Organisation und Architektur von Rechnern

Lecture 15

Instructor:

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http://www.informatik.uni-kiel.de/rtsys/teaching/v-sysinf2

The 5 Minute Review Session

1. **How is the PC predicted (different cases)?**
2. **What are *pipelining hazards*?**
3. **What is *pipeline stalling*?**
4. **How does the pipeline handle mispredicted branches?**
5. **What is *data forwarding*, why is it used?**

Last Time

- **Structures**

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

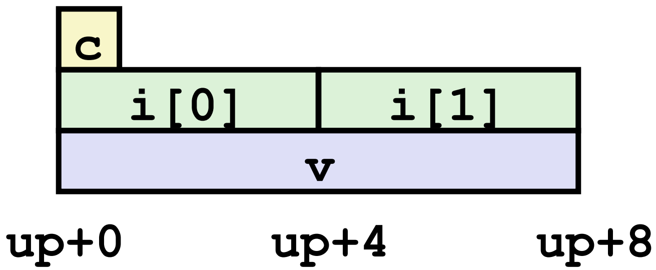
Memory Layout

- **Alignment**

```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

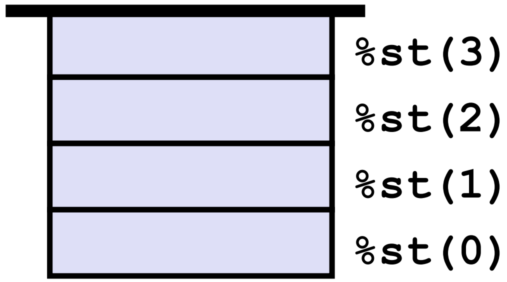
- **Unions**

```
union U1 {
  char c;
  int i[2];
  double v;
} *up;
```

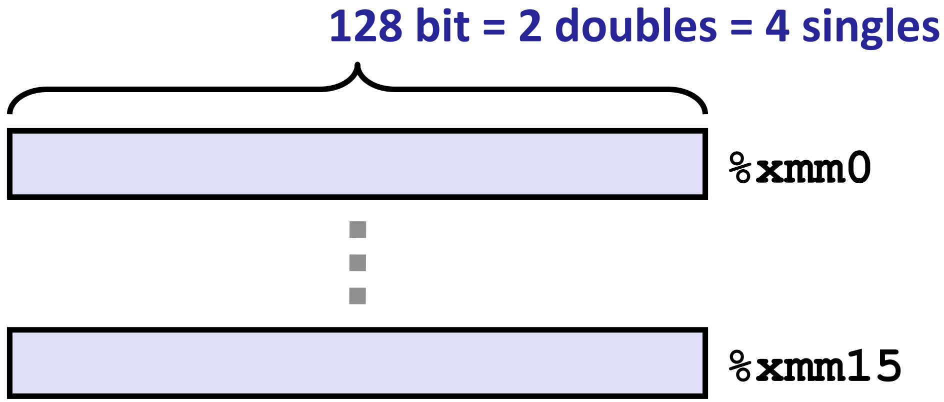


Last Time

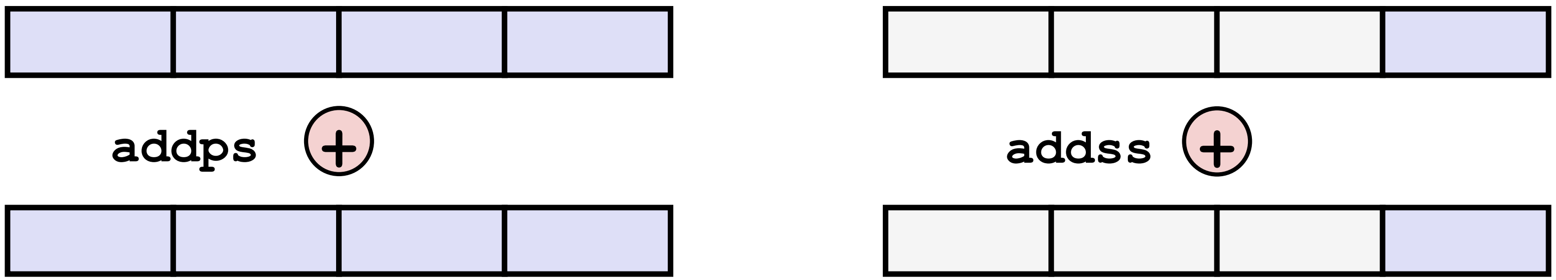
- **Floating point**
  - x87 (getting obsolete)



  - x86-64 (SSE3 and later)



  - Vector mode and scalar mode

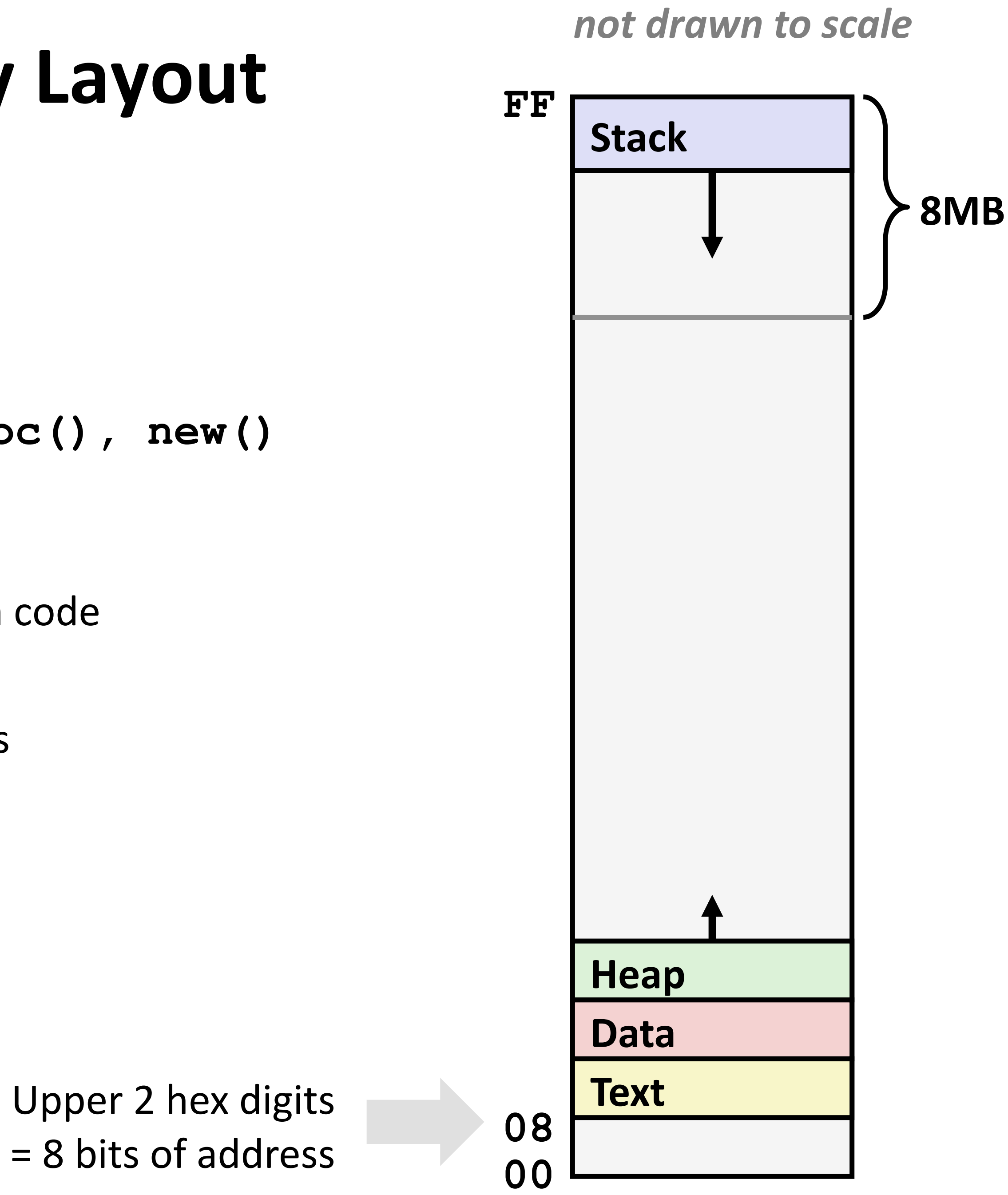


Today

- **Memory layout**
- **Program optimization**
  - Overview
  - Removing unnecessary procedure calls
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
  - Optimization blocker: Procedure calls

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

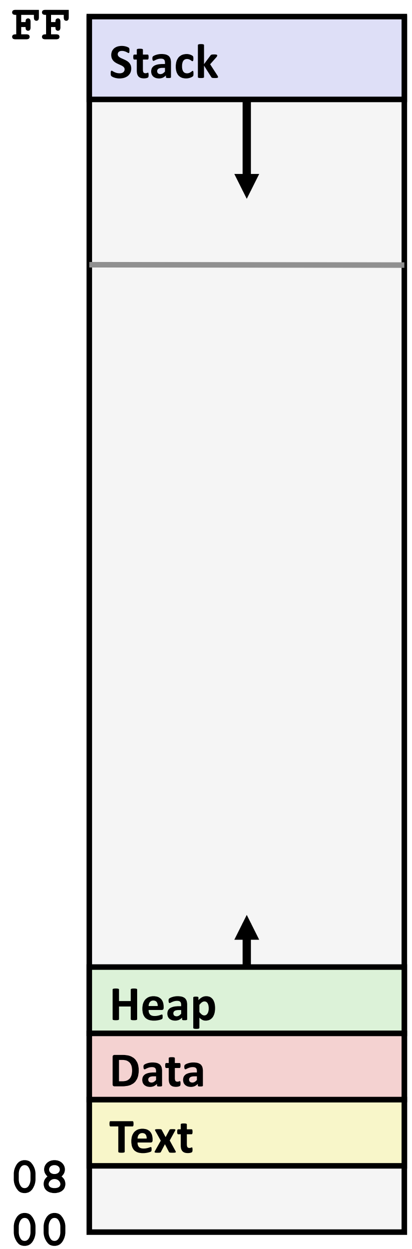


Memory Allocation Example

```
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 ... */
}
```

Where does everything go?

not drawn to scale



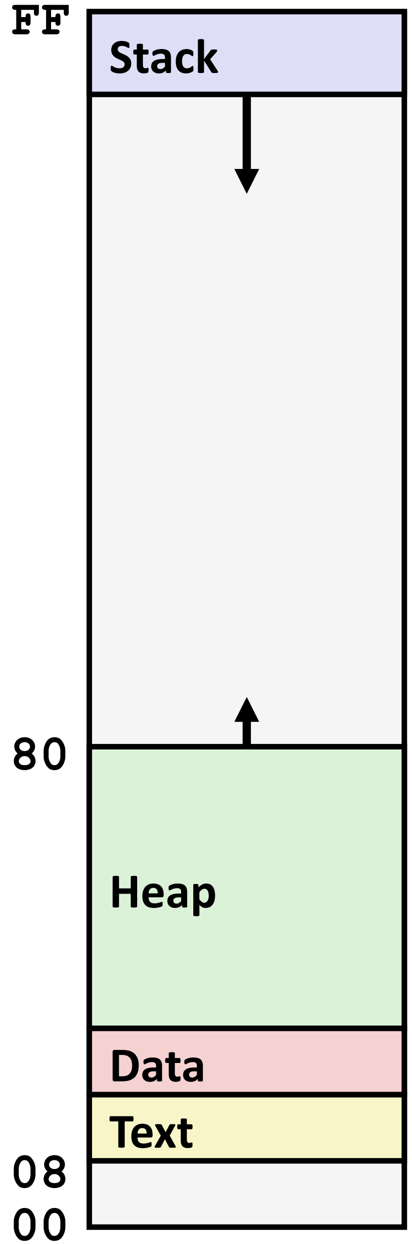
IA32 Example Addresses

address range ~2^{32}

`$esp`	`0xffffbcd0`
`p3`	`0x65586008`
`p1`	`0x55585008`
`p4`	`0x1904a110`
`p2`	`0x1904a008`
`&p2`	`0x18049760`
`beyond`	`0x08049744`
`big_array`	`0x18049780`
`huge_array`	`0x08049760`
`main()`	`0x080483c6`
`useless()`	`0x08049744`
final `malloc()`	`0x006be166`

`malloc()` is dynamically linked
address determined at runtime

not drawn to scale



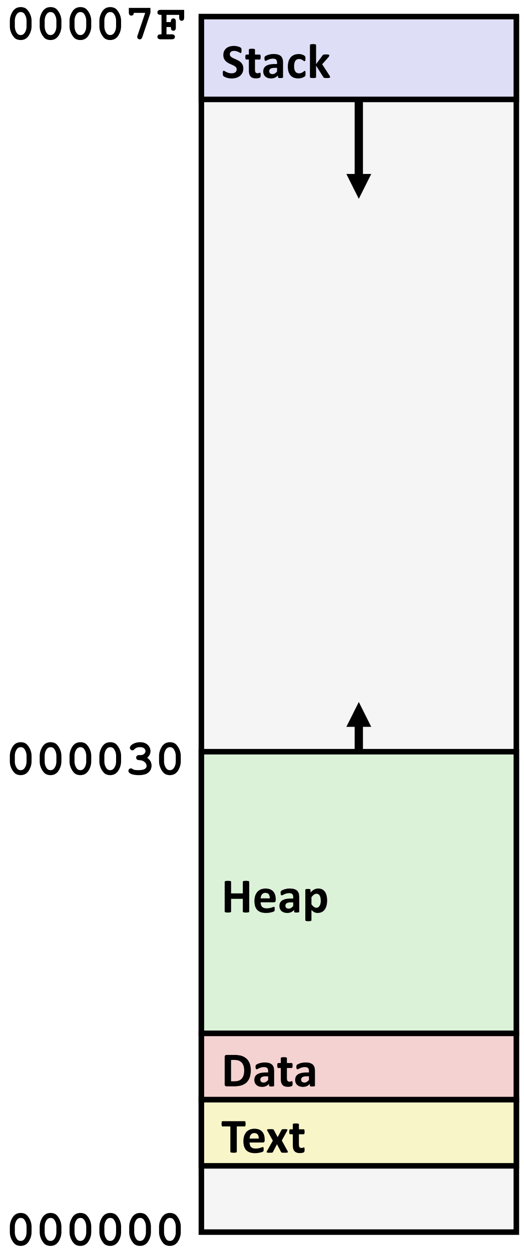
x86-64 Example Addresses

address range ~2^{47}

`$rsp`	`0x7ffffff8d1f8`
`p3`	`0x2aaabaadd010`
`p1`	`0x2aaaaaadc010`
`p4`	`0x000011501120`
`p2`	`0x000011501010`
`&p2`	`0x000010500a60`
`beyond`	`0x000000500a44`
`big_array`	`0x000010500a80`
`huge_array`	`0x000000500a50`
`main()`	`0x000000400510`
`useless()`	`0x000000400500`
final `malloc()`	`0x00386ae6a170`

`malloc()` is dynamically linked
address determined at runtime

not drawn to scale



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: Test Yourself!

`int *p`	p is a pointer to int
`int *p[13]`	
`int *(p[13])`	
`int **p`	p is a pointer to a pointer to an int
`int (*p)[13]`	
`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])()`	
`int (*(*x[3])())[5]`	x is an array[3] of pointers to functions returning pointers to array[5] of ints

C Pointer Declarations (Check out guide)

`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

Today

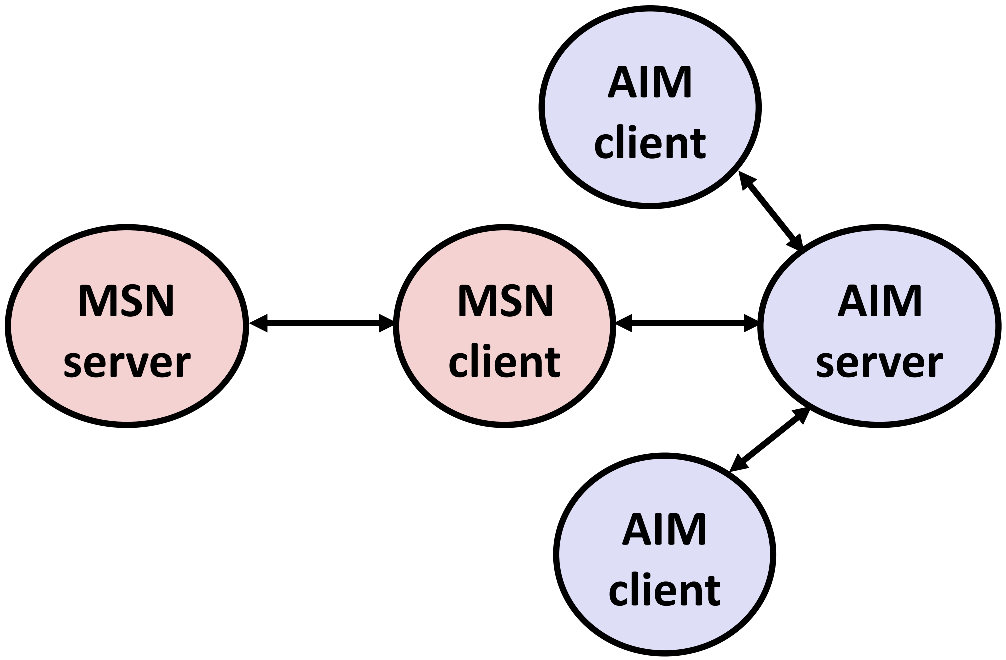
- Memory layout
- **Buffer overflow, worms, and viruses**
- Program optimization
  - Overview
  - Removing unnecessary procedure calls
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
  - Optimization blocker: Procedure calls

Internet Worm and IM War

- **November, 1988**
  - Internet Worm attacks thousands of Internet hosts.
  - How did it happen?

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()`**

```
/* 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;
}
```

  - No way to specify limit on number of characters to read

- **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;
}
```

```
unix>./bufdemo
Type a string:1234567
1234567
```

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

```
unix>./bufdemo
Type a string:123456789ABC
Segmentation Fault
```

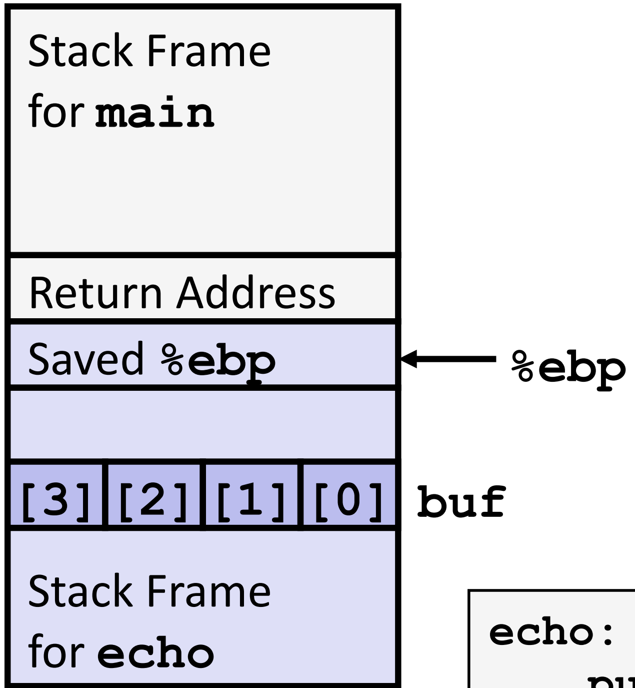
Buffer Overflow Disassembly

```
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

Before call to gets

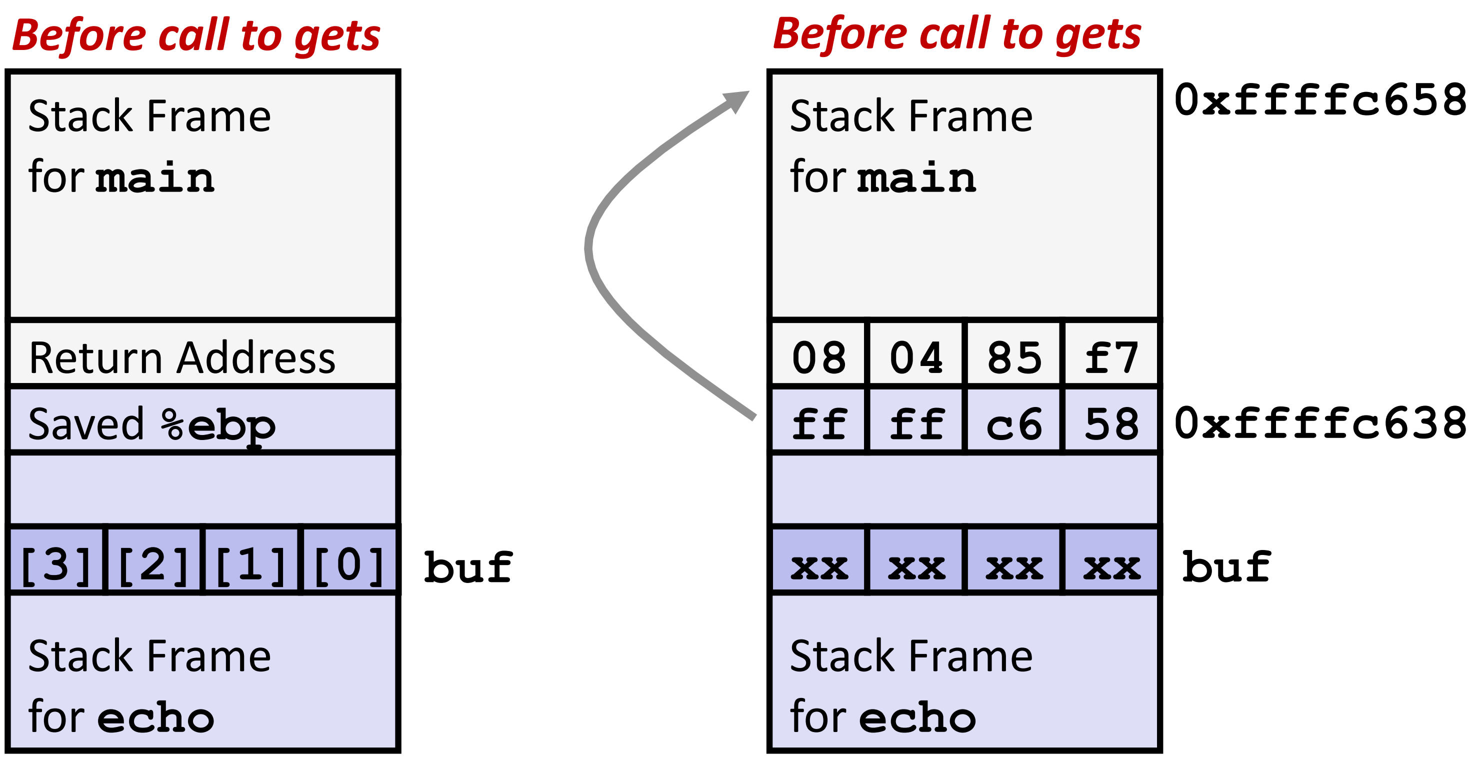



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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

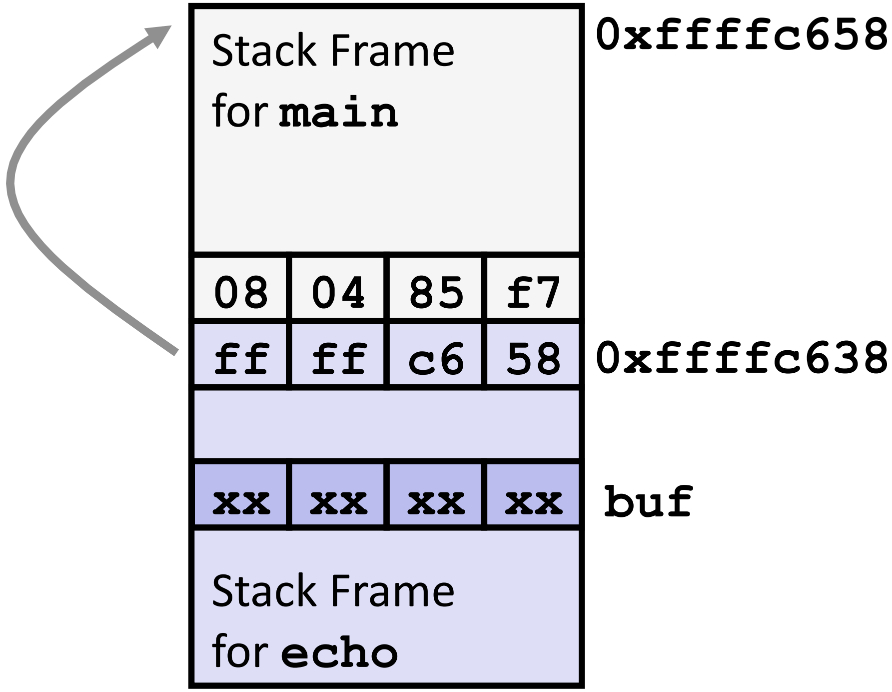
```
unix> gdb bufdemo
(gdb) break echo
Breakpoint 1 at 0x8048583
(gdb) run
Breakpoint 1, 0x8048583 in echo ()
(gdb) print /x $ebp
$1 = 0xffffc638
(gdb) print /x *(unsigned *)$ebp
$2 = 0xffffc658
(gdb) print /x *((unsigned *)$ebp + 1)
$3 = 0x80485f7
```



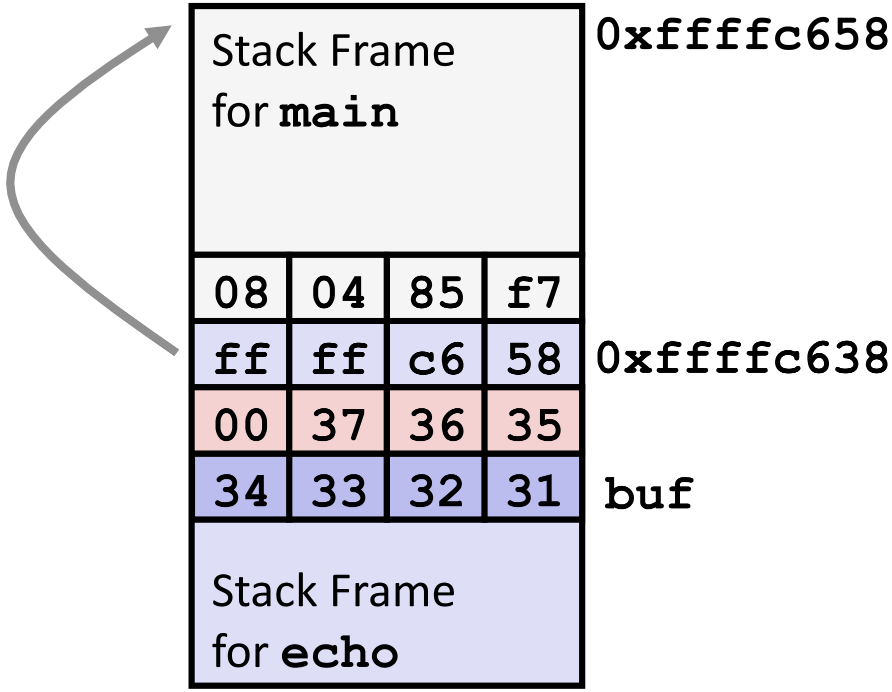

```
80485f2:call  80484f0 <echo>
80485f7:mov   0xfffffffc(%ebp),%ebx # Return Point
```

Buffer Overflow Example #1

Before call to gets



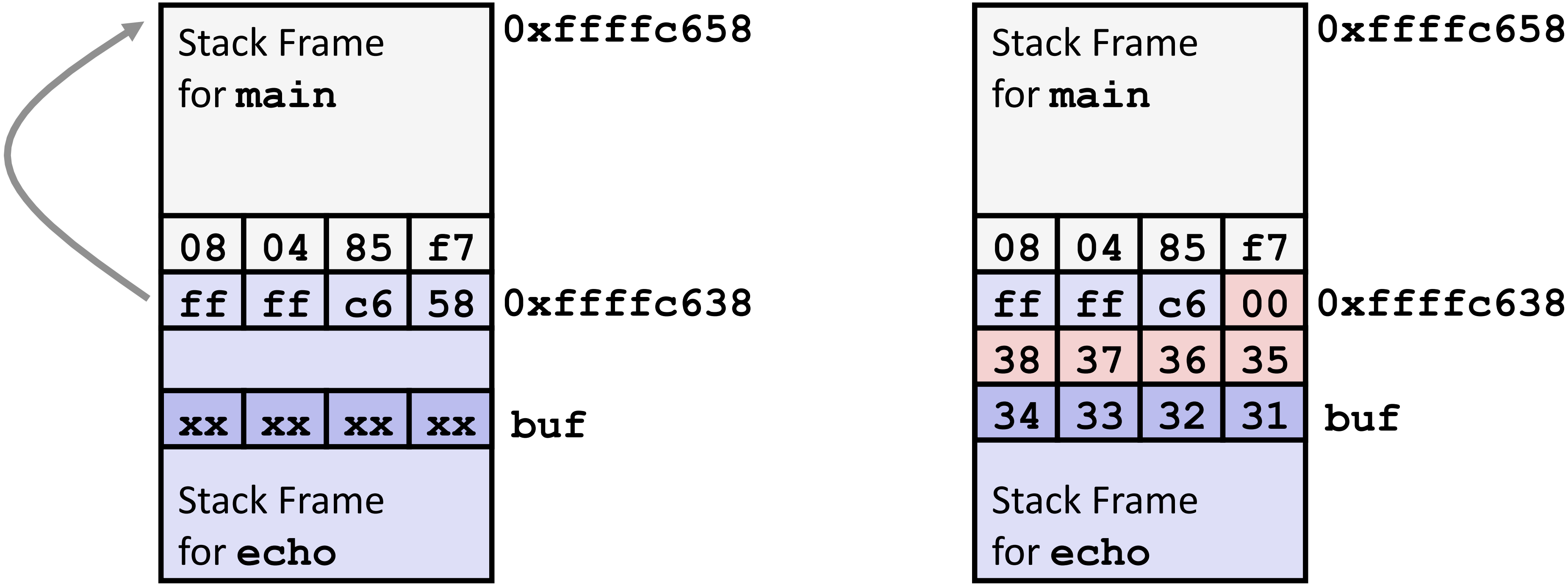
Input 1234567



Overflow buf, but no problem

Buffer Overflow Example #2

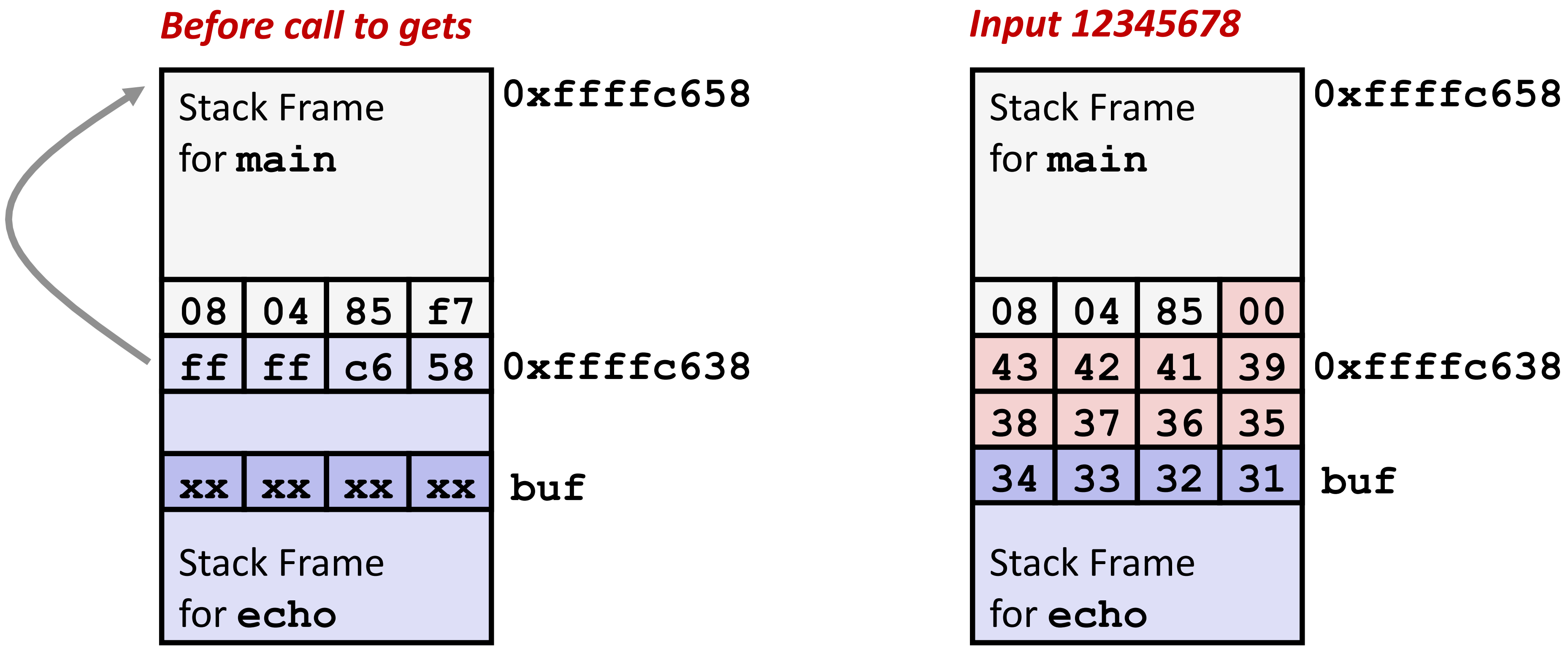
Before call to gets / *Input 12345678*



Base pointer corrupted

```
. . .
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 Example #3



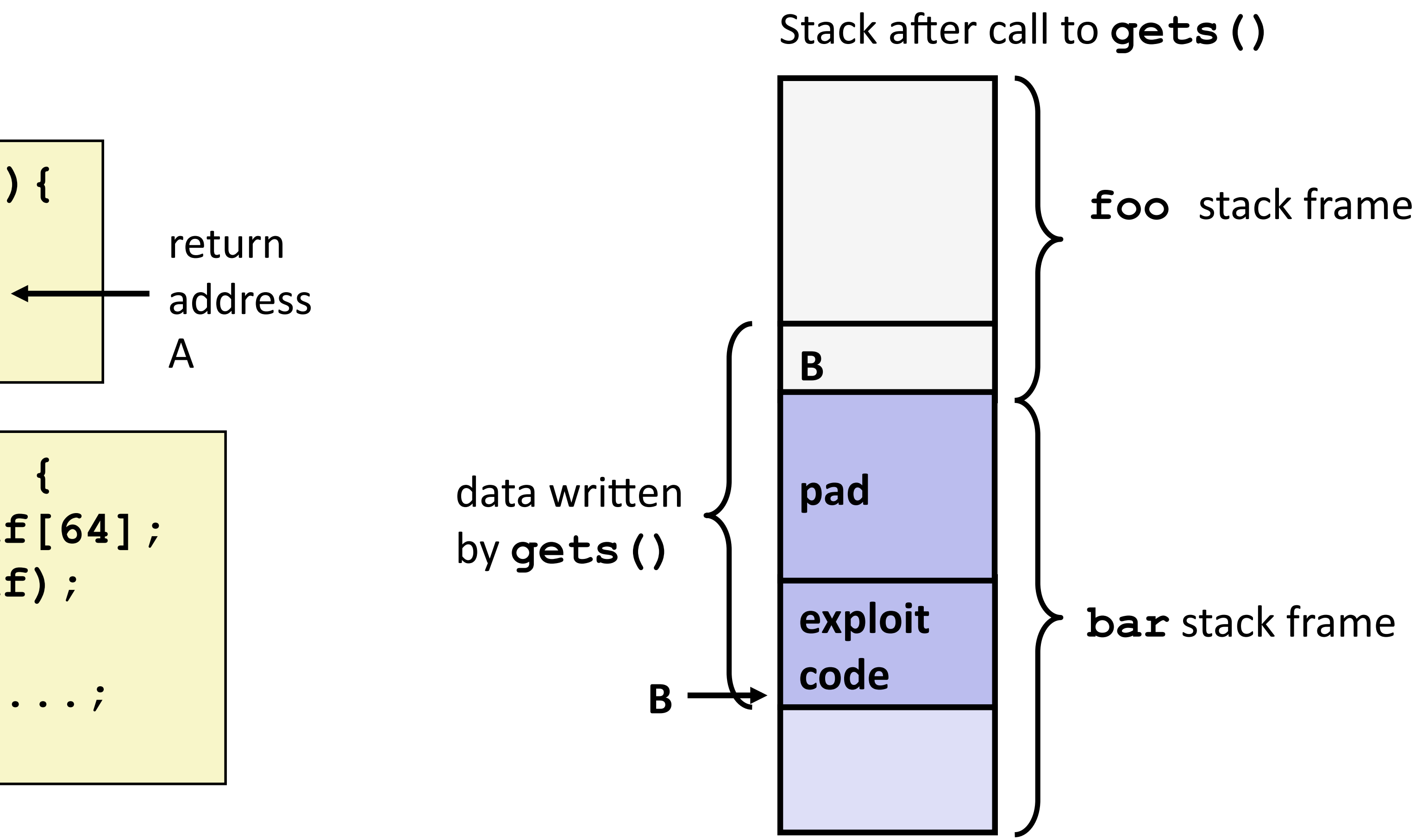
Return address corrupted

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

Malicious Use of Buffer Overflow

```
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!

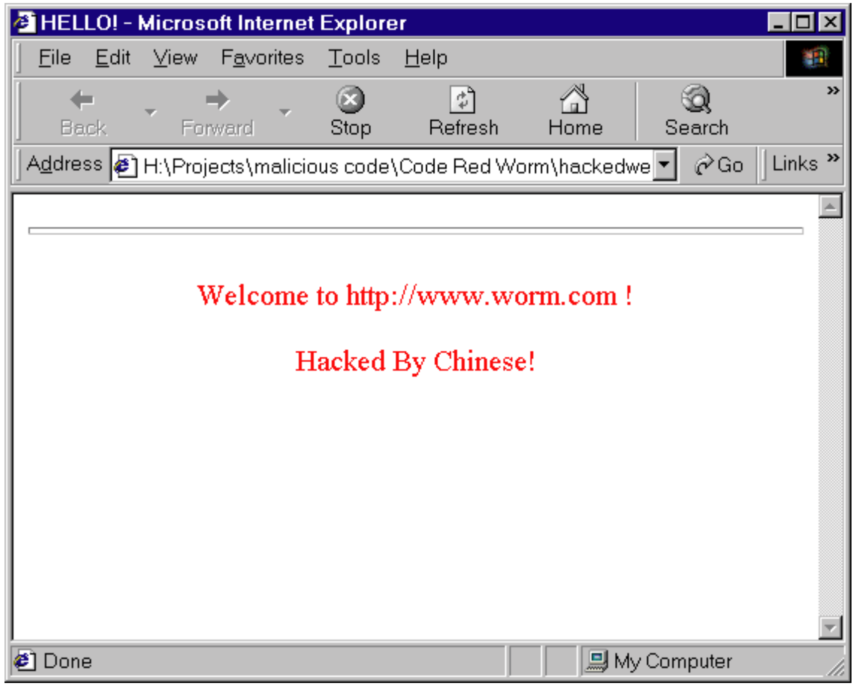
Code Red Worm

- **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?
  NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN....NNNNNNNN
  NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN
  %u9090%u6858%ucbd3%u7801%u9090%u6858%ucbd3%u7801%u
  9090%u6858%ucbd3%u7801%u9090%u9090%u8190%u00c3%u00
  03%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

- **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

```
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
```

- **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

Worms and Viruses

- **Worm: A program that**
  - Can run by itself
  - Can propagate a fully working version of itself to other computers

- **Virus: Code that**
  - Add itself to other programs
  - Cannot run independently

- **Both are (usually) designed to spread among computers and to wreak havoc**

Today

- Memory layout
- **Program optimization**
  - **Overview**
  - Removing unnecessary procedure calls
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  - Strength reduction
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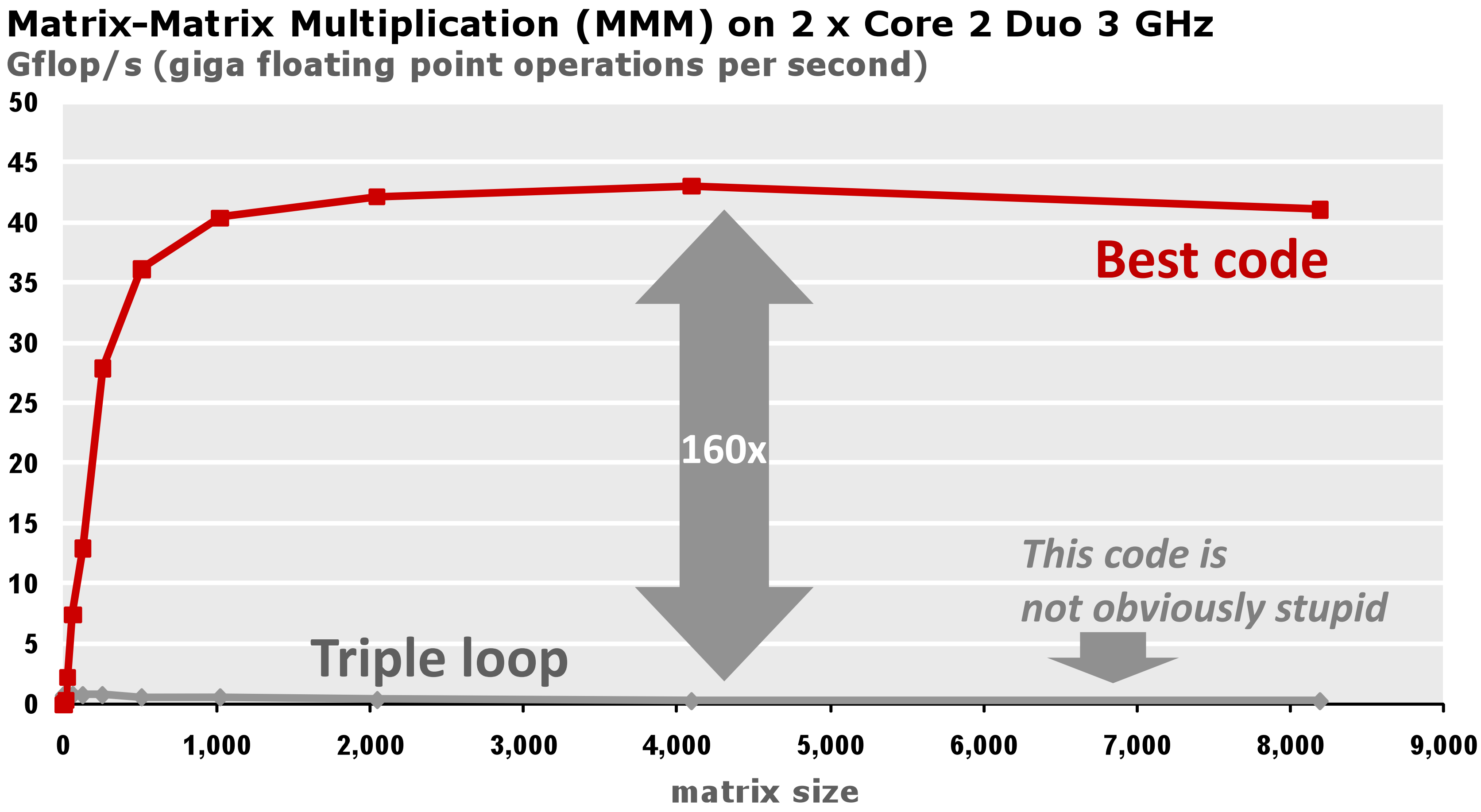
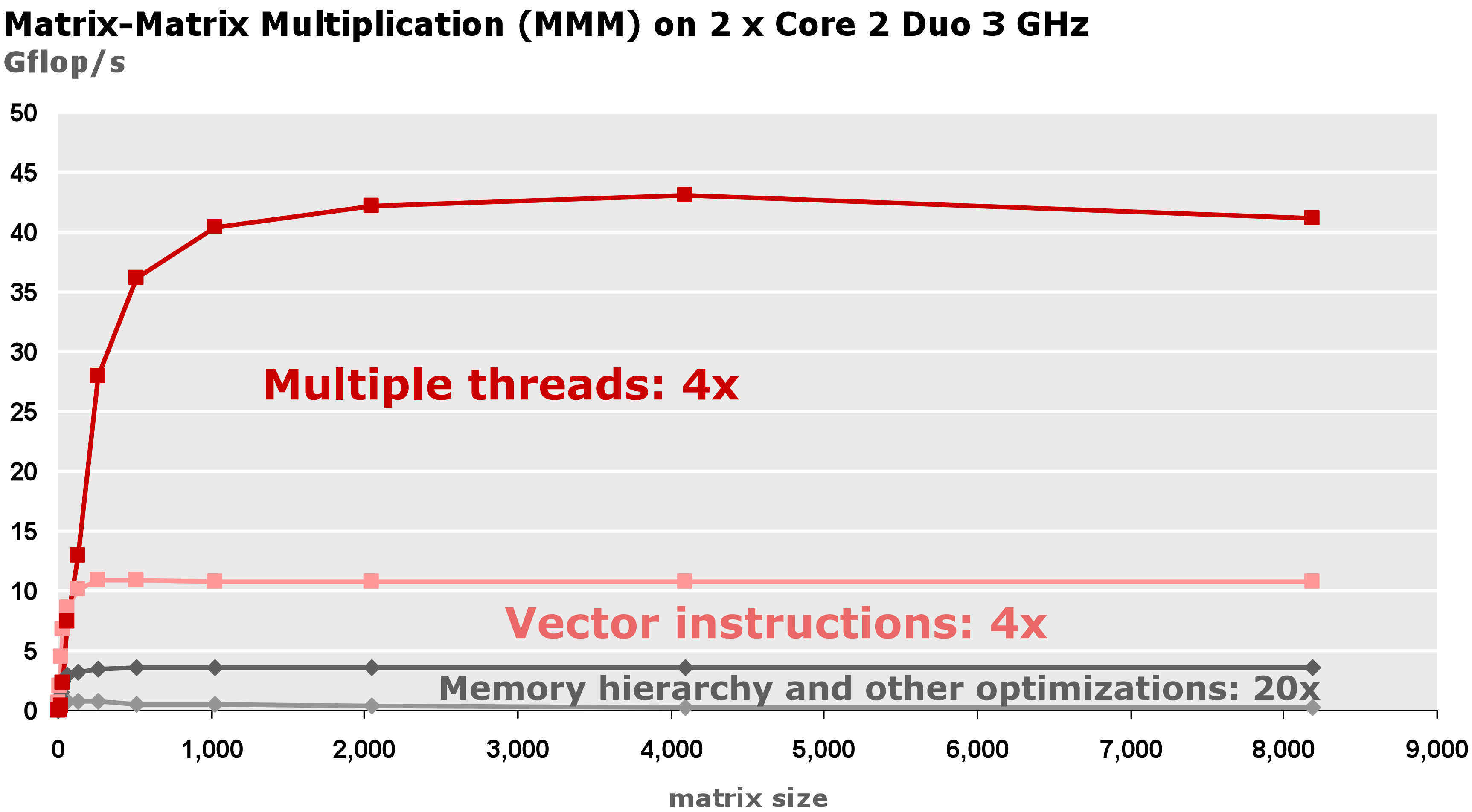
  - Optimization blocker: Procedure calls

Example Matrix Multiplication



- Standard desktop computer, compiler, using optimization flags
- Both implementations have exactly the same operations count ($2n^3$)
- *What is going on?*

MMM Plot: Analysis



- Reason for 20x: Blocking or tiling, loop unrolling, array scalarization, instruction scheduling, search to find best choice
- *Effect: more instruction level parallelism, better register use, less L1/L2 cache misses, less TLB misses*

Harsh Reality

- ***There's more to runtime performance than asymptotic complexity***
- ***One can easily loose 10x, 100x in runtime or even more***
- **What matters:**
  - Constants (100n and 5n is both O(n), but ….)
  - Coding style (unnecessary procedure calls, unrolling, reordering, …)
  - Algorithm structure (locality, instruction level parallelism, …)
  - Data representation (complicated structs or simple arrays)

Harsh Reality

- **Must optimize at multiple levels:**
  - Algorithm
  - Data representations
  - Procedures
  - Loops

- **Must understand system to optimize performance**
  - How programs are compiled and executed
    - Execution units, memory hierarchy
  - How to measure program performance and identify bottlenecks
  - How to improve performance without destroying code modularity and generality

Optimizing Compilers

-O

- Use optimization flags, default is no optimization (-O0)!
- Good choices for gcc: -O2, -O3, -march=xxx, -m64
- Try different flags and maybe different compilers

Example

```
double a[4][4];
double b[4][4];
double c[4][4]; # set to zero

/* Multiply 4 x 4 matrices a and b  */
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    for (i = 0; i < 4; i++)
        for (j = 0; j < 4; j++)
            for (k = 0; k < 4; k++)
                c[i*4+j] += a[i*4 + k]*b[k*4 + j];
}
```

- **Compiled without flags:**
  ~1300 cycles
- **Compiled with –O3 –m64 -march=… –fno-tree-vectorize**
  ~150 cycles
- **Core 2 Duo, 2.66 GHz**

Optimizing Compilers

- **Compilers are good at: mapping program to machine**
  - register allocation
  - code selection and ordering (scheduling)
  - dead code elimination
  - eliminating minor inefficiencies
- **Compilers are not good at: improving asymptotic efficiency**
  - up to programmer to select best overall algorithm
  - big-O savings are (often) more important than constant factors
    - but constant factors also matter
- **Compilers are not good at: overcoming "optimization blockers"**
  - potential memory aliasing
  - potential procedure side-effects

Limitations of Optimizing Compilers

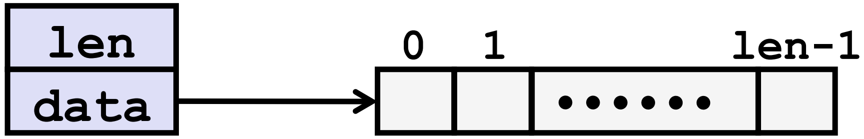
- ***If in doubt, the compiler is conservative***
- **Operate under fundamental constraints**
  - Must not change program behavior under any possible condition
  - Often prevents it from making optimizations when would only affect behavior under pathological conditions.
- **Behavior that may be obvious to the programmer can be obfuscated by languages and coding styles**
  - e.g., data ranges may be more limited than variable types suggest
- **Most analysis is performed only within procedures**
  - Whole-program analysis is too expensive in most cases
- **Most analysis is based only on *static* information**
  - Compiler has difficulty anticipating run-time inputs

Today

- Memory layout
- **Program optimization**
  - Overview
  - **Removing unnecessary procedure calls**
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
  - Optimization blocker: Procedure calls
  - Optimization blocker: Memory aliasing

Example: Data Type for Vectors

```
/* data structure for vectors */
typedef struct{
        int len;
        double *data;
} vec;
```




```
/* retrieve vector element and store at val */
double get_vec_element(*vec, idx, double *val)
{
        if (idx < 0 || idx >= v->len)
                return 0;
        *val = v->data[idx];
        return 1;
}
```

Example: Summing Vector Elements

```
/* retrieve vector element and store at val */
double get_vec_element(*vec, idx, double *val)
{
  if (idx < 0 || idx >= v->len)
        return 0;
  *val = v->data[idx];
  return 1;
}
```

Bound check unnecessary in sum_elements
Why?

```
/* sum elements of vector */
double sum_elements(vec *v, double *res)
{
  int i;
  n = vec_length(v);
  *res = 0.0;
  double val;

  for (i = 0; i < n; i++) {
    get_vec_element(v, i, &val);
         *res += val;
  }
  return res;
}
```

Overhead for every fp +:

- One fct call
- One <
- One >=
- One ||
- One memory variable access

Slowdown:
probably 10x or more

Removing Procedure Call

```
/* sum elements of vector */
double sum_elements(vec *v, double *res)
{
  int i;
  n = vec_length(v);
  *res = 0.0;
  double val;

  for (i = 0; i < n; i++) {
    get_vec_element(v, i, &val);
          *res += val;
  }
  return res;
}
```

```
/* sum elements of vector */
double sum_elements(vec *v, double *res)
{
  int i;
  n = vec_length(v);
  *res = 0.0;
  double *data = get_vec_start(v);

  for (i = 0; i < n; i++)
          *res += data[i];
  return res;
}
```

Removing Procedure Calls

- **Procedure calls can be very expensive**
- **Bound checking can be very expensive**
- **Abstract data types can easily lead to inefficiencies**
  - Usually avoided in superfast numerical library functions

- **Watch your innermost loop!**

- **Get a feel for overhead versus actual computation being performed**

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Code Motion

- **Reduce frequency with which computation is performed**
  - If it will always produce same result
  - Especially moving code out of loop
- **Sometimes also called precomputation**

```
void set_row(double *a, double *b,
   long i, long n)
{
    long j;
    for (j = 0; j < n; j++)
        a[n*i+j] = b[j];
}
```

```
    long j;
    int ni = n*i;
    for (j = 0; j < n; j++)
        a[ni+j] = b[j];
```

Compiler-Generated Code Motion

```
void set_row(double *a, double *b,
   long i, long n)
{
    long j;
    for (j = 0; j < n; j++)
         a[n*i+j] = b[j];
}
```

```
    long j;
    long ni = n*i;
    double *rowp = a+ni;
    for (j = 0; j < n; j++)
         *rowp++ = b[j];
```

```
set_row:
        xorl     %r8d, %r8d            #  j = 0
        cmpq     %rcx, %r8             #  j:n
        jge      .L7                   #  if >= goto done
        movq     %rcx, %rax            #  n
        imulq    %rdx, %rax            #  n*i outside of inner loop
        leaq     (%rdi,%rax,8), %rdx   #  rowp = A + n*i*8
.L5:                                   # loop:
        movq     (%rsi,%r8,8), %rax    #  t = b[j]
        incq     %r8                   #  j++
        movq     %rax, (%rdx)          #  *rowp = t
        addq     $8, %rdx              #  rowp++
        cmpq     %rcx, %r8             #  j:n
        jl       .L5                   #  if < goto loop
.L7:                                   # done:
        rep ; ret                      #  return
```

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Strength Reduction

- **Replace costly operation with simpler one**
- **Example: Shift/add instead of multiply or divide**

  `16*x` → `x << 4`

  - Utility machine dependent
  - Depends on cost of multiply or divide instruction
  - On Pentium IV, integer multiply requires 10 CPU cycles
- **Example: Recognize sequence of products**

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

→

```
int ni = 0;
for (i = 0; i < n; i++) {
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
  ni += n;
}
```

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Share Common Subexpressions

- Reuse portions of expressions
- Compilers often not very sophisticated in exploiting arithmetic properties

*3 mults: i*n, (i–1)*n, (i+1)*n*

```
/* Sum neighbors of i,j */
up =    val[(i-1)*n + j  ];
down =  val[(i+1)*n + j  ];
left =  val[i*n     + j-1];
right = val[i*n     + j+1];
sum = up + down + left + right;
```

```
leaq   1(%rsi), %rax  # i+1
leaq   -1(%rsi), %r8  # i-1
imulq  %rcx, %rsi     # i*n
imulq  %rcx, %rax     # (i+1)*n
imulq  %rcx, %r8      # (i-1)*n
addq   %rdx, %rsi     # i*n+j
addq   %rdx, %rax     # (i+1)*n+j
addq   %rdx, %r8      # (i-1)*n+j
```

*1 mult: i*n*

```
int inj = i*n + j;
up =    val[inj - n];
down =  val[inj + n];
left =  val[inj - 1];
right = val[inj + 1];
sum = up + down + left + right;
```

```
imulq   %rcx, %rsi  # i*n
addq    %rdx, %rsi  # i*n+j
movq    %rsi, %rax  # i*n+j
subq    %rcx, %rax  # i*n+j-n
leaq    (%rsi,%rcx), %rcx # i*n+j+n
```

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Optimization Blocker #1: Procedure Calls

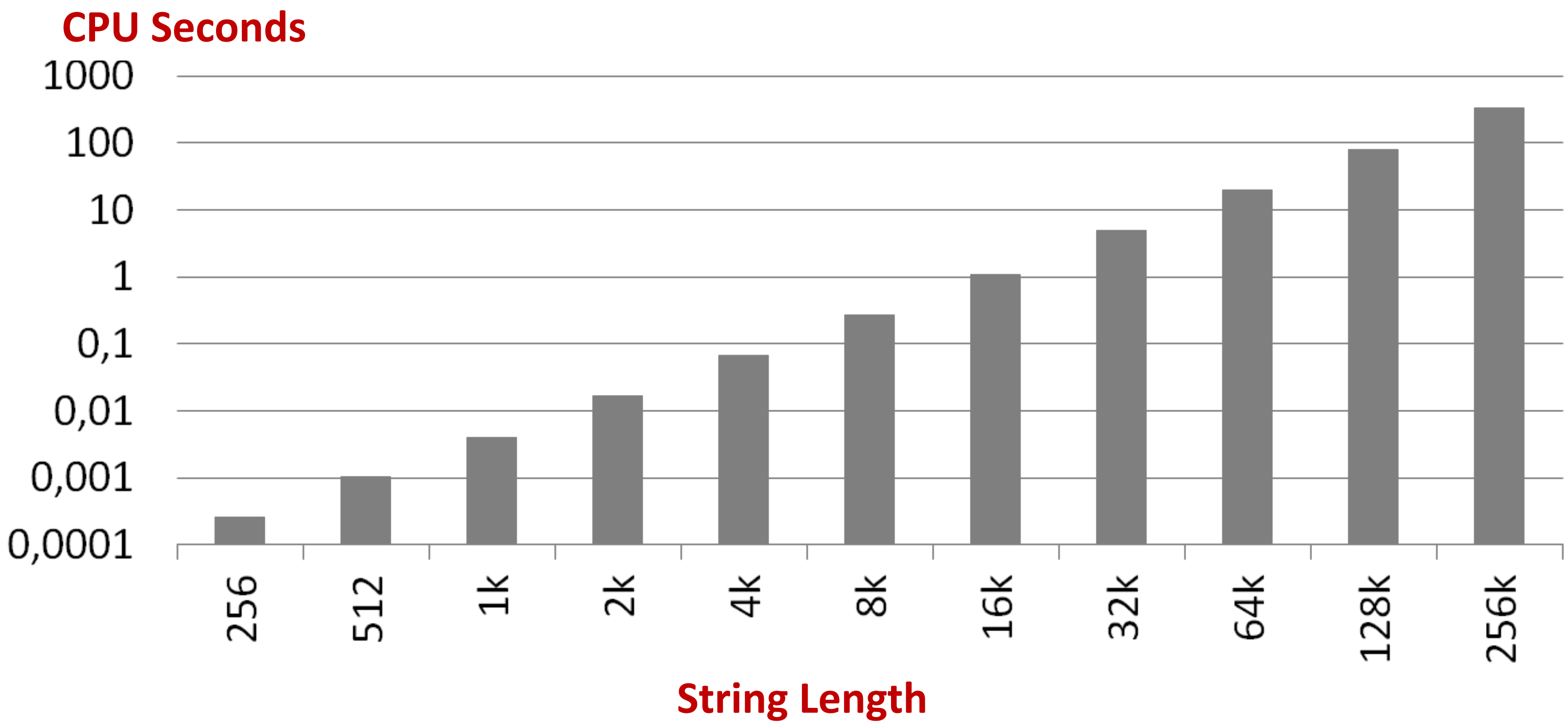
- **Procedure to convert string to lower case**

```
void lower(char *s)
{
  int i;
  for (i = 0; i < strlen(s); i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

Extracted from actual lab submissions

Performance

- Time quadruples when double string length
- Quadratic performance



Why is That?

```
void lower(char *s)
{
  int i;
  for (i = 0; i < strlen(s); i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

- **String length is called in every iteration!**
  - And **`strlen`** is O(n), so **`lower`** is $O(n^2)$

```
/* My version of strlen */
size_t strlen(const char *s)
{
    size_t length = 0;
    while (*s != '\0') {
        s++;
        length++;
    }
    return length;
}
```

Improving Performance

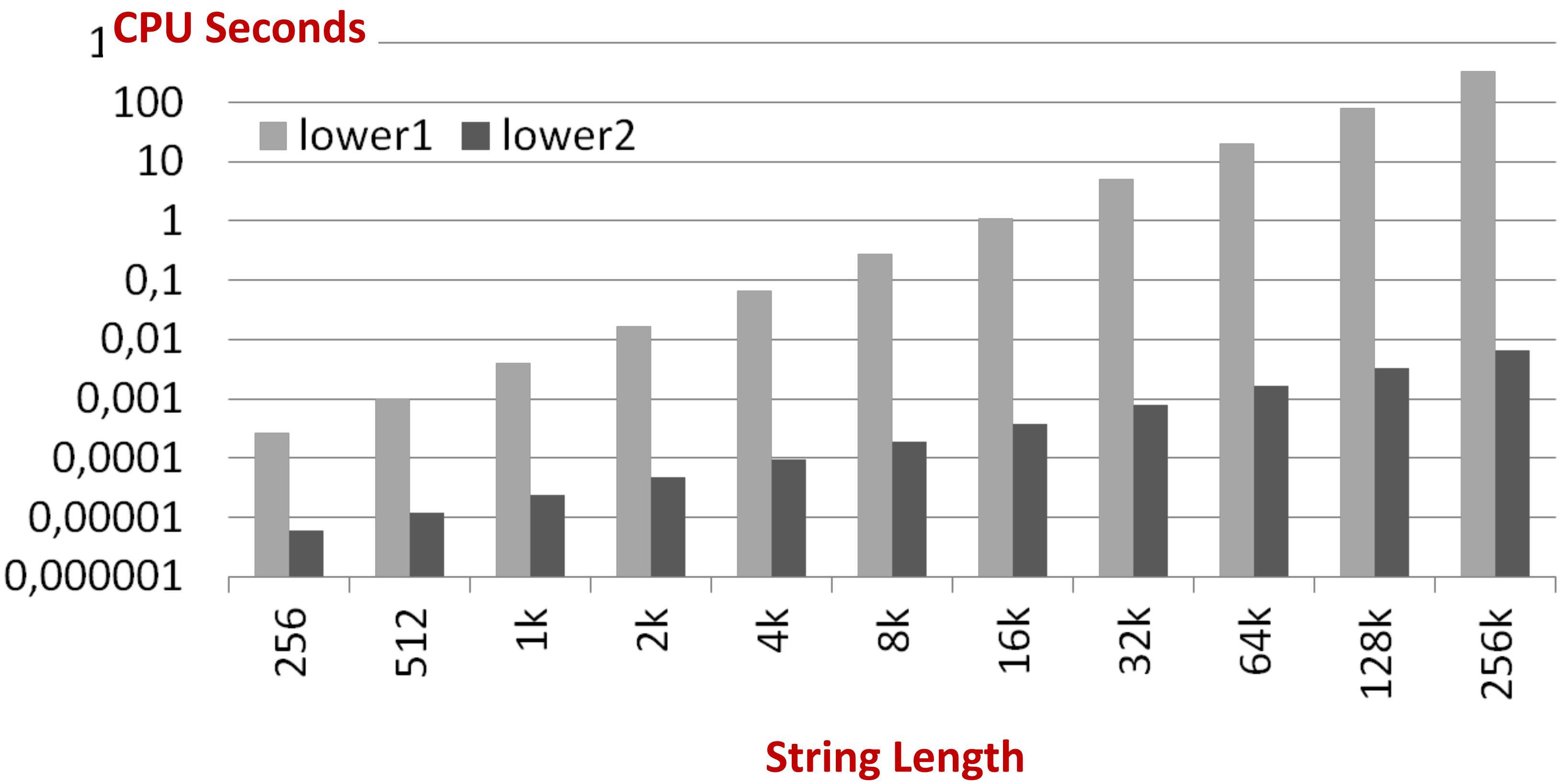
```
void lower(char *s)
{
  int i;
  for (i = 0; i < strlen(s); i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

```
void lower(char *s)
{
  int i;
  int len = strlen(s);
  for (i = 0; i < len; i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

- **Move call to `strlen` outside of loop**
- **Since result does not change from one iteration to another**
- **Form of code motion/precomputation**

Performance

- Lower2: Time doubles when double string length
- Linear performance



Optimization Blocker: Procedure Calls

- **Why couldn't compiler move `strlen` out of inner loop?**
  - Procedure may have side effects
  - Function may not return same value for given arguments
    - Could depend on other parts of global state
    - Procedure `lower` could interact with `strlen`
- **Compiler usually treats procedure call as a black box that cannot be analyzed**
  - Consequence: conservative in optimizations
- **Remedies:**
  - Inline the function if possible
  - Do your own code motion

```
int lencnt = 0;
size_t strlen(const char *s)
{
    size_t length = 0;
    while (*s != '\0') {
        s++; length++;
    }
    lencnt += length;
    return length;
}
```