

Code Optimization

15-213/15-503: Introduction to Computer Systems
12th Lecture, June 17, 2025

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Code Optimization is Hard

■ Code optimization is fun

- If you like solving puzzles and mysteries
- Reading and understanding diverse code bases
- And you like using **all** of your computer science knowledge

■ Performance / Efficiency is in every part of the system

- Compilers and computer architecture research is focused on these objectives
- Data structures and algorithms make huge differences

Today

- Principles and goals of compiler optimization
- Examples of optimizations
- Obstacles to optimization
- Machine-dependent optimization
- Benchmark example

*Back in the Good Old Days,
when the term "software" sounded funny
and Real Computers were made out of drums
and vacuum tubes,*

Real Programmers wrote in machine code.

*Not FORTRAN. Not RATFOR. Not, even,
assembly language.*

Machine Code.

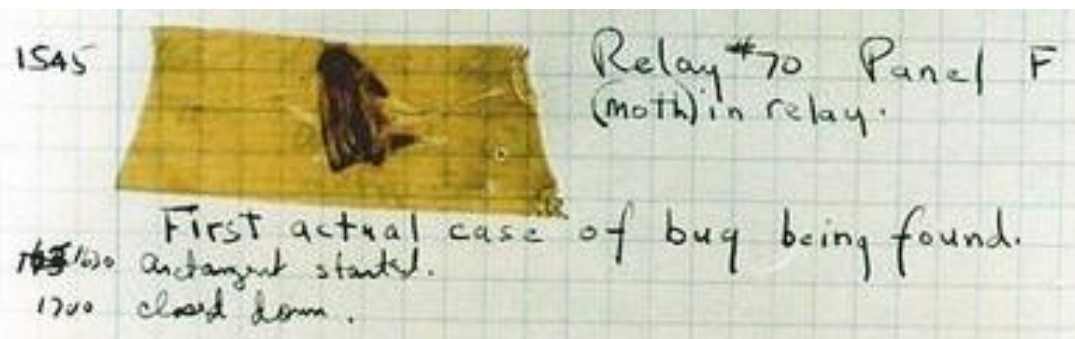
Raw, unadorned, inscrutable hexadecimal numbers. Directly.

— “The Story of Mel, a Real Programmer”

Ed Nather, 1983

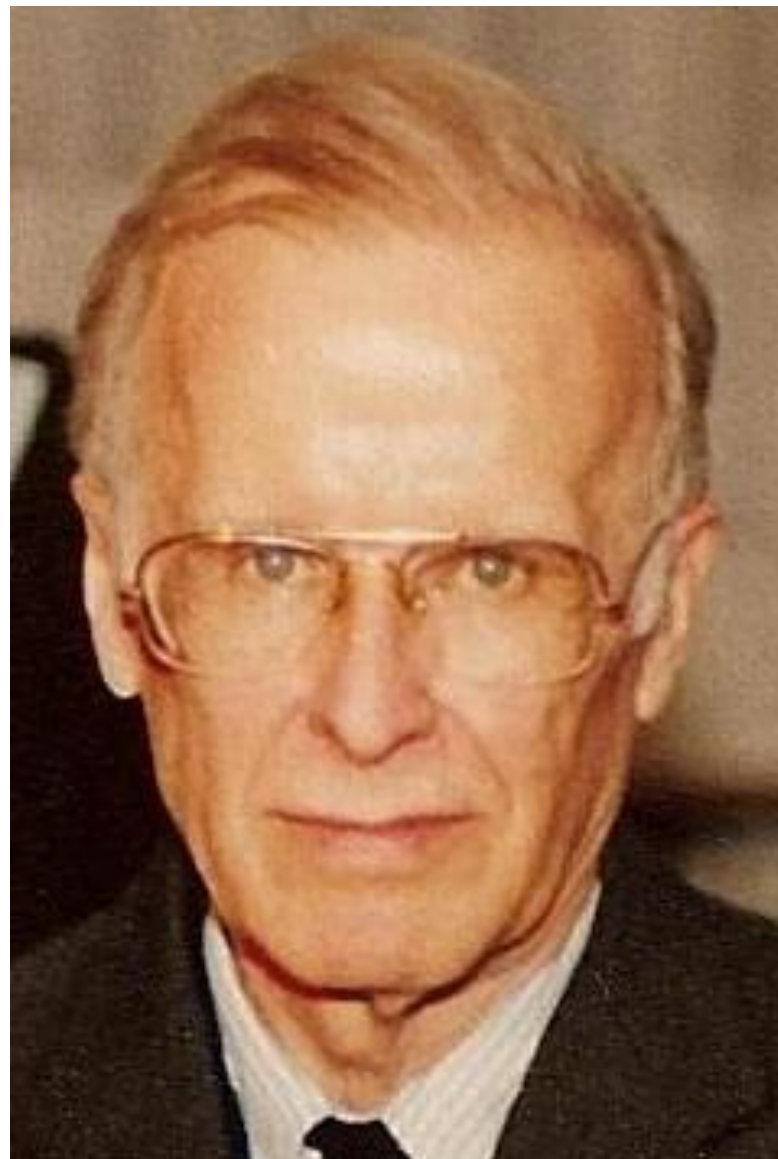
Rear Admiral Grace Hopper

- First person to find an actual bug (a moth)
- Invented first compiler in 1951 (precursor to COBOL)
- “I decided data processors ought to be able to write their programs in English, and the computers would translate them into machine code”



John Backus

- Developed FORTRAN in 1957 for the IBM 704
- Oldest machine-independent programming language still in use today
- “Much of my work has come from being lazy. I didn't like writing programs, and so, when I was working on the IBM 701, I started work on a programming system to make it easier to write programs”



Fran Allen

- Pioneer of many optimizing compilation techniques
- Wrote a paper in 1966 that introduced the concept of the control flow graph, which is still central to compiler theory today
- First woman to win the ACM Turing Award



Goals of compiler optimization

■ Minimize number of instructions

- Don't do calculations more than once
- Don't do unnecessary calculations at all
- Avoid slow instructions (multiplication, division)

■ Avoid waiting for memory

- Keep everything in registers whenever possible
- Access memory in cache-friendly patterns
- Load data from memory early, and only once

■ Avoid branching

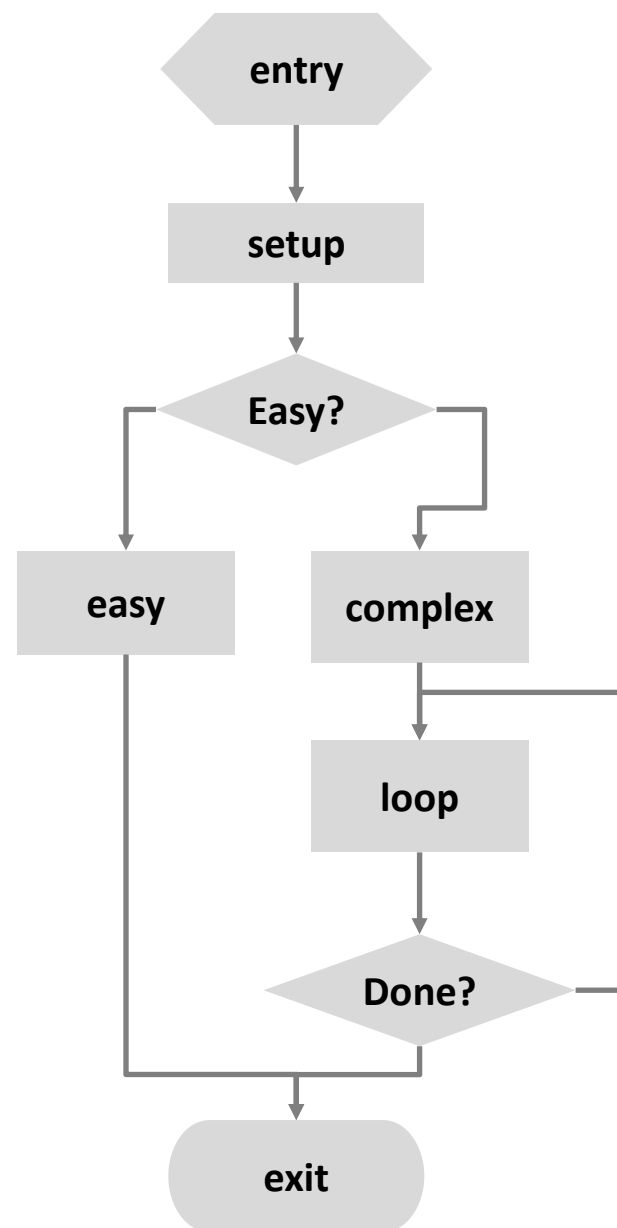
- Don't make unnecessary decisions at all
- Make it easier for the CPU to predict branch destinations
- "Unroll" loops to spread cost of branches over more instructions

Limits to compiler optimization

- **Generally cannot improve algorithmic complexity**
 - Only constant factors, but those can be worth 10x or more...
- **Must not cause *any* change in program behavior**
 - Programmer may not care about “edge case” behavior, but compiler does not know that
 - Exception: language may declare some changes acceptable
- **Often only analyze one function at a time**
 - Whole-program analysis (“LTO”) expensive but gaining popularity
 - Exception: *inlining* merges many functions into one
- **Tricky to anticipate run-time inputs**
 - Profile-guided optimization can help with common case, but...
 - “Worst case” performance can be just as important as “normal”
 - Especially for code exposed to *malicious* input (e.g. network servers)

Two kinds of optimizations

- **Local optimizations**
work inside a single
basic block
 - Constant folding, strength reduction, dead code elimination, (local) CSE, ...
- **Global optimizations**
process the entire
***control flow graph* of a**
function
 - Loop transformations, code motion, (global) CSE, ...



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Next several slides done live...

- <https://godbolt.org/z/Es5s8qsvj>
- Go to Godbolt (the compiler explorer) to play around with C and the resulting assembly generated under different compiler optimizations (change the flag from `-O3` to `-Og`, etc. to see more or less aggressive optimization).
- If you missed class, a lot of the concepts we explored during the live demo are explained in the next few slides, so peek at them and then try playing with the compiler explorer!

Constant folding

- Do arithmetic in the compiler

```
long mask = 0xFF << 8;    →  
long mask = 0xFF00;
```

- Any expression with constant inputs can be folded
- Might even be able to remove library calls...

```
size_t namelen = strlen("Harry Bovik");  →  
size_t namelen = 11;
```

Dead code elimination

- Don't emit code that will never be executed

```
if (0) { puts("Kilroy was here"); }  
if (1) { puts("Only bozos on this bus"); }
```

- Don't emit code whose result is overwritten

```
x = 23;  
x = 42;
```

- These may look silly, but...
 - Can be produced by other optimizations
 - Assignments to x might be far apart

Common subexpression elimination

- Factor out repeated calculations, only do them once

```
norm[i] = v[i].x*v[i].x + v[i].y*v[i].y;
```

→

```
elt = &v[i];
```

```
x = elt->x;
```

```
y = elt->y;
```

```
norm[i] = x*x + y*y;
```

Code motion

- Move calculations out of a loop
- Only valid if every iteration would produce same result

```
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];
```

Inlining

■ Copy body of a function into its caller(s)

- Can create opportunities for many other optimizations
- Can make code much bigger and therefore slower (size; i-cache)

```
int pred(int x) {  
    if (x == 0)  
        return 0;  
    else  
        return x - 1;  
}
```

```
int func(int y) {  
    return pred(y)  
        + pred(0)  
        + pred(y+1);  
}
```

```
int func(int y) {  
    int tmp;  
    if (y == 0) tmp = 0; else tmp = y - 1;  
    if (0 == 0) tmp += 0; else tmp += 0 - 1;  
    if (y+1 == 0) tmp += 0; else tmp += (y + 1) - 1;  
    return tmp;  
}
```

Inlining

■ Copy body of a function into its caller(s)

- Can create opportunities for many other optimizations
- Can make code much bigger and therefore slower

```
int pred(int x) {
    if (x == 0)
        return 0;
    else
        return x - 1;
}
```

```
int func(int y) {
    return pred(y)
        + pred(0)
        + pred(y+1);
}
```

```
int func(int y) {
    int tmp;
    if (y == 0) tmp = 0; else tmp = y - 1;
    if (0 == 0) tmp += 0; else tmp += 0 - 1;
    if (y+1 == 0) tmp += 0; else tmp += (y + 1) - 1;
    return tmp;
}
```

Always true

Does nothing

Can constant fold

Inlining

■ Copy body of a function into its caller(s)

- Can create opportunities for many other optimizations
- Can make code much bigger and therefore slower

```
int func(int y) {
    int tmp;
    if (y == 0) tmp = 0; else tmp = y - 1;
    if (0 == 0) tmp += 0; else tmp += 0 - 1;
    if (y+1 == 0) tmp += 0; else tmp += (y + 1) - 1;
    return tmp;
}
```

```
int func(int y) {
    int tmp = 0;
    if (y != 0) tmp = y - 1;

    if (y != -1) tmp += y;
    return tmp;
}
```

Today

- Principles and goals of compiler optimization
- Examples of optimizations
- **Obstacles to optimization**
- **Machine-dependent optimization**
- **Benchmark example**

Memory Aliasing

```
/* Sum rows of n X n matrix a and store in vector b. */
void sum_rows1(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

```

    movq    $0, (%rsi)
    pxor    %xmm0, %xmm0
.L4:
    addsd   (%rdi), %xmm0
    movsd   %xmm0, (%rsi)
    addq    $8, %rdi
    cmpq    %rcx, %rdi
    jne     .L4
```

- Code updates `b[i]` on every iteration
- Why couldn't compiler optimize this away?

Memory Aliasing

```
/* Sum rows of n X n matrix a and store in vector b. */
void sum_rows1(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

```
double A[9] =
{ 0, 1, 2,
  4, 8, 16},
{ 32, 64, 128};

double B[3] = A+3;

sum_rows1(A, B, 3);
```

```
double A[9] =
{ 0, 1, 2,
  3, 22, 224},
{ 32, 64, 128};
```

Value of B:

init: [4, 8, 16]

i = 0: [3, 8, 16]

i = 1: [3, 22, 16]

i = 2: [3, 22, 224]

- Code updates `b[i]` on every iteration
- Must consider possibility that these updates will affect program behavior

Avoiding Aliasing Penalties

```

/* Sum rows of n X n matrix a and store in vector b. */
void sum_rows2(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        double val = 0;
        for (j = 0; j < n; j++)
            val += a[i*n + j];
        b[i] = val;
    }
}

```

```

.L4:    pxor    %xmm0, %xmm0
        addsd   (%rdi), %xmm0
        addq    $8, %rdi
        cmpq    %rax, %rdi
        jne     .L4
        movsd   %xmm0, (%rsi)

```

- Use a local variable for intermediate results
- Use restrict keyword
 - Tells compiler that this is the “only” pointer to that memory location

Can't move function calls out of loops

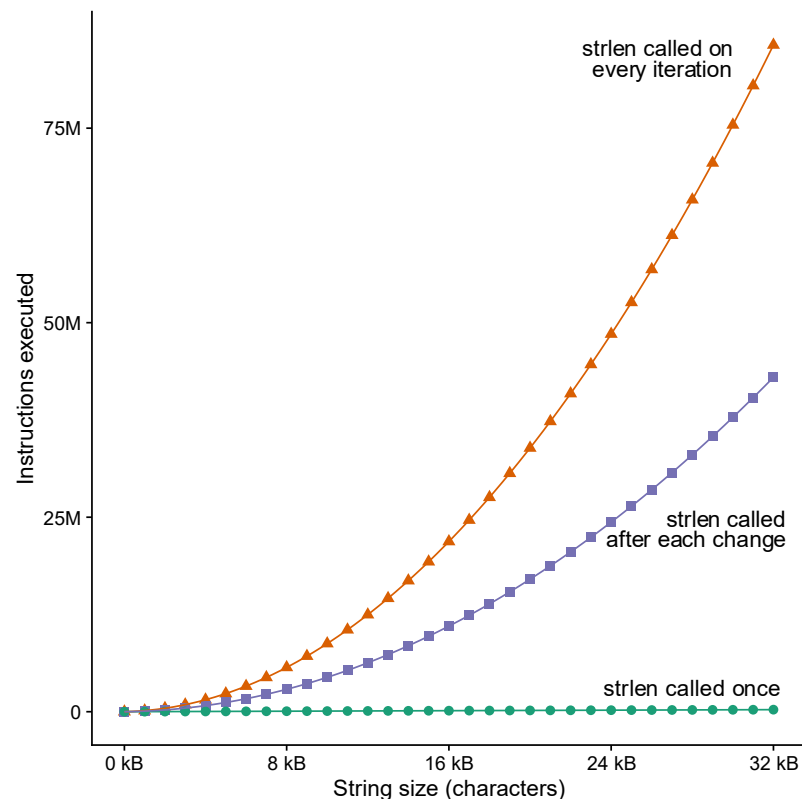
```

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

void lower_still_quadratic(char *s) {
    size_t i, n = strlen(s);
    for (i = 0; i < n; i++)
        if (s[i] >= 'A' && s[i] <= 'Z') {
            s[i] += 'a' - 'A';
            n = strlen(s);
        }
}

void lower_linear(char *s) {
    size_t i, n = strlen(s);
    for (i = 0; i < n; i++)
        if (s[i] >= 'A' && s[i] <= 'Z')
            s[i] += 'a' - 'A';
}

```



Lots more examples of this kind of bug:
accidentallyquadratic.tumblr.com

Can't move function calls out of loops

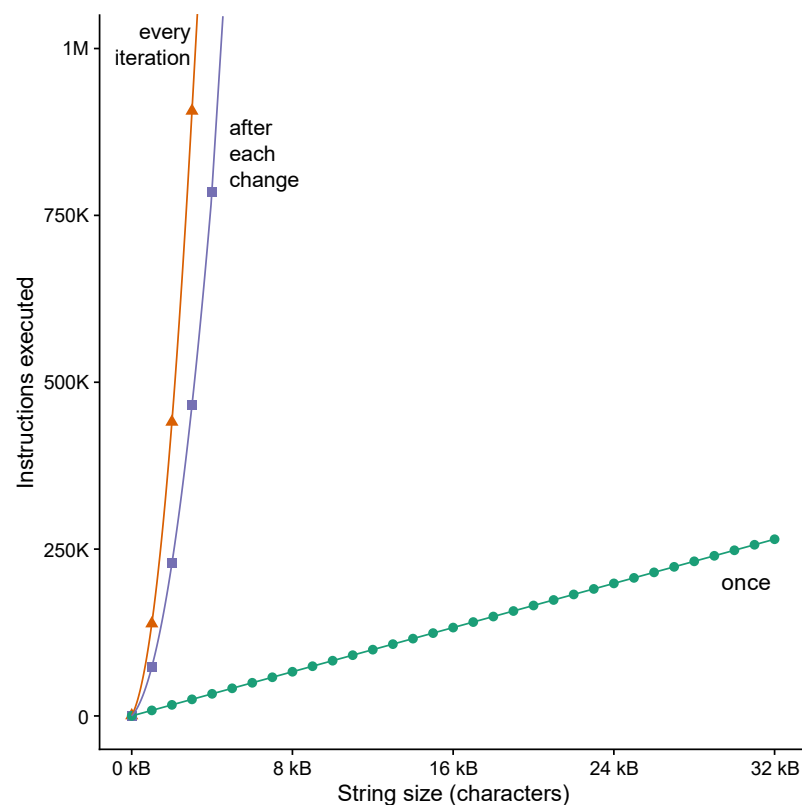
```

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

void lower_still_quadratic(char *s) {
    size_t i, n = strlen(s);
    for (i = 0; i < n; i++)
        if (s[i] >= 'A' && s[i] <= 'Z') {
            s[i] += 'a' - 'A';
            n = strlen(s);
        }
}

void lower_linear(char *s) {
    size_t i, n = strlen(s);
    for (i = 0; i < n; i++)
        if (s[i] >= 'A' && s[i] <= 'Z')
            s[i] += 'a' - 'A';
}

```



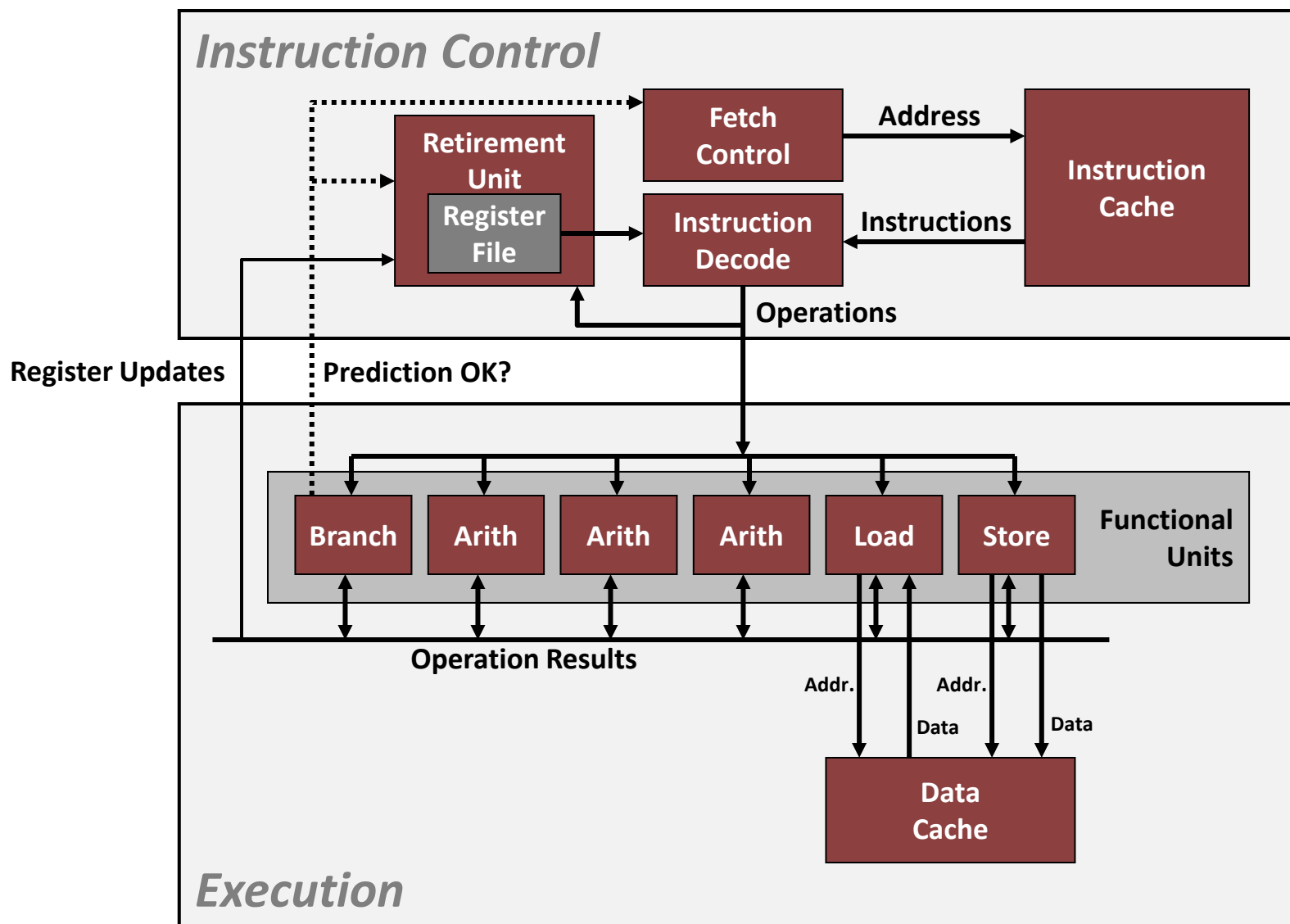
Quiz

<https://canvas.cmu.edu/courses/47415/quizzes/143238>

Today

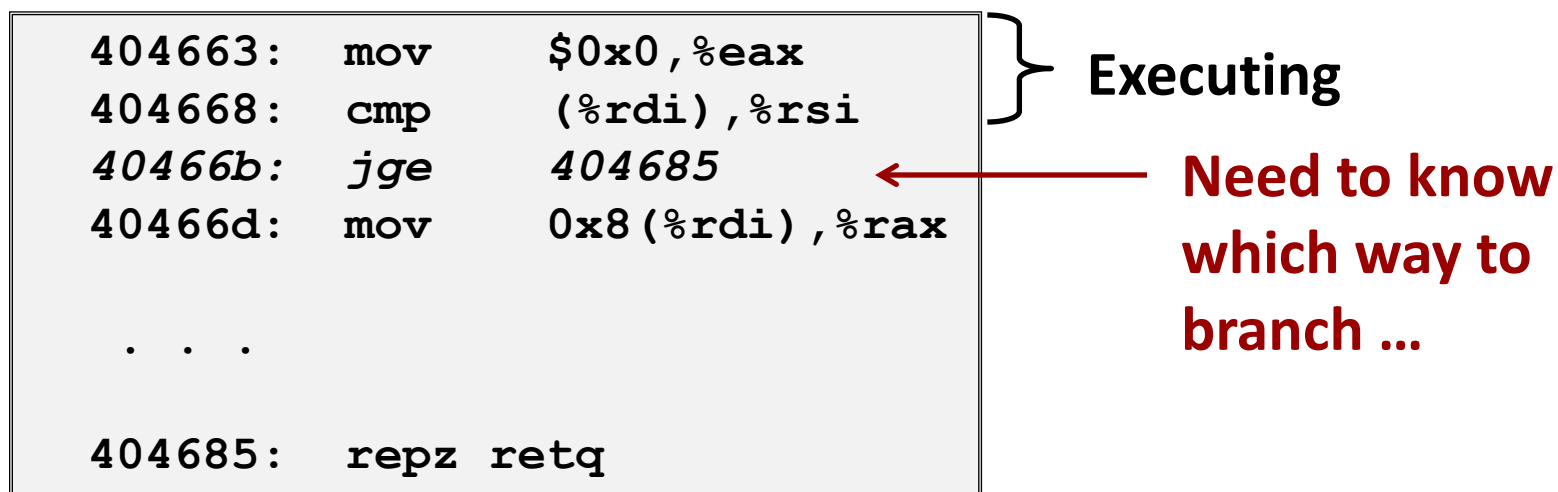
- Principles and goals of compiler optimization
- Examples of optimizations
- Obstacles to optimization
- **Machine-dependent optimization**
- **Benchmark example**

Modern CPU Design



Branches Are A Challenge

- **Instruction Control Unit** must work well ahead of **Execution Unit** to generate enough operations to keep EU busy

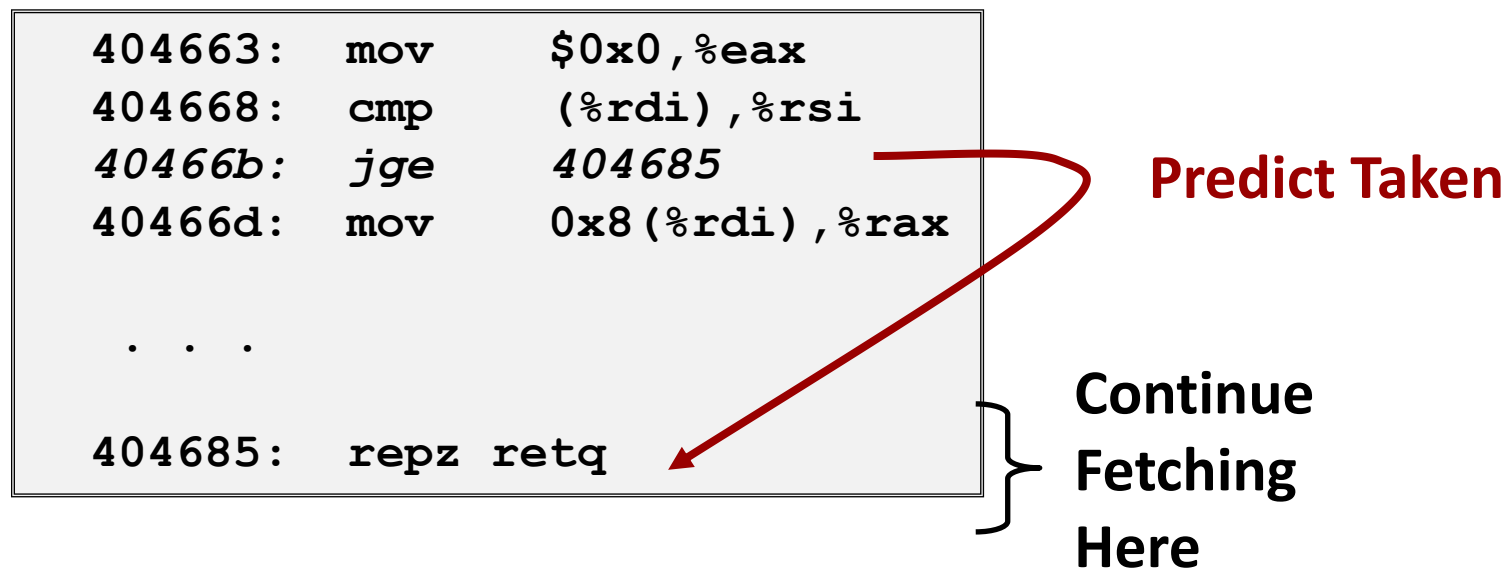


If the CPU has to wait for the result of the `cmp` before continuing to fetch instructions, may waste tens of cycles doing nothing!

Branch Prediction

■ *Guess which way branch will go*

- Begin executing instructions at predicted position
- But don't actually modify register or memory data



Branch Prediction Through Loop

```
401029:  mulsd    (%rdx), %xmm0, %xmm0
40102d:  add      $0x8, %rdx
401031:  cmp      %rax, %rdx
401034:  jne      401029
```

i = 98

Assume
array length = **100**

Predict Taken (OK)

```
401029:  mulsd    (%rdx), %xmm0, %xmm0
40102d:  add      $0x8, %rdx
401031:  cmp      %rax, %rdx
401034:  jne      401029
```

i = 99

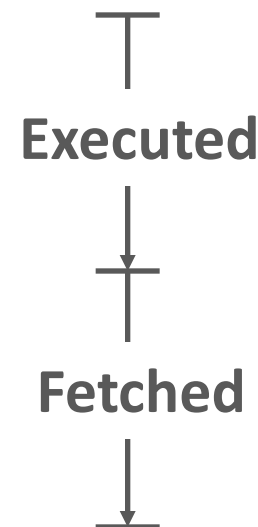
Predict Taken
(Oops)

```
401029:  mulsd    (%rdx), %xmm0, %xmm0
40102d:  add      $0x8, %rdx
401031:  cmp      %rax, %rdx
401034:  jne      401029
```

i = 100

Read
invalid
location

```
401029:  mulsd    (%rdx), %xmm0, %xmm0
40102d:  add      $0x8, %rdx
401031:  cmp      %rax, %rdx
401034:  jne      401029
```

i = 101

Branch Misprediction Invalidation

```
401029:  mulsd    (%rdx), %xmm0, %xmm0
40102d:  add      $0x8, %rdx
401031:  cmp      %rax, %rdx
401034:  jne      401029
```

i = 98

Assume
array length = **100**

Predict Taken (OK)

```
401029:  mulsd    (%rdx), %xmm0, %xmm0
40102d:  add      $0x8, %rdx
401031:  cmp      %rax, %rdx
401034:  jne      401029
```

i = 99

Predict Taken
(Oops)

```
401029:  mulsd    (%rdx), %xmm0, %xmm0
40102d:  add      $0x8, %rdx
401031:  cmp      %rax, %rdx
401034:  jne      401029
```

i = 100

Invalidate

```
401029:  mulsd    (%rdx), %xmm0, %xmm0
40102d:  add      $0x8, %rdx
401031:  cmp      %rax, %rdx
401034:  jne      401029
```

i = 101

Branch Misprediction Recovery

```
401029:  mulsd    (%rdx), %xmm0, %xmm0
```

```
40102d:  add      $0x8, %rdx
```

```
401031:  cmp      %rax, %rdx
```

```
401034:  jne      401029
```

```
401036:  jmp      401040
```

```
. . .
```

```
401040:  movsd    %xmm0, (%r12)
```

i = 99

Definitely not taken

Reload
Pipeline

■ Performance Cost

- Multiple clock cycles on modern processor
- Can be a major performance limiter

Branch Prediction Numbers

■ A simple heuristic:

- Backwards branches are often loops, so predict taken
- Forwards branches are often ifs, so predict not taken

■ Fancier algorithms track behavior of each branch

- Branch behavior often correlates

■ Other notes:

- Subject of ongoing research
- 2011 record (<https://www.jilp.org/jwac-2/program/JWAC-2-program.htm>): 34.1 mispredictions per 1000 instructions
- Current research focuses on the remaining handful of “impossible to predict” branches (strongly data-dependent, no correlation with history)

Optimizing for Branch Prediction

■ Reduce # of branches

- Transform loops
- Unroll loops
- Use conditional moves
 - Not always a good idea

■ Make branches predictable

- Sort data
 - <https://stackoverflow.com/questions/11227809>
- Avoid indirect branches
 - function pointers
 - virtual methods

```
.Loop:
    movzbl 0(%rbp,%rbx), %edx
    leal   -65(%rdx), %ecx
    cmpb   $25, %cl
    ja     .Lskip
    addl   $32, %edx
    movb   %dl, 0(%rbp,%rbx)
.Lskip:
    addl   $1, %rbx
    cmpq   %rax, %rbx
    jb     .Loop
```

```
.Loop:
    movzbl 0(%rbp,%rbx), %edx
    movl   %edx, %esi
    leal   -65(%rdx), %ecx
    addl   $32, %edx
    cmpb   $25, %cl
    cmova  %esi, %edx
    movb   %dl, 0(%rbp,%rbx)
    addl   $1, %rbx
    cmpq   %rax, %rbx
    jb     .Loop
```

Memory write
now
unconditional!

Loop Unrolling

- Amortize cost of loop condition by duplicating body
- Creates opportunities for CSE, code motion, scheduling
- Prepares code for vectorization
- Can hurt performance by increasing code size

```
for (size_t i = 0; i < nelts; i++) {  
    A[i] = B[i]*k + C[i];  
}
```

```
for (size_t i = 0; i < nelts - 4; i += 4) {  
    A[i] = B[i]*k + C[i];  
    A[i+1] = B[i+1]*k + C[i+1];  
    A[i+2] = B[i+2]*k + C[i+2];  
    A[i+3] = B[i+3]*k + C[i+3];  
}
```

When would this change be incorrect?

Scheduling

- Rearrange instructions to make it easier for the CPU to keep all functional units busy
- For instance, move all the loads to the top of an unrolled loop
 - Now maybe it's more obvious why we need lots of registers

```
for (size_t i = 0; i < nelts - 4; i += 4) {
    A[i] = B[i]*k + C[i];
    A[i+1] = B[i+1]*k + C[i+1];
    A[i+2] = B[i+2]*k + C[i+2];
    A[i+3] = B[i+3]*k + C[i+3];
}
```

```
for (size_t i = 0; i < nelts - 4; i += 4) {
    B0 = B[i]; B1 = B[i+1]; B2 = B[i+2]; B3 = B[i+3];
    C0 = C[i]; C1 = C[i+1]; C2 = C[i+2]; C3 = C[i+3];
    A[i] = B0*k + C0;
    A[i+1] = B1*k + C1;
    A[i+2] = B2*k + C2;
    A[i+3] = B3*k + C3;
}
```

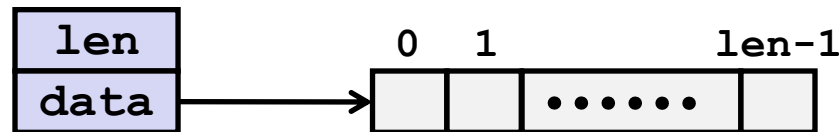
When would *this* change be incorrect?

Today

- Principles and goals of compiler optimization
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- Obstacles to optimization
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- **Benchmark example**

Benchmark Example: Data Type for Vectors

```
/* data structure for vectors */
typedef struct{
    size_t len;
    data_t *data;
} vec;
```



■ Data Types

- Use different declarations for `data_t`
- `int`
- `long`
- `float`
- `double`

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

Benchmark Computation

```
void combine1(vec_ptr v, data_t *dest)
{
    long int i;
    *dest = IDENT;
    for (i = 0; i < vec_length(v); i++) {
        data_t val;
        get_vec_element(v, i, &val);
        *dest = *dest OP val;
    }
}
```

Compute sum or
product of vector
elements

■ Data Types

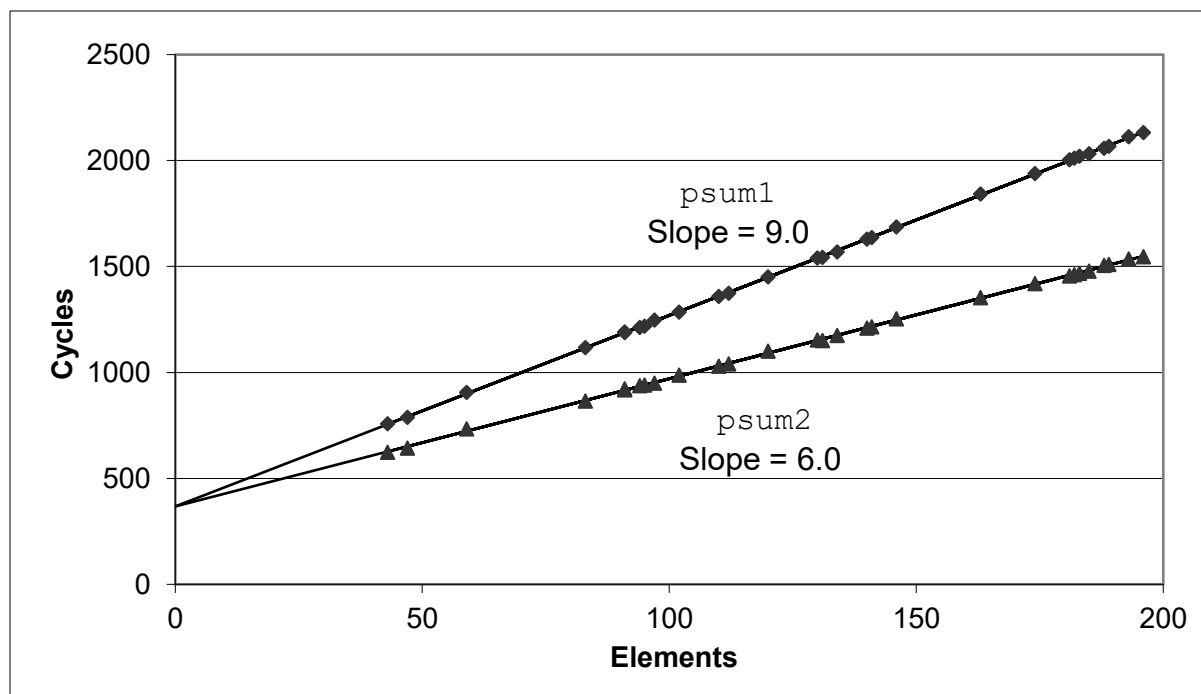
- Use different declarations for `data_t`
- `int`
- `long`
- `float`
- `double`

■ Operations

- Use different definitions of `OP` and `IDENT`
- `+` / `0`
- `*` / `1`

Cycles Per Element (CPE)

- Convenient way to express performance of program that operates on vectors or lists
- Length = n
- In our case: **CPE = cycles per OP**
- $\text{Cycles} = \text{CPE} * n + \text{Overhead}$
 - CPE is slope of line



Benchmark Performance

```
void combine1(vec_ptr v, data_t *dest)
{
    long int i;
    *dest = IDENT;
    for (i = 0; i < vec_length(v); i++) {
        data_t val;
        get_vec_element(v, i, &val);
        *dest = *dest OP val;
    }
}
```

Compute sum or
product of vector
elements

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -O1	10.12	10.12	10.17	11.14
Combine1 -O3	4.5	4.5	6	7.8

Results in CPE (cycles per element)

Basic Optimizations

```
void combine4(vec_ptr v, data_t *dest)
{
    long i;
    long length = vec_length(v);
    data_t *d = get_vec_start(v);
    data_t t = IDENT;
    for (i = 0; i < length; i++)
        t = t OP d[i];
    *dest = t;
}
```

- Move `vec_length` out of loop
- Avoid bounds check on each cycle
- Accumulate in temporary

Effect of Basic Optimizations

```
void combine4(vec_ptr v, data_t *dest)
{
    long i;
    long length = vec_length(v);
    data_t *d = get_vec_start(v);
    data_t t = IDENT;
    for (i = 0; i < length; i++)
        t = t OP d[i];
    *dest = t;
}
```

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -O1	10.12	10.12	10.17	11.14
Combine1 -O3	4.5	4.5	6	7.8
Combine4	1.27	3.01	3.01	5.01

Loop Unrolling

```
void unroll2a_combine(vec_ptr v, data_t *dest)
{
    long length = vec_length(v);
    long limit = length-1;
    data_t *d = get_vec_start(v);
    data_t x0 = IDENT;
    data_t x1 = IDENT;
    long i;
    /* Combine 2 elements at a time */
    for (i = 0; i < limit; i+=2) {
        x0 = x0 OP d[i];
        x1 = x1 OP d[i+1];
    }
    /* Finish any remaining elements */
    for (; i < length; i++) {
        x0 = x0 OP d[i];
    }
    *dest = x0 OP x1;
}
```

Loop Unrolled Assembly

- Remember modern CPU designs
 - Multiple functional units
- So how many cycles should this loop take to execute?

.L3:

```
addq    (%rdx), %rcx
addq    $16, %rdx
addq    -8(%rdx), %rdi
cmpq    %r8, %rdx
jne     .L3
```

Effect of Loop Unrolling

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -O1	10.12	10.12	10.17	11.14
Combine1 -O3	4.5	4.5	6	7.8
Combine4	1.27	3.01	3.01	5.01
Unroll	0.81	1.51	1.51	2.51

Multiple
instructions
every cycle!

Going Further

- **Compiler optimizations are an easy gain**
 - 20 CPE down to 3-5 CPE

- **With careful hand tuning and computer architecture knowledge**
 - 4-16 elements per cycle
 - Newest compilers are closing this gap

Summary: Getting High Performance

- **Good compiler and flags**
- **Don't do anything sub-optimal**
 - Watch out for hidden algorithmic inefficiencies
 - Write compiler-friendly code
 - Watch out for optimization blockers:
procedure calls & memory references
 - Look carefully at innermost loops (where most work is done)
- **Tune code for machine**
 - Exploit instruction-level parallelism
 - Avoid unpredictable branches
 - Make code cache friendly