HARVARD
School of Engineering and Applied Sciences

# Cache Performance
## Measurement and Optimization

*CS61, Lecture 14*

Prof. Stephen Chong

October 18, 2011

# Announcements

- HW 4: Malloc
  - Final deadline Thursday
  - You should have received comments on your design document
  - Please seek a meeting or feedback from course staff if needed
  - MMTMOH: Mammoth Multi-TF Malloc Office Hours
    - Wednesday evening. See website for details
- Midterm exam
  - Thursday Oct 27
  - Practice exams posted on iSites
    (both College and Extension)

# Mid-course evaluation

- 43 responses (122 enrolled students)
- Pace seems about right
  - Some thought too slow, some thought too fast
- Making sections effective
  - Not compulsory (no in-section quizzes)
  - Section notes are available on website before section
    - Generally on Friday
    - Encouraged to look at notes before section, figure out where you need to focus
- Lecture videos available to all students
  - Link from the schedule page
- Feedback
  - HW1 feedback took time; assignments available for pickup in MD 143
  - HW2 and 3 (binary bomb and buffer bomb) feedback was automatic
  - Will endeavor to give you timely feedback on remaining assignments

# Dennis Ritchie '63

- Co-creator of C programming language
- Co-developer (with Ken Thompson) of UNIX operating system
    - C is the foundation of UNIX
- Undergrad ('63)and PhD ('68) at Harvard
- Worked at Bell Labs for 40 years
- Profound impact on computer science

1941-2011

# Topics for today

- Cache performance metrics
- Discovering your cache's size and performance
- The “Memory Mountain”
- Matrix multiply, six ways
- Blocked matrix multiplication
- Exploiting locality in your programs

# Cache Performance Metrics

- **Miss Rate**
  - Fraction of memory references not found in cache (# misses / # references)
  - Typical numbers:
    - 3-10% for L1
    - Can be quite small (e.g., < 1%) for L2, depending on size and locality.
- **Hit Time**
  - Time to deliver a line in the cache to the processor (includes time to determine whether the line is in the cache)
  - Typical numbers: 1-2 clock cycles for L1; 5-20 clock cycles for L2
- **Miss Penalty**
  - Additional time required because of a miss
    - Typically 50-200 cycles for main memory
- Average access time = hit time + (miss rate × miss penalty)

# Wait, what do those numbers mean?

- Huge difference between a hit and a miss
  - Could be 100x, if just L1 and main memory
- Would you believe 99% hits is twice as good as 97%?
  - Consider:
    cache hit time of 1 cycle
    miss penalty of 100 cycles
- Average access time:
  - 97% hits: 1 cycle + 0.03 * 100 cycles = 4 cycles
  - 99% hits: 1 cycle + 0.01 * 100 cycles = 2 cycles
- This is why "miss rate" is used instead of "hit rate"

# Writing Cache Friendly Code

- Repeated references to variables are good (**temporal locality**)
- Stride-1 reference patterns are good (**spatial locality**)
- Examples:
  - cold cache, 4-byte words, 4-word cache blocks

```
int sum_array_rows(int a[M][N]) {
  int i, j, sum = 0;

  for (i = 0; i < M; i++)
     for (j = 0; j < N; j++)
        sum += a[i][j];
  return sum;
}
```

Miss rate = 1/4 = 25%

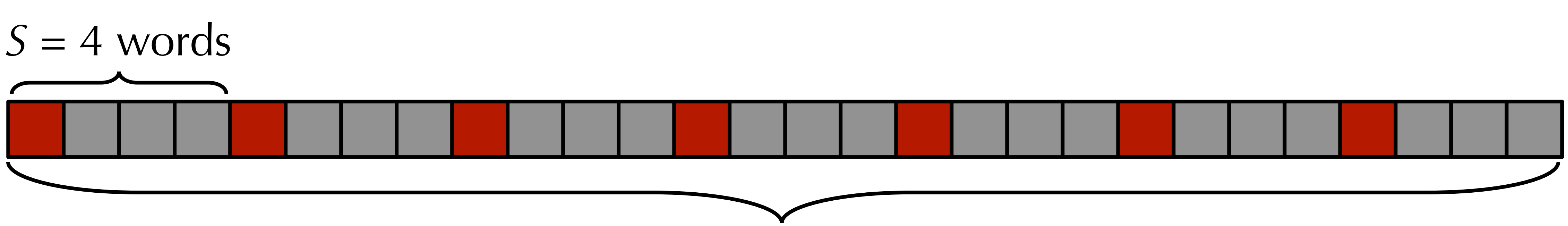
```
int sum_array_cols(int a[M][N]) {
  int i, j, sum = 0;

  for (j = 0; j < N; j++)
     for (i = 0; i < M; i++)
        sum += a[i][j];
  return sum;
}
```

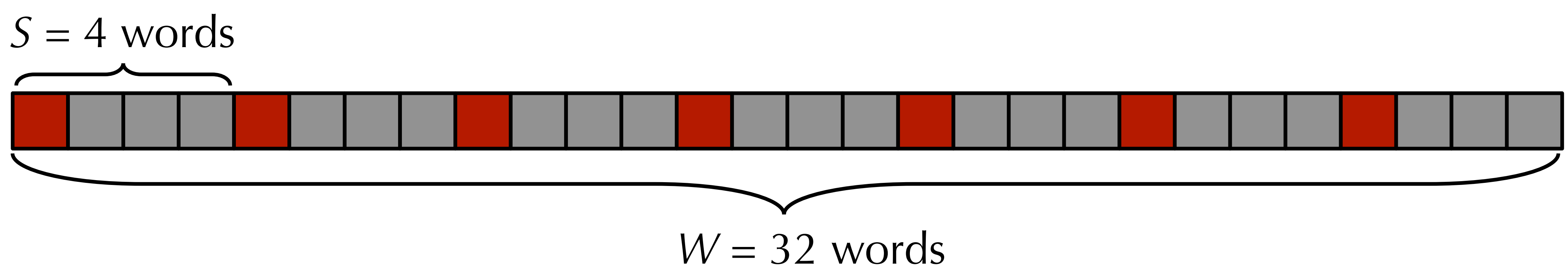
Miss rate = 100%

# Determining cache characteristics

- Say you have a machine but don’t know its cache size or speeds.
- How would you figure these values out?
- Idea: Write a program to measure the cache's behavior and performance.
  - Program needs to perform memory accesses with different locality patterns.
- Simple approach:
  - Allocate array of size *W* words
  - Loop over the array repeatedly with stride *S* and measure memory access time
  - Vary *W* and *S* to estimate cache characteristics



# Determining cache characteristics

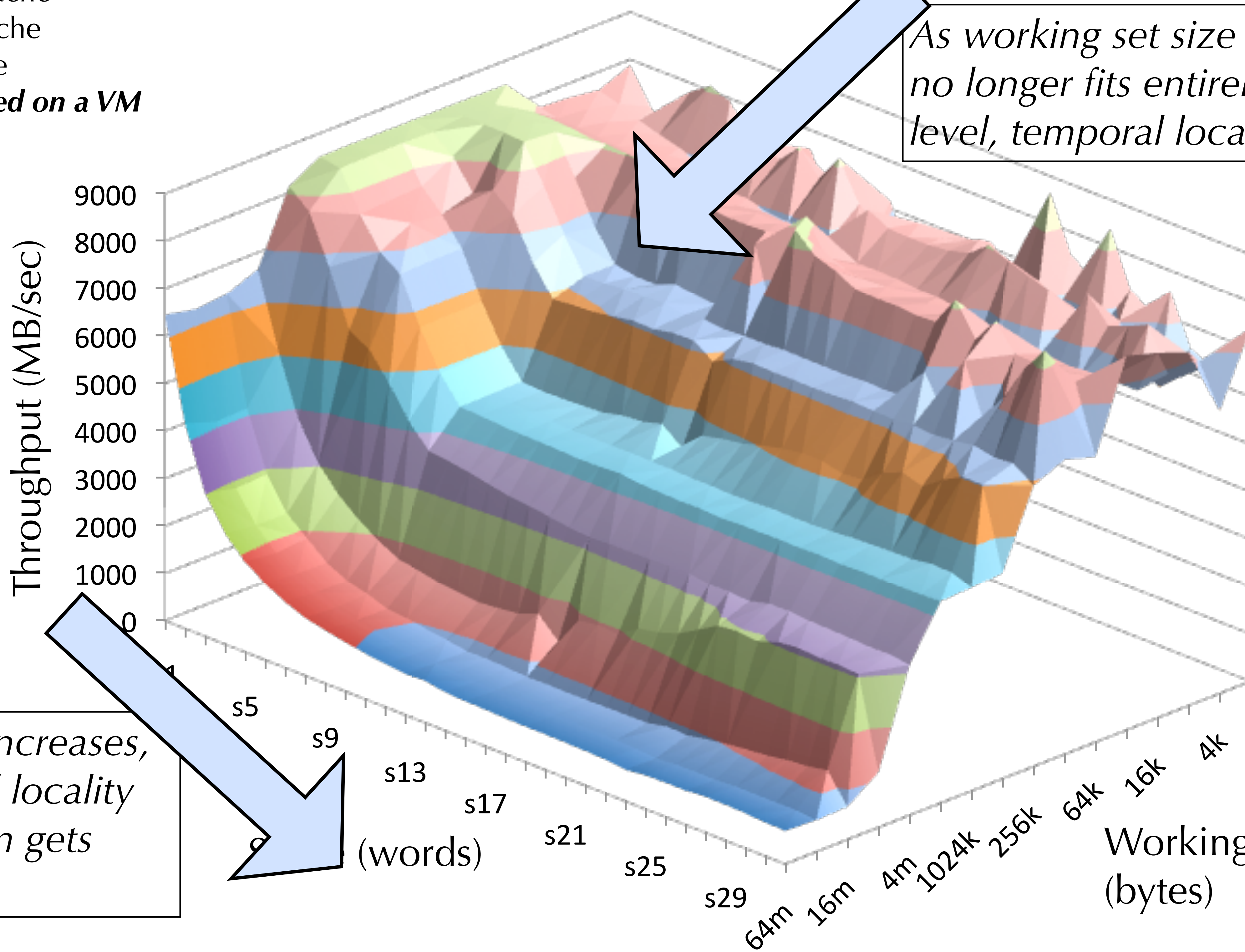



- What happens as you vary $W$ and $S$?
- Changing $W$ varies total amount of memory accessed by program
  - As $W$ gets larger than one cache level, performance of program will drop
- Changing $S$ varies the spatial locality of each access.
  - If $S$ is less than the size of a cache line, sequential accesses will be fast.
  - If $S$ is greater than the size of a cache line, sequential accesses will be slower.
- See end of lecture notes for example C program to do this.

# The Memory Mountain

Intel Core i7
2.7 GHz
32 KB L1 d-cache
256 KB L2 cache
8MB L3 cache
***CAVEAT: Tested on a VM***

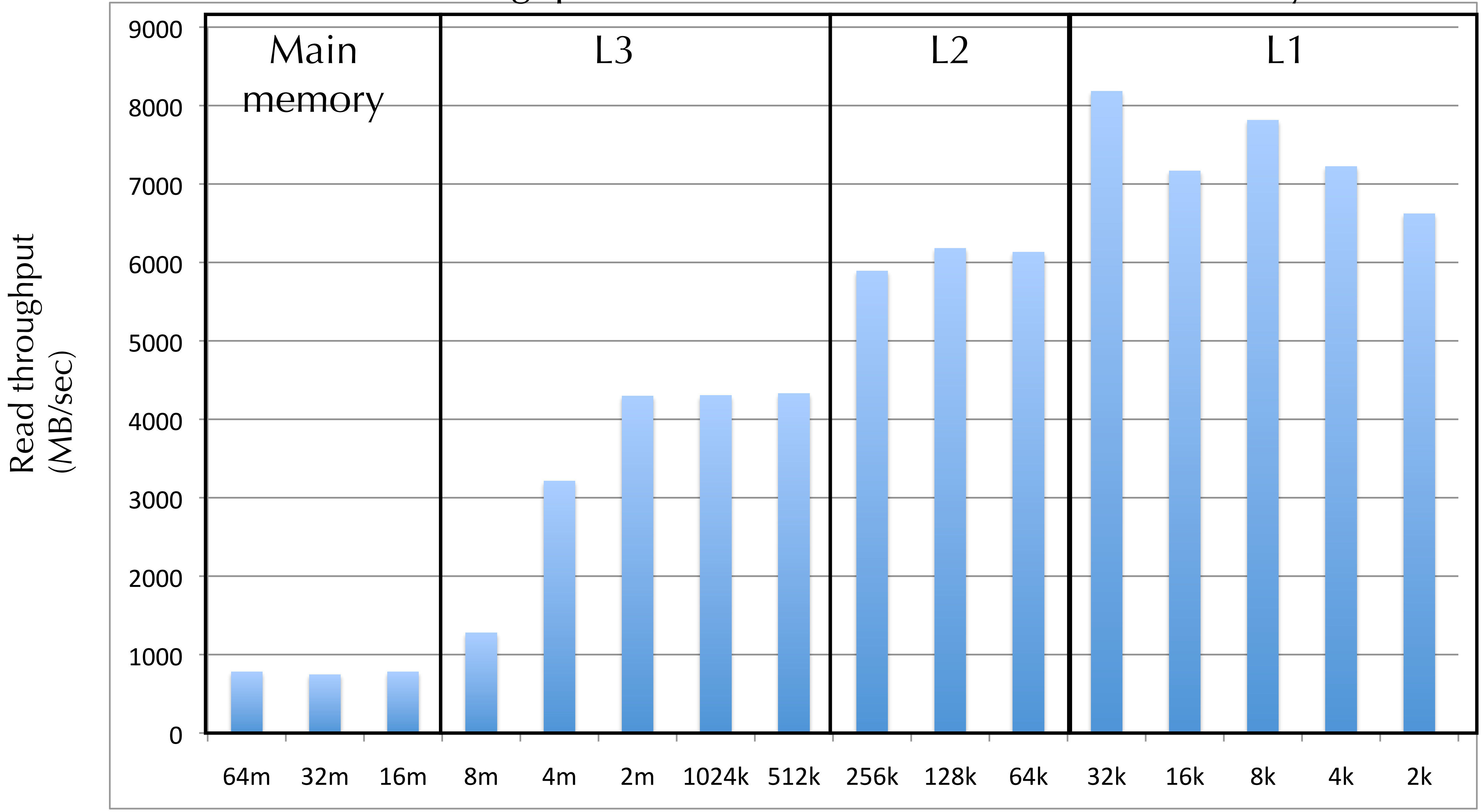
*As working set size increases, no longer fits entirely in a cache level, temporal locality worsens.*




*As stride increases, the spatial locality of program gets worse*

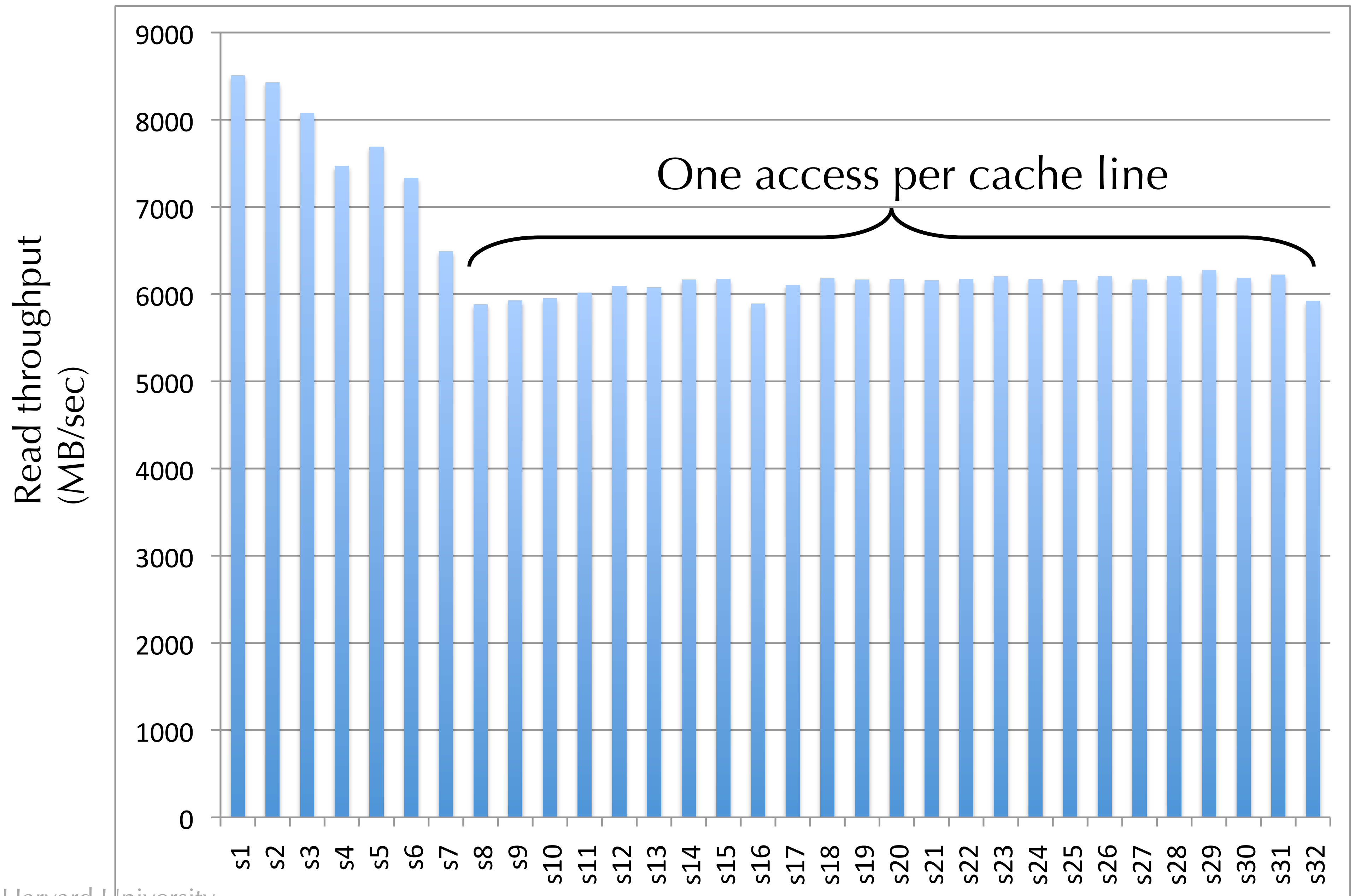
# Varying Working Set

- Keep stride constant at $S$ = 16 words, and vary $W$ from 1KB to 64MB
  - Shows size and read throughputs of different cache levels and memory

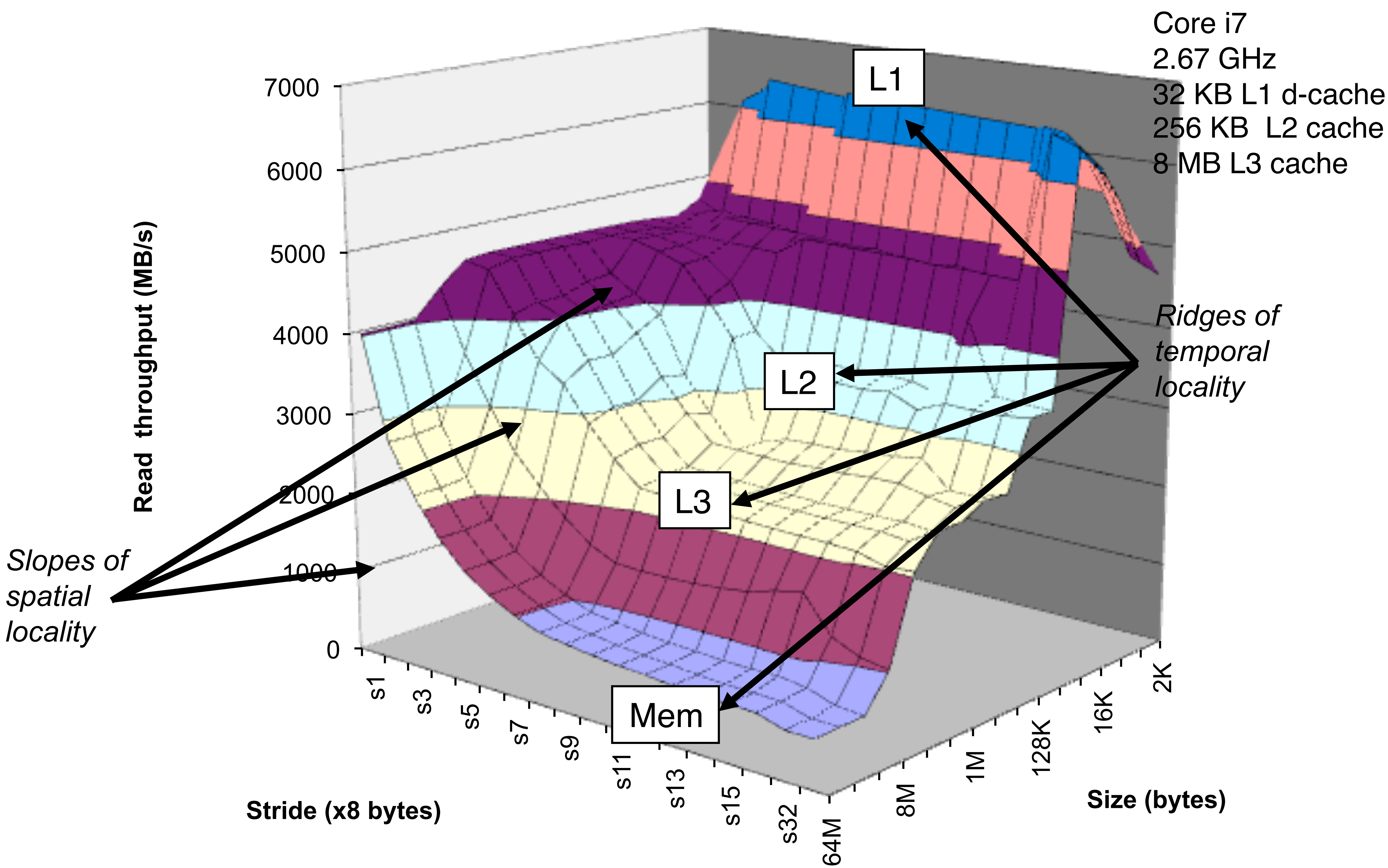


# Varying stride

- Keep working set constant at *W* = 256 KB, vary stride from 1-32 words

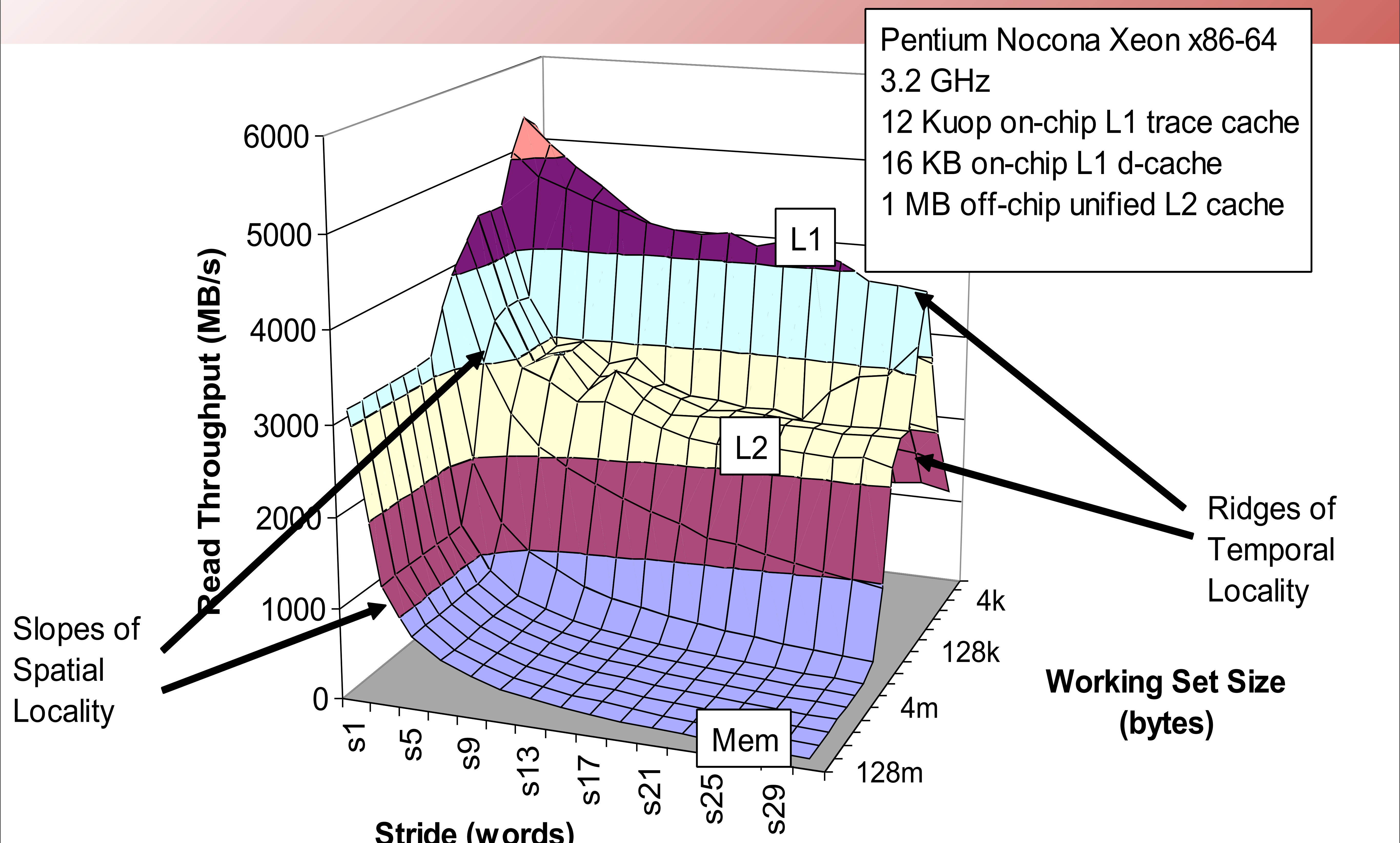


# Core i7

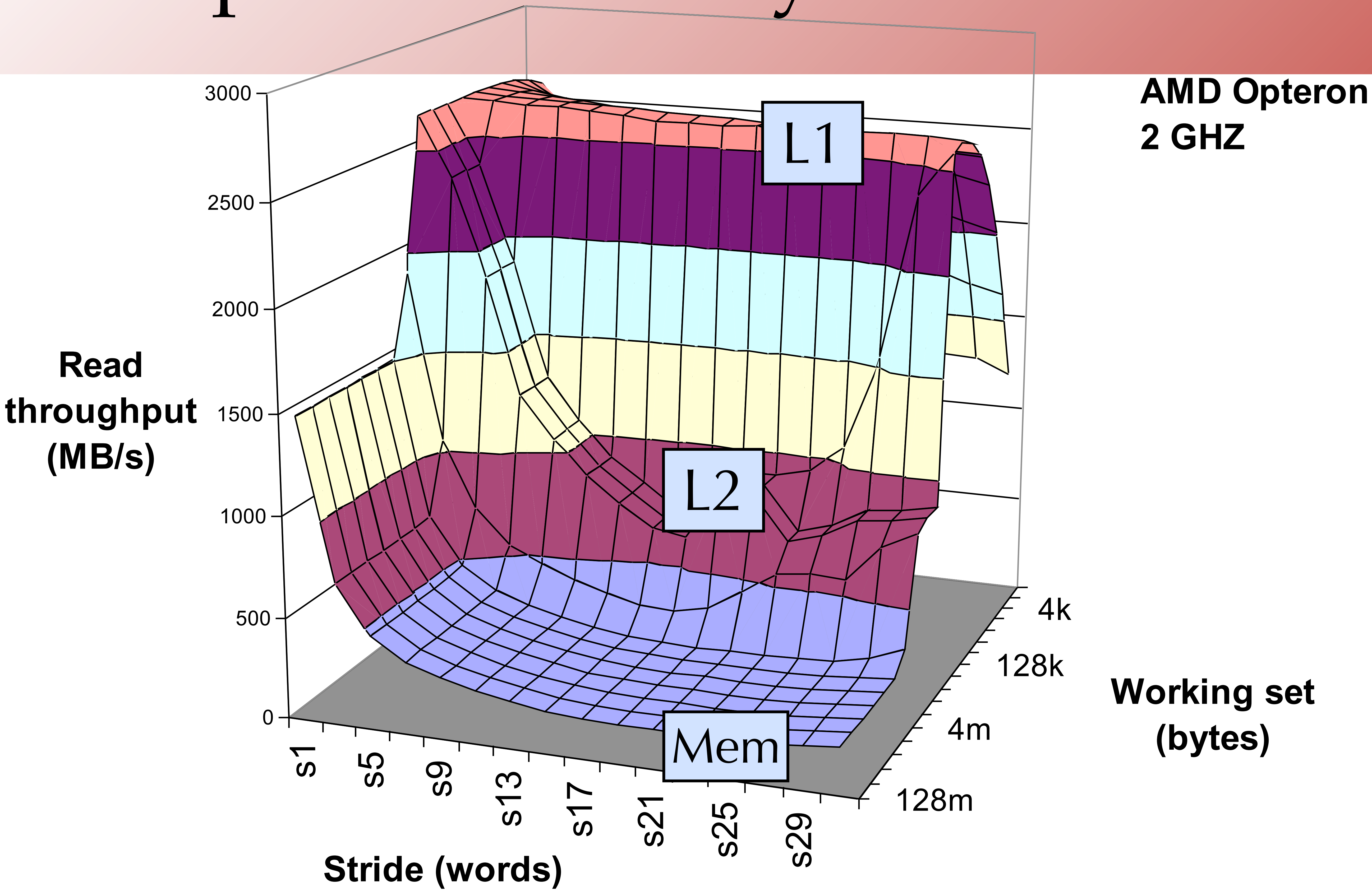


Core i7
2.67 GHz
32 KB L1 d-cache
256 KB L2 cache
8 MB L3 cache
L1
L2
L3
Mem
Ridges of temporal locality
Slopes of spatial locality
Read throughput (MB/s)
7000
6000
5000
4000
3000
2000
1000
0
s1
s3
s5
s7
s9
s11
s13
s15
s32
Stride (x8 bytes)
64M
8M
1M
128K
16K
2K
Size (bytes)

# Pentium Xeon



# Opteron Memory Mountain



# Topics for today

- Cache performance metrics
- Discovering your cache's size and performance
- The “Memory Mountain”
- Matrix multiply, six ways
- Blocked matrix multiplication
- Exploiting locality in your programs

# Matrix Multiplication Example

- Matrix multiplication is heavily used in numeric and scientific applications.
  - It's also a nice example of a program that is highly sensitive to cache effects.
- Multiply two N x N matrices
  - $O(N^3)$ total operations
  - Read N values for each source element
  - Sum up N values for each destination

```
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    /* 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

# Matrix Multiplication Example

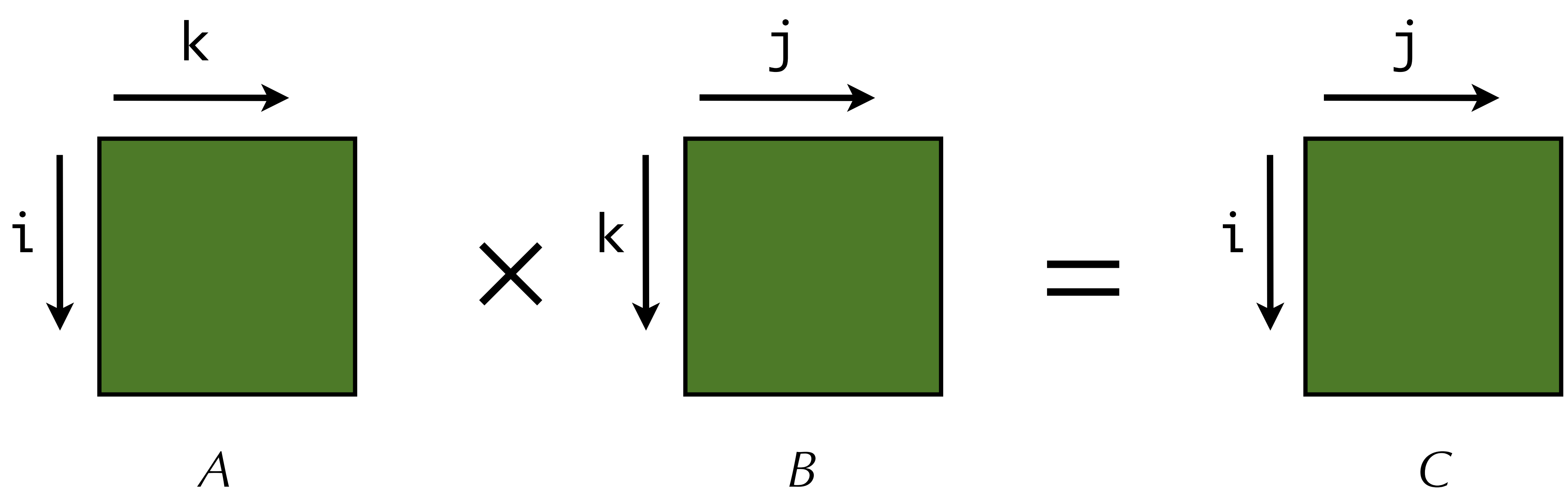
```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

$$4\times3 \;+\; 2\times2 \;+\; 7\times5 = 51$$

$$\begin{array}{|c|c|c|}\hline 4 & 2 & 7 \\ \hline 1 & 8 & 2 \\ \hline 6 & 0 & 1 \\ \hline \end{array} \times \begin{array}{|c|c|c|}\hline 3 & 0 & 1 \\ \hline 2 & 4 & 5 \\ \hline 5 & 9 & 1 \\ \hline \end{array} = \begin{array}{|c|c|c|}\hline 51 & \phantom{00} & \phantom{00} \\ \hline & & \\ \hline & & \\ \hline \end{array}$$

# Miss Rate Analysis for Matrix Multiply

- Assume:
  - Line size = 32B (big enough for four 64-bit "double" values)
  - Matrix dimension N is very large
  - Cache is not big enough to hold multiple rows
- Analysis Method:
  - Look at access pattern of inner loop

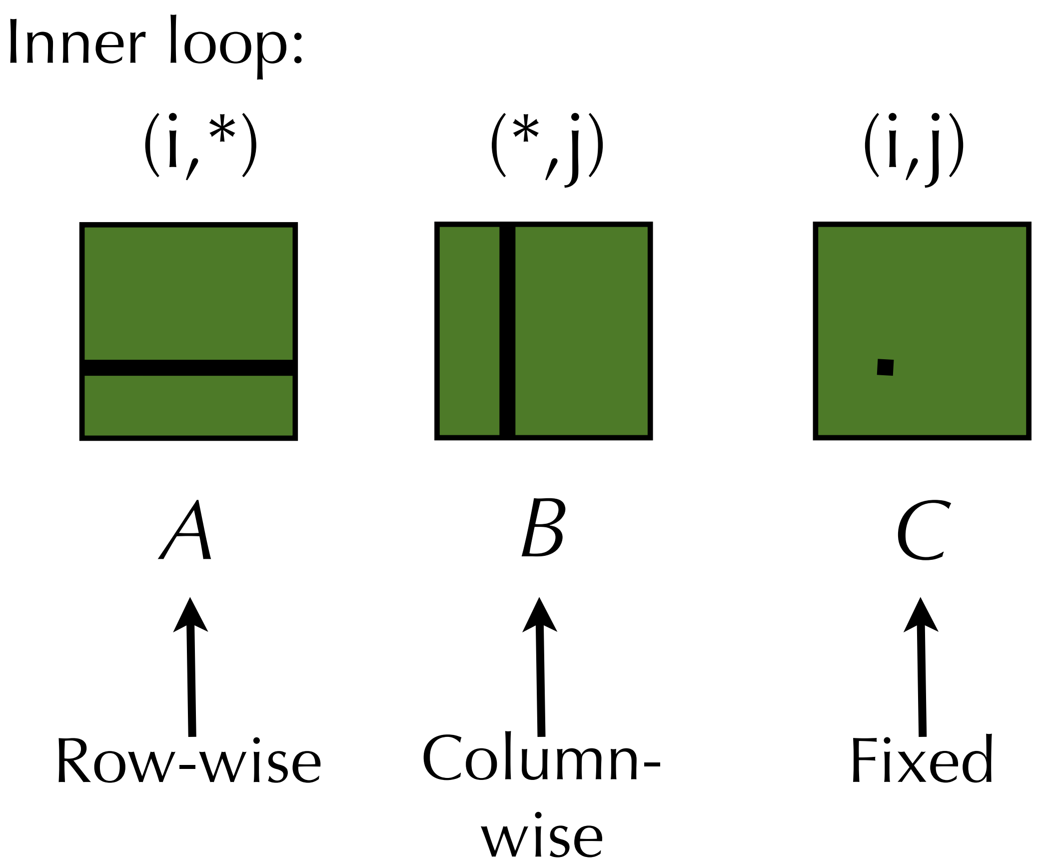


# Layout of C Arrays in Memory (review)

- 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
  - Compulsory miss rate: (8 bytes per double) / (block size of cache)
- Stepping through rows in one column:
  - ```
    for (i = 0; i < n; i++)
          sum += a[i][0];
    ```
  - Accesses distant elements — no spatial locality!
  - Compulsory miss rate = 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;
  }
}
```



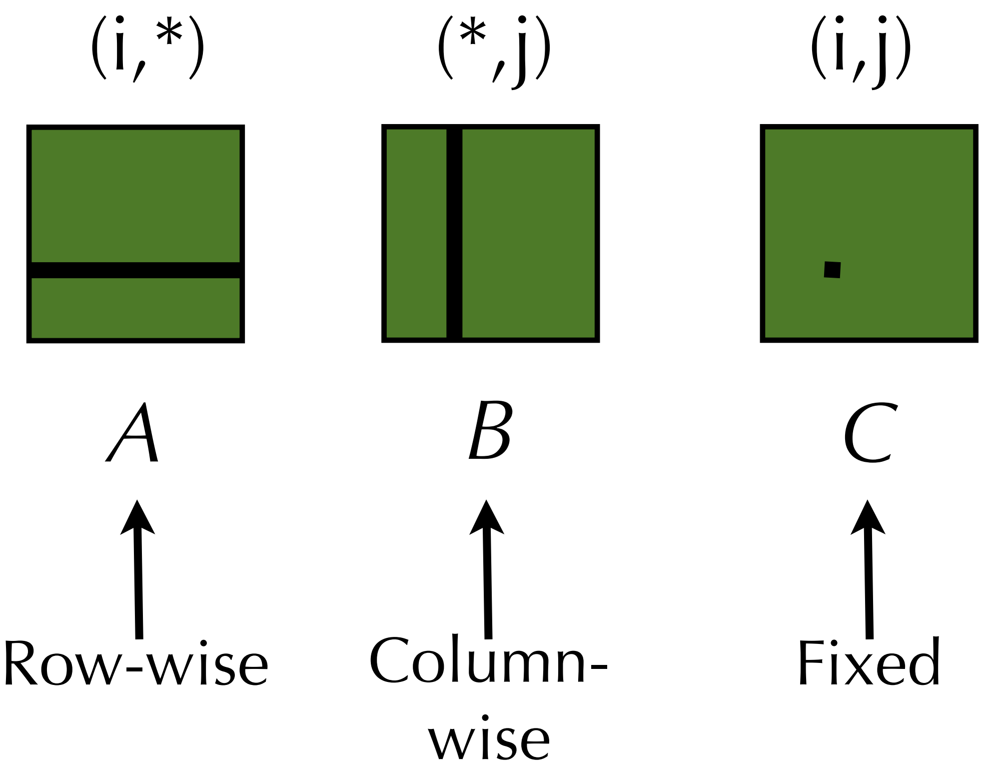

- 2 loads, 0 stores per iteration
- Assume cache line size of 32 bytes, so 4 doubles per line
- Misses per iteration:

A = 0.25 B = 1 C = 0 Total: 1.25

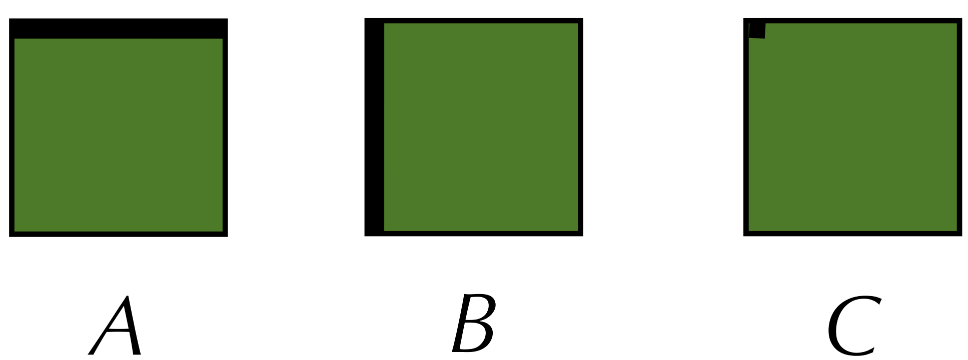
# Cache miss analysis

```
/* 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:




First iteration:



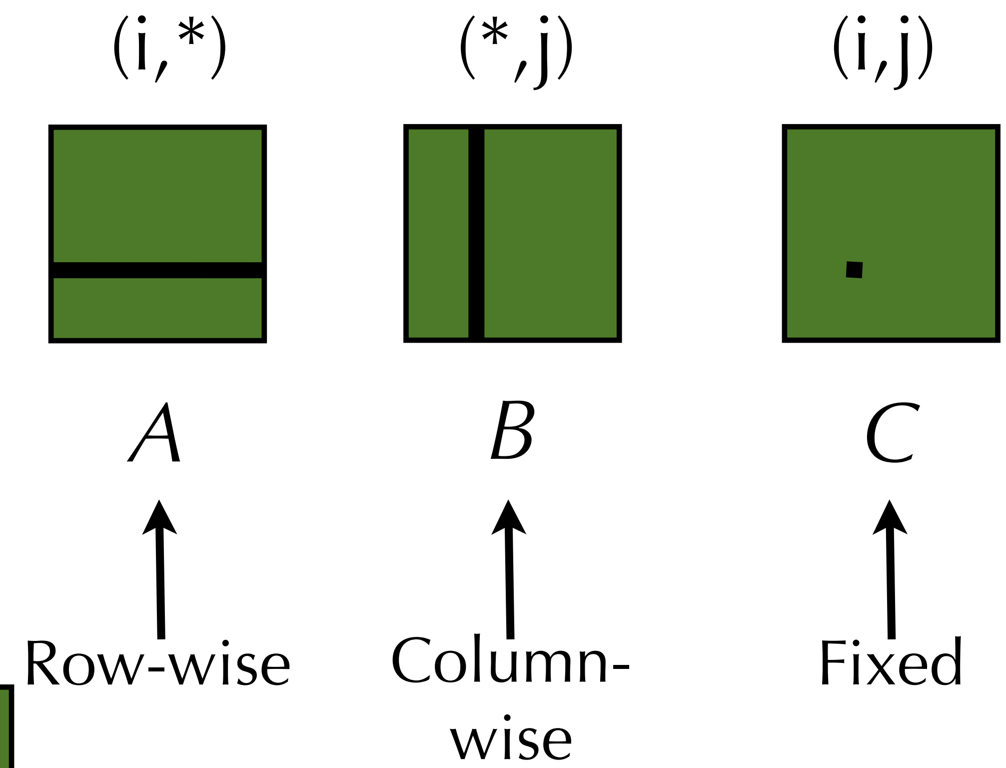

After first iteration in cache (schematic):

4 doubles wide

# Cache miss analysis

```
/* 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;
  }
}
```

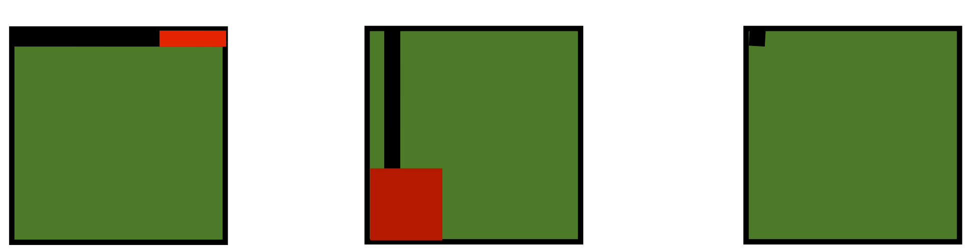
Inner loop:




First iteration:

A B C

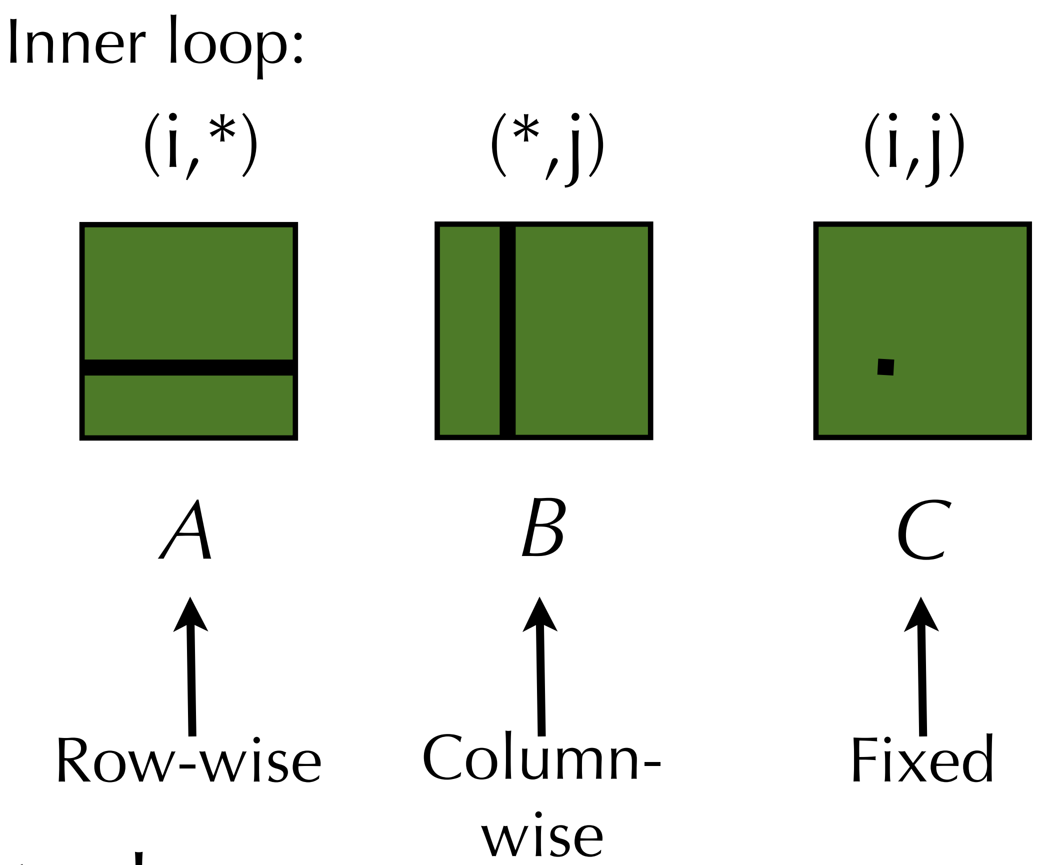
After first iteration in cache (schematic):



4 doubles wide

# 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;
  }
}
```

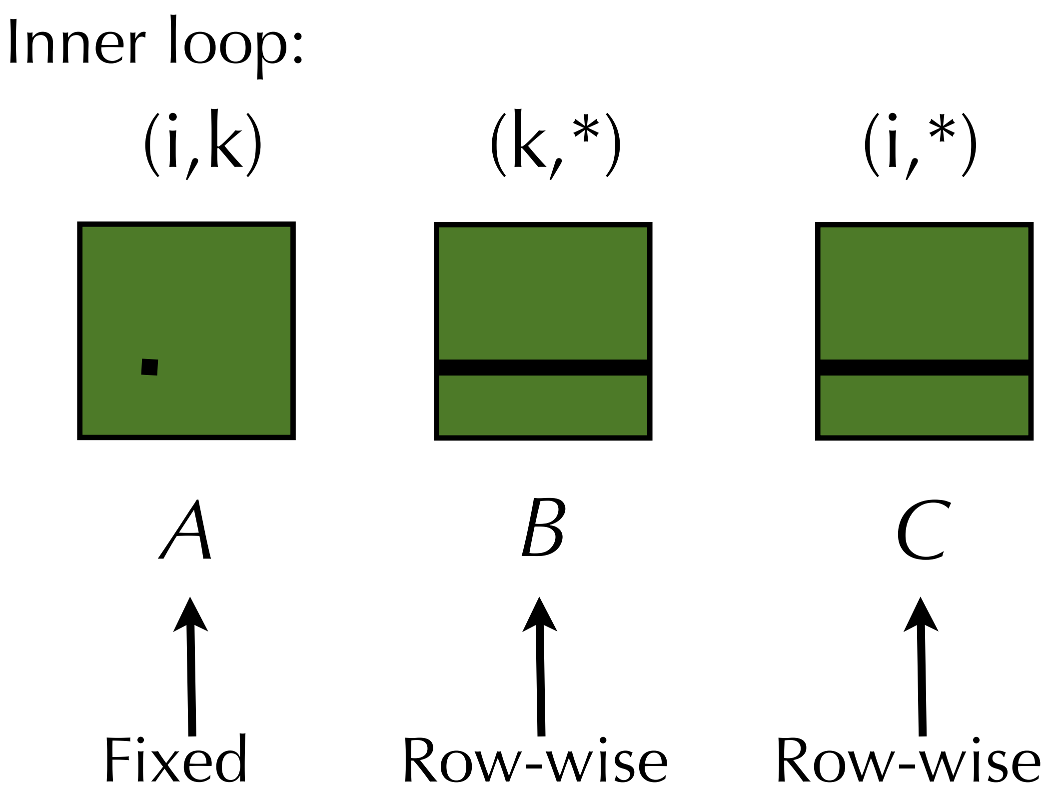



- Same as ijk, just swapped order of outer loops
- 2 loads, 0 stores per iteration
- Assume cache line size of 32 bytes, so 4 doubles per line
- Misses per iteration:

A = 0.25 B = 1 C = 0 Total: 1.25

# 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];
  }
}
```



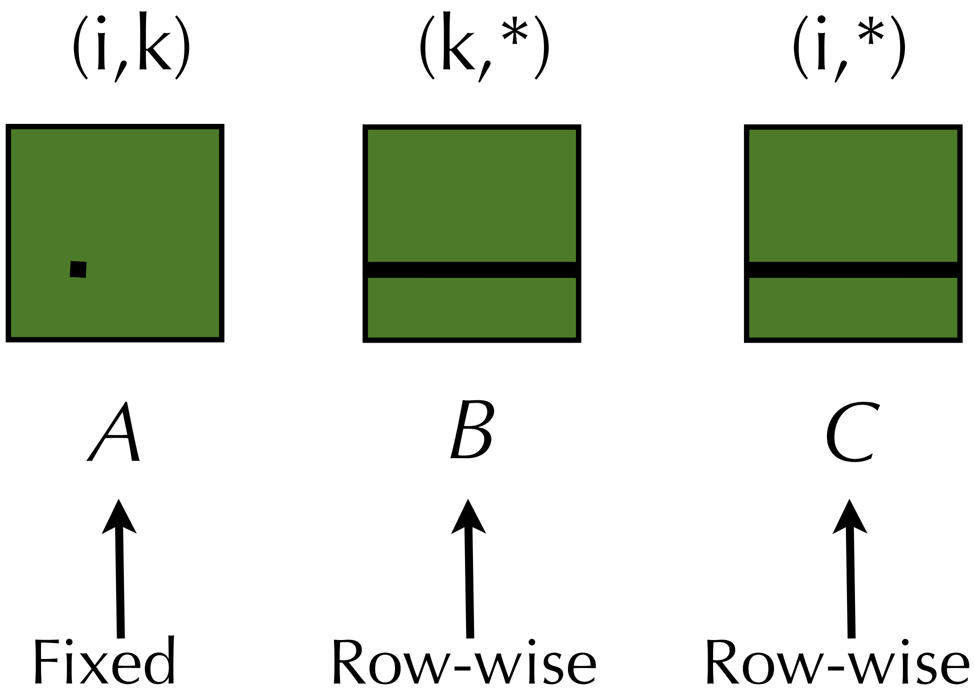

- 2 load, 1 store per iteration
- Assume cache line size of 32 bytes, so 4 doubles per line
- Misses per iteration:

A = 0 B = 0.25 C = 0.25 Total: 0.5

# 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:



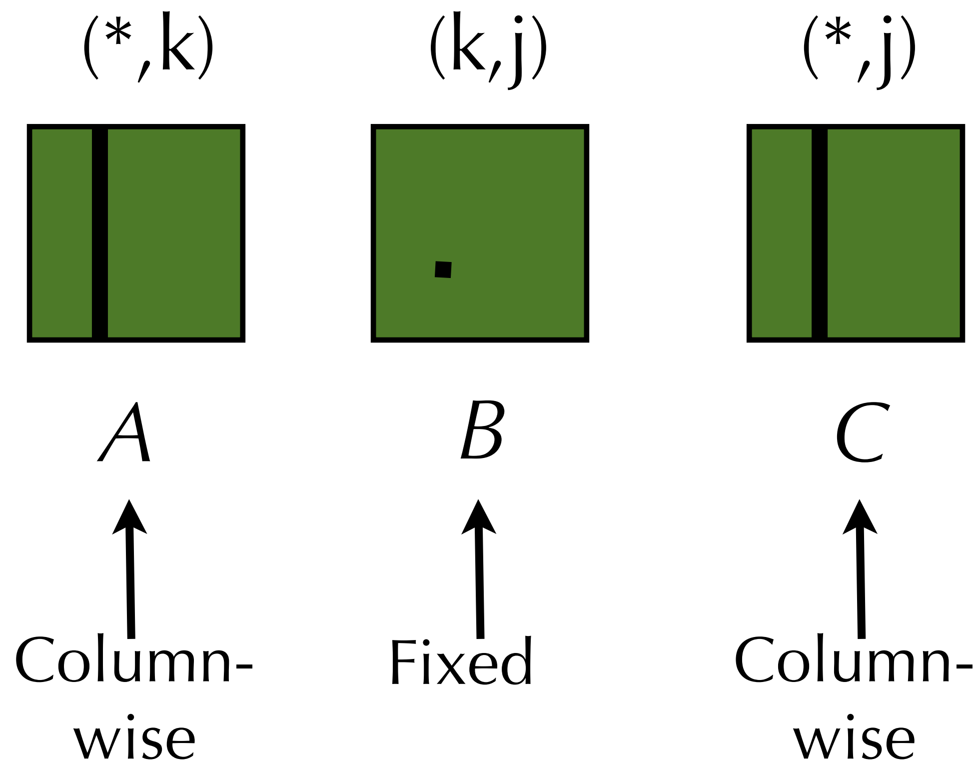

- Same as kij, just swapped order of outer loops
- 2 load, 1 store per iteration
- Assume cache line size of 32 bytes, so 4 doubles per line
- Misses per iteration:

A = 0 B = 0.25 C = 0.25 Total: 0.5

# 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;
  }
}
```

Inner loop:

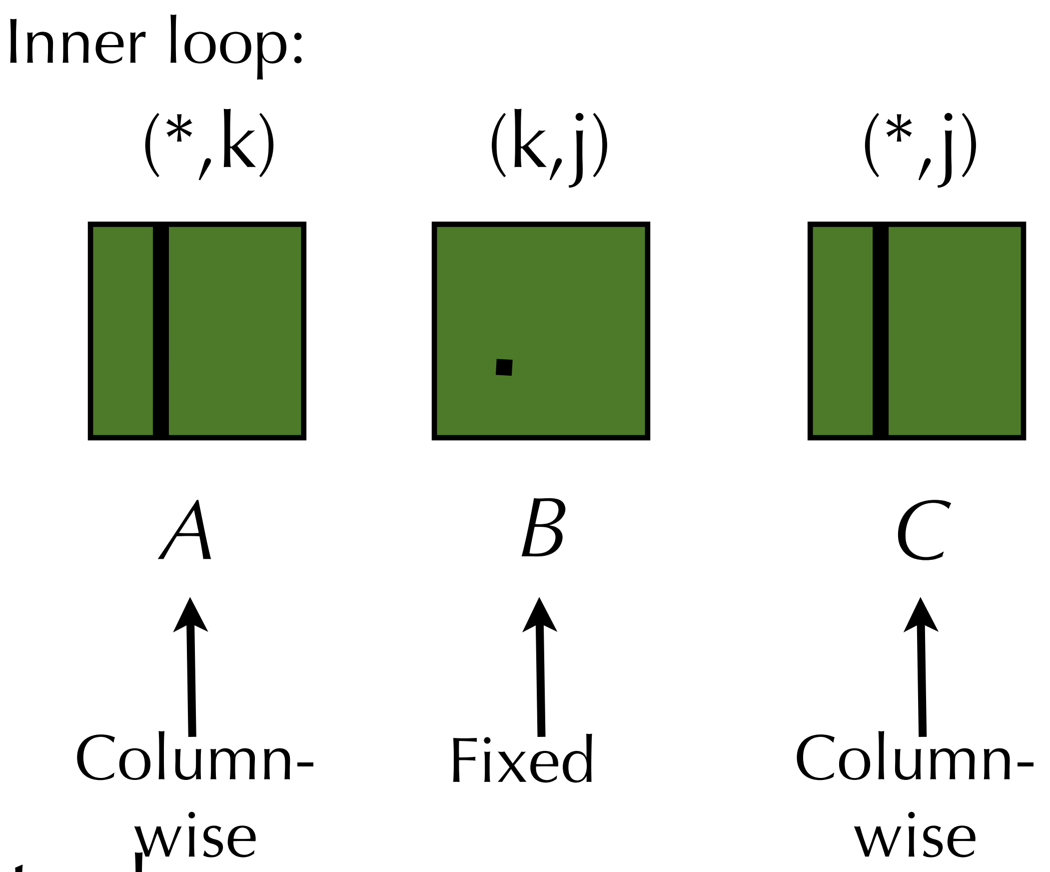



- 2 load, 1 store per iteration
- Assume cache line size of 32 bytes, so 4 doubles per line
- Misses per iteration:

A = 1 B = 0 C = 1 Total: 2

# 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;
  }
}
```




- Same as kji, just swapped order of outer loops
- 2 load, 1 store per iteration
- Assume cache line size of 32 bytes, so 4 doubles per line
- Misses per iteration:

A = 1 B = 0 C = 1 Total: 2

# 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;
 }
}
```

**ijk or jik:**

2 loads, 0 stores

misses/iter = 1.25

```
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];
 }
}
```

**kij or ikj:**

2 loads, 1 store

misses/iter = 0.5

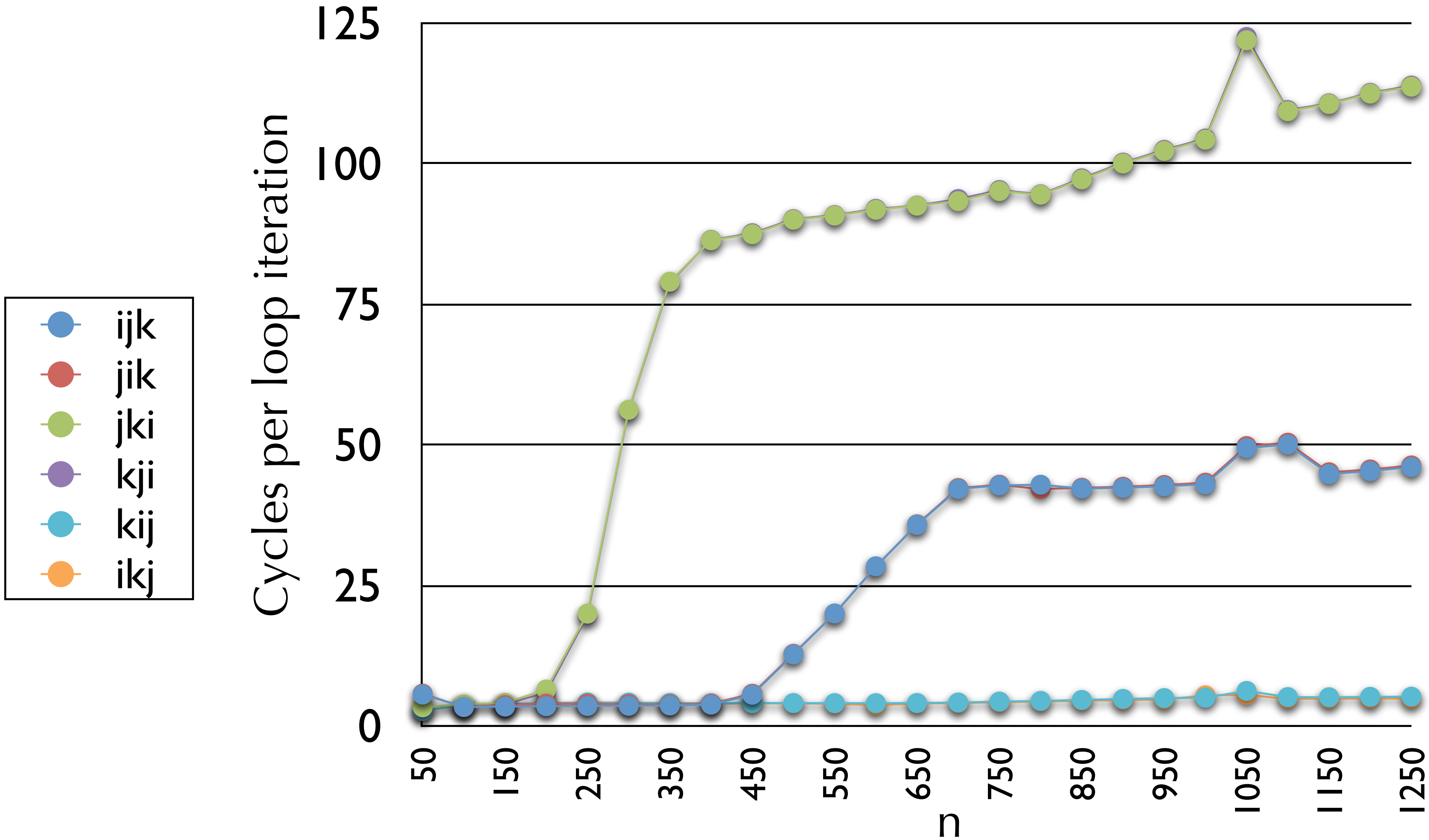
```
for (j=0; j<n; j++) {
 for (k=0; k<n; k++) {
   r = b[k][j];
   for (i=0; i<n; i++)
    c[i][j] += a[i][k] * r;
 }
}
```

**jki or kji:**

2 loads, 1 store

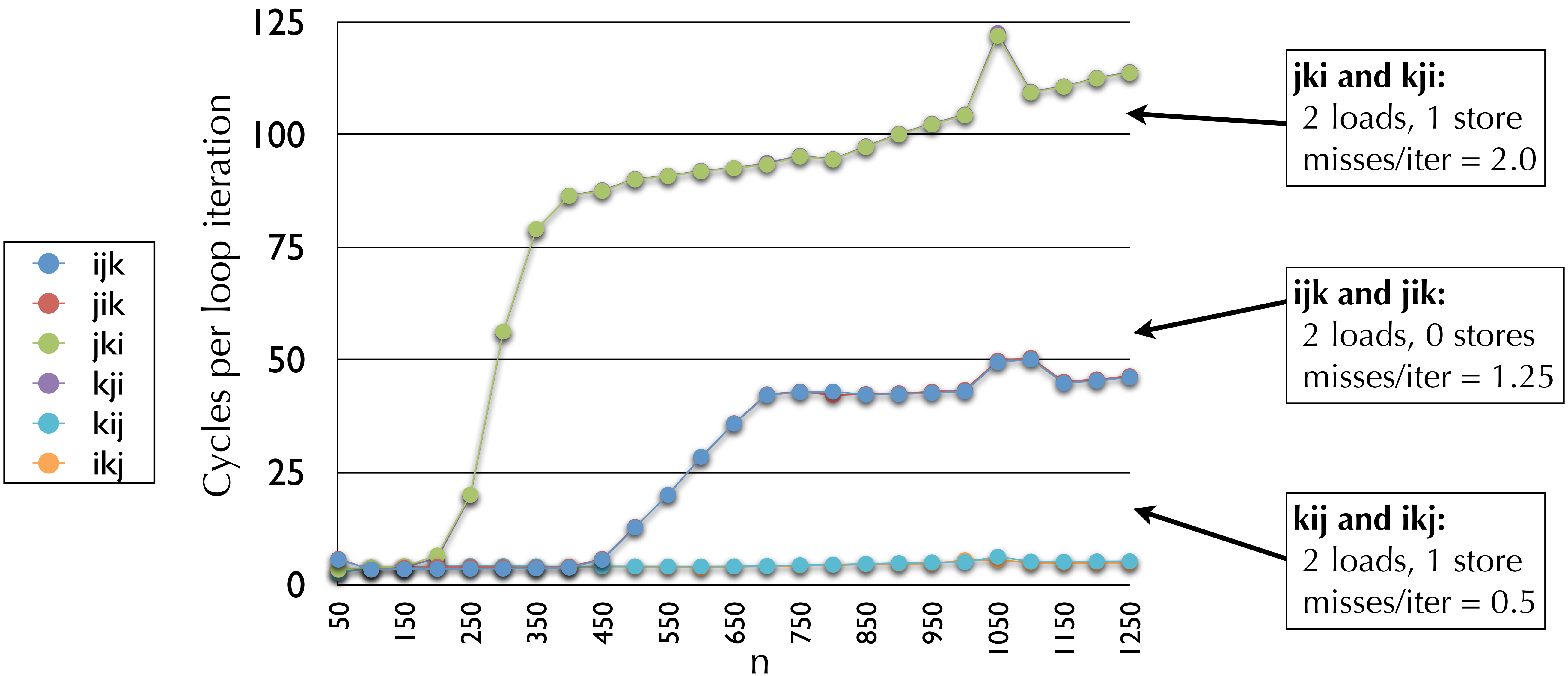
misses/iter = 2.0

# Matrix Multiply Performance




- Each implementation doing same number of arithmetic operations, but ~20× difference!
- Pairs with same number of mem. references and misses per iteration almost identical

# Matrix Multiply Performance




- Miss rate better predictor or performance than number of mem. accesses!
- For large N, kij and ikj performance almost constant.
  Due to **hardware prefetching**, able to recognize stride-1 patterns.

# Topics for today

- Cache performance metrics
- Discovering your cache's size and performance
- The “Memory Mountain”
- Matrix multiply, six ways
- Blocked matrix multiplication
- Exploiting locality in your programs

# Using blocking to improve locality

- Blocked matrix multiplication
  - Break matrix into smaller blocks and perform independent multiplications on each block.
  - Improves locality by operating on one block at a time.
  - Best if each block can fit in the cache!
- Example: Break each matrix into four sub-blocks

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \times \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$$

Key idea: Sub-blocks (i.e., $A_{xy}$) can be treated just like scalars.

$$C_{11} = A_{11}B_{11} + A_{12}B_{21} \qquad C_{12} = A_{11}B_{12} + A_{12}B_{22}$$

$$C_{21} = A_{21}B_{11} + A_{22}B_{21} \qquad C_{22} = A_{21}B_{12} + A_{22}B_{22}$$

# Blocked Matrix Multiply

```
void bmmm(int n, double a[n][n], double b[n][n], double c[n][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][j1] += a[i1][k1] * b[k1][j1];
}
```

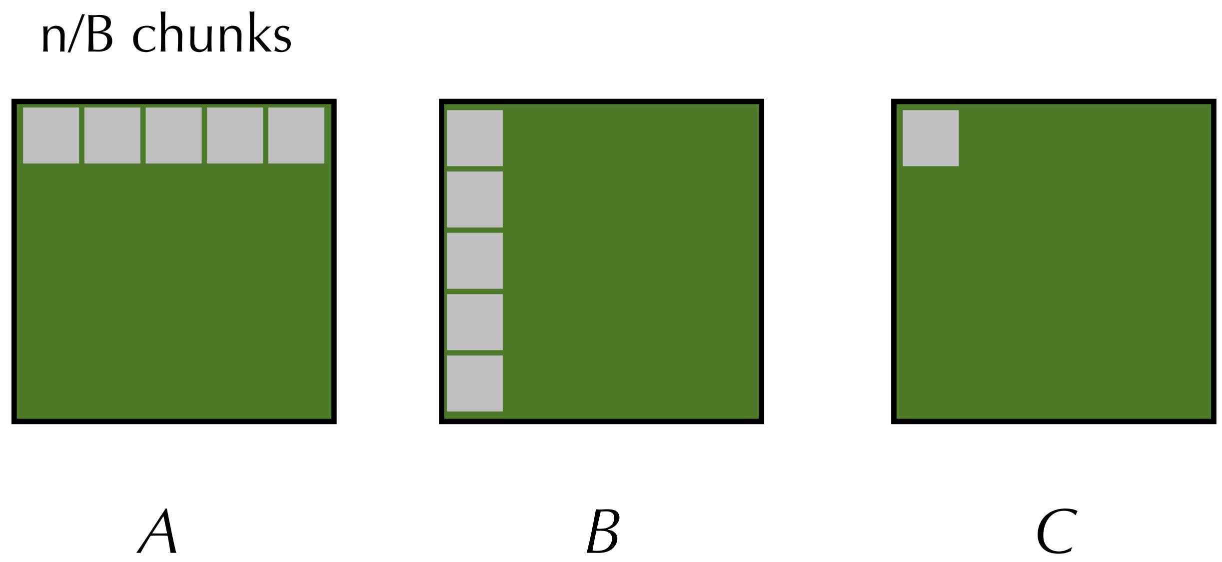
Code becomes harder to read!
Is it worth it?

Tradeoff between performance and maintainability...

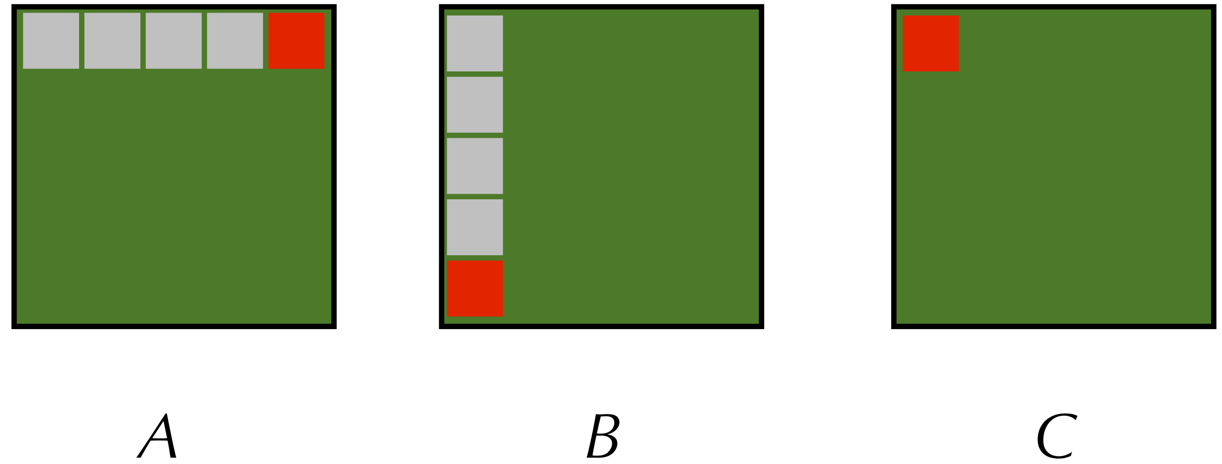
- Partition arrays into *bsize* × *bsize* chunks
- Innermost (i1, j1, k1) loop pair multiplies an *A* chunk by a *B* chunk and accumulates result in a *C* chunk

# Blocked matrix multiply

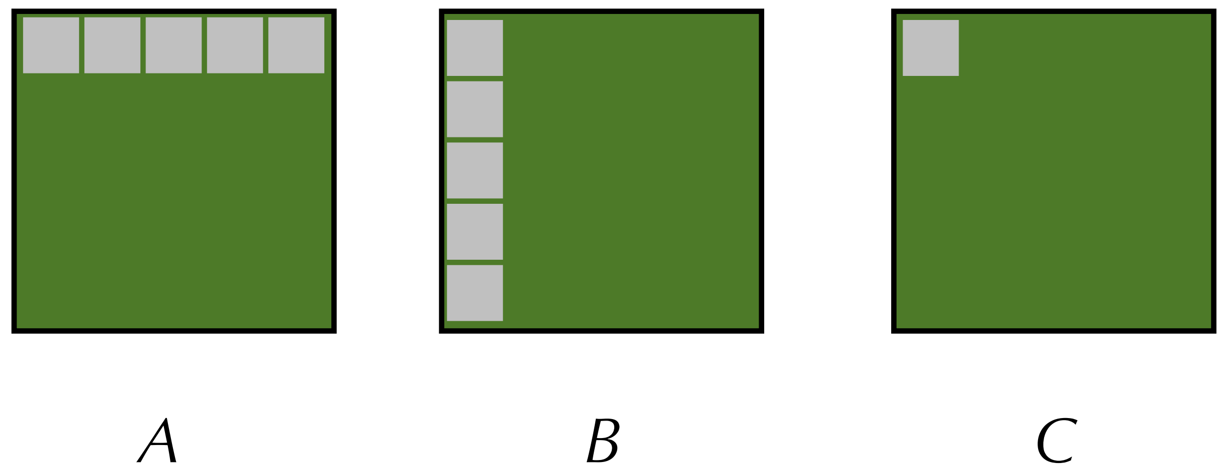
- Assume 3 chunks can fit into the cache, i.e., $3bsize^2 < C$
- First block iteration




- After first iteration in cache (schematic)

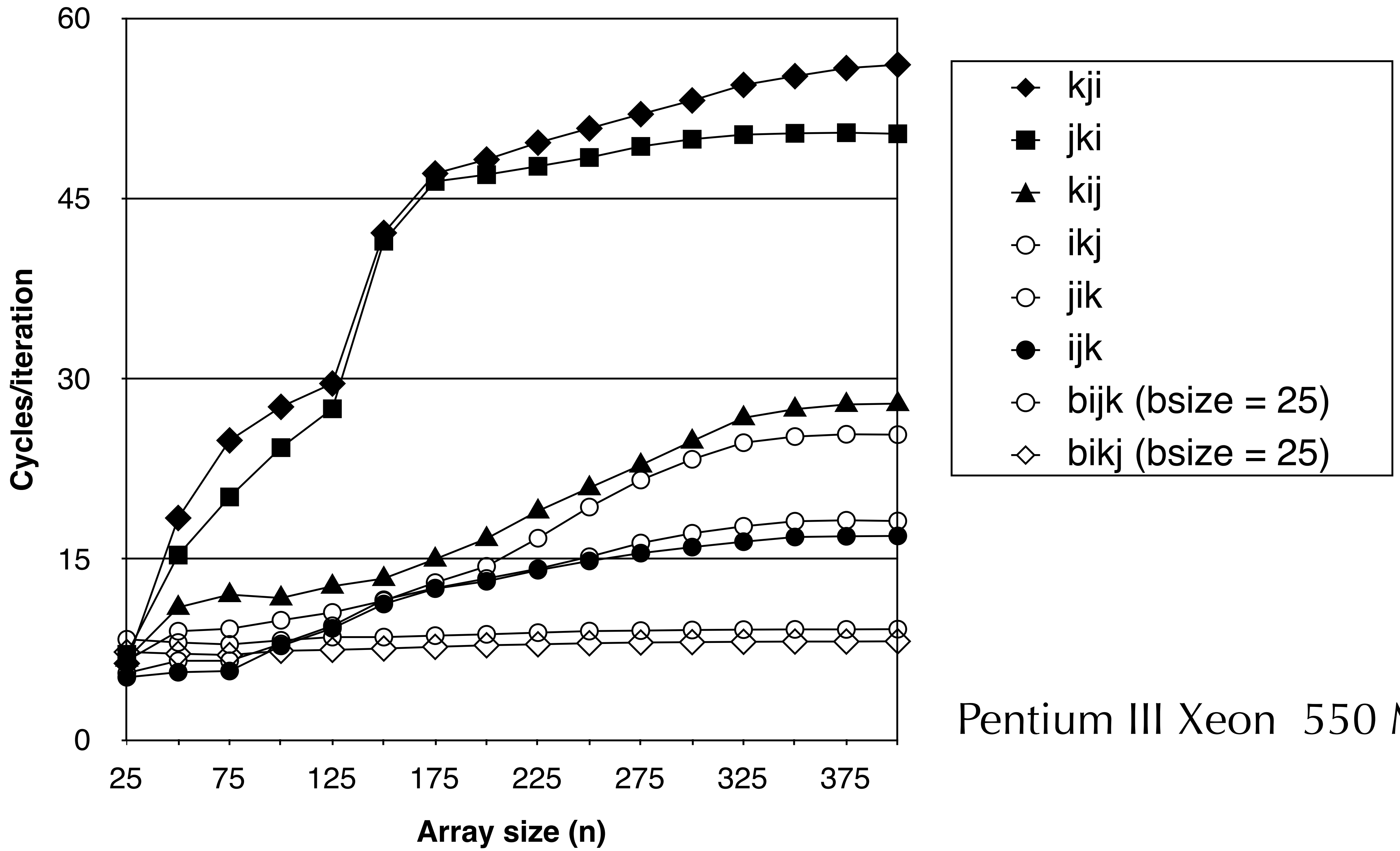


# Cache miss analysis




- Assume 3 chunks can fit into the cache
- Assume *bsize* is a multiple of 4
- $bsize^2/4$ misses per chunk, so $3/4 \times bsize^2$ misses per chunk iteration
- $(n/bsize)^3$ chunk iterations
- Total of $(n/bsize)^3 \times 3/4 \times bsize^2$ misses $= n^3 \times 3/(4 * bsize)$
- Compare with $n^3 \times 1/2$ total misses for kij algorithm

# Blocked Matrix Multiply Performance

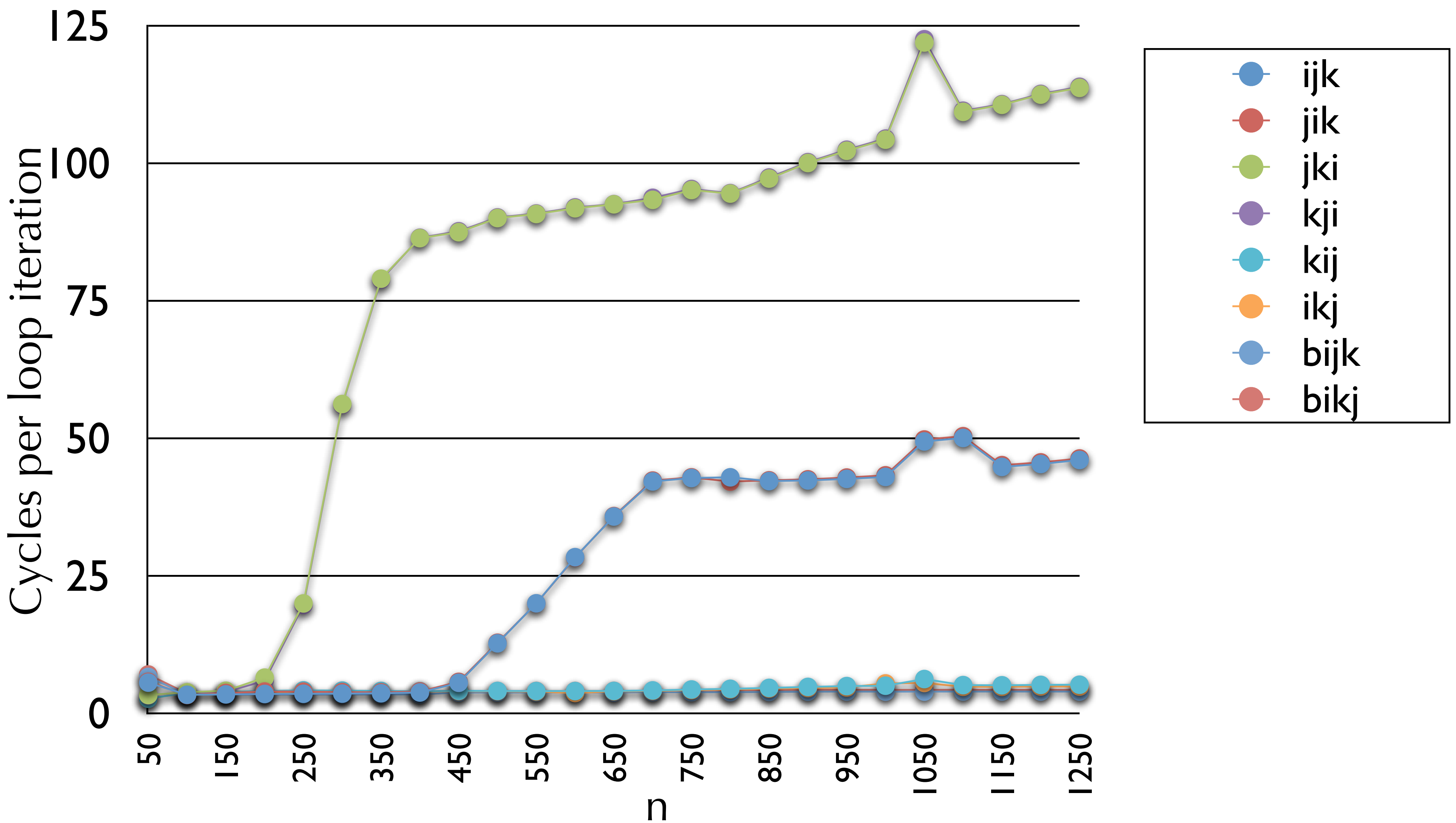



Pentium III Xeon 550 Mhz

- Blocking (bijk and bikj) improves performance by a factor of two over unblocked versions (ijk and jik)
  - Relatively insensitive to array size.

# Blocked Matrix Multiply Performance

Intel Core i7
2.7 GHz
32 KB L1 d-cache
256 KB L2 cache
8MB L3 cache
***CAVEAT: Tested on a VM***



# Blocked Matrix Multiply Performance

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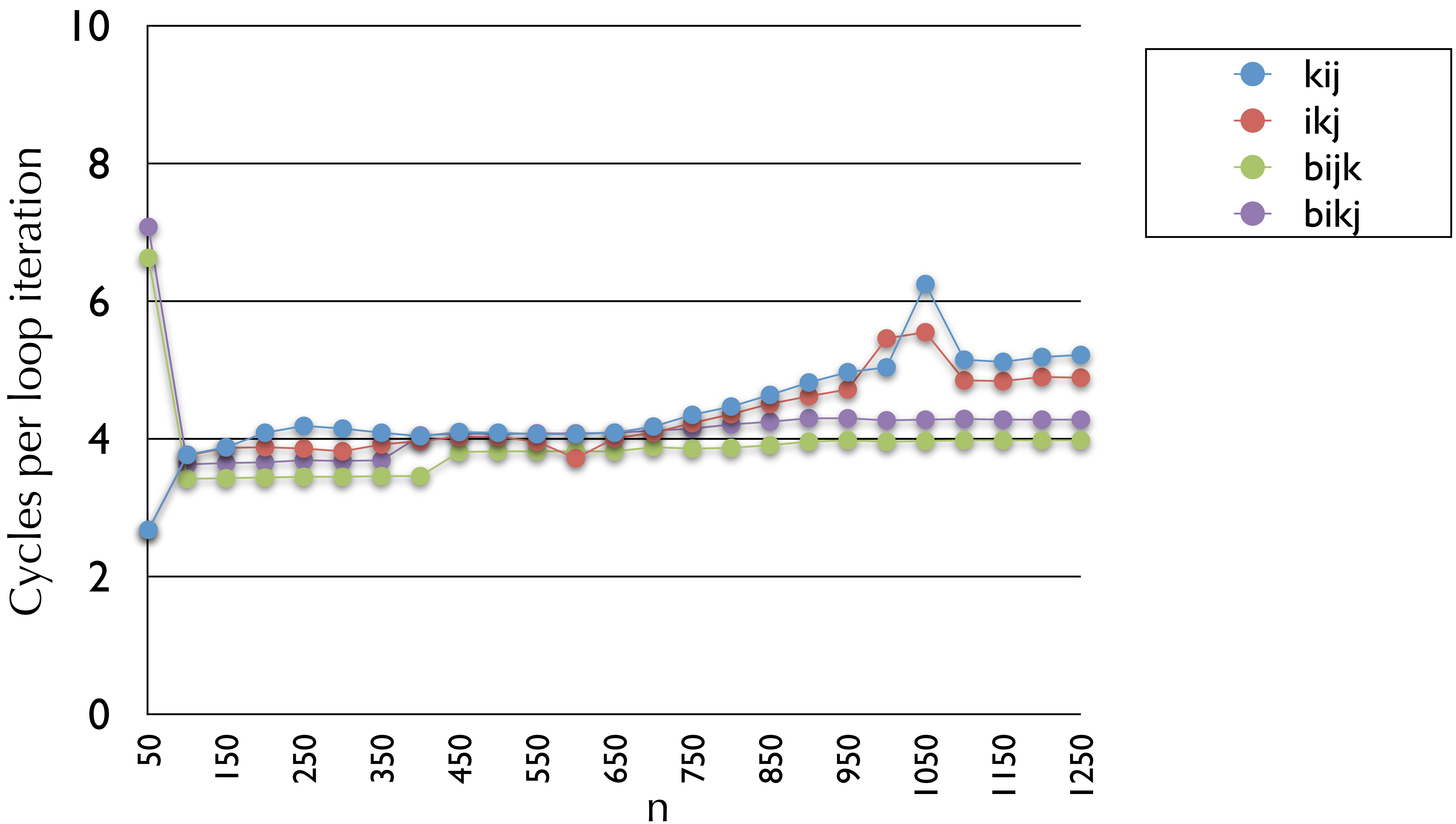
***CAVEAT: Tested on a VM***



# Exploiting locality in your programs

- Focus attention on inner loops
  - This is where most computation and memory accesses in your program occurs
- Try to maximize spatial locality
  - Read data objects sequentially, with stride 1, in the order they are stored in memory
- Try to maximize temporal locality
  - Use a data object as often as possible once it has been read from memory

# Next lecture

- Virtual memory
  - Using memory as a cache for disk

# Cache performance test program

```
/* The test function */
void test(int elems, int stride) {
    int i, result = 0;
    volatile int sink;

    for (i = 0; i < elems; i += stride)
        result += data[i];
    sink = result; /* So compiler doesn't optimize away the loop */
}

/* Run test(elems, stride) and return read throughput (MB/s) */
double run(int size, int stride)
{
    uint64_t start_cycles, end_cycles, diff;
    int elems = size / sizeof(int);

    test(elems, stride);                        /* warm up the cache */
    start_cycles = get_cpu_cycle_counter();     /* Read CPU cycle counter */
    test(elems, stride);                        /* Run test */
    end_cycles = get_cpu_cycle_counter();       /* Read CPU cycle counter again */
    diff = end_cycles - start_cycles;           /* Compute time */
    return (size / stride) / (diff / CPU_MHZ);  /* convert cycles to MB/s */
}
```

# Cache performance main routine

```
#define CPU_MHZ 2.8 * 1024.0 * 1024.0; /* e.g., 2.8 GHz */
#define MINBYTES (1 << 10)  /* Working set size ranges from 1 KB */
#define MAXBYTES (1 << 23)  /* ... up to 8 MB */
#define MAXSTRIDE 16        /* Strides range from 1 to 16 */
#define MAXELEMS MAXBYTES/sizeof(int)

int data[MAXELEMS];         /* The array we'll be traversing */

int main()
{
    int size;        /* Working set size (in bytes) */
    int stride;      /* Stride (in array elements) */

    init_data(data, MAXELEMS); /* Initialize each element in data to 1 */
    for (size = MAXBYTES; size >= MINBYTES; size >>= 1) {
        for (stride = 1; stride <= MAXSTRIDE; stride++)
            printf("%.1f\t", run(size, stride));
        printf("\n");
    }
    exit(0);
}
```