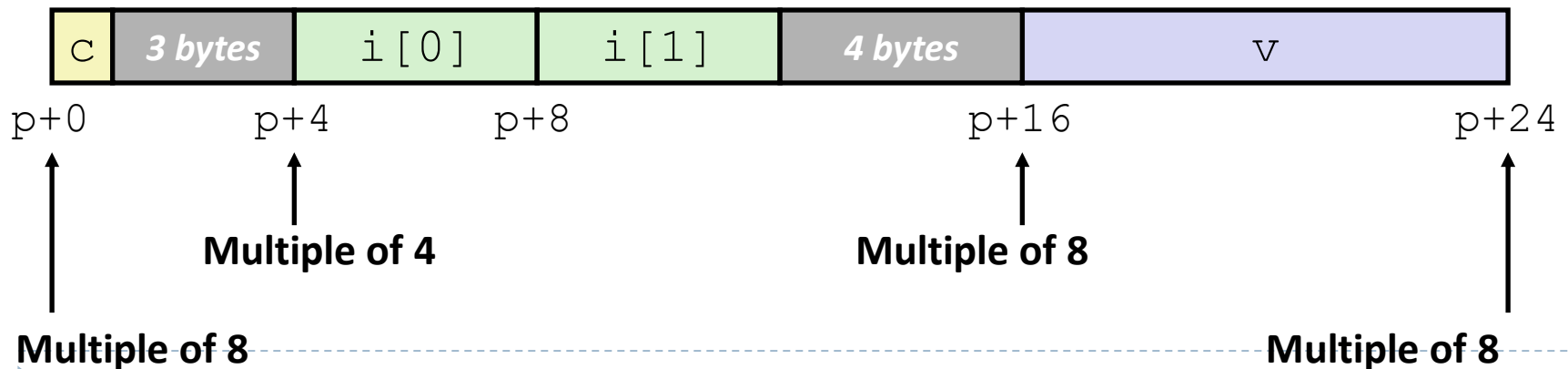
▶ Unaligned Data



```
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, 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)

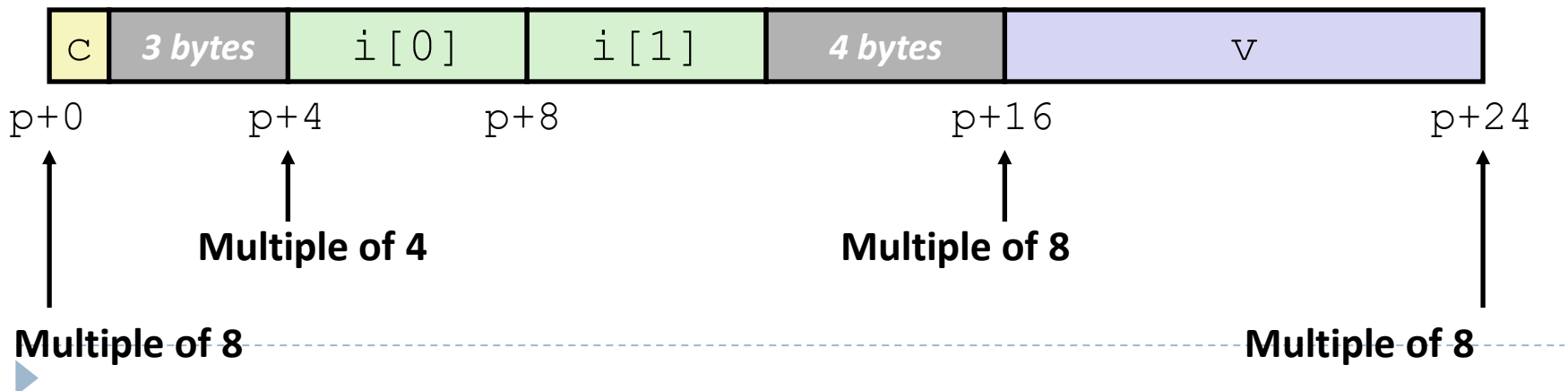
- ▶ 1 byte: **char**, ...
 - ▶ no restrictions on address
- ▶ 2 bytes: **short**, ...
 - ▶ lowest 1 bit of address must be 0_2
- ▶ 4 bytes: **int**, **float**, ...
 - ▶ lowest 2 bits of address must be 00_2
- ▶ 8 bytes: **double**, **char ***, ...
 - ▶ Windows & Linux:
 - ▶ lowest 3 bits of address must be 000_2
- ▶ 16 bytes: **long double**
 - ▶ Linux:
 - ▶ lowest 3 bits of address must be 000_2
 - ▶ i.e., treated the same as a 8-byte primitive data type



Satisfying Alignment with Structures

- ▶ 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

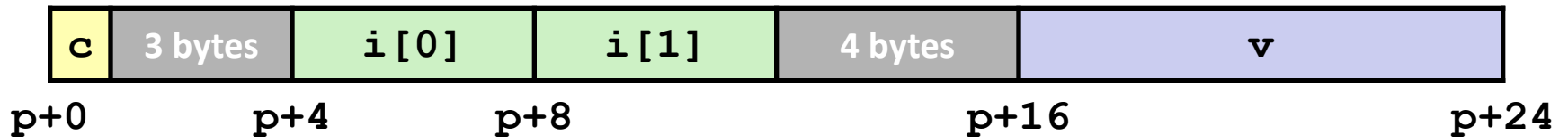
```
struct S1 {  
    char c;  
    int i[2];  
    double v;  
} *p;
```



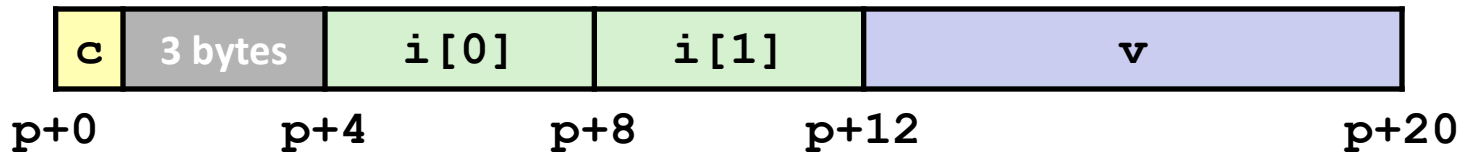
Different Alignment Conventions

- ▶ x86-64 or IA32 Windows:
 - ▶ $K = 8$, due to **double** element

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



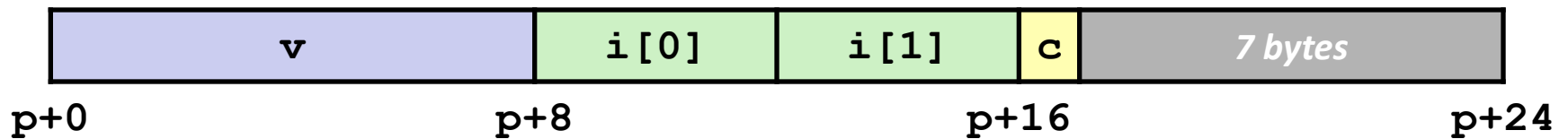
- ▶ IA32 Linux
 - ▶ $K = 4$; **double** treated like a 4-byte data type



Meeting Overall Alignment Requirement

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

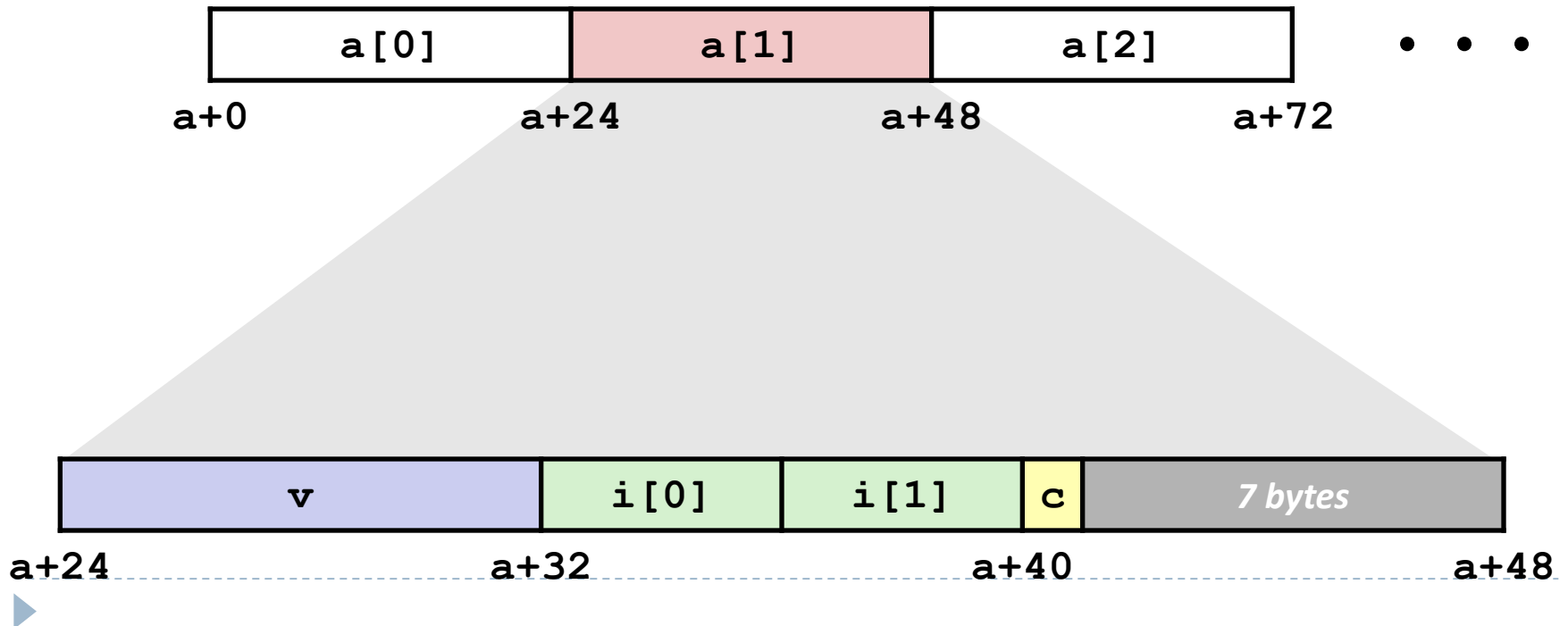
```
struct S2 {  
    double v;  
    int i[2];  
    char c;  
} *p;
```



Arrays of Structures

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

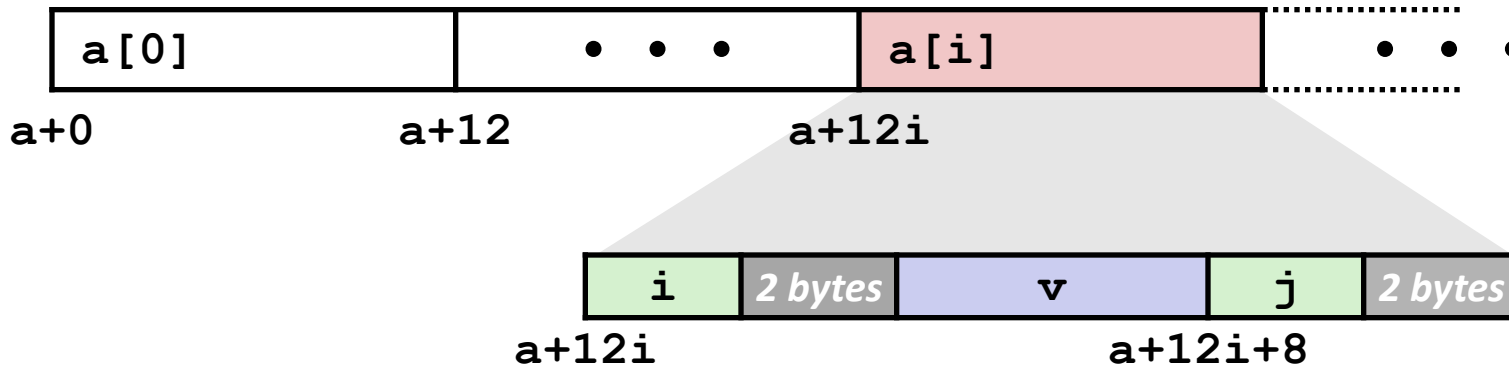
```
struct S2 {  
    double v;  
    int i[2];  
    char c;  
} a[10];
```



Accessing Array Elements

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

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



```
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

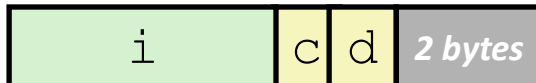
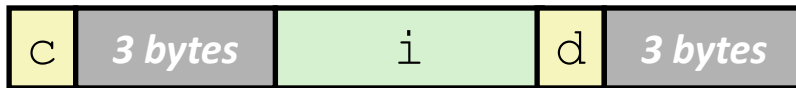
- Put large data types first

```
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

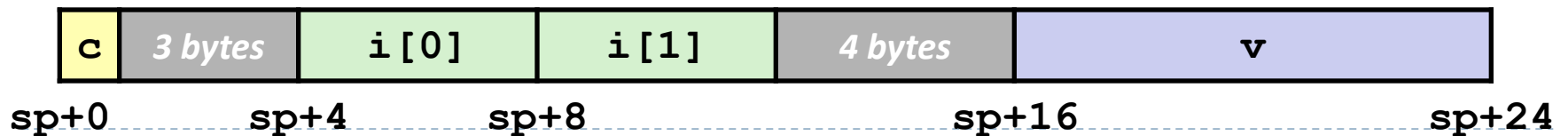
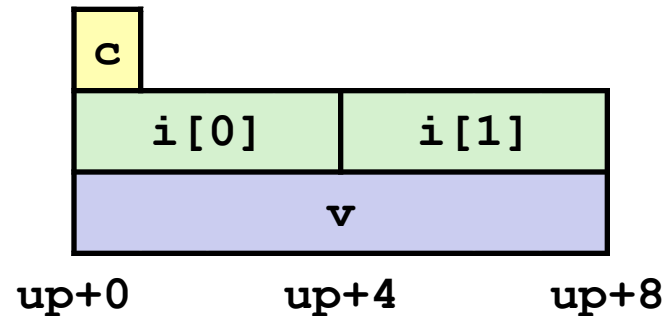


Union Allocation

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

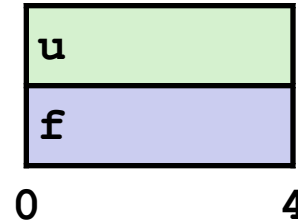
```
union U1 {  
    char c;  
    int i[2];  
    double v;  
} *up;
```

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



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

Byte Ordering Example

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

32-bit	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]							

64-bit	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]							

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]);

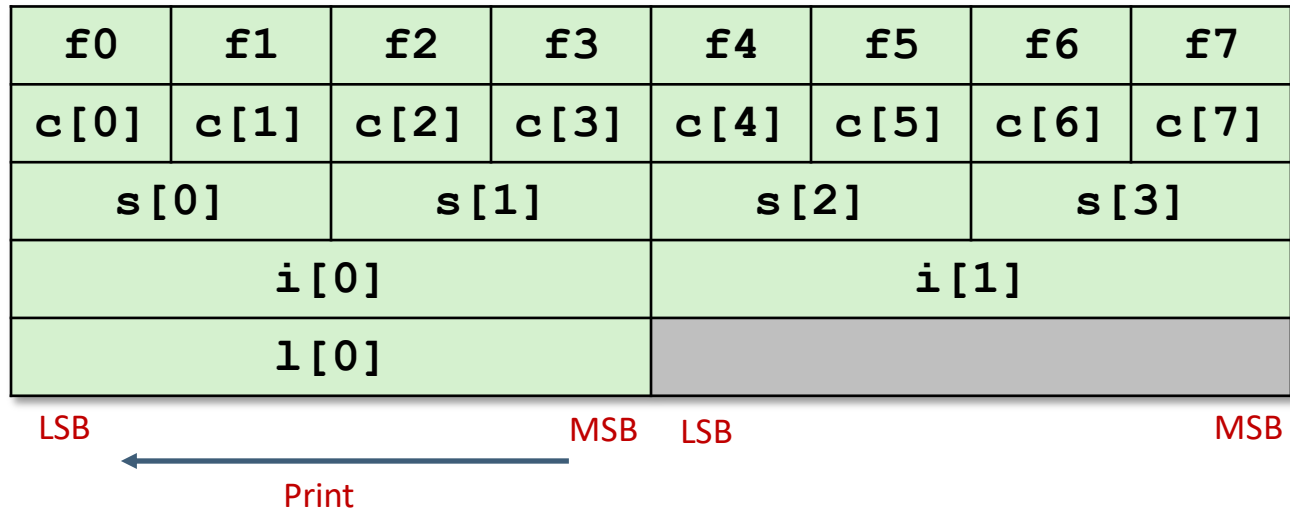
printf("Shorts 0-3 == [0x%x,0x%x,0x%x,0x%x]\n",
    dw.s[0], dw.s[1], dw.s[2], dw.s[3]);

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



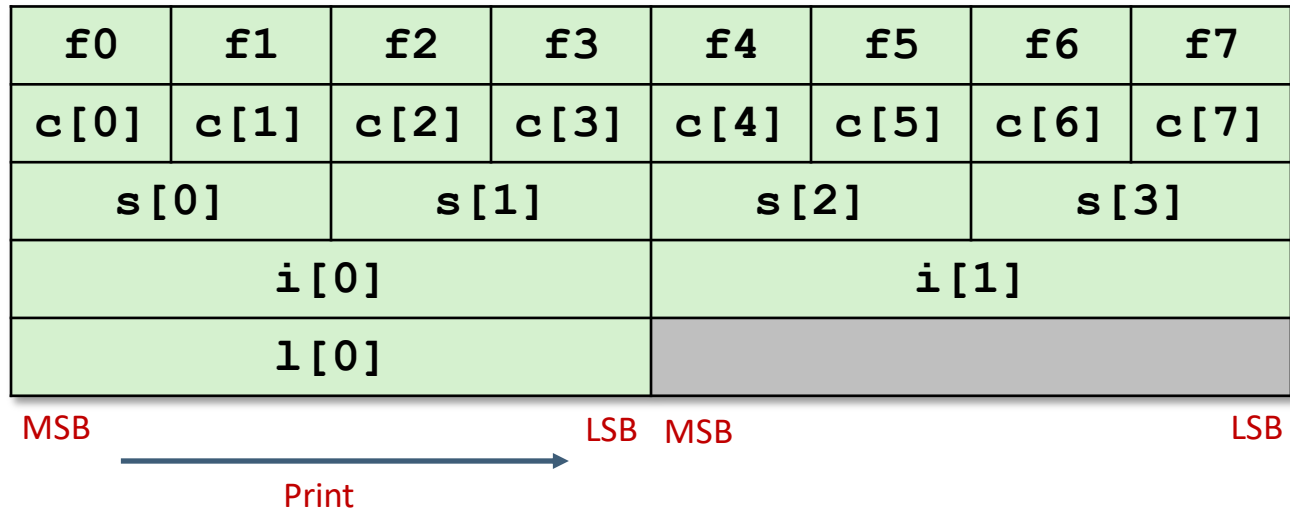
Output:

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]



Little Endian

LSB

Print

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

- Structures

- Alignment

- ▶ Unions

- ▶ **Memory Layout**

- ▶ Buffer Overflow

- ▶ Vulnerability

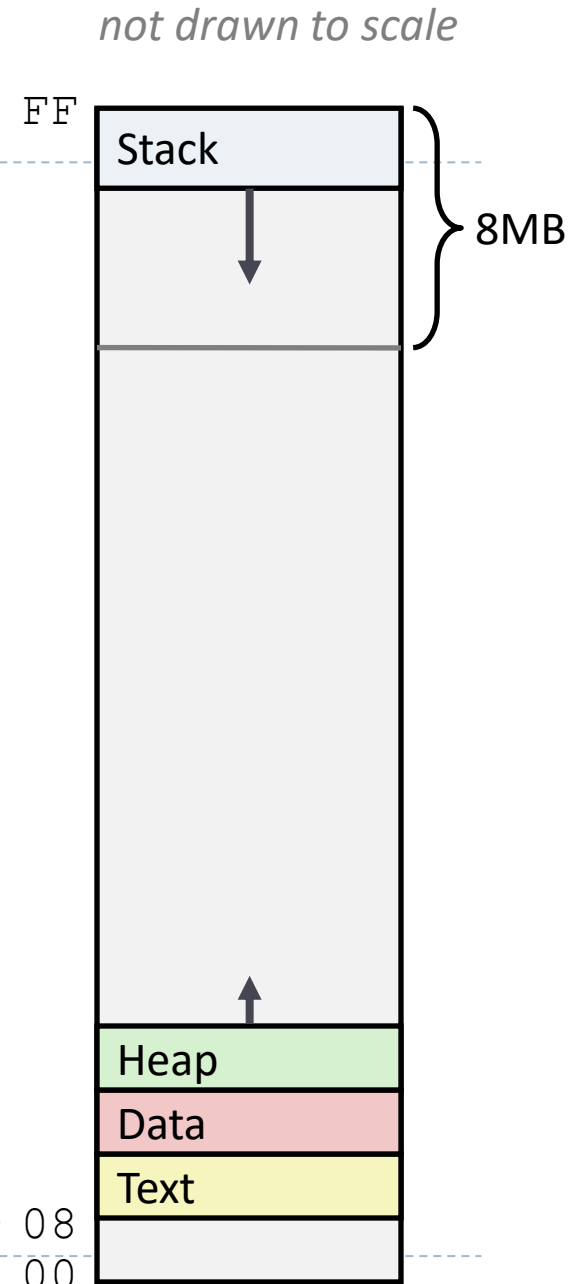
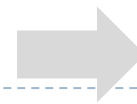
- ▶ Protection



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., arrays & strings declared in code
- ▶ **Text**
 - ▶ Executable machine instructions
 - ▶ Read-only

Upper 2 hex digits
= 8 bits of address



Memory Allocation Example

not drawn to scale

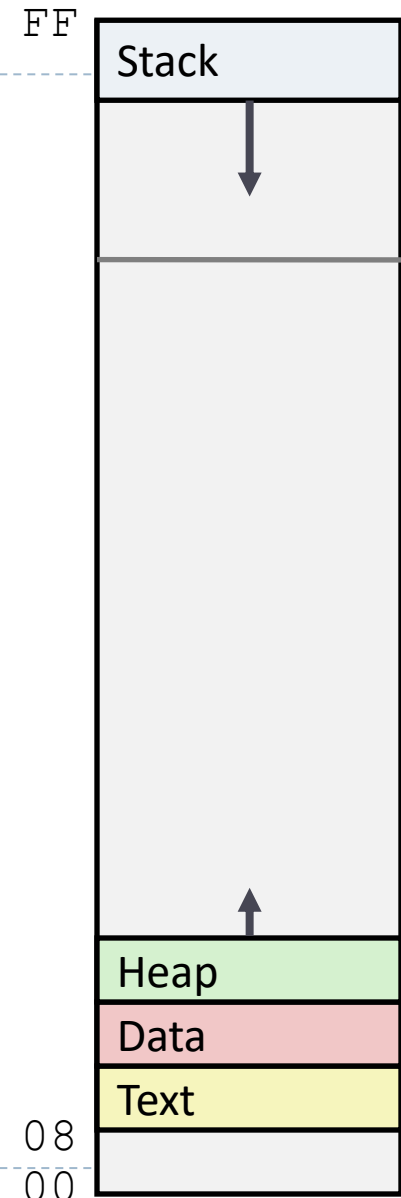
```
char big_array[1<<24]; /* 16 MB */
char huge_array[1<<28]; /* 256 MB */

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?



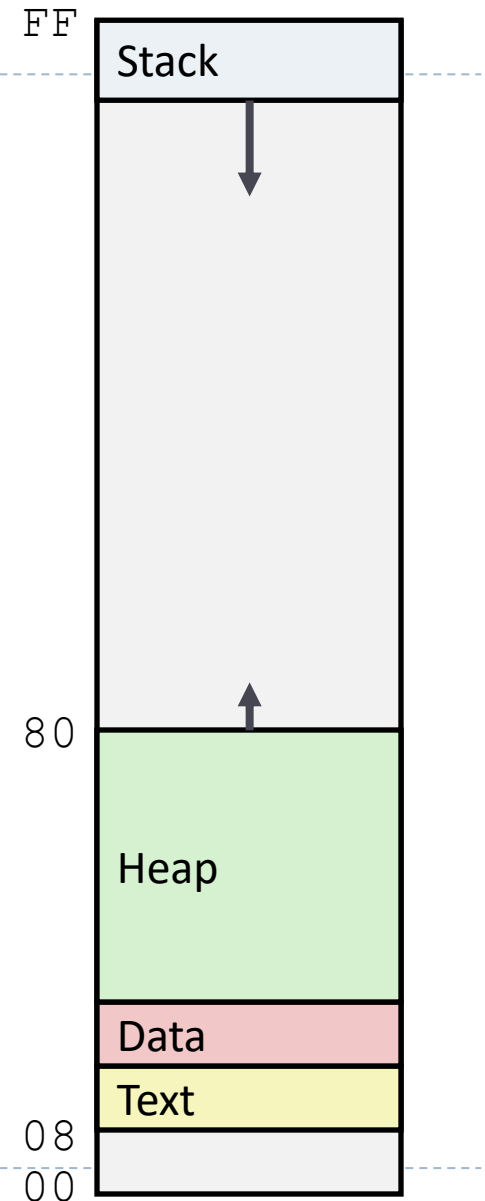
IA32 Example Addresses

address range $\sim 2^{32}$

\$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



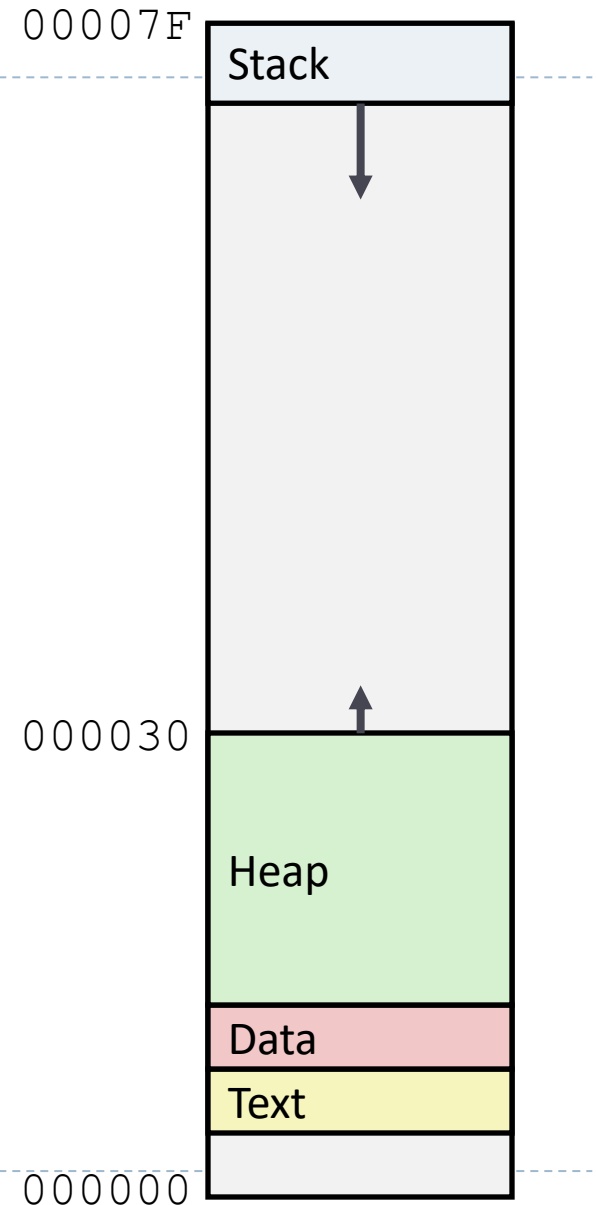
x86-64 Example Addresses

address range $\sim 2^{47}$

\$rsp	0x00007fffffff8d1f8
p3	0x00002aaabaadd010
p1	0x00002aaaaadc010
p4	0x0000000011501120
p2	0x0000000011501010
&p2	0x0000000010500a60
&beyond	0x0000000000500a44
big_array	0x0000000010500a80
huge_array	0x0000000000500a50
main()	0x0000000000400510
useless()	0x0000000000400500
final malloc()	0x000000386ae6a170

malloc() is dynamically linked
address determined at runtime

not drawn to scale



Today

■ Structures

- Alignment

▶ Unions

▶ Memory Layout

▶ **Buffer Overflow**

- ▶ Vulnerability
- ▶ Protection



Internet Worm and IM War

- ▶ **November, 1988**

- ▶ Internet Worm attacks thousands of Internet hosts.
- ▶ How did it happen?



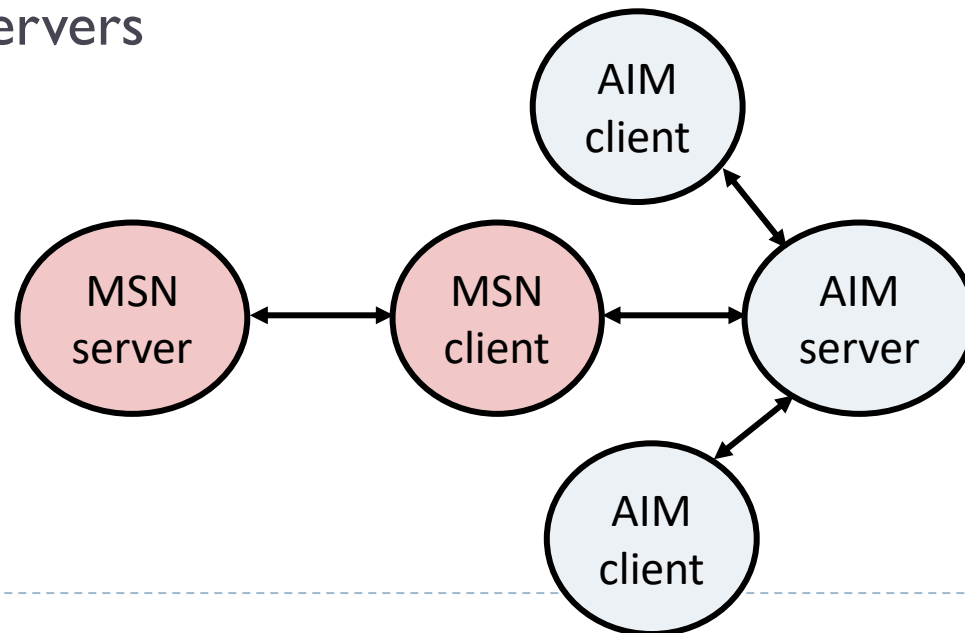
Internet Worm and IM War

▶ November, 1988

- ▶ Internet Worm attacks thousands of Internet hosts.
- ▶ How did it happen?

▶ 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?
 - ▶ 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:1234567  
1234567
```

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

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



Buffer Overflow Disassembly

echo:

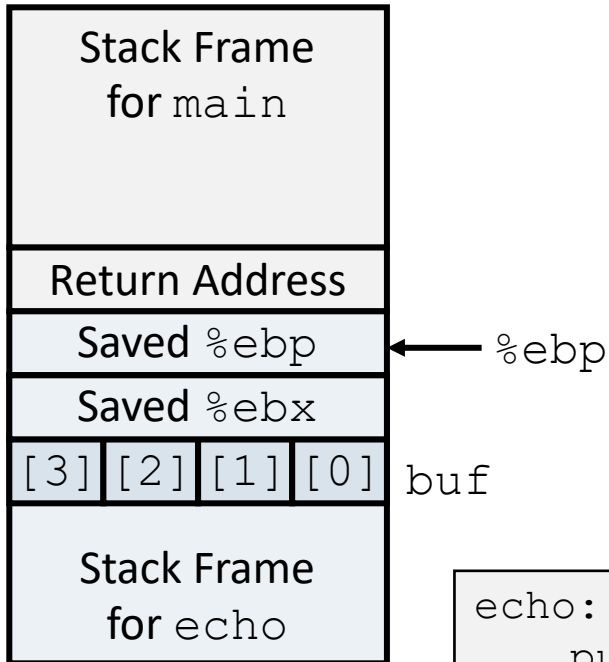
80485c5:	55	push	%ebp
80485c6:	89 e5	mov	%esp,%ebp
80485c8:	53	push	%ebx
80485c9:	83 ec 14	sub	\$0x14,%esp
80485cc:	8d 5d f8	lea	0xffffffff8(%ebp),%ebx
80485cf:	89 1c 24	mov	%ebx, (%esp)
80485d2:	e8 9e ff ff ff	call	8048575 <gets>
80485d7:	89 1c 24	mov	%ebx, (%esp)
80485da:	e8 05 fe ff ff	call	80483e4 <puts@plt>
80485df:	83 c4 14	add	\$0x14,%esp
80485e2:	5b	pop	%ebx
80485e3:	5d	pop	%ebp
80485e4:	c3	ret	

call_echo:

80485eb:	e8 d5 ff ff ff	call	80485c5 <echo>
80485f0:	c9	leave	
80485f1:	c3	ret	

Buffer Overflow Stack

Before call to gets



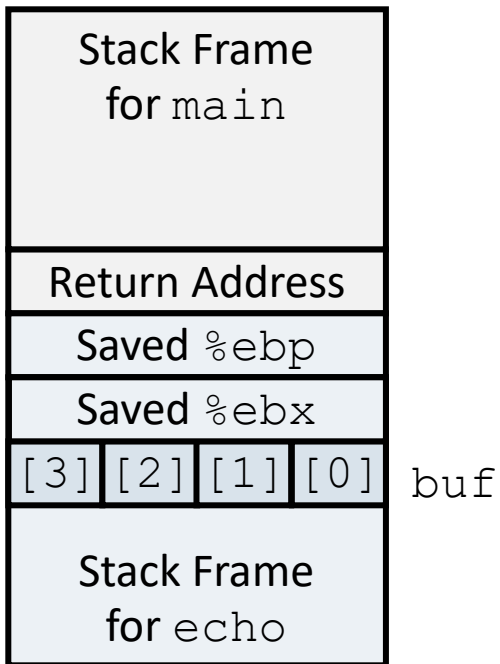
```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

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

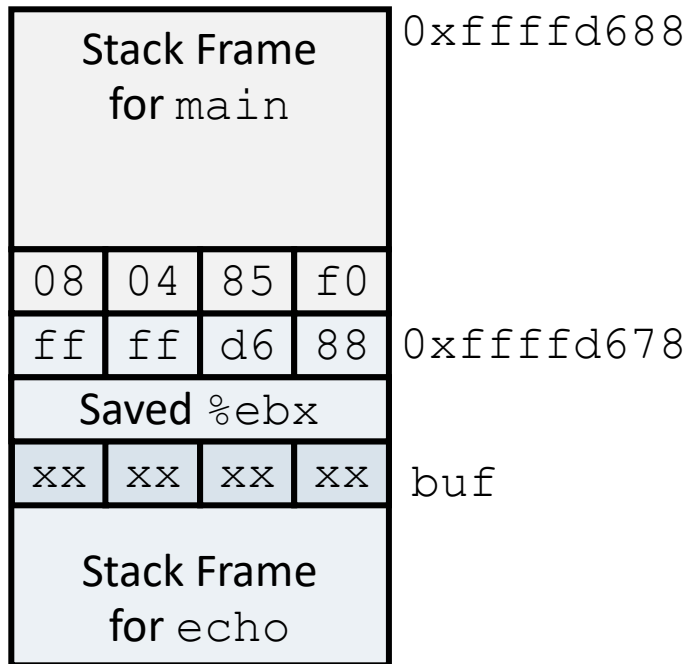
Buffer Overflow Stack Example

```
unix> gdb bufdemo
(gdb) break echo
Breakpoint 1 at 0x80485c9
(gdb) run
Breakpoint 1, 0x80485c9 in echo ()
(gdb) print /x $ebp
$1 = 0xffffd678
(gdb) print /x *(unsigned *)$ebp
$2 = 0xffffd688
(gdb) print /x *((unsigned *)$ebp + 1)
$3 = 0x80485f0
```

Before call to gets



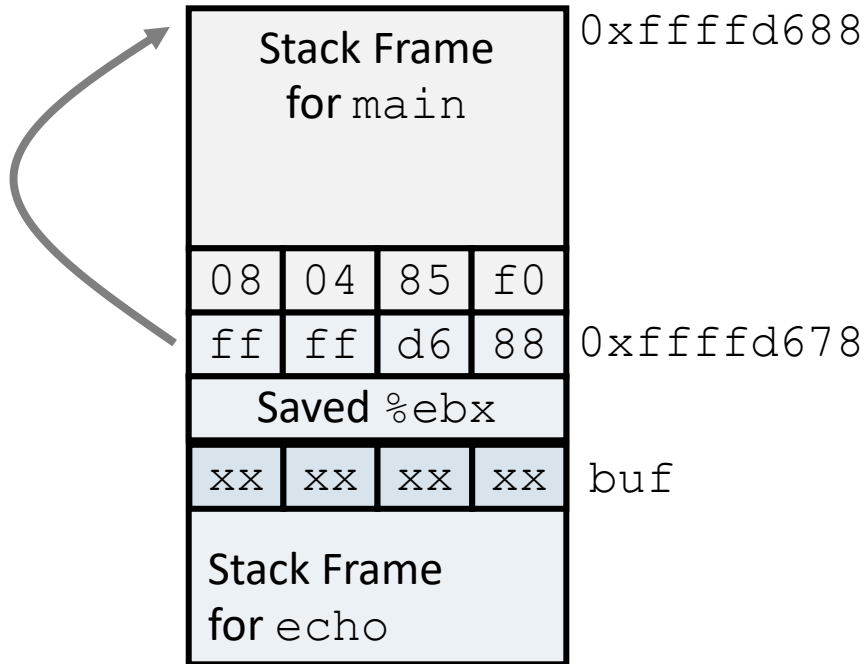
Before call to gets



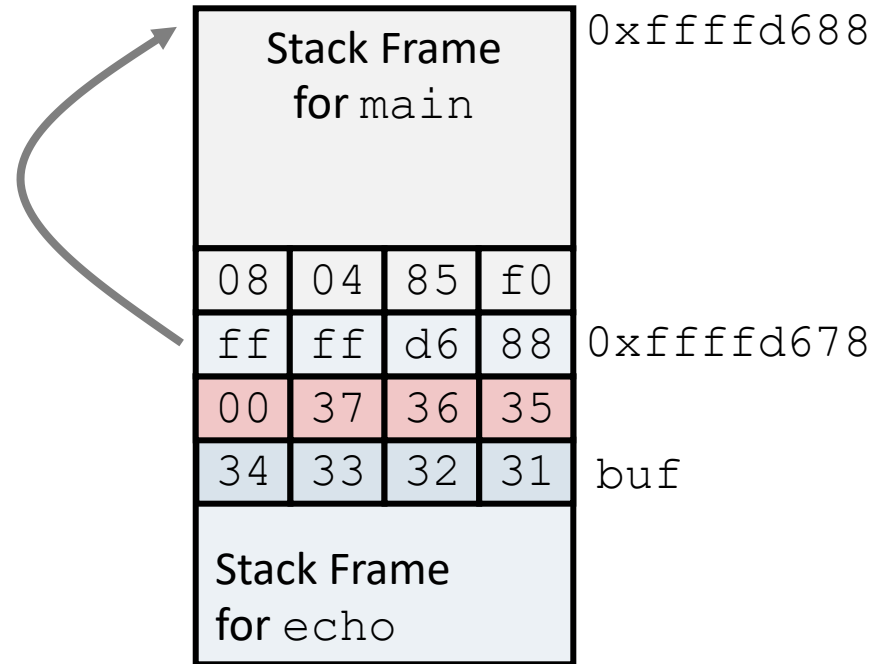
```
80485eb: e8 d5 ff ff ff call 80485c5 <echo>
80485f0: c9 leave
```

Buffer Overflow Example #1

Before call to gets



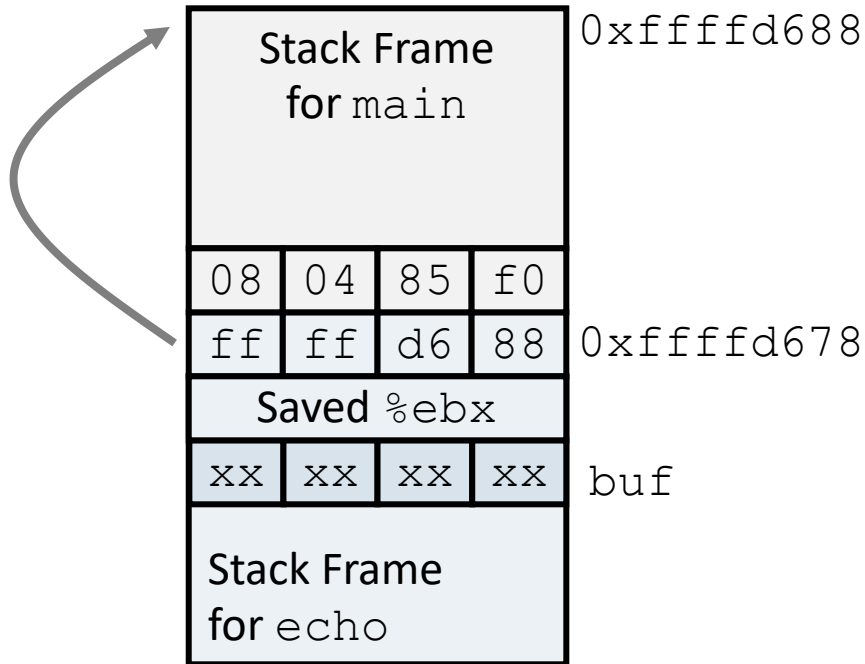
Input 1234567



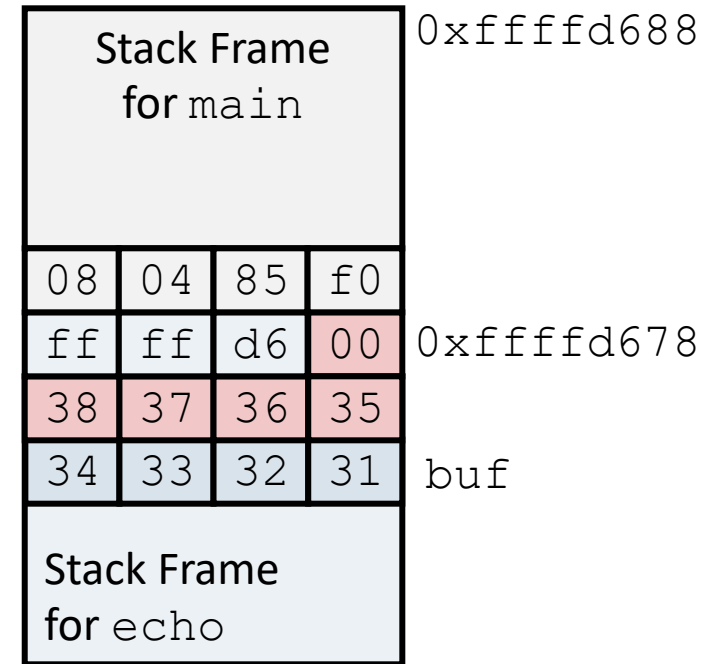
Overflow buf, and corrupt %ebx,
but no problem

Buffer Overflow Example #2

Before call to gets



Input 12345678

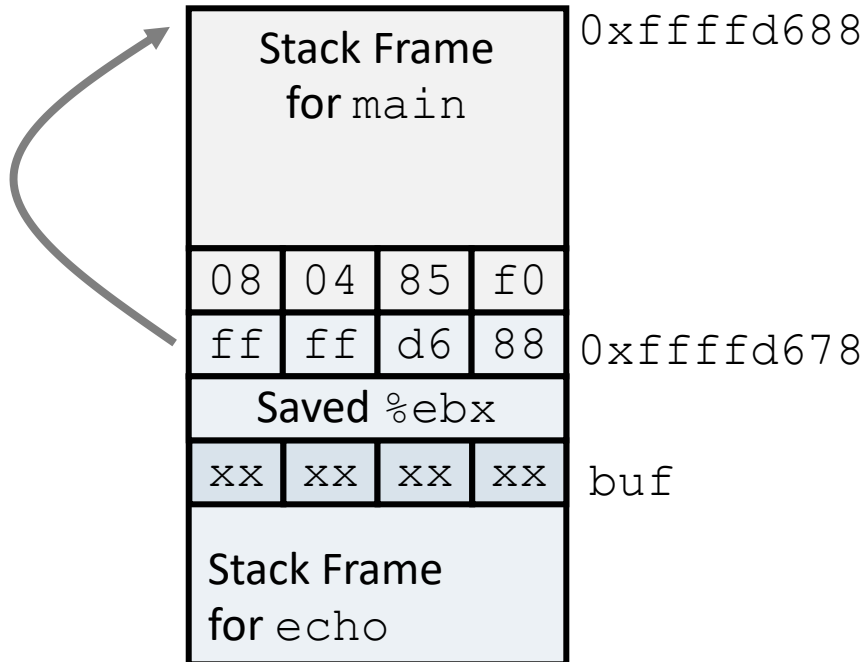


Base pointer corrupted

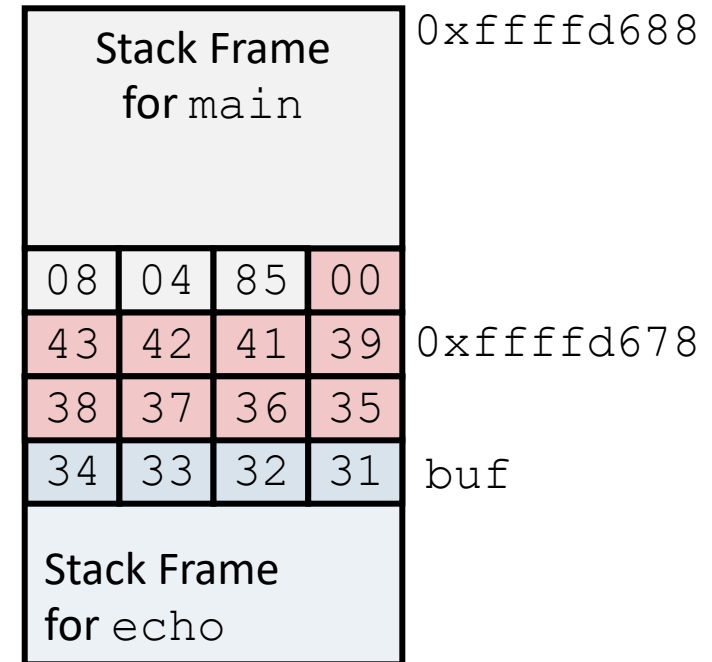
```
. . .
80485eb:  e8 d5 ff ff ff  call    80485c5 <echo>
80485f0:  c9                leave   # Set %ebp to corrupted value
80485f1:  c3                ret
```

Buffer Overflow Example #3

Before call to gets



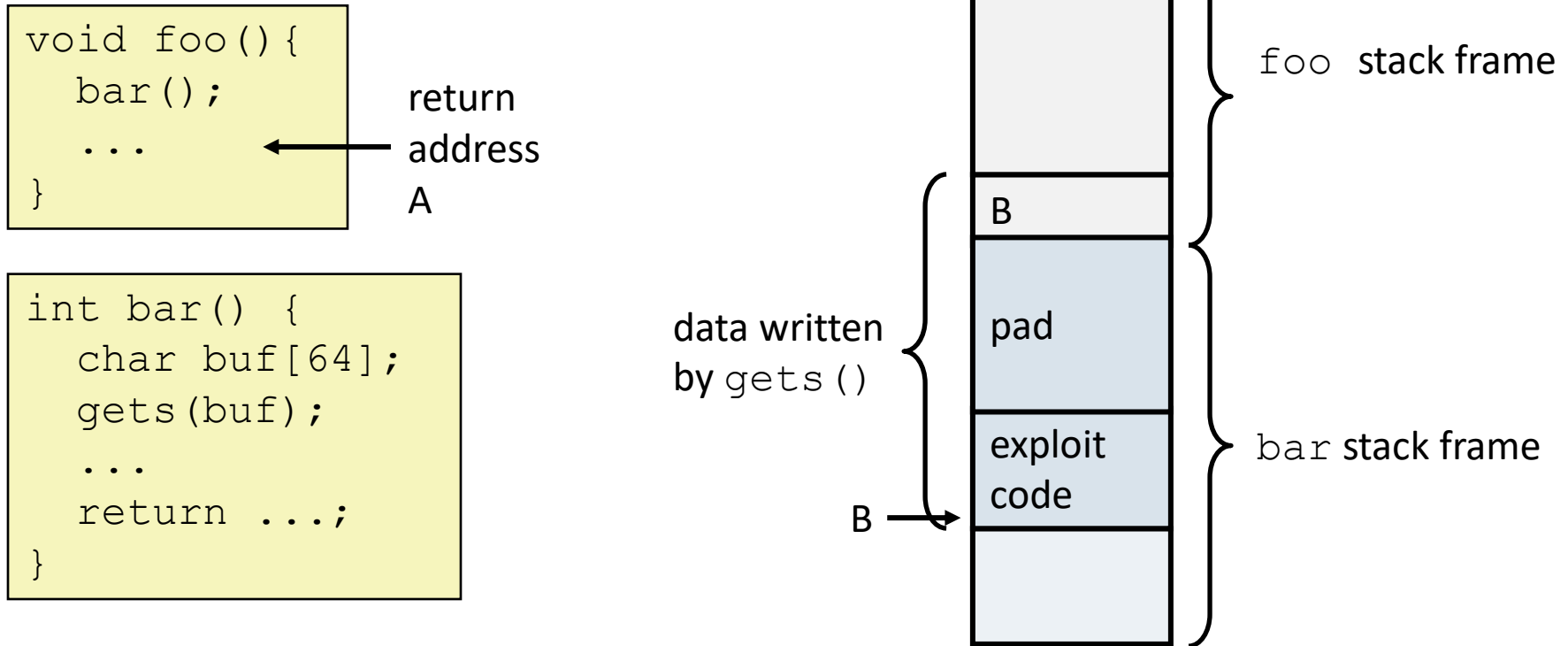
Input 123456789ABC



Return address corrupted

```
80485eb:  e8 d5 ff ff ff  call  80485c5 <echo>
80485f0:  c9              leave # Desired return point
```

Malicious Use of Buffer Overflow



- ▶ 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

▶ 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
-

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

(gdb) run
(gdb) print /x $ebp
$1 = 0xfffffc638

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

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

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:1234  
1234
```

```
unix>./bufdemo-protected  
Type a string:12345  
*** stack smashing detected ***
```



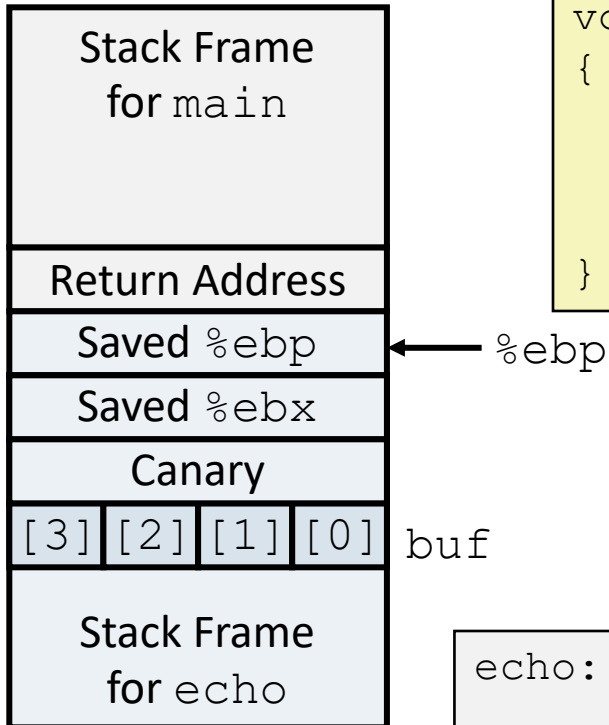
Protected Buffer Disassembly

echo:

804864d:	55	push	%ebp
804864e:	89 e5	mov	%esp,%ebp
8048650:	53	push	%ebx
8048651:	83 ec 14	sub	\$0x14,%esp
8048654:	65 a1 14 00 00 00	mov	%gs:0x14,%eax
804865a:	89 45 f8	mov	%eax,0xffffffff8(%ebp)
804865d:	31 c0	xor	%eax,%eax
804865f:	8d 5d f4	lea	0xfffffffff4(%ebp),%ebx
8048662:	89 1c 24	mov	%ebx, (%esp)
8048665:	e8 77 ff ff ff	call	80485e1 <gets>
804866a:	89 1c 24	mov	%ebx, (%esp)
804866d:	e8 ca fd ff ff	call	804843c <puts@plt>
8048672:	8b 45 f8	mov	0xfffffffff8(%ebp),%eax
8048675:	65 33 05 14 00 00 00	xor	%gs:0x14,%eax
804867c:	74 05	je	8048683 <echo+0x36>
804867e:	e8 a9 fd ff ff	call	804842c <FAIL>
8048683:	83 c4 14	add	\$0x14,%esp
8048686:	5b	pop	%ebx
8048687:	5d	pop	%ebp
8048688:	c3	ret	

Setting Up Canary

Before call to gets

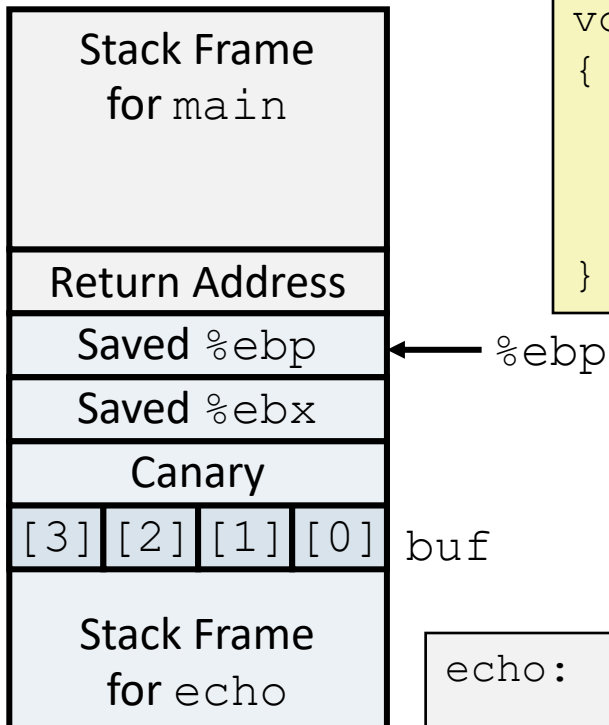


```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movl    %gs:20, %eax    # Get canary
    movl    %eax, -8(%ebp)  # Put on stack
    xorl    %eax, %eax      # Erase canary
    . . .
```


Checking Canary

Before call to gets

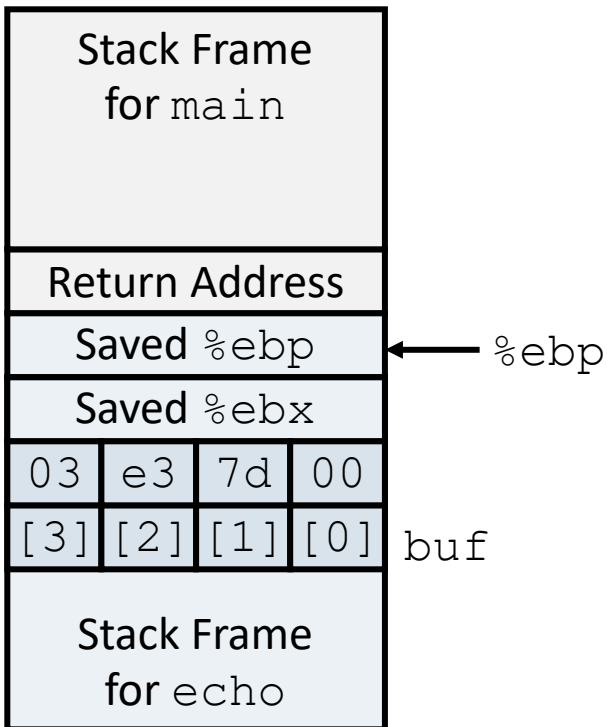


```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

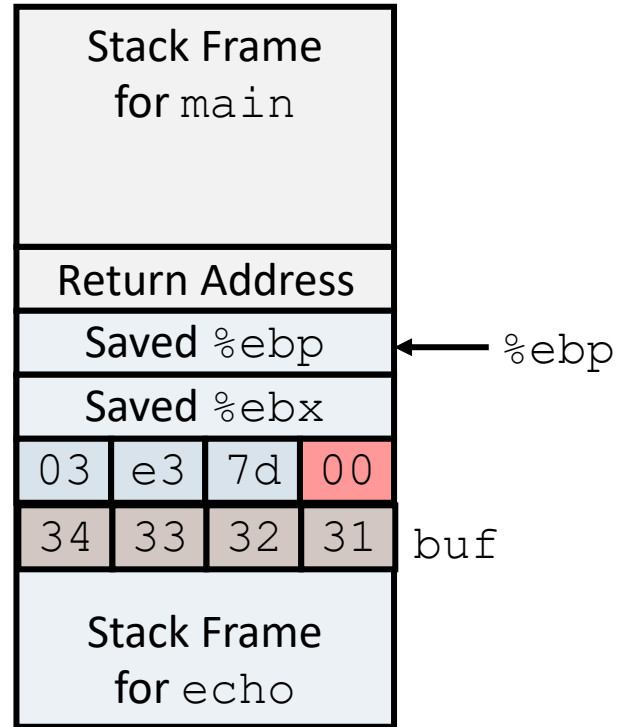
```
echo:
    . . .
    movl    -8(%ebp), %eax    # Retrieve from stack
    xorl    %gs:20, %eax     # Compare with Canary
    je      .L24              # Same: skip ahead
    call    __stack_chk_fail # ERROR
.L24:
    . . .
```

Canary Example

Before call to gets



Input 1234



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

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

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



Today

- Structures

- Alignment

- ▶ Unions

- ▶ Memory Layout

- ▶ Buffer Overflow

- ▶ Vulnerability

- ▶ Protection

