The Alchemist by Mattheus von Helmont

# COMP201

# Computer Systems & Programming

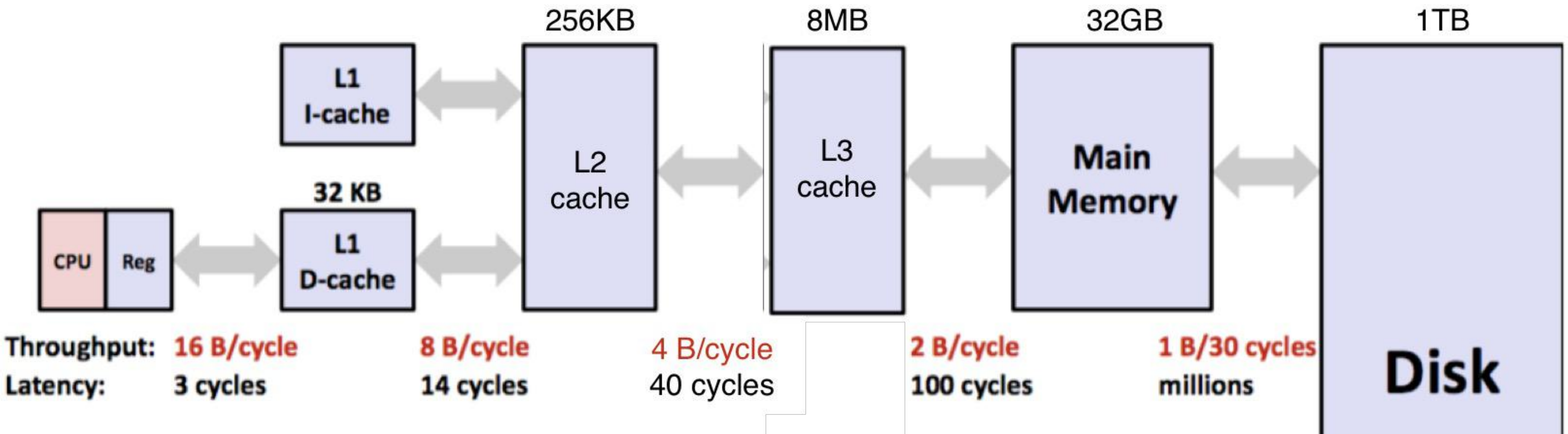
## Lecture #23 – Optimization

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Spring 2025

# Recap: Caching

- Processor speed is not the only bottleneck in program performance – memory access is perhaps even more of a bottleneck!
- Memory exists in levels and goes from *really fast* (registers) to *really slow* (disk).
- As data is more frequently used, it ends up in faster and faster memory.



# Recap: Caching

All caching depends on locality.

**Temporal locality**

- Repeat access to the same data tends to be co-located in TIME
- Intuitively: things I have used recently, I am likely to use again soon

**Spatial locality**

- Related data tends to be co-located in SPACE
- Intuitively: data that is near a used item is more likely to also be accessed

# Recap: Writing Cache Friendly Code

- Make the common case go fast
  - Focus on the inner loops of the core functions

- Minimize the misses in the inner loops
  - Repeated references to variables are good (temporal locality)
  - Stride-1 reference patterns are good (spatial locality)

**Key idea:** Our qualitative notion of locality is quantified through our understanding of cache memories

# Recap: The Memory Mountain

- **Read throughput** (read bandwidth)
  - Number of bytes read from memory per second (MB/s)

- **Memory mountain:** Measured read throughput as a function of spatial and temporal locality.
  - Compact way to characterize memory system performance.

# Recap: Memory Mountain Test Function

```
long data[MAXELEMS];  /* Global array to traverse */

/* test - Iterate over first "elems" elements of
 *        array “data” with stride of "stride", using
 *        using 4x4 loop unrolling.
 */
int test(int elems, int stride) {
    long i, sx2=stride*2, sx3=stride*3, sx4=stride*4;
    long acc0 = 0, acc1 = 0, acc2 = 0, acc3 = 0;
    long length = elems, limit = length - sx4;

    /* Combine 4 elements at a time */
    for (i = 0; i < limit; i += sx4) {
        acc0 = acc0 + data[i];
        acc1 = acc1 + data[i+stride];
        acc2 = acc2 + data[i+sx2];
        acc3 = acc3 + data[i+sx3];
    }

    /* Finish any remaining elements */
    for (; i < length; i++) {
        acc0 = acc0 + data[i];
    }
    return ((acc0 + acc1) + (acc2 + acc3));
}
```

mountain/mountain.c

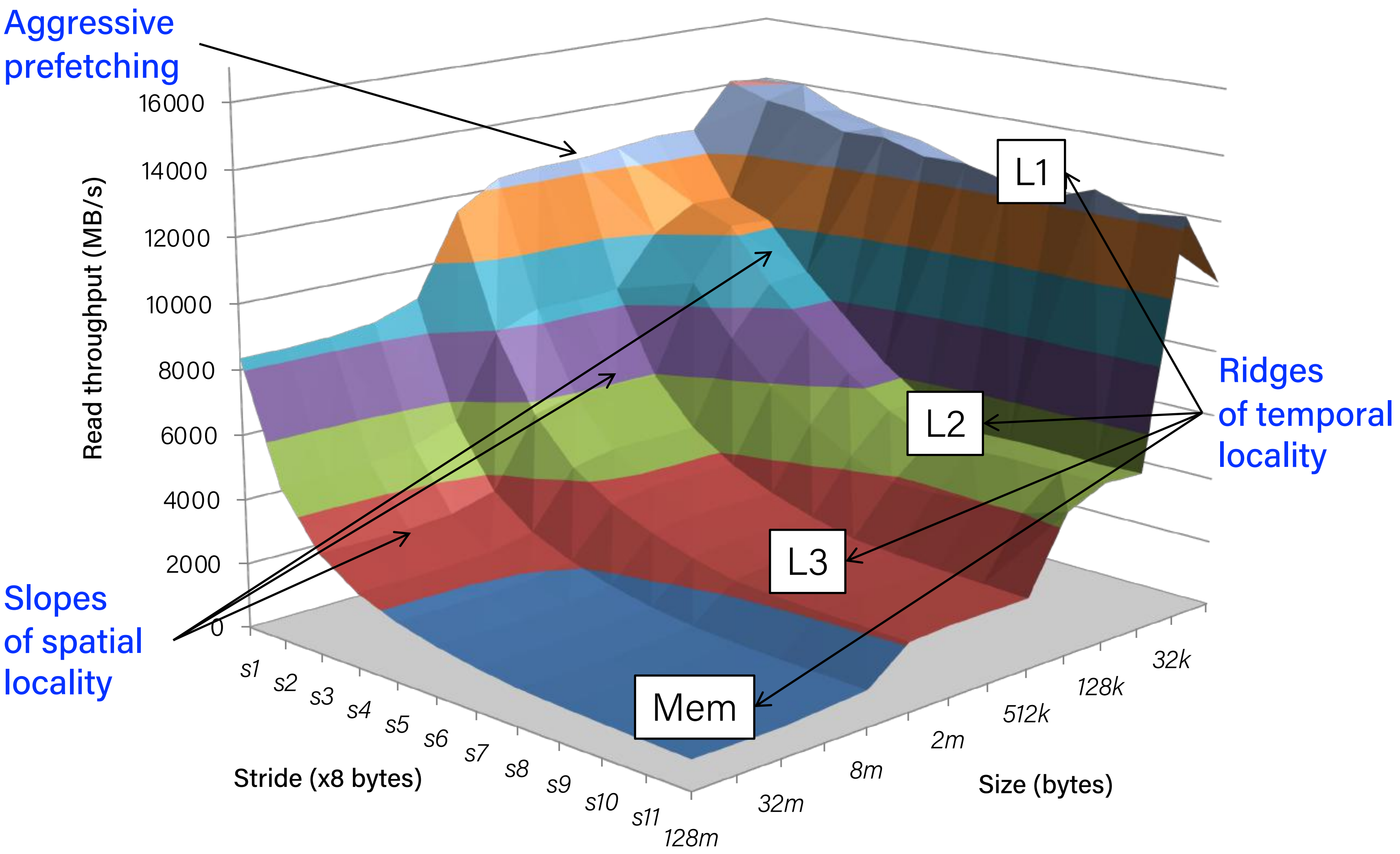
Call `test()` with many combinations of `elems` and `stride`.

For each elems and stride:

1. Call test() once to warm up the caches.

2. Call test() again and measure the read throughput(MB/s)

# Recap: The Memory Mountain




Core i7 Haswell
2.1 GHz
32 KB L1 d-cache
256 KB L2 cache
8 MB L3 cache
64 B block size

# Learning Goals

- Understand how we can optimize our code to improve efficiency and speed
- Learn about the optimizations GCC can perform

# Plan for Today

- Writing cache-friendly code
- Optimization

**Disclaimer:** Slides for this lecture were borrowed from
—Nick Troccoli's Stanford CS107 class
—Ashley Taylor's Stanford CS106B class

# Plan for Today

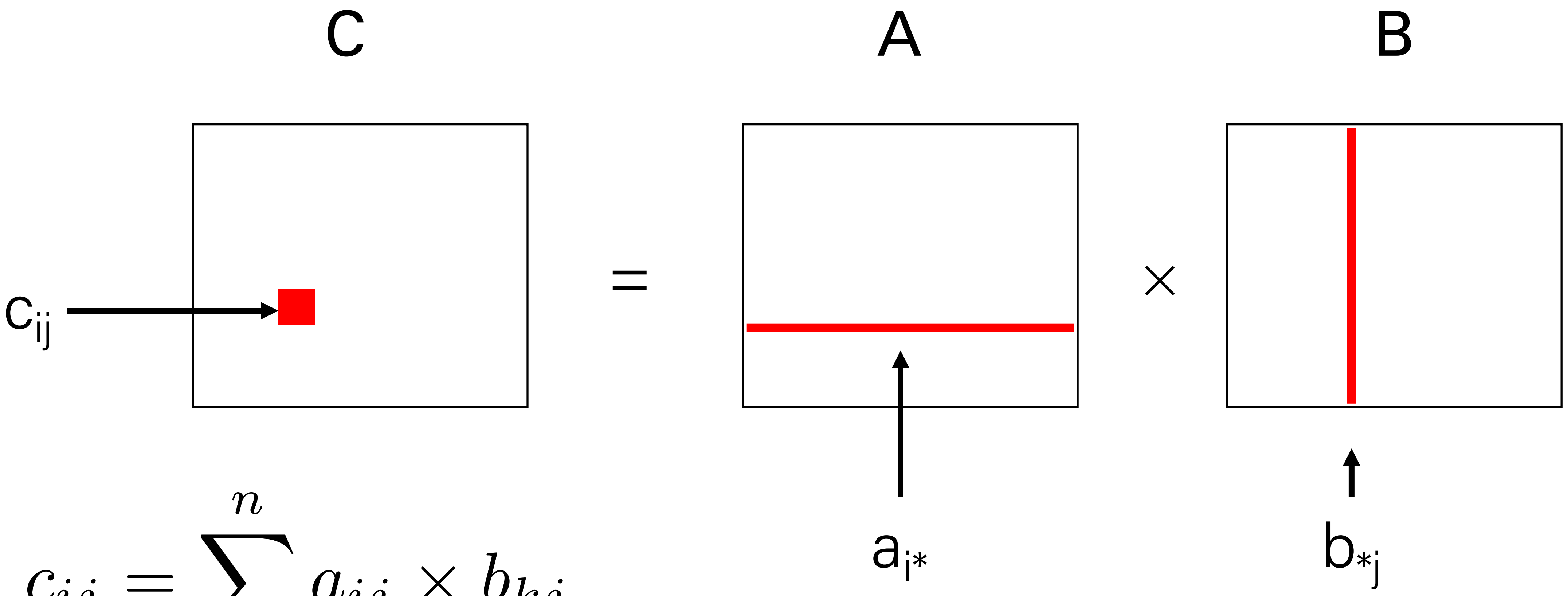
- Writing cache-friendly code
- Optimization

# Lecture Plan

- Writing cache-friendly code
  - Rearranging loops to improve spatial locality
  - Using blocking to improve temporal locality
- Optimization

# Example: Matrix Multiplication

# Matrix Multiplication Example




$$c_{ij} = \sum_{k=1}^{n} a_{ij} \times b_{kj}$$

# Matrix Multiplication Example

- Description:
  - Multiply N x N matrices
  - Matrix elements are doubles (8 bytes)
  - $O(N^3)$ total operations
  - N reads per source element
  - N values summed per destination
    - but may be able to hold in register

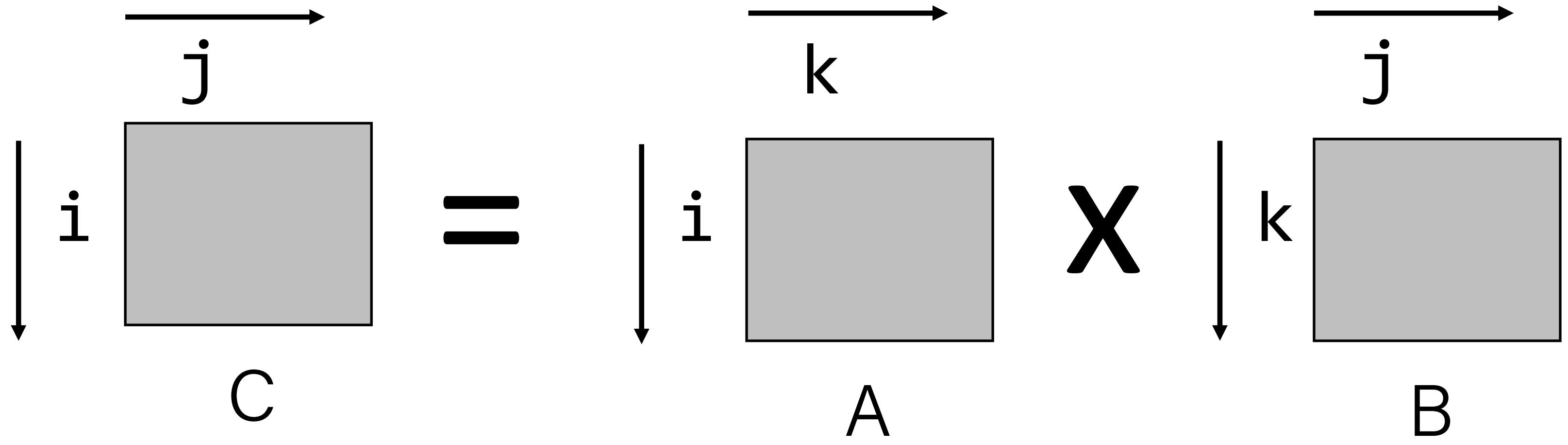
```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

Variable `sum` held in register

`matmult/mm.c`

# Miss Rate Analysis for Matrix Multiply

- Assume
  - Block size = 32B (<u>big enough for four doubles</u>)
  - Matrix dimension (N) is very large
    - Approximate 1/N as 0.0
  - Cache is not even big enough to hold multiple rows
- **Analysis Method:**
  - Look at access pattern of inner loop



# Layout of C Arrays in Memory (review)

- *C arrays allocated in row-major order*
  - *each row in contiguous memory locations*

- Stepping through columns in one row:

```
for (i = 0; i < N; i++)
  sum += a[0][i];
```

  - accesses successive elements
  - if block size (B) > sizeof(aij) bytes, exploit spatial locality

    miss rate = sizeof(aij) / B

- Stepping through rows in one column:

```
for (i = 0; i < n; i++)
  sum += a[i][0];
```

  - accesses distant elements
  - no spatial locality!

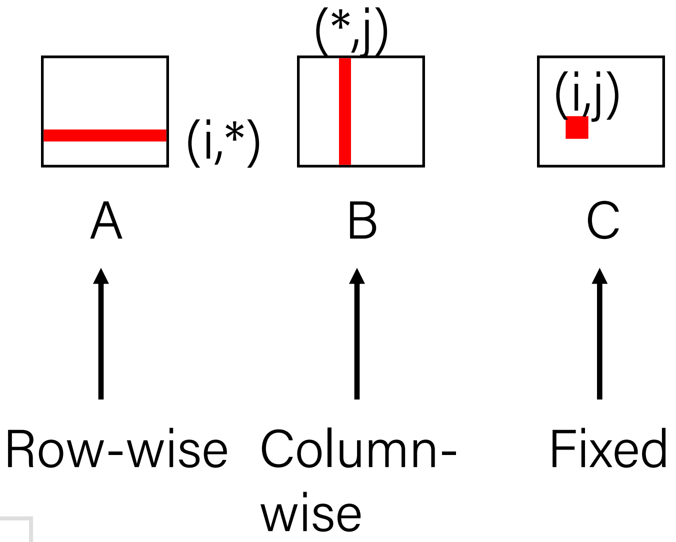
    miss rate = 1 (i.e. 100%)

# Matrix Multiplication (ijk)

```
/* ijk */
for (i=0; i<n; i++) {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

`matmult/mm.c`

Inner loop:




Misses per inner loop iteration:

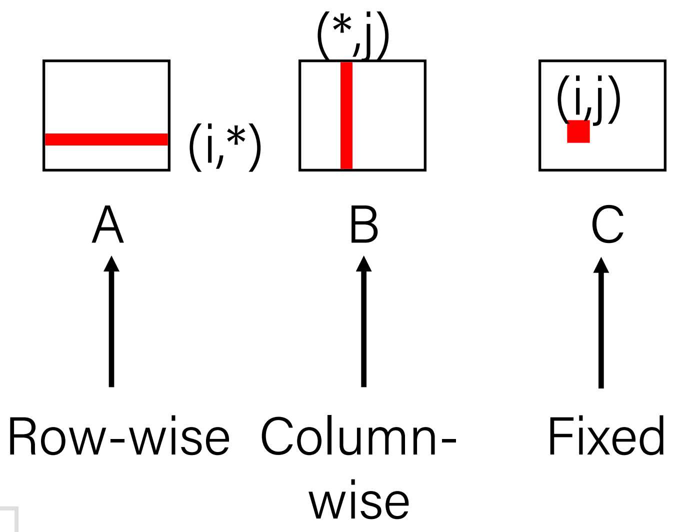
| A | B | C |
|---|---|---|
| 0.25 | 1.0 | 0.0 |

# Matrix Multiplication (jik)

```
/* jik */
for (j=0; j<n; j++) {
  for (i=0; i<n; i++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

matmult/mm.c

Inner loop:




Misses per inner loop iteration:

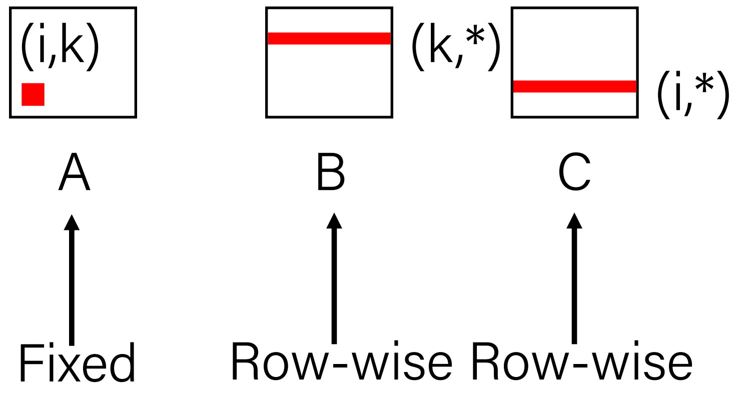
| A | B | C |
|---|---|---|
| 0.25 | 1.0 | 0.0 |

# Matrix Multiplication (kij)

```
/* kij */
for (k=0; k<n; k++) {
  for (i=0; i<n; i++) {
    r = a[i][k];
    for (j=0; j<n; j++)
      c[i][j] += r * b[k][j];
  }
}
```

matmult/mm.c

Inner loop:



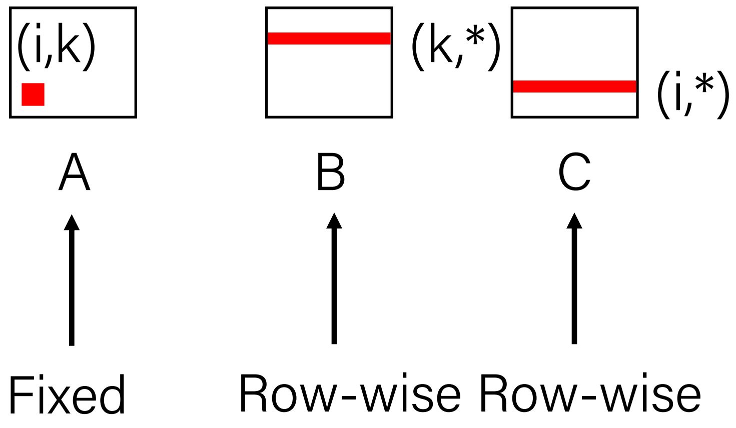

Misses per inner loop iteration:

| A | B | C |
|---|---|---|
| 0.0 | 0.25 | 0.25 |

# Matrix Multiplication (ikj)

```
/* ikj */
for (i=0; i<n; i++) {
  for (k=0; k<n; k++) {
    r = a[i][k];
    for (j=0; j<n; j++)
      c[i][j] += r * b[k][j];
  }
}
```

Inner loop:




matmult/mm.c

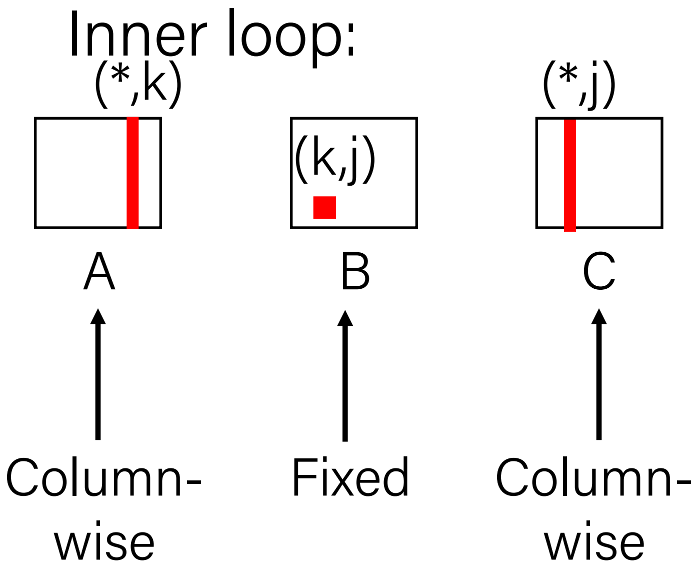
Misses per inner loop iteration:

| A | B | C |
|---|---|---|
| 0.0 | 0.25 | 0.25 |

# Matrix Multiplication (jki)

```
/* jki */
for (j=0; j<n; j++) {
  for (k=0; k<n; k++) {
    r = b[k][j];
    for (i=0; i<n; i++)
      c[i][j] += a[i][k] * r;
  }
}
```

matmult/mm.c



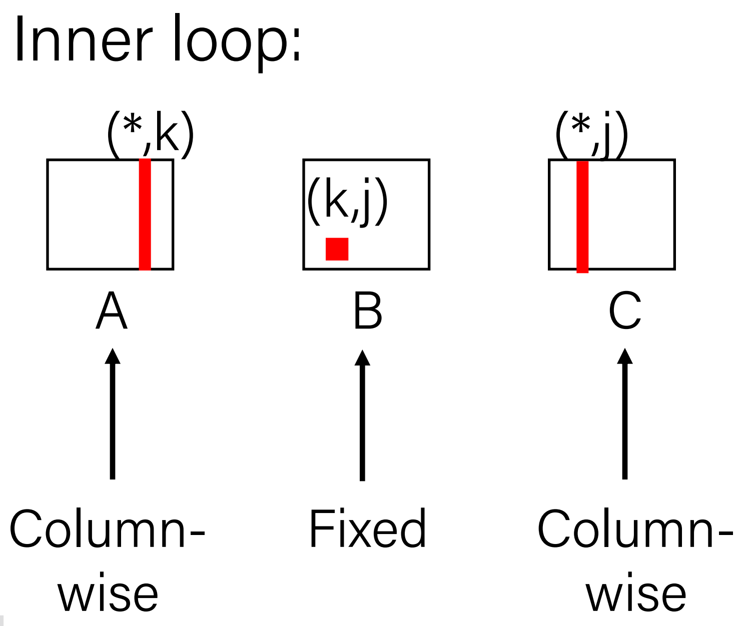

Misses per inner loop iteration:

| A | B | C |
|---|---|---|
| 1.0 | 0.0 | 1.0 |

# Matrix Multiplication (kji)

```
/* kji */
for (k=0; k<n; k++) {
  for (j=0; j<n; j++) {
    r = b[k][j];
    for (i=0; i<n; i++)
      c[i][j] += a[i][k] * r;
  }
}
```

matmult/mm.c




Misses per inner loop iteration:

| A | B | C |
|---|---|---|
| 1.0 | 0.0 | 1.0 |

# Summary of Matrix Multiplication

```
for (i=0; i<n; i++) {
  for (j=0; j<n; j++) {
   sum = 0.0;
   for (k=0; k<n; k++)
     sum += a[i][k] * b[k][j];
   c[i][j] = sum;
 }
}
```

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

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

ijk (& jik):

- 2 loads, 0 stores
- misses/iter = 1.25

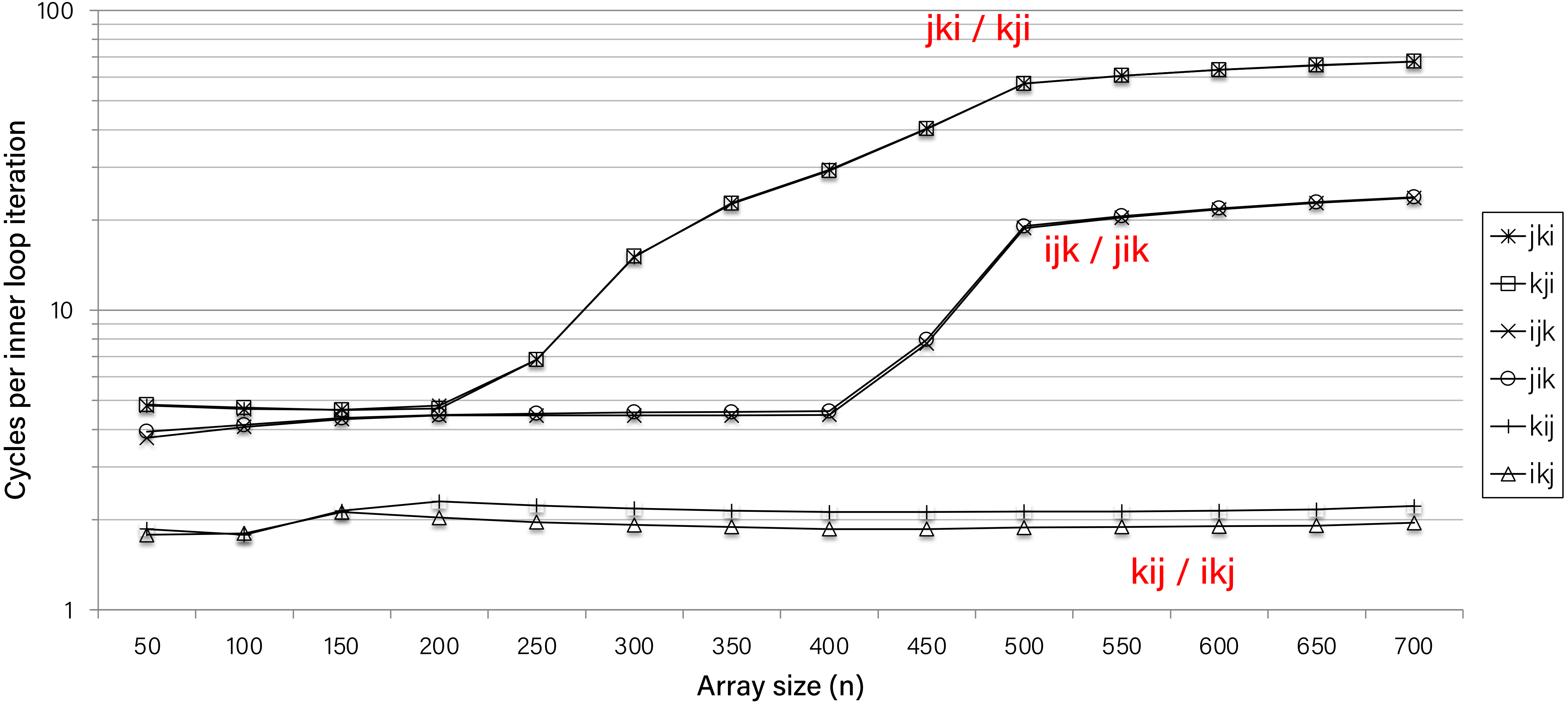
kij (& ikj):

- 2 loads, 1 store
- misses/iter = 0.5

jki (& kji):

- 2 loads, 1 store
- misses/iter = 2.0

# Core i7 Matrix Multiply Performance

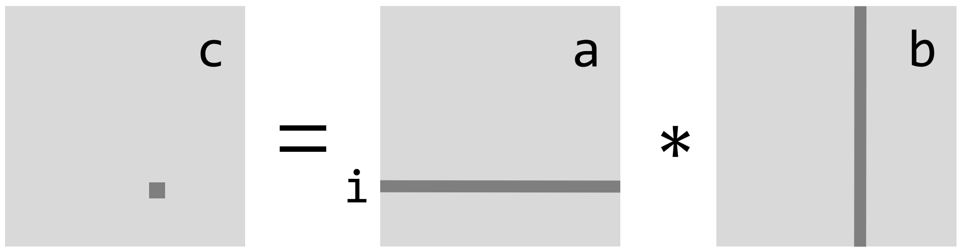


# Lecture Plan

- Writing cache-friendly code
  - Rearranging loops to improve spatial locality
  - Using blocking to improve temporal locality
- Optimization

# Example: Matrix Multiplication

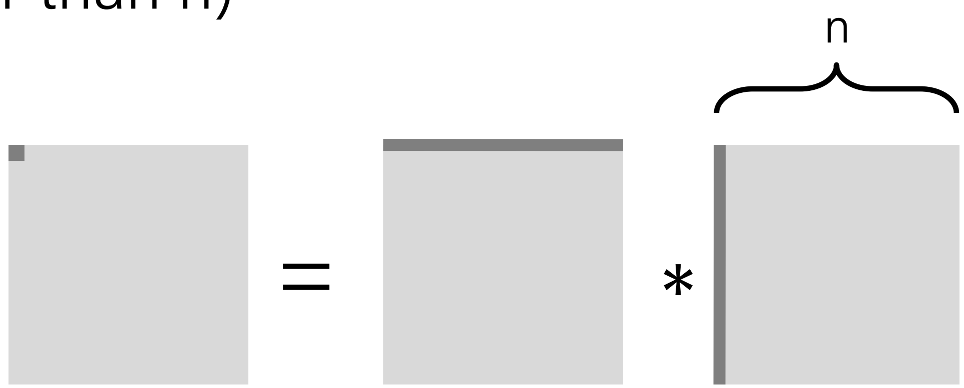
```
c = (double *) calloc(sizeof(double), n*n);

/* Multiply n x n matrices a and b  */
void mmm(double *a, double *b, double *c, int n) {
    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];
}
```



# Cache Miss Analysis

- Assume
  - Matrix elements are doubles
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)

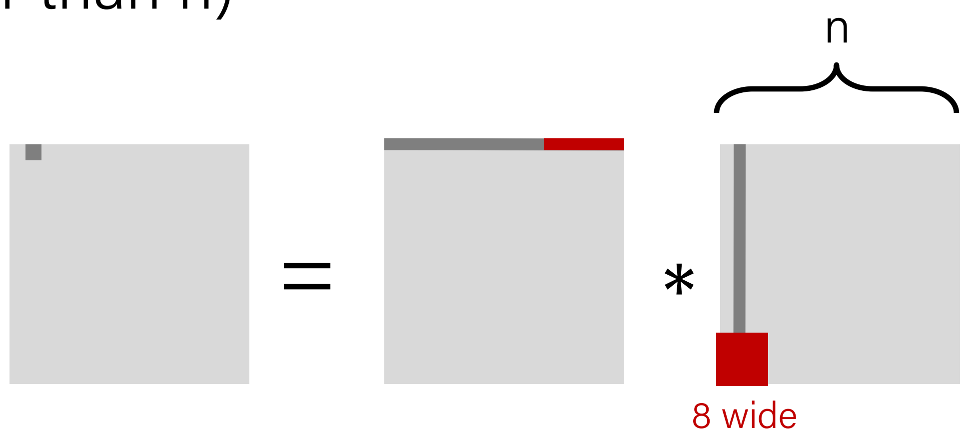
- **First iteration:**
  - n/8 + n = 9n/8 misses




  - Afterwards in cache: (schematic)

# Cache Miss Analysis

- Assume
  - Matrix elements are doubles
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)



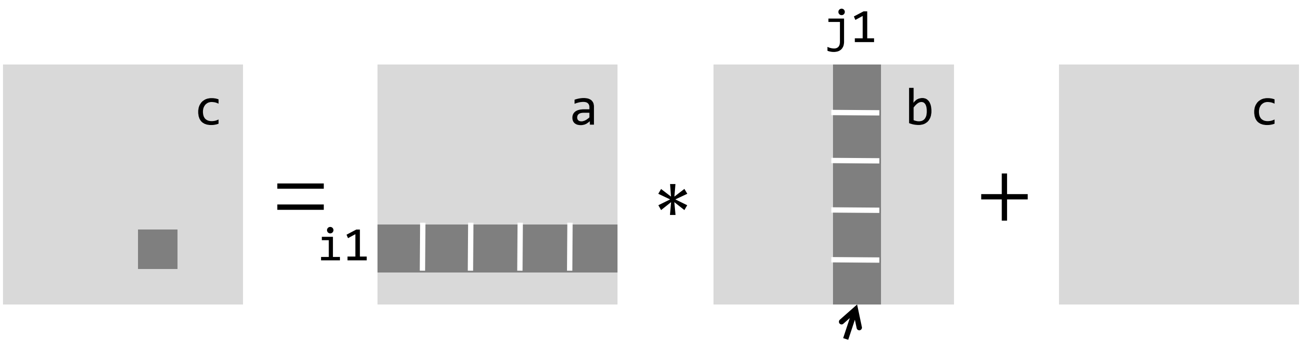

- **Second iteration:**
  - Again:
    $n/8 + n = 9n/8$ misses

- **Total misses:**
  - $9n/8 * n^2 = (9/8) * n^3$

# Blocked Matrix Multiplication

```
c = (double *) calloc(sizeof(double), n*n);

/* Multiply n x n matrices a and b  */
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    for (i = 0; i < n; i+=B)
        for (j = 0; j < n; j+=B)
             for (k = 0; k < n; k+=B)
                  /* B x B mini matrix multiplications */
                   for (i1 = i; i1 < i+B; i++)
                       for (j1 = j; j1 < j+B; j++)
                           for (k1 = k; k1 < k+B; k++)
                               c[i1*n+j1] += a[i1*n + k1]*b[k1*n + j1];
}
```

matmult/bmm.c

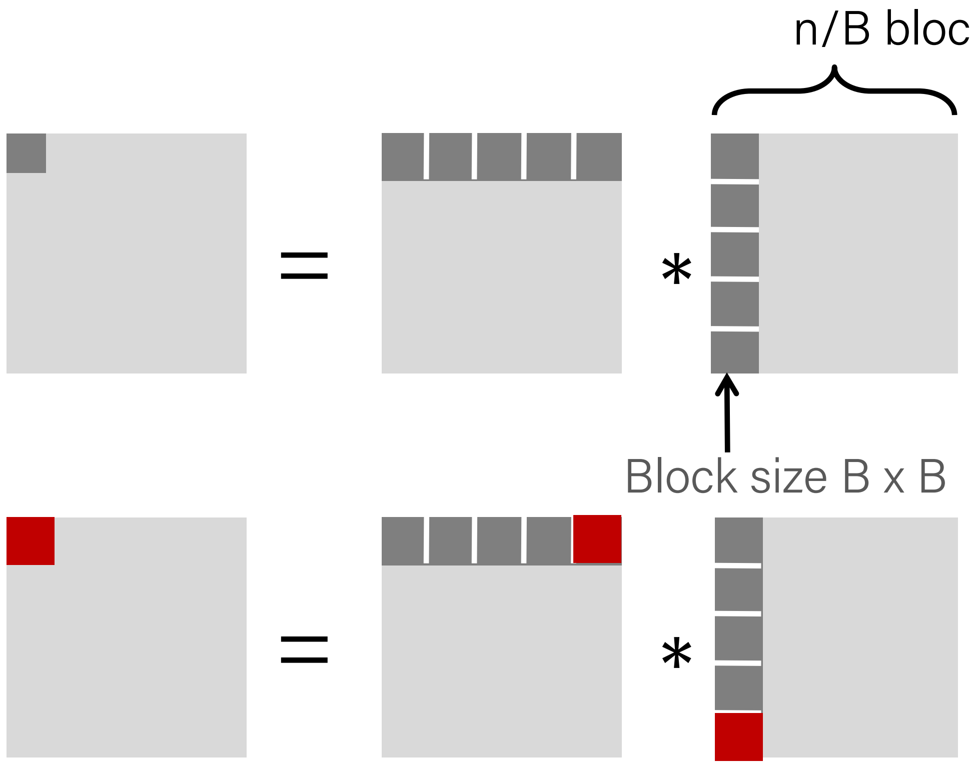



Block size B x B

# Cache Miss Analysis

- Assume
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)
  - Three blocks ■ fit into cache: $3B^2 < C$

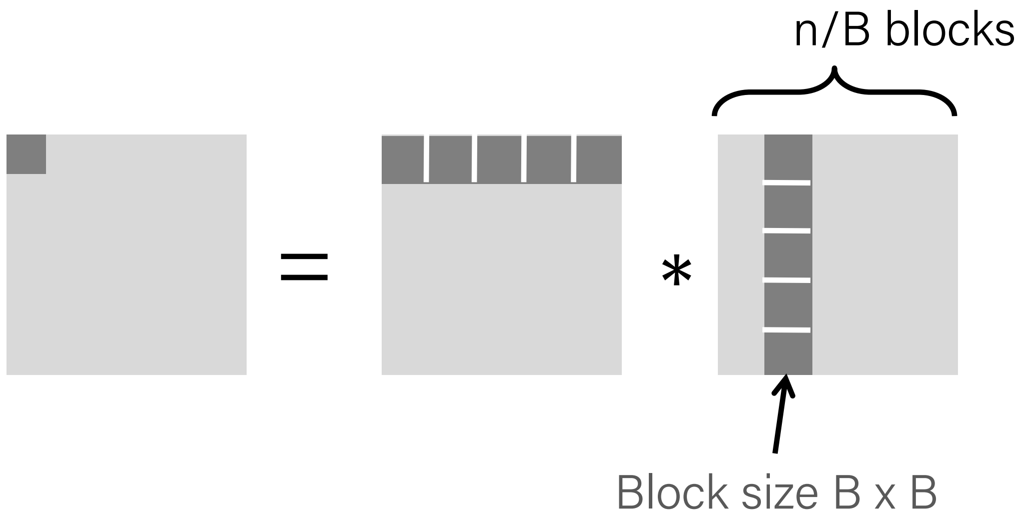
- **First (block) iteration:**
  - $B^2/8$ misses for each block
  - $2n/B * B^2/8 = nB/4$ (omitting matrix c)
  - Afterwards in cache (schematic)



# Cache Miss Analysis

- Assume:
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)
  - Three blocks fit into cache: $3B^2 < C$

- **Second (block) iteration**:
  - Same as first iteration
  - $2n/B * B^2/8 = nB/4$




- Total misses:
  - $nB/4 * (n/B)^2 = n^3/(4B)$

# Blocking Summary

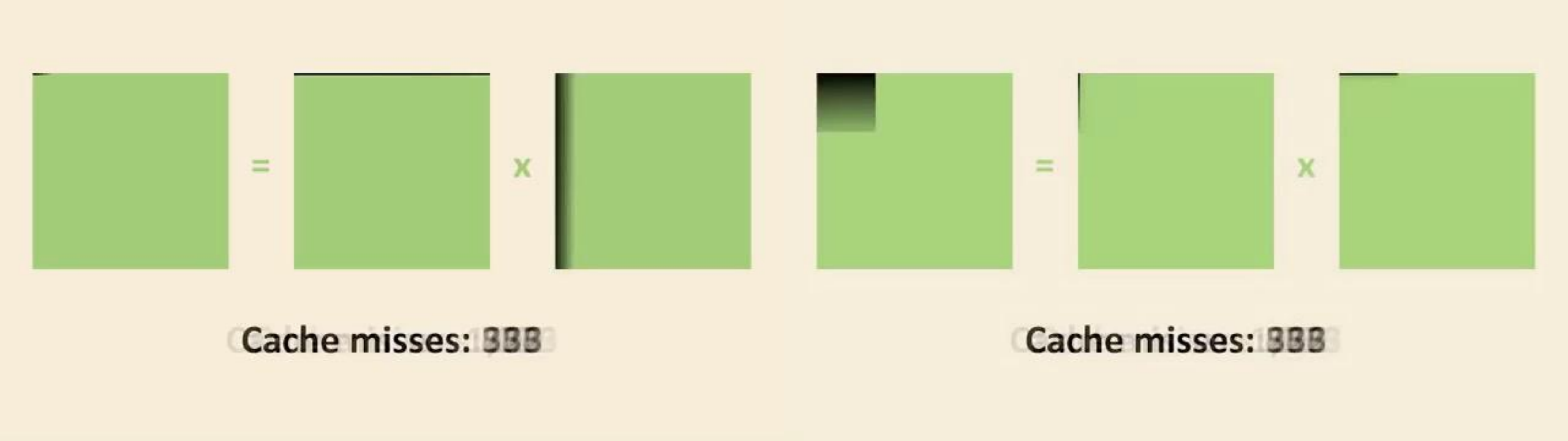
- **No blocking:** $(9/8) * n^3$
- **Blocking:** $1/(4B) * n^3$

- **Suggest largest possible block size B, but limit $3B^2$ < C!**

- **Reason for dramatic difference:**
  – Matrix multiplication has inherent temporal locality:
    - Input data: $3n^2$, computation $2n^3$
    - Every array elements used $O(n)$ times!
  – But program has to be written properly

# Naïve vs. Blocked Matrix Multiplication

Naïve Multiplication | Blocked Multiplication




≈ 1,020,000 cache misses

≈ 90,000 cache misses

Video credit: Vasily Volkov

# Recap

- Cache memories can have significant performance impact
- You can write your programs to exploit this!
  - Focus on the inner loops, where bulk of computations and memory accesses occur.
  - Try to maximize spatial locality by reading data objects with sequentially with stride 1.
  - Try to maximize temporal locality by using a data object as often as possible once it’s read from memory.

# Lecture Plan

- Writing cache-friendly codes
- Optimization
  - What is optimization?
  - GCC Optimization
  - Limitations of GCC Optimization
  - Caching revisited

# Optimization

- Optimization is the task of making your program faster or more efficient with space or time. You already know explorations of efficiency with Big-O notation!
- *Targeted, intentional* optimizations to alleviate bottlenecks can result in big gains. But it's important to only work to optimize where necessary.

# Optimization

Most of what you need to do with optimization can be summarized by:

1) If doing something seldom and only on small inputs, do whatever is simplest to code, understand, and debug
2) If doing things a lot, or on big inputs, make the primary algorithm's Big-O cost reasonable
3) **Let `gcc` do its magic from there**
4) Optimize explicitly as a last resort

# GCC Optimization

- Today, we'll be comparing two levels of optimization in the gcc compiler:
  - `gcc -O0  // mostly just literal translation of C`
  - `gcc -O2  // enable nearly all reasonable optimizations`
  - (we use `-Og`, like `-O0` but with less needless use of the stack)

- There are other custom and more aggressive levels of optimization, e.g.:
  - `-O3     //more aggressive than -O2, trade size for speed`
  - `-Os     //optimize for size`
  - `-Ofast  //disregard standards compliance (!!)`

- **Exhaustive list of gcc optimization-related flags:**
  - https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html

# Example: Matrix Multiplication

Here's a standard matrix multiply, a triply-nested for loop:

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

```
./mult          // -O0 (no optimization)
matrix multiply  25^2: cycles    0.43M
matrix multiply  50^2: cycles    3.02M
matrix multiply 100^2: cycles   24.82M
```

```
./mult_opt      // -O2 (with optimization)
matrix multiply  25^2: cycles    0.13M (opt)
matrix multiply  50^2: cycles    0.66M (opt)
matrix multiply 100^2: cycles    5.55M (opt)
```

# GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- Strength Reduction
- Code Motion
- Tail Recursion
- Loop Unrolling

# GCC Optimizations

Optimizations may target one or more of:

- Static instruction count
- Dynamic instruction count
- Cycle count / execution time

# GCC Optimizations

- **<u>Constant Folding</u>**
- Common Sub-expression Elimination
- Dead Code
- Strength Reduction
- Code Motion
- Tail Recursion
- Loop Unrolling

# Constant Folding

**Constant Folding** pre-calculates constants at compile-time where possible.

```
int seconds = 60 * 60 * 24 * n_days;
```

What is the consequence of this for you as a programmer?
What should you do differently or the same knowing that compilers can do this for you? 🤔

# Constant Folding

```
int fold(int param) {
    char arr[5];
    int a = 0x107;
    int b = a * sizeof(arr);
    int c = sqrt(2.0);
    return a * param + (a + 0x15 / c + strlen("Hello") * b - 0x37) / 4;
}
```

# Constant Folding: Before (-O0)

```
0000000000400626 <fold>:
  400626:       55                      push   %rbp
  400627:       53                      push   %rbx
  400628:       48 83 ec 08             sub    $0x8,%rsp
  40062c:       89 fd                   mov    %edi,%ebp
  40062e:       f2 0f 10 05 da 00 00    movsd  0xda(%rip),%xmm0
  400635:       00
  400636:       e8 d5 fe ff ff          callq  400510 <sqrt@plt>
  40063b:       f2 0f 2c c8             cvttsd2si %xmm0,%ecx
  40063f:       69 ed 07 01 00 00       imul   $0x107,%ebp,%ebp
  400645:       b8 15 00 00 00          mov    $0x15,%eax
  40064a:       99                      cltd
  40064b:       f7 f9                   idiv   %ecx
  40064d:       8d 98 07 01 00 00       lea    0x107(%rax),%ebx
  400653:       bf 04 07 40 00          mov    $0x400704,%edi
  400658:       e8 93 fe ff ff          callq  4004f0 <strlen@plt>
  40065d:       48 69 c0 23 05 00 00    imul   $0x523,%rax,%rax
  400664:       48 63 db                movslq %ebx,%rbx
  400667:       48 8d 44 18 c9          lea    -0x37(%rax,%rbx,1),%rax
  40066c:       48 c1 e8 02             shr    $0x2,%rax
  400670:       01 e8                   add    %ebp,%eax
  400672:       48 83 c4 08             add    $0x8,%rsp
  400676:       5b                      pop    %rbx
  400677:       5d                      pop    %rbp
  400678:       c3                      retq
```

# Constant Folding: After (-O2)

```
0000000000004004f0 <fold>:
  4004f0:        69 c7 07 01 00 00        imul   $0x107,%edi,%eax
  4004f6:        05 a5 06 00 00           add    $0x6a5,%eax
  4004fb:        c3                       retq
  4004fc:        0f 1f 40 00              nopl   0x0(%rax)
```

# GCC Optimizations

- Constant Folding
- **Common Sub-expression Elimination**
- Dead Code
- Strength Reduction
- Code Motion
- Tail Recursion
- Loop Unrolling

# Common Sub-Expression Elimination

**Common Sub-Expression Elimination** prevents the recalculation of the same thing many times by doing it once and saving the result.

```
int a = (param2 + 0x201);
int b = param1 * (param2 + 0x201) + a;
return a * (param2 + 0x201) + b * (param2 + 0x201);
```

# Common Sub-Expression Elimination

**Common Sub-Expression Elimination** prevents the recalculation of the same thing many times by doing it once and saving the result.

This optimization is done even at `-O0`!

```
int a = (param2 + 0x201);
int b = param1 * (param2 + 0x201) + a;
return a * (param2 + 0x201) + b * (param2 + 0x201);
```

```
00000000004004f0 <subexp>:
  4004f0:  81 c6 07 01 00 00      add    $0x201,%esi
  4004f6:  0f af fe               imul   %esi,%edi
  4004f9:  8d 04 77               lea    (%rdi,%rsi,2),%eax
  4004fc:  0f af c6               imul   %esi,%eax
  4004ff:  c3                     retq
```

# GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- **Dead Code**
- Strength Reduction
- Code Motion
- Tail Recursion
- Loop Unrolling

# Dead Code

**Dead code elimination** removes code that doesn't serve a purpose:

```
if (param1 < param2 && param1 > param2) {
    printf("This test can never be true!\n");
}

// Empty for loop
for (int i = 0; i < 1000; i++);

// If/else that does the same operation in both cases
if (param1 == param2) {
    param1++;
} else {
    param1++;
}

// If/else that more trickily does the same operation in both cases
if (param1 == 0) {
    return 0;
} else {
    return param1;
}
```

# Dead Code: Before (-O0)

```
0000000000004004d6 <dead_code>:
  4004d6:     b8 00 00 00 00              mov    $0x0,%eax
  4004db:     eb 03                       jmp    4004e0 <dead_code+0xa>
  4004dd:     83 c0 01                    add    $0x1,%eax
  4004e0:     3d e7 03 00 00              cmp    $0x3e7,%eax
  4004e5:     7e f6                       jle    4004dd <dead_code+0x7>
  4004e7:     39 f7                       cmp    %esi,%edi
  4004e9:     75 05                       jne    4004f0 <dead_code+0x1a>
  4004eb:     8d 47 01                    lea    0x1(%rdi),%eax
  4004ee:     eb 03                       jmp    4004f3 <dead_code+0x1d>
  4004f0:     8d 47 01                    lea    0x1(%rdi),%eax
  4004f3:     f3 c3                       repz retq
```

# Dead Code: After (-O2)

```
0000000004004f0 <dead_code>:
  4004f0: 8d 47 01              lea    0x1(%rdi),%eax
  4004f3: c3                    retq
  4004f4: 66 2e 0f 1f 84 00 00  nopw   %cs:0x0(%rax,%rax,1)
  4004fb: 00 00 00
  4004fe: 66 90                 xchg   %ax,%ax
```

# GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- **Strength Reduction**
- Code Motion
- Tail Recursion
- Loop Unrolling

# Strength Reduction

**Strength reduction** changes divide to multiply, multiply to add/shift, and mod to AND to avoid using instructions that cost many cycles (multiply and divide).

```
int a = param2 * 32;
int b = a * 7;
int c = b / 3;
int d = param2 % 2;

for (int i = 0; i <= param2; i++) {
    c += param1[i] + 0x107 * i;
}
return c + d;
```

# Strength Reduction: After (-O3)

```
unsigned udiv19(unsigned arg) {
return arg / 19;
}
```

```
udiv19(unsigned int):
        mov   eax, edi
        mov   edx, 2938661835
        imul  rax, rdx
        shr   rax, 32
        sub   edi, eax
        shr   edi
        add   eax, edi
        shr   eax, 4
        ret
```

https://godbolt.org/z/Wq8ra3

What really happens here?

$$a \cdot \frac{1}{19} \approx \frac{a \cdot \frac{2938661835}{2^{32}} + \frac{a - a \cdot \frac{2938661835}{2^{32}}}{2^{1}}}{2^{4}}$$

$$a \cdot \frac{1}{19} \approx \left(a \cdot 2938661835 \cdot 2^{-32} + \left(a - a \cdot 2938661835 \cdot 2^{-32}\right) \cdot 2^{-1}\right) \cdot 2^{-4}$$

$$a \cdot \frac{1}{19} \approx a \cdot \frac{7233629131}{137438953472}$$

# GCC Optimizations

- Constant Folding
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# Code Motion

**Code motion** moves code outside of a loop if possible.

```
for (int i = 0; i < n; i++) {
  sum += arr[i] + foo * (bar + 3);
}
```

Common subexpression elimination deals with expressions that appear multiple times in the code.  Here, the expression appears once, but is calculated each loop iteration.

# GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- Strength Reduction
- Code Motion
- **Tail Recursion**
- Loop Unrolling

# Tail Recursion

**Tail recursion** is an example of where GCC can identify recursive patterns that can be more efficiently implemented iteratively.

```
long factorial(int n) {
  if (n <= 1) {
      return 1;
  }
  else return n * factorial(n - 1);
}
```

# Tail Recursion

**Tail recursion:** When a recursive call is made as the final action of a recursive function.

```
long factorial(int n) {
  if (n <= 1) {
      return 1;
  }
  else return n * factorial(n - 1);
}
```

# Tail-recursive factorial

```
// returns n!, or 1 * 2 * 3 * 4 * ... * n.
long factorial(int n, long accum = 1) {
  if (n <= 1) {
      return accum;
  }
  else return factorial(n - 1, accum * n);
}
```

- Tail recursive solutions often end up passing partial computations as parameters that would otherwise be computed after the recursive call

# Non-recursive factorial

```
// returns n!, or 1 * 2 * 3 * 4 * ... * n.
long factorial(int n) {
  long accum = 1;
  for (int i = 1; i <= n; i++) {
      accum *= i;
  }
  return accum;
}
```

- Sometimes looking at the non-recursive version of a function can help you find the tail recursive solution
  - Often looks more like the non-recursive version, with a variable or parameter keeping track of partial computations
  - Loop is replaced by a recursive call

# GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- Strength Reduction
- Code Motion
- Tail Recursion
- **Loop Unrolling**

# Loop Unrolling

**Loop Unrolling:** Do **n** loop iterations' worth of work per actual loop iteration, so we save ourselves from doing the loop overhead (test and jump) every time, and instead incur overhead only every n-th time.

```
for (int i = 0; i <= n - 4; i += 4) {
    sum += arr[i];
    sum += arr[i + 1];
    sum += arr[i + 2];
    sum += arr[i + 3];
} // after the loop handle any leftovers
```

# Limitations of GCC Optimization

GCC can't optimize everything! You ultimately may know more than GCC does.

```
int char_sum(char *s) {
    int sum = 0;
    for (size_t i = 0; i < strlen(s); i++) {
        sum += s[i];
    }
    return sum;
}
```

What is the bottleneck? **`strlen` called for every character**
What can GCC do? **code motion – pull `strlen` out of loop**

# Limitations of GCC Optimization

GCC can’t optimize everything! You ultimately may know more than GCC does.

```
void lower1(char *s) {
    for (size_t i = 0; i < strlen(s); i++) {
        if (s[i] >= 'A' && s[i] <= 'Z') {
            s[i] -= ('A' - 'a');
        }
    }
}
```

What is the bottleneck?
What can GCC do?

**`strlen` called for every character**

**nothing! `s` is changing, so GCC doesn’t know if length is constant across iterations. But <u>we</u> know its length doesn’t change.**

# Optimizing Your Code

- Explore various optimizations you can make to your code to reduce instruction count and runtime.
  - More efficient Big-O for your algorithms
  - Explore other ways to reduce instruction count
    - Look for hotspots using `callgrind`
    - Optimize using `–O2`
    - And more...

# Compiler Optimizations

*Why not always just compile with* `-O2`*?*

- Difficult to debug optimized executables – only optimize when complete
- Optimizations may not *always* improve your program. The compiler does its best, but may not work, or slow things down, etc. Experiment to see what works best!

*Why should we bother saving repeated calculations in variables if the compiler has common subexpression elimination?*

- The compiler may not always be able to optimize every instance. Plus, it can help reduce redundancy!

# Recap

- Writing cache-friendly code
- Optimization

**Next time:** *Linking*

# Course Evaluations

- I hope you can take the time to fill out the end-semester COMP201 course evaluation.
- I sincerely appreciate any feedback you have about the course and read every piece of feedback we receive.
- I am always looking for ways to improve!