15-213

"The course that gives CMU its Zip!"

Cache Memories
Oct 11, 2001

Topics

- **Generic cache memory organization**
- **Direct mapped caches**
- **Set associative caches**
- **Impact of caches on performance**

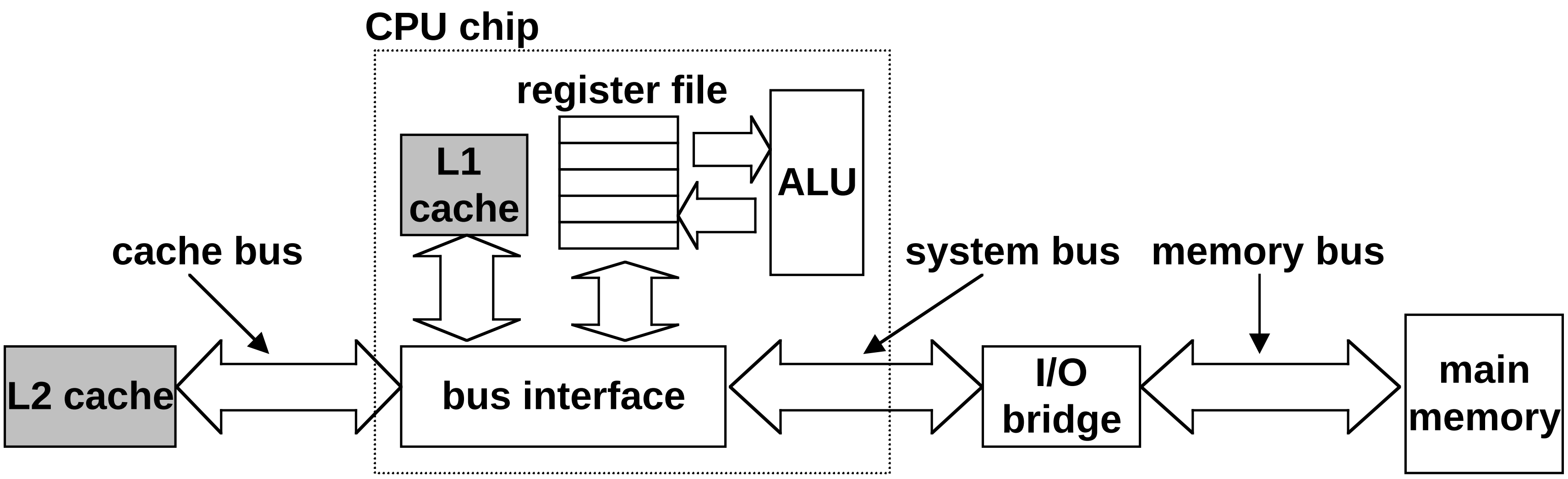
Cache memories

Cache memories are small, fast SRAM-based memories managed automatically in hardware.

- Hold frequently accessed blocks of main memory

CPU looks first for data in L1, then in L2, then in main memory.

Typical bus structure:



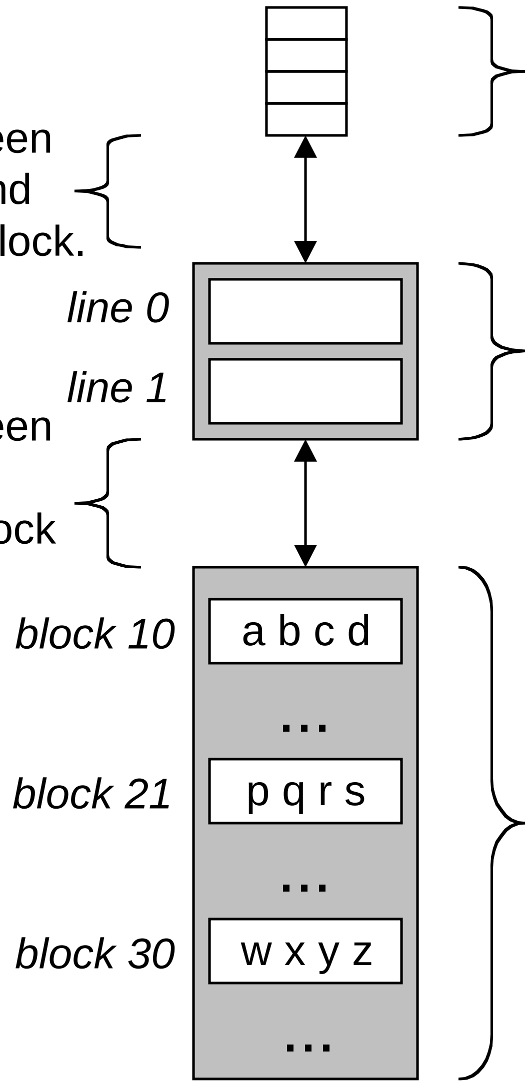
Inserting an L1 cache between the CPU and main memory

The tiny, very fast CPU **register file** has room for four 4-byte words.

The transfer unit between the CPU register file and the cache is a 4-byte block.

The small fast **L1 cache** has room for two 4-word blocks.

The transfer unit between the cache and main memory is a 4-word block (16 bytes).



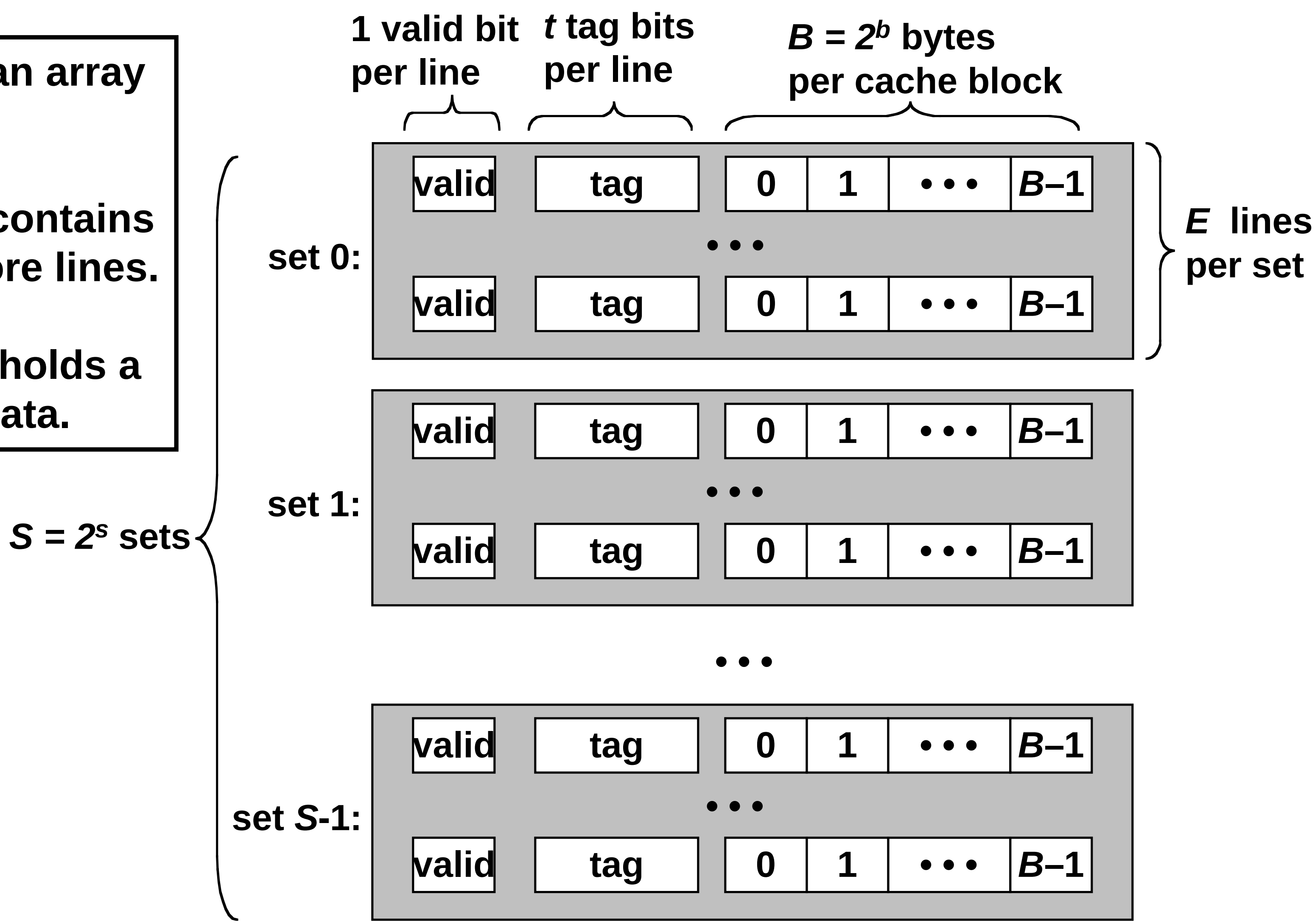
The big slow **main memory** has room for many 4-word blocks.

General organization of a cache memory

Cache is an array of sets.

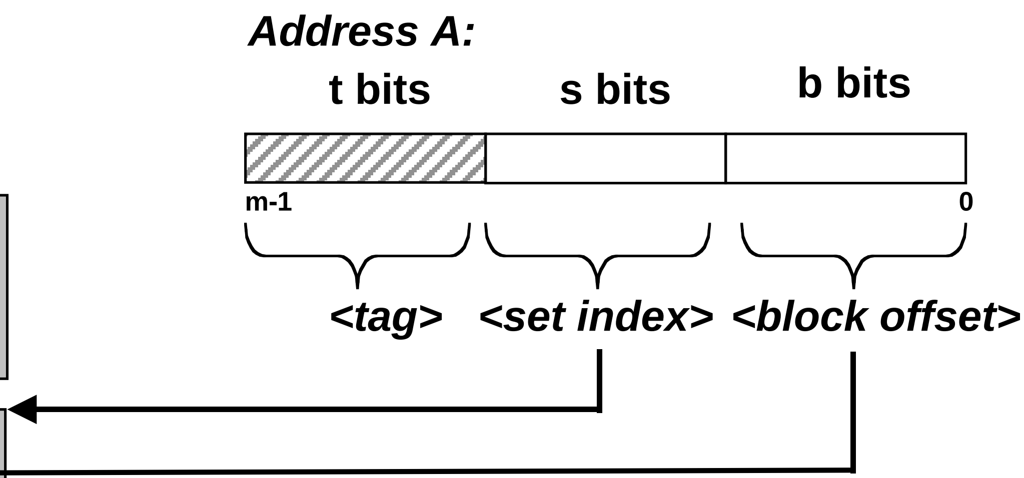
Each set contains one or more lines.

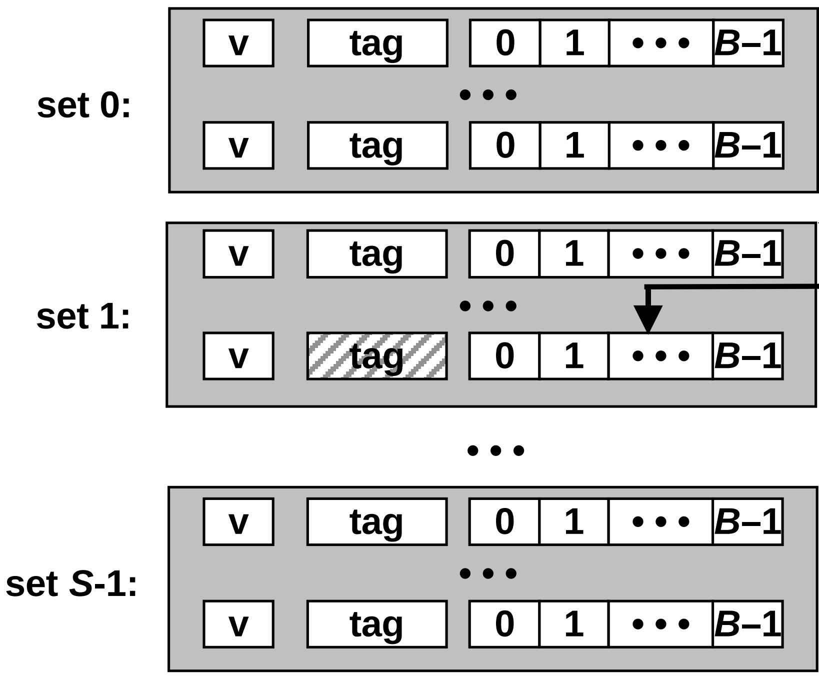
Each line holds a block of data.



Cache size: $C = B \times E \times S$ data bytes

Addressing caches



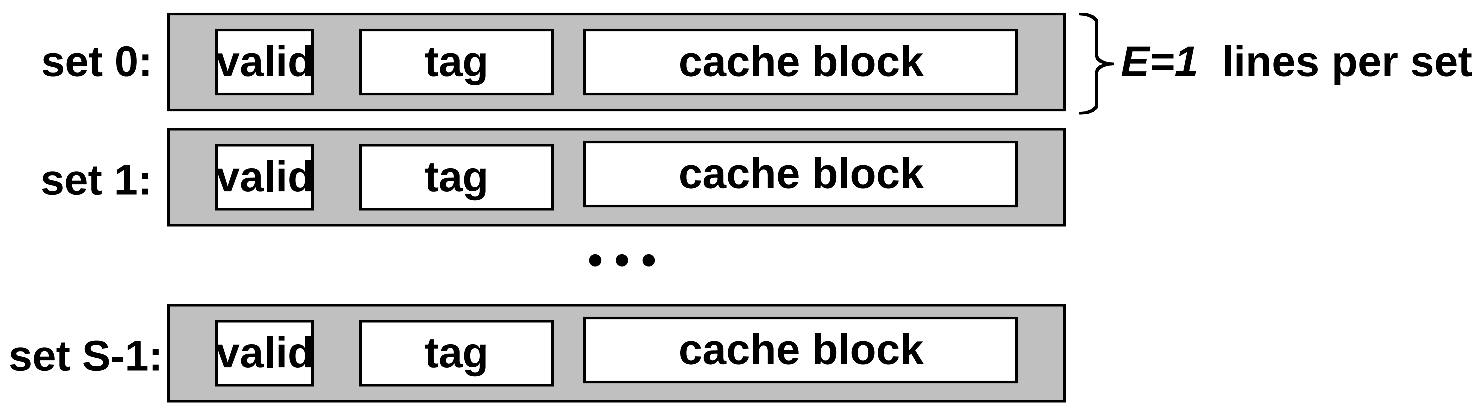


The word at address A is in the cache if the tag bits in one of the <valid> lines in set <set index> match <tag>.

The word contents begin at offset <block offset> bytes from the beginning of the block.

Direct-mapped cache

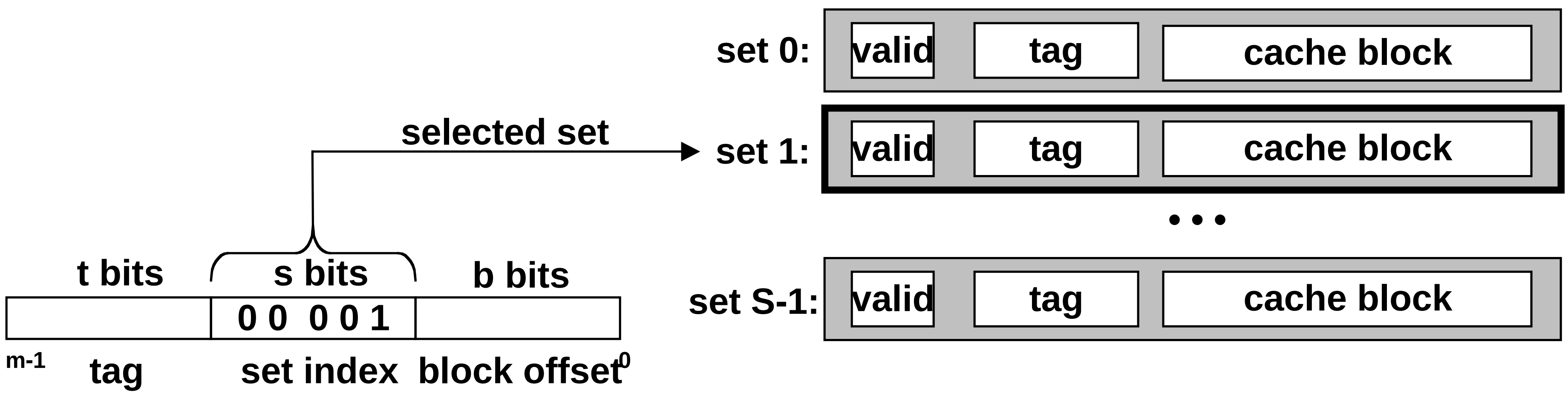
- Simplest kind of cache
- Characterized by exactly one line per set.



Accessing direct-mapped caches

Set selection

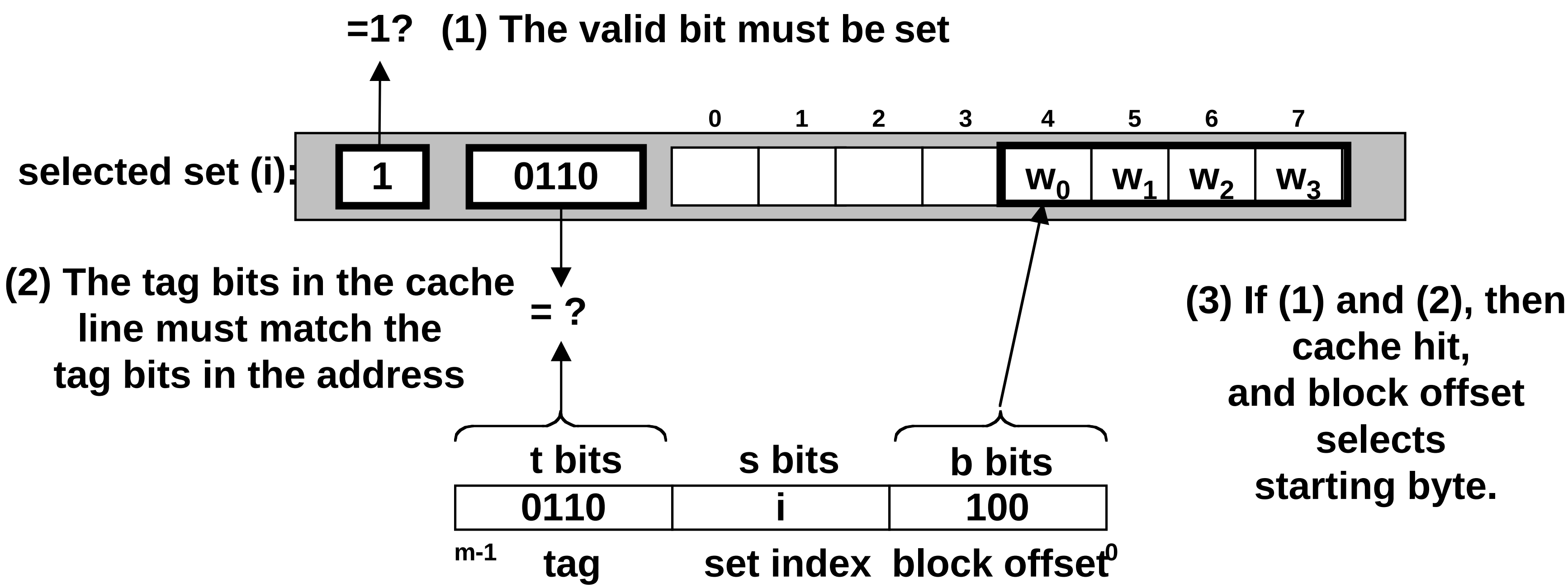
- Use the set index bits to determine the set of interest.



Accessing direct-mapped caches

Line matching and word selection

- find a valid line in the selected set with a matching tag (line matching)
- then extract the word (word selection)



Direct-mapped cache simulation

t=1	s=2	b=1
x	xx	x

M=16 byte addresses, B=2 bytes/block, S=4 sets, E=1 entry/set
Address trace (reads):
0 [0000] 1 [0001] 13 [1101] 8 [1000] 0 [0000]

(1) 0 [0000] (miss)

v	tag	data

(2) 13 [1101] (miss)

v	tag	data

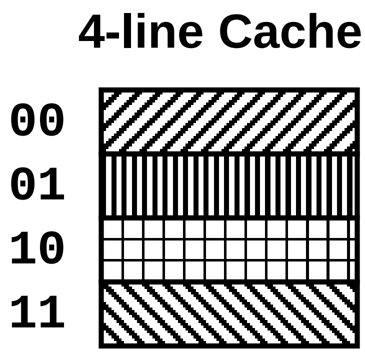
(3) 8 [1000] (miss)

v	tag	data

(4) 0 [0000] (miss)

v	tag	data

Why use middle bits as index?

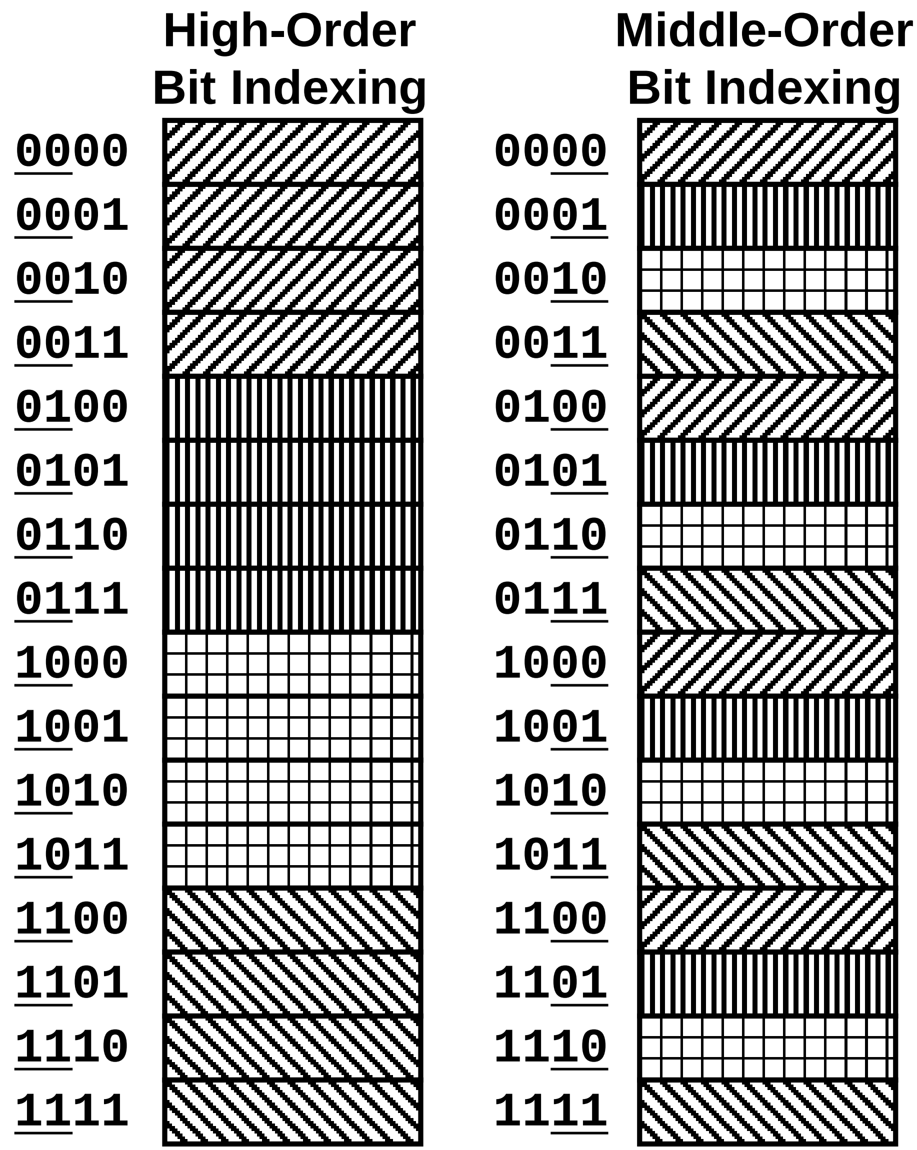


High-Order Bit Indexing

- Adjacent memory lines would map to same cache entry
- Poor use of spatial locality

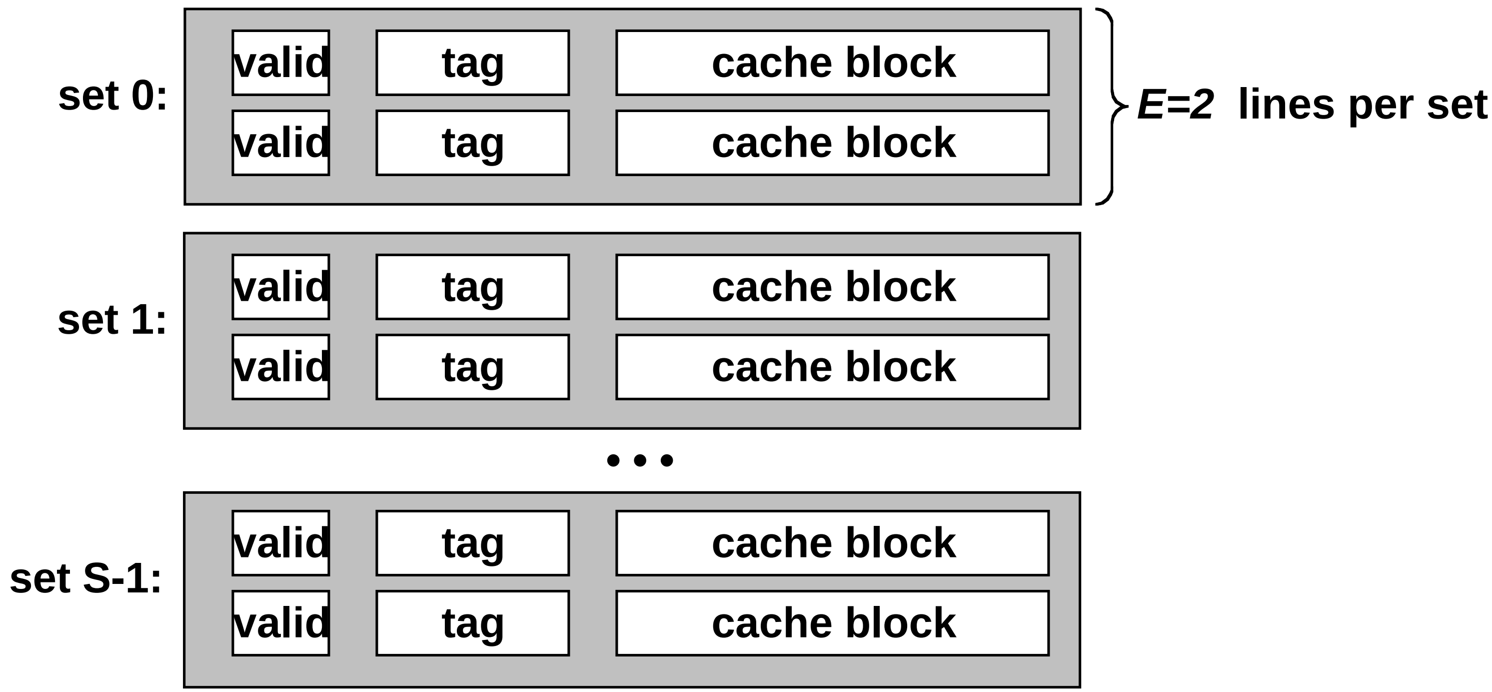
Middle-Order Bit Indexing

- Consecutive memory lines map to different cache lines
- Can hold C-byte region of address space in cache at one time



Set associative caches

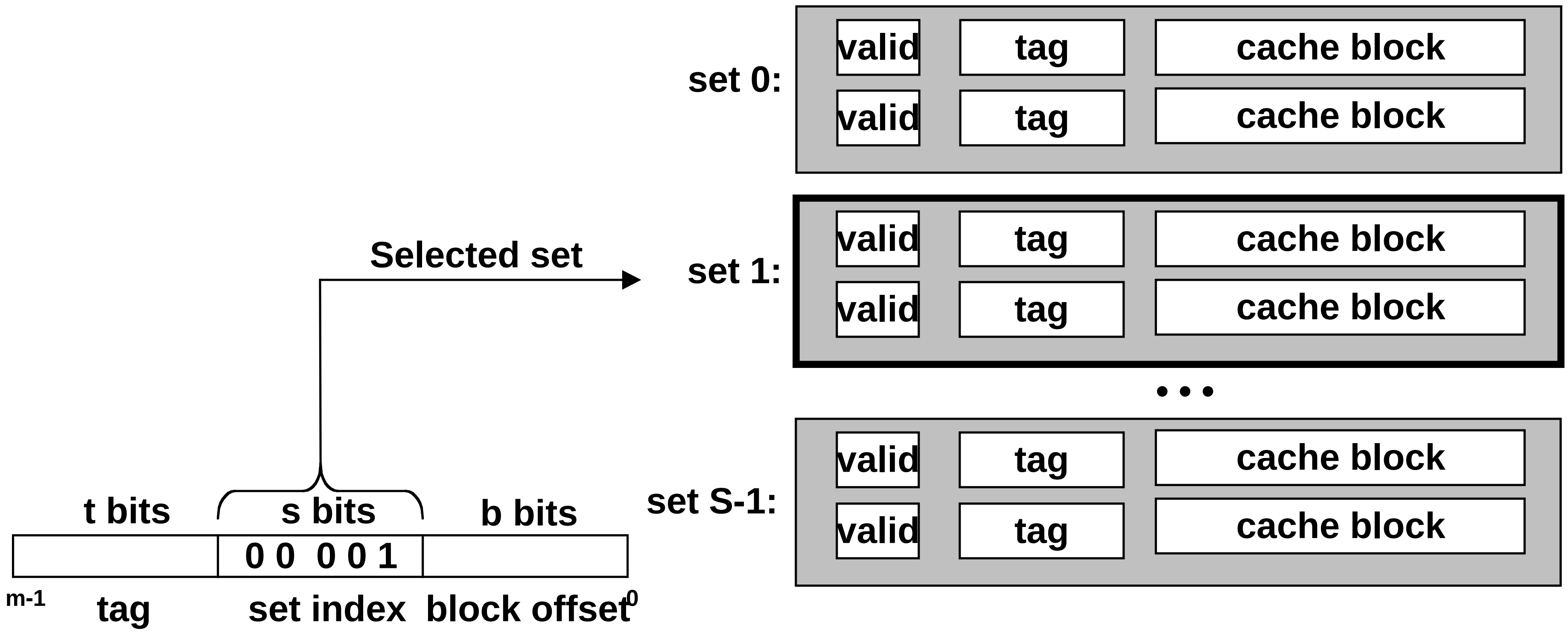
Characterized by more than one line per set



Accessing set associative caches

Set selection

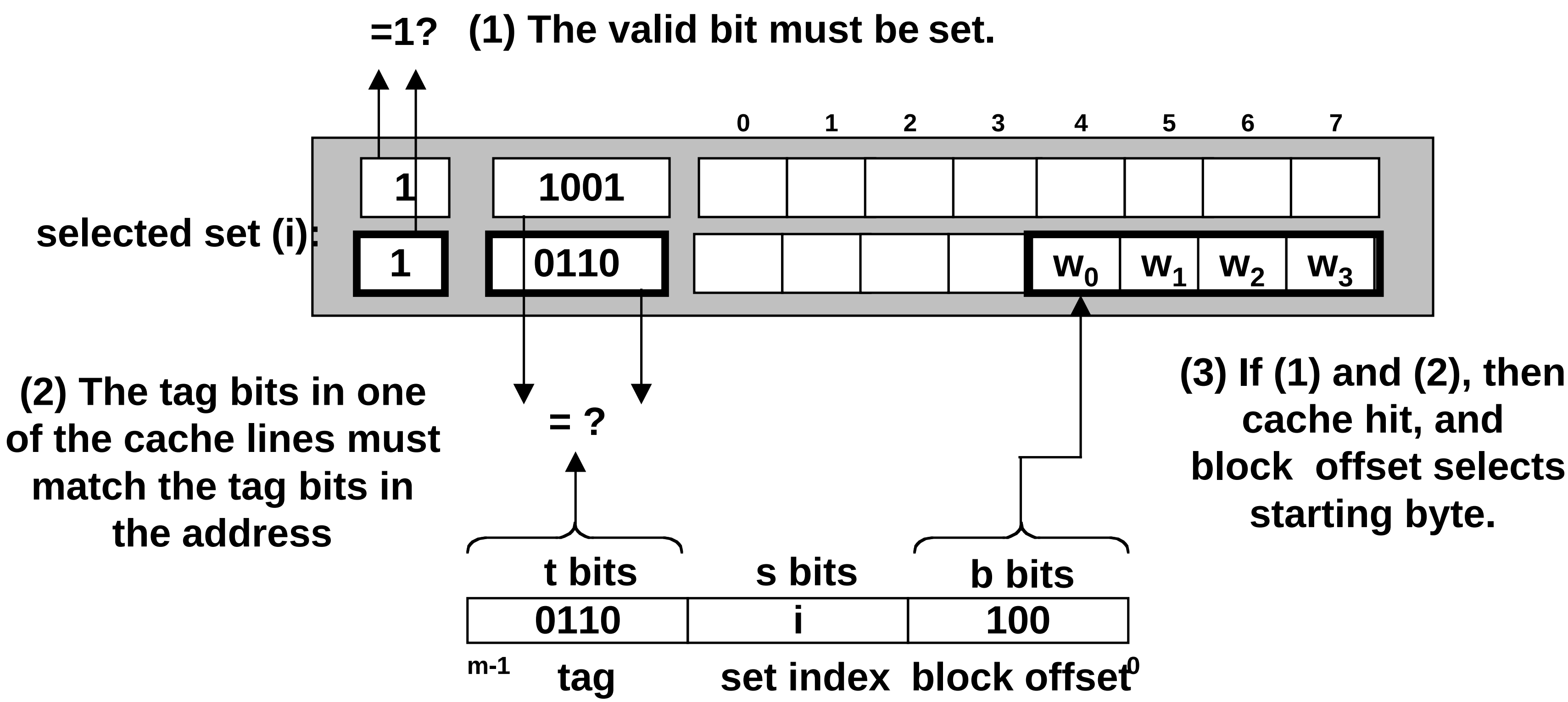
- identical to direct-mapped cache



Accessing set associative caches

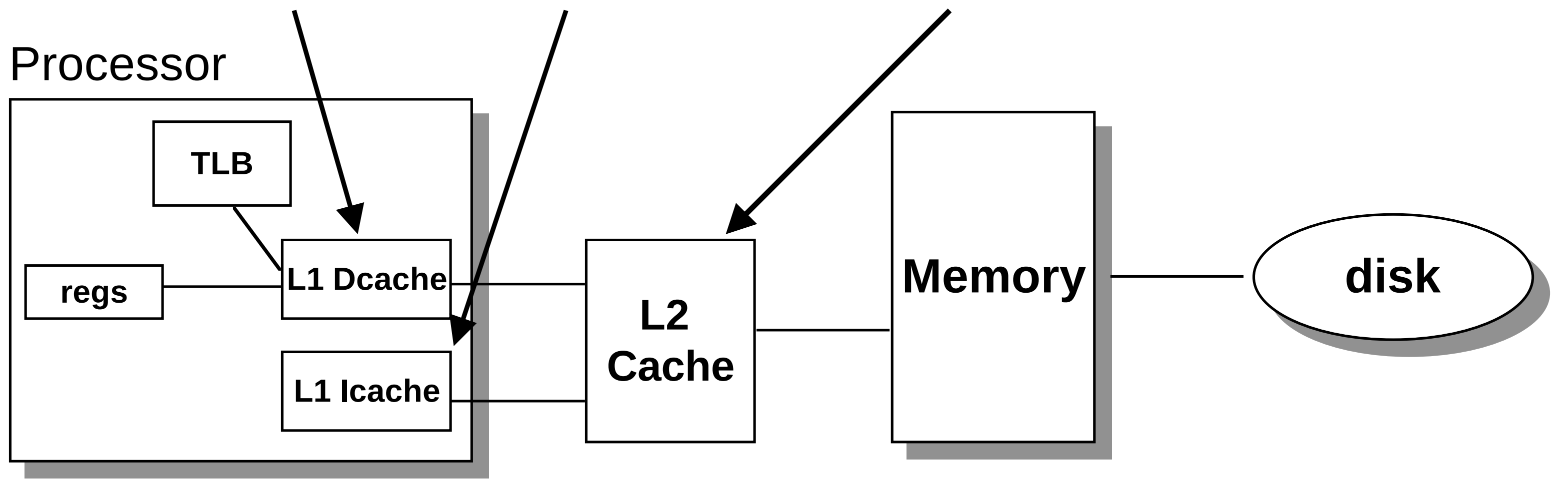
Line matching and word selection

- must compare the tag in each valid line in the selected set.



Multi-level caches

Options: ***separate*** data and instruction caches, or a ***unified*** cache

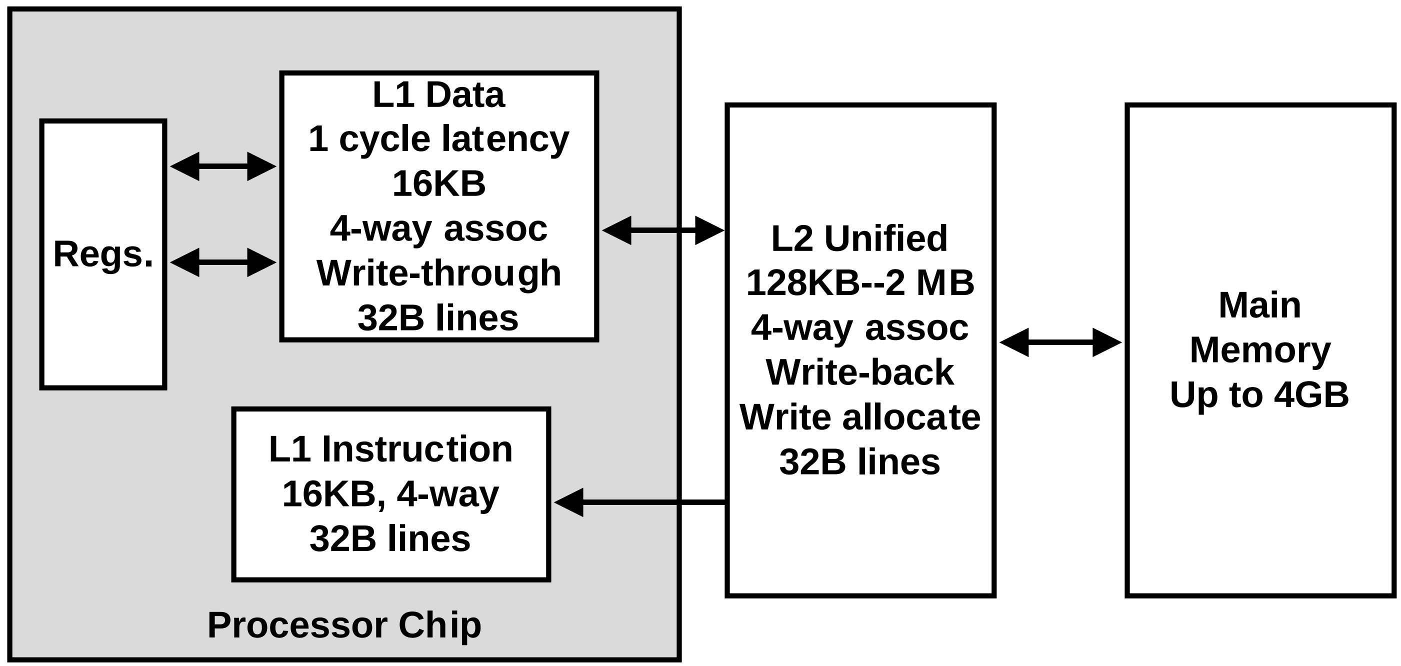


size:	200 B	8-64 KB	1-4MB SRAM	128 MB DRAM	30 GB
speed:	3 ns	3 ns	6 ns	60 ns	8 ms
$/Mbyte:			$100/MB	$1.50/MB	$0.05/MB
line size:	8 B	32 B	32 B	8 KB	

larger, slower, cheaper

larger line size, higher associativity, more likely to write back

Intel Pentium cache hierarchy



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, 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)**
- **Typical numbers:**

  1 clock cycle for L1

  3-8 clock cycles for L2

Miss Penalty

- **additional time required because of a miss**
  - Typically 25-100 cycles for main memory

Writing cache friendly code

Repeated references to variables are good (temporal locality)

Stride-1 reference patterns are good (spatial locality)

Example

- **cold cache, 4-byte words, 4-word cache blocks**

```
int sumarrayrows(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;
}
```

```
int sumarraycols(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 =

Miss rate =

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.

Memory mountain test function

```
/* 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, double Mhz)
{
    double cycles;
    int elems = size / sizeof(int);

    test(elems, stride);                       /* warm up the cache */
    cycles = fcyc2(test, elems, stride, 0);  /* call test(elems,stride) */
    return (size / stride) / (cycles / Mhz); /* convert cycles to MB/s */
}
```

Memory mountain main routine

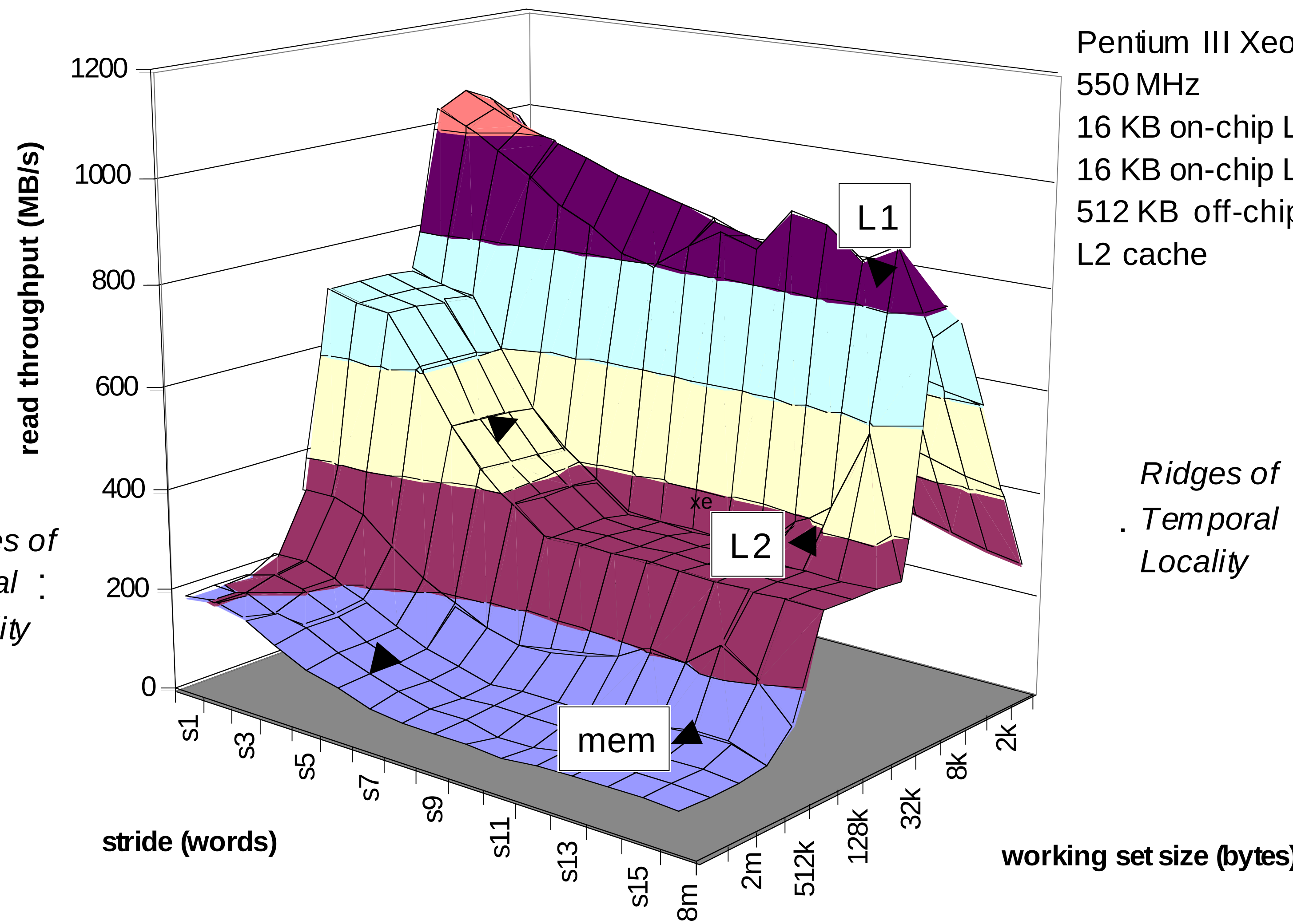
```
/* mountain.c - Generate the memory mountain. */
#define MINBYTES (1 << 10)  /* Working set size ranges from 1 KB */
#define MAXBYTES (1 << 23)  /* ... up to 8 MB */
#define MAXSTRIDE 16        /* Strides range from 1 to 16 */
#define MAXELEMS MAXBYTES/sizeof(int)

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

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

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

The Memory Mountain



Pentium III Xeon
550 MHz
16 KB on-chip L1 d-cache
16 KB on-chip L1 i-cache
512 KB off-chip unified
L2 cache

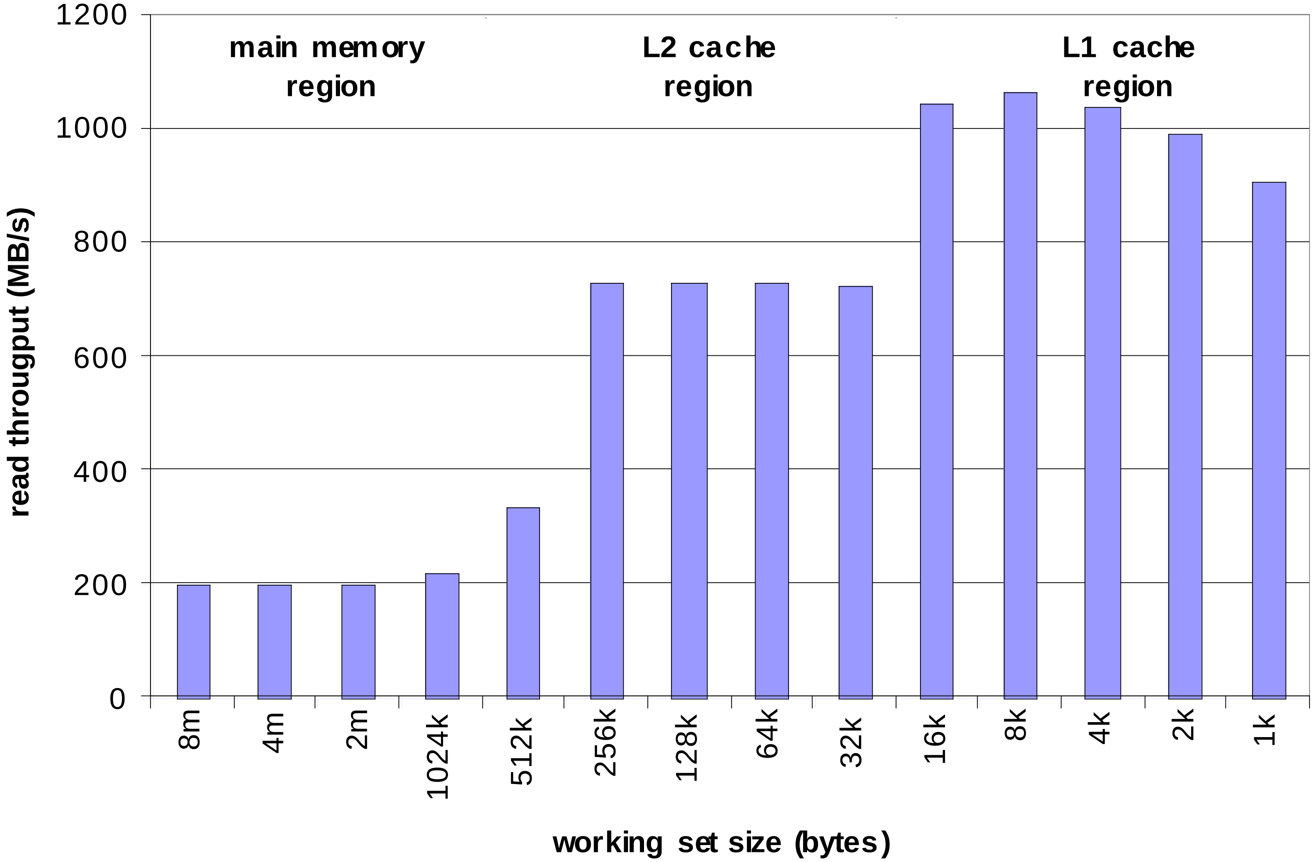
Ridges of Temporal Locality

Slopes of Spatial Locality

Ridges of temporal locality

Slice through the memory mountain with stride=1

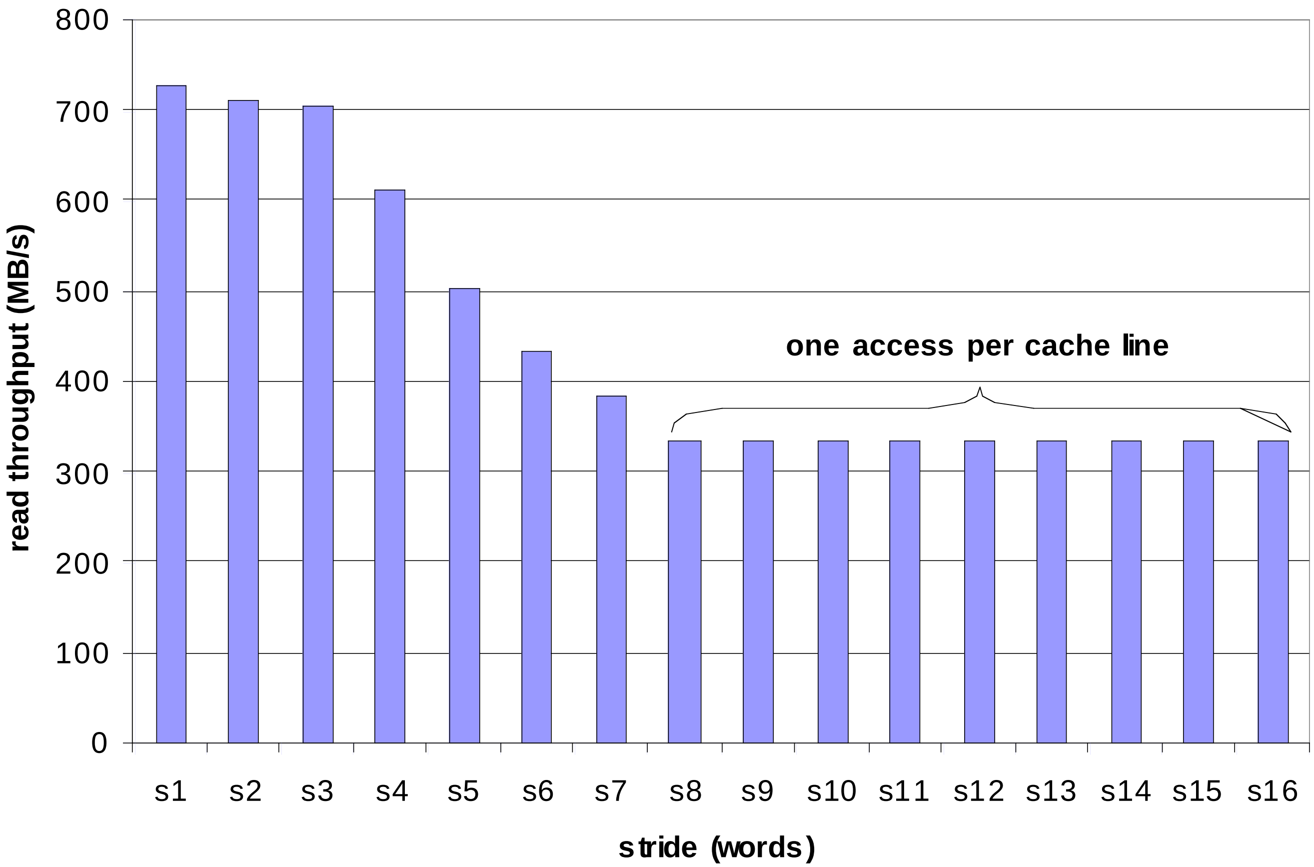
- **illuminates read throughputs of different caches and memory**



A slope of spatial locality

Slice through memory mountain with size=256KB

- **shows cache block size.**



Matrix multiplication example

Major Cache Effects to Consider

- **Total cache size**
  - Exploit temporal locality and keep the working set small (e.g., by using blocking)
- **Block size**
  - Exploit spatial locality

Description:

- **Multiply N x N matrices**
- **O(N^3) total operations**
- **Accesses**
  - 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*

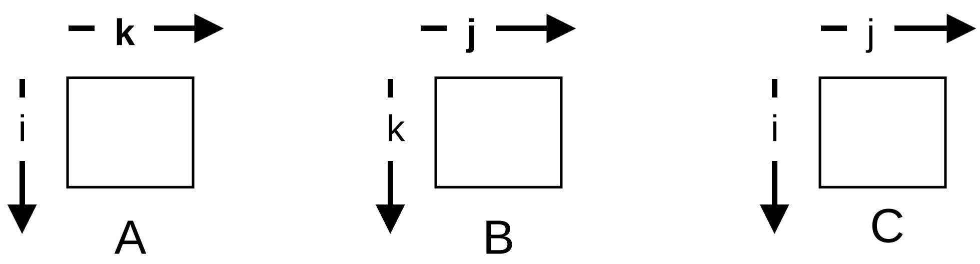
Miss rate analysis for matrix multiply

Assume:

- **Line size = 32B (big enough for 4 64-bit words)**
- **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 arrays in memory

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) > 4 bytes, exploit spatial locality**
  - compulsory miss rate = 4 bytes / B

Stepping through rows in one column:

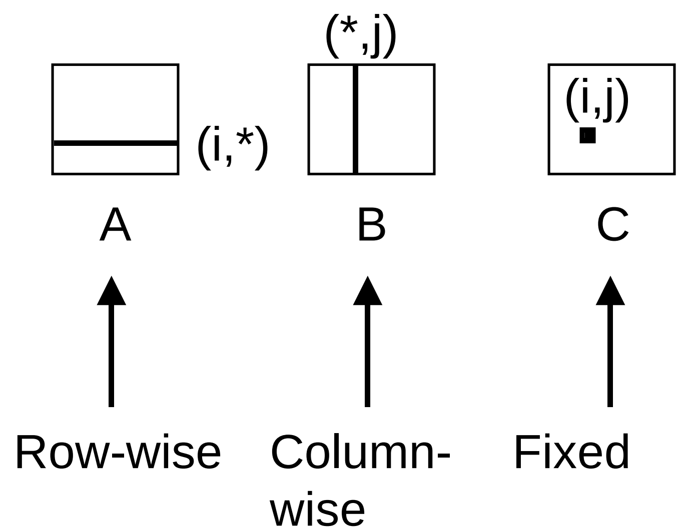
```
for (i = 0; i < n; i++)
   sum += a[i][0];
```

- **accesses distant elements**
- ***no spatial locality!***
  - compulsory miss rate = 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;
  }
}
```

Inner loop:

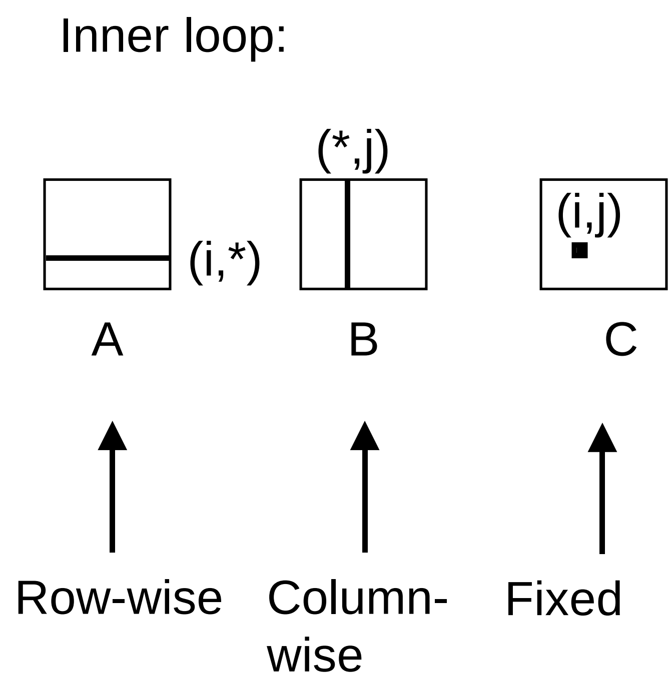


<u>Misses per Inner Loop Iteration:</u>

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
  }
}
```

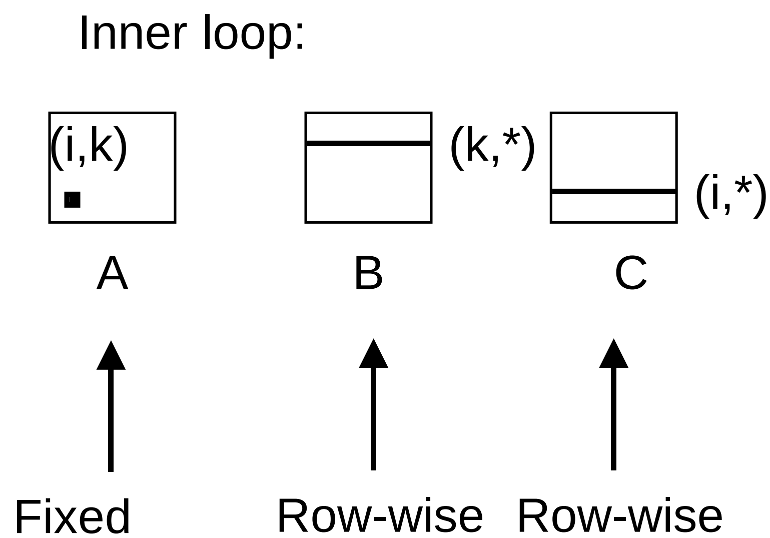


Misses per Inner Loop Iteration:

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];
  }
}
```

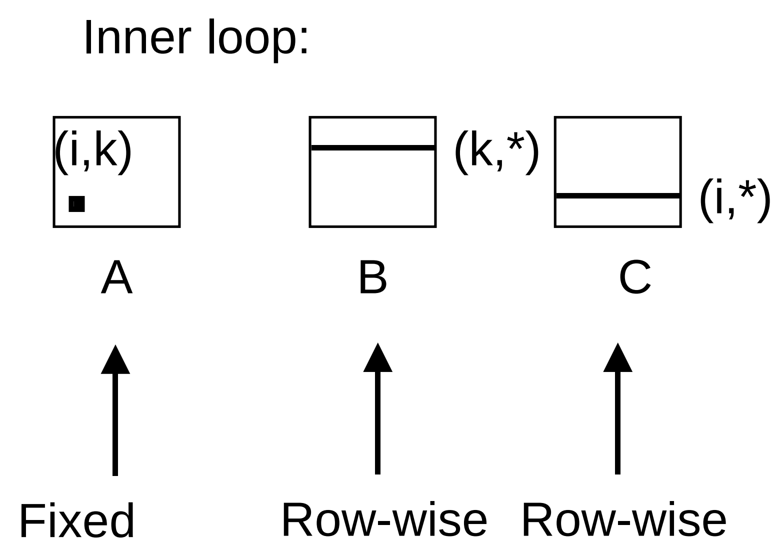


Misses per Inner Loop Iteration:

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];
  }
}
```

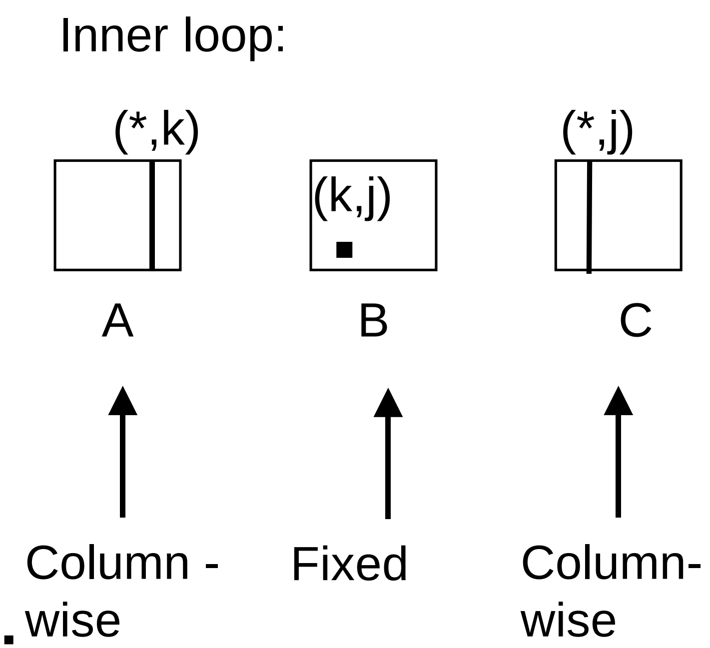


Misses per Inner Loop Iteration:

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;
  }
}
```



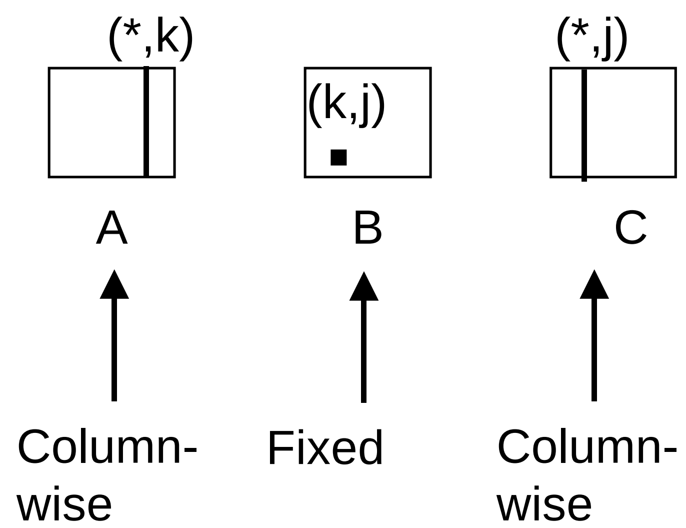
Misses per Inner Loop Iteration:

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;
  }
}
```

Inner loop:



<u>Misses per Inner Loop Iteration:</u>

A	B	C
1.0	0.0	1.0

Summary of matrix multiplication

ijk (& jik):
- 2 loads, 0 stores
- misses/iter = **1.25**

```
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;
   }
}
```

kij (& ikj):
- 2 loads, 1 store
- misses/iter = **0.5**

```
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];
    }
}
```

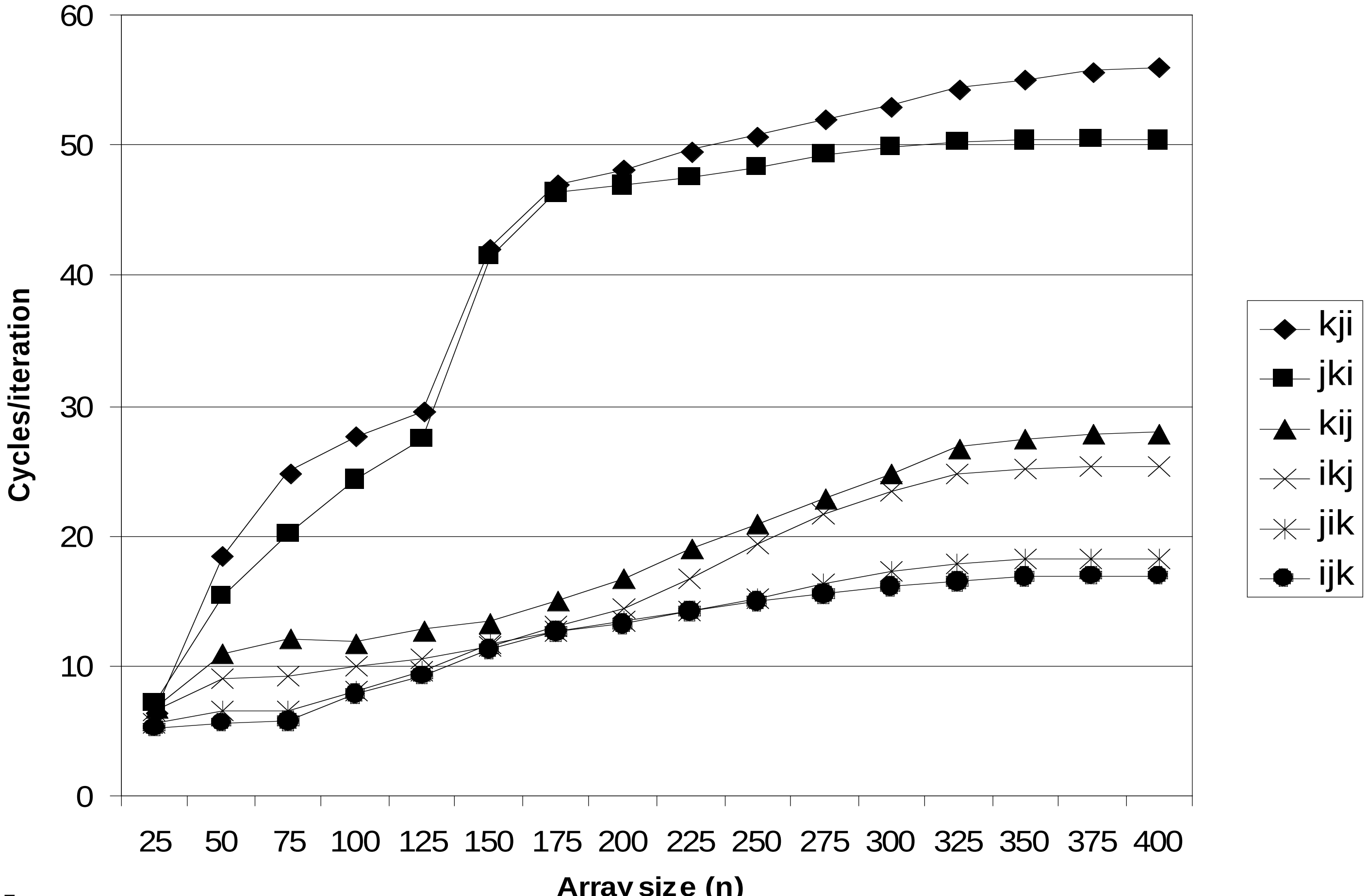
jki (& kji):
- 2 loads, 1 store
- misses/iter = **2.0**

```
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;
    }
}
```

Pentium matrix multiply performance

Notice that miss rates are helpful but not perfect predictors.

– Code scheduling matters, too.



Improving temporal locality by blocking

Example: Blocked matrix multiplication

- **"block" (in this context) does not mean "cache block".**
- **Instead, it mean a sub-block within the matrix.**
- **Example: N = 8; sub-block size = 4**

$$\begin{bmatrix} A11 & A12 \\ A21 & A22 \end{bmatrix} \times \begin{bmatrix} B11 & B12 \\ B21 & B22 \end{bmatrix} = \begin{bmatrix} C11 & C12 \\ C21 & C22 \end{bmatrix}$$

<u>Key idea:</u> Sub-blocks (i.e., $\mathbf{A_{xy}}$) can be treated just like scalars.

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

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

Blocked matrix multiply (bijk)

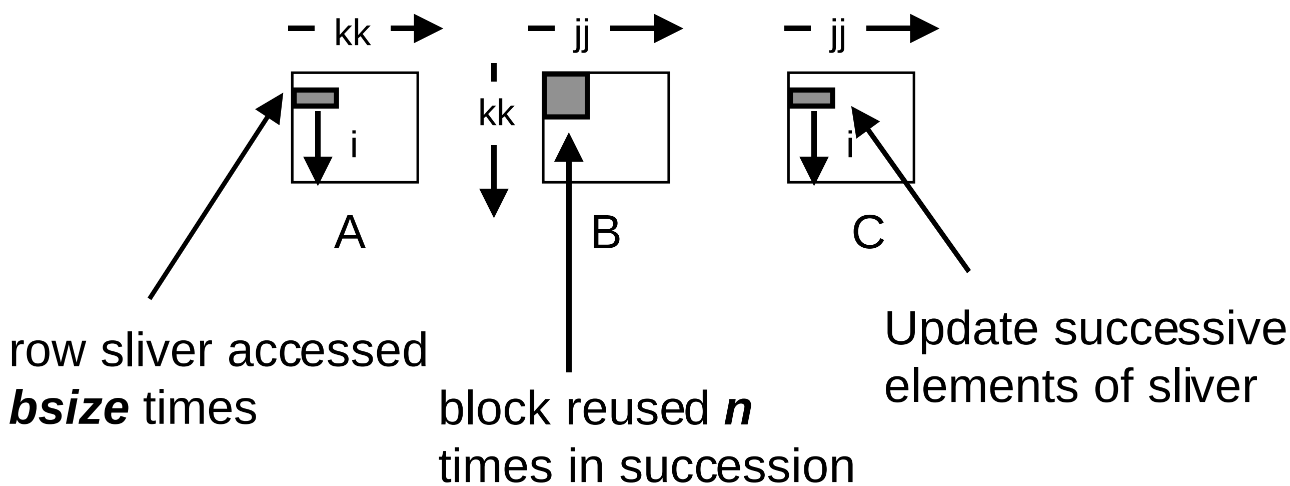
```
for (jj=0; jj<n; jj+=bsize) {
  for (i=0; i<n; i++)
    for (j=jj; j < min(jj+bsize,n); j++)
      c[i][j] = 0.0;
  for (kk=0; kk<n; kk+=bsize) {
    for (i=0; i<n; i++) {
      for (j=jj; j < min(jj+bsize,n); j++) {
        sum = 0.0
        for (k=kk; k < min(kk+bsize,n); k++) {
          sum +=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

Blocked matrix multiply analysis

- **Innermost loop pair multiplies a 1 X *bsize* sliver of A by a *bsize* X *bsize* block of B and accumulates into 1 X *bsize* sliver of C**
- **Loop over i steps through n row slivers of A & C, using same B**

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

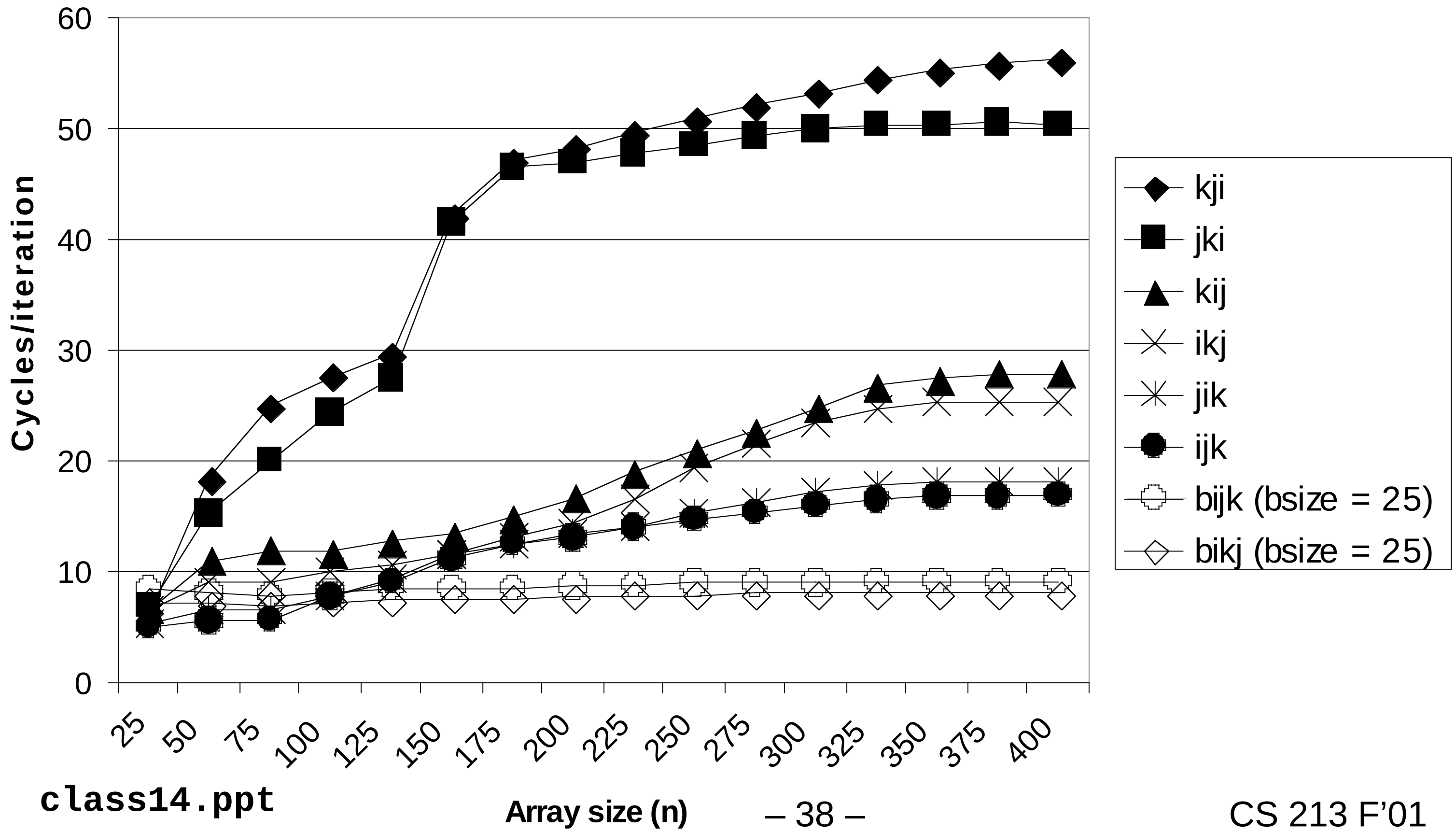
Innermost Loop Pair



Pentium blocked matrix multiply performance

Blocking (bijk and bikj) improves performance by a factor of two over unblocked versions (ijk and jik)

- **relatively insensitive to array size.**



Concluding observations

Programmer can optimize for cache performance

- **How data structures are organized**
- **How data accessed**
  - Nested loop structure
  - Blocking (see text) is a general technique

All machines like "cache friendly code"

- **Getting absolute optimum performance very platform specific**
  - Cache sizes, line sizes, associativities, etc.
- **Can get most of the advantage with generic code**
  - Keep working set reasonably small (temporal locality)
  - Use small strides (spatial locality)