15-213

"The course that gives CMU its Zip!"

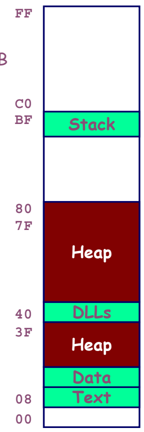
Machine-Level Programming V: Miscellaneous Topics
Feb 6, 2003

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

Linux Memory Layout

Red Hat v. 6.2 ~1920MB memory limit

Upper 2 hex digits of address



Stack
- Runtime stack (8MB limit)

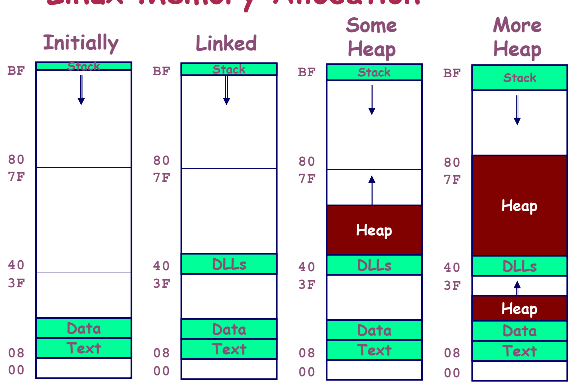
Heap
- Dynamically allocated storage
- When call `malloc`, `calloc`, `new`

DLLs
- 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

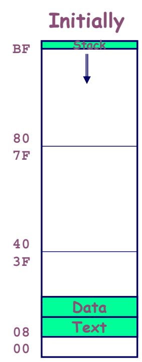
Text
- Executable machine instructions
- Read-only

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`

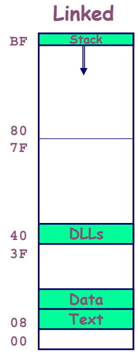
Stack
- Address `0xbffffc78`

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 DLL region



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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 ... */
}
```

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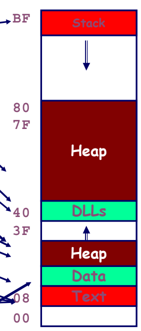
Example Addresses

$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



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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

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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.

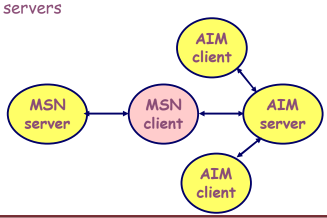
Internet Worm and IM War

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

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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;
}
```

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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
```

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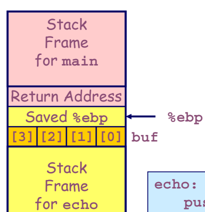
Buffer Overflow Stack




```
/* 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
    . . .
```

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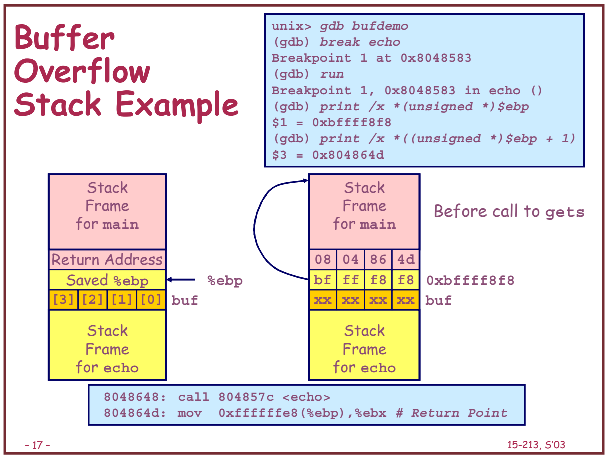
Buffer Overflow Stack Example
unix> gdb bufdemo
(gdb) break echo
Breakpoint 1 at 0x8048583
(gdb) run
Breakpoint 1, 0x8048583 in echo ()
(gdb) print /x *(unsigned *)$ebp
$1 = 0xbffff8f8
(gdb) print /x *((unsigned *)$ebp + 1)
$3 = 0x804864d
Stack Frame for main
Return Address
Saved %ebp
%ebp
[3] [2] [1] [0] buf
Stack Frame for echo
Stack Frame for main
08 04 86 4d
bf ff f8 f8 0xbffff8f8
xx xx xx xx buf
Stack Frame for echo
Before call to gets
8048648: call 804857c <echo>
804864d: mov 0xffffffe8(%ebp),%ebx # Return Point
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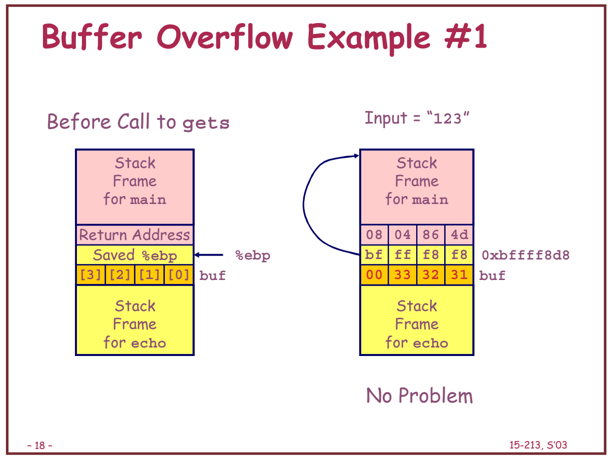
Buffer Overflow Example #1
Before Call to gets
Input = "123"
Stack Frame for main
Return Address
Saved %ebp
%ebp
[3] [2] [1] [0] buf
Stack Frame for echo
Stack Frame for main
08 04 86 4d
bf ff f8 f8 0xbffff8d8
00 33 32 31 buf
Stack Frame for echo
No Problem
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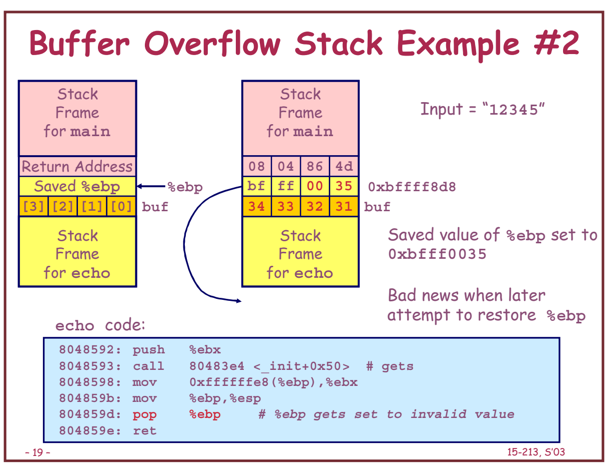
Buffer Overflow Stack Example #2
Stack Frame for main
Return Address
Saved %ebp
%ebp
[3] [2] [1] [0] buf
Stack Frame for echo
Stack Frame for main
08 04 86 4d
bf ff 00 35 0xbffff8d8
34 33 32 31 buf
Stack Frame for echo
Input = "12345"
Saved value of %ebp set to 0xbfff0035
Bad news when later attempt 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
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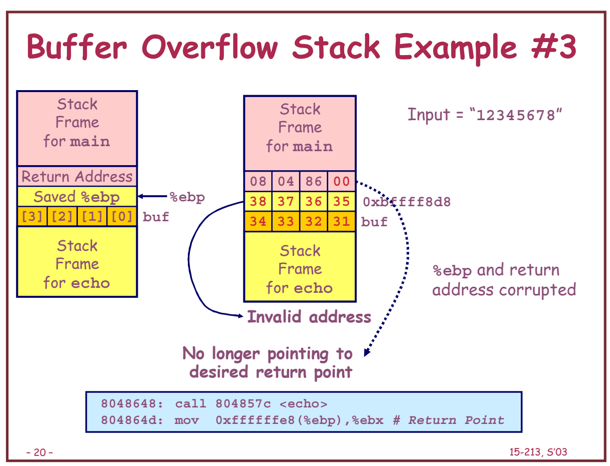
Buffer Overflow Stack Example #3
Stack Frame for main
Return Address
Saved %ebp
%ebp
[3] [2] [1] [0] buf
Stack Frame for echo
Stack Frame for main
08 04 86 00
38 37 36 35 0xbffff8d8
34 33 32 31 buf
Stack Frame for echo
Input = "12345678"
%ebp and return address corrupted
Invalid address
No longer pointing to desired return point
8048648: call 804857c <echo>
804864d: mov 0xffffffe8(%ebp),%ebx # Return Point
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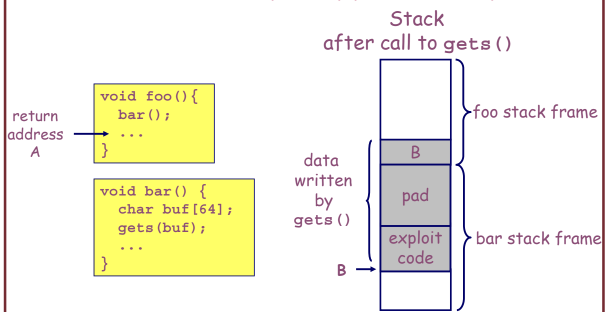
Malicious Use of Buffer Overflow



- 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.

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 cre                                   you
can use this information to he
friendly exterior they are nef                                   ty.

Sincerely,
Phil Bucking
Founder, Bucking Consulting
```

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?NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN....
  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 "-" "-"
```

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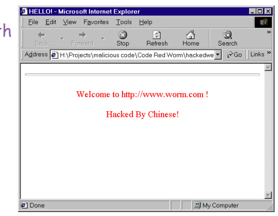
Code Red Exploit Code

- 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



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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

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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

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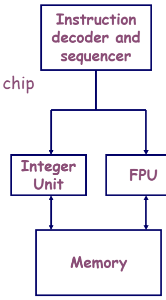
IA32 Floating Point

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

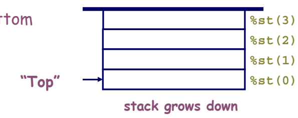
- single precision (C `float`): 32 bits
- double precision (C `double`): 64 bits
- extended precision (C `long double`): 80 bits

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

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
```

Floating Po

```
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
s (%ebx,%eax,4)          # push x[i]
ls (%ecx,%eax,4)         # st(0)*=y[i]
dp                       # st(1)+=st(0)
                         # pop
l %eax                   # i++
l %edx,%eax              # if i<n repeat
.L5
l -4(%ebp),%ebx          # finish
l %ebp, %esp
l %ebp
                         # st(0) = result
```

```
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;
}
```

Floating Po

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

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