15-213

“The course that gives CMU its Zip!”

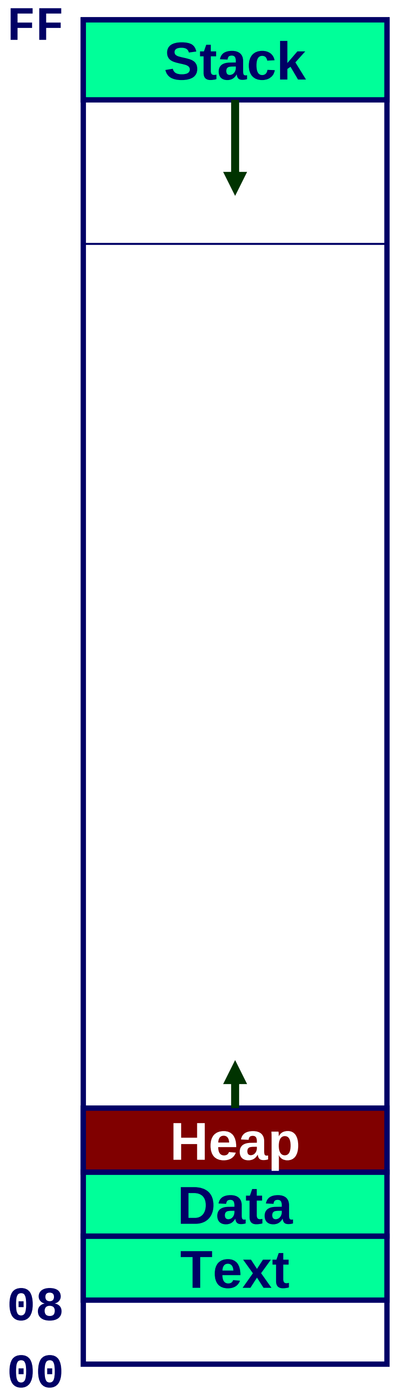
Machine-Level Programming V: Advanced Topics February 7, 2008

Topics

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

IA32 Linux Memory Layout

Upper
2 hex
digits of
address



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

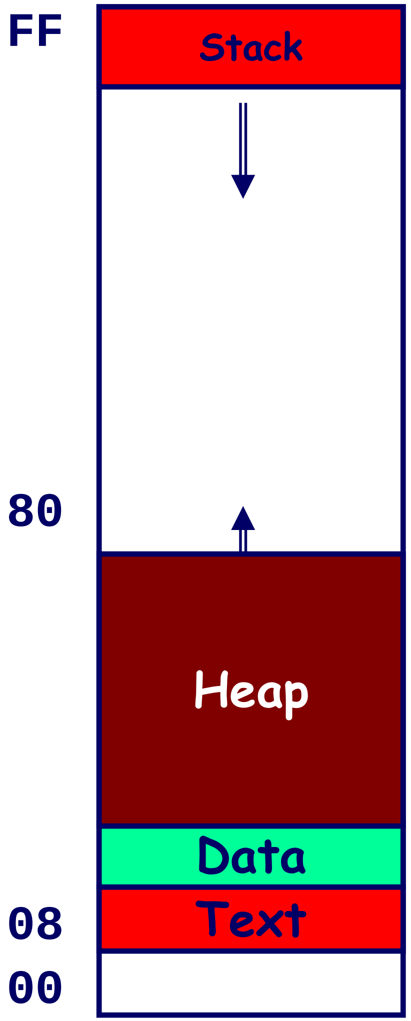
Memory Allocation Example

```
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}

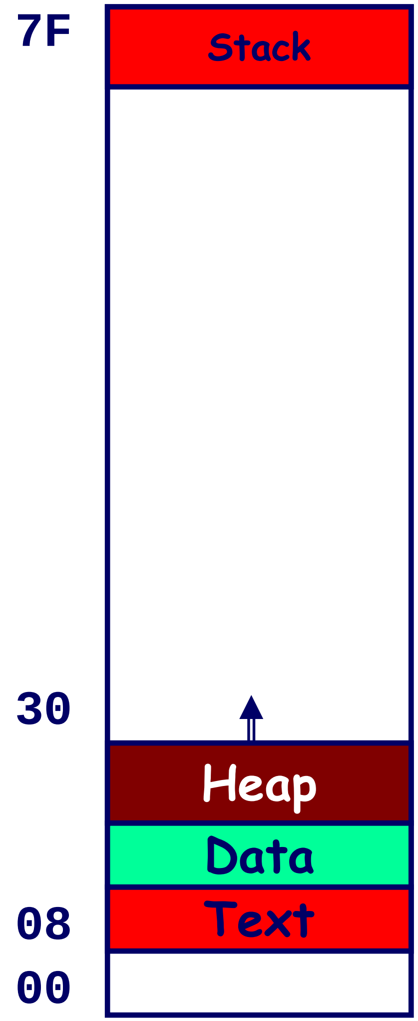


`&p2` `0x18049760`

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 $\sim 2^{47}$



`&p2` `0x000010500a60`

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

- **-> 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.

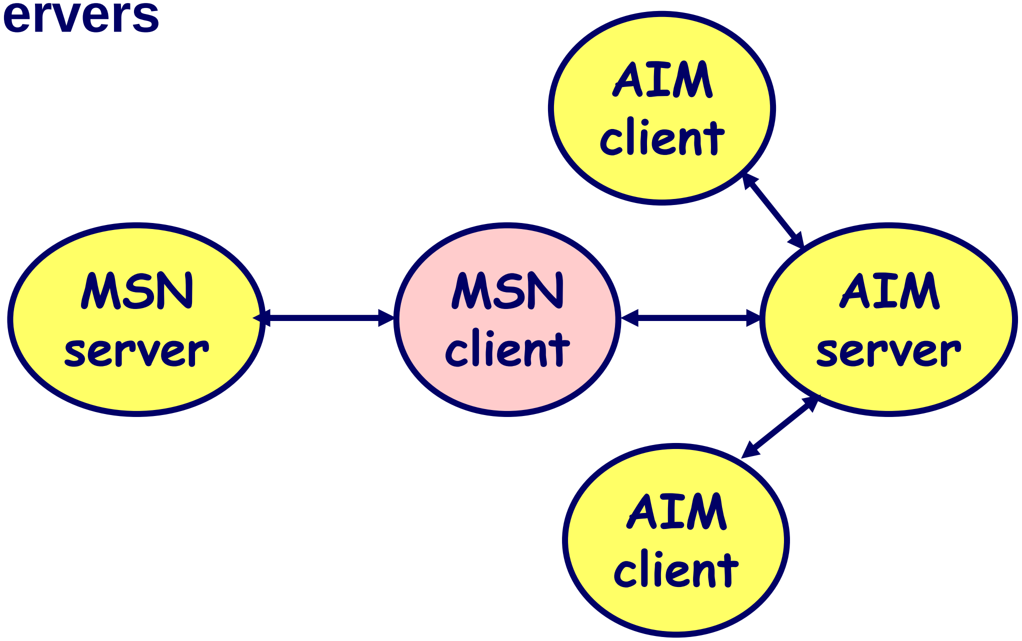
Internet Worm and IM War

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;
}
```

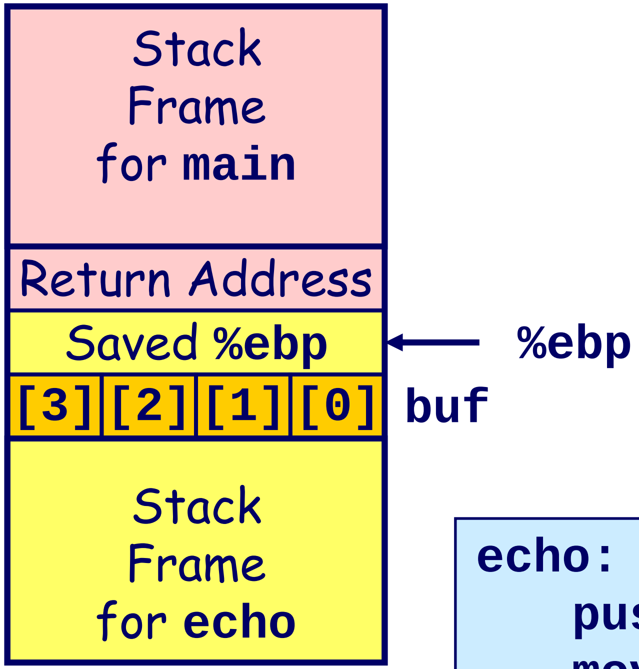
Buffer Overflow Executions

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

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

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

Buffer Overflow Stack

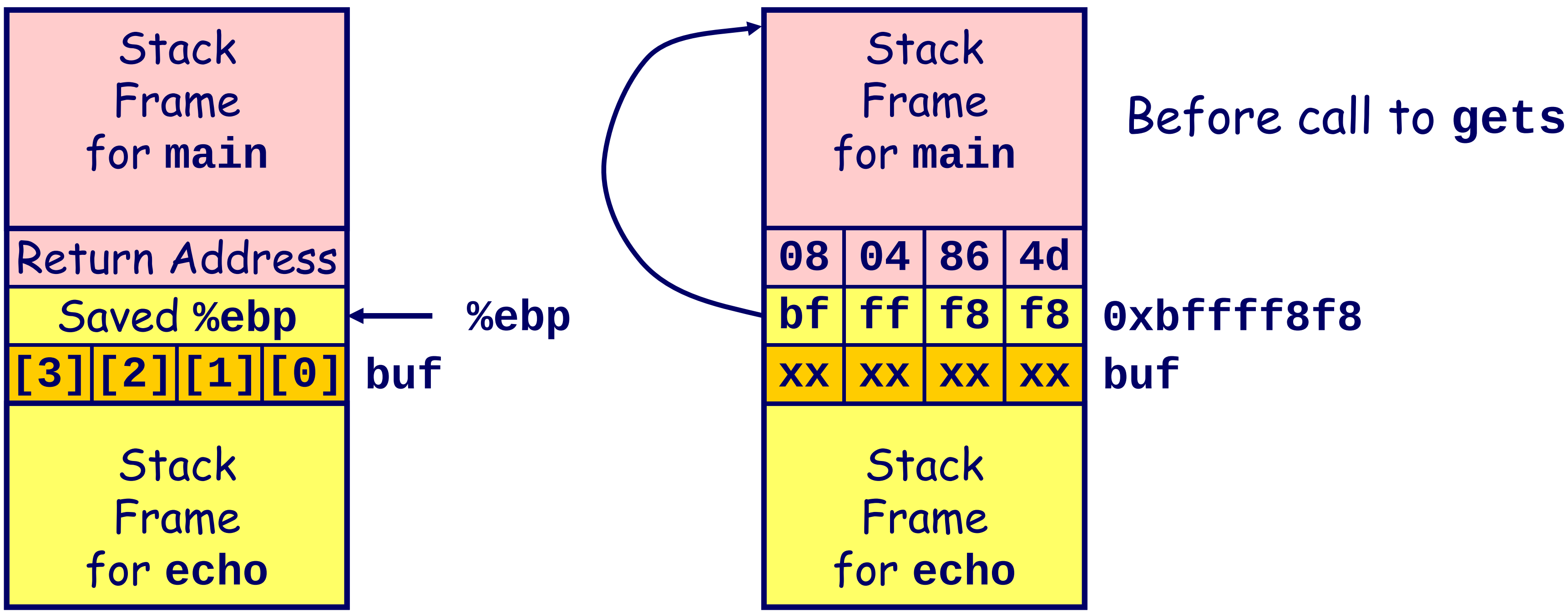



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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
```

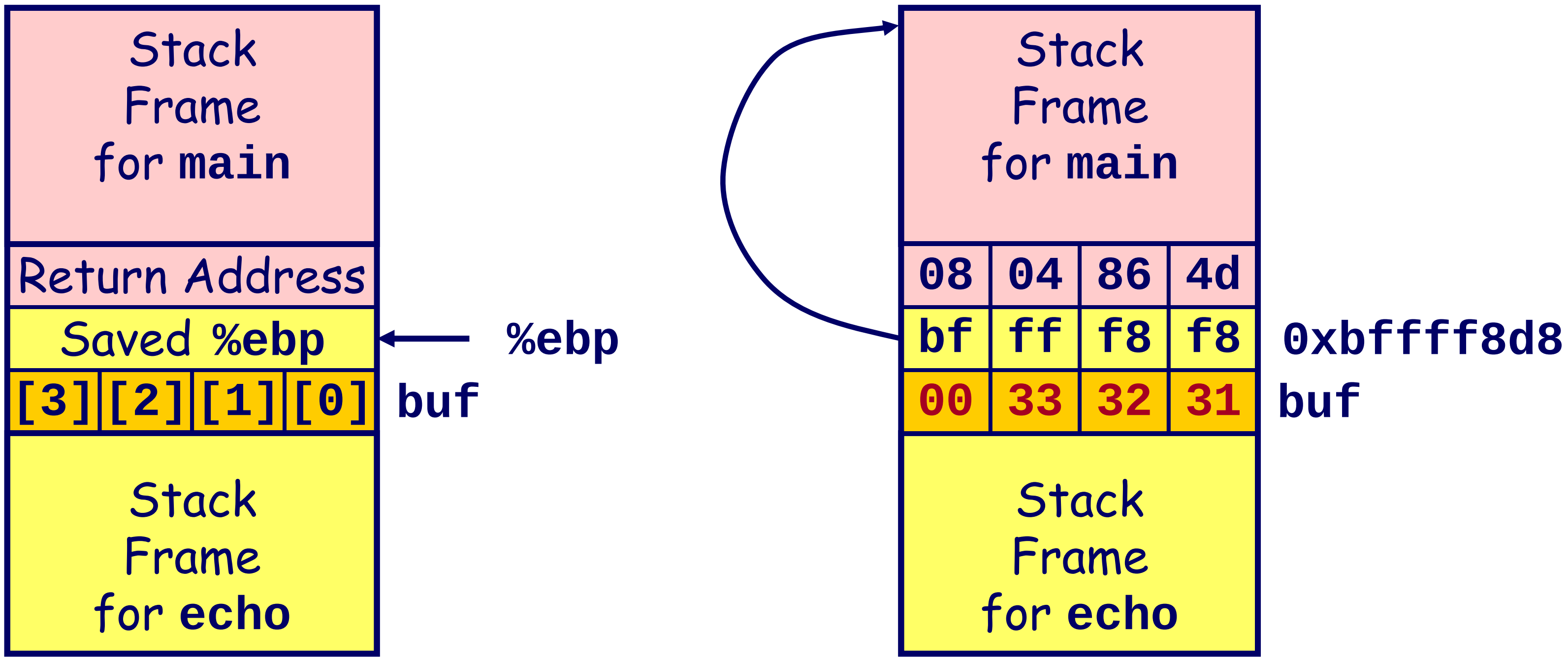



```
8048648:  call 804857c <echo>
804864d:  mov  0xffffffe8(%ebp),%ebx # Return Point
```

Buffer Overflow Example #1

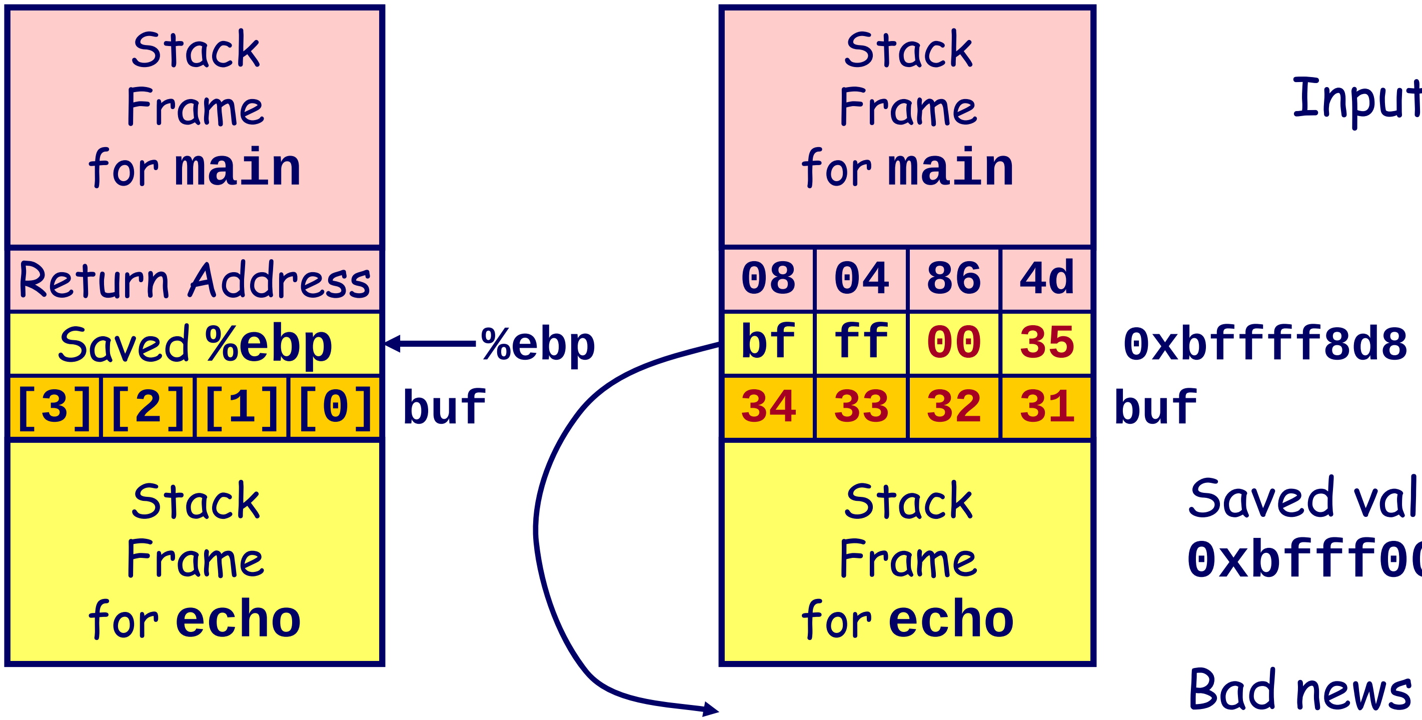
Before Call to **gets**

Input = "**123**"



No Problem

Buffer Overflow Stack Example #2



Input = "**12345**"

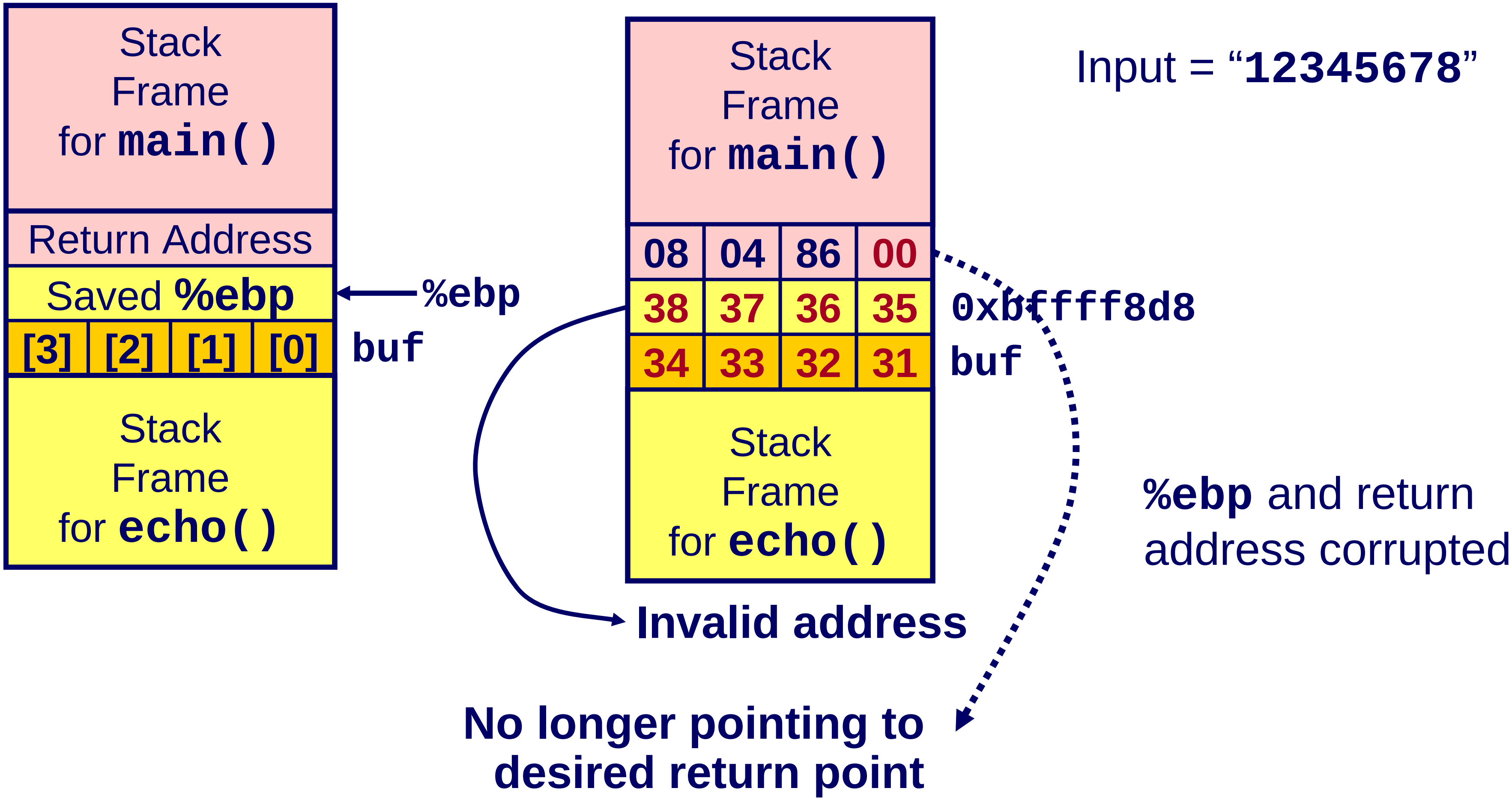
Saved value of **%ebp** set to **0xbfff0035**

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
```

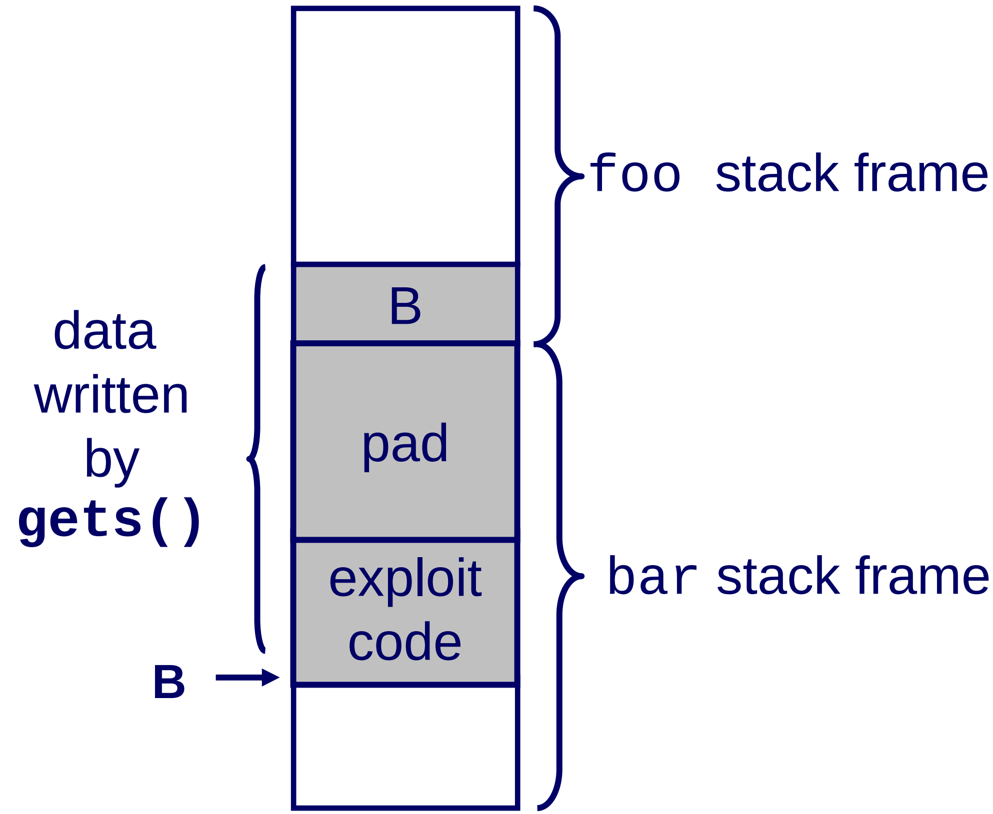
Malicious Use of Buffer Overflow

return address A

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

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

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.**

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

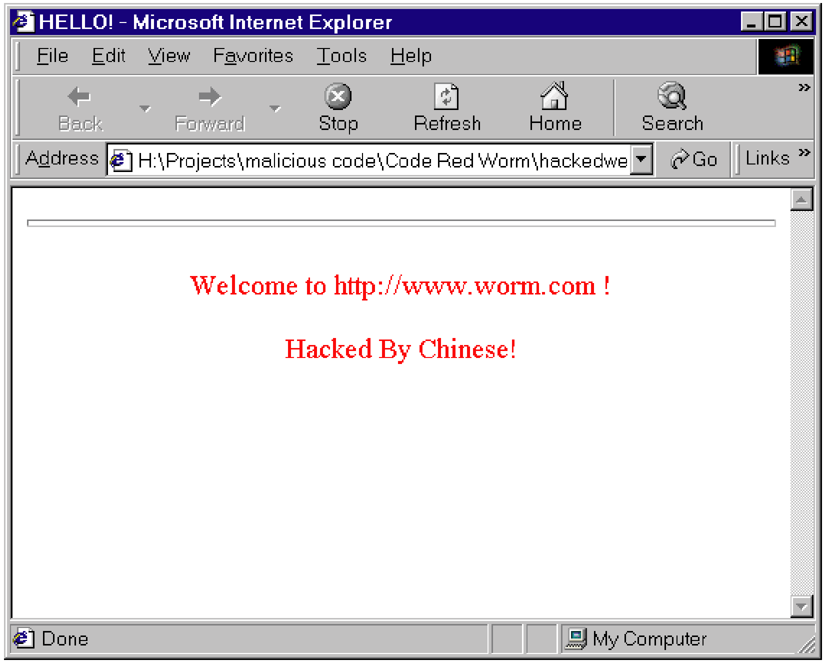
When We Set Up CS:APP Web Site

- Received strings of form

```
GET
  /default.ida?NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN....
  NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN%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);
}
```

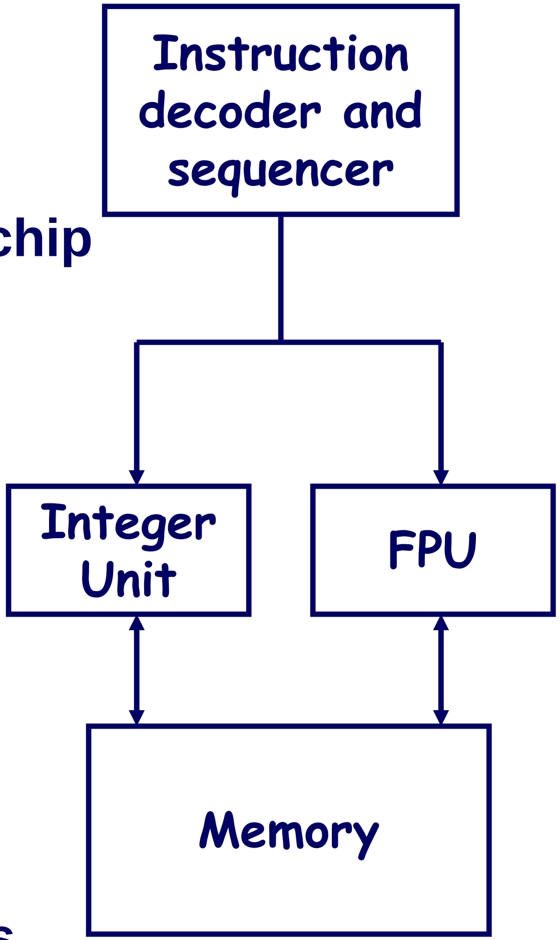
Use Library Routines that Limit String Lengths

- `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

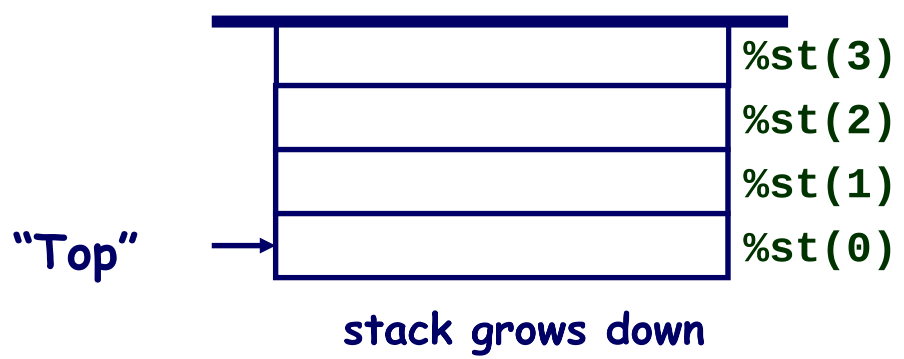
- single precision (C `float`): 32 bits
- double precision (C `double`): 64 bits
- extended precision (C `long double`): 80 bits

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

IA32 FP 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`

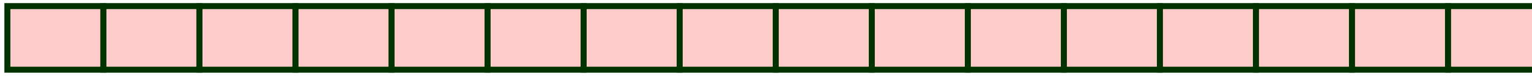
	%st(0)

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

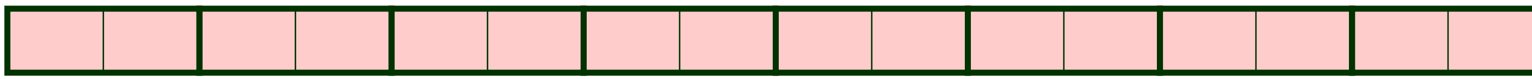
Programming with SSE3

XMM Registers

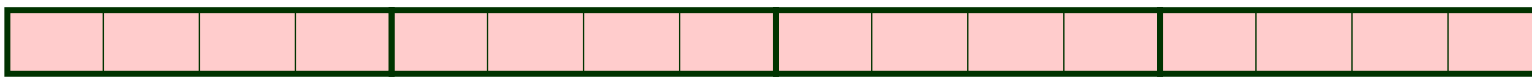
- 16 total, each 16 bytes
- 16 single-byte integers



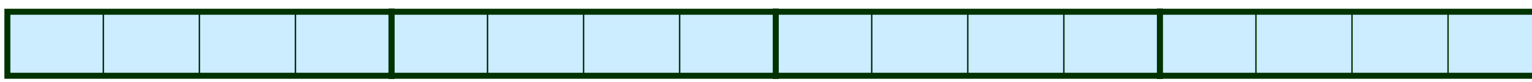
- 8 16-bit integers



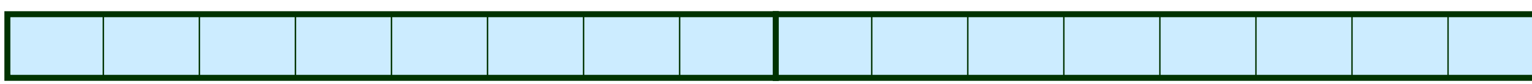
- 4 32-bit integers



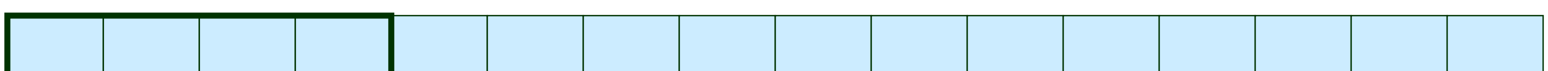
- 4 single-precision floats



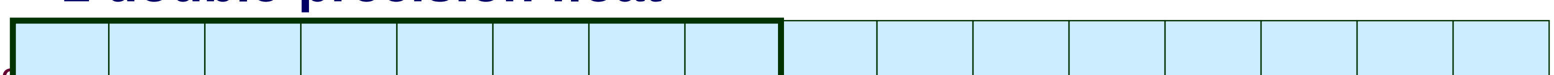
- 2 double-precision floats



- 1 single-precision float



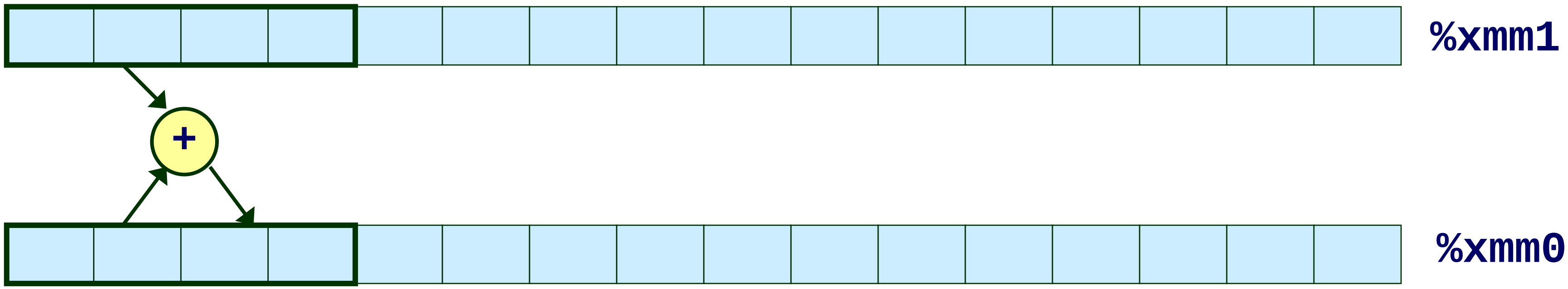
- 1 double-precision float



Scalar & SIMD Operations

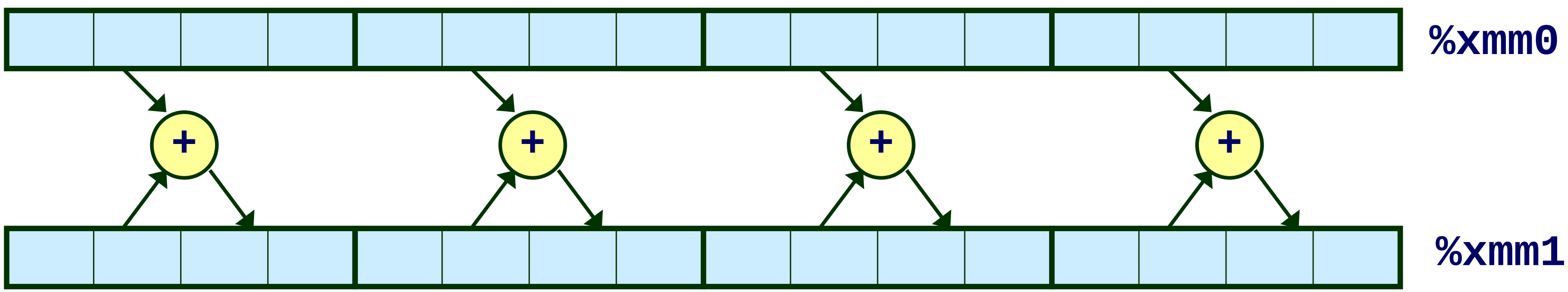
- **Scalar Operations: Single Precision**

`addss %xmm0,%xmm1`



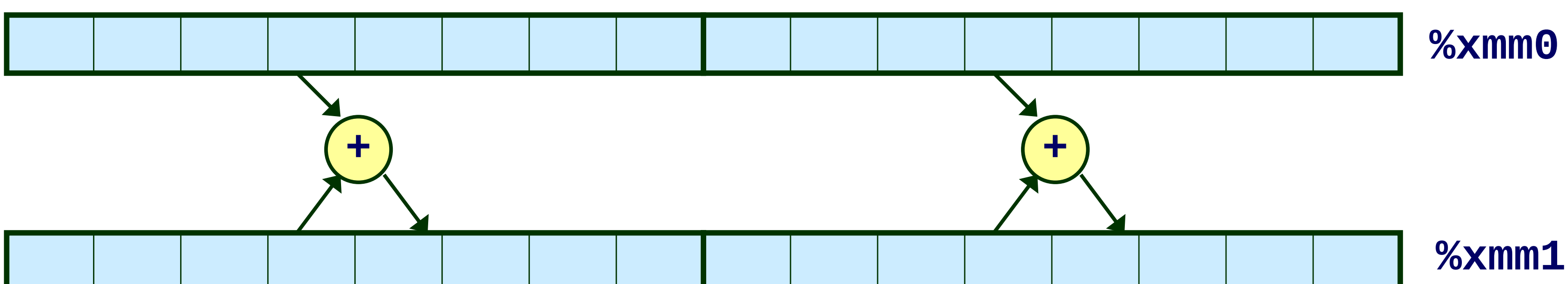
- **SIMD Operations: Single Precision**

`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