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

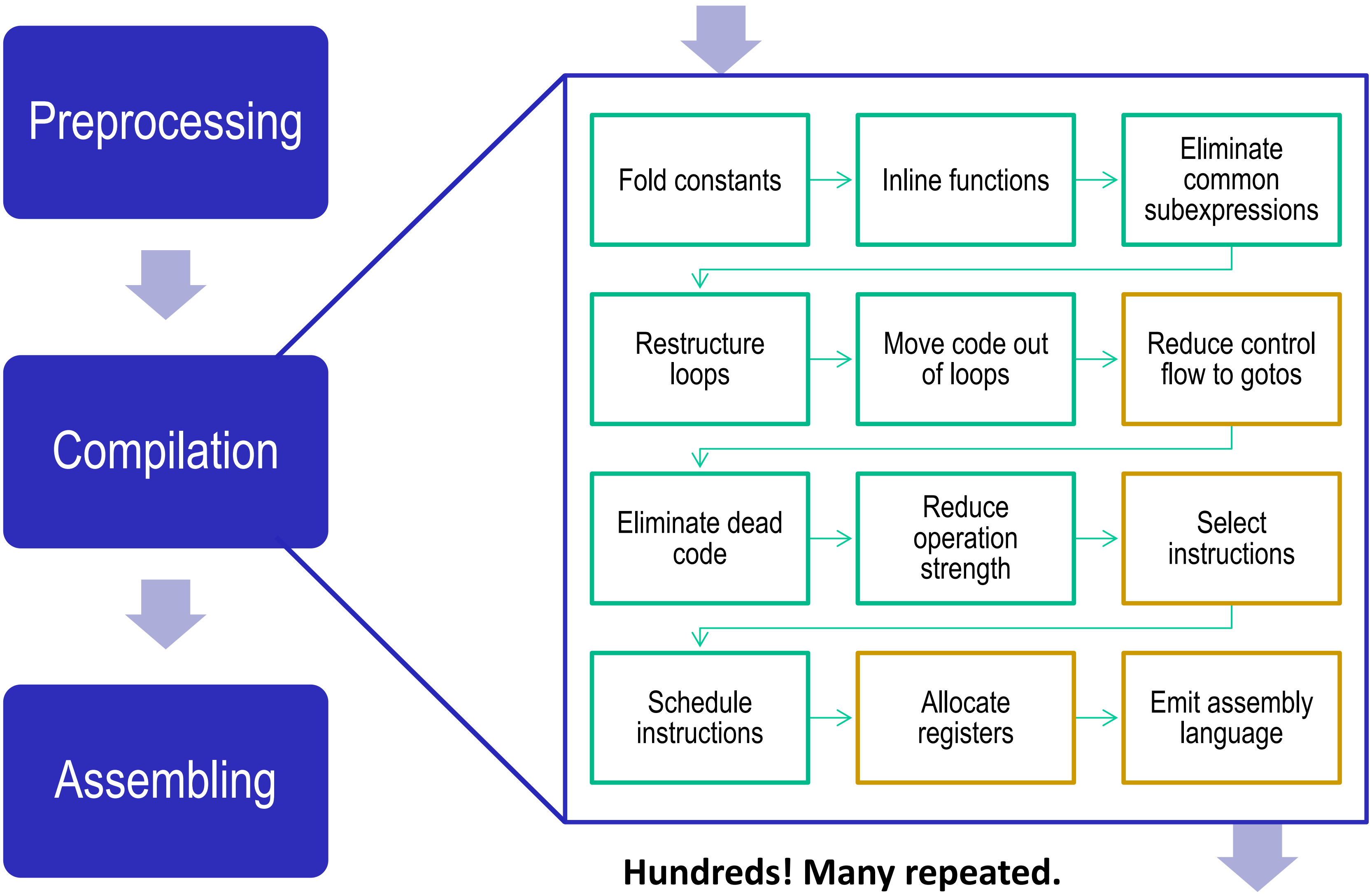
Limits to compiler optimization

- **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)

Performance Realities

- **There's more to performance than asymptotic complexity**
- **Constant factors matter too!**
  - Easily see 10:1 performance range depending on how code is written
  - Must optimize at multiple levels:
    - algorithm, data representations, procedures, and loops
- **Must understand system to optimize performance**
  - How programs are compiled and executed
  - How modern processors + memory systems operate
  - How to measure program performance and identify bottlenecks
  - How to improve performance without destroying code modularity and generality

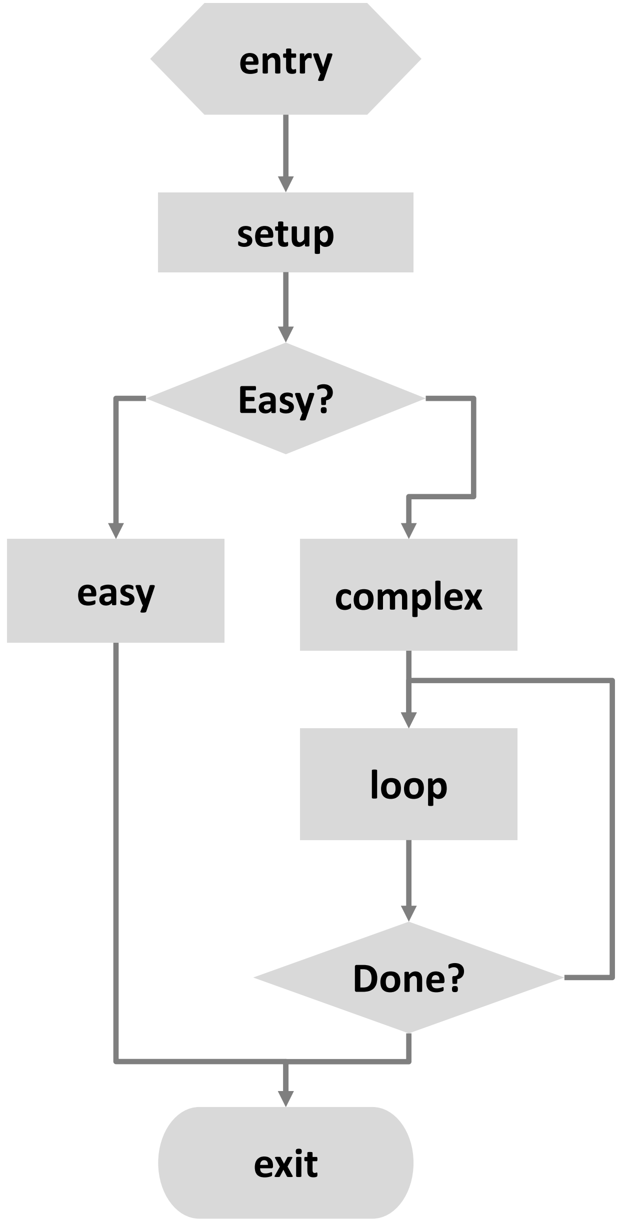
Compilation is a pipeline



Hundreds! Many repeated.

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, …



Today

- Principles and goals of compiler optimization
- Local optimization
  - Constant folding, strength reduction, dead code elimination, common subexpression elimination
- Global optimization
  - Inlining, code motion, loop transformations
- Obstacles to optimization
  - Memory aliasing, procedure calls, non-associative arithmetic
- Quiz
- Machine-dependent optimization
  - Branch predictability, loop unrolling, scheduling, vectorization

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;
```

Strength reduction

- Replace expensive operations with cheaper ones

```
long a = b * 5;      →
long a = (b << 2) + b;
```

- Multiplication and division are the usual targets
- Multiplication is often hiding in memory access expressions

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;
```

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- **Quiz**
- **Machine-dependent optimization**
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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

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  - Can make code much bigger and therefore slower

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

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];
```

Loop Transformations

Rearrange entire loop nests for maximum efficiency

```
/* Two stages of some calculation */
void compute(double *a, double *b, long n) {
  for (long i = 0; i < n; i++)
    for (long j = 0, j < n; j++)
      a[j*n + i] = atan2(i, j);

  for (long i = 0; i < n; i++)
    for (long j = 0, j < n; j++)
      b[i*n + j] = a[i*n + j]
                 + (i >= 1 && j >= 1)
                   ? a[(i-1)*n + (j-1)]
                   : 0;
}
```

Loop Transformations

Loop interchange: do iterations in cache-friendly order

```
/* Two stages of some calculation */
void compute(double *a, double *b, long n) {
  for (long i = 0; i < n; i++)
    for (long j = 0, j < n; j++)
      a[i*n + j] = atan2(j, i);

  for (long i = 0; i < n; i++)
    for (long j = 0, j < n; j++)
      b[i*n + j] = a[i*n + j]
                 + (i >= 1 && j >= 1)
                   ? a[(i-1)*n + (j-1)]
                   : 0;
}
```

Loop Transformations

Loop fusion: combine adjacent loops with the same limits

```
/* Two stages of some calculation */
void compute(double *a, double *b, long n) {
  for (long i = 0; i < n; i++) {
    for (long j = 0, j < n; j++) {
      a[i*n + j] = atan2(j, i);

  for (long i = 0; i < n; i++)
    for (long j = 0, j < n; j++)
      b[i*n + j] = a[i*n + j]
                  + (i >= 1 && j >= 1)
                    ? a[(i-1)*n + (j-1)]
                    : 0;
    }
  }
}
```

Loop Transformations

Induction variable elimination: replace loop indices with algebra

```
/* Two stages of some calculation */
void compute(double *a, double *b, long n) {
  for (long i = 0; i < n*n; i++) {
    for (long j = 0; j < n; j++) {
      a[i] = atan2(i%n, i/n);




      b[i]       = a[i]
                 + (i >= n && i%n >= 1)
                   ? a[i - n - 1]
                   : 0;
    }
  }
}
```

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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];
    }
}
```

```
# sum_rows1 inner loop
.L4:
        movsd   (%rsi,%rax,8), %xmm0    # FP load
        addsd   (%rdi), %xmm0           # FP add
        movsd   %xmm0, (%rsi,%rax,8)    # FP store
        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;
    }
}
```

```
# sum_rows2 inner loop
.Loop:
        addsd   (%rdi), %xmm0       # FP load + add
        addq    $8, %rdi
        cmpq    %rax, %rdi
        jne     .Loop
```

- Use a local variable for intermediate results

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;
    }
}
```

```
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,  27, 224},
   32,  64, 128};
```

Value of B:

```
init:   [4, 8, 16]

i = 0: [3, 8, 16]

i = 1: [3, 27, 16]

i = 2: [3, 27, 224]
```

- Still changes A in the middle of the operation
- Different results

Avoiding Aliasing Penalties

```
/* Sum rows of n X n matrix a and store in vector b. */
void sum_rows3(double *restrict a, double *restrict 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];
    }
}
```

```
# sum_rows3 inner loop
.Loop:
        addsd   (%rdi), %xmm0        # FP load + add
        addq    $8, %rdi
        cmpq    %rax, %rdi
        jne     .Loop
```

- Use `restrict` qualifier to tell compiler that a and b cannot alias
- Less reliable than using local variables

Avoiding Aliasing Penalties

```
subroutine sum_rows4(a, b, n)
    implicit none
    integer, parameter :: dp = kind(1.d0)
    real(kind=dp), dimension(:), intent(in) :: a
    real(kind=dp), dimension(:), intent(out) :: b
    integer, intent(in) :: n
    integer :: i, j
    do i = 1,n
        b(i) = 0
        do j = 1,n
            b(i) = b(i) + a(i*n + j)
        end
    end
end
```

```
# sum_rows4 inner loop
.Loop:
        addsd   (%rdi), %xmm0        # FP load + add
        addq    $8, %rdi
        cmpq    %rax, %rdi
        jne     .Loop
```

- Use Fortran
- Array parameters in Fortran are assumed not to alias

Function calls are opaque

- **Compiler examines one function at a time**
  - Some exceptions for code in a single file
- **Must assume a function call could do anything**
- **Cannot usually**
  - move function calls
  - change number of times a function is called
  - cache data from memory in registers across function calls

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

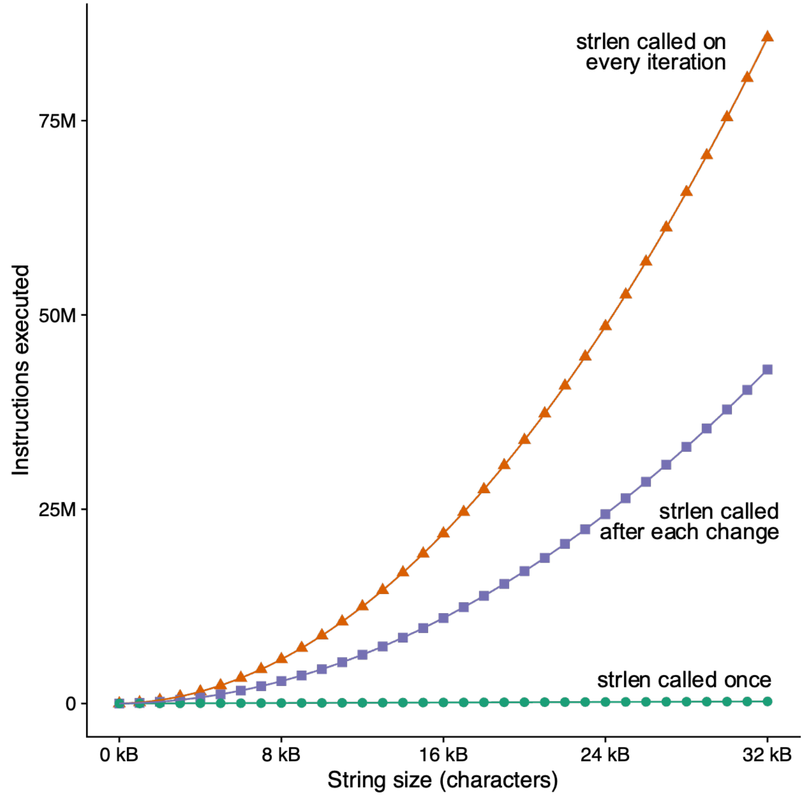
- **O(n) execution time**
- **Return value depends on:**
  - value of *s*
  - contents of memory at address *s*
    - Only cares about whether individual bytes are zero
    - Does not modify memory
- **Compiler might know *some* of that (but probably not)**

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';
}
```



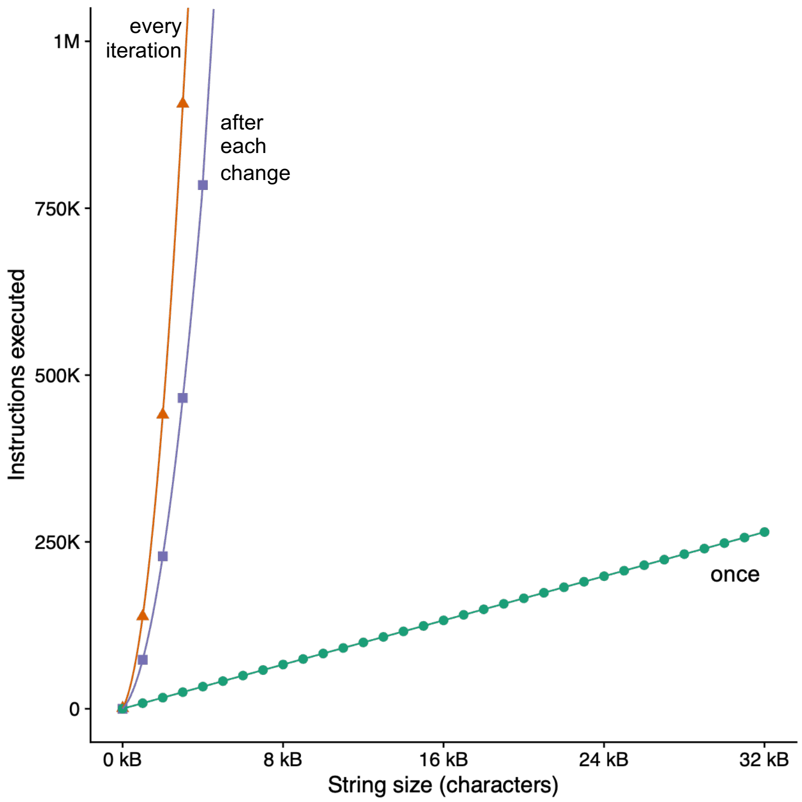
Lots more examples of this kind of bug: accidentallyquadratic.tumblr.com

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';
}
```



Non-associative arithmetic

- **When is $(\boldsymbol{a} \odot \boldsymbol{b}) \odot \boldsymbol{c}$ not equal to $\boldsymbol{a} \odot (\boldsymbol{b} \odot \boldsymbol{c})$?**
  - Octonions
  - Vector cross product
  - *Floating-point numbers*

- **Example: $\boldsymbol{a} = 1.0$, $\boldsymbol{b} = 1.5{\times}10^{38}$, $\boldsymbol{c} = -1.5{\times}10^{38}$** (single precision IEEE fp)

$$a + b = 1.5{\times}10^{38} \qquad (a + b) + c = 0$$

$$b + c = 0 \qquad a + (b + c) = 1$$

- **Blocks any optimization that changes order of operations**

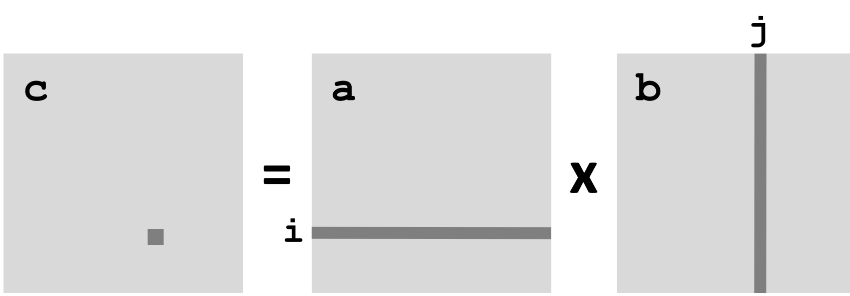
Non-associative arithmetic

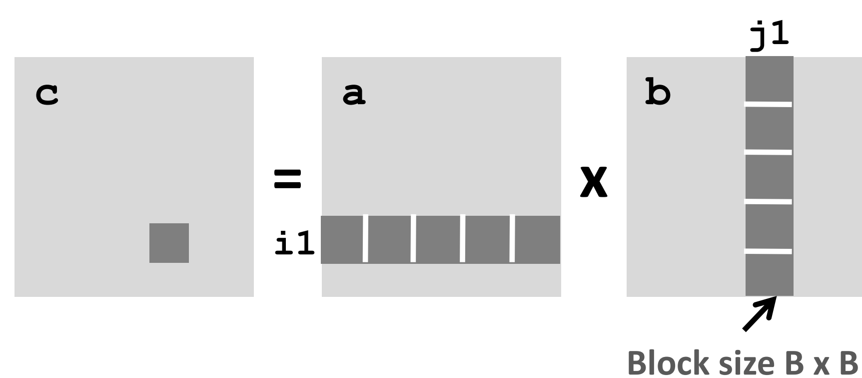
```
void mmm(double *a, double *b,
         double *c, int n) {
  memset(c, 0, n*n*sizeof(double));

  int i, j, k;
  for (i = 0; i < n; i++)
    for (j = 0; j < n; j++)
      for (k = 0; k < n; k++)
        c[i*n + j] += a[i*n + k]
                    * b[k*n + j];
}
```

```
void mmm(double *a, double *b,
         double *c, int n) {
  memset(c, 0, n*n*sizeof(double));

  int i, j, k, i1, j1, k1;
  for (i = 0; i < n; i+=B)
    for (j = 0; j < n; j+=B)
      for (k = 0; k < n; k+=B)
        for (i1 = i; i1 < i+B; i1++)
          for (j1 = j; j1 < j+B; j1++)
            for (k1 = k; k1 < k+B; k1++)
              c[i1*n+j1] += a[i1*n + k1]
                          * b[k1*n + j1];
}
```





Compiler cannot do this transformation automatically