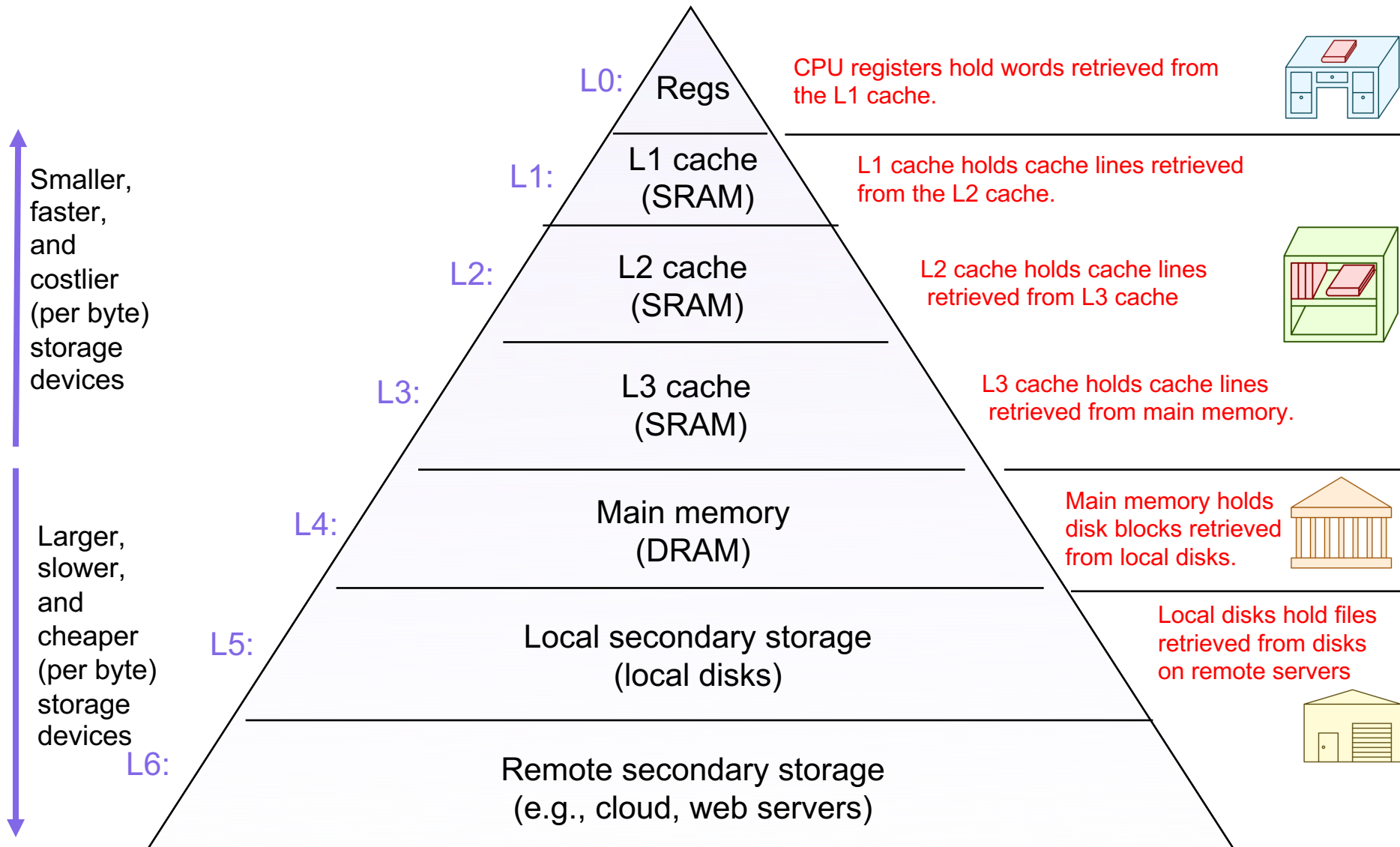


Lecture 14: Optimization with Caches

CS 105

Spring 2023

Review: Memory Hierarchy

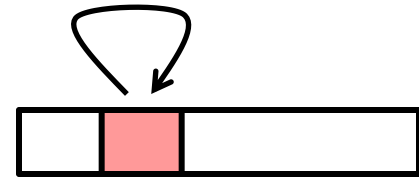


Review: Principle of Locality

Programs tend to use data and instructions with addresses near or equal to those they have used recently

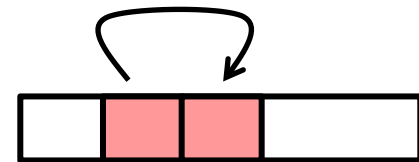
- ▶ **Temporal locality:**

- ▶ Recently referenced items are likely to be referenced again in the near future



- ▶ **Spatial locality:**

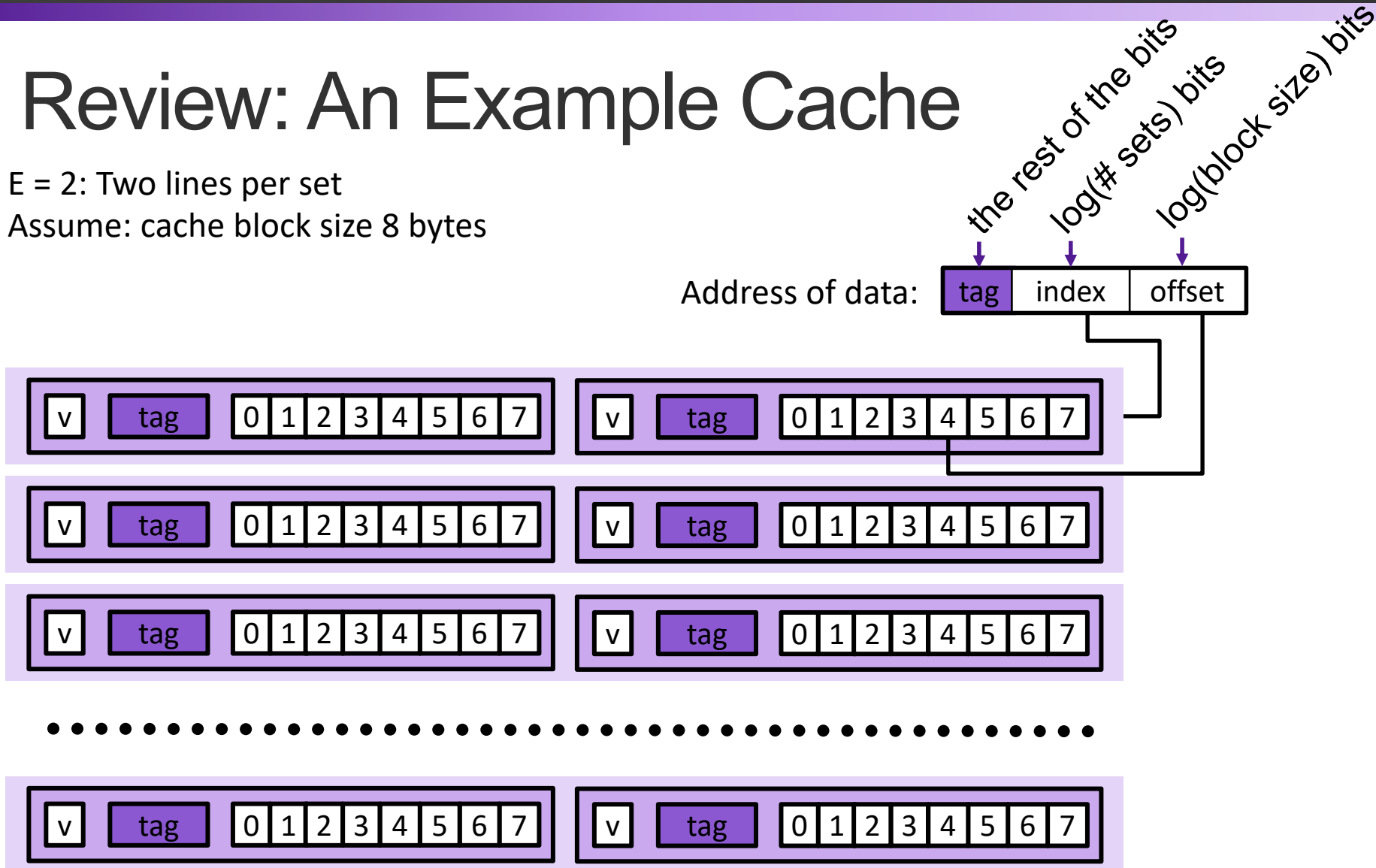
- ▶ Items with nearby addresses tend to be referenced close together in time



Review: An Example Cache

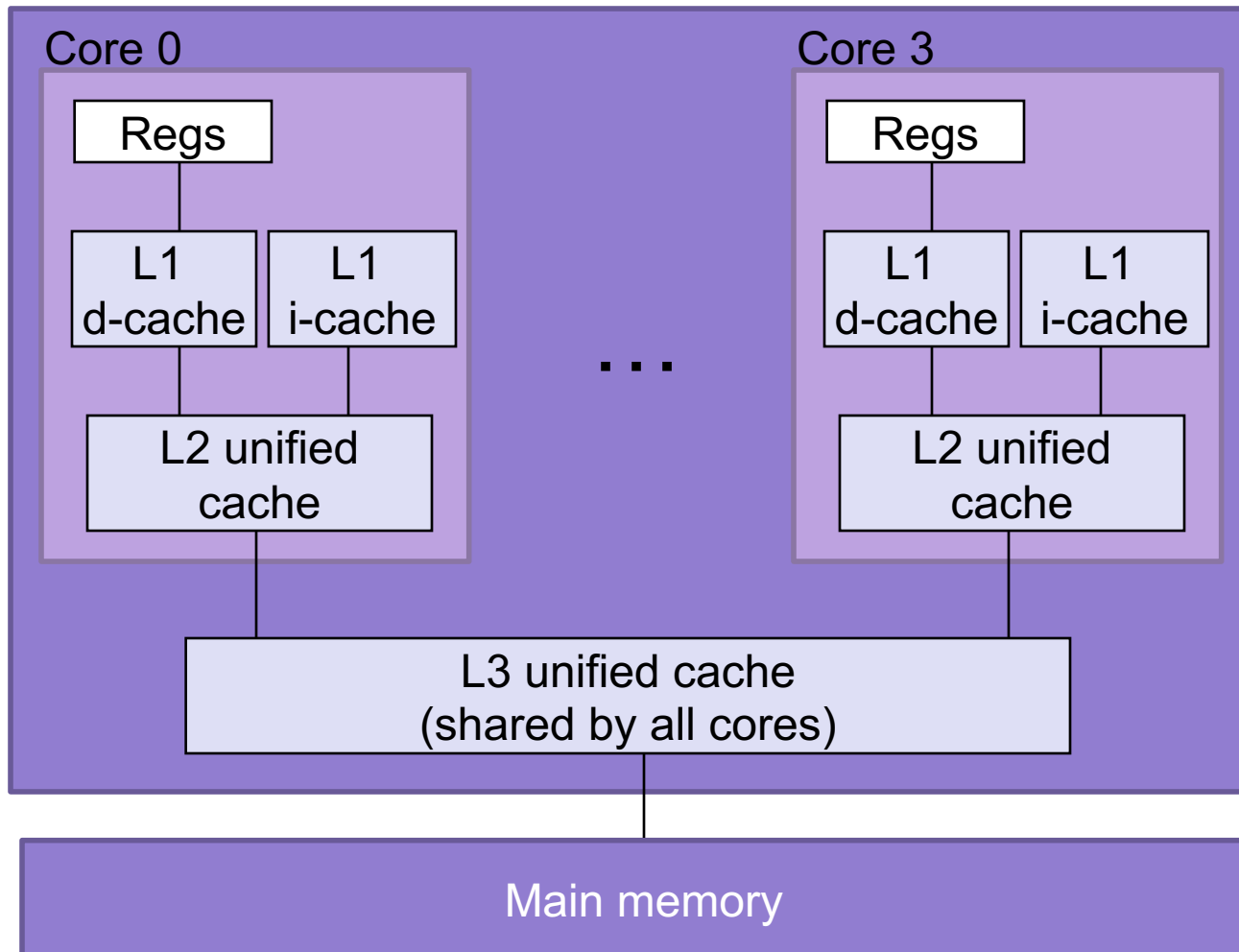
E = 2: Two lines per set

Assume: cache block size 8 bytes



Typical Intel Core i7 Hierarchy

Processor package



L1 i-cache and d-cache:
32 KB, 8-way,
Access: 4 cycles

L2 unified cache:
256 KB, 8-way,
Access: 10 cycles

L3 unified cache:
8 MB, 16-way,
Access: 40-75 cycles

Block size: 64 bytes for
all caches.

Cache Performance Metrics

- Miss Rate
 - Fraction of memory references not found in cache (misses / accesses)
 - Typically 3-10% for L1
 - can be quite small (e.g., < 1%) for L2, depending on size, etc.
- Hit Time
 - Time to deliver a line in the cache to the processor
 - includes time to determine whether the line is in the cache
 - Typically 4 clock cycles for L1, 10 clock cycles for L2
- Miss Penalty
 - Additional time required because of a miss
 - typically 50-200 cycles for main memory (Trend: increasing!)

Memory Performance with Caching

- **Read throughput (aka 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.

Memory Mountain Test Function

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)

```
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;

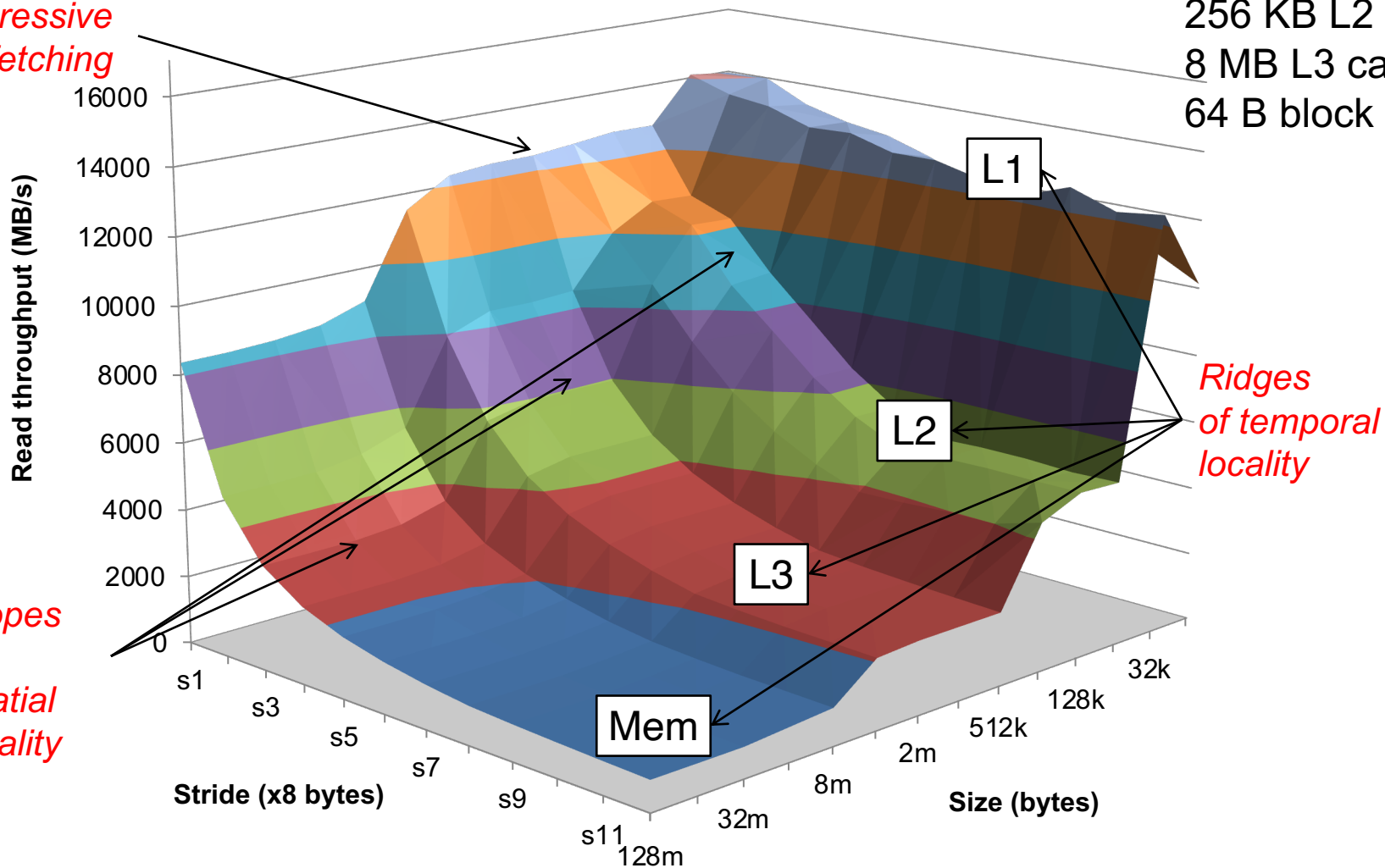
    /* Combine 4 elements at a time */
    for (i = 0; i < limit; i += sx4) {
        acc0 = acc0 + data[i];
        acc1 = acc1 + data[i+stride];
        acc2 = acc2 + data[i+sx2];
        acc3 = acc3 + data[i+sx3];
    }

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


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

Aggressive prefetching



Exercise 1: Locality

- Which of the following functions is better in terms of locality with respect to array src?

```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
    int i,j;
    for (i = 0; i < 2048; i++)
        for (j = 0; j < 2048; j++)
            dst[i][j] = src[i][j];
}
```

```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
    int i,j;
    for (j = 0; j < 2048; j++)
        for (i = 0; i < 2048; i++)
            dst[i][j] = src[i][j];
}
```

Exercise 1: Locality

- Which of the following functions is better in terms of locality with respect to array src?

```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
    int i,j;
    for (i = 0; i < 2048; i++)
        for (j = 0; j < 2048; j++)
            dst[i][j] = src[i][j];
}
```

4.3ms

```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
    int i,j;
    for (j = 0; j < 2048; j++)
        for (i = 0; i < 2048; i++)
            dst[i][j] = src[i][j];
}
```

81.8ms

2.0 GHz Intel Core i7 Haswell

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**)

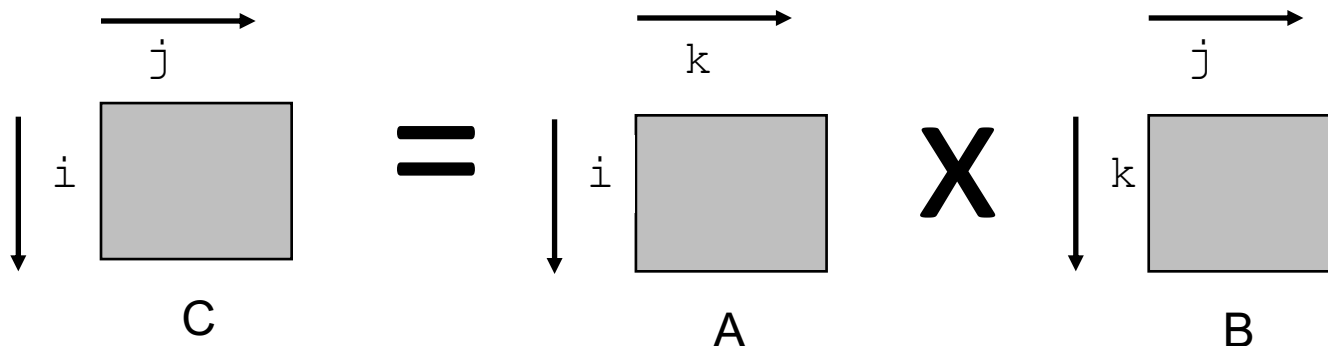
Example: Matrix Multiplication

- Multiply $N \times N$ matrices
- Matrix elements are doubles (8 bytes)
- $O(N^3)$ total operations
- N reads per source element
- N values summed per destination

```
/* 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;
    }
}
```

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)

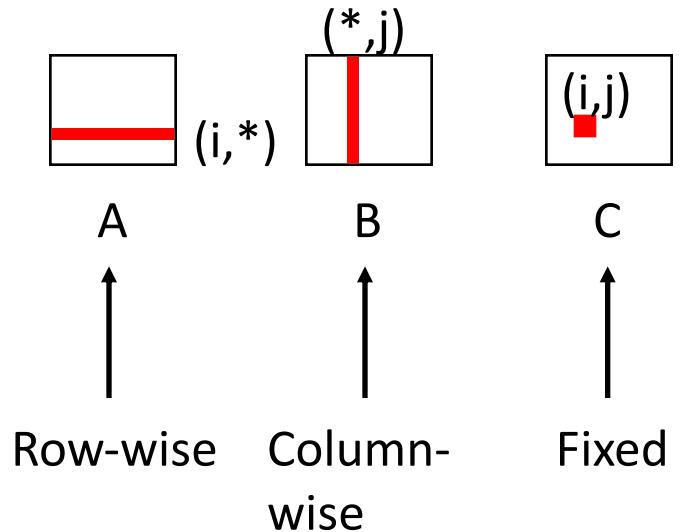
- C arrays allocated in row-major order
 - each row in contiguous memory locations
- Stepping through columns in one row:
 - accesses successive elements
 - if data block size (B) $>$ $\text{sizeof}(a_{ij})$ bytes, exploit spatial locality
 - miss rate = $\text{sizeof}(a_{ij}) / B$
- Stepping through rows in one column:
 - accesses distant elements
 - no spatial locality!
 - miss rate = 1 (i.e. 100%)

Matrix Multiplication (ijk)

(jik is similar)

```
/* 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;
  }
}
```

Inner loop:



Misses per inner loop iteration:

<u>A</u>	<u>B</u>	<u>C</u>
0.25	1.0	0.0

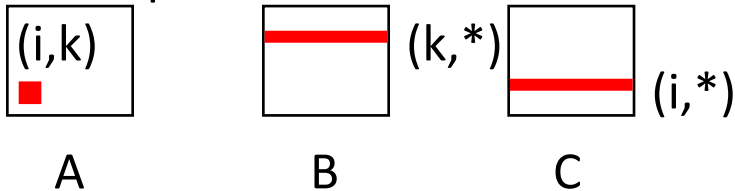
2 loads, no stores
per inner loop iteration

Exercise 2: Matrix Multiplication

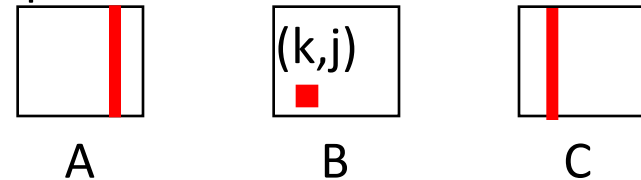
```
/* kij */  
for (k=0; k<n; k++) {  
  for (i=0; i<n; i++) {  
    r = a[i][k];  
    for (j=0; j<n; j++)  
      c[i][j] += r * b[k][j];  
  }  
}
```

```
/* 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;  
  }  
}
```

Inner loop:



Inner loop: (*,k)



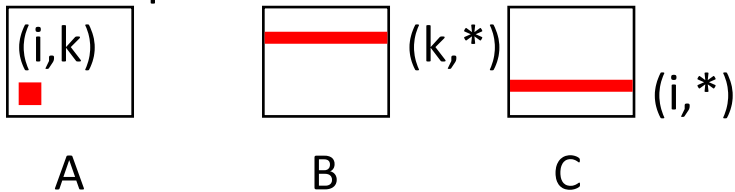
Exercise 2: Matrix Multiplication

```

/* 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];
  }
}

```

Inner loop:



2 loads, 1 store per inner loop iteration

Misses per inner loop iteration:

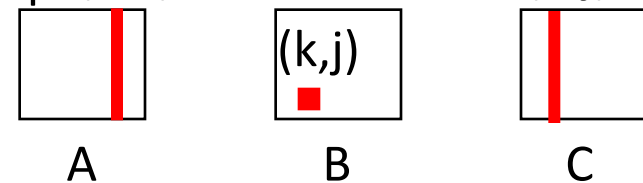
<u>A</u>	<u>B</u>	<u>C</u>
0.0	0.25	0.25

```

/* 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;
  }
}

```

Inner loop: (*,k)



2 loads, 1 store per inner loop iteration

Misses per inner loop iteration:

<u>A</u>	<u>B</u>	<u>C</u>
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):

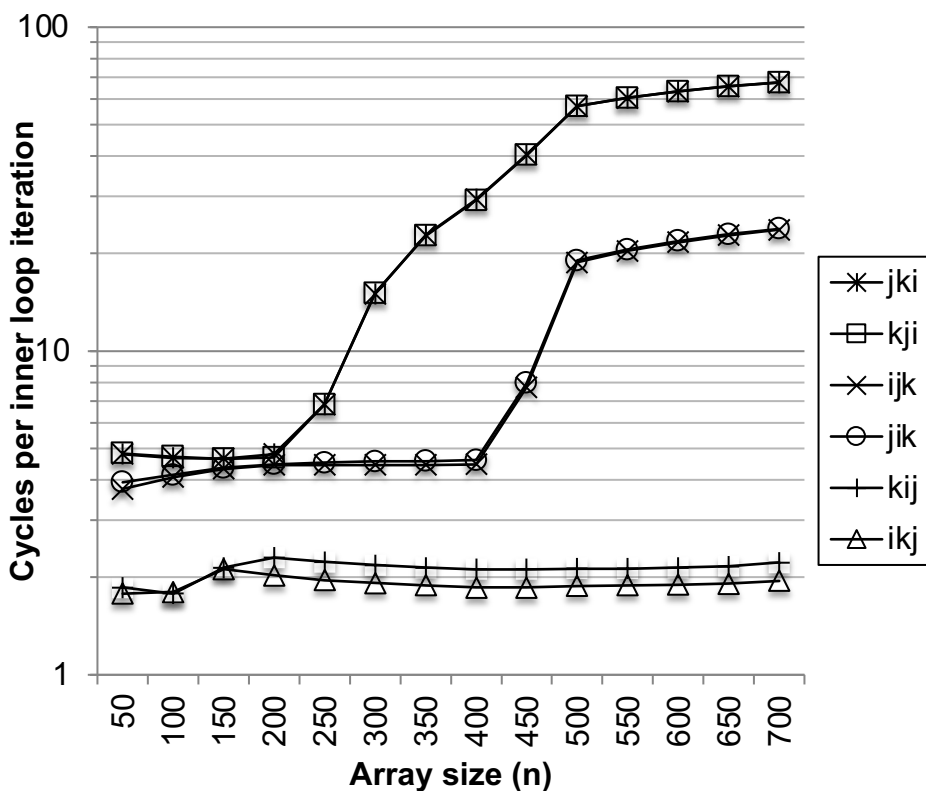
- 2 loads, 1 store
- misses/iter = 0.5

jki (& kji):

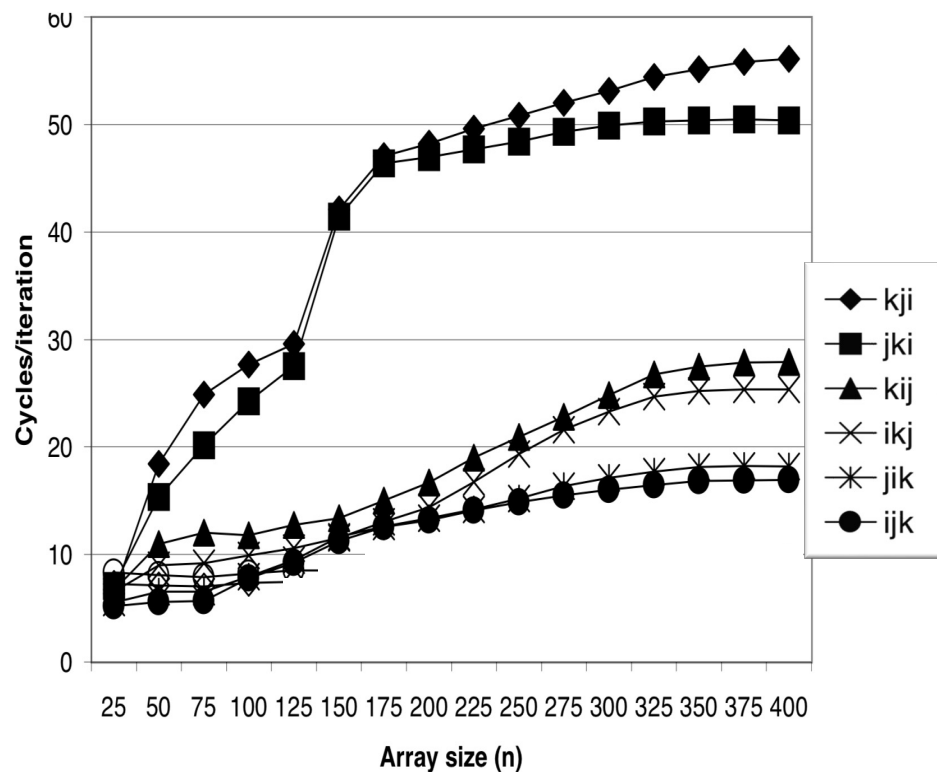
- 2 loads, 1 store
- misses/iter = 2.0

Matrix Multiply Performance

Core i7



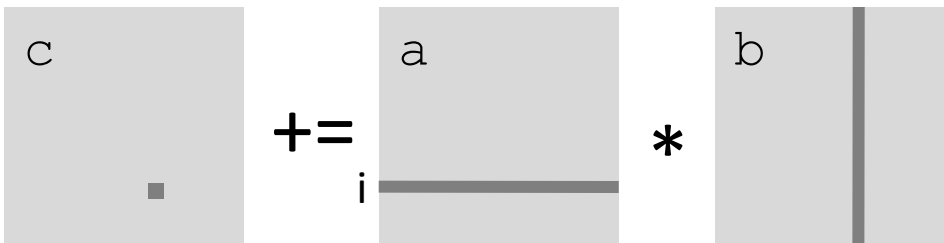
Pentium III Xeon



Can we do better?

```
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];
}
```

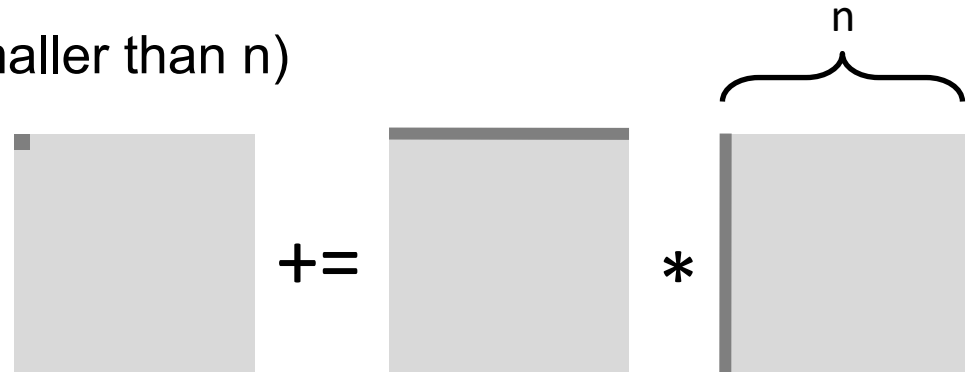


Cache Miss Analysis

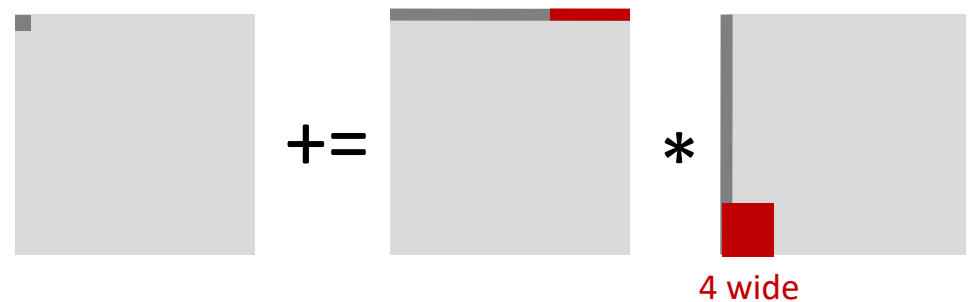
- Assume:
 - Matrix elements are doubles
 - Cache data block = 4 doubles
 - Cache size $C \ll n$ (much smaller than n)

- First iteration:

- $n/4 + n = 5n/4$ misses



- Afterwards **in cache**:
(schematic)

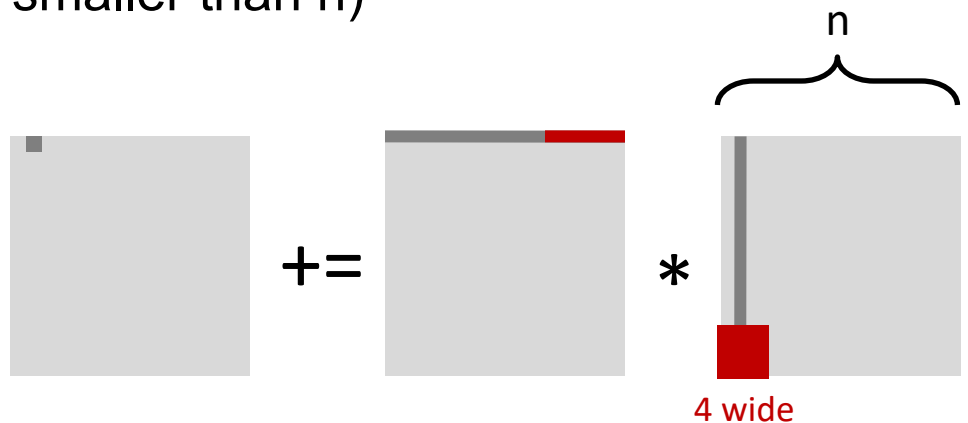


Cache Miss Analysis

- Assume:
 - Matrix elements are doubles
 - Cache data block = 4 doubles
 - Cache size $C \ll n$ (much smaller than n)

- Second iteration:

- $n/4 + n = 5n/4$ misses

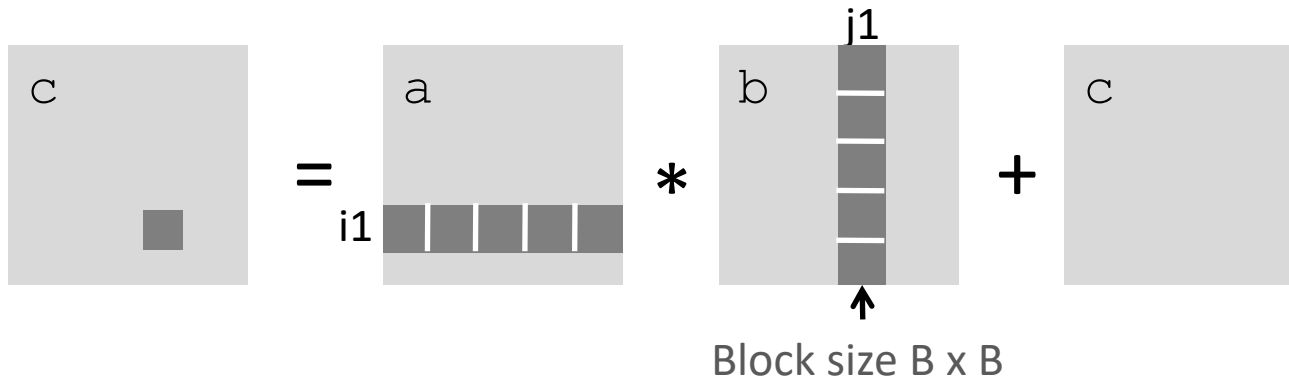


- Total misses:

- $5n/4 * n^2 = (5/4) * n^3$

Blocked Matrix Multiplication

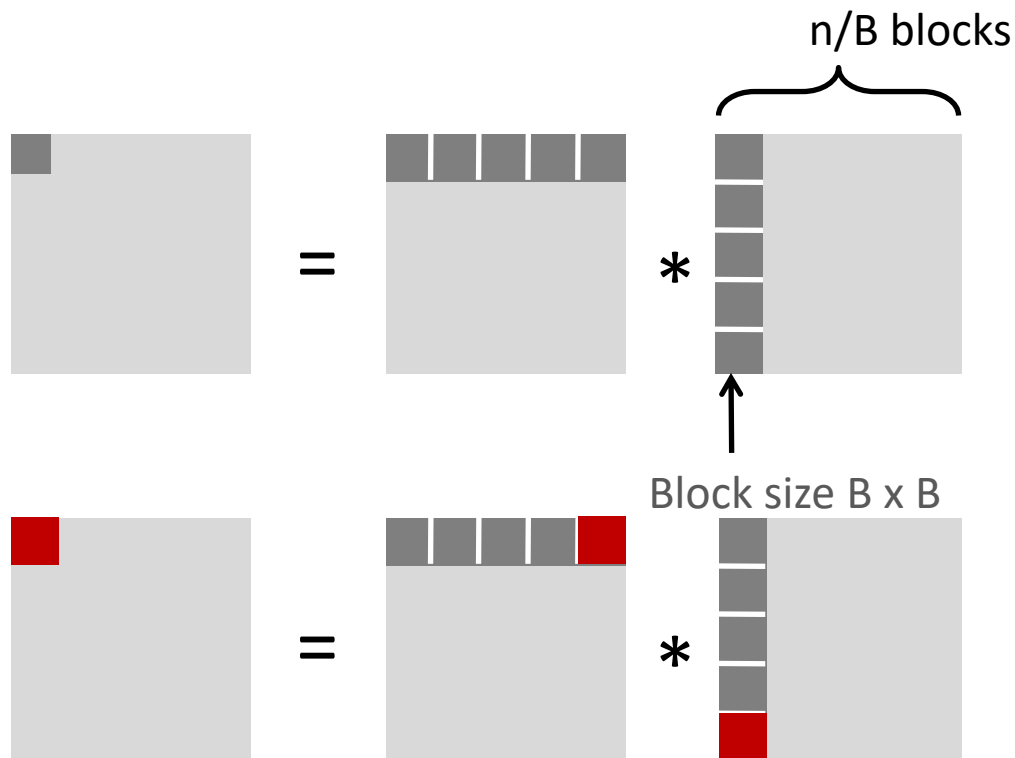
```
c = (double *) calloc(sizeof(double), n*n);  
  
/* Multiply n x n matrices a and b */  
void mmm(double *a, double *b, double *c, int n) {  
    int i, j, k;  
    for (i = 0; i < n; i+=B)  
        for (j = 0; j < n; j+=B)  
            for (k = 0; k < n; k+=B)  
                /* B x B mini matrix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



Cache Miss Analysis

- Assume:
 - Cache data block = 4 doubles
 - Cache size $C \ll n$ (much smaller than n)
 - Three blocks \blacksquare fit into cache: $3B^2 < C$

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



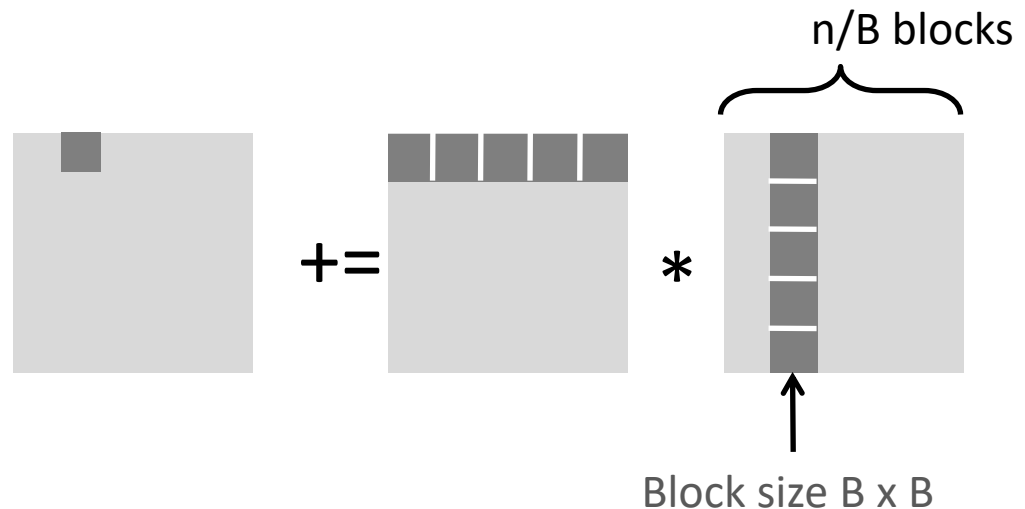
- Afterwards in cache
(schematic)

Cache Miss Analysis

- Assume:
 - Cache block = 4 doubles
 - Cache size $C \ll n$ (much smaller than n)
 - Three blocks \blacksquare fit into cache: $3B^2 < C$

- Second (block) iteration:

- Same as first iteration
- $2n/B * B^2/4 = nB/2$



- Total misses:

- $nB/2 * (n/B)^2 = n^3/(2B)$

Blocking Summary

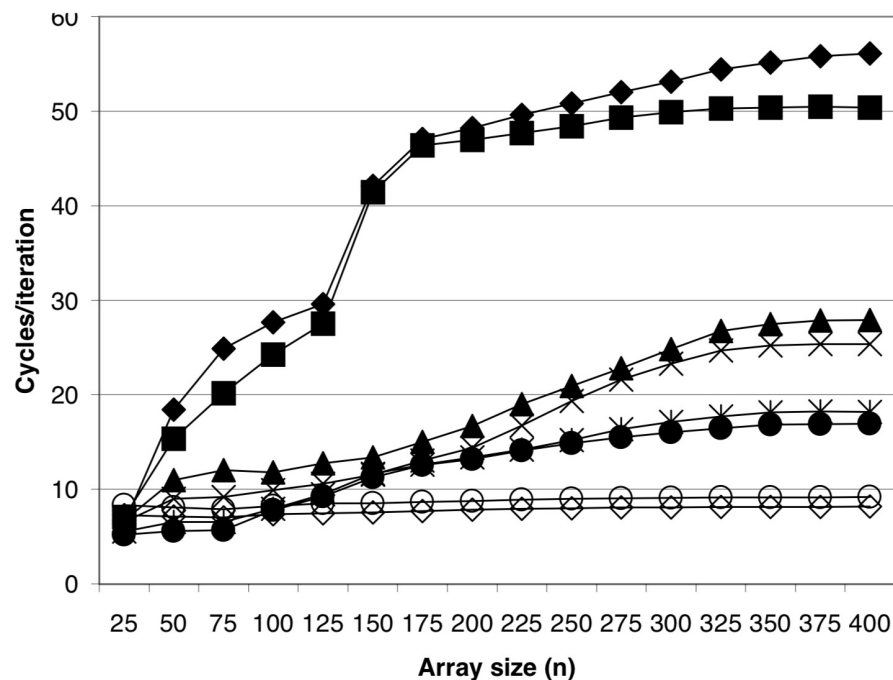
- No blocking: $(5/4) * n^3$
- Blocking: $n^3 / (2B)$

- 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

A reality check

- This analysis only holds on some machines!
- Intel Core i7 does aggressive pre-fetching for one-stride programs, so blocking doesn't actually improve performance
- But on a Pentium III Xeon:



And that's the end of Part 1



1...2...	...1,306... 1,307...
BAAA	BAAA

