15-213

"The course that gives CMU its Zip!"

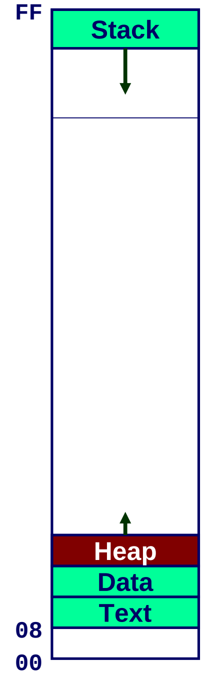
Machine-Level Programming V: Advanced Topics
Sept. 18, 2008

Topics

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

class08.ppt

Upper 2 hex digits of address



IA32 Linux Memory Layout

Stack

- Runtime stack (8MB limit)

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

Memory Allocation Example

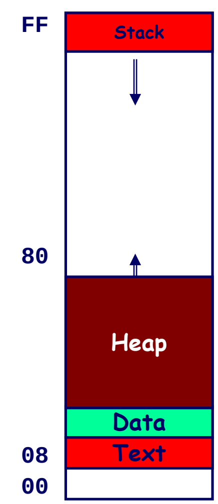
```
char big_array[1<<24];  /*  16 MB */
char huge_array[1<<28]; /* 256 MB */

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 ... */
}
```


IA32 Example Addresses

$esp	0xffffbcd0
p3	0x65586008
p1	0x55585008
p4	0x1904a110
p2	0x1904a008
beyond	0x08049744
big_array	0x18049780
huge_array	0x08049760
main()	0x080483c6
useless()	0x08049744
final malloc()	0x006be166

address range ~2^{32}

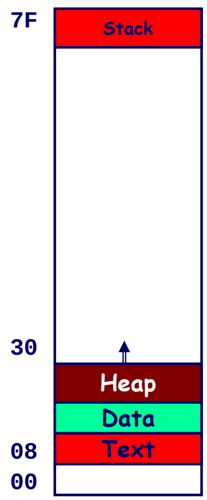
&p2 0x18049760



x86-64 Example Addresses

`$rsp`	`0x7ffffff8d1f8`
`p3`	`0x2aaabaadd010`
`p1`	`0x2aaaaaadc010`
`p4`	`0x000011501120`
`p2`	`0x000011501010`
`beyond`	`0x000000500a44`
`big_array`	`0x000010500a80`
`huge_array`	`0x000000500a50`
`main()`	`0x000000400510`
`useless()`	`0x000000400500`
final `malloc()`	`0x00386ae6a170`

address range ~2^{47}



`&p2` `0x000010500a60`

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>

- `->` has very high precedence
- `()` has very high precedence
- monadic `*` just below

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 declaration

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.

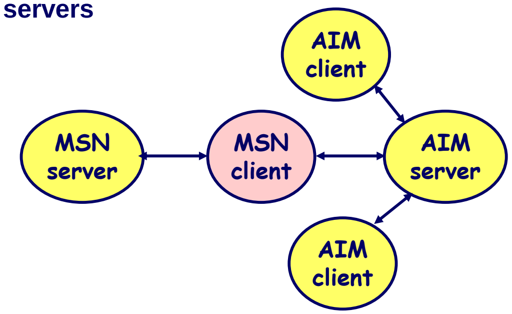
Internet Worm and IM War

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 = getchar();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *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:1234567
1234567
```

```
unix>./bufdemo
Type a string:123455678
Segmentation Fault
```

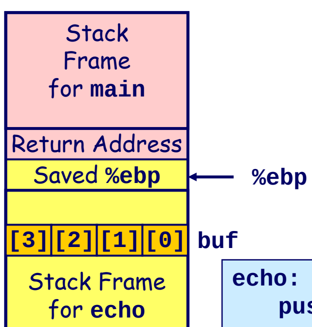
```
unix>./bufdemo
Type a string:1234556789ABC
Segmentation Fault
```


Buffer Overflow Disassembly

```
080484f0 <echo>:
 80484f0: 55                push   %ebp
 80484f1: 89 e5             mov    %esp,%ebp
 80484f3: 53                push   %ebx
 80484f4: 8d 5d f8          lea    0xfffffff8(%ebp),%ebx
 80484f7: 83 ec 14          sub    $0x14,%esp
 80484fa: 89 1c 24          mov    %ebx,(%esp)
 80484fd: e8 ae ff ff ff    call   80484b0 <gets>
 8048502: 89 1c 24          mov    %ebx,(%esp)
 8048505: e8 8a fe ff ff    call   8048394 <puts@plt>
 804850a: 83 c4 14          add    $0x14,%esp
 804850d: 5b                pop    %ebx
 804850e: c9                leave
 804850f: c3                ret
```

```
 80485f2: e8 f9 fe ff ff    call   80484f0 <echo>
 80485f7: 8b 5d fc          mov 0xfffffffc(%ebp),%ebx
 80485fa: c9                leave
 80485fb: 31 c0             xor    %eax,%eax
 80485fd: c3                ret
```

Buffer Overflow Stack

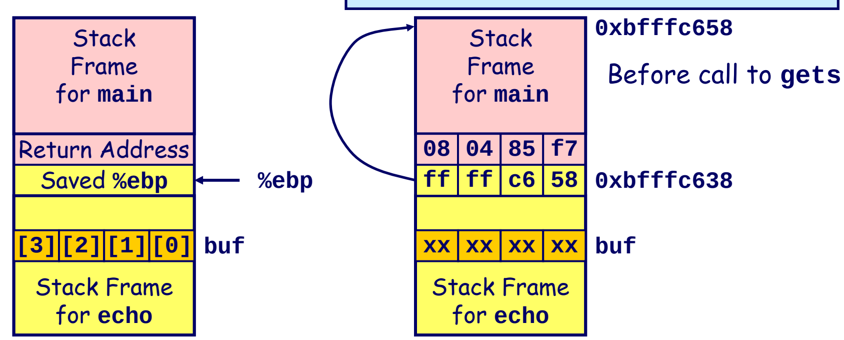



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
   pushl %ebp           # Save %ebp on stack
   movl  %esp, %ebp
   pushl %ebx           # Save %ebx
   leal  -8(%ebp),%ebx  # Compute buf as %ebp-8
   subl  $20, %esp      # Allocate stack space
   movl  %ebx, (%esp)   # 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 $ebp
$1 = 0xffffc638
(gdb) print /x *(unsigned *)$ebp
$2 = 0xffffc658
(gdb) print /x *((unsigned *)$ebp + 1)
$3 = 0x80485f7
```

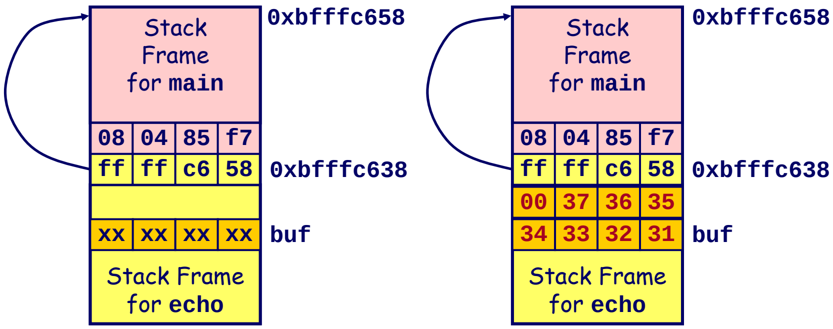



```
80485f2:  call 80484f0 <echo>
80485f7:  mov  0xfffffffc(%ebp),%ebx # Return Point
```

Buffer Overflow Example #1

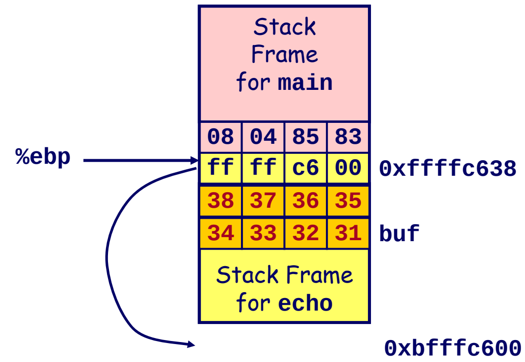
Before Call to gets

Input = "1234567"



Overflow buf, but no problem

Buffer Overflow Stack Example #2



Input = "12345678"

Saved value of %ebp set to 0xbfffc600

echo code restores %ebp with corrupted value

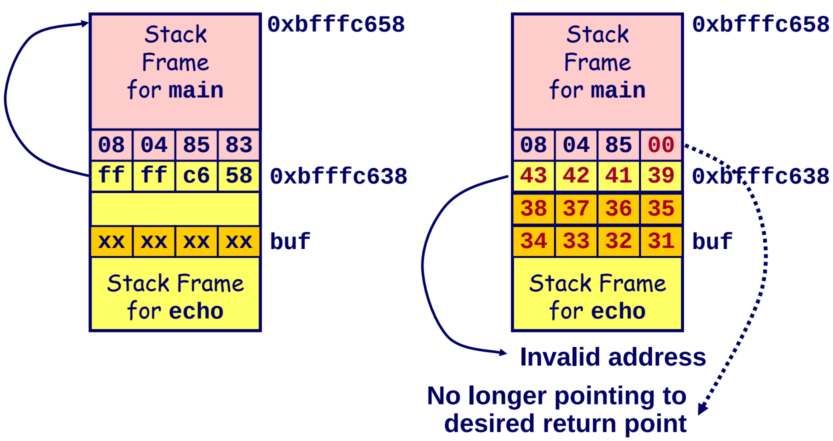
end of echo code:

```
. . .
804850a:  83 c4 14   add    $0x14,%esp   # deallocate space
804850d:  5b         pop    %ebx         # restore %ebx
804850e:  c9         leave               # movl %ebp, %esp; popl %ebp
804850f:  c3         ret                 # Return
```


Buffer Overflow Stack Example #3

Before Call to gets

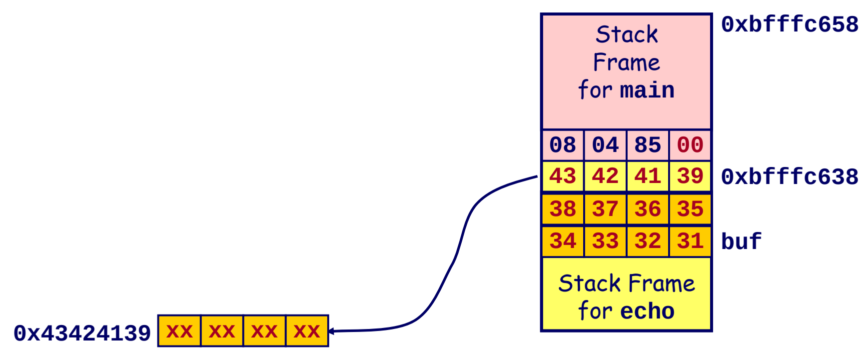
Input = "123456789ABC"




```
80485f2:  call 80484f0 <echo>
80485f7:  mov  0xfffffffc(%ebp),%ebx # Return Point
```


Example #3 Failure

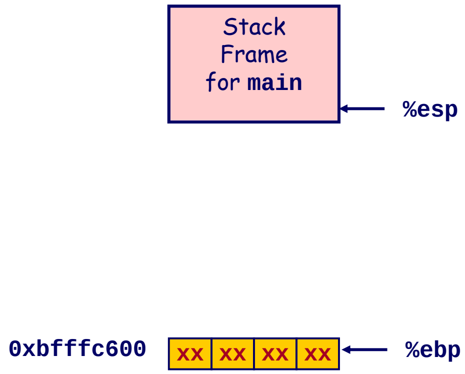
Input = "123456789ABC"



end of echo code:

```
. . .
804850a:  83 c4 14   add    $0x14,%esp   # deallocate space
804850d:  5b         pop    %ebx         # restore %ebx
804850e:  c9         leave               # movl %ebp, %esp; popl %ebp
804850f:  c3         ret                 # Return (Invalid)
```

Example #2 Failure



Input = "12345678"

echo code restores %ebp with corrupted value

Subsequent references based on %ebp invalid

Return from echo:

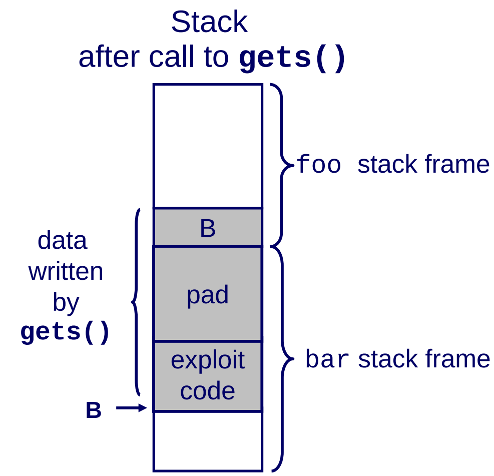
```
80485f2:  e8 f9 fe ff ff  call   80484f0 <echo>

80485f7:  8b 5d fc        mov    0xfffffffc(%ebp),%ebx  # bad ref?
80485fa:  c9              leave  # movl %ebp,%esp; popl %ebp
80485fb:  31 c0           xor    %eax,%eax
80485fd:  c3              ret                           # bad ref
```

Malicious Use of Buffer Overflow

return address A

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

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



- **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 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

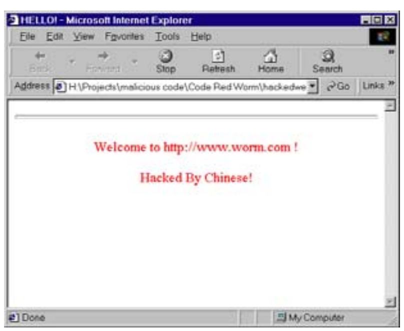
When We Set Up CS:APP Web Site

- Received strings of form

```
GET
  /default.ida?NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN....
  NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN%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 `%ns` where *n* is a suitable integer

System-Level Protections

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

(gdb) run
(gdb) print /x $ebp
$1 = 0xffffc638

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

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

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
- Add explicit "execute" permission

IA32 Floating Point

History

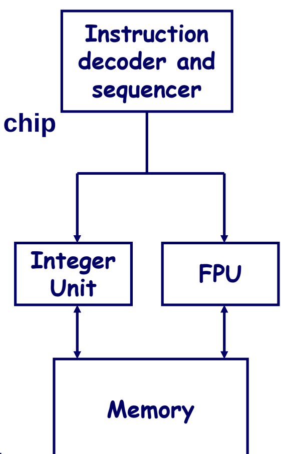
- 8086: first computer to implement IEEE FP
  - separate 8087 FPU (floating point unit)
- 486: merged FPU and Integer Unit onto one chip

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

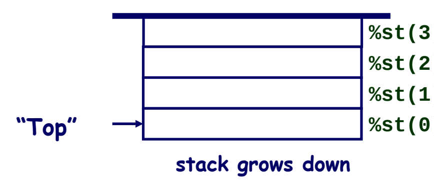


FPU Data Register Stack

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!

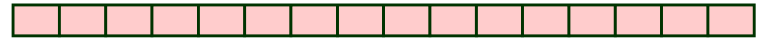
Sample instructions:

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

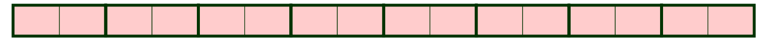
Programming with SSE3

XMM Registers

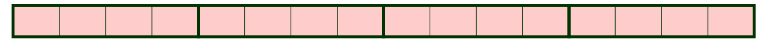
- 16 total, each 16 bytes
- 16 single-byte integers



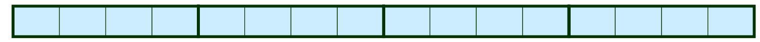
- 8 16-bit integers



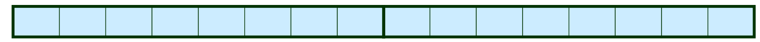
- 4 32-bit integers



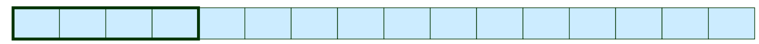
- 4 single-precision floats



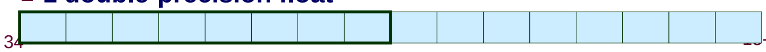
- 2 double-precision floats



- 1 single-precision float

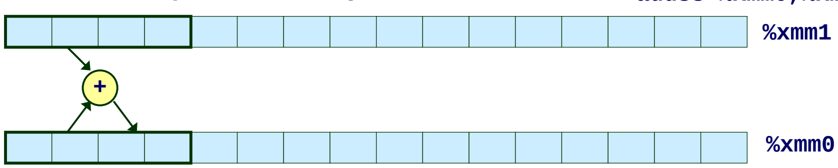


- 1 double-precision float

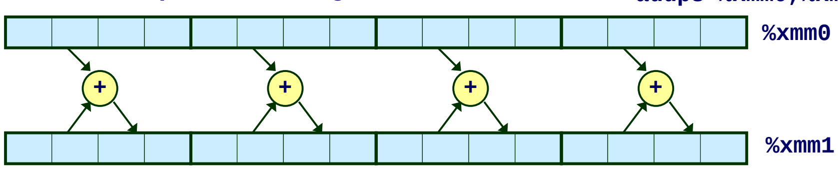


Scalar & SIMD Operations

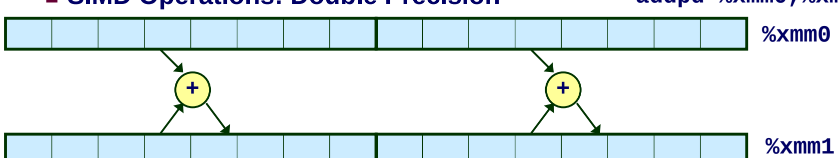
- Scalar Operations: Single Precision `addss %xmm0,%xmm1`



- SIMD Operations: Single Precision `addps %xmm0,%xmm1`



- SIMD Operations: Double Precision `addpd %xmm0,%xmm1`



x86-64 FP Code Example

Compute Inner Product of Two Vectors

- Single precision arithmetic
- Common computation
- Uses SSE3 instructions

```
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;
}
```

```
ipf:
  xorps   %xmm1, %xmm1        #  result = 0.0
  xorl    %ecx, %ecx          #  i = 0
  jmp     .L8                 #  goto middle
.L10:                         # loop:
  movslq  %ecx,%rax           #  icpy = i
  incl    %ecx                # i++
  movss (%rsi,%rax,4), %xmm0  # t =  a[icpy]
  mulss (%rdi,%rax,4), %xmm0  # t *= b[icpy]
  addss   %xmm0, %xmm1        # result += t
.L8:                          # middle:
  cmpl    %edx, %ecx          # i:n
  jl      .L10                # if < goto loop
  movaps  %xmm1, %xmm0        # return result
  ret
```

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

Floating Point

- IA32: Strange "shallow stack" architecture
- x86-64: SSE3 permits more conventional, register-based approach

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