15-213

"The course that gives CMU its Zip!"

Machine-Level Programming V: Advanced Topics September 28, 2004

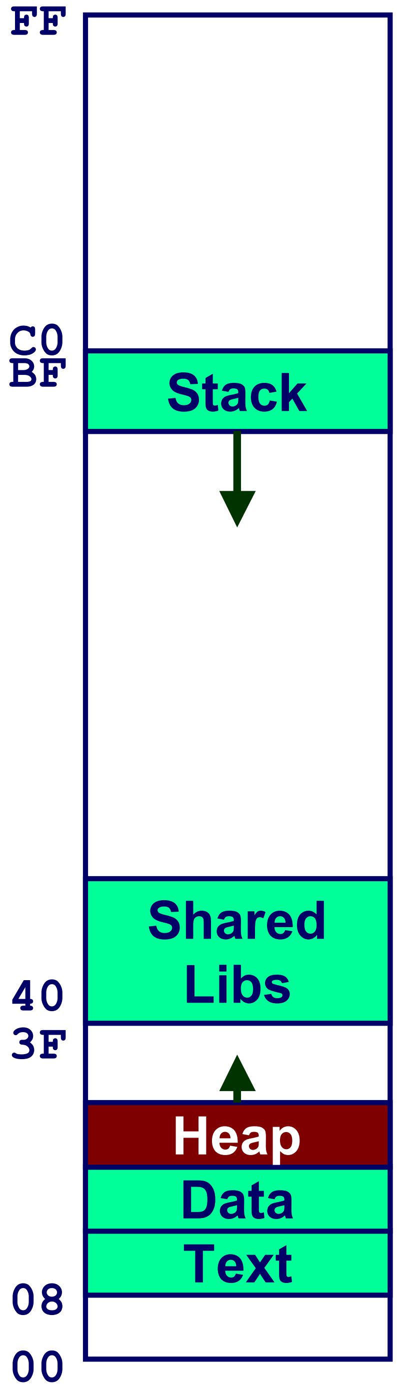
Topics

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

`class09.ppt`

Linux Memory Layout

Red Hat v. 6.2 ~1920MB memory limit



Upper 2 hex digits of address

Stack

- Runtime stack (8MB limit)

Heap

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

Shared Libraries

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

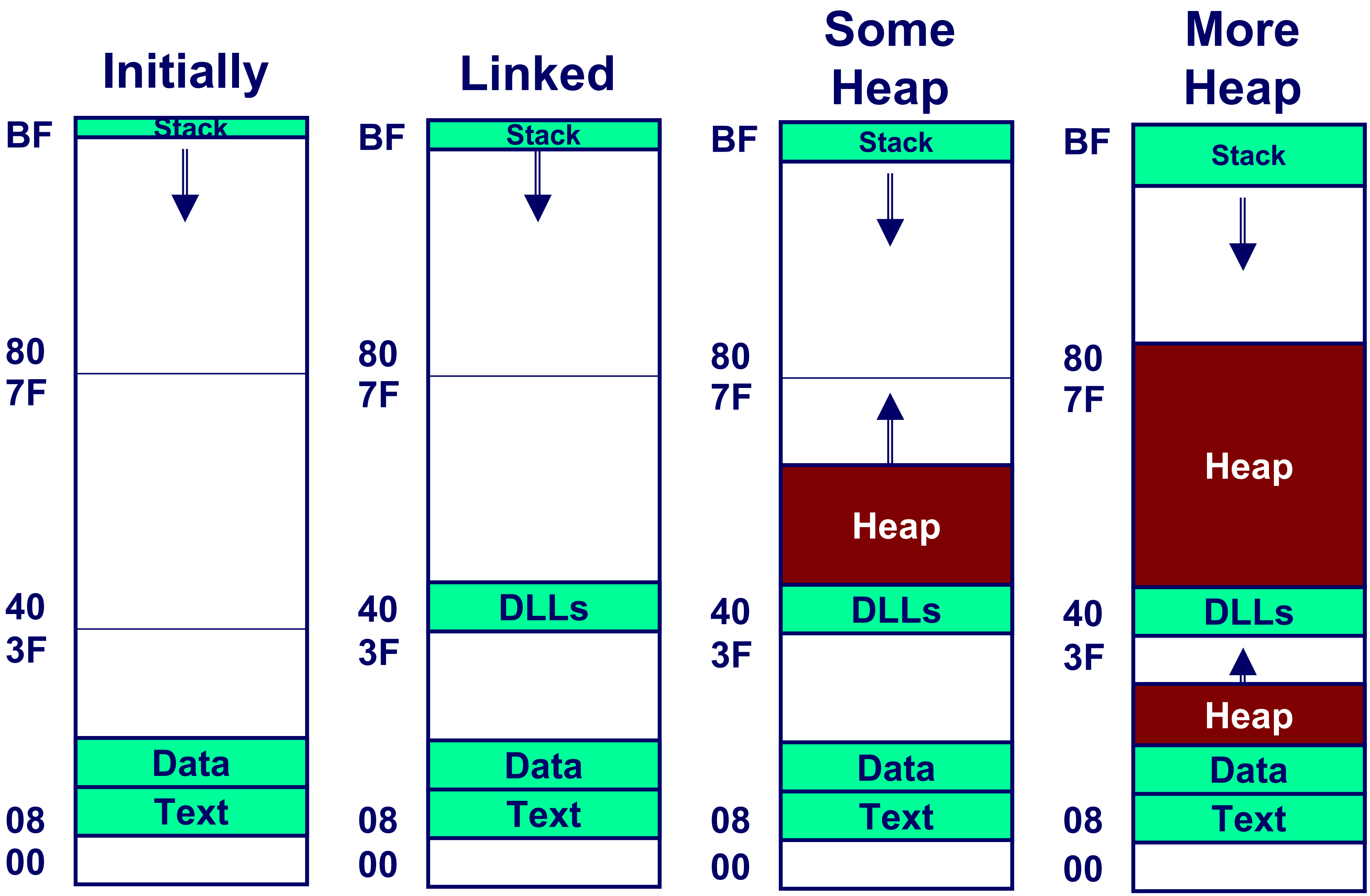
Data

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

Text

- Executable machine instructions
- Read-only

Linux Memory Allocation



Text & Stack Example

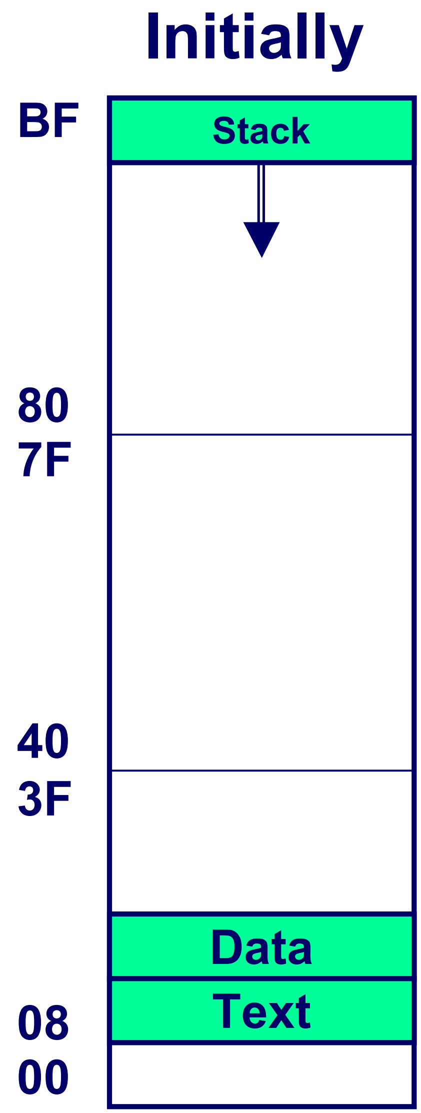
```
(gdb) break main
(gdb) run
  Breakpoint 1, 0x804856f in main ()
(gdb) print $esp
  $3 = (void *) 0xbffffc78
```

Main

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

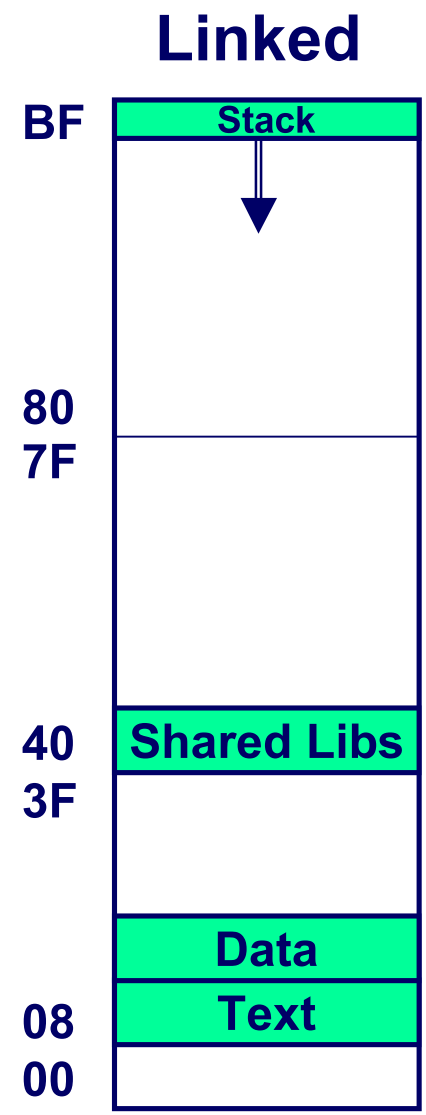
Stack

- Address `0xbffffc78`



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

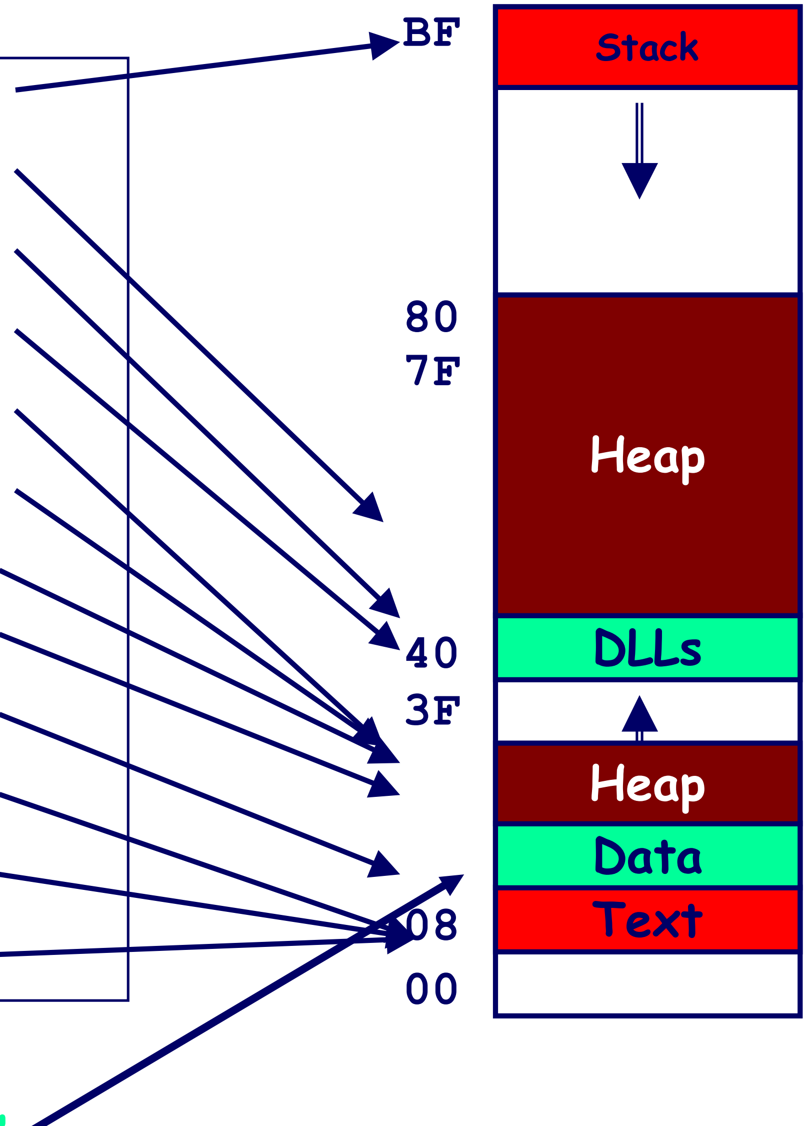
- Code in shared library region

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 ... */
}
```

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`



`&p2?` `0x1904a42c`

C operators

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

Note: Monadic +, -, and * have higher precedence than dyadic 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

Avoiding Complex Declarations

Use Typedef to build up the decl

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.

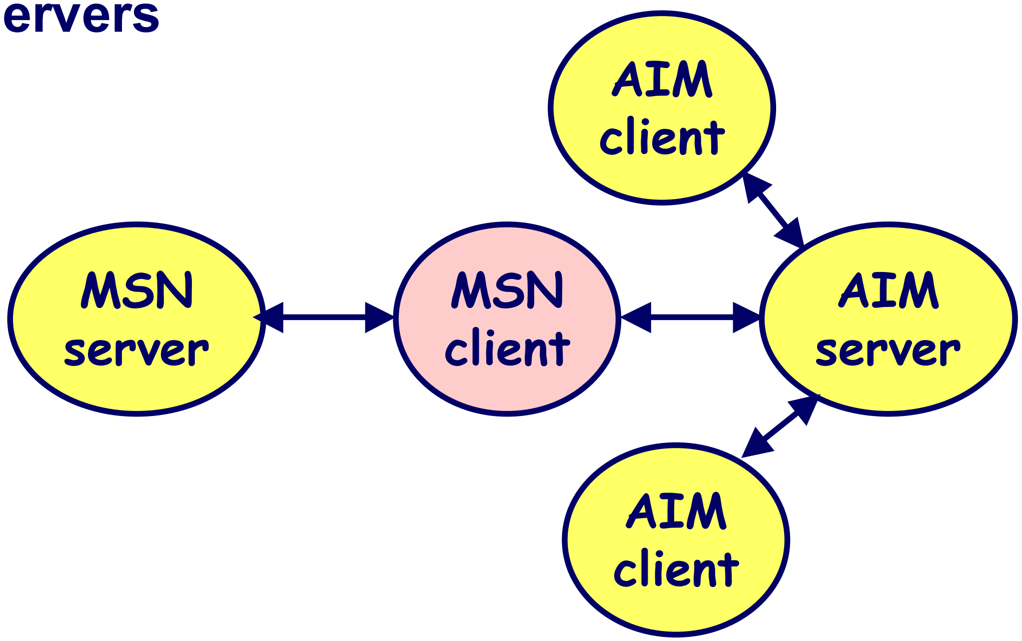
Internet Worm and IM War

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 do not check argument sizes.
- allows target buffers to overflow.

String Library Code

- Implementation of Unix function `gets()`
  - No way to specify limit on number of characters to read

```
/* Get string from stdin */
char *gets(char *dest)
{
    int c = getc();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getc();
    }
    *p = '\0';
    return dest;
}
```

- 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;
}
```

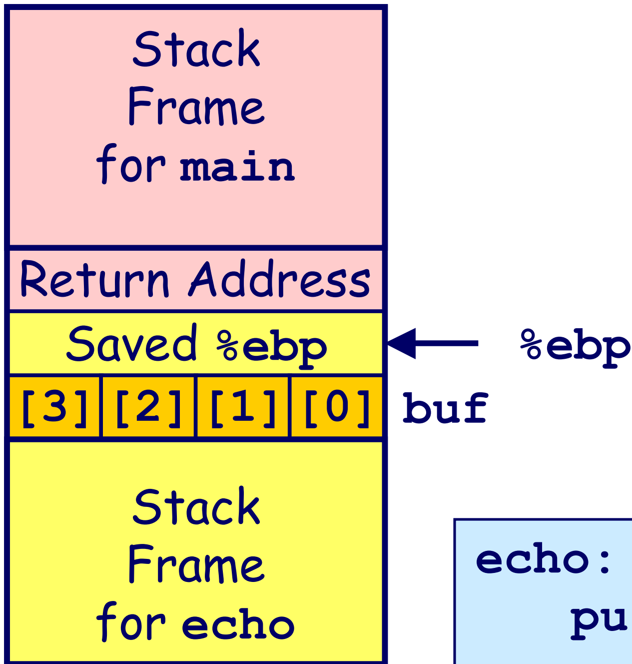
Buffer Overflow Executions

```
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

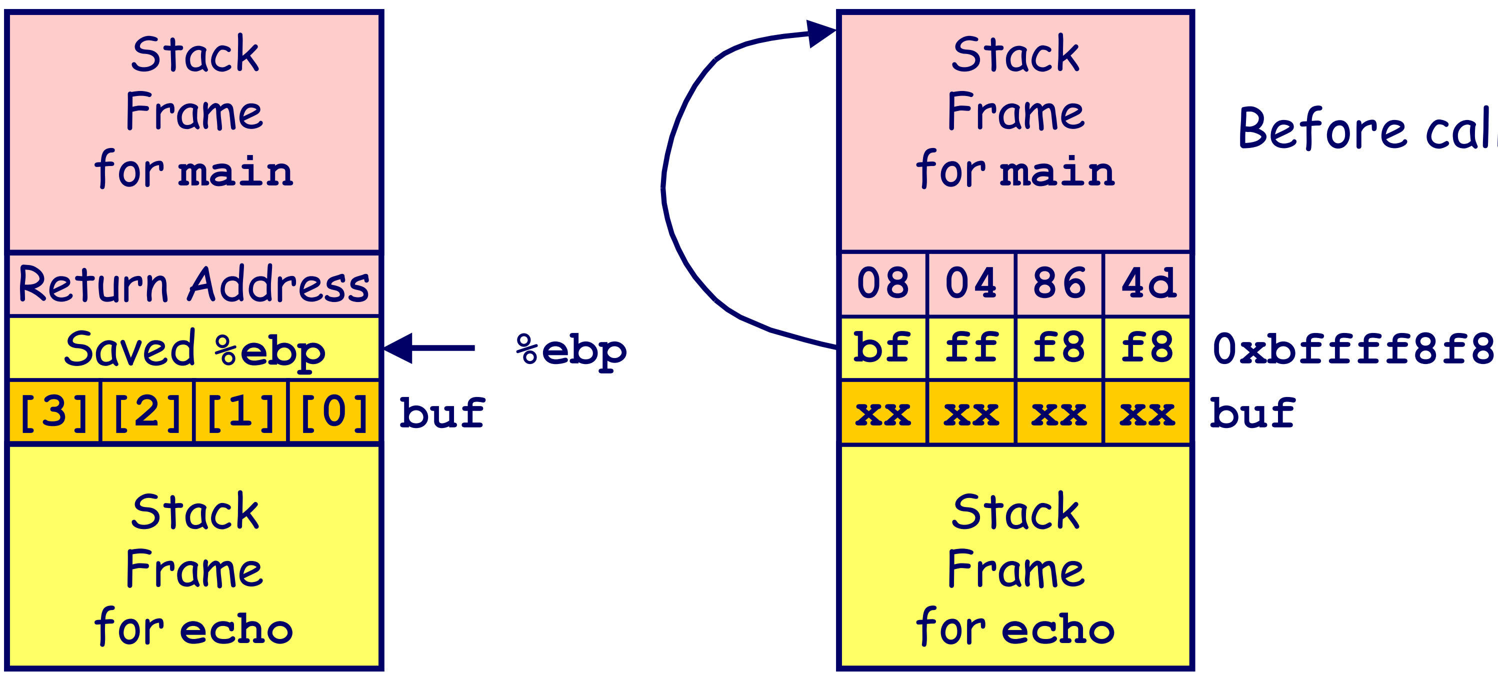



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    pushl %ebp              # Save %ebp on stack
    movl %esp,%ebp
    subl $20,%esp           # Allocate stack space
    pushl %ebx              # Save %ebx
    addl $-12,%esp          # Allocate stack space
    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
```

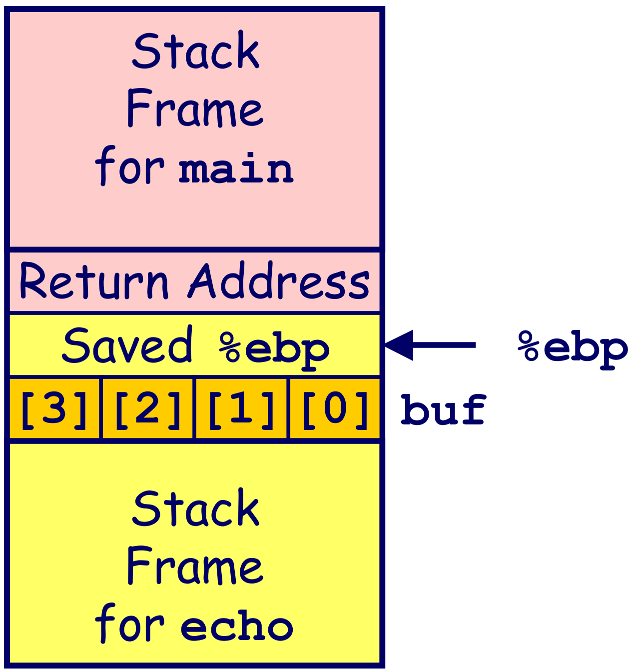


Before call to gets

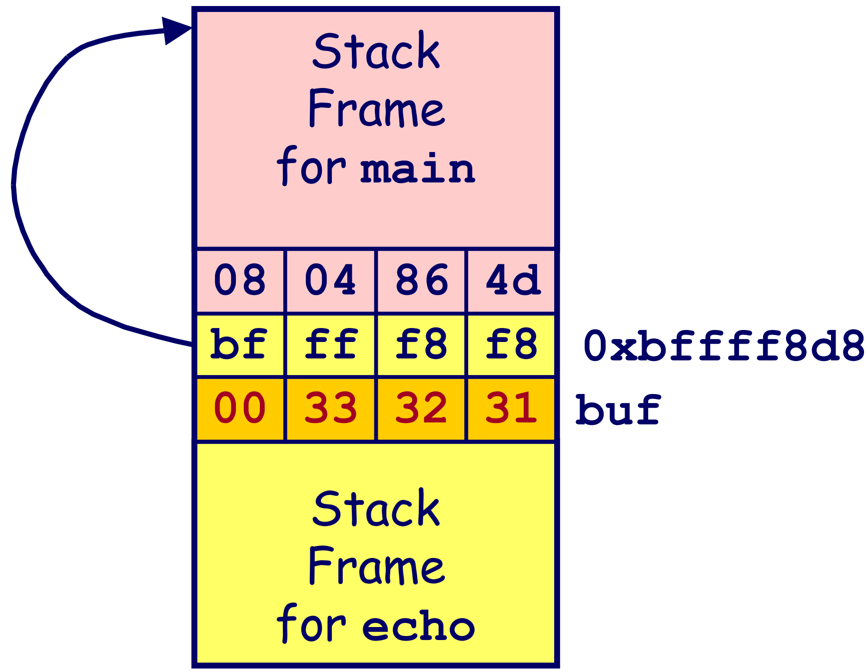
```
8048648:  call  804857c <echo>
804864d:  mov   0xffffffe8(%ebp),%ebx # Return Point
```

Buffer Overflow Example #1

Before Call to gets

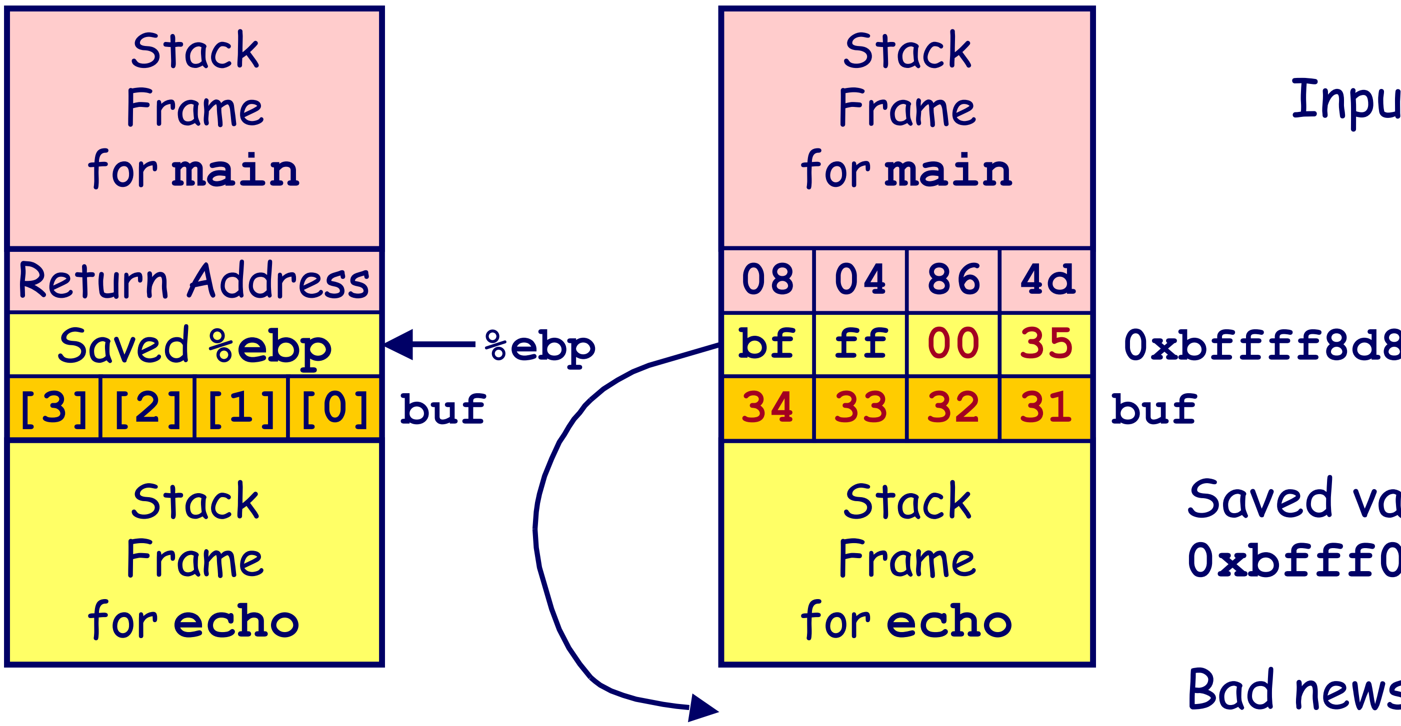


Input = "123"



No Problem

Buffer Overflow Stack Example #2



Input = "12345"

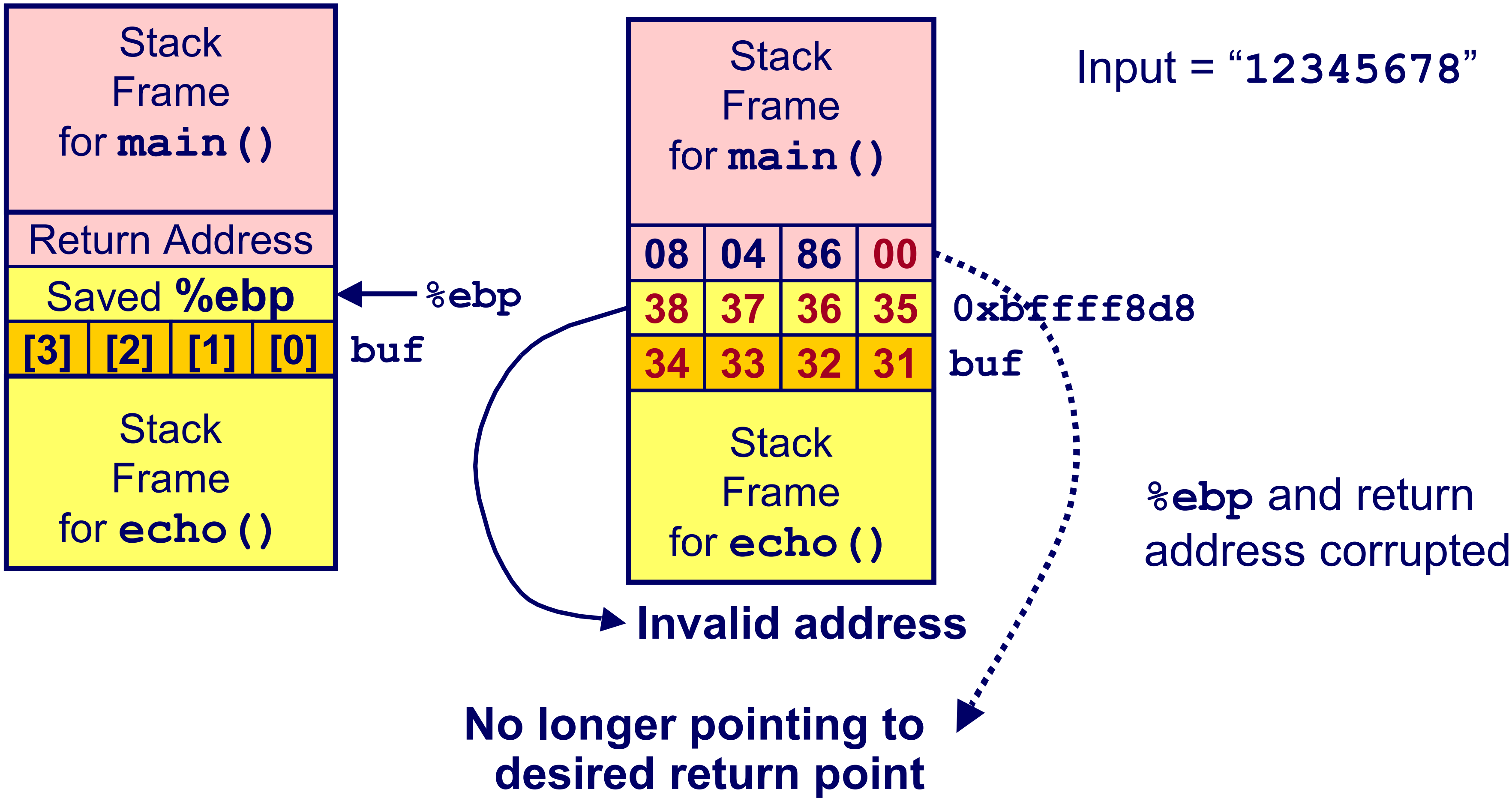
Saved value of %ebp set to 0xbfff0035

Bad news when later attempt to restore %ebp

echo code:

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

Buffer Overflow Stack Example #3




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

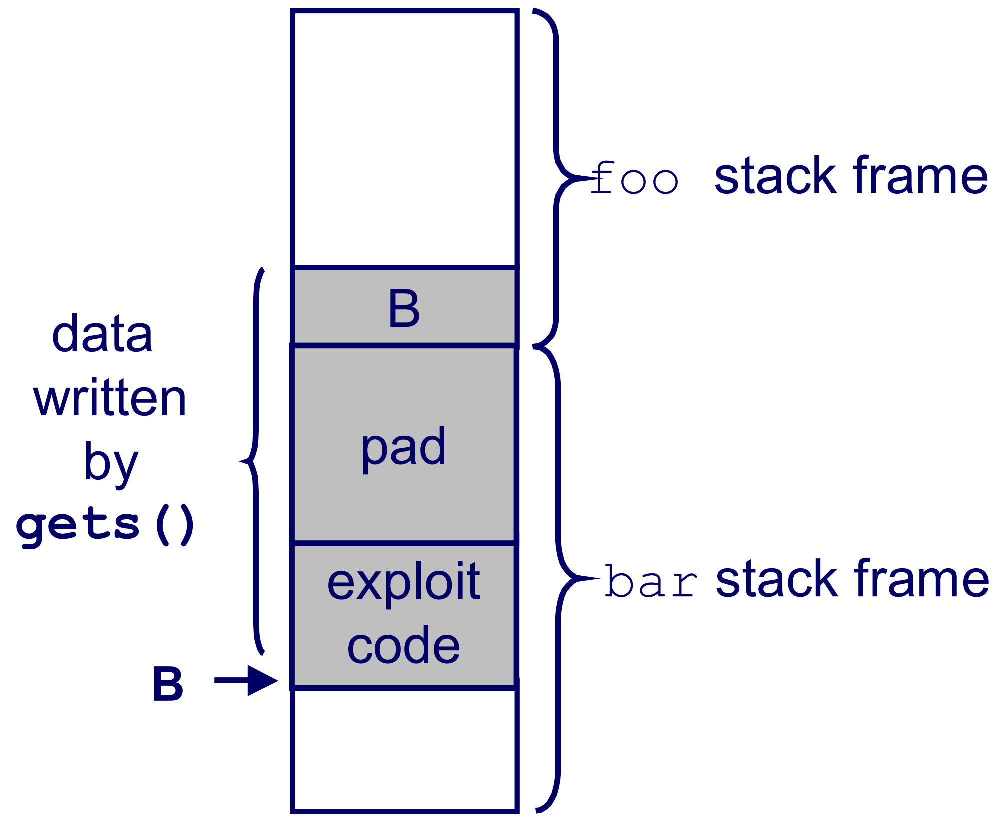
Malicious Use of Buffer Overflow

return address *A*

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

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

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.**

The Internet Worm

11/2	18:24	first west coast computer infected
	19:04	ucb gateway infected
	20:00	mit attacked
	20:49	cs.utah.edu infected
	21:21	load avg reaches 5 on cs.utah.edu
	21:41	load avg reaches 7
	22:01	load avg reaches 16
	22:20	worm killed on cs.utah.edu
	22:41	cs.utah.edu reinfected, load avg 27
	22:49	cs.utah.edu shut down
	23:31	reinfected, load reaches 37

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!

Code Red Worm

History

- **June 18, 2001. Microsoft announces buffer overflow vulnerability in IIS Internet server**
- **July 19, 2001. over 250,000 machines infected by new virus in 9 hours**
- **White house must change its IP address. Pentagon shut down public WWW servers for day**

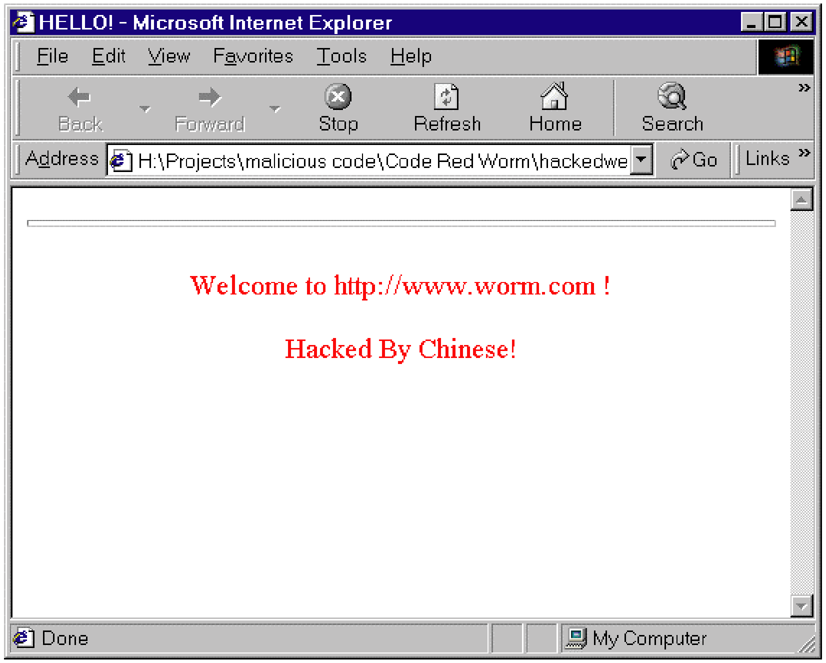
When We Set Up CS:APP Web Site

- **Received strings of form**

```
GET
  /default.ida?NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN....
  NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN%u9090%u6858%uc
  bd3%u7801%u9090%u6858%ucbd3%u7801%u9090%u6858%ucbd3%u780
  1%u9090%u9090%u8190%u00c3%u0003%u8b00%u531b%u53ff%u0078%
  u0000%u00=a
HTTP/1.0" 400 325 "-" "-"
```

Code Red Exploit Code

- Starts 100 threads running
- Spread self
  - Generate random IP addresses & send attack string
  - Between 1st & 19th of month
- Attack www.whitehouse.gov
  - Send 98,304 packets; sleep for 4-1/2 hours; repeat
    - » Denial of service attack
  - Between 21st & 27th of month
- Deface server's home page
  - After waiting 2 hours



Code Red Effects

Later Version Even More Malicious

- Code Red II
- As of April, 2002, over 18,000 machines infected
- Still spreading

Paved Way for NIMDA

- Variety of propagation methods
- One was to exploit vulnerabilities left behind by Code Red II

ASIDE (security flaws start at home)

- .rhosts used by Internet Worm
- Attachments used by MyDoom (1 in 6 emails Monday morning!)

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** `%`*`n`*`s` **where** *n* **is a suitable integer**

IA32 Floating Point

History

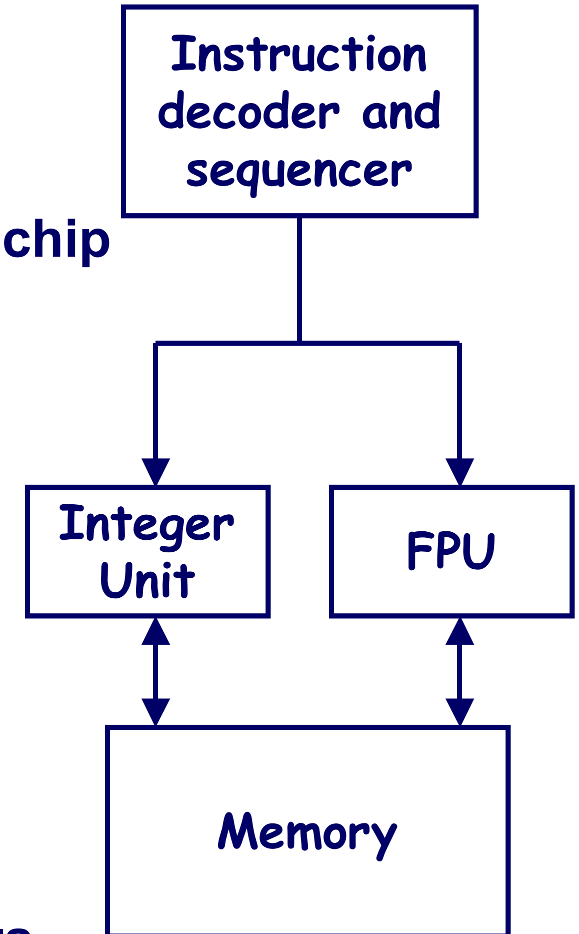
- 8086: first computer to implement IEEE FP
  - separate 8087 FPU (floating point unit)
- 486: merged FPU and Integer Unit onto one chip

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

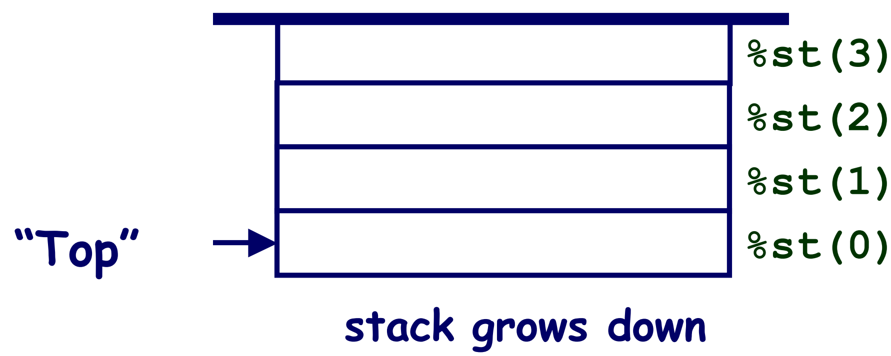


FPU Data Register Stack

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 fp 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

Testing & Comparing FP Numbers

Special FP-instructions to compare the two top stack locations

```
float x;
int n = 0;

for (x = 0.0; x < 10.0; x += 0.1)
{
    n++;
}

n = ??
```

Caution: Need to consider the FP representation properties!

FP Rounding Modes

```
int fegetround(void);
int fesetround(int rounding_mode);
```

4 Rounding modes:

- `FE_TONEAREST` towards nearest FP number
- `FE_DOWNWARD` towards -infinity
- `FE_UPWARD` towards +inifinity
- `FE_TOWARDZERO` towards 0.0

Useful for

- Implementing interval arithmetic
- Compute conservative bounds
- Estimate numerical errors

Floating Point Code Example

Compute Inner Product of Two Vectors

- Single precision arithmetic
- Common computation

```
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/shared-libs 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

Final Observations (Cont.)

Assembly Language

- Very different than programming in C
- Architecture specific (IA-32, X86-64, Sparc, PPC, MIPS, ARM, 370, …)
- No types, no data structures, no safety, just bits&bytes
- Rarely used to program
- Needed to access the full capabilities of a machine
- Important to understand for debugging and optimization