15-213

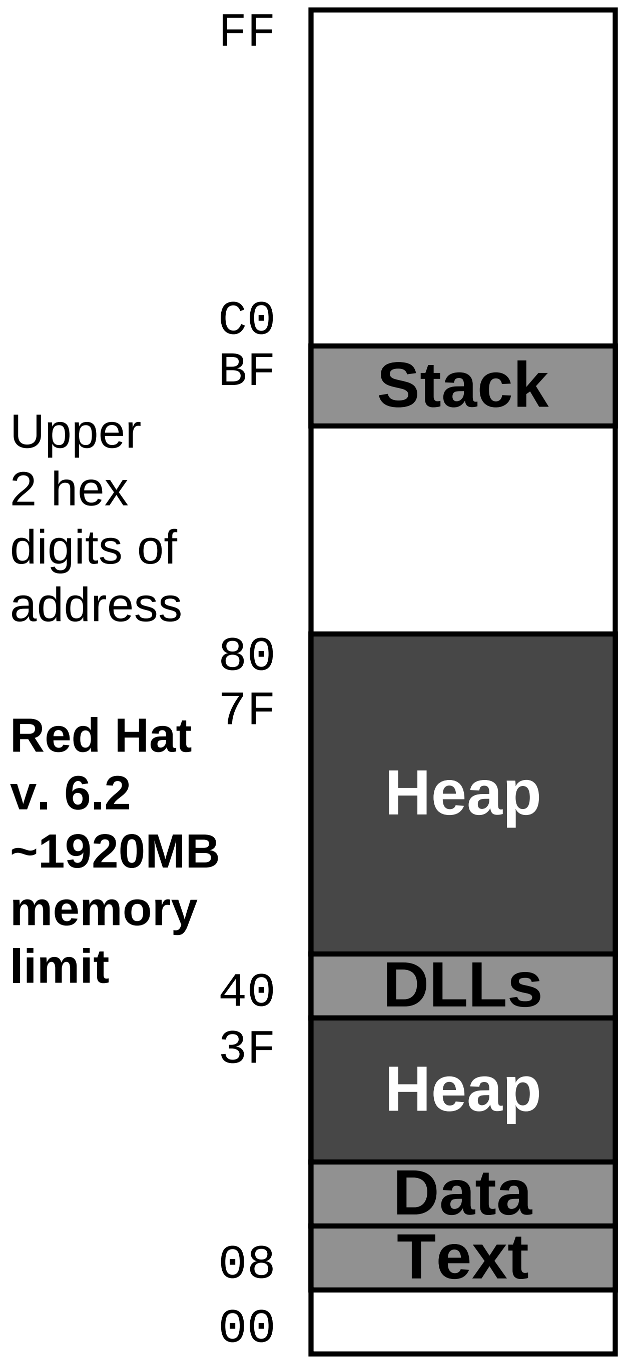
"The course that gives CMU its Zip!"

Machine Language V: Miscellaneous Topics Sept. 25, 2001

Topics

- **Linux Memory Layout**
- **Understanding Pointers**
- **Buffer Overflow**
- **Floating Point Code**

Linux Memory Layout



Stack

- Runtime stack (8MB limit)

Heap

- Dynamically allocated storage
- When call `malloc`, `calloc`, `new`

DLLs

- Dynamically Linked Libraries
- Library routines (e.g., `printf`, `malloc`)
- Linked into object code when first executed

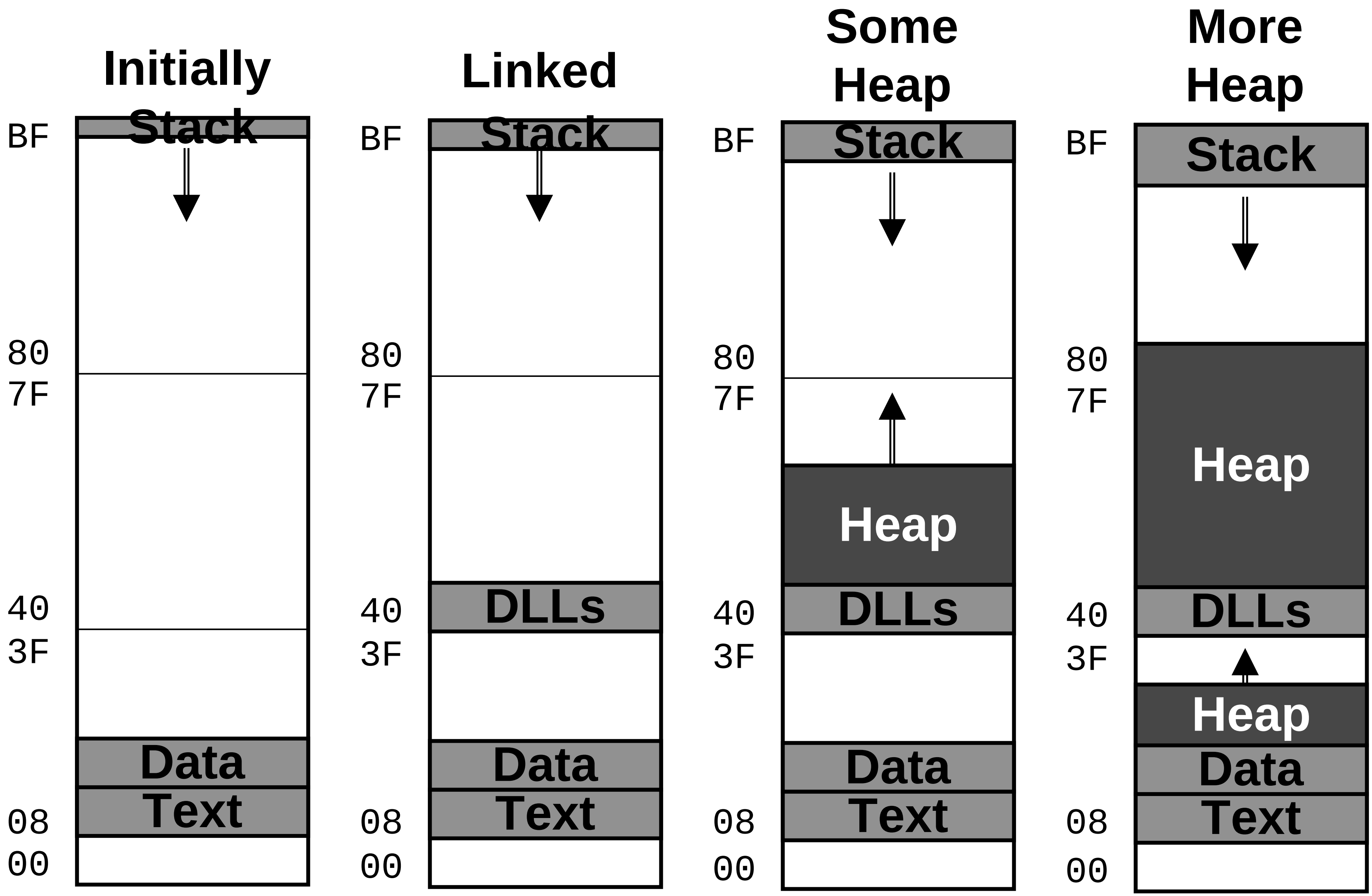
Data

- Statically allocated data
- E.g., arrays & strings declared in code

Text

- Executable machine instructions
- Read-only

Linux Memory Allocation



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 ... */
}
```

Dynamic Linking Example

```
(gdb) print malloc
  $1 = {<text variable, no debug info>}
    0x8048454 <malloc>
(gdb) run
  Program exited normally.
(gdb) print malloc
  $2 = {void *(unsigned int)}
    0x40006240 <malloc>
```

Initially

- Code in text segment that invokes dynamic linker
- Address `0x8048454` should be read `0x08048454`

Final

- Code in DLL region

Breakpointing Example

```
(gdb) break main
(gdb) run
  Breakpoint 1, 0x804856f in main ()
(gdb) print $esp
  $3 = (void *) 0xbffffc78
```

Main

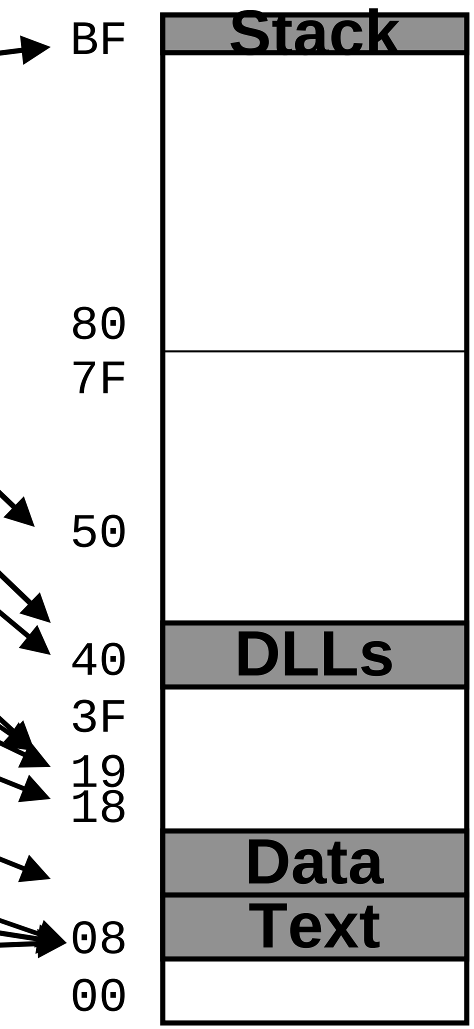
- Address `0x804856f` should be read `0x0804856f`

Stack

- Address `0xbffffc78`

Example Addresses

$esp	0xbffffc78
p3	0x500b5008
p1	0x400b4008
Final malloc	0x40006240
p4	0x1904a640
p2	0x1904a538
beyond	0x1904a524
big_array	0x1804a520
huge_array	0x0804a510
main()	0x0804856f
useless()	0x08048560
Initial malloc	0x08048454



C operators

```
Operators                                              Associativity

()  []  ->  .                                          left to right
!  ~  ++  --  +  -  *  &  (type)  sizeof               right to left
*  /  %                                                left to right
+  -                                                   left to right
<<  >>                                                 left to right
<  <=  >  >=                                           left to right
==  !=                                                 left to right
&                                                      left to right
^                                                      left to right
|                                                      left to right
&&                                                     left to right
||                                                     left to right
?:                                                     right to left
=  +=  -=  *=  /=  %=  &=  ^=  !=  <<=  >>=            right to left
,                                                      left to right
```

Note: Unary +, -, and * have higher precedence than binary forms

C pointer declarations

`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

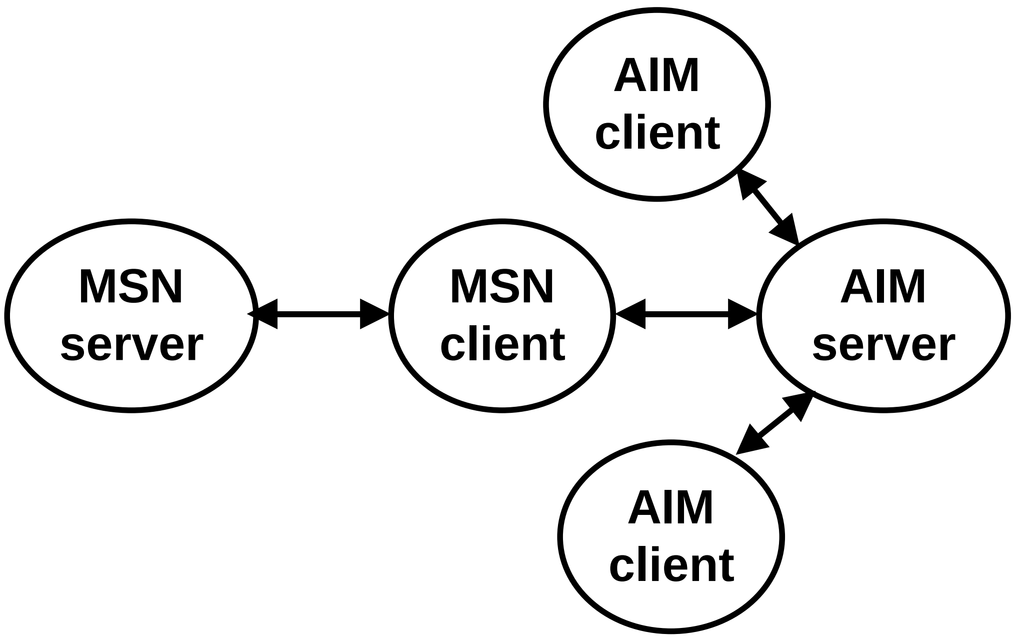
Internet Worm and IM War

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 Unix functions, such as `gets()` and `strcpy()`, do not check argument sizes.
- allows target buffers to overflow.

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;
}
```

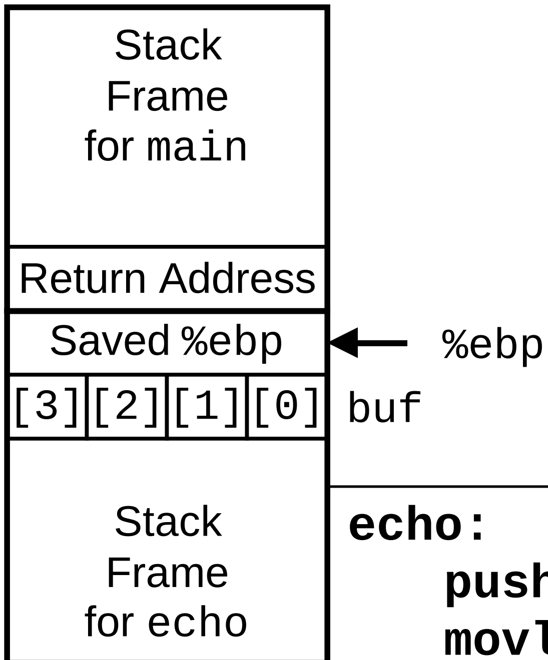
Buffer Overflow Executions

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

```
unix>./bufdemo
Type a string:12345
Segmentation Fault
```

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

Buffer Overflow Stack



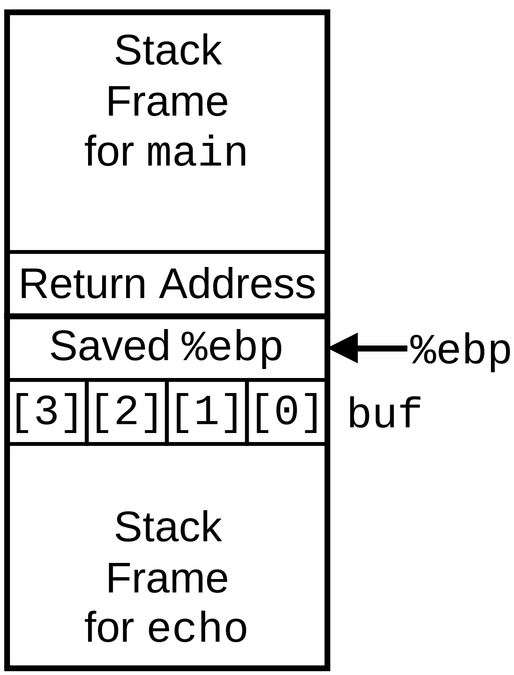

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

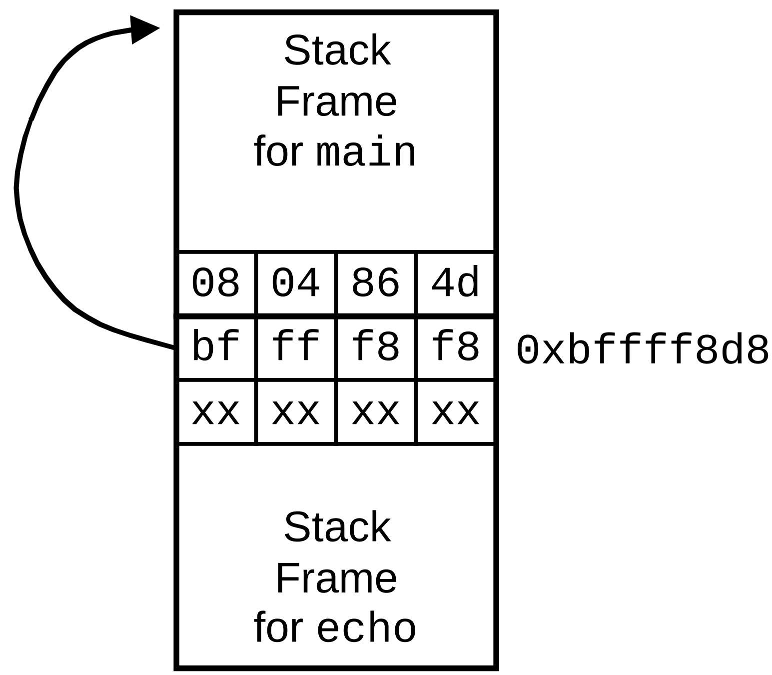
```
echo:
   pushl %ebp              # Save %ebp on stack
   movl %esp,%ebp
   subl $20,%esp           # Allocate space on stack
   pushl %ebx              # Save %ebx
   addl $-12,%esp          # Allocate space on stack
   leal -4(%ebp),%ebx      # Compute buf as %ebp-4
   pushl %ebx              # 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 *(unsigned *)$ebp
$1 = 0xbffff8f8
(gdb) print /x *((unsigned *)$ebp + 1)
$3 = 0x804864d
```

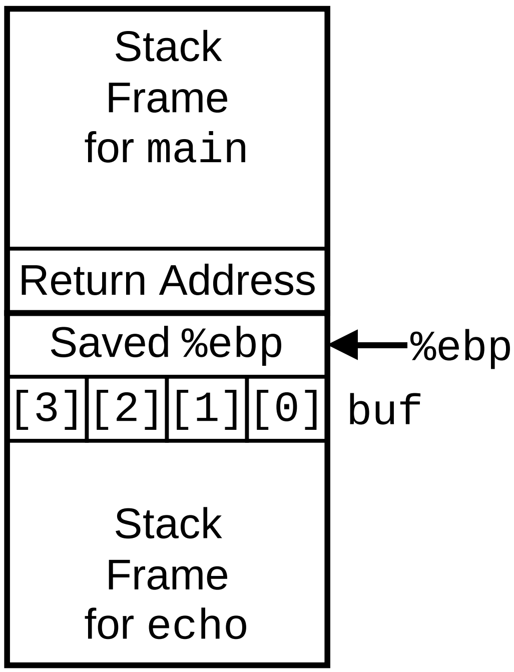
Before Call to `gets`



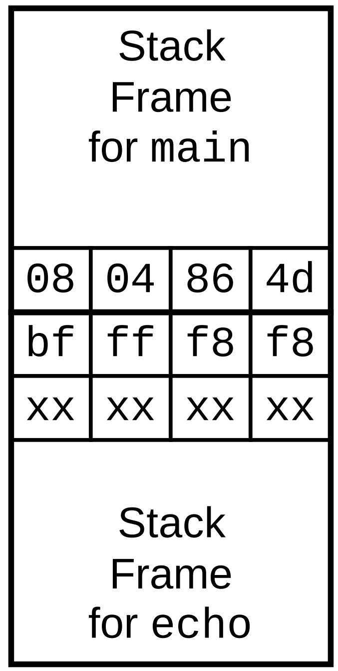



```
8048648:  call 804857c <echo>
804864d:  mov  0xffffffe8(%ebp),%ebx # Return Point
```

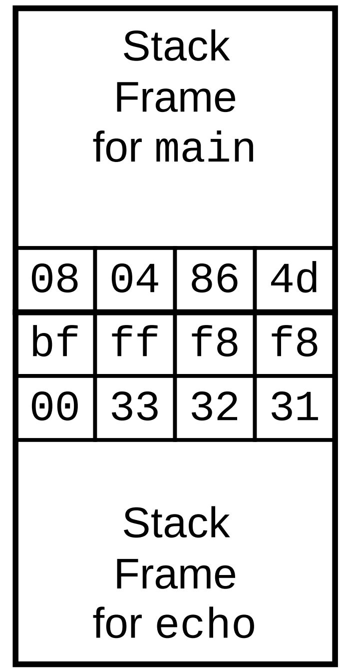
Buffer Overflow Stack Example #1



Before Call to gets

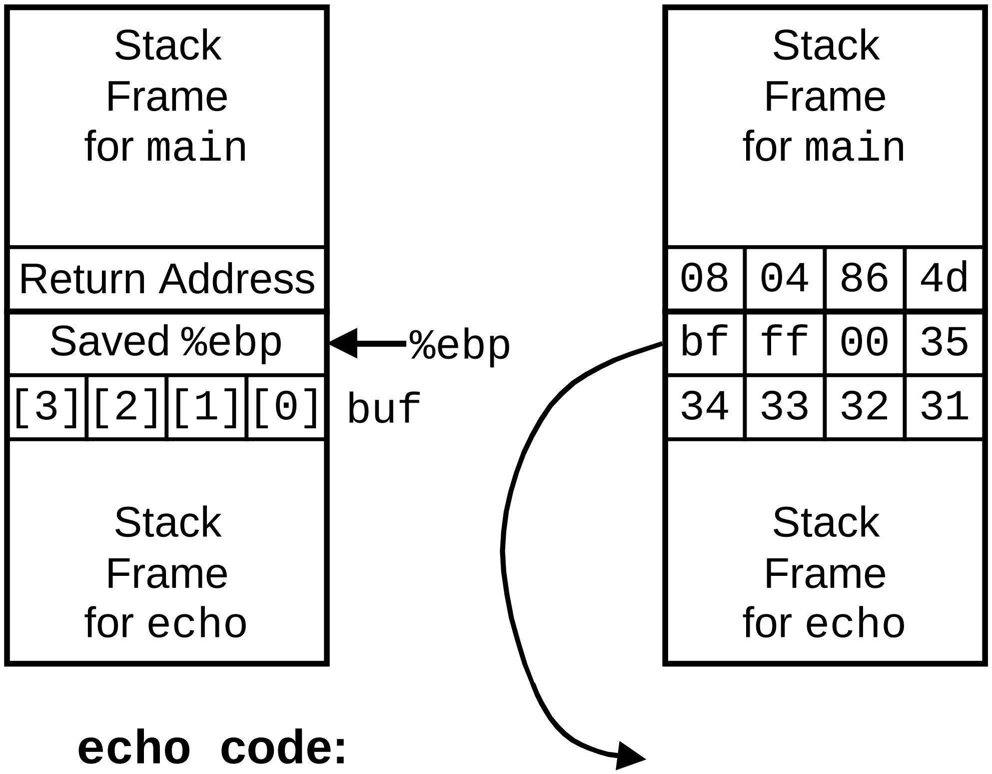


Input = “123”



No Problem

Buffer Overflow Stack Example #2



0xbffff8d8

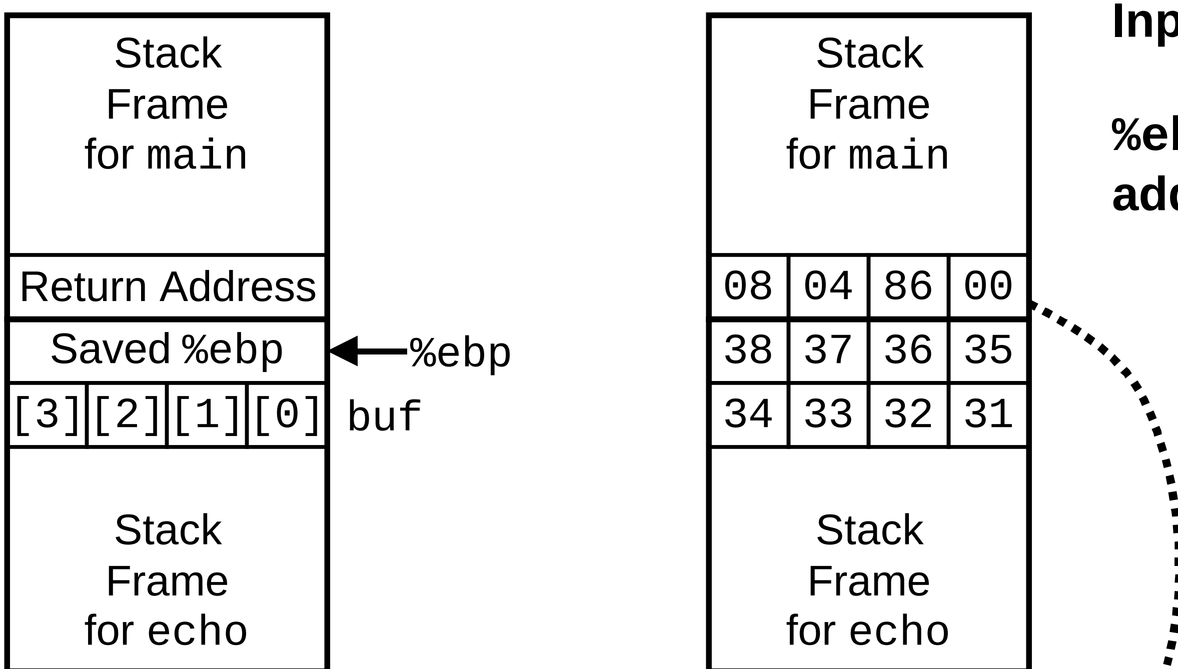
Input = “12345”

Saved value of `%ebp` set to `0xbfff0035`

`echo` code:

```
8048592:  push   %ebx
8048593:  call   80483e4 <_init+0x50>
8048598:  mov    0xffffffe8(%ebp),%ebx
804859b:  mov    %ebp,%esp
804859d:  pop    %ebp     # %ebp gets set to invalid value
804859e:  ret
```

Buffer Overflow Stack Example



Input = "12345678"

%ebp and return address corrupted

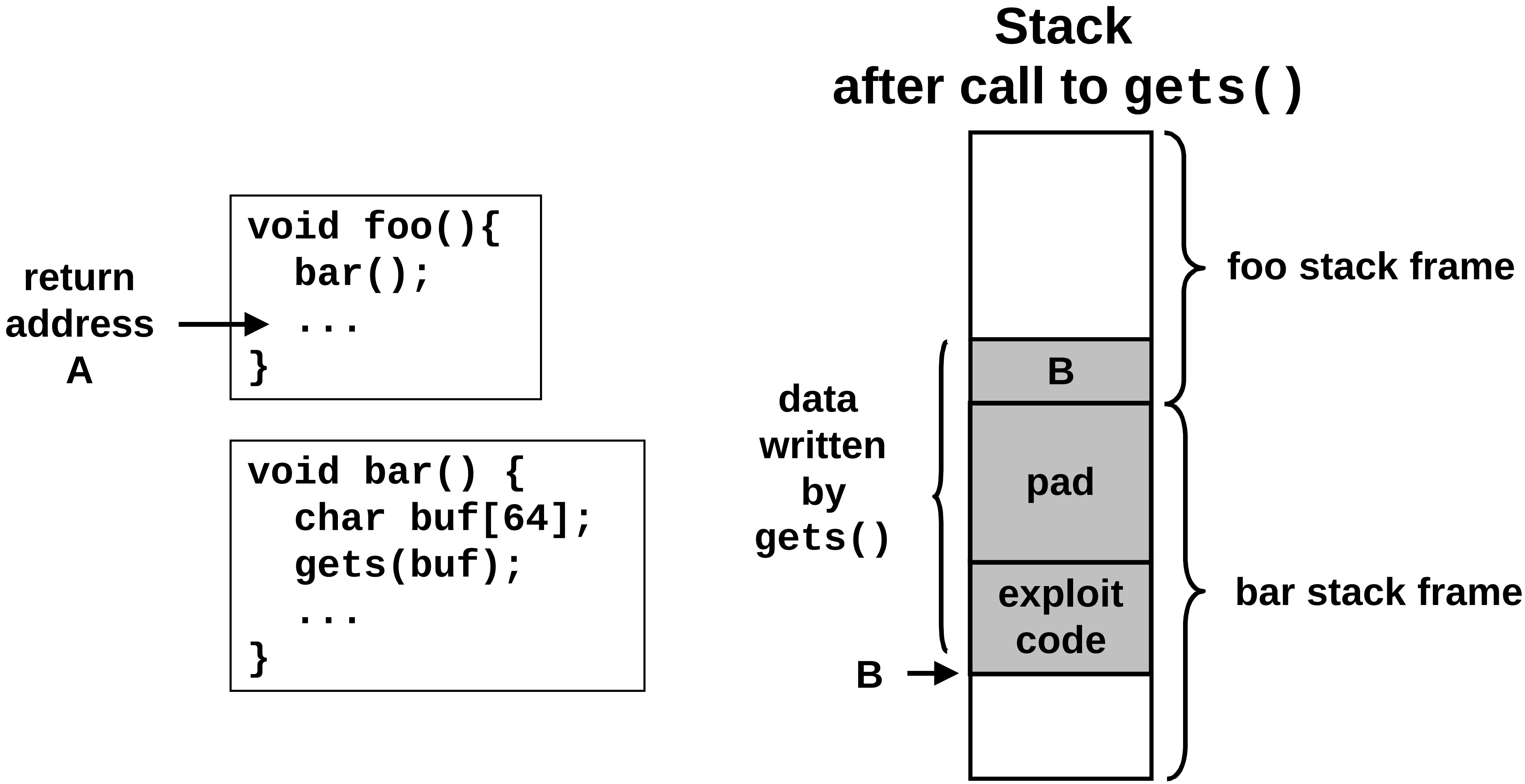
Function good_echo

```
80485fc:  80 3c 33 0a     cmpb   $0xa,(%ebx,%esi,1)
8048600:  75 ae           jne    80485b0 <good_echo+0x10>
8048602:  a1 b8 97 04 08  mov    0x80497b8,%eax
```

Malicious Use of Buffer Overflow

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

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



- 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.**

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!

IA32 Floating Point

History

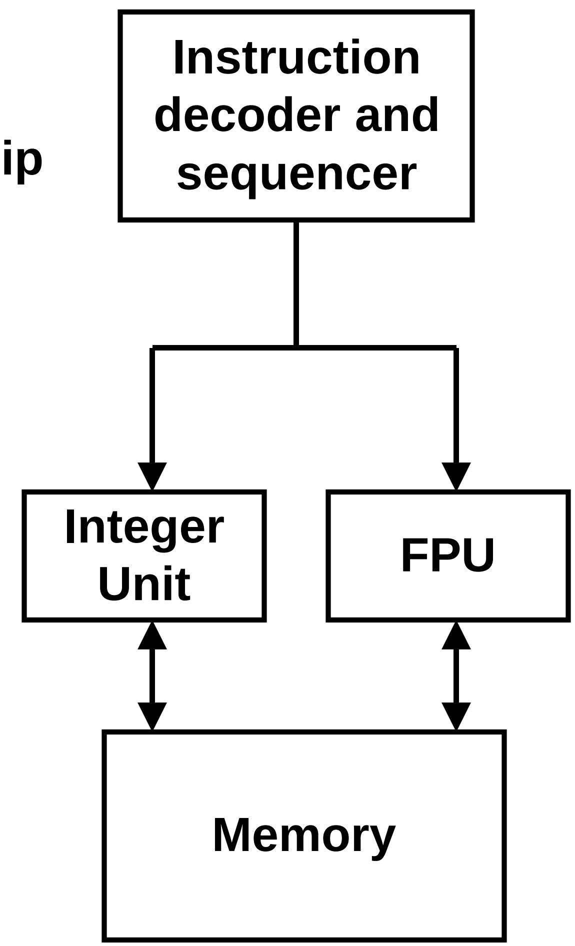
- **8086: first computer to implement IEEE FP**
  - separate 8087 FPU (floating point unit)
- **486: merged FPU and Integer Unit onto one chip**

Summary

- **Hardware to add, multiply, and divide**
- **Floating point data registers**
- **Various control & status registers**

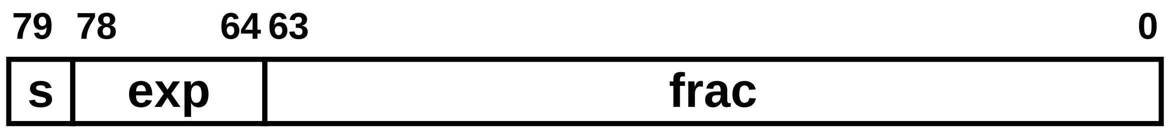
Floating Point Formats

- **single precision (C `float`): 32 bits**
- **double precision (C `double`): 64 bits**
- **extended precision (C `long double`): 80 bits**



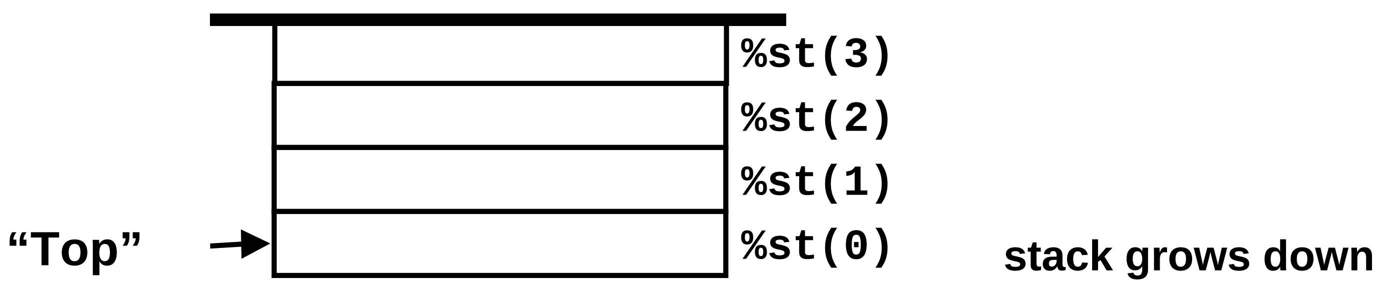
FPU Data Register Stack

FPU register format (extended precision)



FPU registers

- 8 registers
- Logically forms shallow stack
- Top called `%st(0)`
- When push too many, bottom values disappear



FPU instructions

Large number of floating point instructions and formats

- ~50 basic instruction types
- load, store, add, multiply
- sin, cos, tan, arctan, and log!

Sample instructions:

Instruction	Effect	Description
`fldz`	push 0.0	Load zero
`flds Addr`	push M[Addr]	Load single precision real
`fmuls Addr`	`%st(0) <- %st(0)*`M[Addr]	Multiply
`faddp`	`%st(1) <- %st(0)+%st(1);` pop	Add and pop

Floating Point Code Example

Compute Inner Product of Two Vectors

- Single precision arithmetic
- Scientific computing and

signal processing workhorse

```
float ipf (float x[],
           float y[],
           int n)
{
  int i;
  float result = 0.0;

  for (i = 0; i < n; i++) {
    result += x[i] * y[i];
  }
  return result;
}
```

```
   pushl %ebp                # setup
   movl %esp,%ebp
   pushl %ebx

   movl 8(%ebp),%ebx         # %ebx=&x
   movl 12(%ebp),%ecx        # %ecx=&y
   movl 16(%ebp),%edx        # %edx=n
   fldz                      # push +0.0
   xorl %eax,%eax            # i=0
   cmpl %edx,%eax            # if i>=n done
   jge .L3
.L5:
   flds (%ebx,%eax,4)        # push x[i]
   fmuls (%ecx,%eax,4)       # st(0)*=y[i]
   faddp                     # st(1)+=st(0); pop
   incl %eax                 # i++
   cmpl %edx,%eax            # if i<n repeat
   jl .L5
.L3:
   movl -4(%ebp),%ebx        # finish
   movl %ebp, %esp
   popl %ebp
   ret                       # st(0) = result
```

Inner Product Stack Trace

Initialization

1. `fldz`

0.0	**%st(0)**

Iteration 0

2. `flds (%ebx,%eax,4)`

0.0	**%st(1)**
x[0]	**%st(0)**

3. `fmuls (%ecx,%eax,4)`

0.0	**%st(1)**
x[0]*y[0]	**%st(0)**

4. `faddp`

0.0+x[0]*y[0]	**%st(0)**

Iteration 1

5. `flds (%ebx,%eax,4)`

x[0]*y[0]	**%st(1)**
x[1]	**%st(0)**

6. `fmuls (%ecx,%eax,4)`

x[0]*y[0]	**%st(1)**
x[1]*y[1]	**%st(0)**

7. `faddp`

	%st(0)

x[0]*y[0]+x[1]*y[1]

Final Observations

Memory Layout

- **OS/machine dependent (including kernel version)**
- **Basic partitioning: stack/data/text/heap/DLL found in most machines**

Type Declarations in C

- **Notation obscure, but very systematic**

Working with Strange Code

- **Important to analyze nonstandard cases**
  - E.g., what happens when stack corrupted due to buffer overflow
- **Helps to step through with GDB**

IA32 Floating Point

- **Strange "shallow stack" architecture**