

Cache Memories

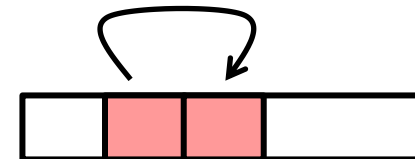
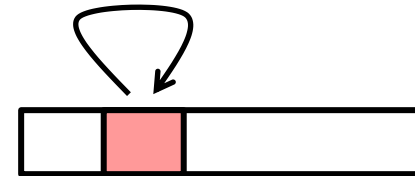
15-213/18-213/15-513: Introduction to Computer Systems
11th Lecture, June 17, 2021

Today

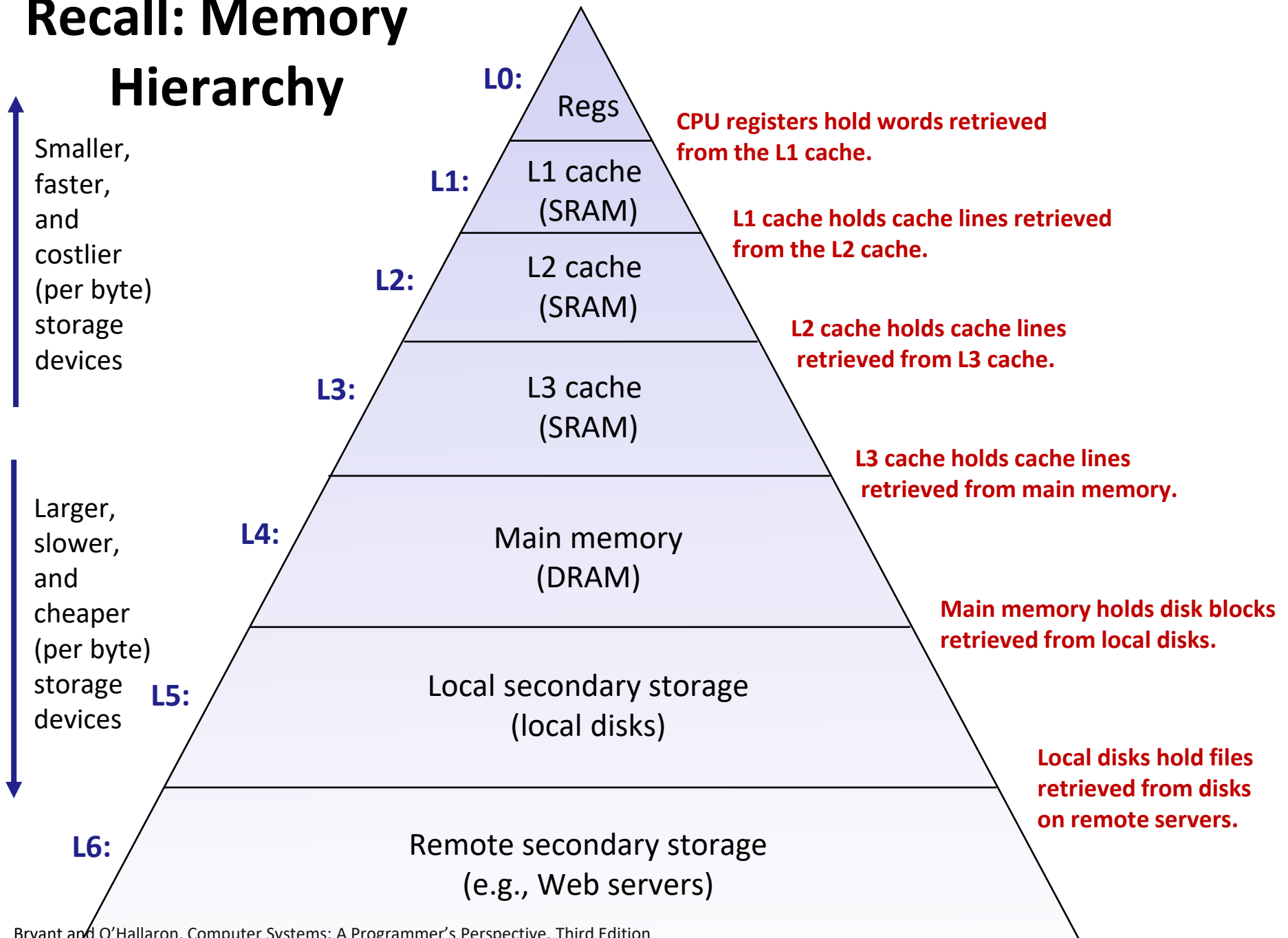
- **Cache memory organization and operation**
- **Performance impact of caches**
 - The memory mountain
 - Rearranging loops to improve spatial locality
 - Using blocking to improve temporal locality

Recall: Locality

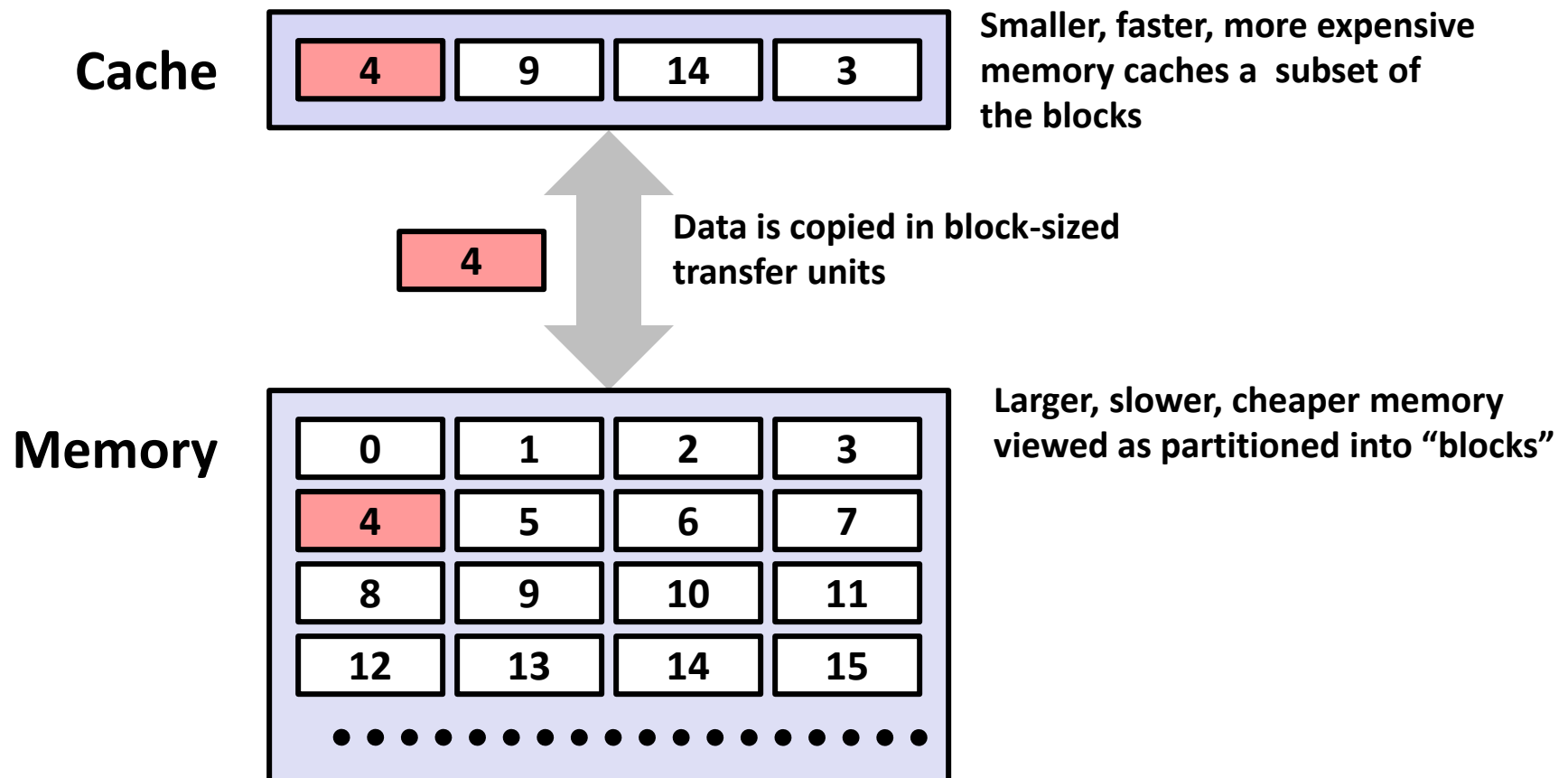
- **Principle of Locality:** Programs tend to use data and instructions with addresses near or equal to those they have used recently
- **Temporal locality:**
 - Recently referenced items are likely to be referenced again in the near future
- **Spatial locality:**
 - Items with nearby addresses tend to be referenced close together in time



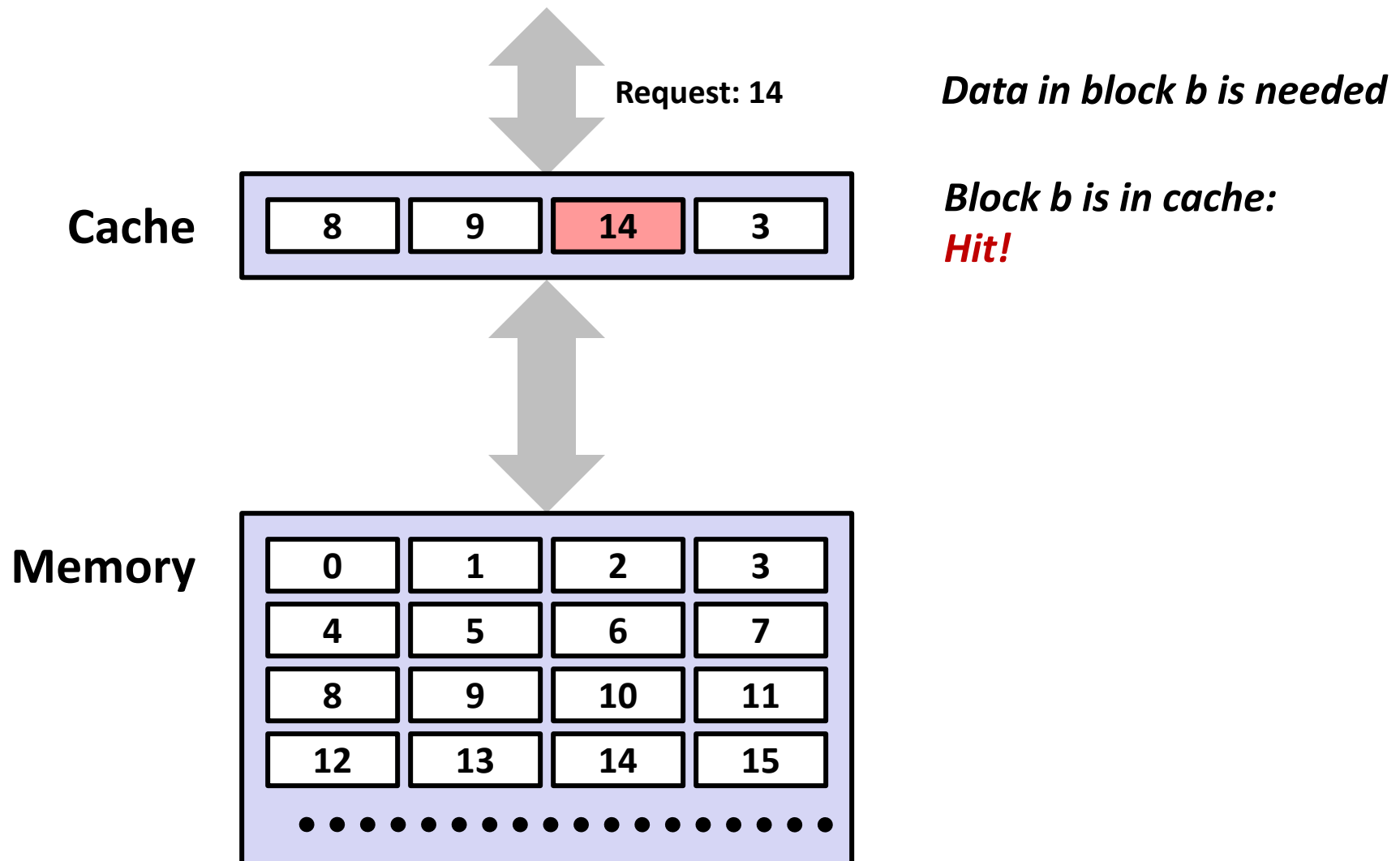
Recall: Memory Hierarchy



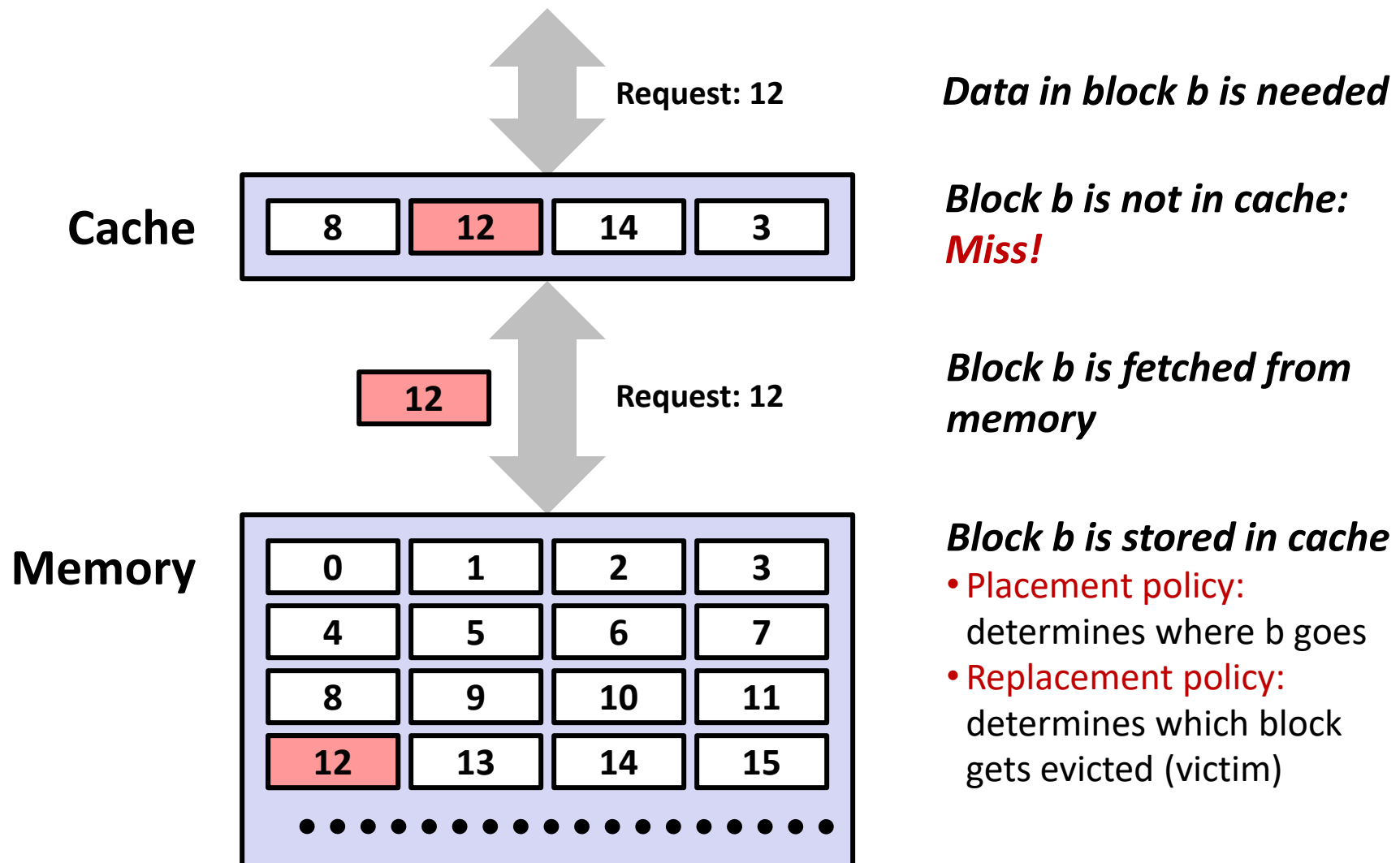
Recall: General Cache Concepts



General Cache Concepts: Hit



General Cache Concepts: Miss



Recall: General Caching Concepts:

3 Types of Cache Misses

■ Cold (compulsory) miss

- Cold misses occur because the cache starts empty and this is the first reference to the block.

■ Capacity miss

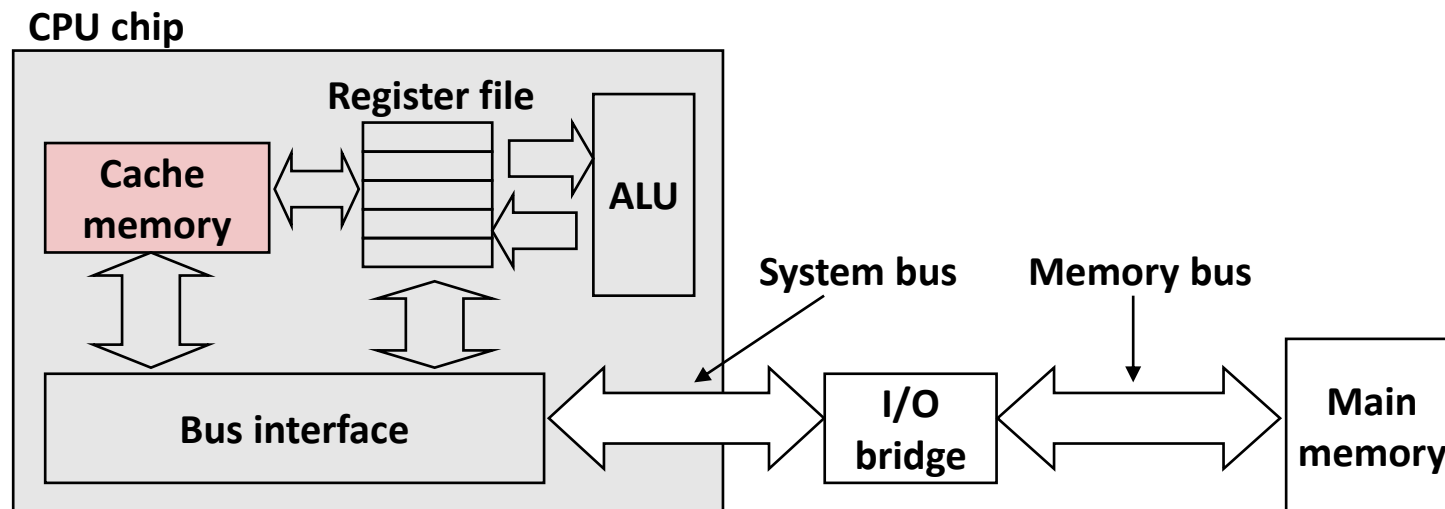
- Occurs when the set of active cache blocks (**working set**) is larger than the cache.

■ Conflict miss

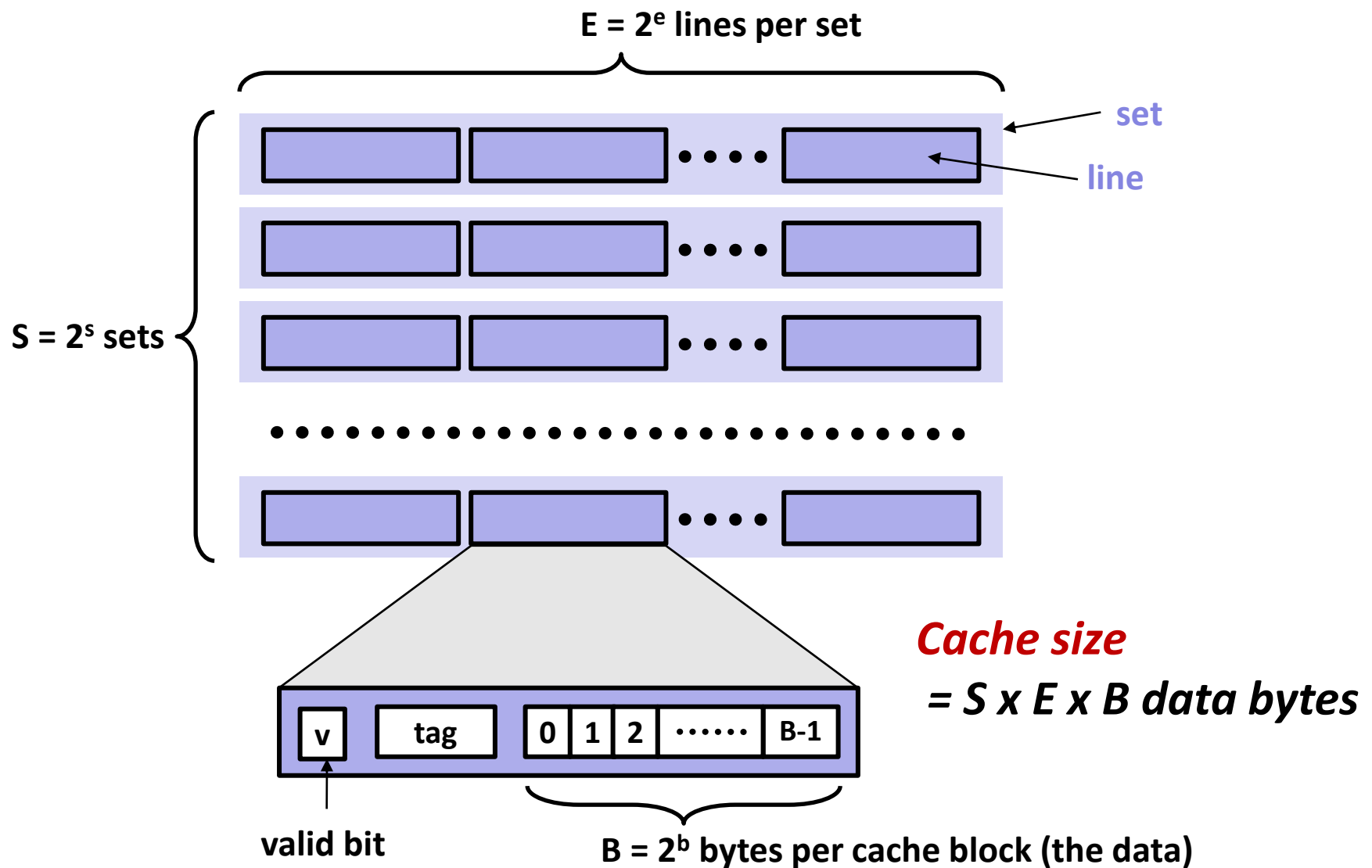
- Most caches limit blocks at level $k+1$ to a small subset (sometimes a singleton) of the block positions at level k .
 - E.g. Block i at level $k+1$ must be placed in block $(i \bmod 4)$ at level k .
- Conflict misses occur when the level k cache is large enough, but multiple data objects all map to the same level k block.
 - E.g. Referencing blocks 0, 8, 0, 8, 0, 8, ... would miss every time.

Cache Memories

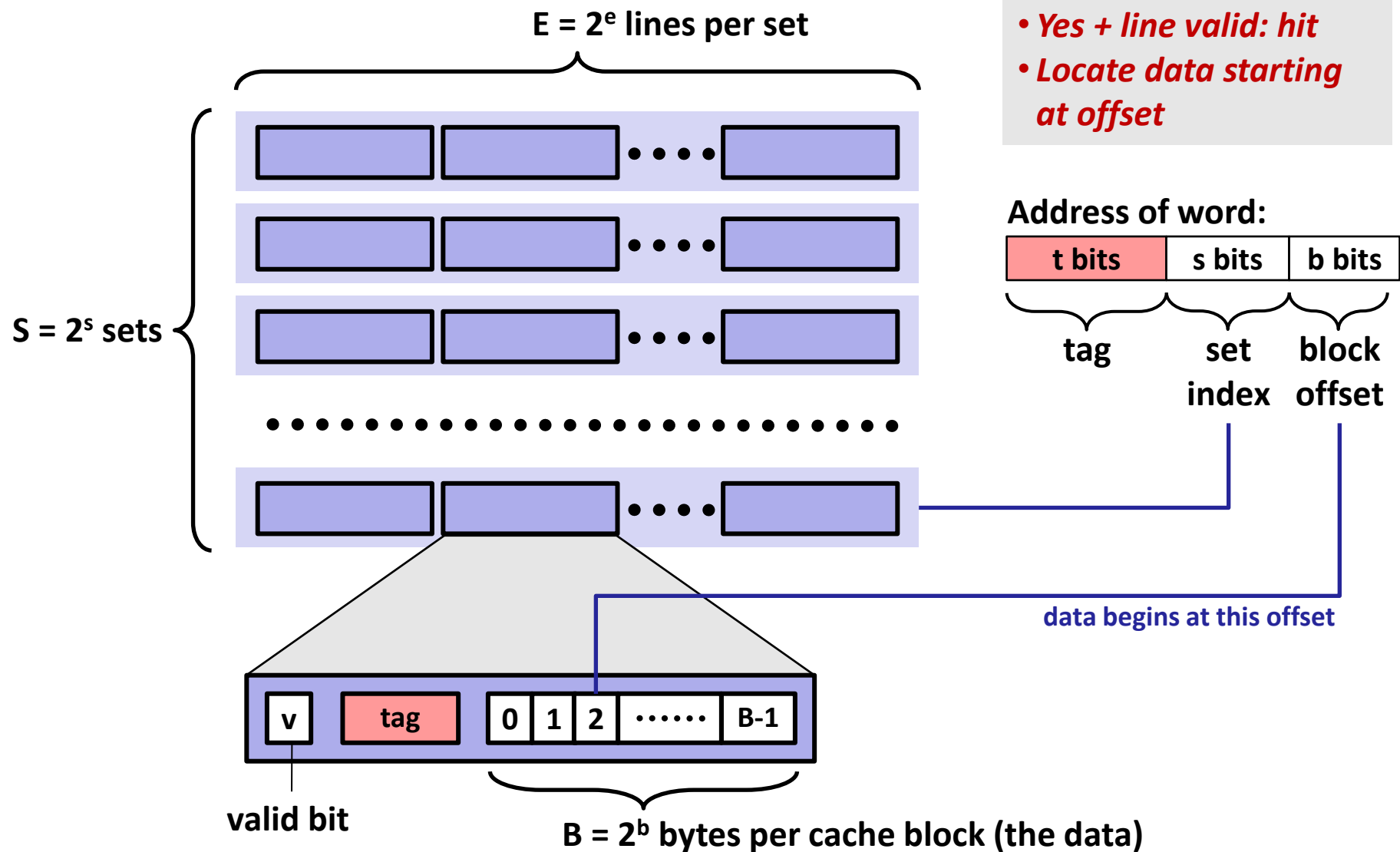
- **Cache memories** are small, fast SRAM-based memories managed automatically in hardware
 - Hold frequently accessed blocks of main memory
- **CPU looks first for data in cache**
- **Typical system structure:**



General Cache Organization (S, E, B)



Cache Read

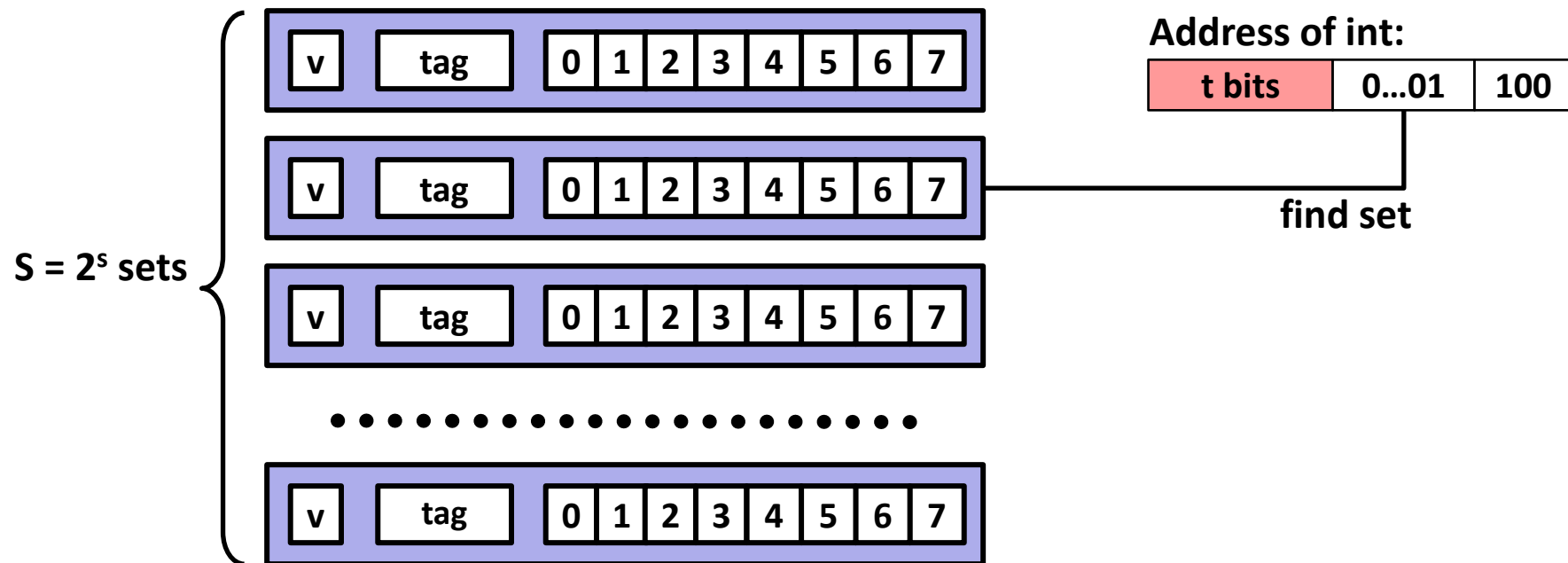


- *Locate set*
- *Check if any line in set has matching tag*
- *Yes + line valid: hit*
- *Locate data starting at offset*

Example: Direct Mapped Cache ($E = 1$)

Direct mapped: One line per set

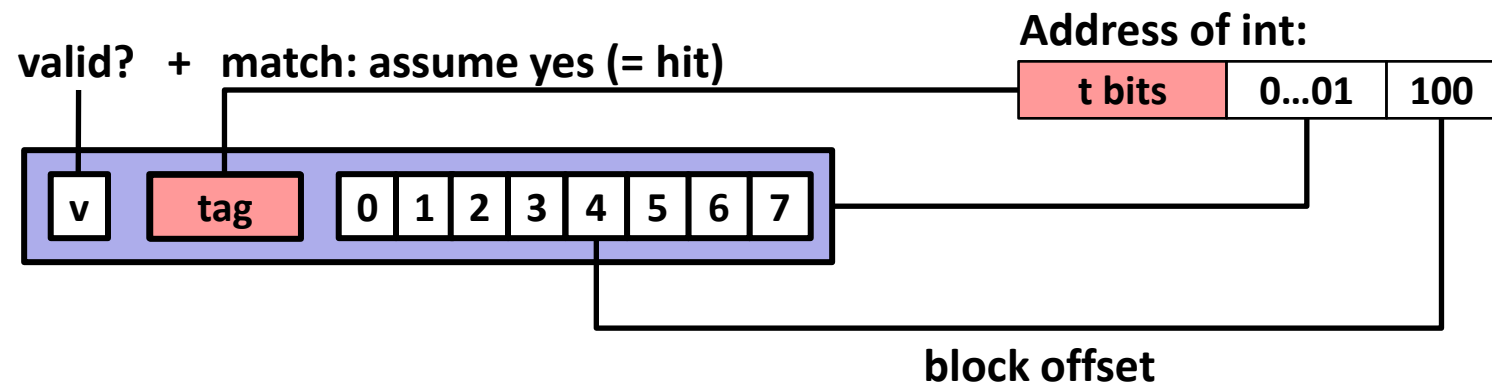
Assume: cache block size $B=8$ bytes



Example: Direct Mapped Cache (E = 1)

Direct mapped: One line per set

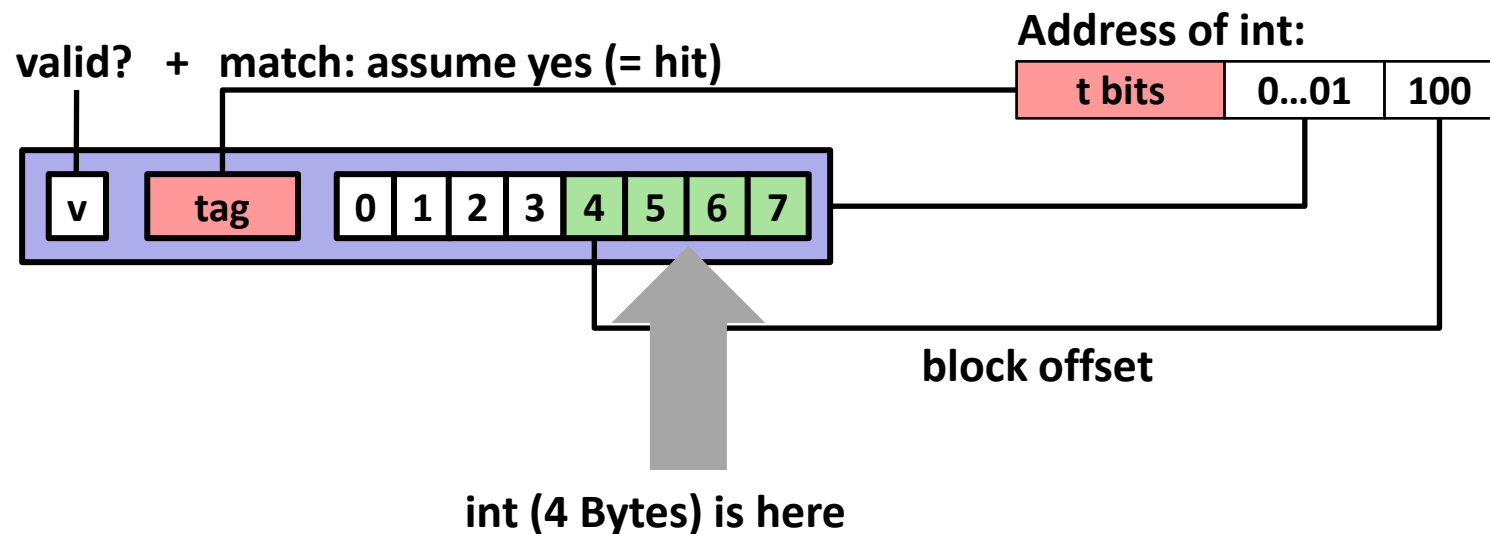
Assume: cache block size B=8 bytes



Example: Direct Mapped Cache (E = 1)

Direct mapped: One line per set

Assume: cache block size B=8 bytes



If tag doesn't match (= miss): old line is evicted and replaced

Direct-Mapped Cache Simulation

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

4-bit addresses (address space size M=16 bytes)
 S=4 sets, E=1 Blocks/set, B=2 bytes/block

Address trace (reads, one byte per read):

0	[<u>0</u> <u>0</u> <u>0</u> 0] ₂ ,	miss
1	[<u>0</u> <u>0</u> 0 <u>1</u>] ₂ ,	hit
7	[0 <u>1</u> <u>1</u> 1] ₂ ,	miss
8	[<u>1</u> 0 <u>0</u> 0] ₂ ,	miss
0	[<u>0</u> <u>0</u> <u>0</u> 0] ₂	miss

	v	Tag	Block
Set 0	1	0	M[0-1]
Set 1	0		
Set 2	0		
Set 3	1	0	M[6-7]

E-way Set Associative Cache (Here: E = 2)

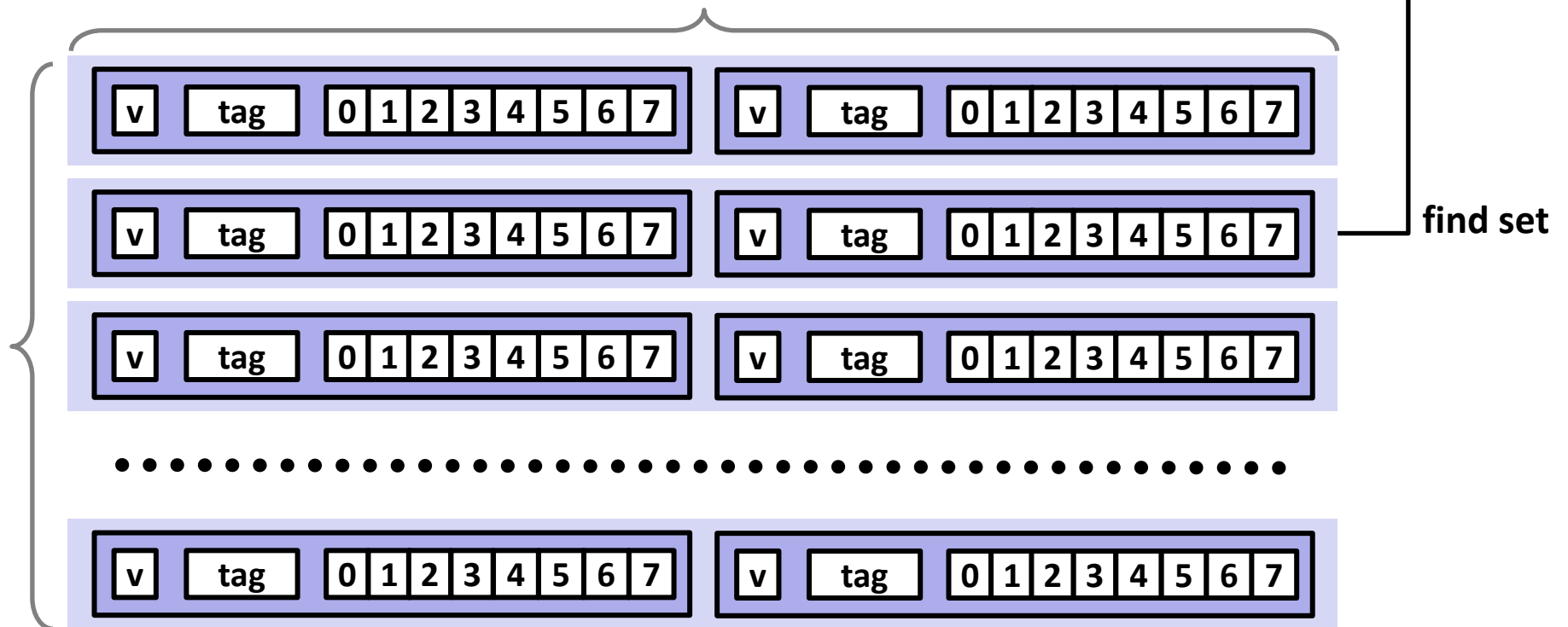
E = 2: Two lines per set

Assume: cache block size B=8 bytes

Address of short int:

t bits	0...01	100
--------	--------	-----

2 lines per set

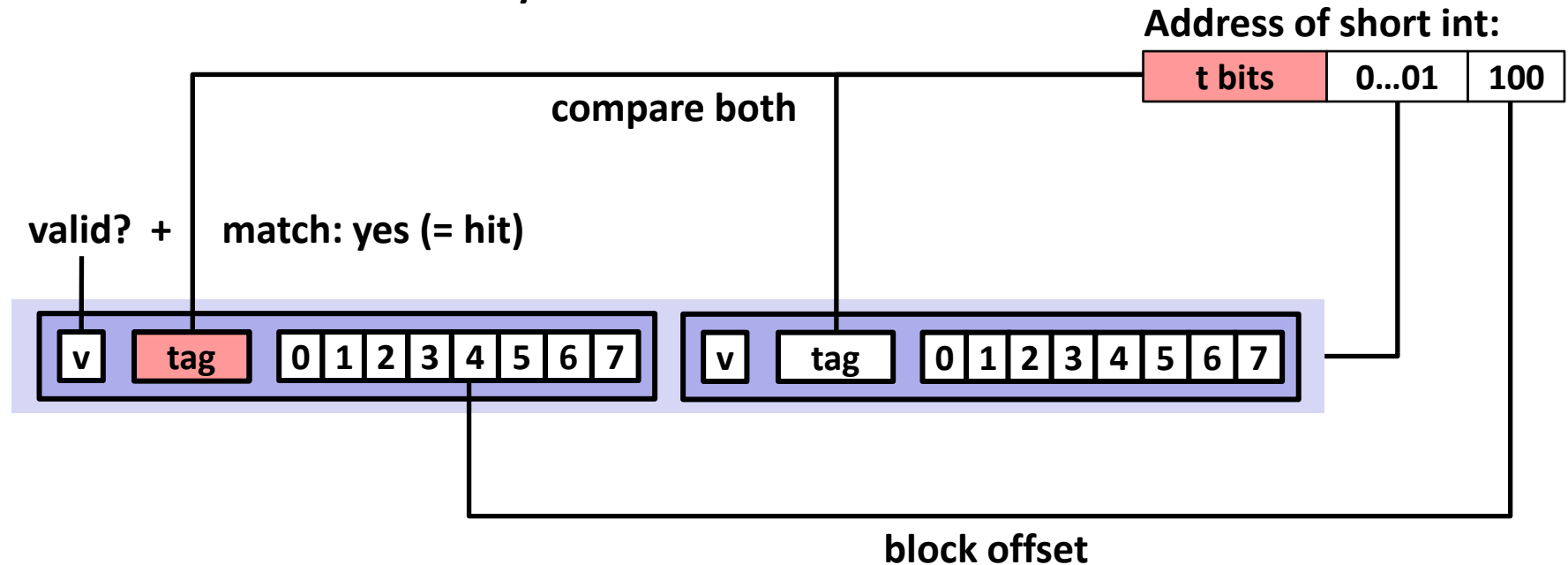


S sets

E-way Set Associative Cache (Here: E = 2)

E = 2: Two lines per set

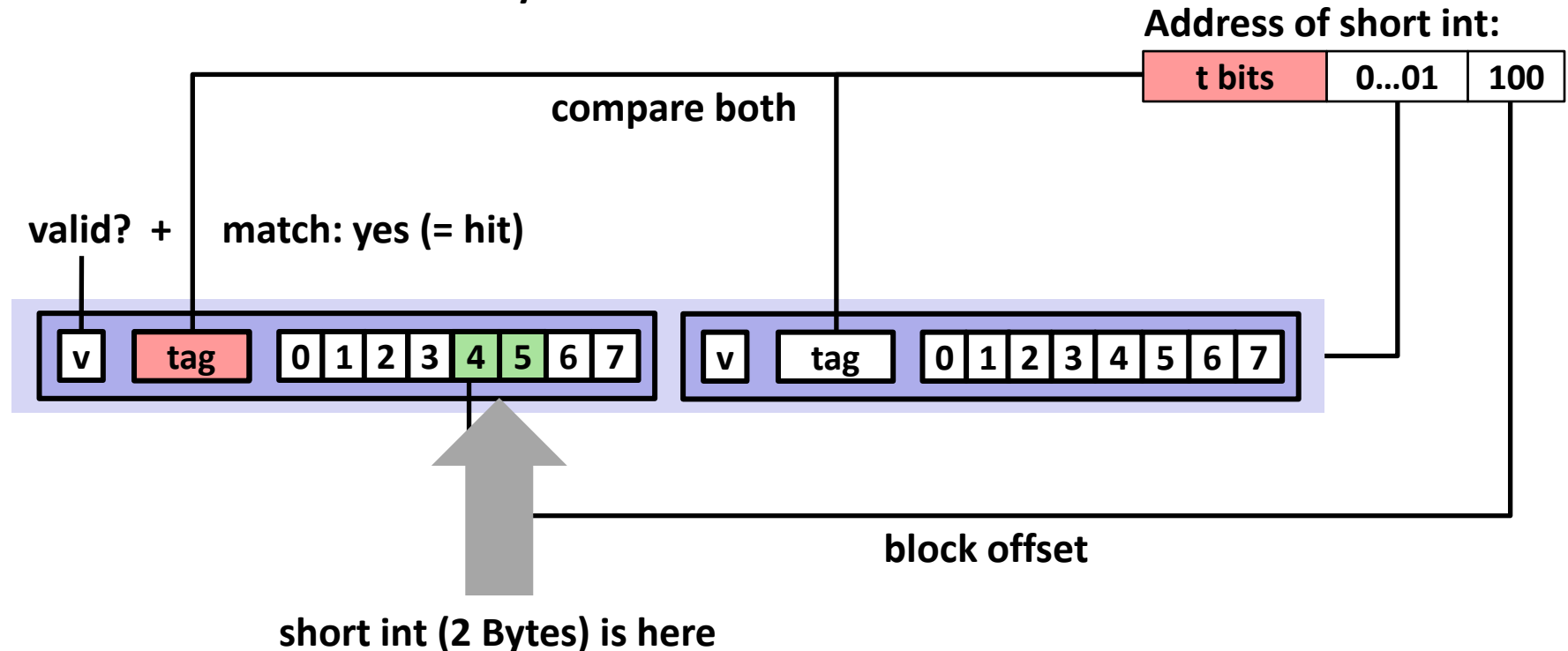
Assume: cache block size B=8 bytes



E-way Set Associative Cache (Here: E = 2)

E = 2: Two lines per set

Assume: cache block size B=8 bytes



No match or not valid (= miss):

- One line in set is selected for eviction and replacement
- Replacement policies: random, least recently used (LRU), ...

2-Way Set Associative Cache Simulation

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

4-bit addresses (M=16 bytes)

S=2 sets, E=2 blocks/set, B=2 bytes/block

Address trace (reads, one byte per read):

0	[00 <u>0</u> 0 ₂],	miss
1	[00 <u>0</u> 1 ₂],	hit
7	[01 <u>1</u> 1 ₂],	miss
8	[10 <u>0</u> 0 ₂],	miss
0	[00 <u>0</u> 0 ₂]	hit

	v	Tag	Block
Set 0	1	00	M[0-1]
	1	10	M[8-9]
Set 1	1	01	M[6-7]
	0		

What about writes?

■ Multiple copies of data exist:

- L1, L2, L3, Main Memory, Disk

■ What to do on a write-hit?

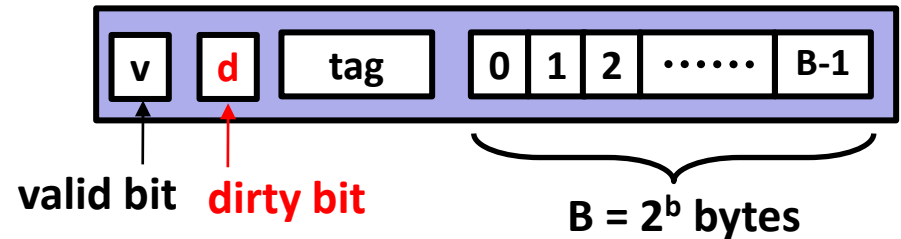
- **Write-through** (write immediately to memory)
- **Write-back** (defer write to memory until replacement of line)
 - Each cache line needs a dirty bit (set if data has been written to)

■ What to do on a write-miss?

- **Write-allocate** (load into cache, update line in cache)
 - Good if more writes to the location will follow
- **No-write-allocate** (writes straight to memory, does not load into cache)

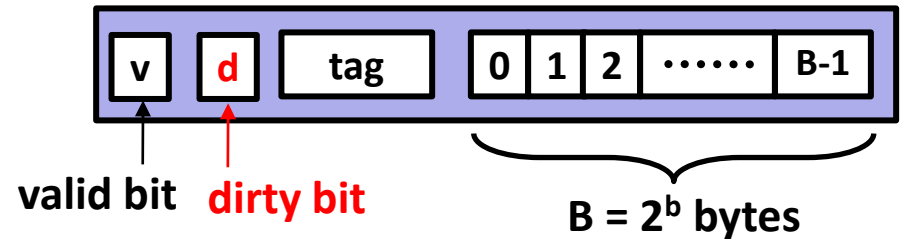
■ Typical

- Write-through + No-write-allocate
- **Write-back + Write-allocate**



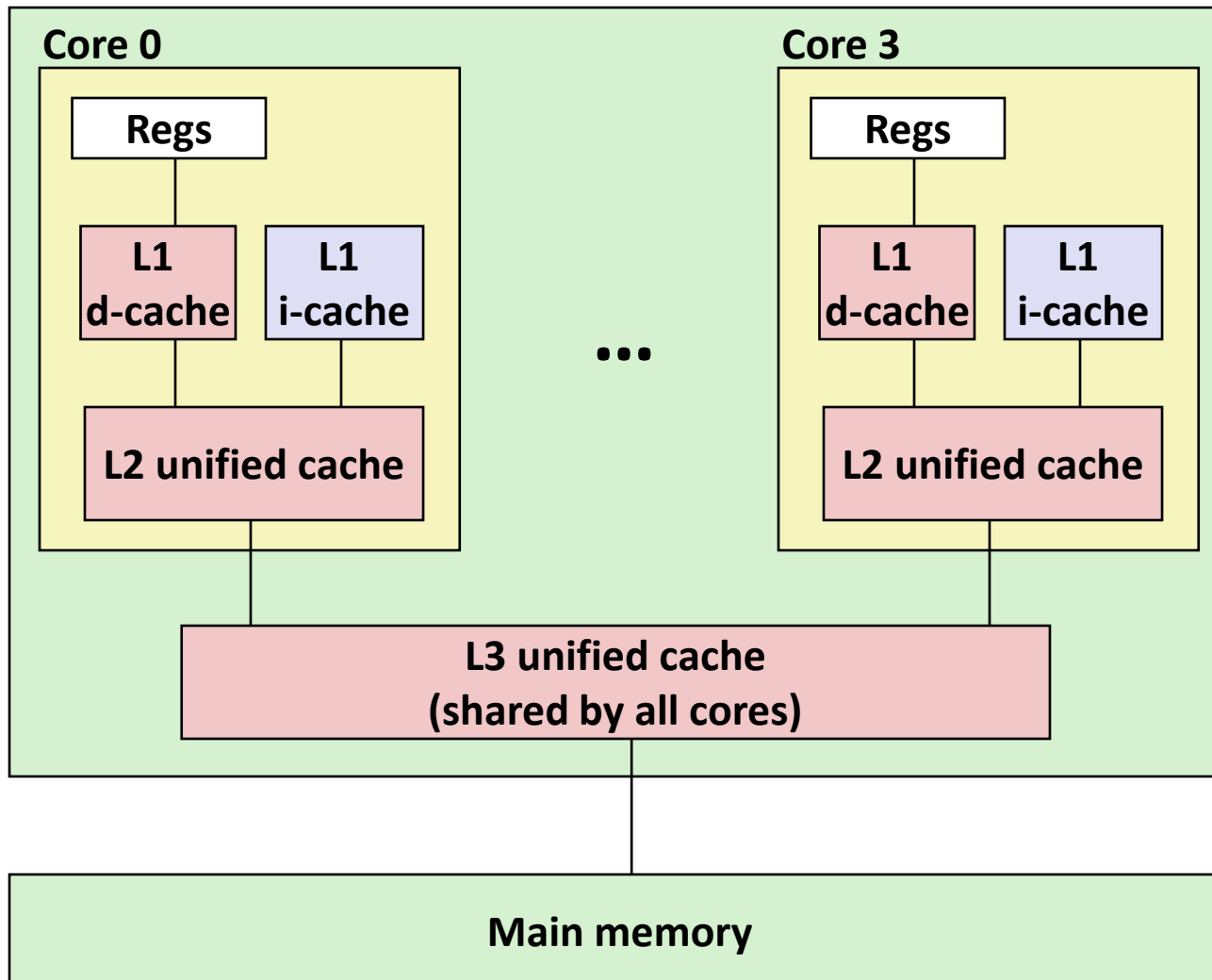
Practical Write-back Write-allocate

- A write to address X is issued
- If it is a hit
 - Update the contents of block
 - Set dirty bit to 1 (bit is sticky and only cleared on eviction)
- If it is a miss
 - Fetch block from memory (per a read miss)
 - The perform the write operations (per a write hit)
- If a line is evicted and dirty bit is set to 1
 - The entire block of 2^b bytes are written back to memory
 - Dirty bit is cleared (set to 0)
 - Line is replaced by new contents



Intel Core i7 Cache 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)
= $1 - \text{hit rate}$
- Typical numbers (in percentages):
 - 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:
 - 4 clock cycle 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!)

Let's think about those numbers

- **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 this simplified example:
 - cache hit time of 1 cycle
 - miss penalty of 100 cycles
 - Average access time:
 - 97% hits: $1 \text{ cycle} + 0.03 \times 100 \text{ cycles} = 4 \text{ cycles}$
 - 99% hits: $1 \text{ cycle} + 0.01 \times 100 \text{ cycles} = 2 \text{ cycles}$
- **This is why “miss rate” is used instead of “hit rate”**

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

Today

- Cache organization and operation
- **Performance impact of caches**
 - The memory mountain
 - Rearranging loops to improve spatial locality
 - Using blocking to improve temporal locality

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

```

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

/* test - Iterate over first "elems" elements of
 *      array "data" with stride of "stride",
 *      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

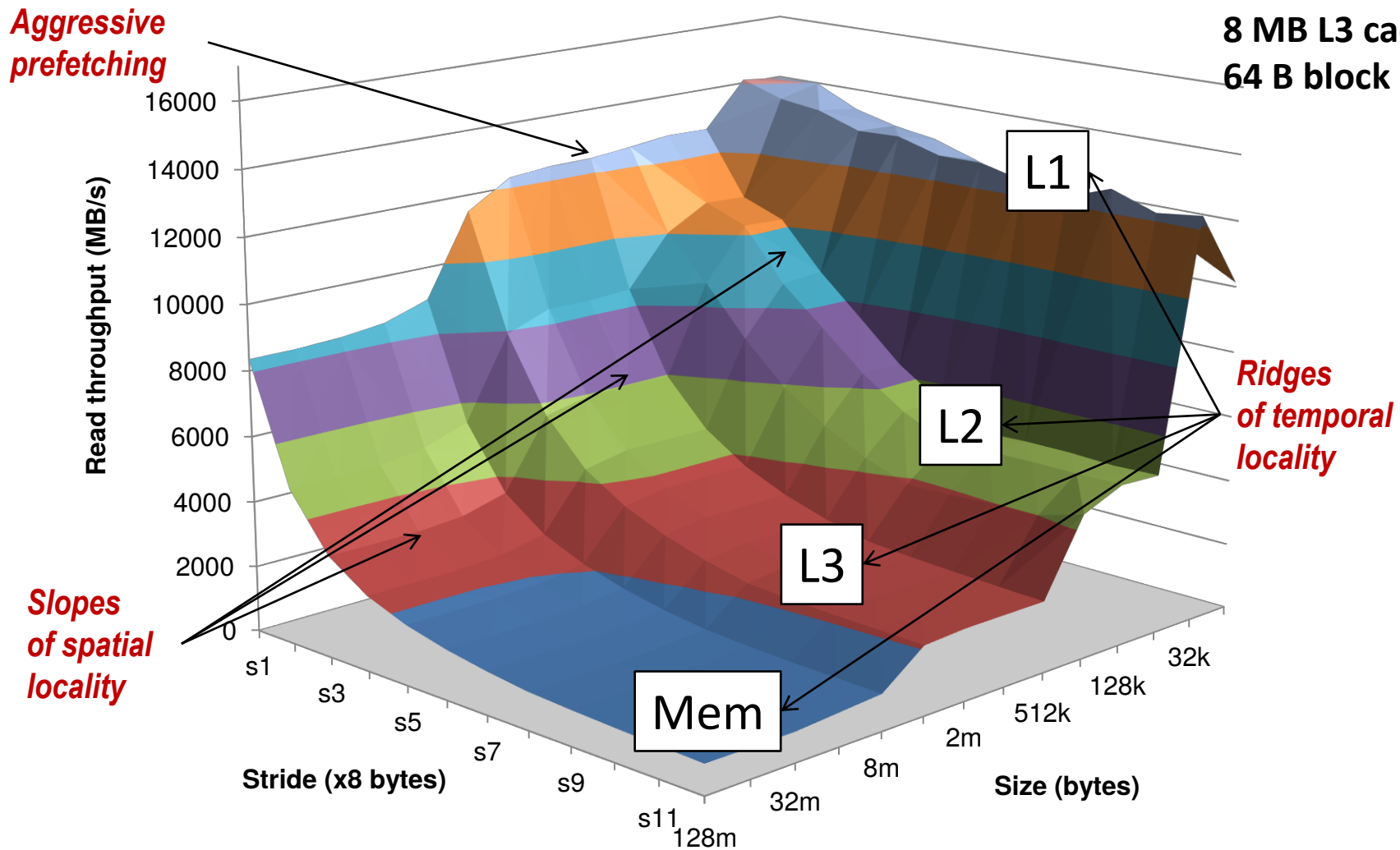
Call test () with many combinations of elems and stride.

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)

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



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Matrix Multiplication Example

■ Description:

- 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
 - but may be able to hold in register

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

matmult/mm.c

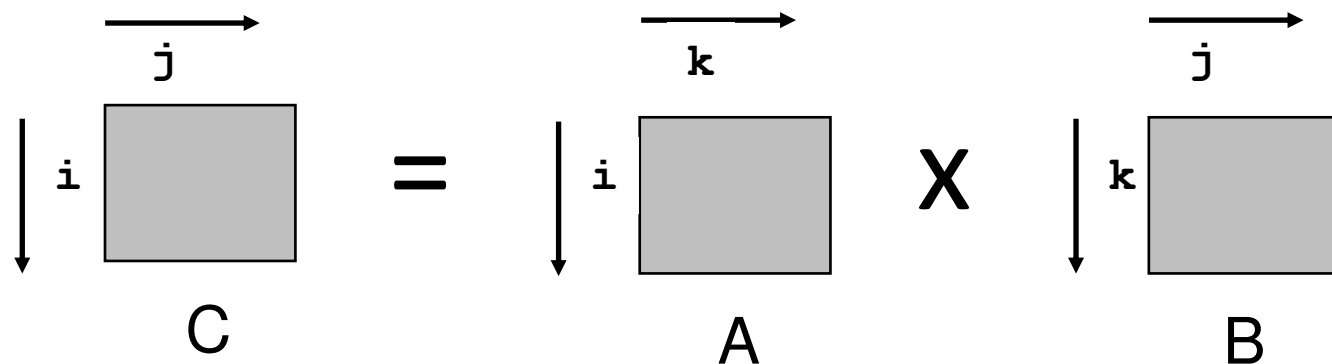
Miss Rate Analysis for Matrix Multiply

■ 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(a_{ij}) bytes, exploit spatial locality
 - miss rate = sizeof(a_{ij}) / 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%)

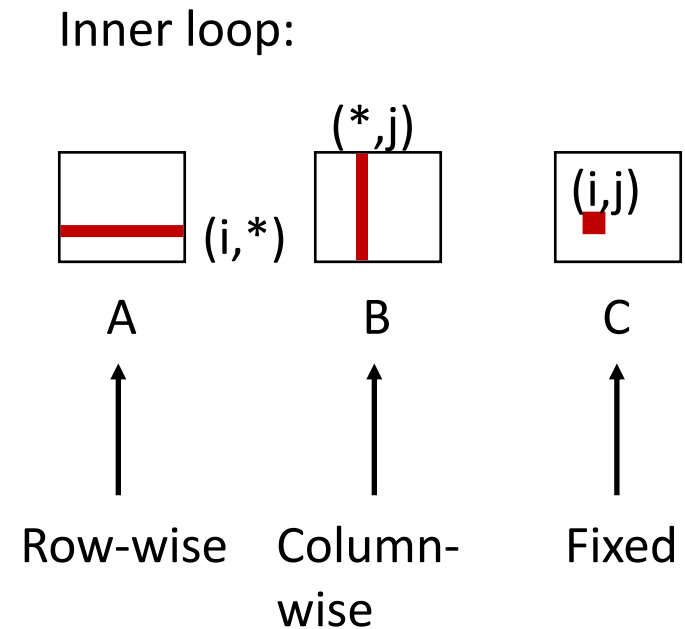
Matrix Multiplication (ijk)

```

/* 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



Miss rate for inner loop iterations:

A

B

C

Block size = 32B (four doubles)

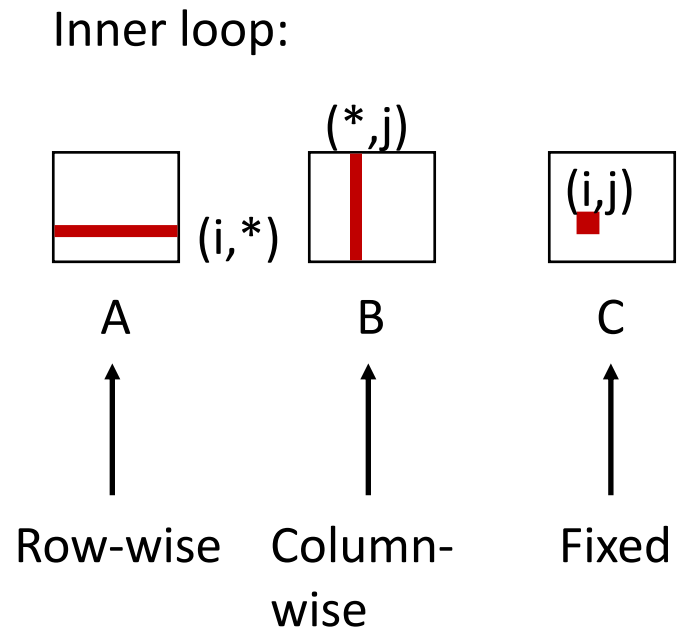
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/* ijk */
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        sum = 0.0;
        for (k=0; k<n; k++)
            sum += a[i][k] * b[k][j];
        c[i][j] = sum;
    }
}

```

matmult/mm.c



Miss rate for inner loop iterations:

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

Block size = 32B (four doubles)

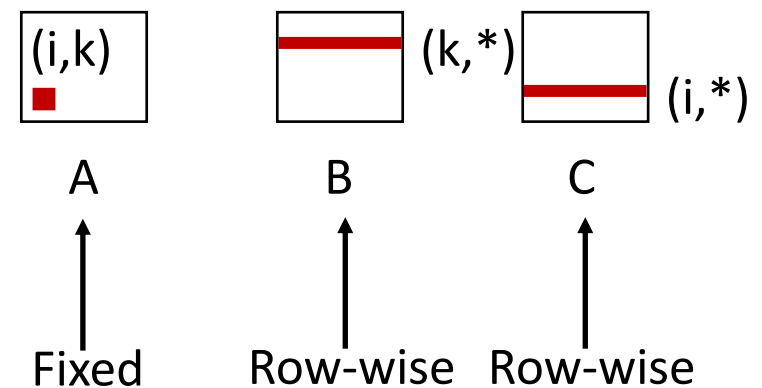
Matrix Multiplication (kij)

```

/* 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:



Miss rate for inner loop iterations:

A

B

C

Block size = 32B (four doubles)

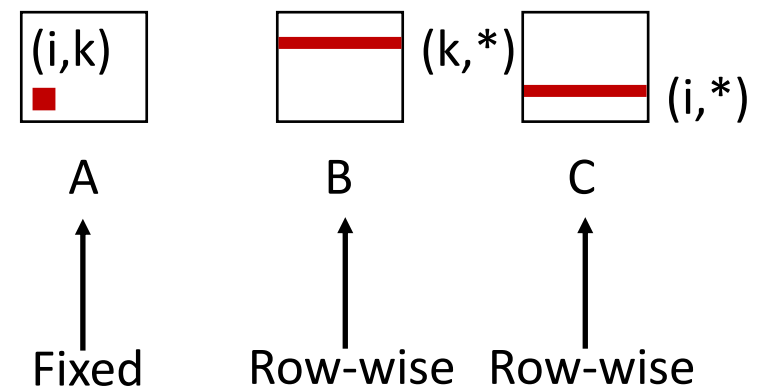
Matrix Multiplication (kij)

```

/* 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:



Miss rate for inner loop iterations:

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

Block size = 32B (four doubles)

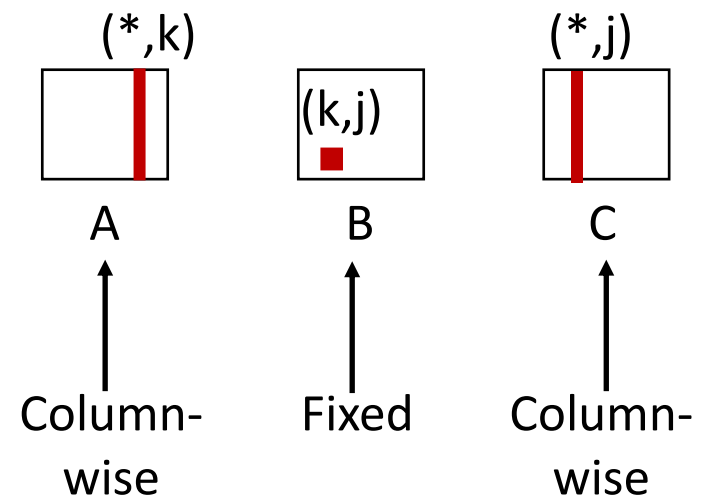
Matrix Multiplication (jki)

```

/* 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

```

Inner loop:



Miss rate for inner loop iterations:

A

B

C

Block size = 32B (four doubles)

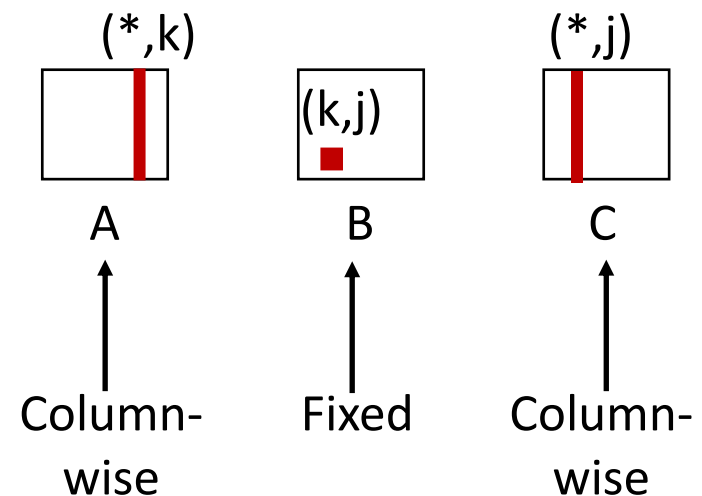
Matrix Multiplication (jki)

```

/* 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

```

Inner loop:



Miss rate for inner loop iterations:

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

Block size = 32B (four doubles)

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 (& jik):

- 2 loads, 0 stores
- avg 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 (& ikj):

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

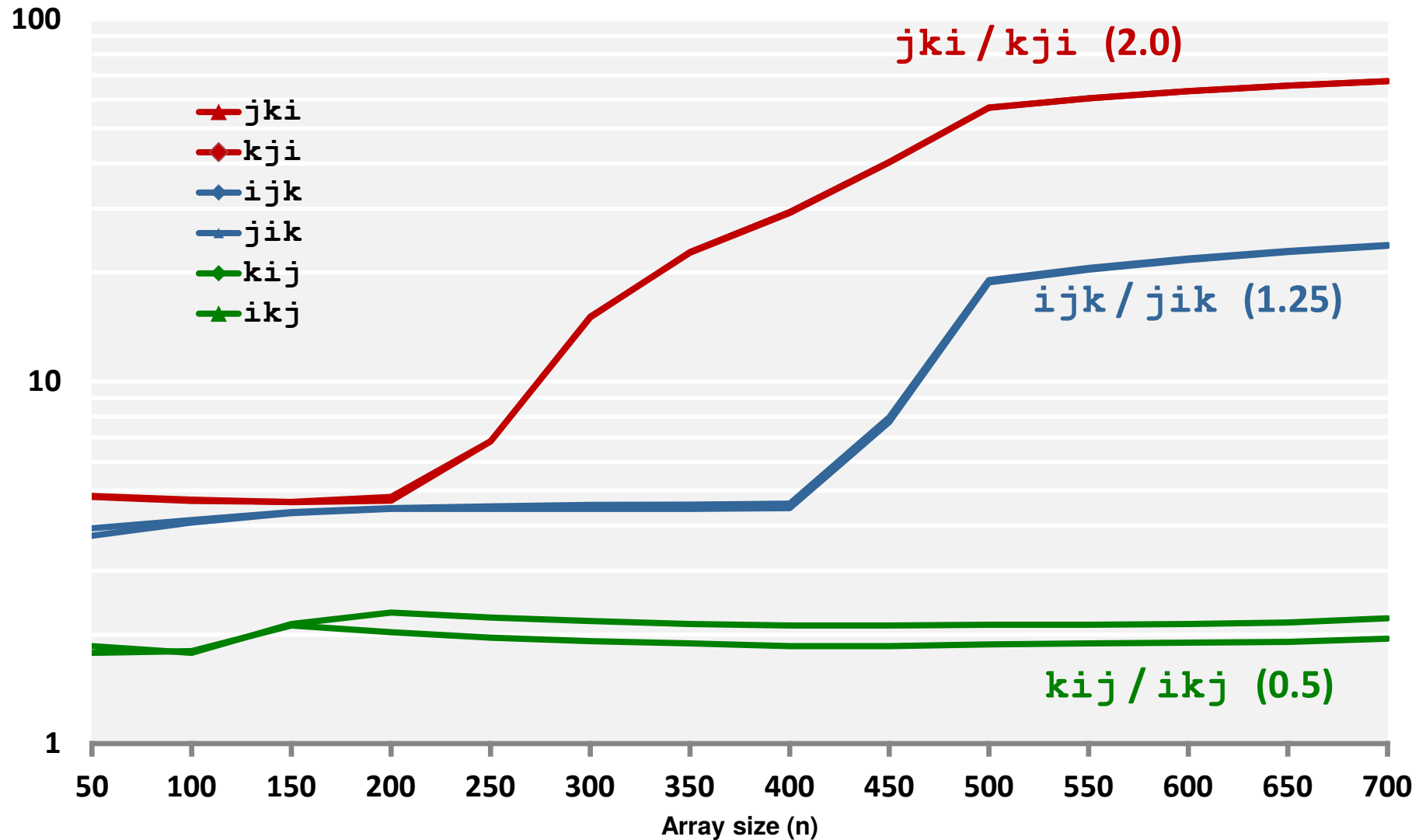
```
for (j=0; j<n; j++) {
    for (k=0; k<n; k++) {
        r = b[k][j];
        for (i=0; i<n; i++)
            c[i][j] += a[i][k] * r;
    }
}
```

jki (& kji):

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

Core i7 Matrix Multiply Performance

Cycles per inner loop iteration



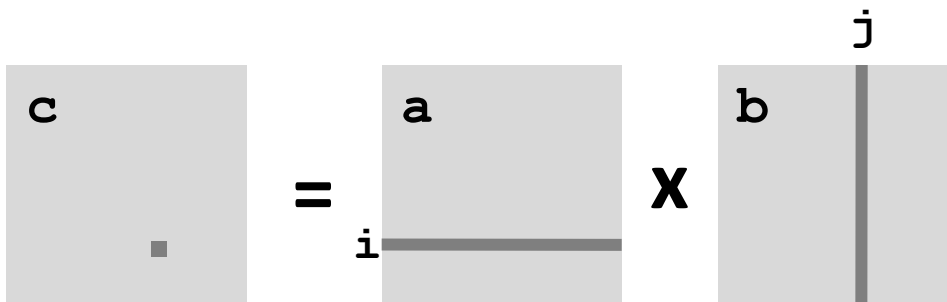
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Example: Matrix Multiplication

```
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

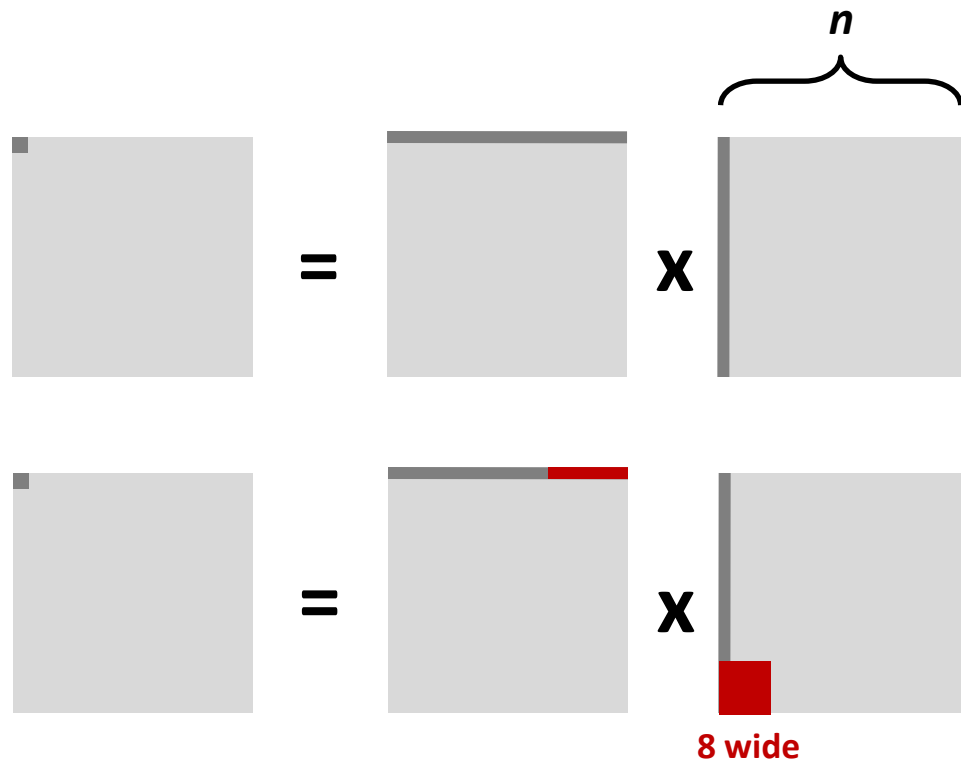
■ Assume:

- Matrix elements are doubles
- Cache block = 8 doubles
- Cache size $C \ll n$ (much smaller than n)

■ First iteration:

- $n/8 + n = 9n/8$ misses

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



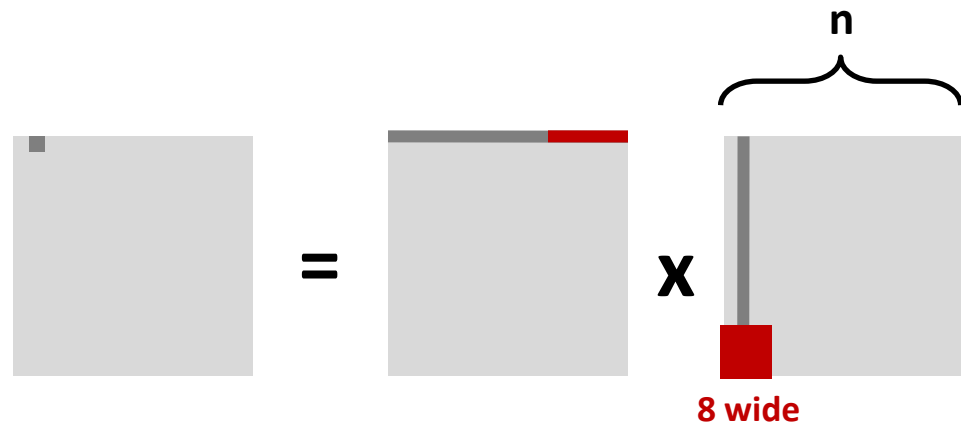
Cache Miss Analysis

■ Assume:

- Matrix elements are doubles
- Cache block = 8 doubles
- Cache size $C \ll n$ (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

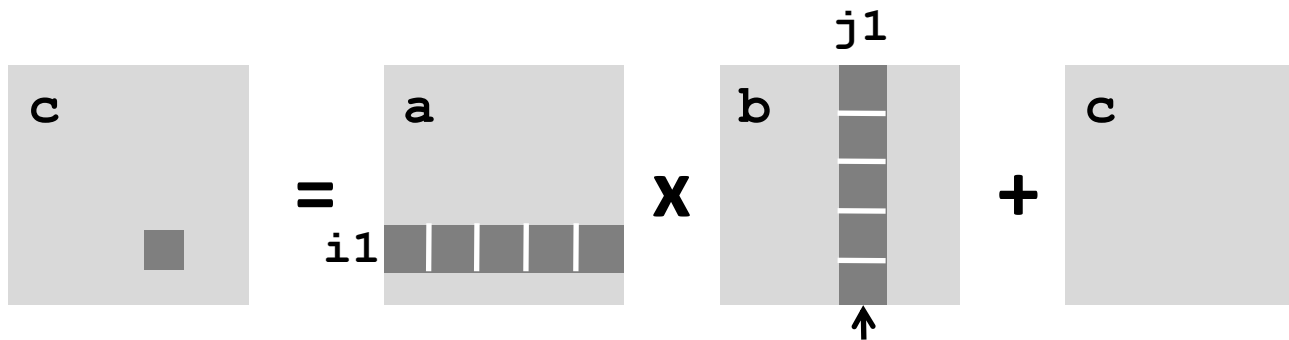
```

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; i1++)
                    for (j1 = j; j1 < j+B; j1++)
                        for (k1 = k; k1 < k+B; k1++)
                            c[i1*n+j1] += a[i1*n + k1]*b[k1*n + j1];
}

```


matmult/bmm.c



Block size $B \times B$

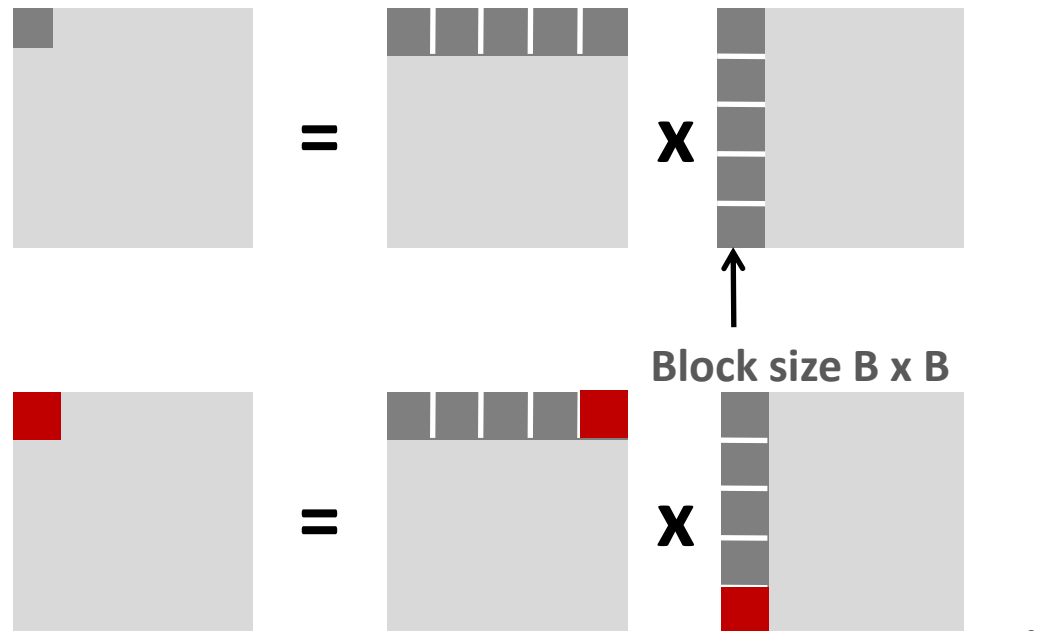
Cache Miss Analysis

■ Assume:

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

■ First (block) iteration:

- $B^2/8$ misses for each block
- $2n/B \times B^2/8 = nB/4$
(omitting matrix c)




- Afterwards in cache
(schematic)



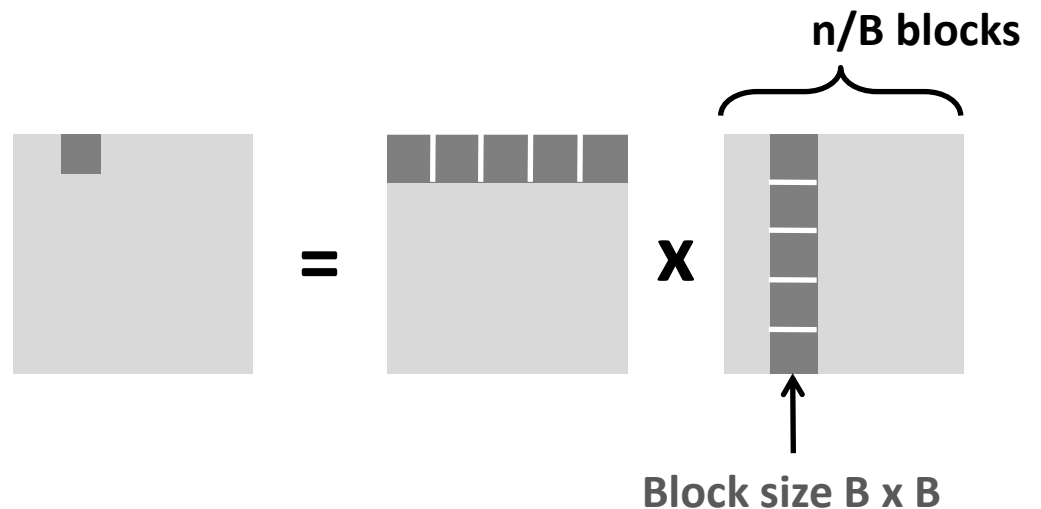
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- Cache size $C \ll n$ (much smaller than n)
- Three blocks  fit into cache: $3B^2 < C$

■ Second (block) iteration:

- Same as first iteration
- $2n/B \times B^2/8 = nB/4$



■ Total misses:

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

Blocking Summary

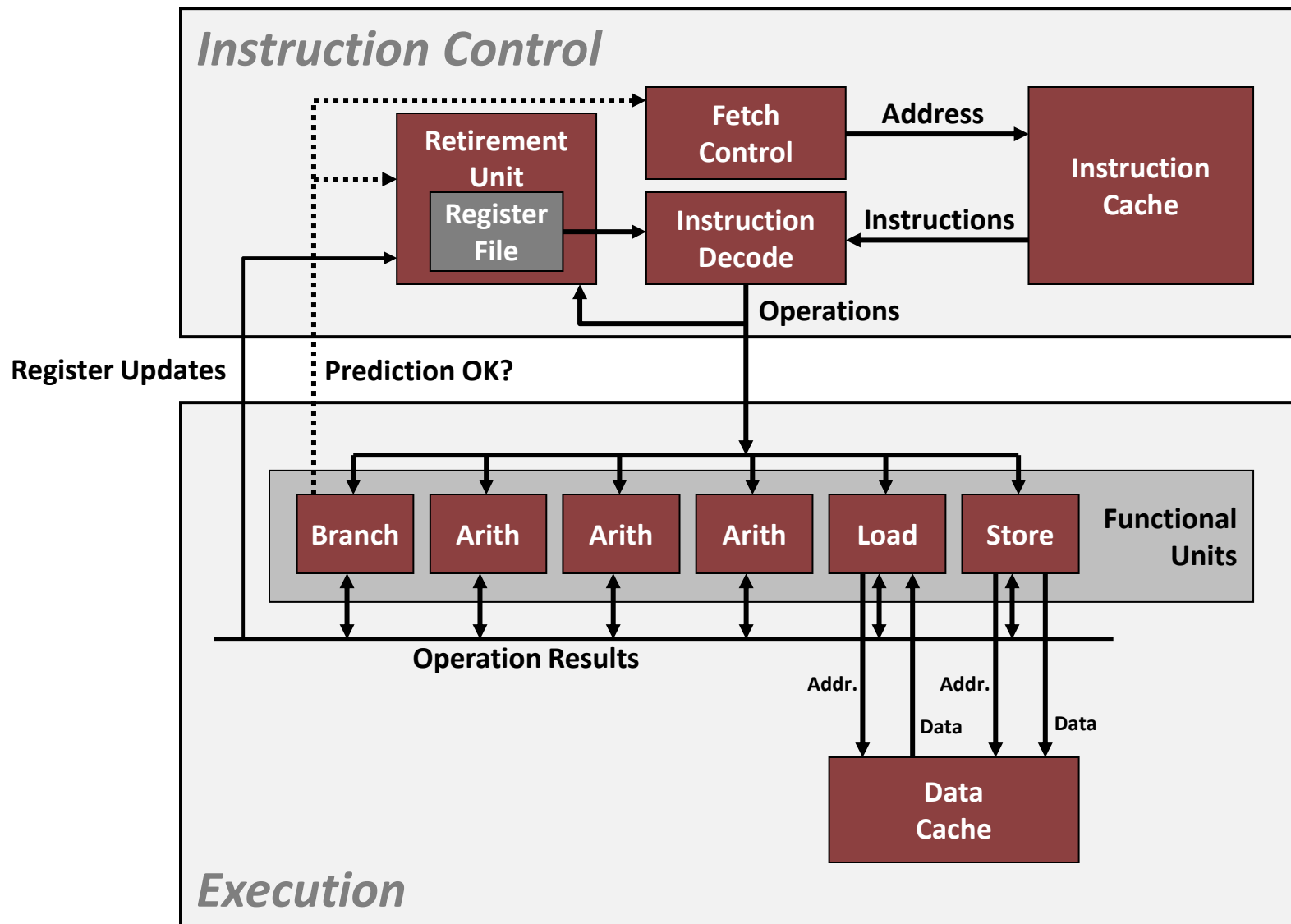
- No blocking: $(9/8) n^3$ misses
- Blocking: $(1/(4B)) n^3$ misses
- Use largest block size B , such that B satisfies $3B^2 < C$
 - Fit three blocks in cache! Two input, one output.
- Reason for dramatic difference:
 - Matrix multiplication has inherent temporal locality:
 - Input data: $3n^2$, computation $2n^3$
 - Every array elements used $O(n)$ times!
 - But program has to be written properly

Cache Summary

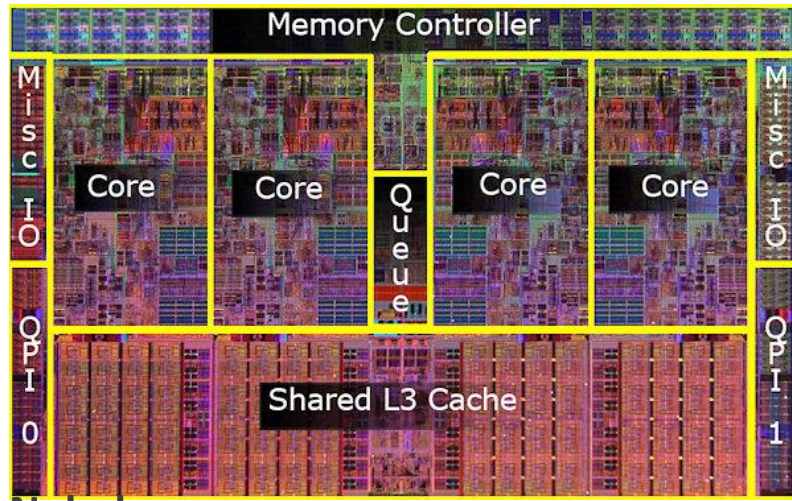
- **Cache memories can have significant performance impact**
- **You can write your programs to exploit this!**
 - Focus on the inner loops, where bulk of computations and memory accesses occur.
 - Try to maximize spatial locality by reading data objects sequentially with stride 1.
 - Try to maximize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

Supplemental slides

Recall: Modern CPU Design

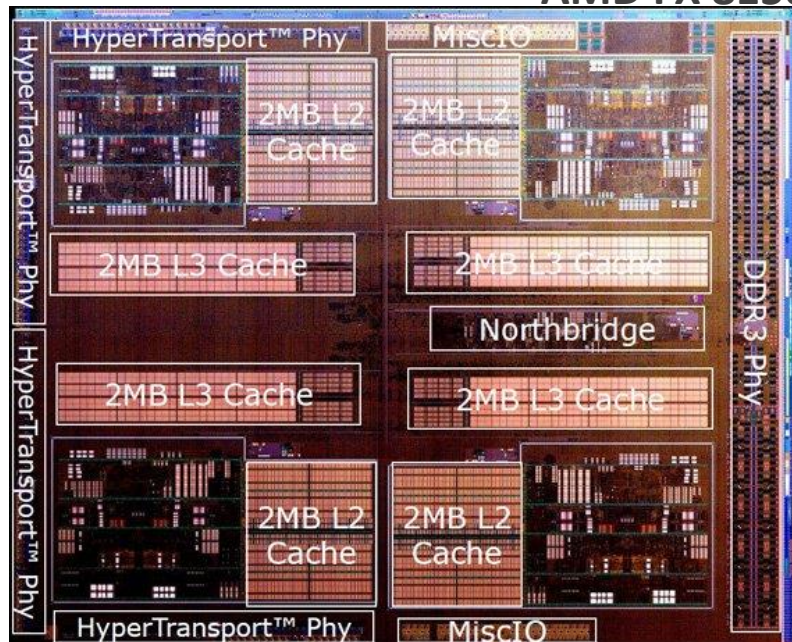


What it Really Looks Like

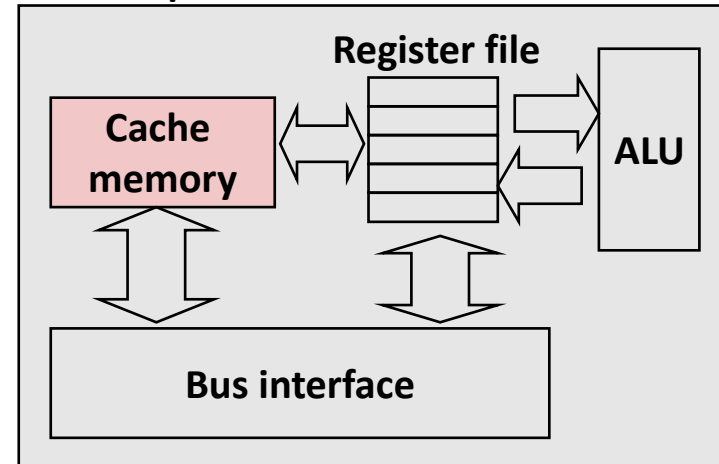


Nehalem

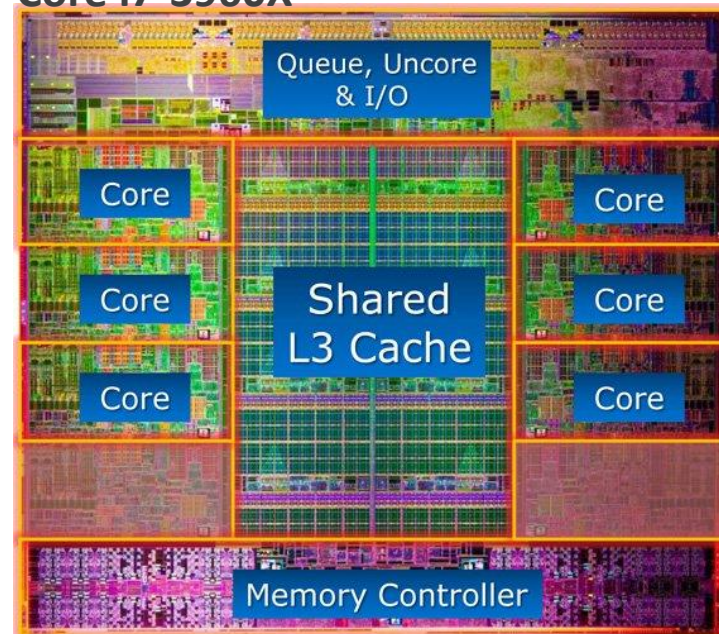
AMD FX 8150



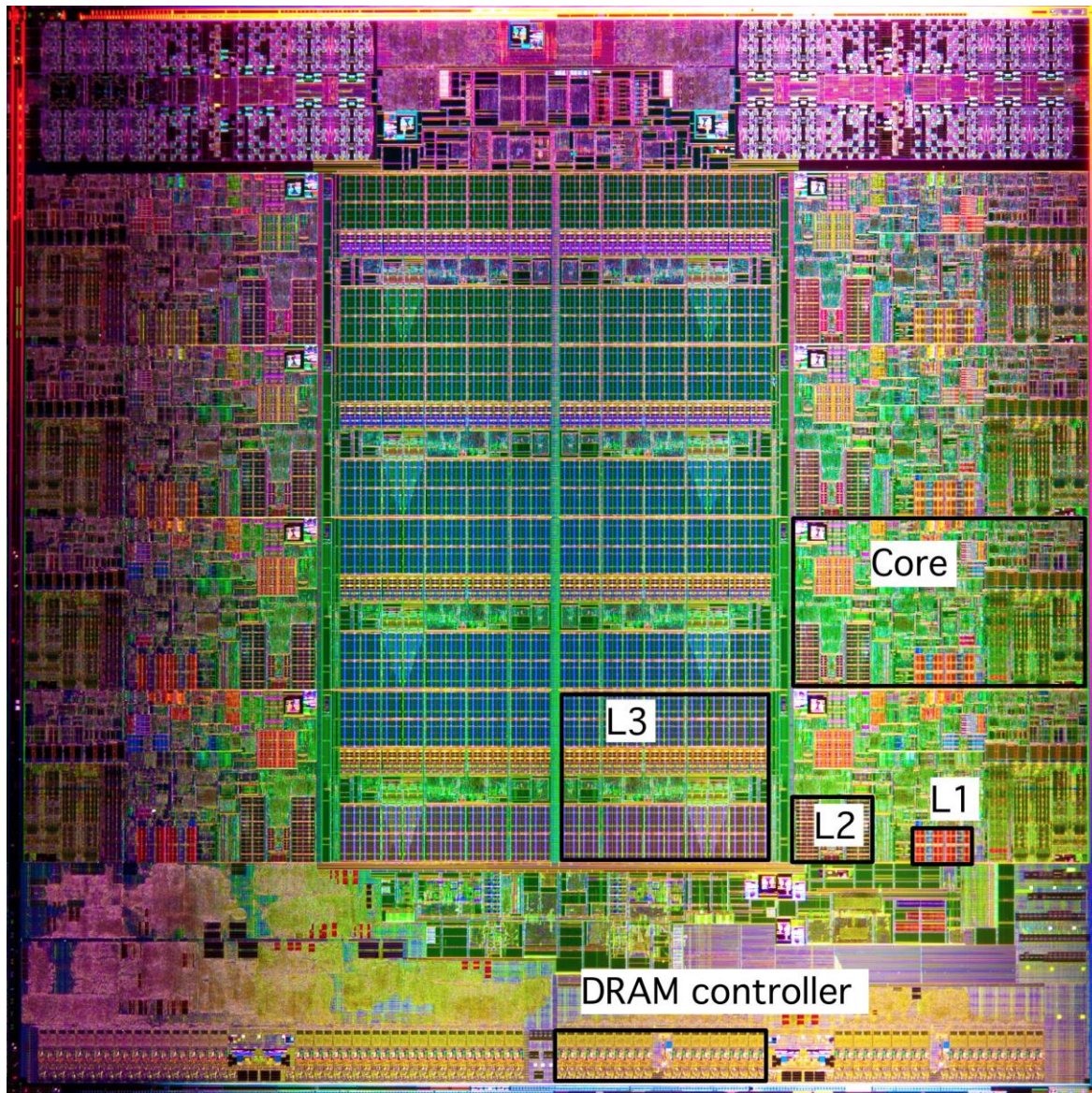
CPU chip



Core i7-3960X



What it Really Looks Like (Cont.)



Intel Sandy Bridge
Processor Die

L1: 32KB Instruction + 32KB Data
L2: 256KB
L3: 3–20MB

Why Index Using Middle Bits?

Direct mapped: One line per set

Assume: cache block size 8 bytes

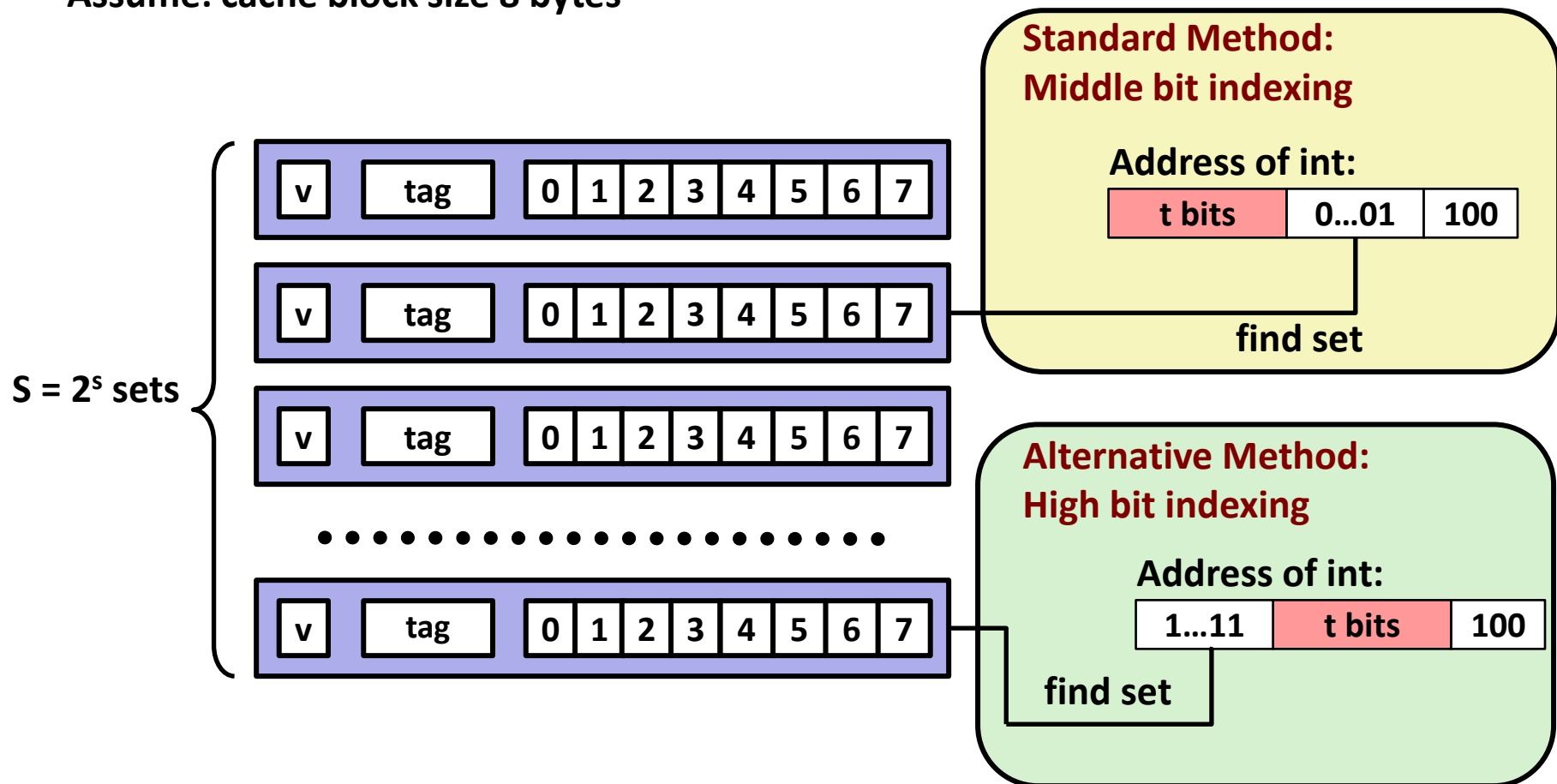
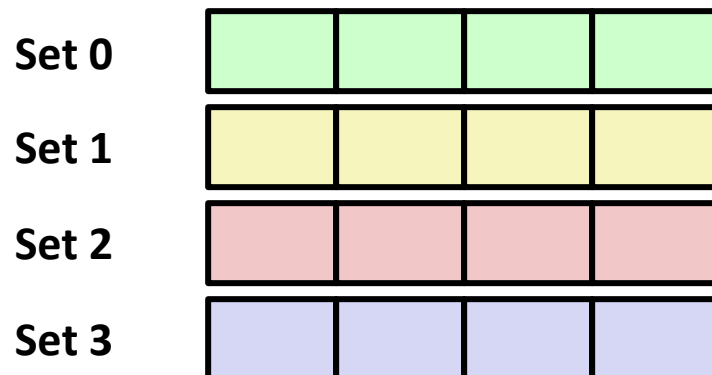


Illustration of Indexing Approaches

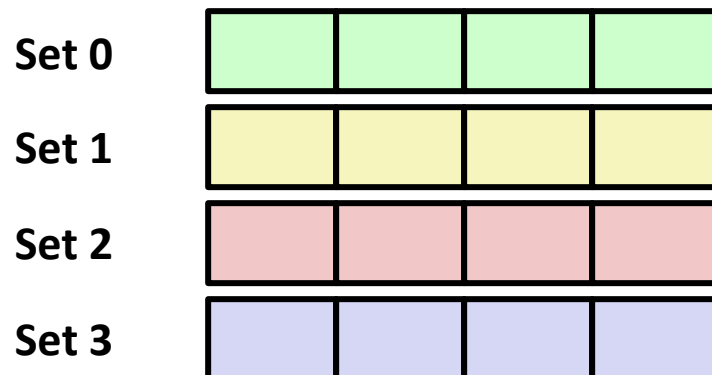
- 64-byte memory
 - 6-bit addresses
- 16 byte, direct-mapped cache
- Block size = 4. (Thus, 4 sets; why?)
- 2 bits tag, 2 bits index, 2 bits offset



				0000xx
				0001xx
				0010xx
				0011xx
				0100xx
				0101xx
				0110xx
				0111xx
				1000xx
				1001xx
				1010xx
				1011xx
				1100xx
				1101xx
				1110xx
				1111xx

Middle Bit Indexing

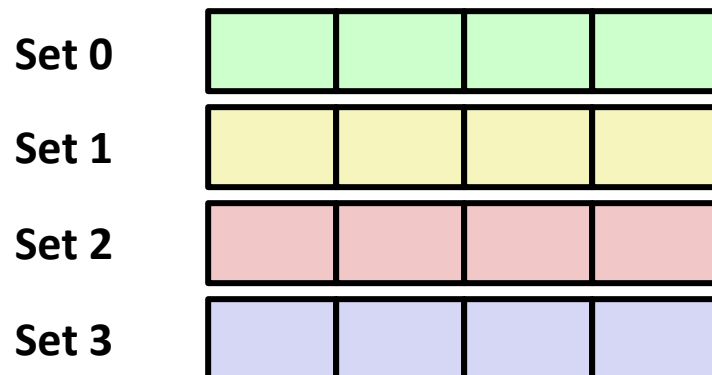
- Addresses of form **TTSSBB**
 - **TT** Tag bits
 - **SS** Set index bits
 - **BB** Offset bits
- Makes good use of spatial locality



				0000xx
				0001xx
				0010xx
				0011xx
				0100xx
				0101xx
				0110xx
				0111xx
				1000xx
				1001xx
				1010xx
				1011xx
				1100xx
				1101xx
				1110xx
				1111xx

High Bit Indexing

- Addresses of form **SS****TT****BB**
 - **SS** Set index bits
 - **TT** Tag bits
 - **BB** Offset bits
- Program with high spatial locality would generate lots of conflicts



				0000xx
				0001xx
				0010xx
				0011xx
				0100xx
				0101xx
				0110xx
				0111xx
				1000xx
				1001xx
				1010xx
				1011xx
				1100xx
				1101xx
				1110xx
				1111xx

Example: Core i7 L1 Data Cache

32 kB 8-way set associative

64 bytes/block

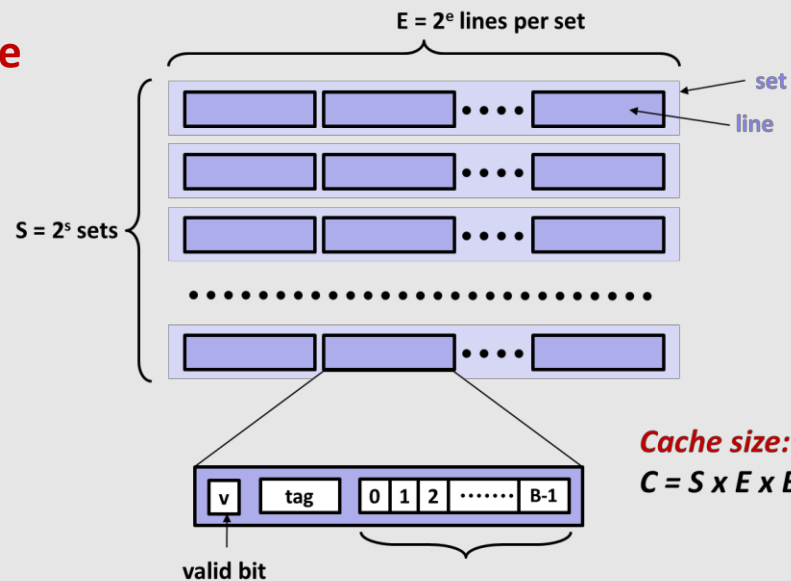
47 bit address range

B =

S = , s =

E = , e =

C =

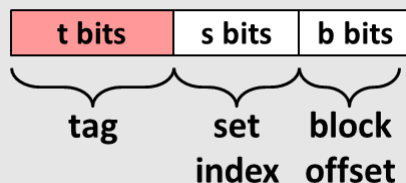


Cache size:

$C = S \times E \times B$ data bytes

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

Address of word:



Block offset: . bits

Set index: . bits

Tag: . bits

Stack Address:

0x00007f7262a1e010

Block offset: 0x??

Set index: 0x??

Tag: 0x??

Example: Core i7 L1 Data Cache

32 kB 8-way set associative

64 bytes/block

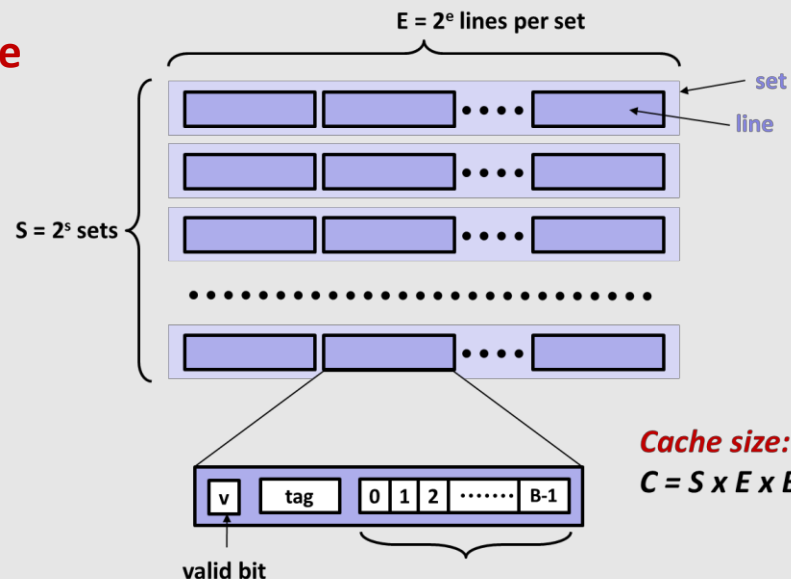
47 bit address range

$B = 64$

$S = 64, s = 6$

$E = 8, e = 3$

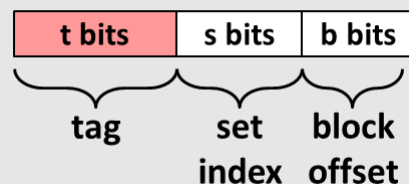
$C = 64 \times 64 \times 8 = 32,768$



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

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

Address of word:



Block offset: 6 bits

Set index: 6 bits

Tag: 35 bits

Stack Address:

0x00007f7262a1e010

0000 0001 0000

Block offset: 0x10

Set index: 0x0

Tag: 0x7f7262a1e

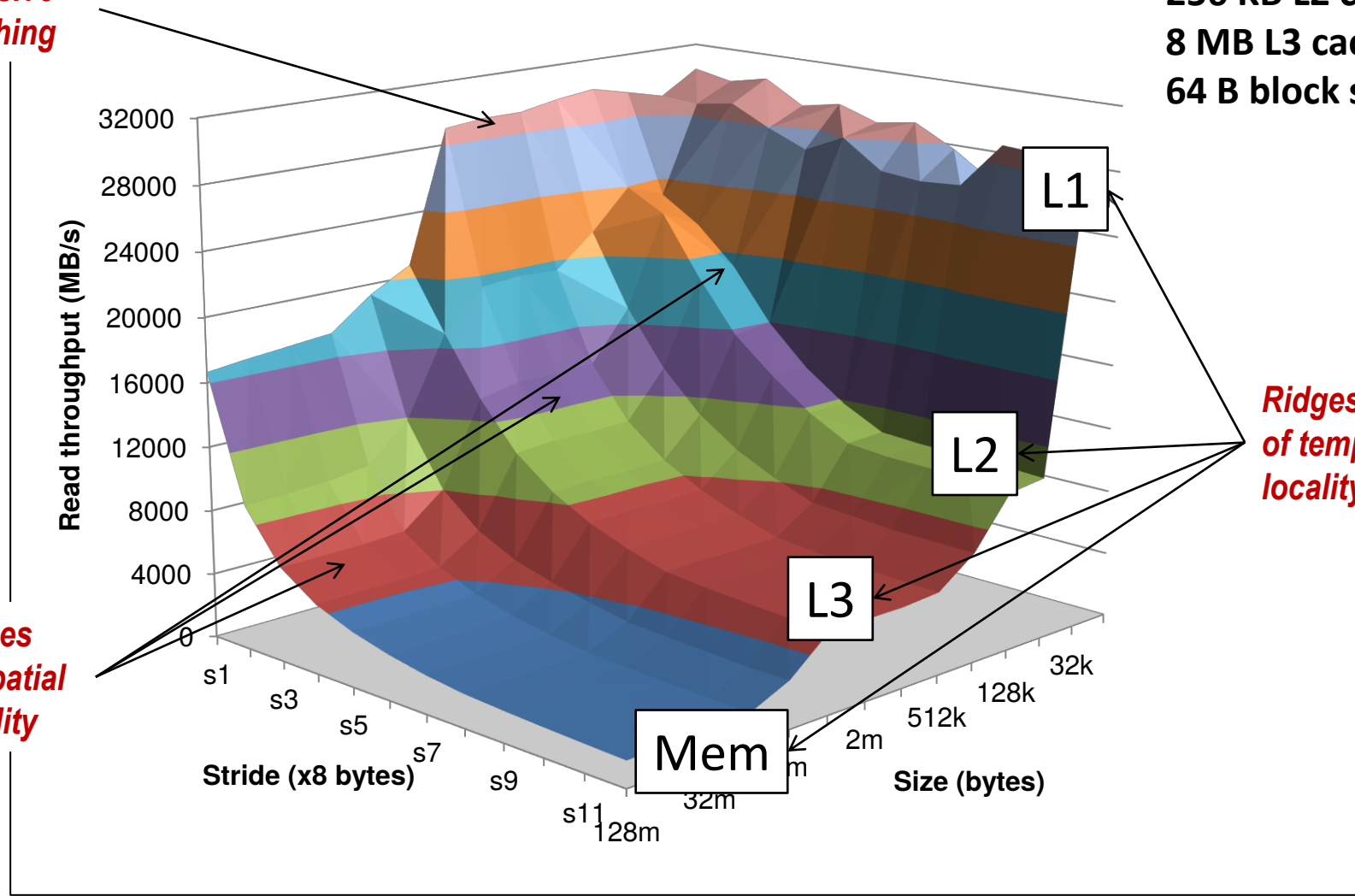
The Memory Mountain

Core i5 Haswell
 3.1 GHz
 32 KB L1 d-cache
 256 KB L2 cache
 8 MB L3 cache
 64 B block size

*Aggressive
prefetching*

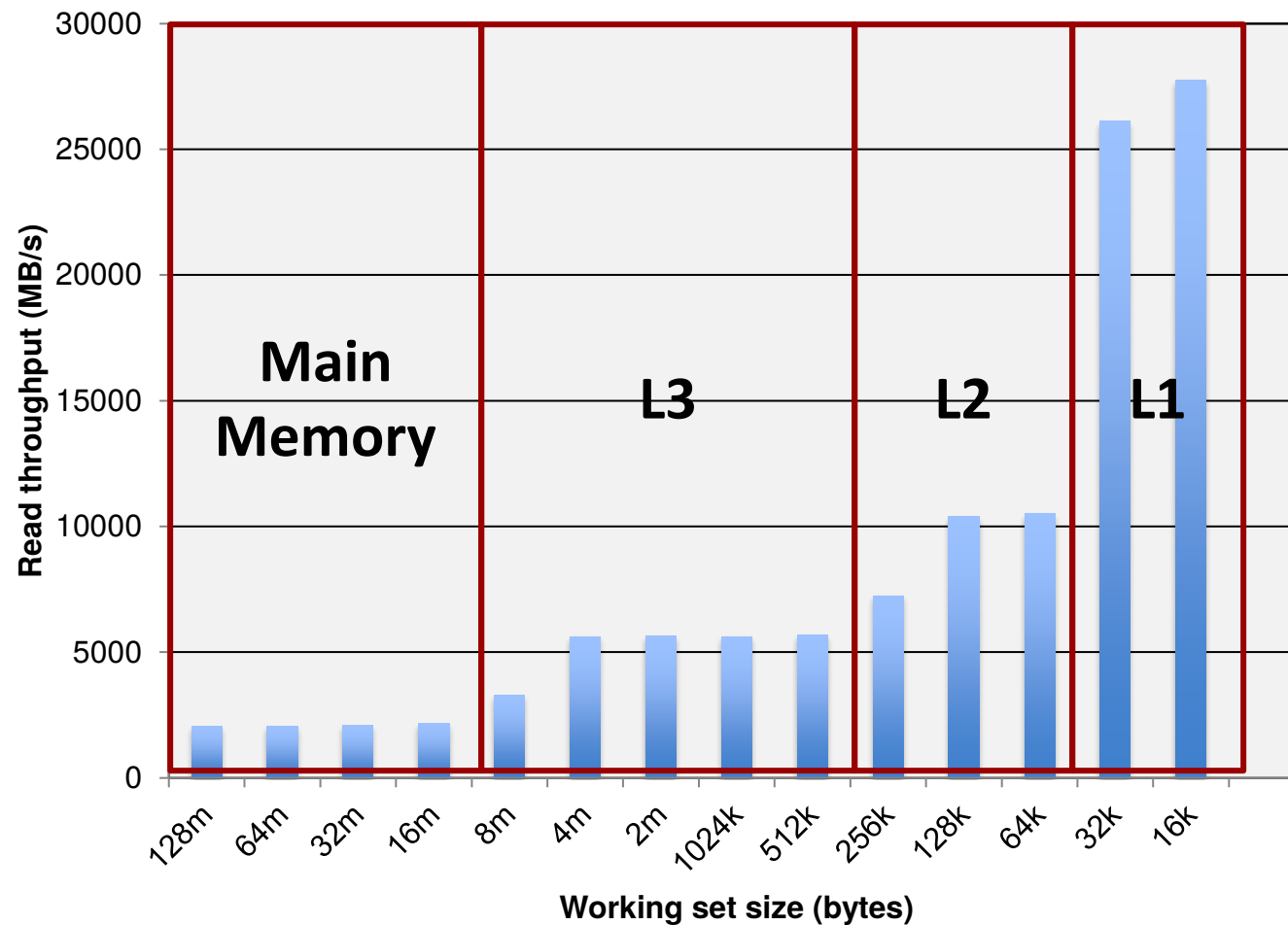
*Slopes
of spatial
locality*

*Ridges
of temporal
locality*



Cache Capacity Effects from Memory Mountain

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

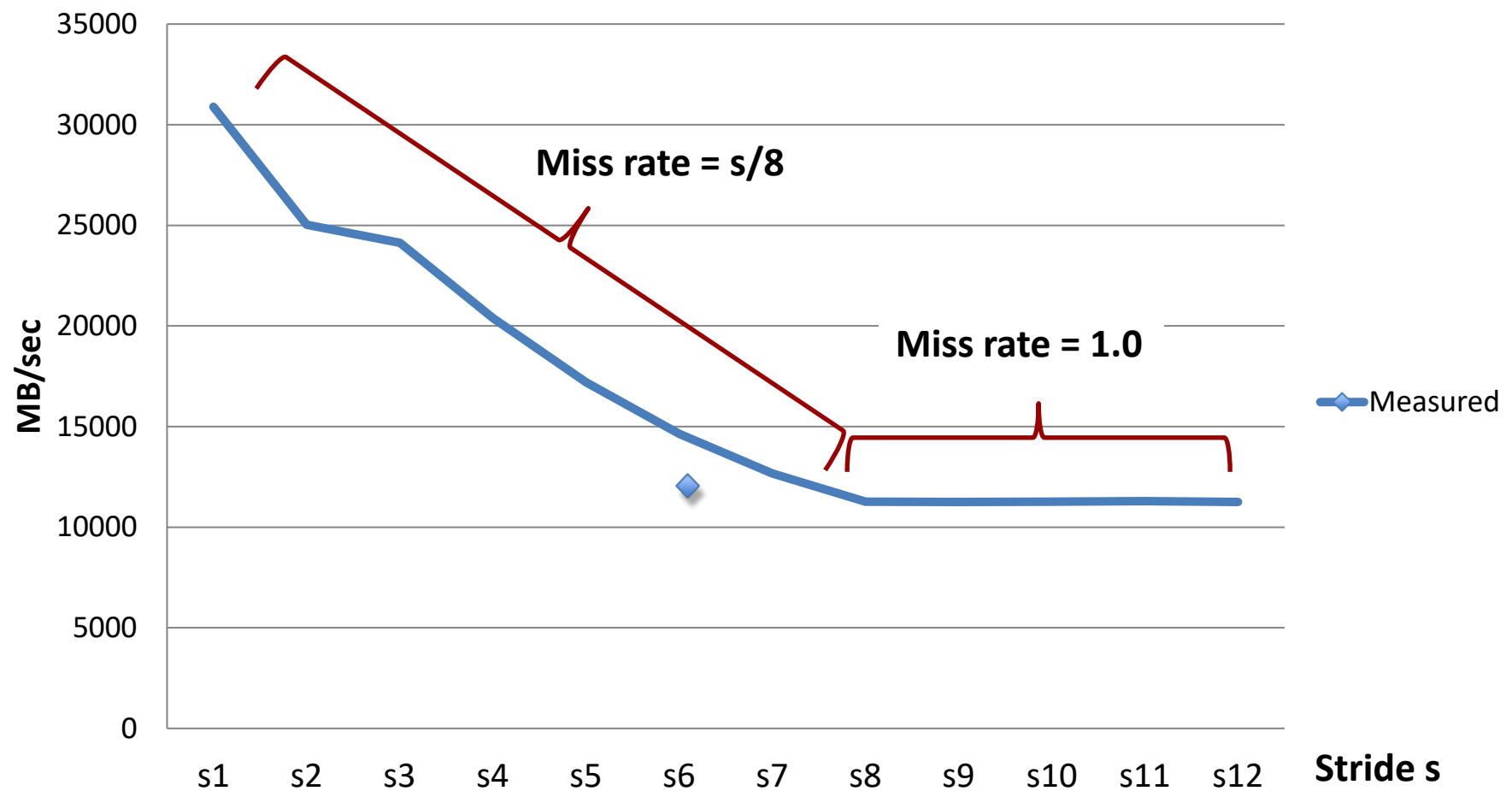


Slice through
memory
mountain with
stride=8

Cache Block Size Effects from Memory Mountain

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

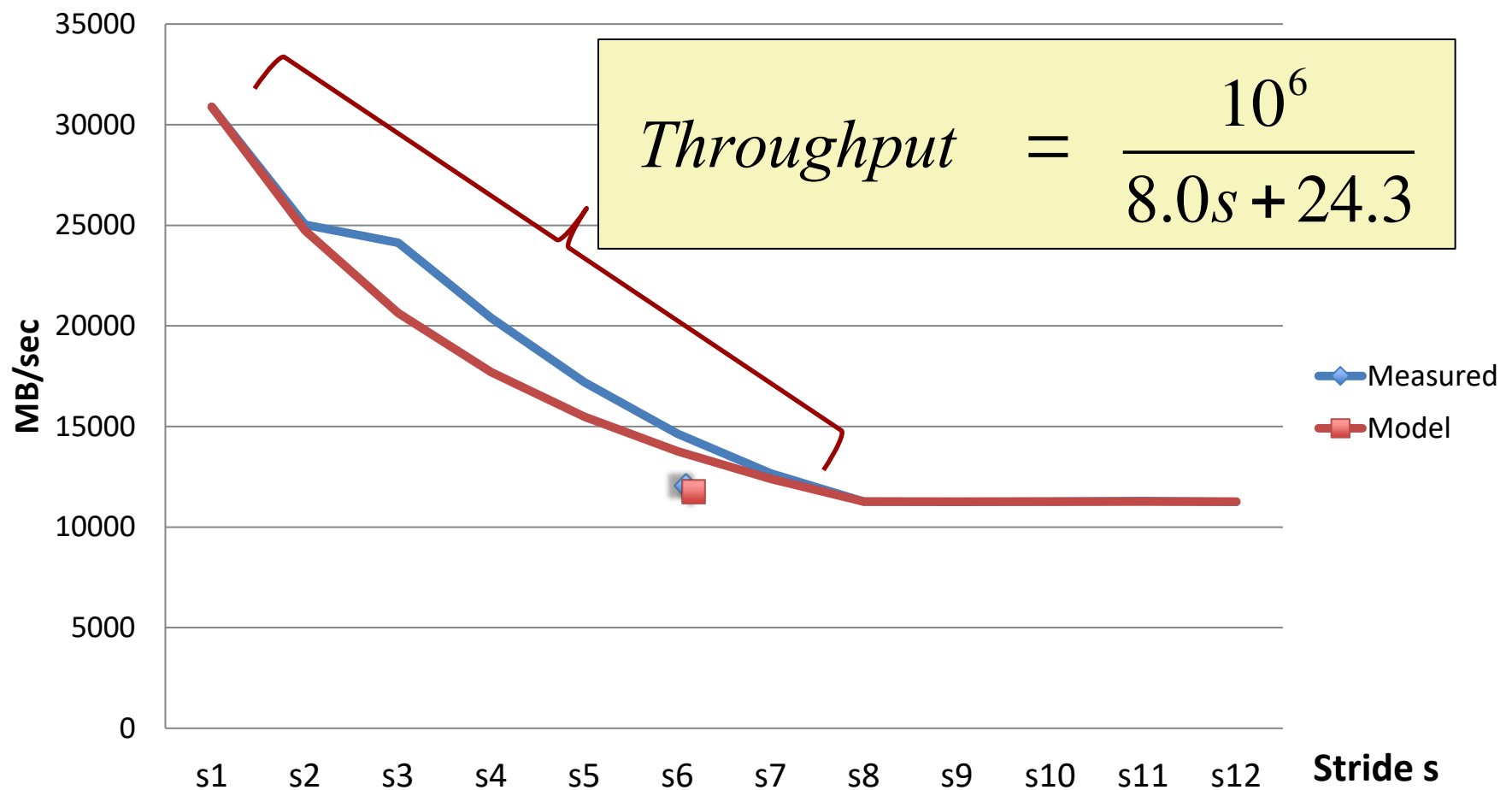
Throughput for size = 128K



Modeling Block Size Effects from Memory Mountain

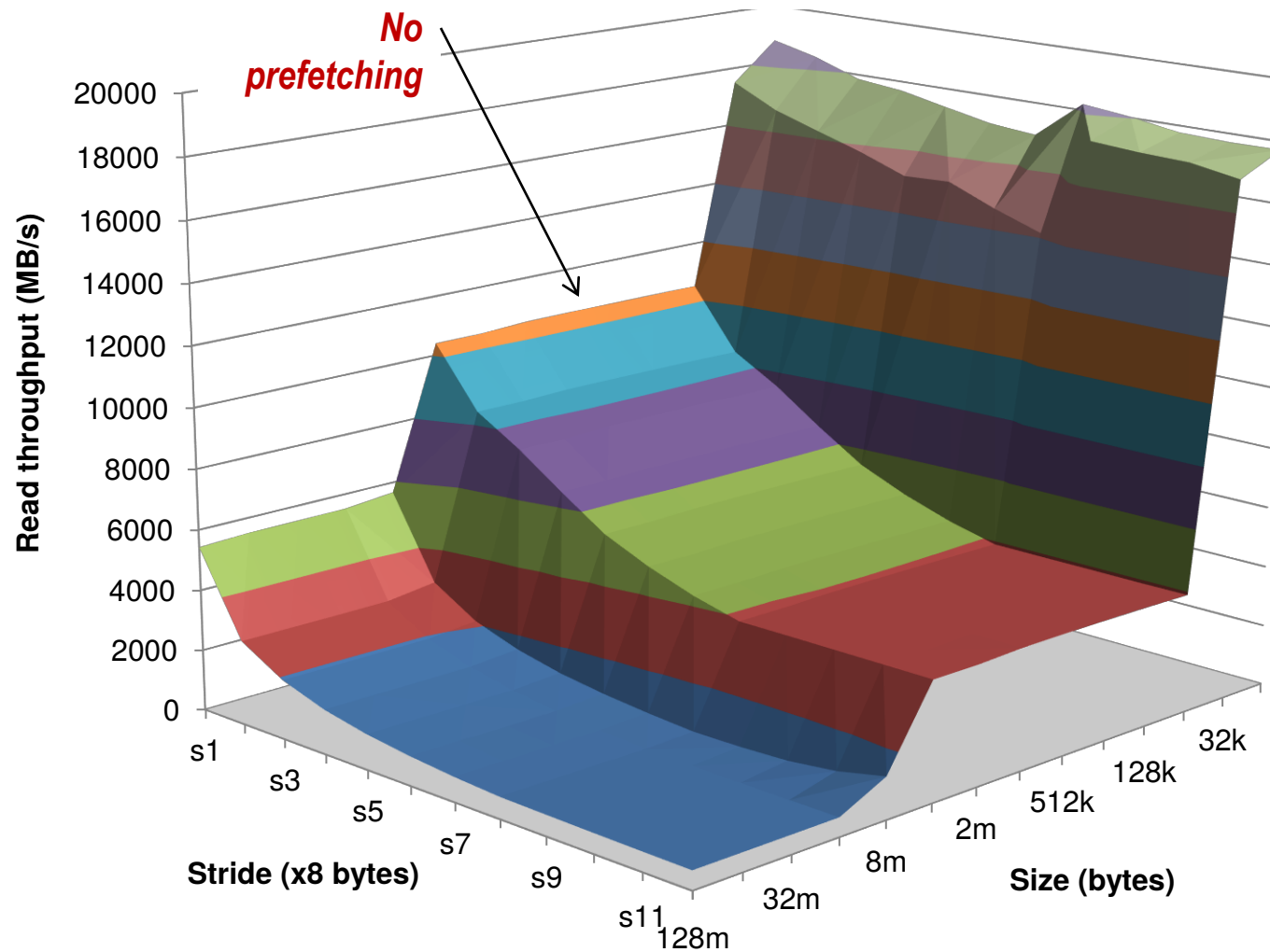
Core i7 Haswell
2.26 GHz
32 KB L1 d-cache
256 KB L2 cache
8 MB L3 cache
64 B block size

Throughput for size = 128K



2008 Memory Mountain

Core 2 Duo
2.4 GHz
32 KB L1 d-cache
6MB L2 cache
64 B block size



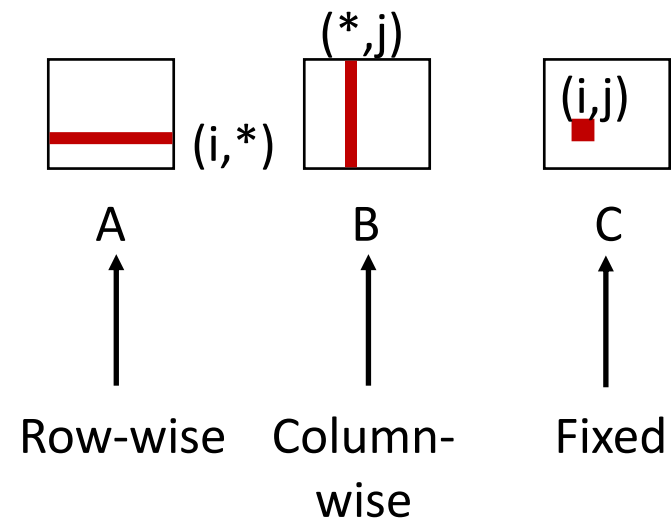
Matrix Multiplication (jik)

```

/* 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:

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

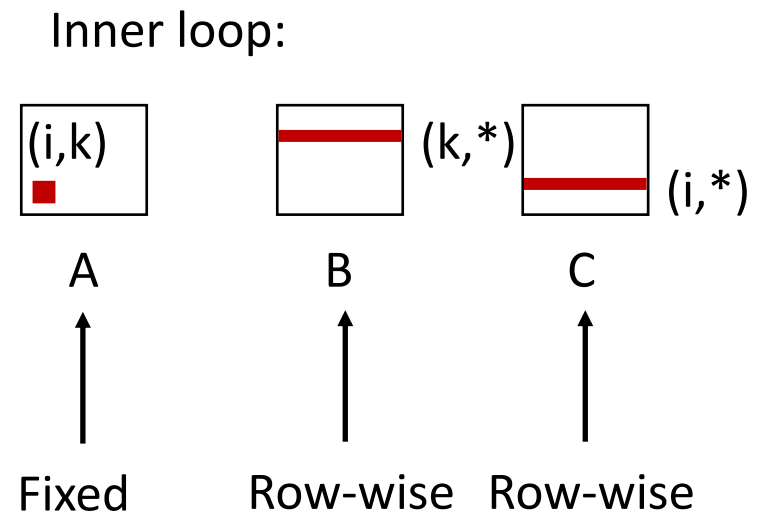
Block size = 32B (four doubles)

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

```



Misses per inner loop iteration:

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

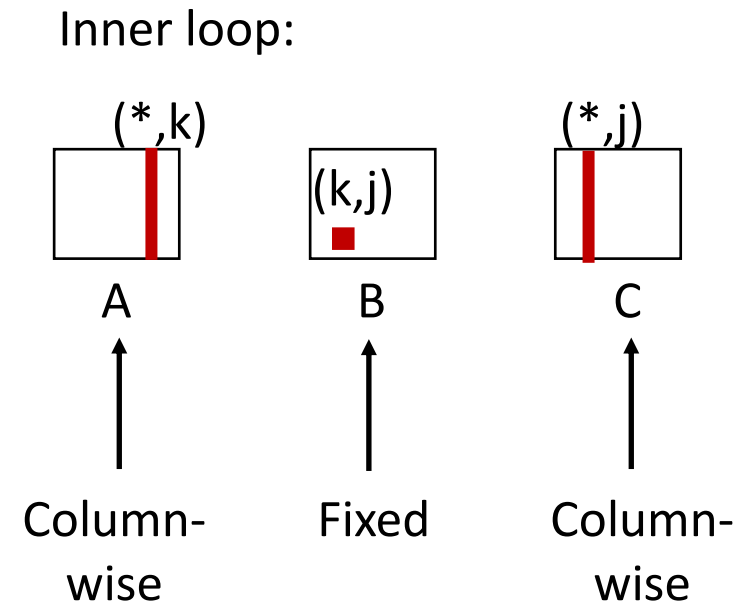
Block size = 32B (four doubles)

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:

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

Block size = 32B (four doubles)