15-213

"The course that gives CMU its Zip!"

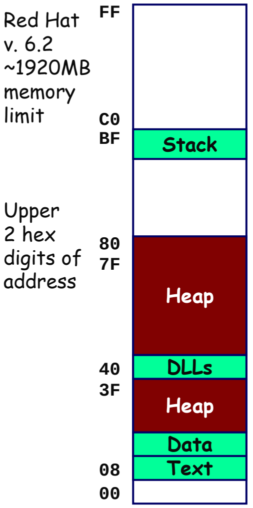
Machine-Level Programming V: Miscellaneous Topics

Feb 10, 2004

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

class09.ppt

Linux Memory Layout



Stack
- Runtime stack (8MB limit)

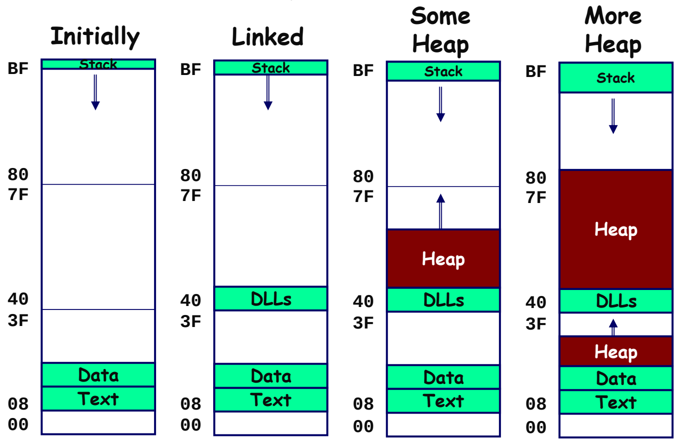
Heap
- Dynamically allocated storage
- When call **`malloc`**, **`calloc`**, **`new`**

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

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

Text
- Executable machine instructions
- Read-only

Linux Memory Allocation

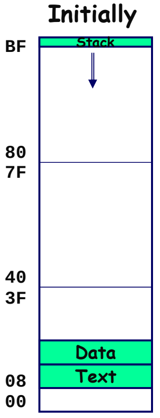


Text & Stack Example

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

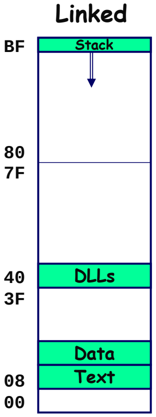
Main
- Address **`0x804856f`** should be read **`0x0804856f`**

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

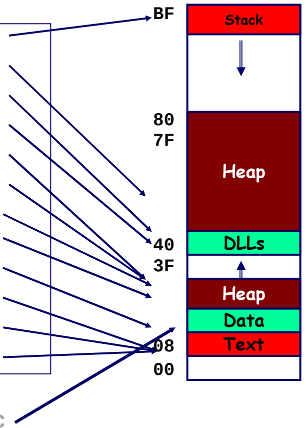
Memory Allocation Example

```
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

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

Avoiding Complex Declarations

Use Typedef to build up the decl

Instead of **`int (*(*x[3])())[5]`** :

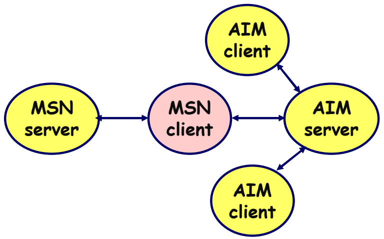
```
typedef int fiveints[5];
typedef fiveints* p5i;
typedef p5i (*f_of_p5is)();
f_of_p5is x[3];
```

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;
}
```

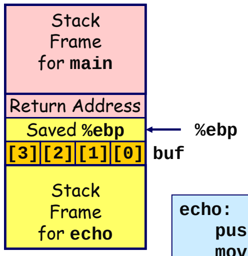
Buffer Overflow Executions

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

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

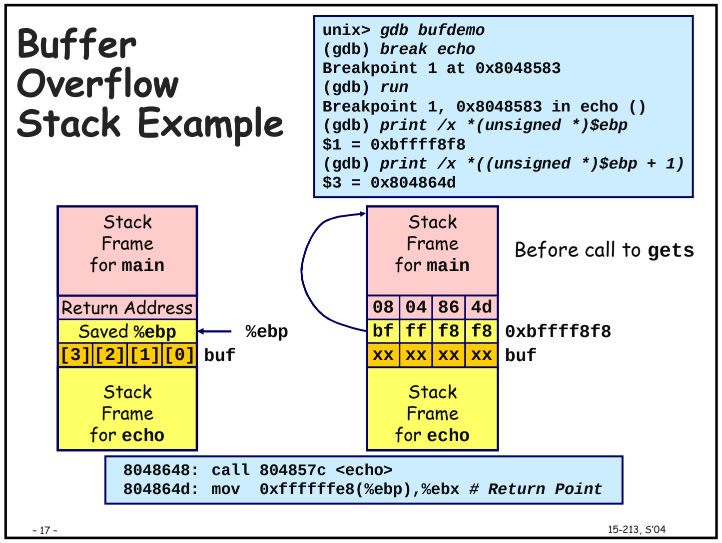
```
unix>./bufdemo
Type a string:12345678
Segmentation Fault
```

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
   . . .
```

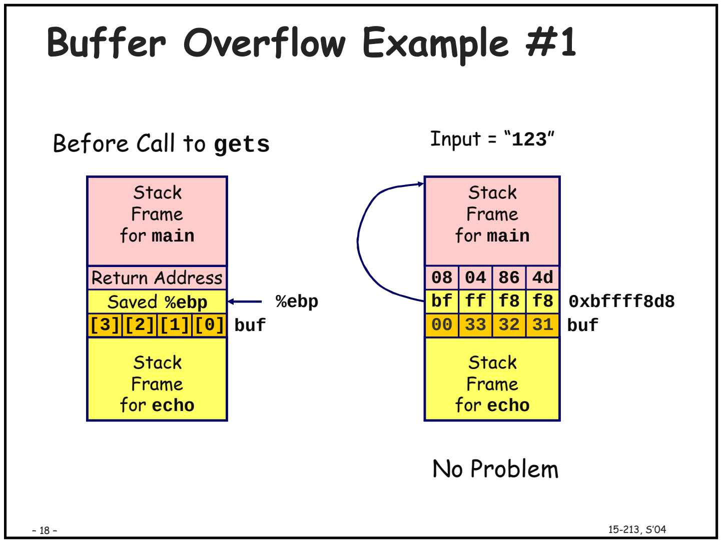


Buffer Overflow Stack Example

```
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
```

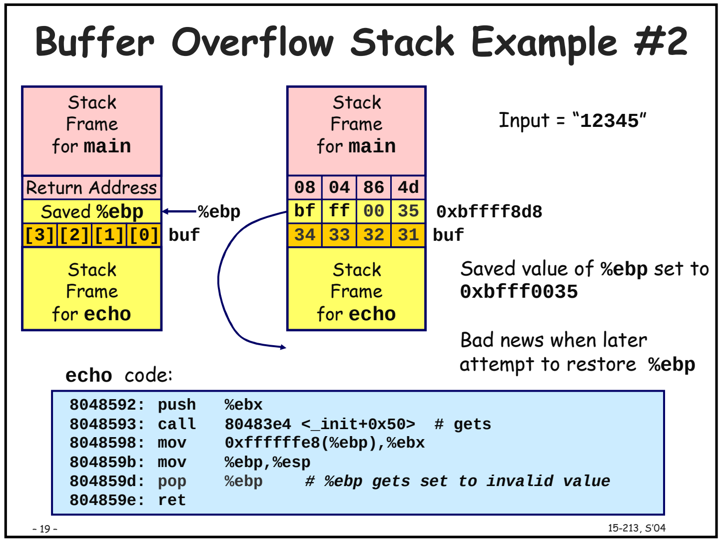


Buffer Overflow Example #1

Before Call to **gets**

Input = "**123**"

No Problem



Buffer Overflow Stack Example #2

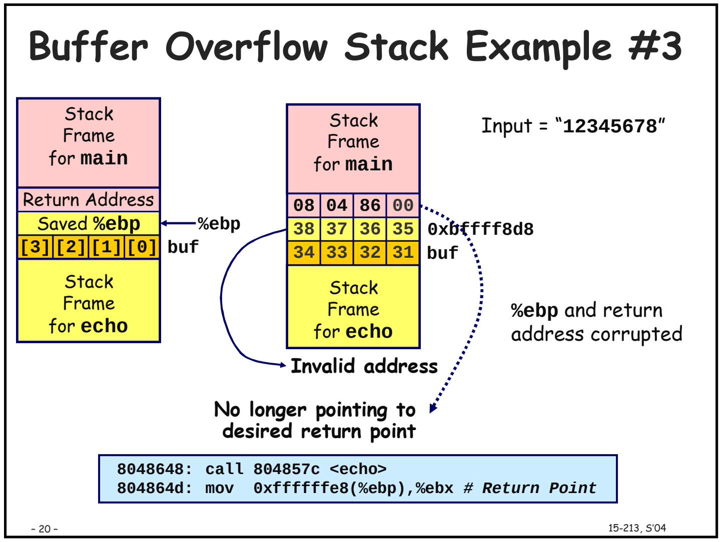
Input = "**12345**"

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

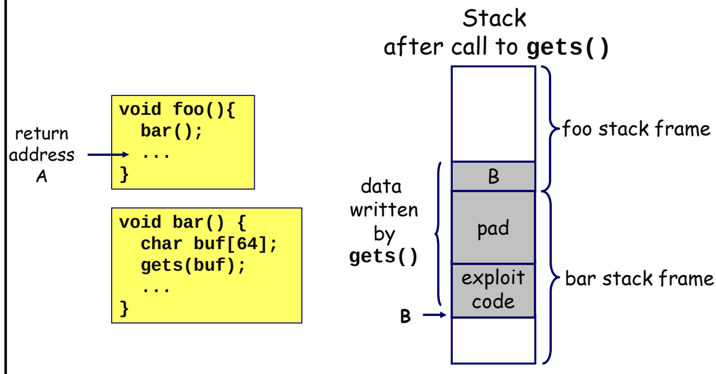
Input = "**12345678**"

%ebp and return address corrupted

No longer pointing to desired return point

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

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.

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 cred you
can use this information to he
friendly exterior they are nef ity.

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?NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN....
  NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN%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

H:\Projects\malicious code\Code Red Worm\hackedwe

Welcome to http://www.worm.com !

Hacked By Chinese!

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!)

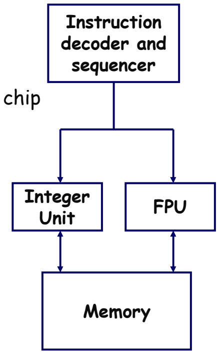
Avoiding Overflow Vulnerability

```
/* 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

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

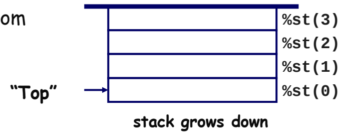
- single precision (C `float`): 32 bits
- double precision (C `double`): 64 bits
- extended precision (C `long double`): 80 bits

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



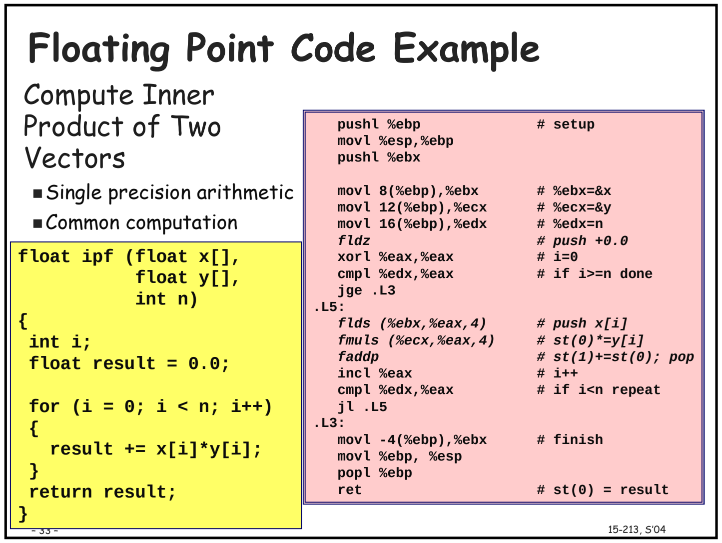
FPU instructions

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



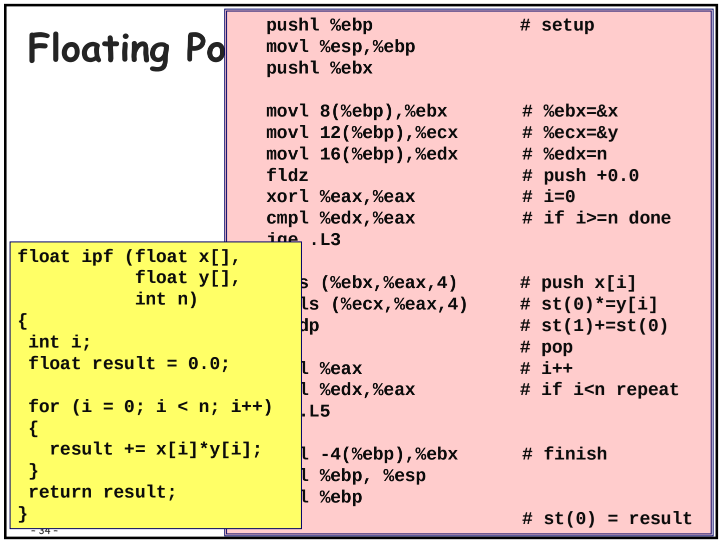
Floating Point Code Example

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;
}
```

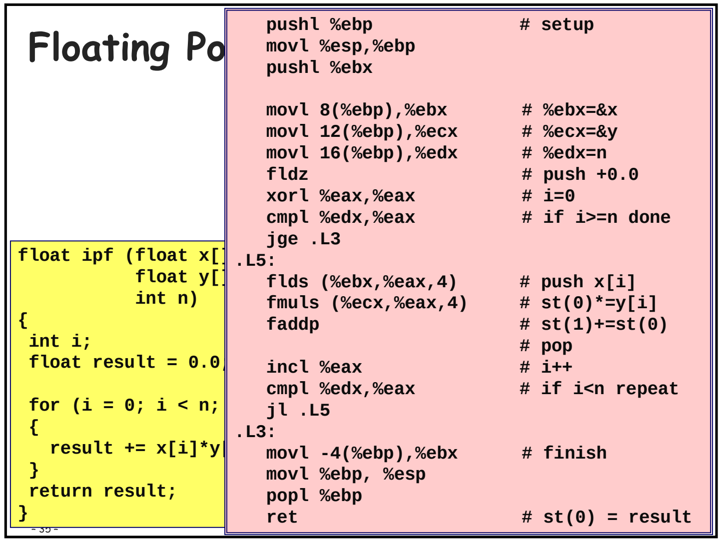
```
   pushl %ebp                  # setup
   movl %esp,%ebp
   pushl %ebx

   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
```

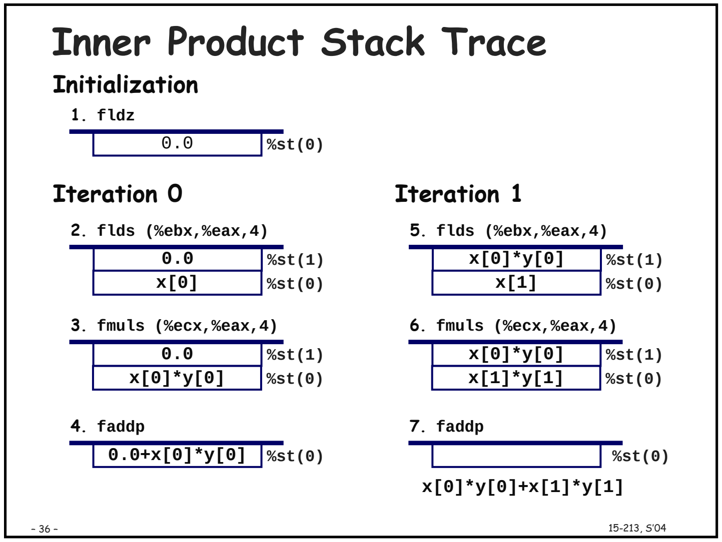
```
float ipf (float x[],
           float y[],
           int n)
{
 int i;
 float result = 0.0;

 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`

Iteration 0

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

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

4. `faddp`

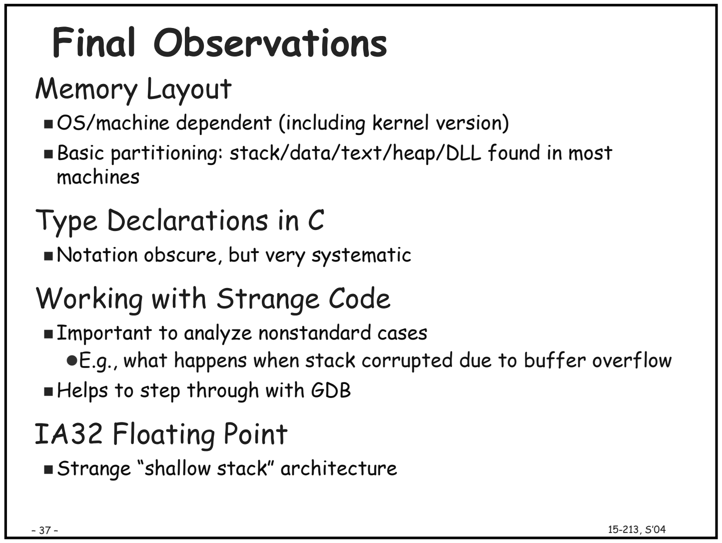
Iteration 1

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

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

7. `faddp`

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

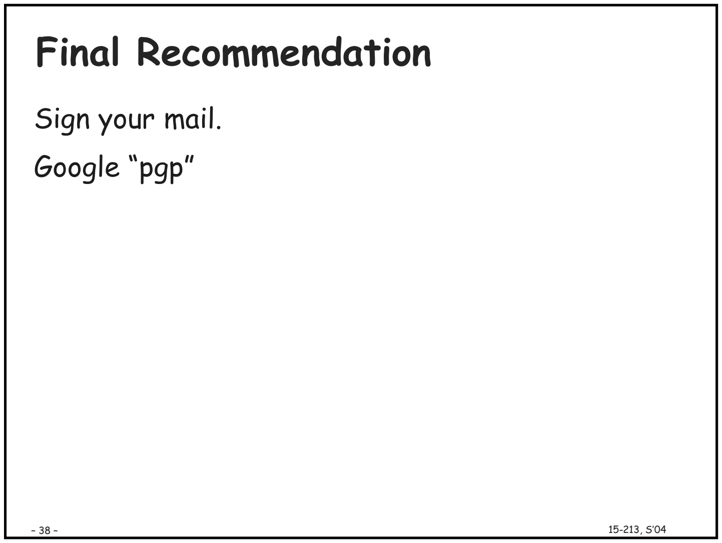
- Notation obscure, but very systematic

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



Final Recommendation

Sign your mail.

Google “pgp”