The Alchemist by Mattheus von Helmont

COMP201

Computer Systems & Programming

Lecture #24 – Optimization

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Fall 2021

Good news, everyone!

- Assignment 6 will be out tomorrow!
  - Don’t miss Efehan’s Zoom session (time and date will be announced soon).

Image: Professor Farnsworth (Futurama)

Recap

- Cache memory organization and operation
- Memory mountain

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

```c
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

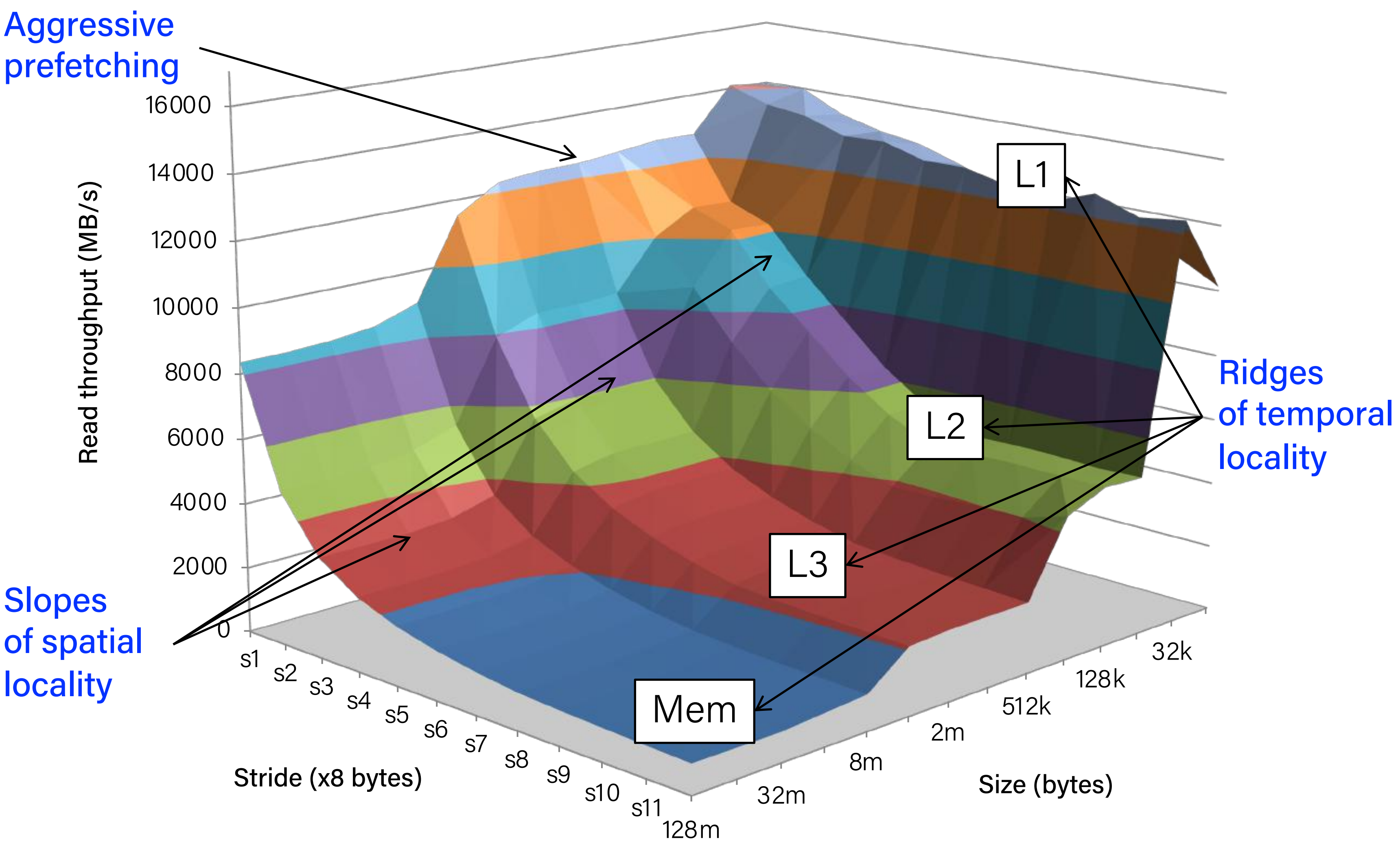
Call `test()` with many combinations of `elems` and `stride`.

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

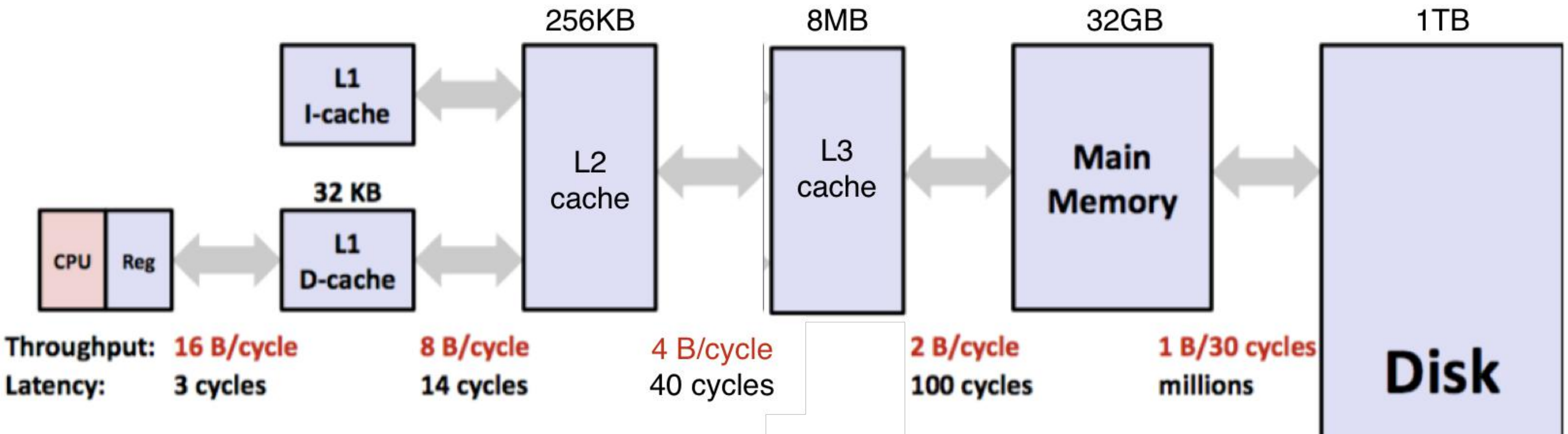
Disclaimer: Slides for this lecture were borrowed from
—Nick Troccoli's Stanford CS107 class
—Ashley Taylor's Stanford CS106B class

Plan for Today

- Writing cache-friendly code
- Optimization

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.



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

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)

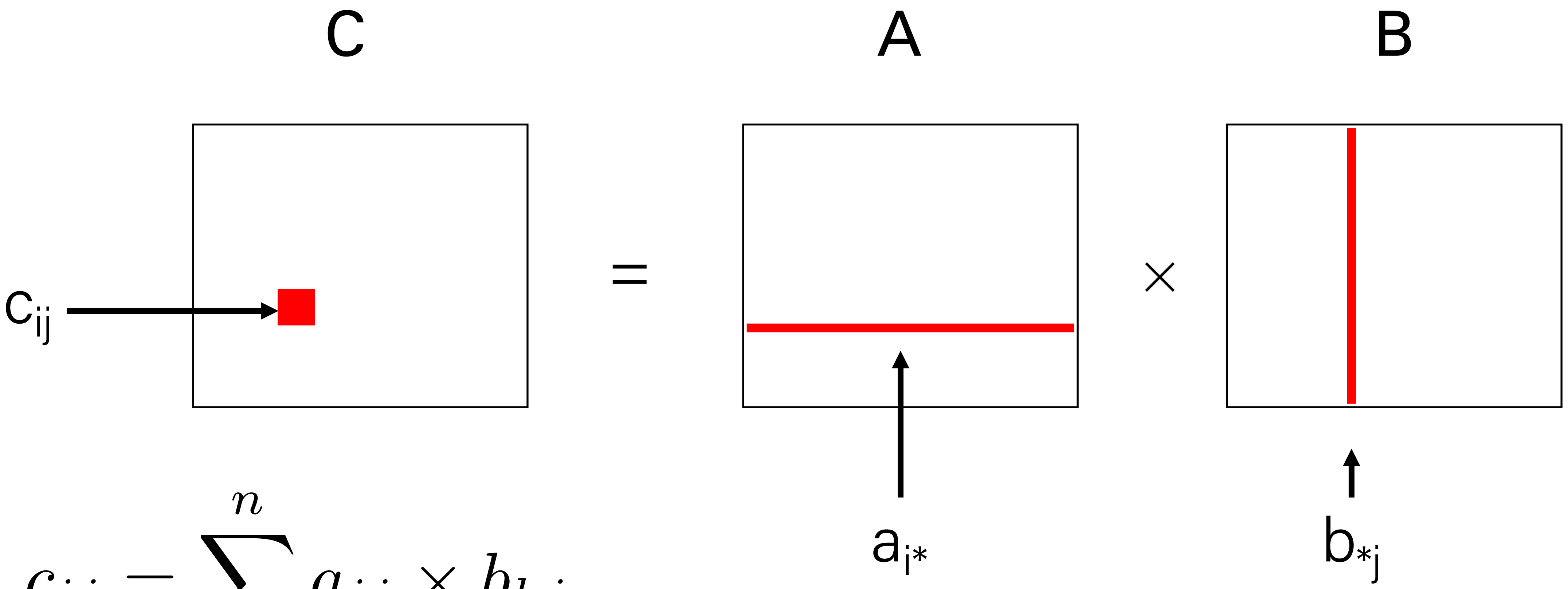
Key idea: Our qualitative notion of locality is quantified through our understanding of cache memories

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

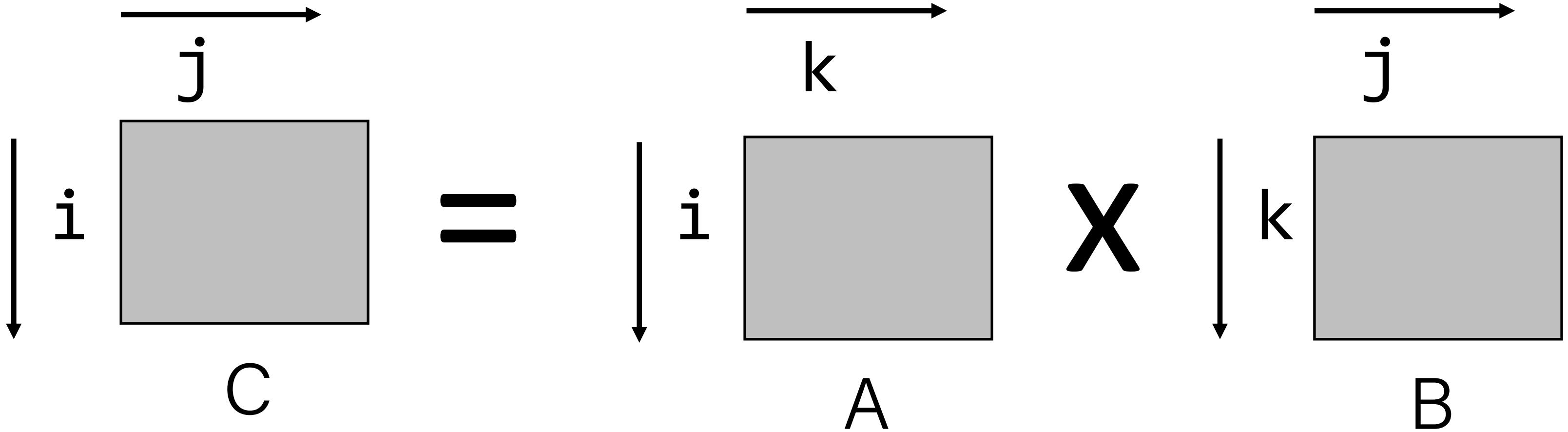
Variable `sum` held in register

```
/* 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;
  }
}
```

`matmult/mm.c`

Miss Rate Analysis for Matrix Multiply

- Assume
  - Block size = 32B (big enough for four doubles)
  - 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!

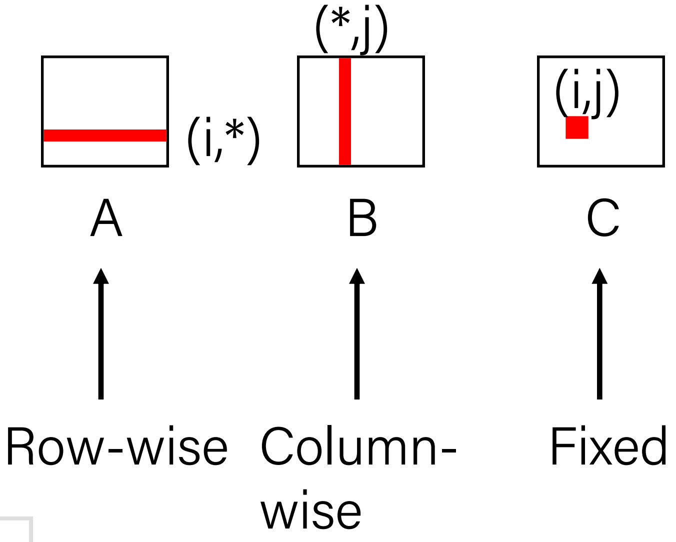
    miss rate = 1 (i.e. 100%)

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:

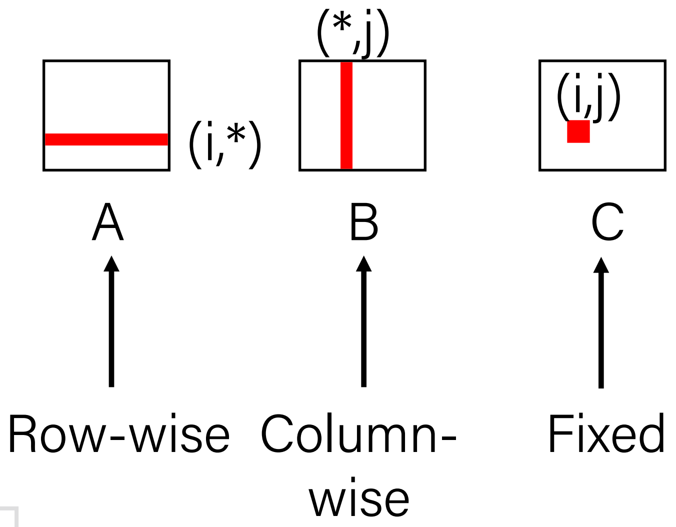
A	B	C
0.25	1.0	0.0

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:

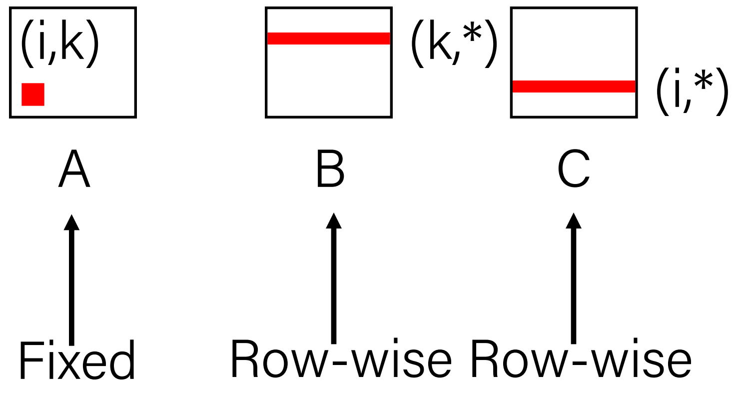
A	B	C
0.25	1.0	0.0

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:

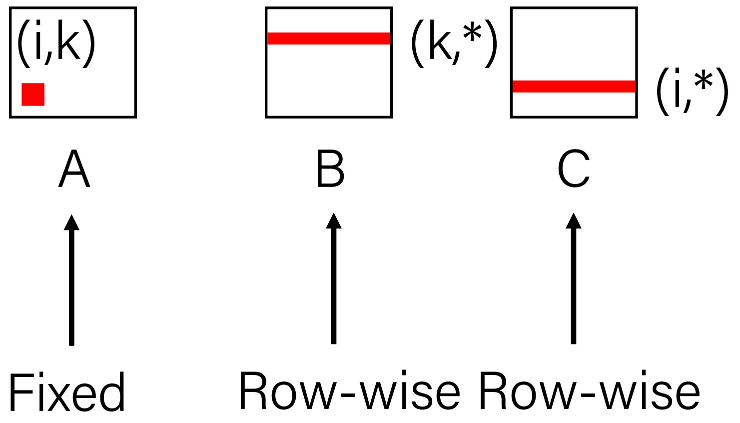
A	B	C
0.0	0.25	0.25

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];
  }
}
```

`matmult/mm.c`

Inner loop:



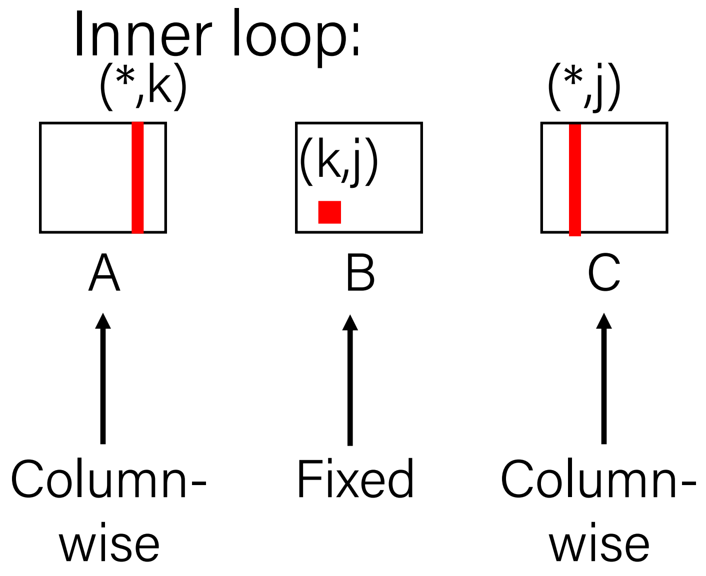
Misses per inner loop iteration:

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:

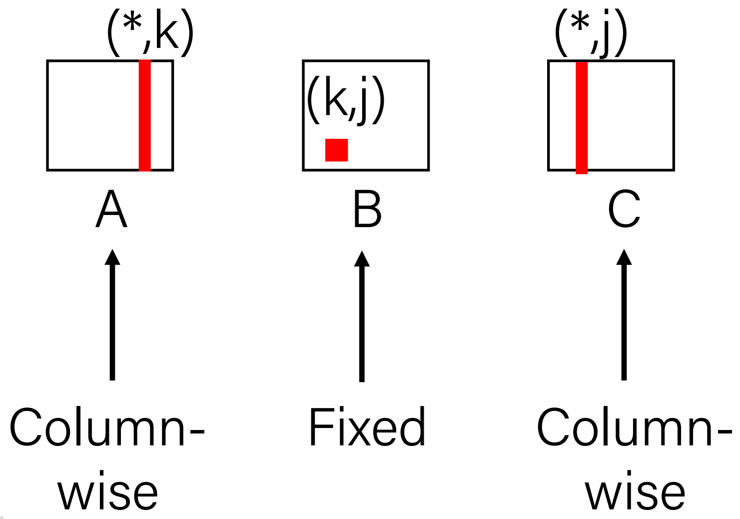
A	B	C
1.0	0.0	1.0

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`

Inner loop:



<u>Misses per inner loop iteration:</u>

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];
 }
}
```

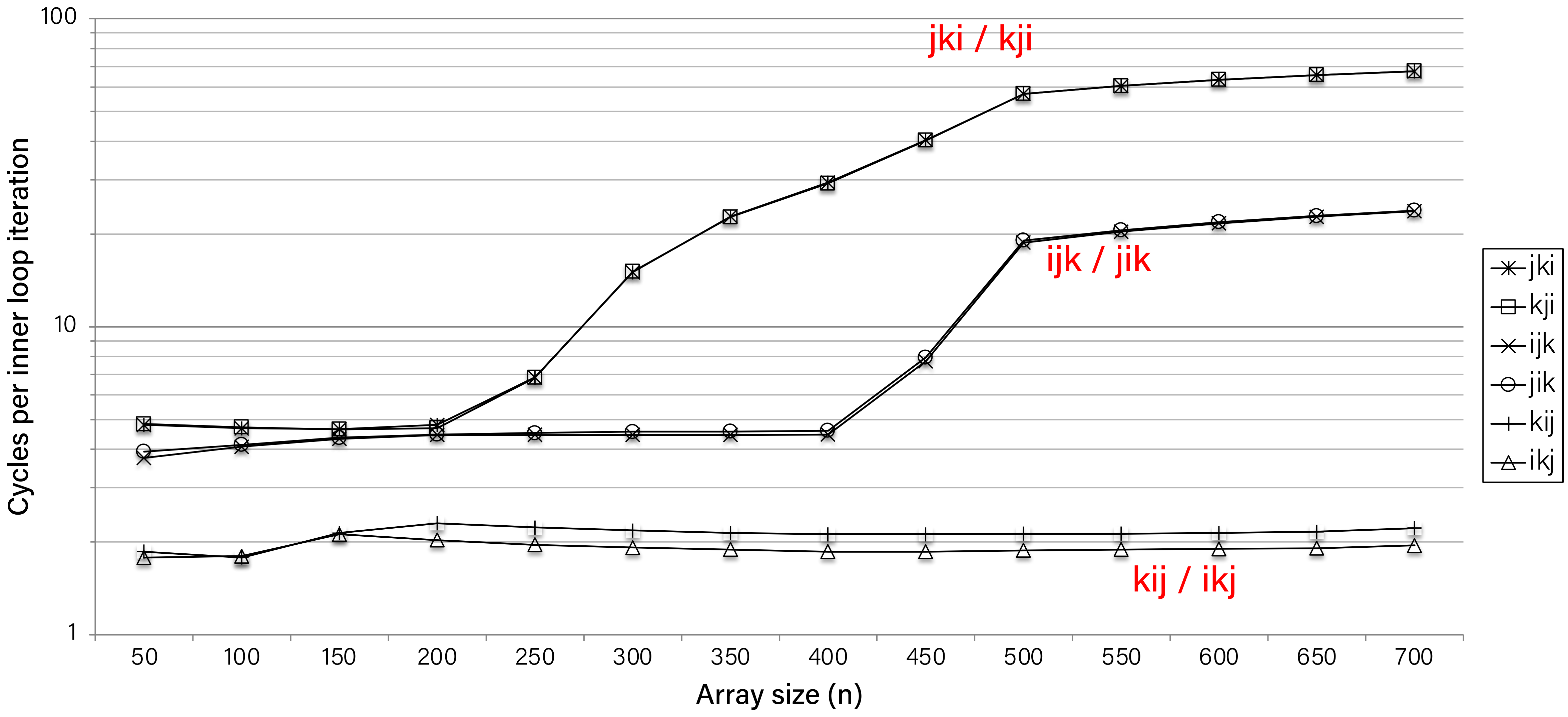
```
for (j=0; j<n; j++) {
 for (k=0; k<n; k++) {
   r = b[k][j];
   for (i=0; i<n; i++)
    c[i][j] += a[i][k] * r;
 }
}
```

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

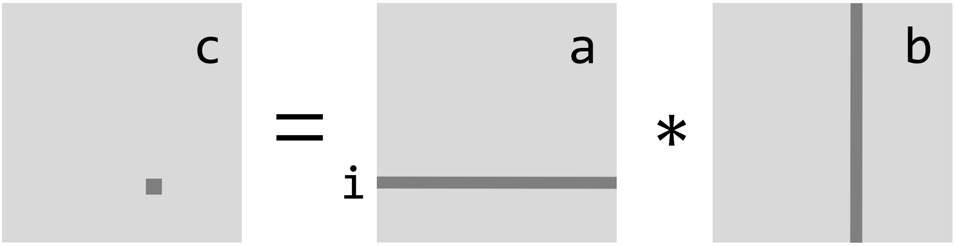


Lecture Plan

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

Example: Matrix Multiplication

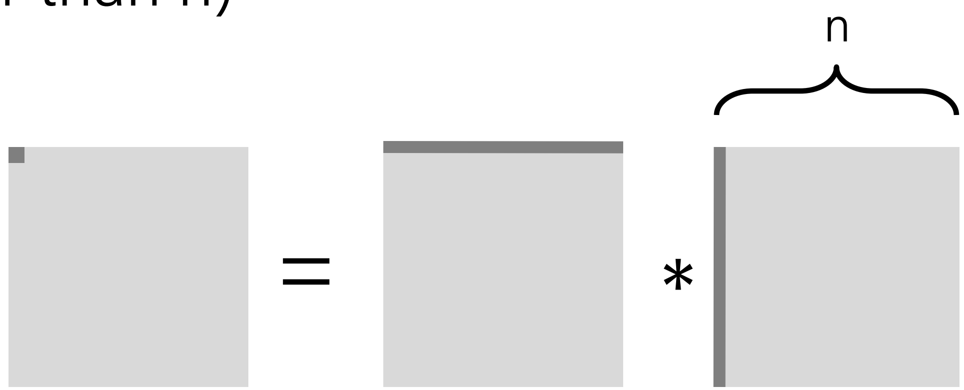
```
c = (double *) calloc(sizeof(double), n*n);

/* 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];
}
```



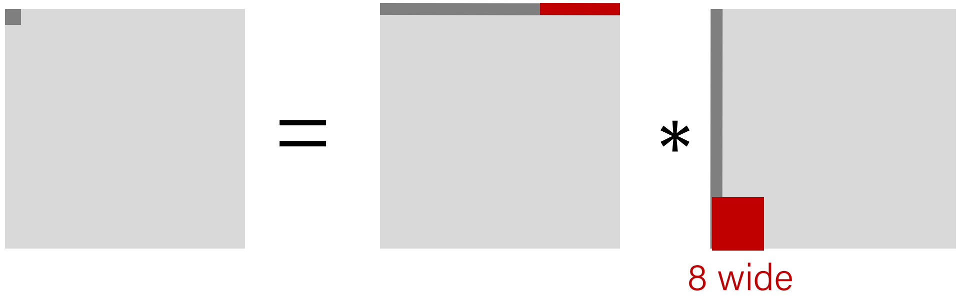
Cache Miss Analysis

- 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

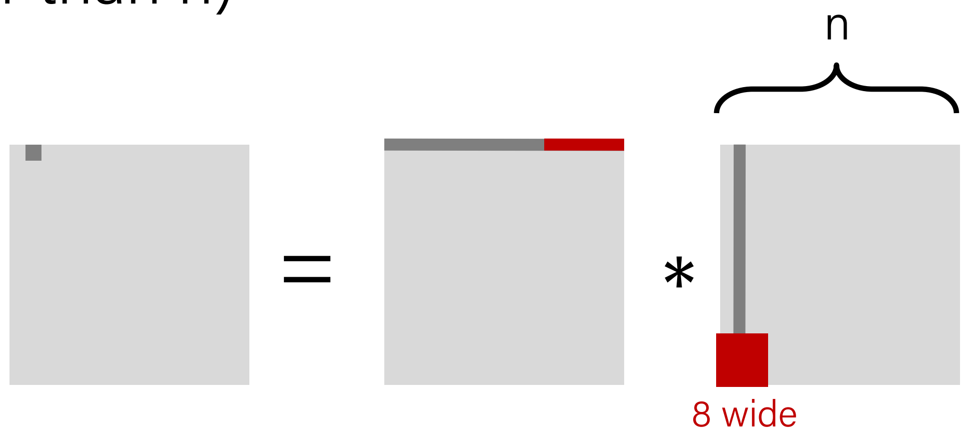


  - Afterwards in cache:
    (schematic)



Cache Miss Analysis

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



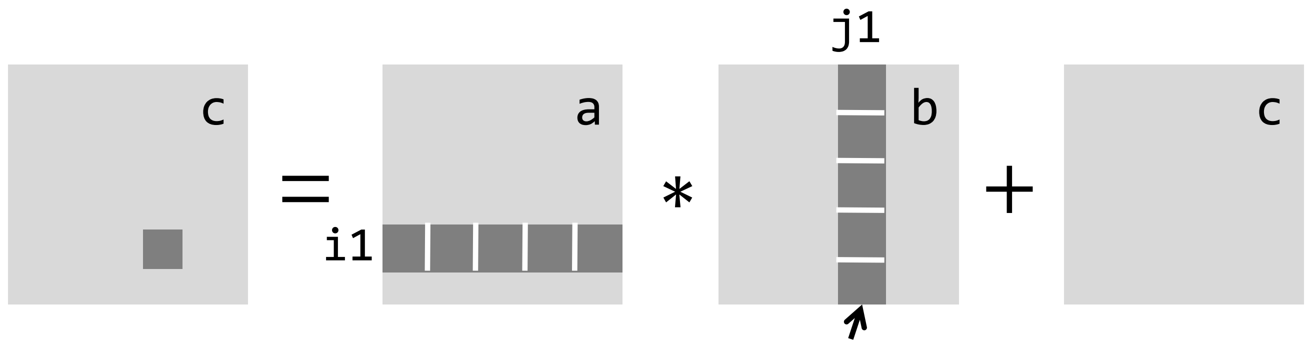
- **Second iteration:**
  - Again:
    $n/8 + n = 9n/8$ misses

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

Blocked Matrix Multiplication

```c
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

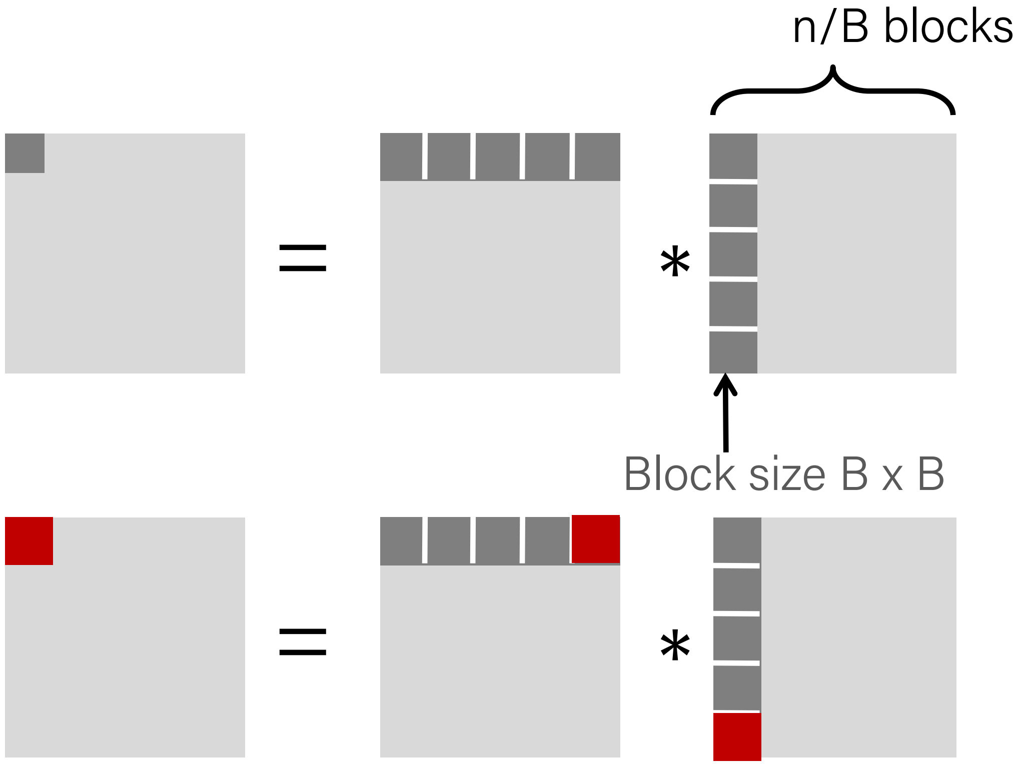


Block size B x B

Cache Miss Analysis

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

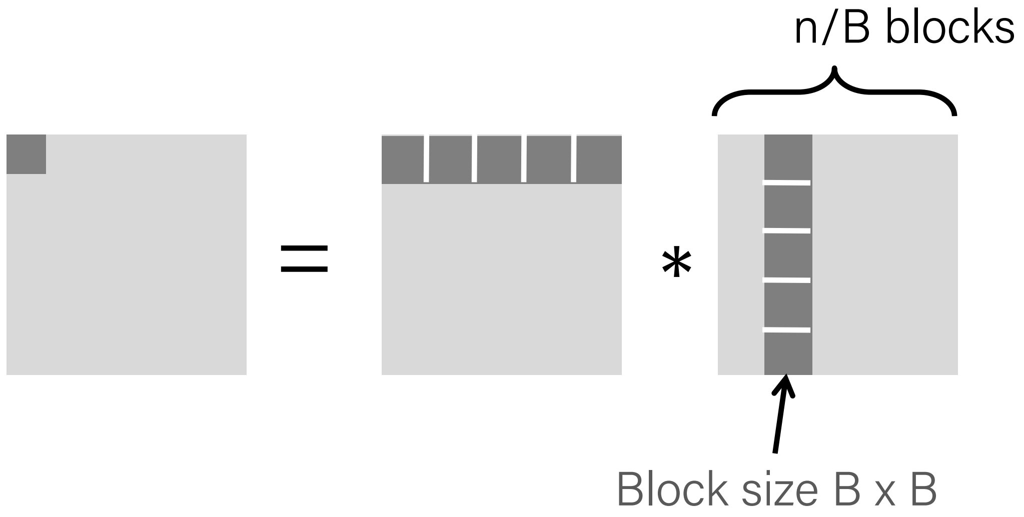
- **First (block) iteration:**
  - $B^2/8$ misses for each block
  - $2n/B * B^2/8 = nB/4$ (omitting matrix c)
  - Afterwards in cache (schematic)



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 $3B^2 < C$!**

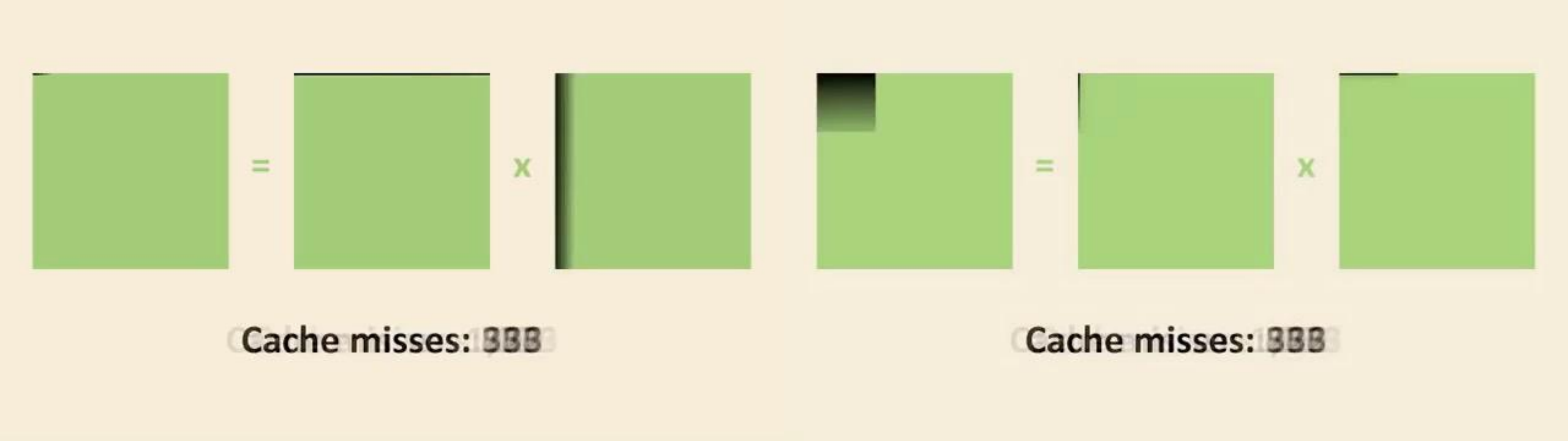
- **Reason for dramatic difference:**
  – Matrix multiplication has inherent temporal locality:
    - Input data: $3n^2$, computation $2n^3$
    - Every array elements used O(n) times!

  – 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 thing 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
- The Force

GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
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- Strength Reduction
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- Tail Recursion
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GCC Optimizations

Optimizations may target one or more of:

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

GCC Optimizations

- **Constant Folding**
- 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)

```
00000000004004f0 <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
- **<u>Dead Code</u>**
- 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)

```
00000000004004f0 <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
- **<u>Strength Reduction</u>**
- 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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- **<u>Code Motion</u>**
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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
- <u>**Tail Recursion**</u>
- 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?

`strlen` called for every character

What can GCC do?

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...

Optimizing Your Code

- Explore various optimizations you can make to your code to reduce instruction count and runtime.
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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: Debugging and design