Introduction to Computer Systems

15-213/18-243, spring 2009
10th Lecture, Feb. 16th

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Last Time

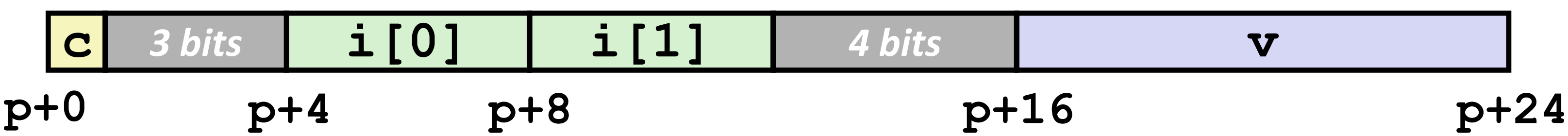
- **Structures**

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

Memory Layout

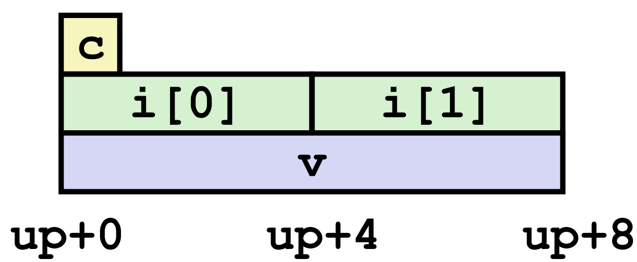
- **Alignment**

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



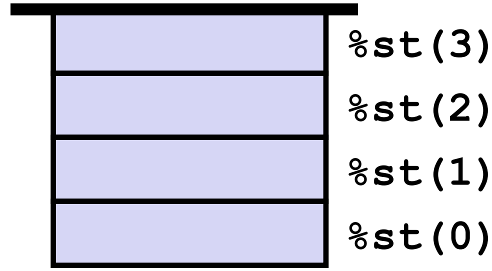
- **Unions**

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

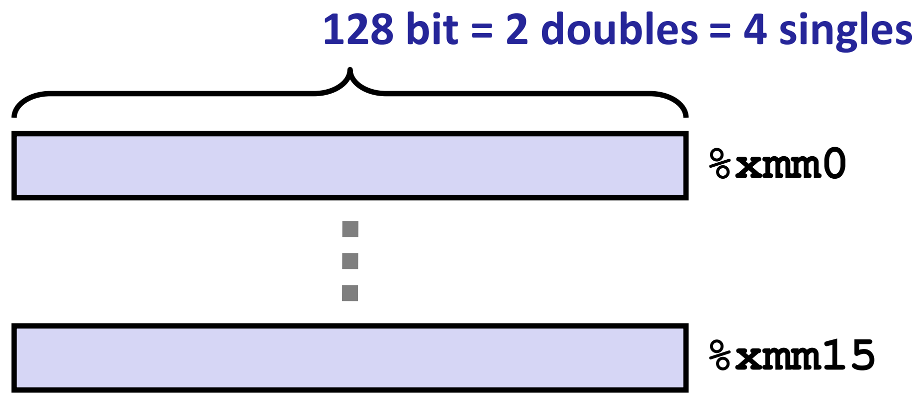


Last Time

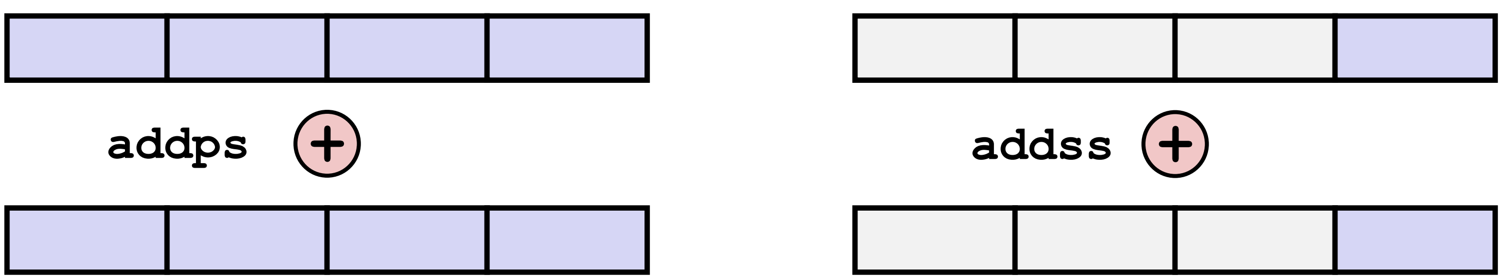
- **Floating point**
  - x87 (getting obsolete)



  - x86-64 (SSE3 and later)



  - Vector mode and scalar mode

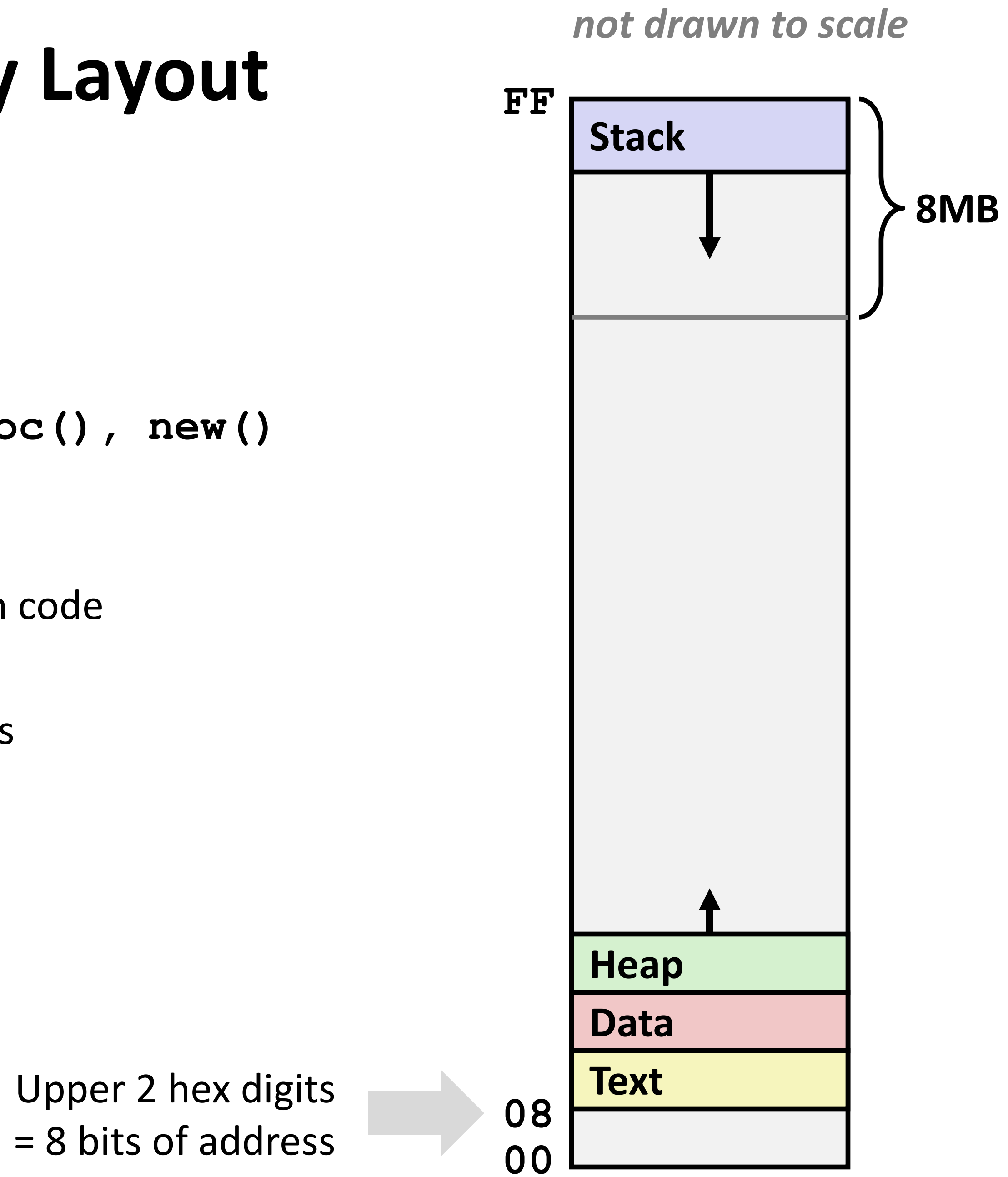


Today

- **Memory layout**
- **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

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

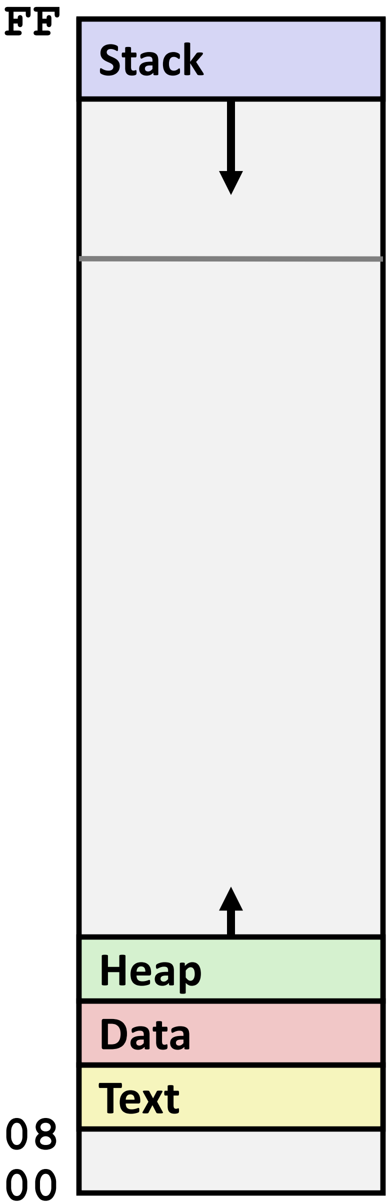


Memory Allocation Example

```
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



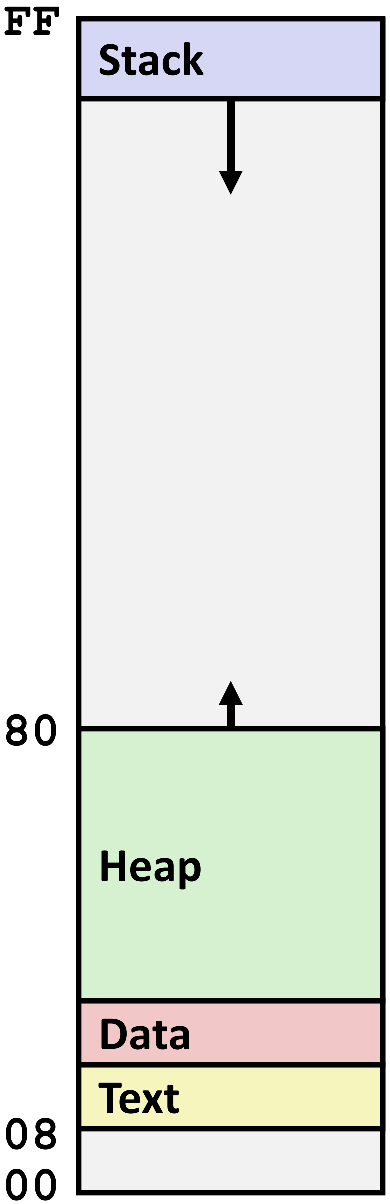
IA32 Example Addresses

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



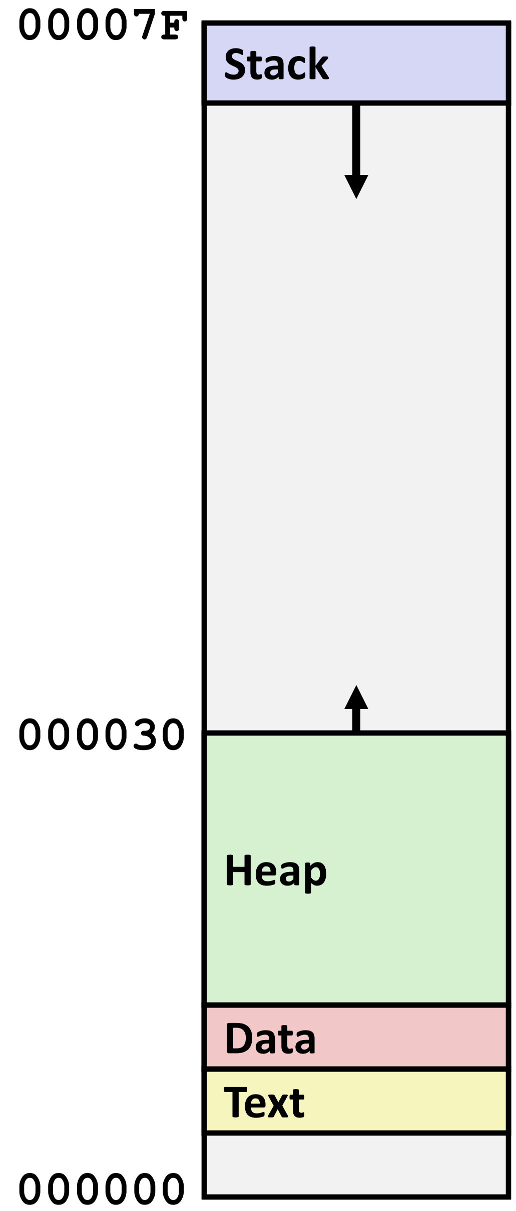
x86-64 Example Addresses

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

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Internet Worm and IM War

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

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
```

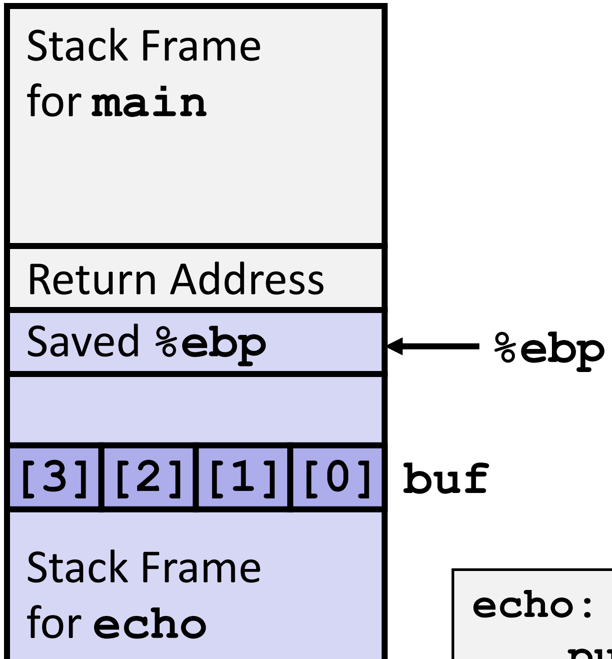
Buffer Overflow Disassembly

```
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

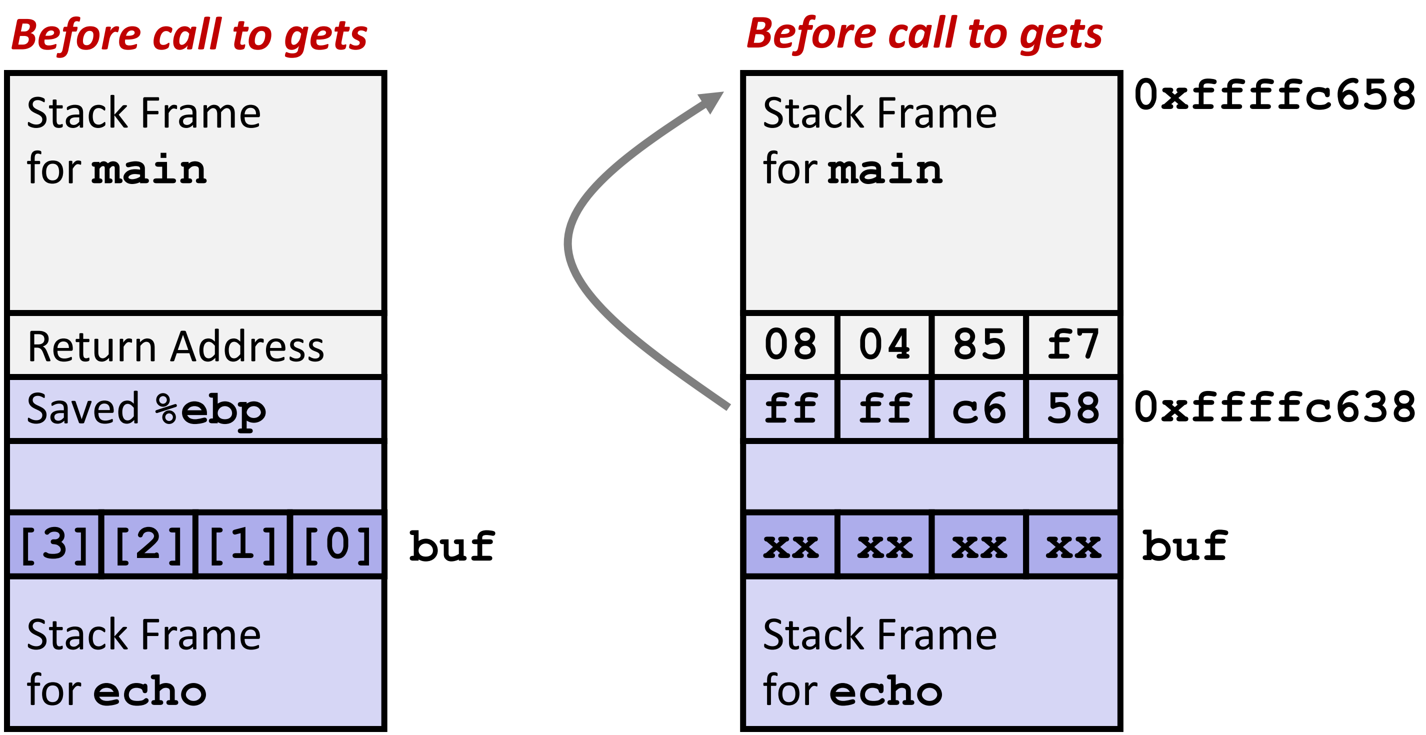



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
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
    . . .
```

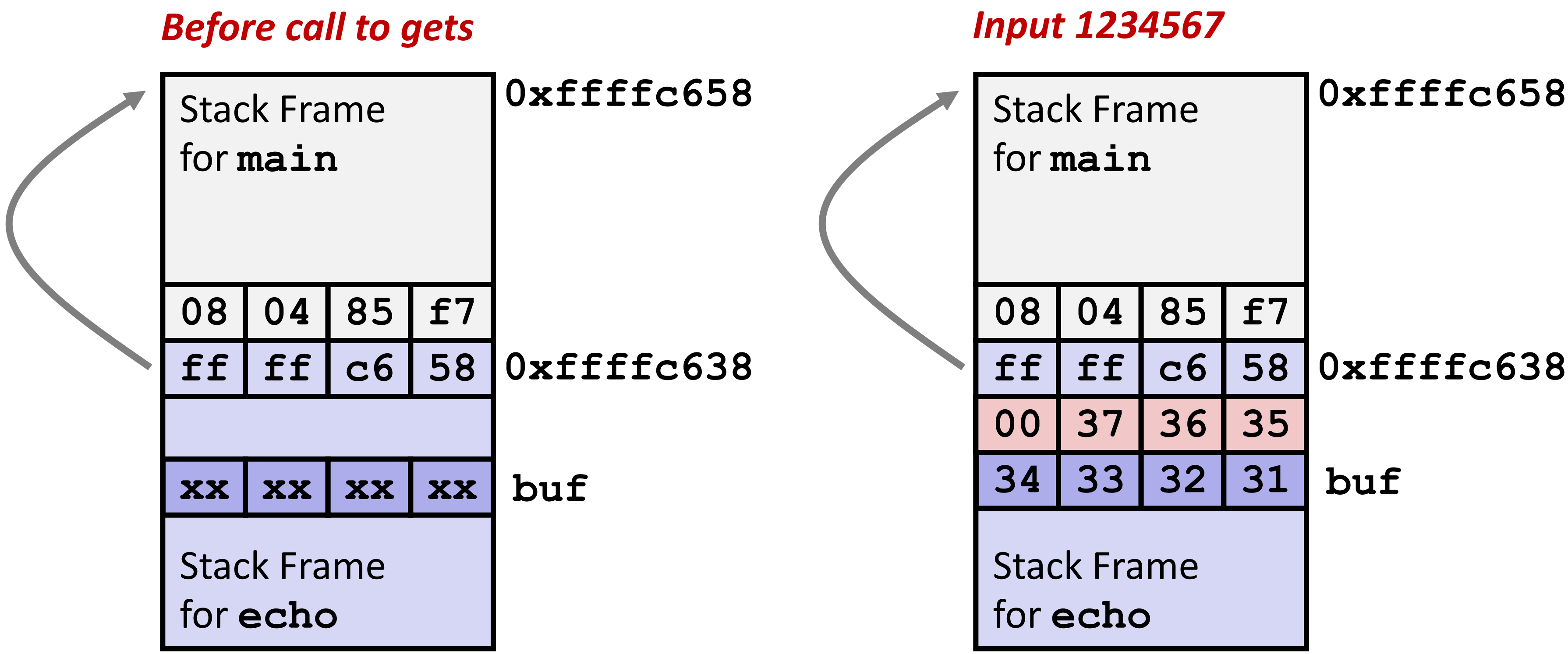
Buffer Overflow Stack Example

```
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
```

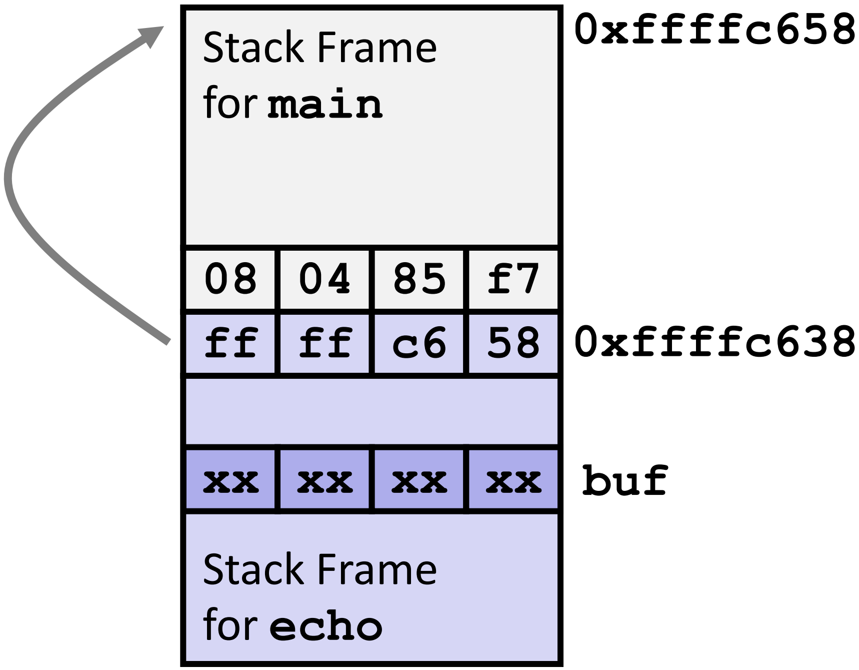
Buffer Overflow Example #1



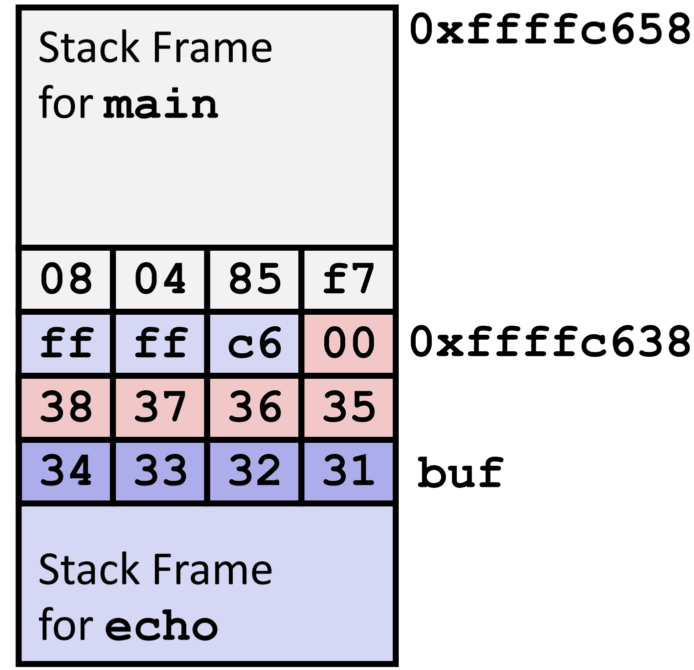
Overflow buf, but no problem

Buffer Overflow Example #2

Before call to gets



Input 12345678

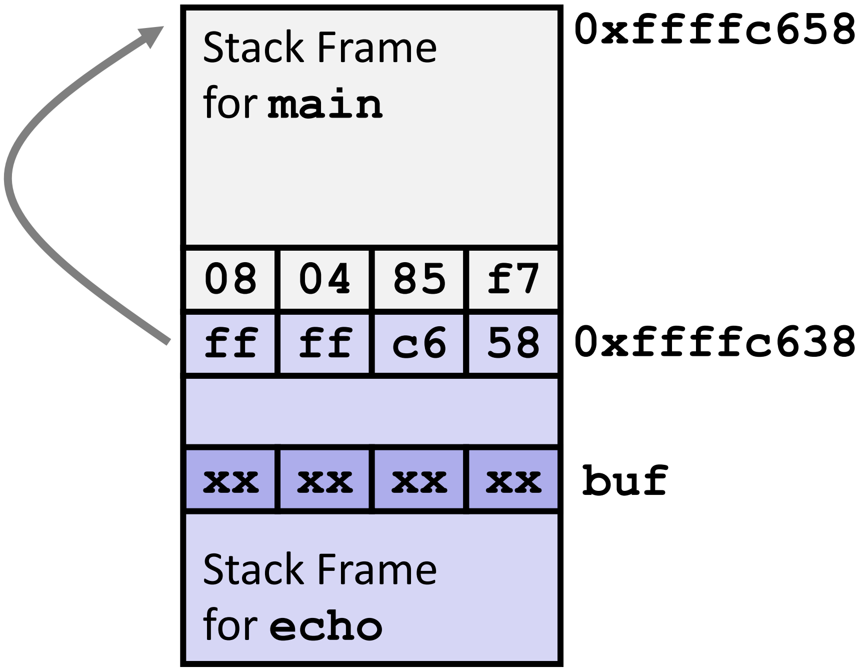


Base pointer corrupted

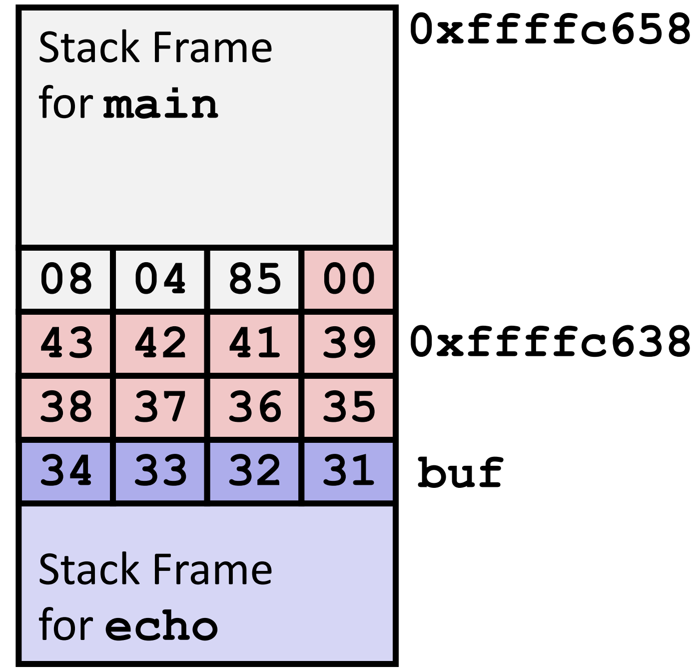
```
. . .
804850a:  83 c4 14    add    $0x14,%esp    # deallocate space
804850d:  5b          pop    %ebx          # restore %ebx
804850e:  c9          leave                # movl %ebp, %esp; popl %ebp
804850f:  c3          ret                  # Return
```

Buffer Overflow Example #3

Before call to gets



Input 12345678



Return address corrupted

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

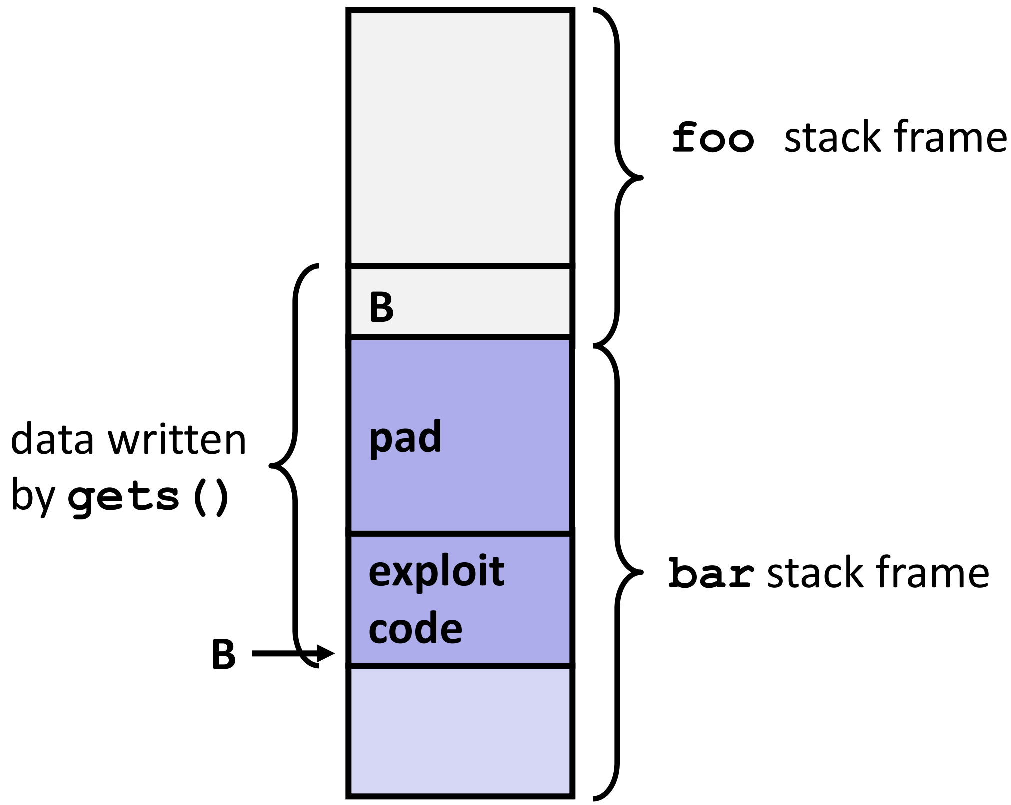
Malicious Use of Buffer Overflow

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

return address A

```
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.

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

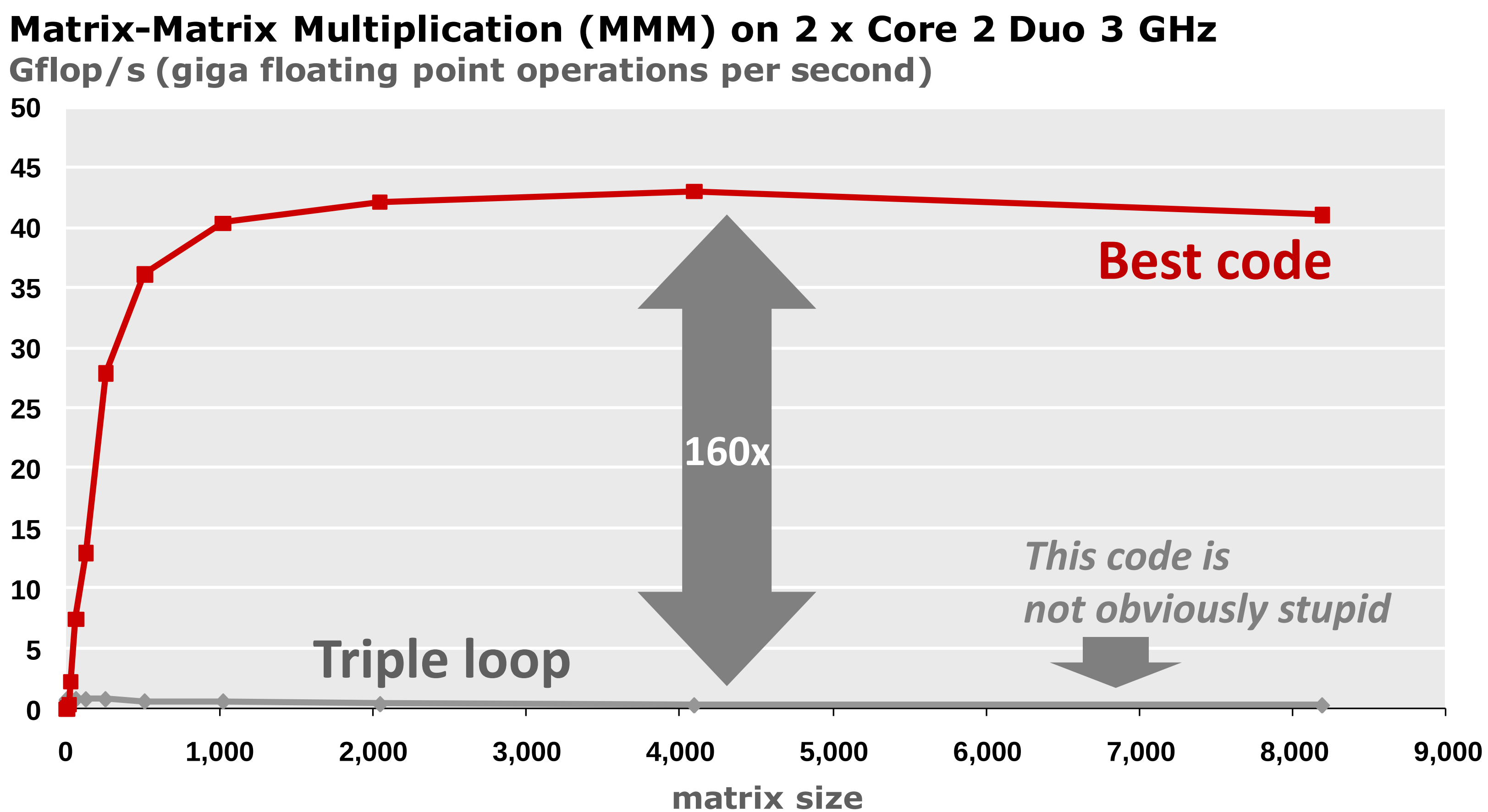
Worms and Viruses

- **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

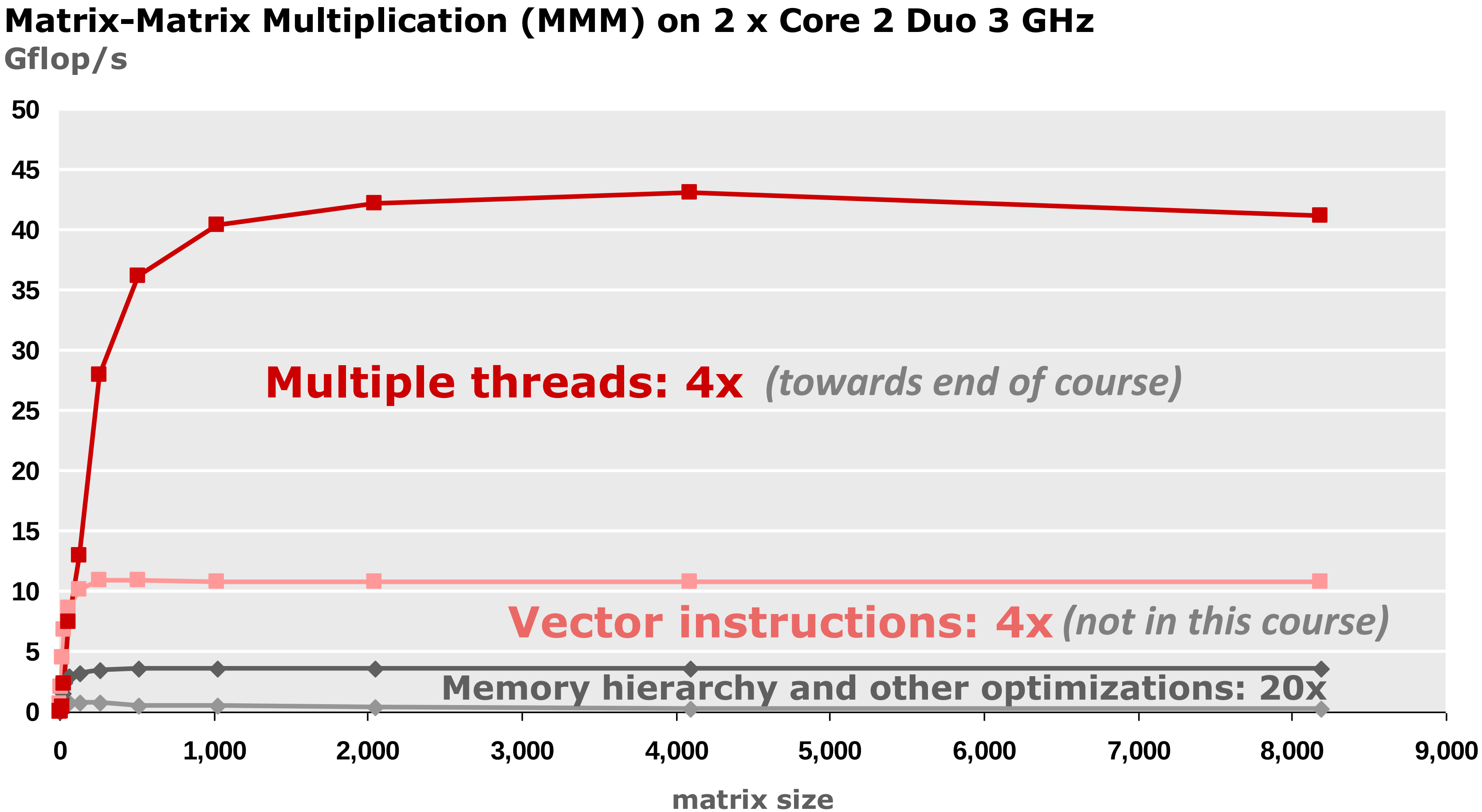
- Memory layout
- Buffer overflow, worms, and viruses
- **Program optimization**
  - **Overview**
  - Removing unnecessary procedure calls
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
  - Optimization blocker: Procedure calls

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

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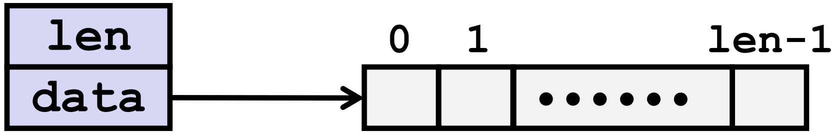
Example: Data Type for Vectors

```
/* 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 for 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];
```

Where are the FP operations?

```
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 < goot loop
.L7:                                     # done:
        rep ; ret                        #  return
```

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
  - Optimization blocker: Memory aliasing

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

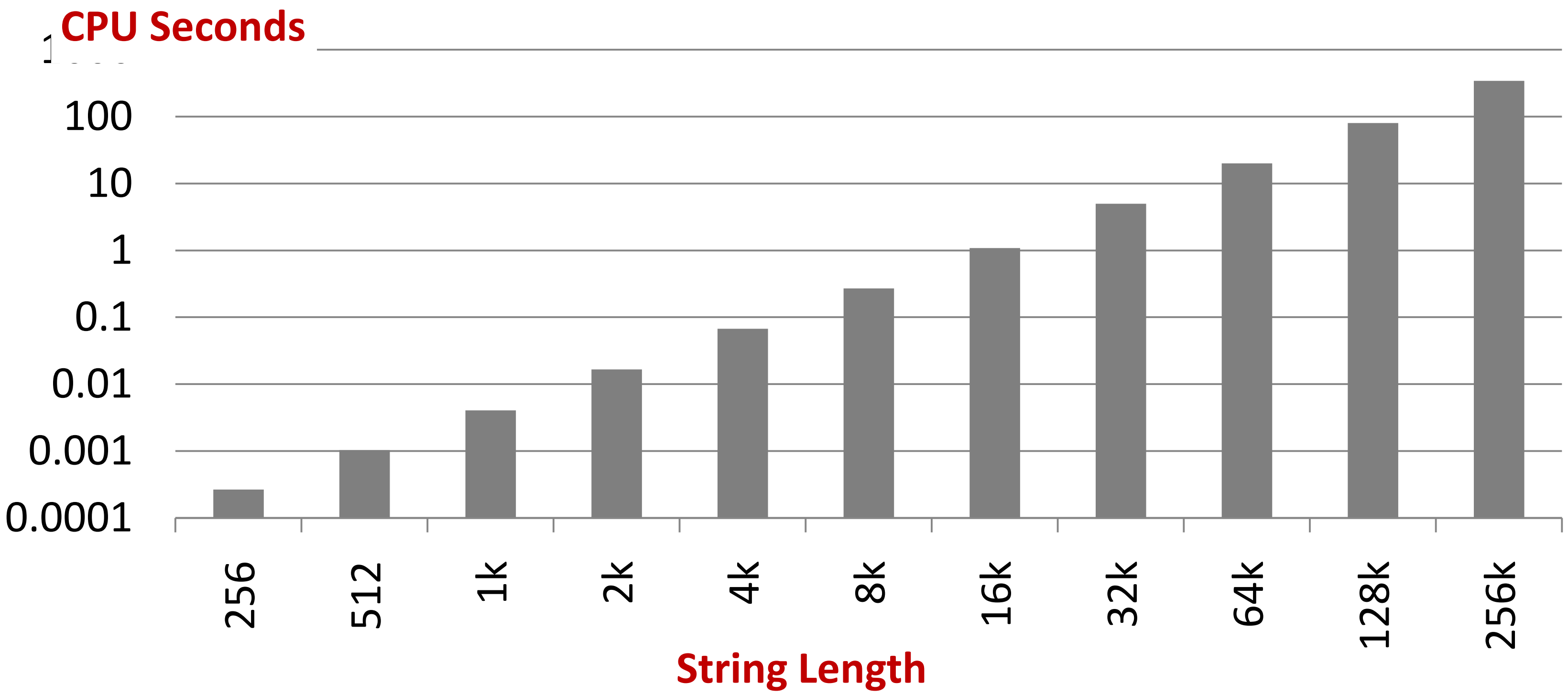
- **Procedure to convert string to lower case**

```
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 213 lab submissions, Fall 1998

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

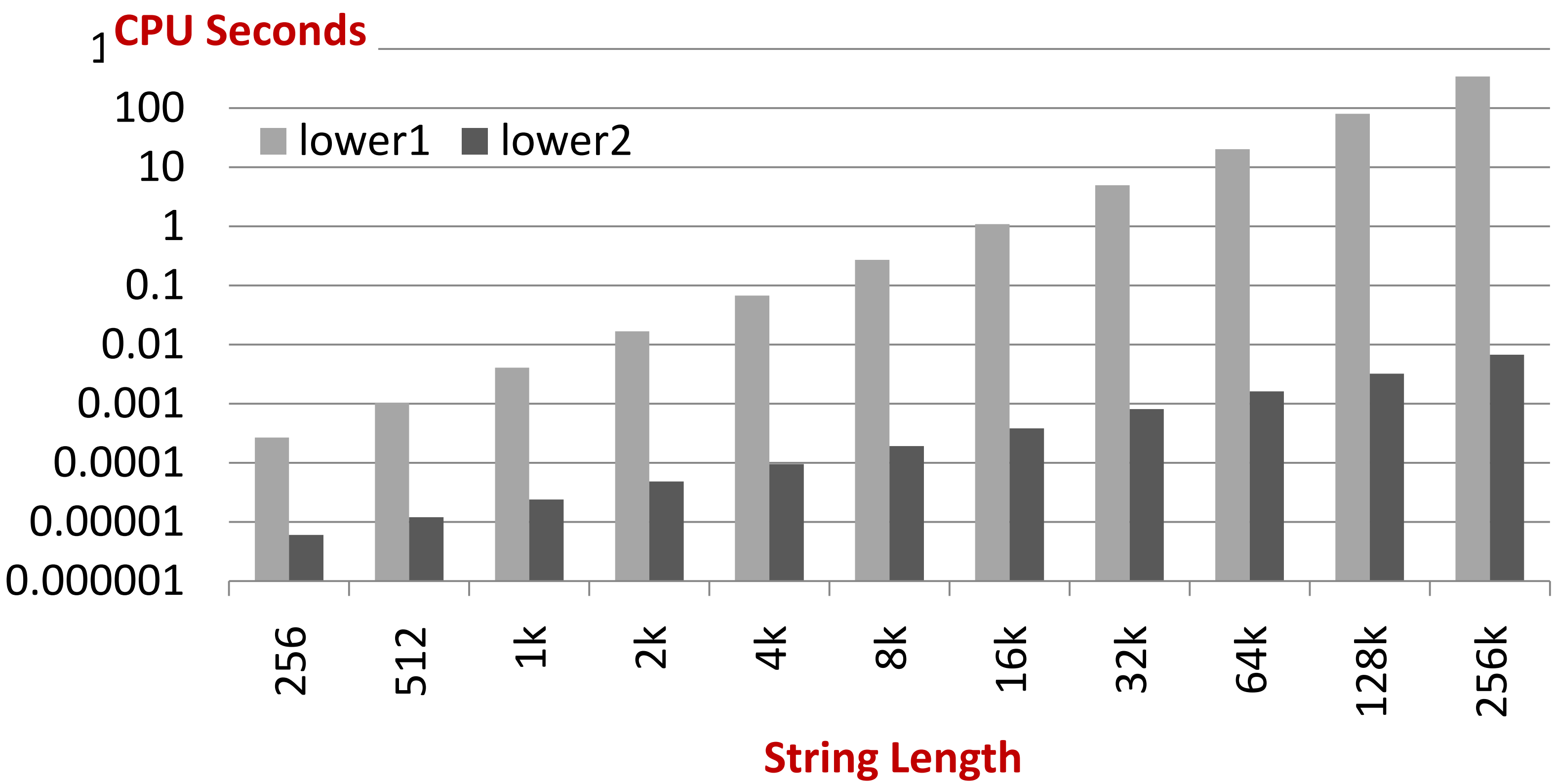
```
void lower(char *s)
{
  int i;
  for (i = 0; i < strlen(s); i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

```
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;
}
```