

COMP201

Computer Systems & Programming

Lecture #30 – Cache Memories

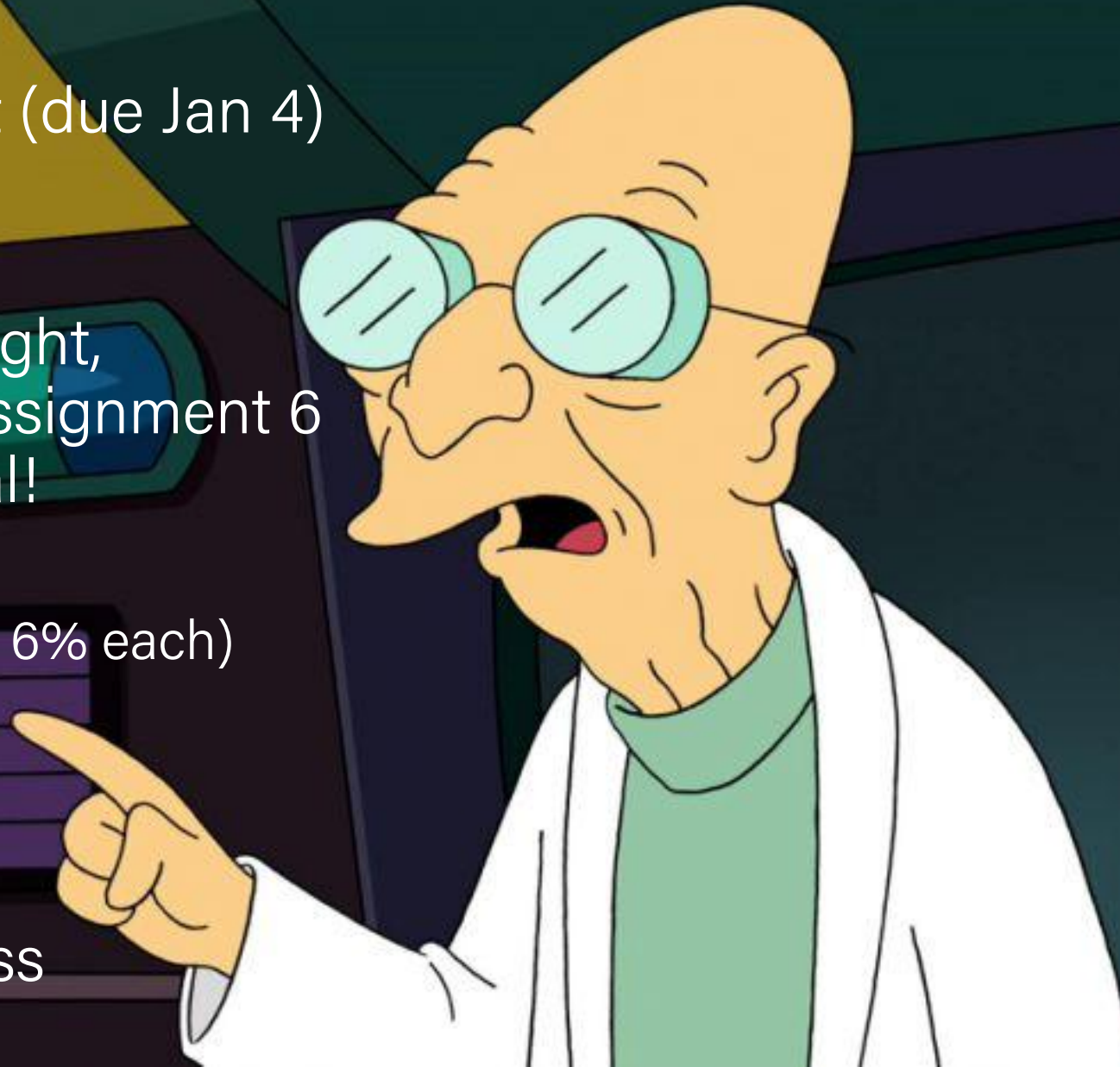


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Aykut Erdem // Koç University // Fall 2020

Good news, everyone!

- Assignment 5 is out (due Jan 4)
- No labs this week!
- After a second thought, I decided to drop Assignment 6 and make it optional!
 - Assignment 0 2%,
Assignment 1-5 5% 6% each)
- I finished grading your exam papers though I want to give it one more pass



Recap

- Storage technologies and trends
- Locality of reference
- Caching in the memory hierarchy

Plan for 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

Disclaimer: Slides for this lecture were borrowed from
—Randal E. Bryant and David R. O'Hallaron's CMU 15-213 class

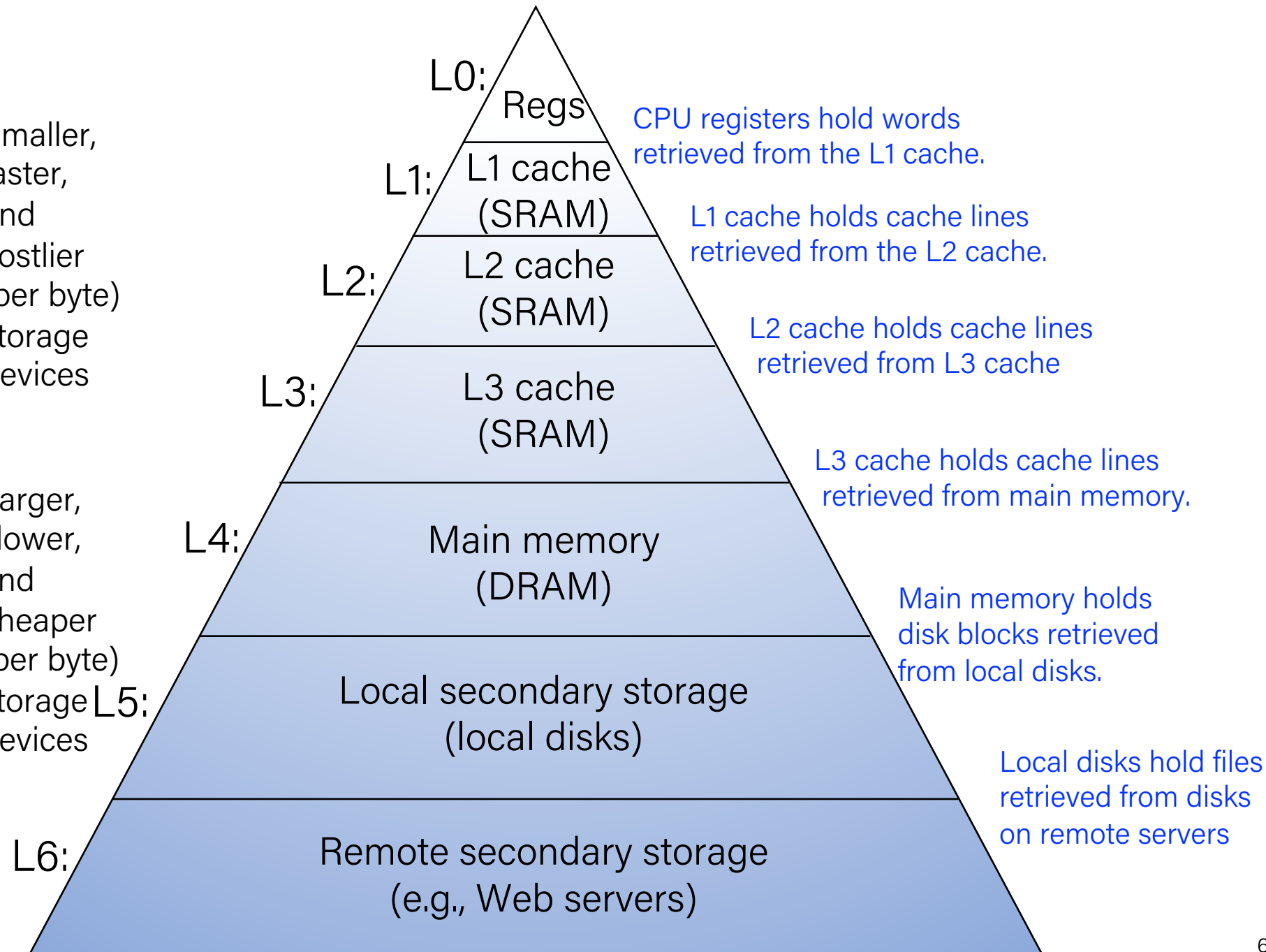
Lecture Plan

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

Example Memory Hierarchy

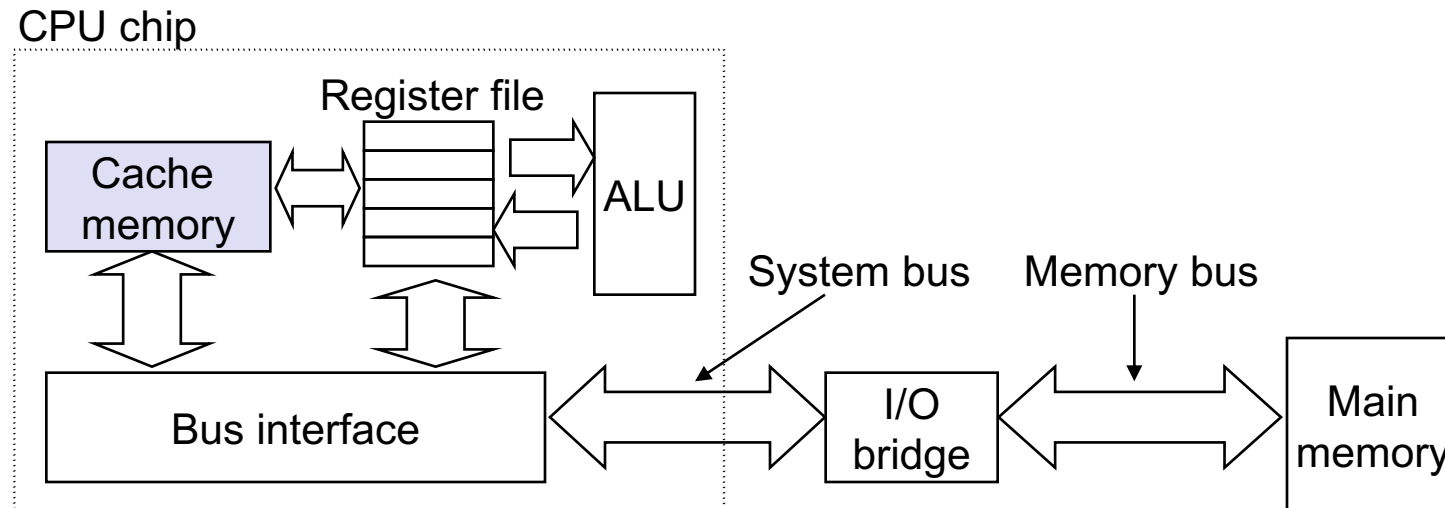
↑
Smaller,
faster,
and
costlier
(per byte)
storage
devices

↓
Larger,
slower,
and
cheaper
(per byte)
storage
devices



Cache Memories

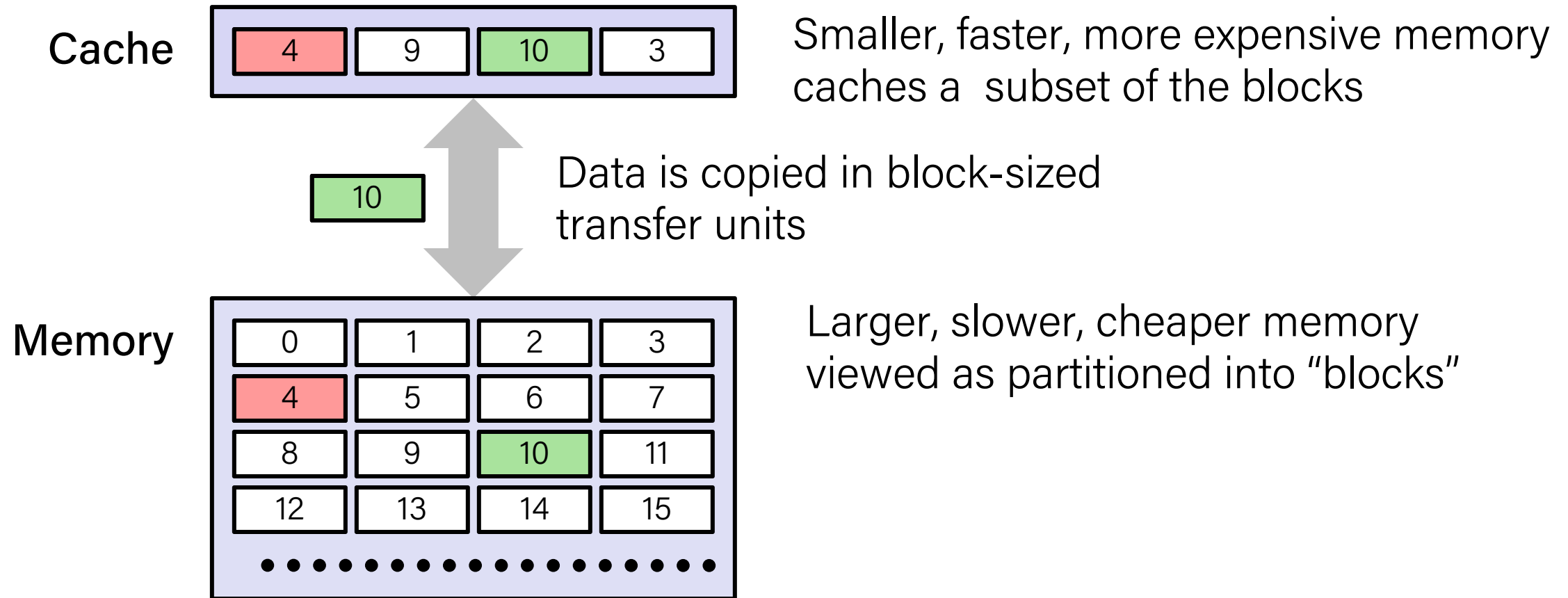
- Cache memories are small, fast SRAM-based memories managed automatically in hardware
 - Hold frequently accessed blocks of main memory
- CPU looks first for data in cache
- Typical system structure:



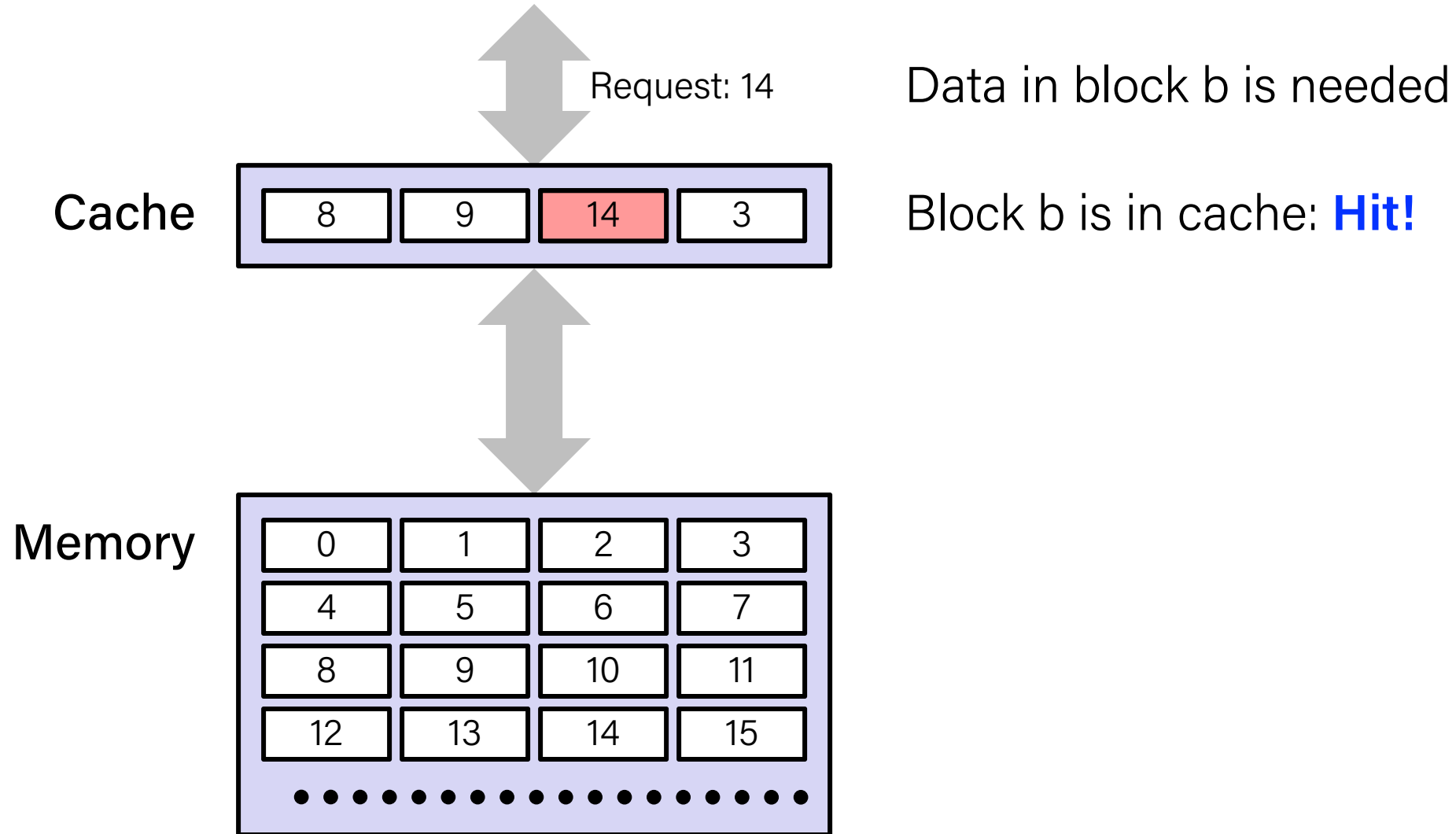
Examples of Caching in the Mem. Hierarchy

Cache Type	What is Cached?	Where is it Cached?	Latency (cycles)	Managed By
Registers	4-8 bytes words	CPU core	0	Compiler
TLB	Address translations	On-Chip TLB	0	Hardware MMU
L1 cache	64-byte blocks	On-Chip L1	4	Hardware
L2 cache	64-byte blocks	On-Chip L2	10	Hardware
Virtual Memory	4-KB pages	Main memory	100	Hardware + OS
Buffer cache	Parts of files	Main memory	100	OS
Disk cache	Disk sectors	Disk controller	100,000	Disk firmware
Network buffer cache	Parts of files	Local disk	10,000,000	NFS client
Browser cache	Web pages	Local disk	10,000,000	Web browser
Web cache	Web pages	Remote server disks	1,000,000,000	Web proxy server

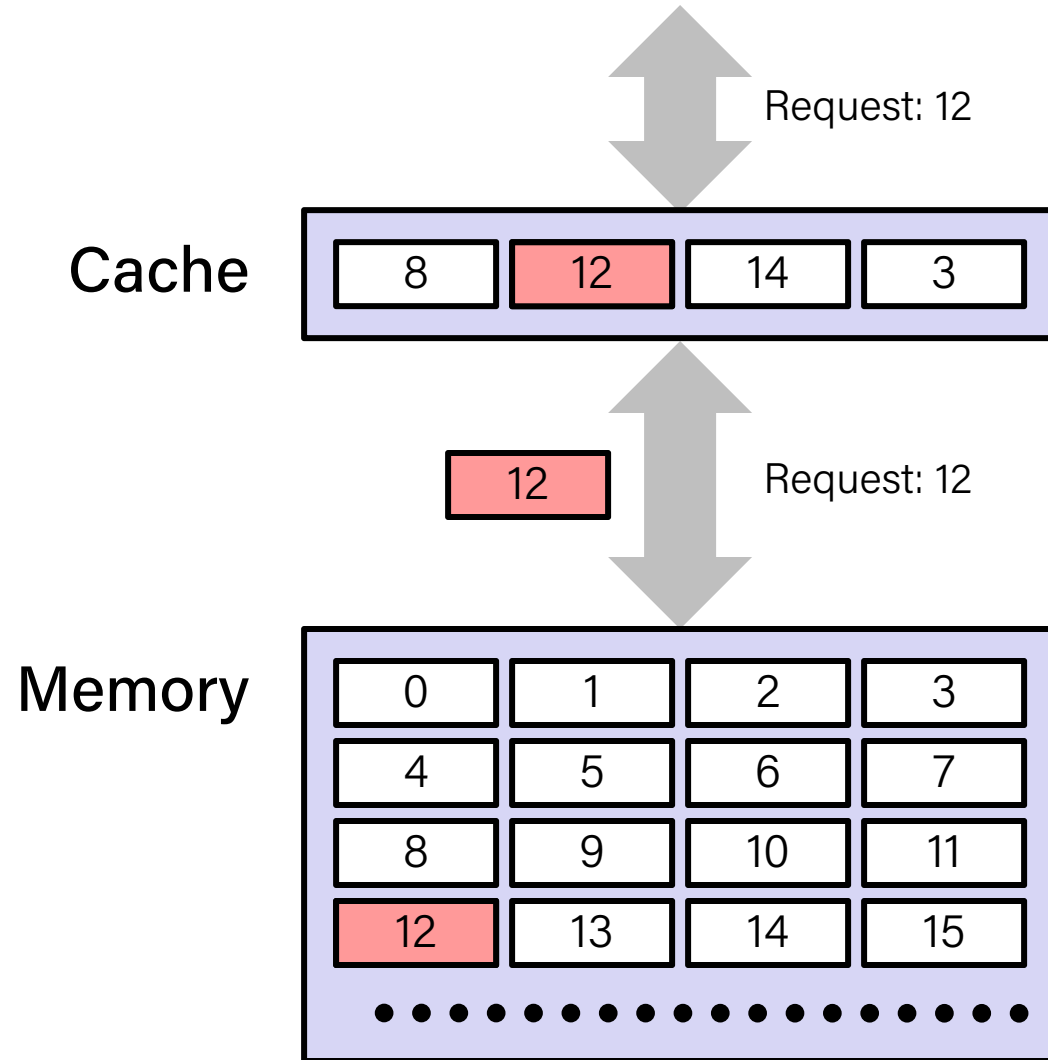
General Cache Concepts



General Cache Concepts: Hit



General Cache Concepts: Miss



Data in block b is needed

Block b is not in cache: **Miss!**

Block b is fetched from memory

Block b is stored in cache

- **Placement policy:** determines where b goes
- **Replacement policy:** determines which block gets evicted (victim)

Types of Cache Misses

- **Cold (compulsory) miss**

- Cold misses occur because the cache is empty.

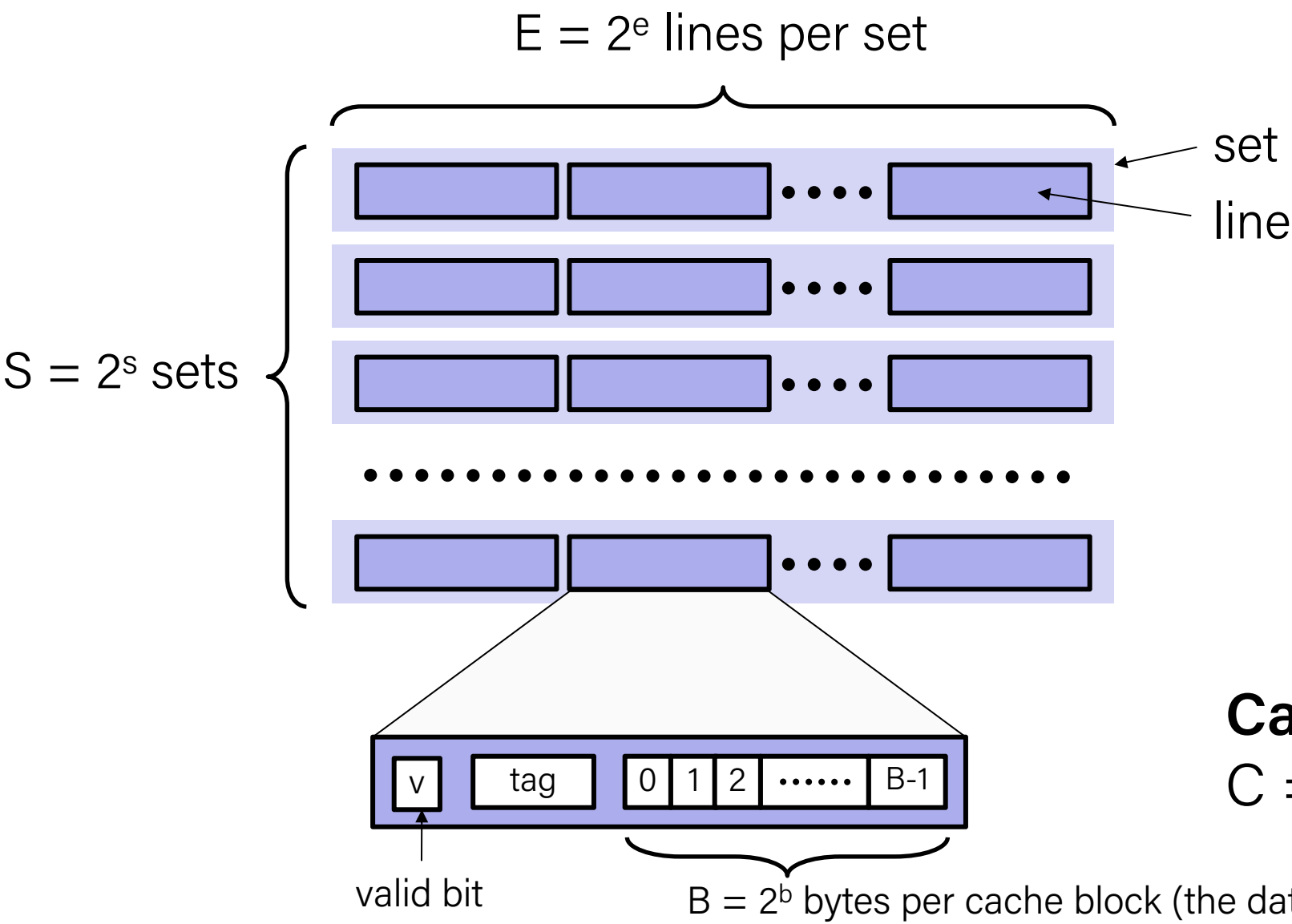
- **Conflict miss**

- 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.

- **Capacity miss**

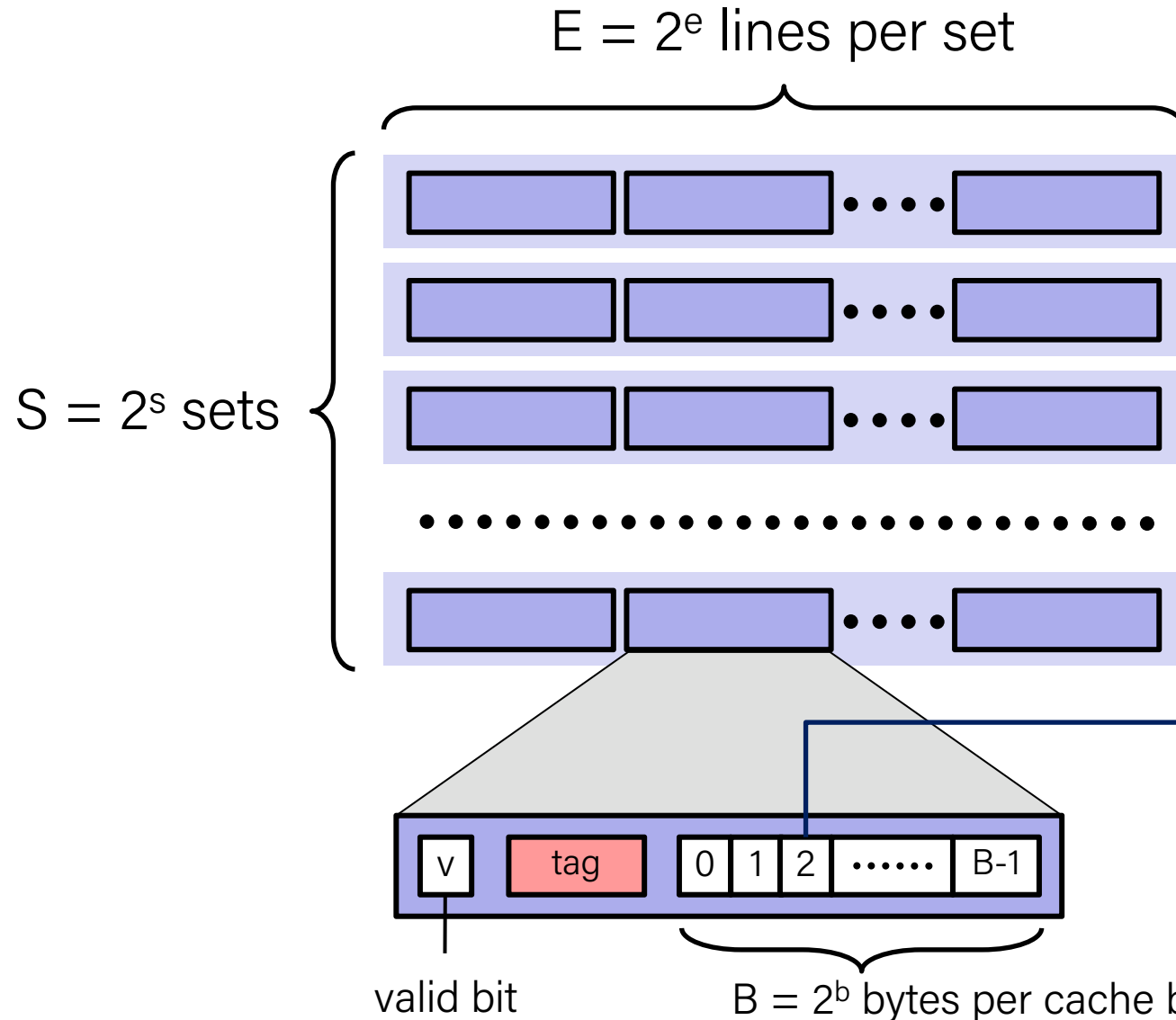
- Occurs when the set of active cache blocks (working set) is larger than the cache.

General Cache Organization (S, E, B)



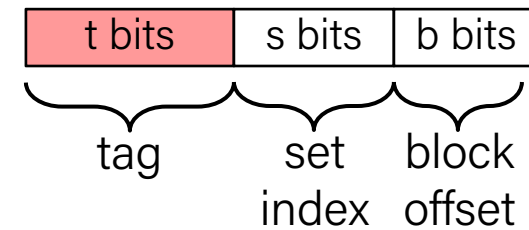
Cache size:
 $C = S \times E \times B$ data bytes

Cache Read



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

Address of word:

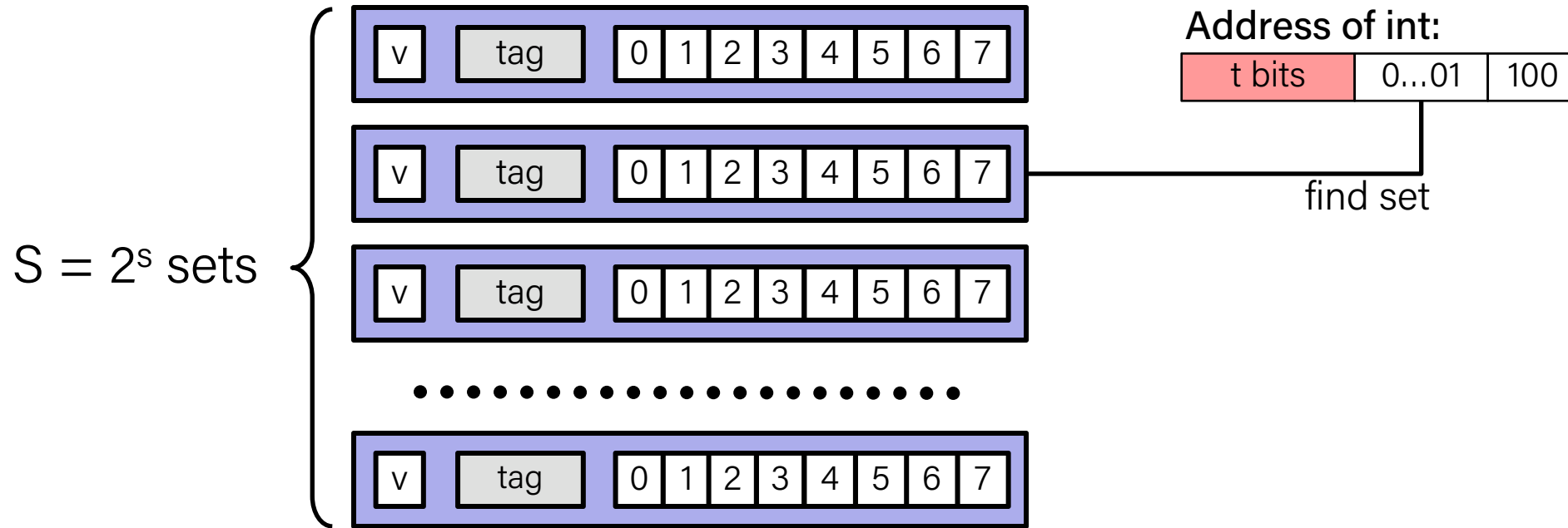


data begins at this offset

Example: Direct Mapped Cache (E = 1)

Direct mapped: One line per set

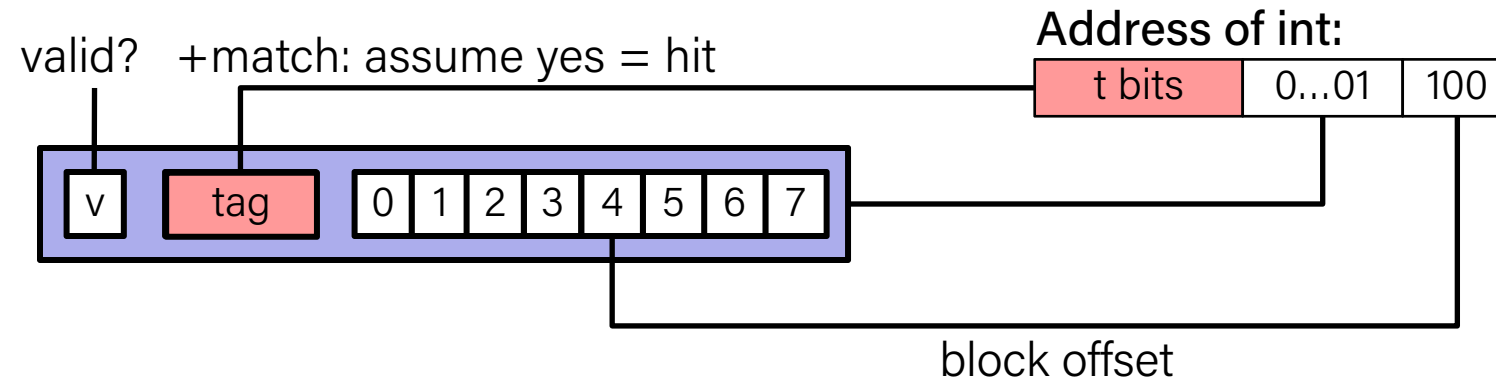
Assume: cache block size 8 bytes



Example: Direct Mapped Cache (E = 1)

Direct mapped: One line per set

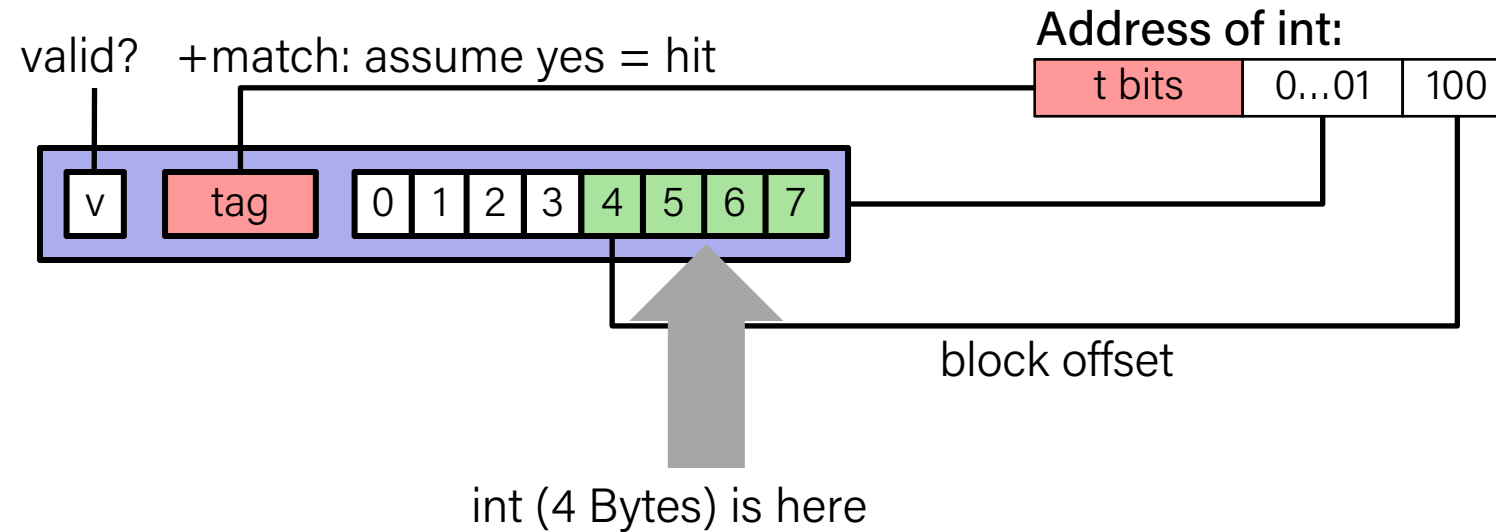
Assume: cache block size 8 bytes



Example: Direct Mapped Cache (E = 1)

Direct mapped: One line per set

Assume: cache block size 8 bytes



If tag doesn't match: old line is evicted and replaced

Direct-Mapped Cache Simulation

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

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

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

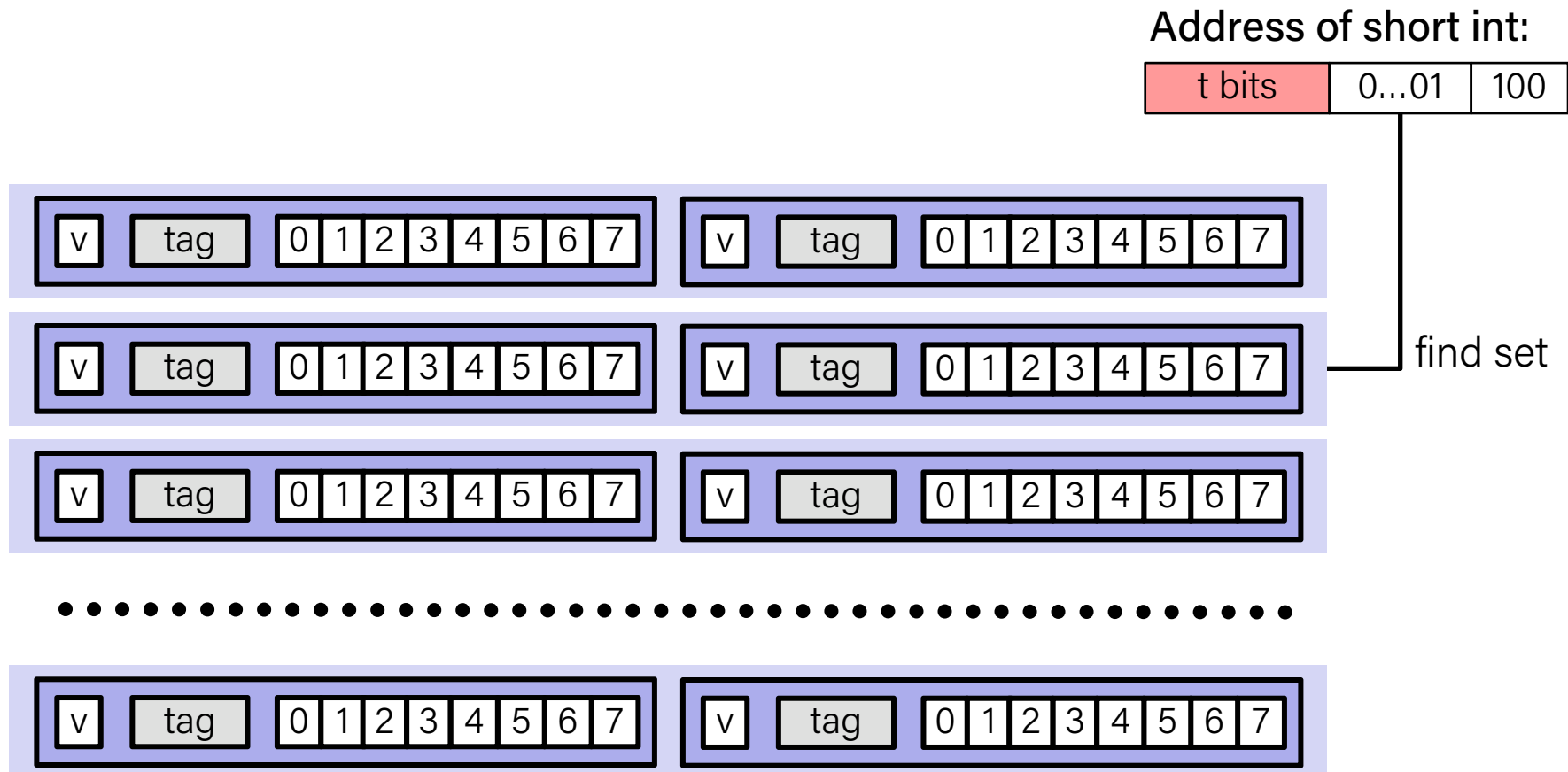
Address trace (reads, one byte per read):

0	[<u>0000</u> ₂],	miss
1	[<u>0001</u> ₂],	hit
7	[<u>0111</u> ₂],	miss
8	[<u>1000</u> ₂],	miss
0	[<u>0000</u> ₂]	miss

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

$E = 2$: Two lines per set

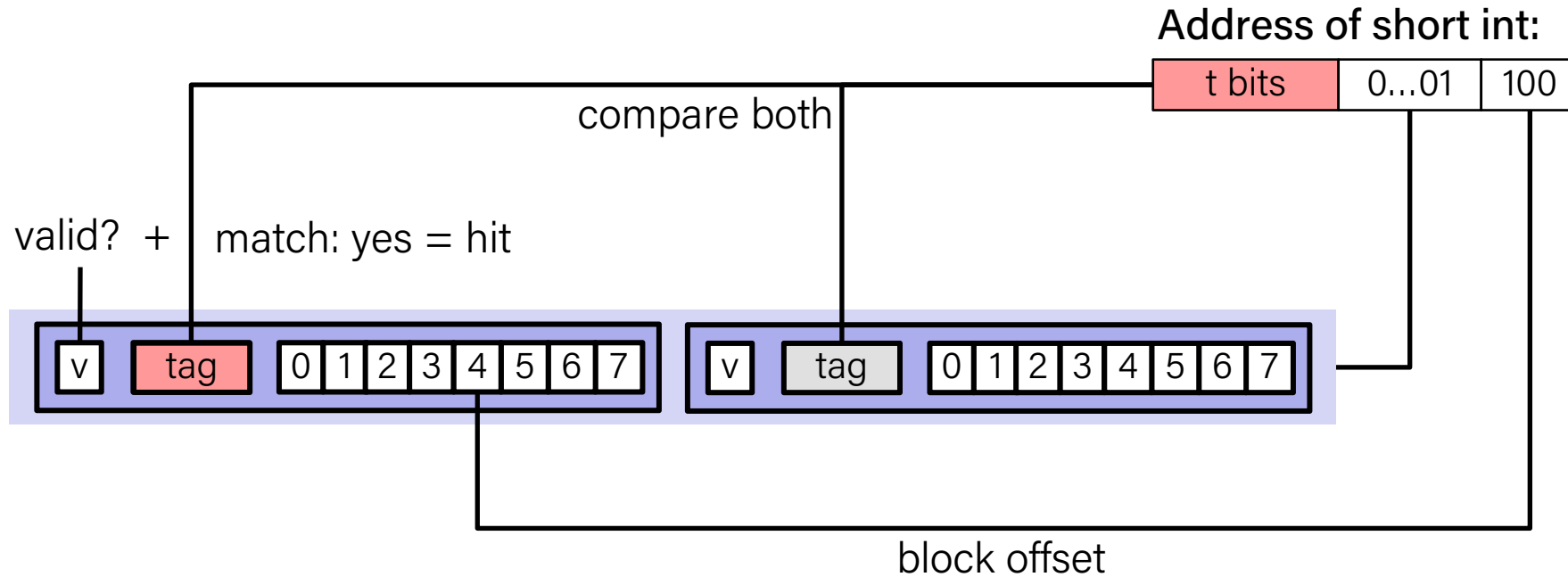
Assume: cache block size 8 bytes



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

E = 2: Two lines per set

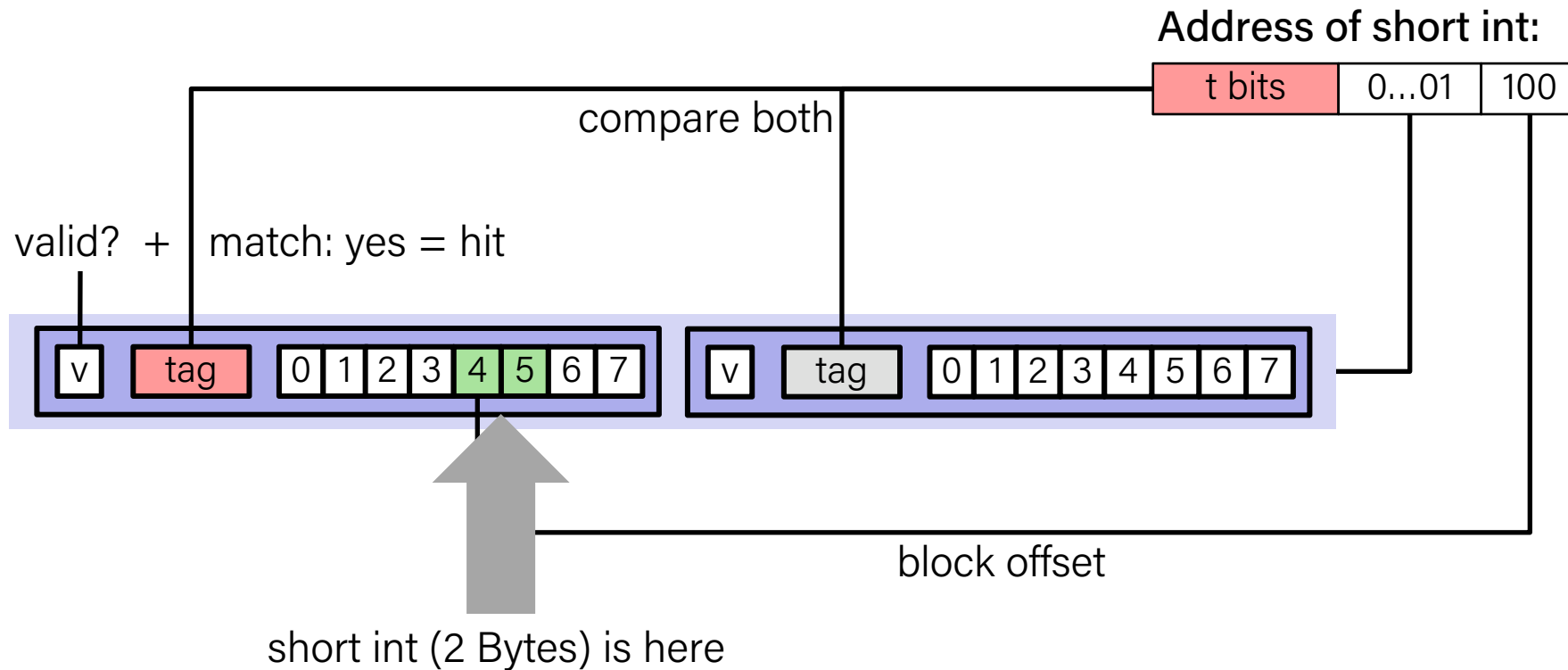
Assume: cache block size 8 bytes



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

$E = 2$: Two lines per set

Assume: cache block size 8 bytes



No match:

- 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
----	---	---

M=16 byte addresses, B=2 bytes/block,
S=2 sets, E=2 blocks/set

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

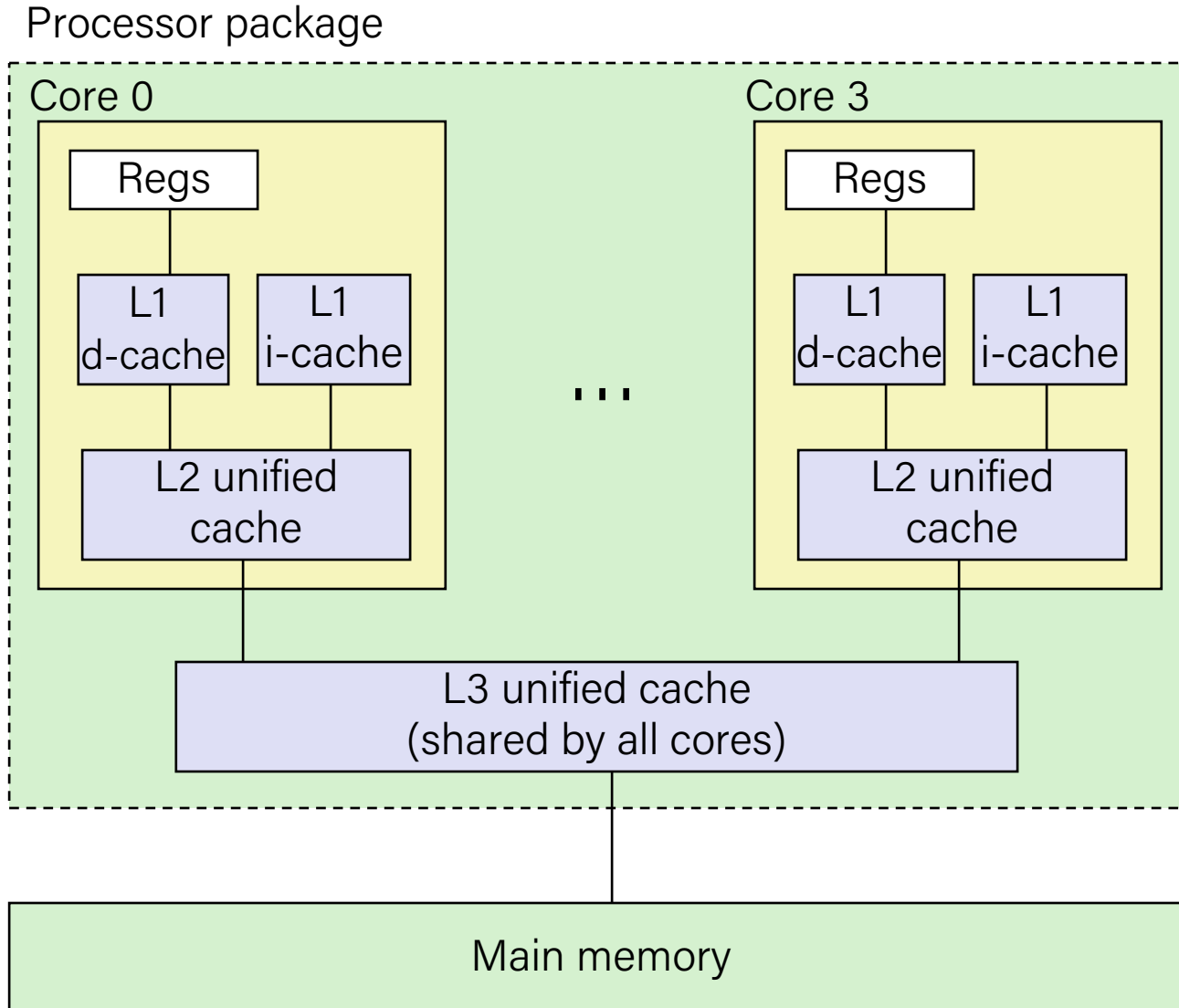
	v	Tag	Block
Set 0	1	00	M[0-1]
	1	10	M[8-9]
Set 1	1	01	M[6-7]
	0		

Question Break

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)
 - Need a dirty bit (line different from memory or not)
- **What to do on a write-miss?**
 - **Write-allocate** (load into cache, update line in cache)
 - Good if more writes to the location follow
 - **No-write-allocate** (writes straight to memory, does not load into cache)
- **Typical**
 - Write-through + No-write-allocate
 - Write-back + Write-allocate

Intel Core i7 Cache Hierarchy



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 – 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:
cache hit time of 1 cycle
miss penalty of 100 cycles
 - Average access time:
 - 97% hits: $1 \text{ cycle} + 0.03 * 100 \text{ cycles} = 4 \text{ cycles}$
 - 99% hits: $1 \text{ cycle} + 0.01 * 100 \text{ cycles} = 2 \text{ cycles}$
- **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

Lecture Plan

- 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
 *      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));
}
```

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

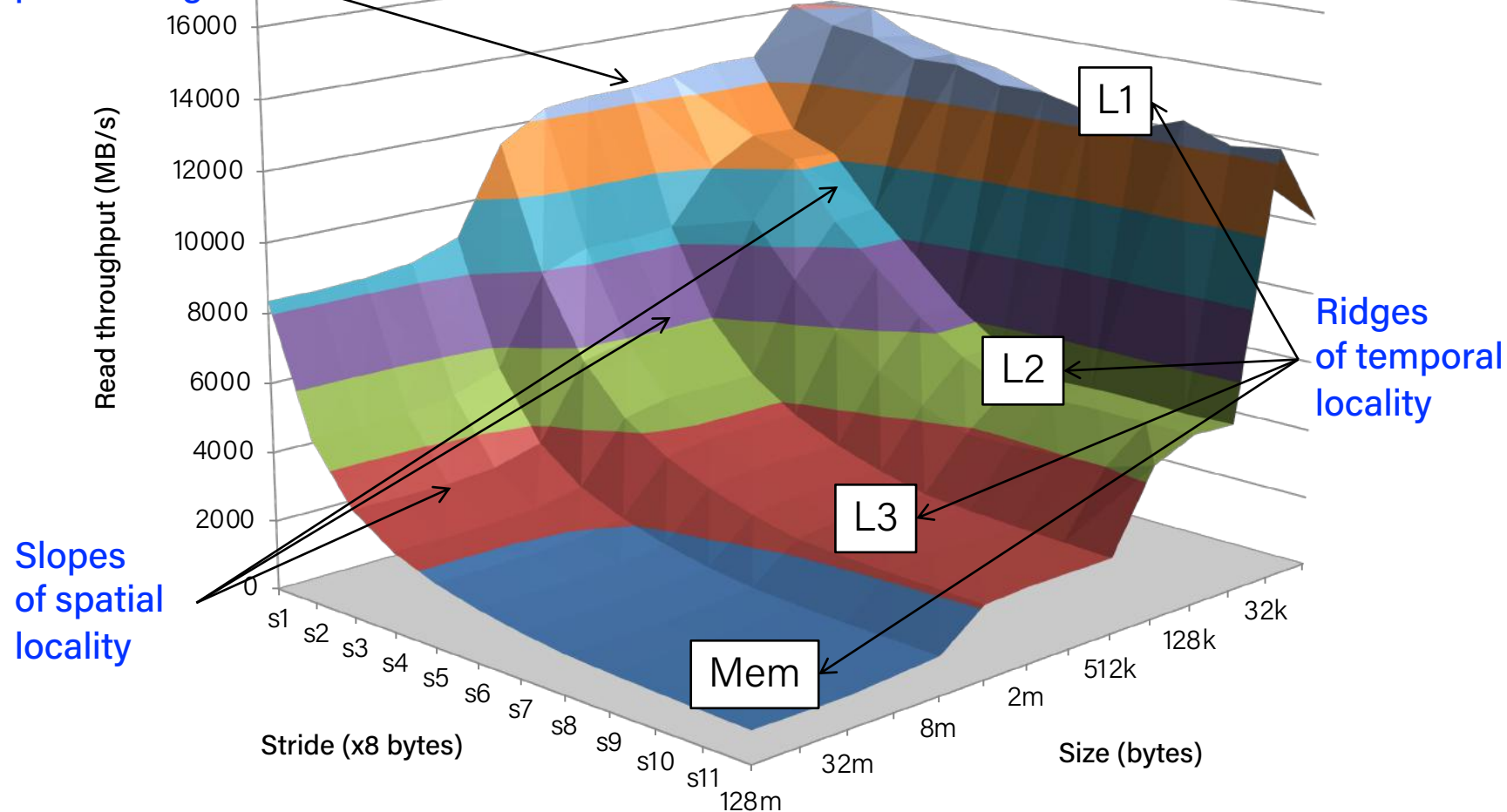
For each elems and stride:

1. Call test() once to warm up the caches.
2. Call test() again and measure the read throughput(MB/s)

mountain/mountain.c

The Memory Mountain

Aggressive
prefetching



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

Lecture Plan

- Cache organization and operation
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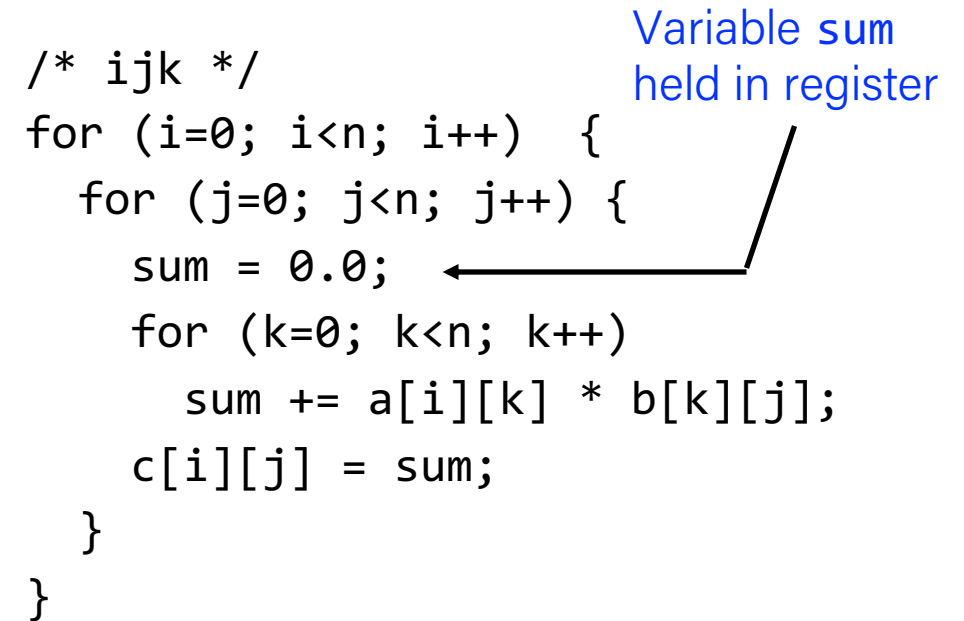
Matrix Multiplication Example

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

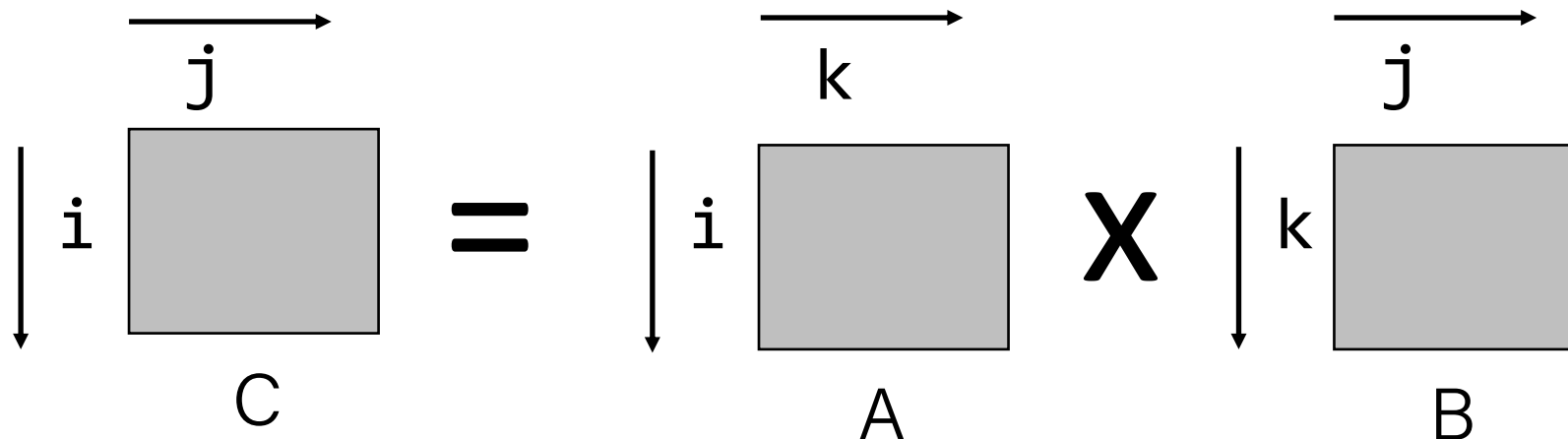
Variable sum
held in register



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:

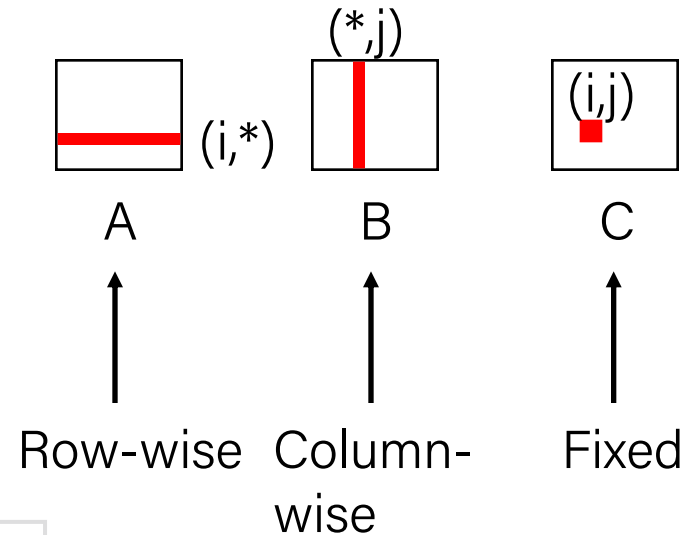
```
for (i = 0; i < n; i++)  
    sum += a[i][0];
```

 - 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;
    }
}
```

Inner loop:



matmult/mm.c

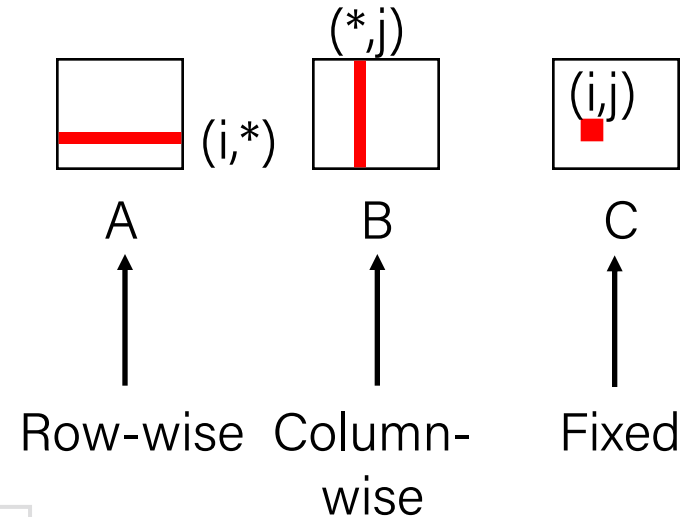
Misses per inner loop iteration:

<u>A</u>	<u>B</u>	<u>C</u>
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
    }
}
```

Inner loop:



matmult/mm.c

Misses per inner loop iteration:

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

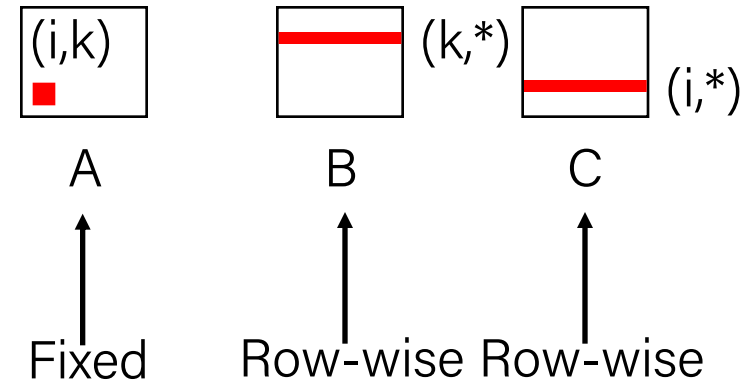
Matrix Multiplication (kij)

```
/* 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:

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

Inner loop:

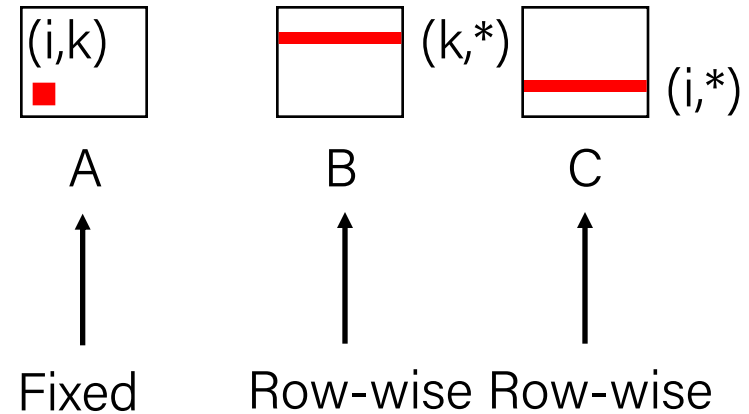


matmult/mm.c

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:



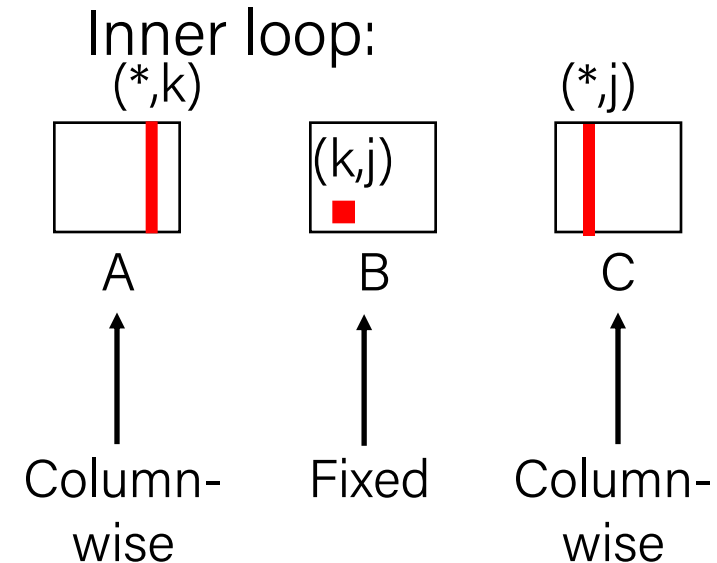
matmult/mm.c

Misses per inner loop iteration:

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

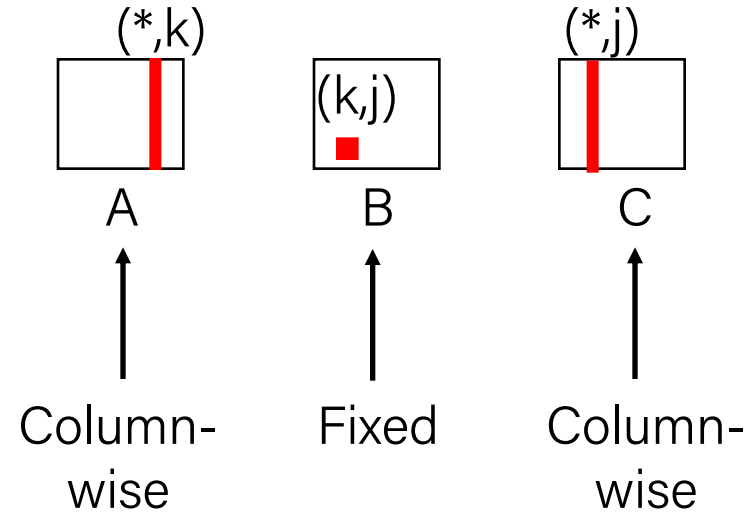
<u>A</u>	<u>B</u>	<u>C</u>
1.0	0.0	1.0

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:



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

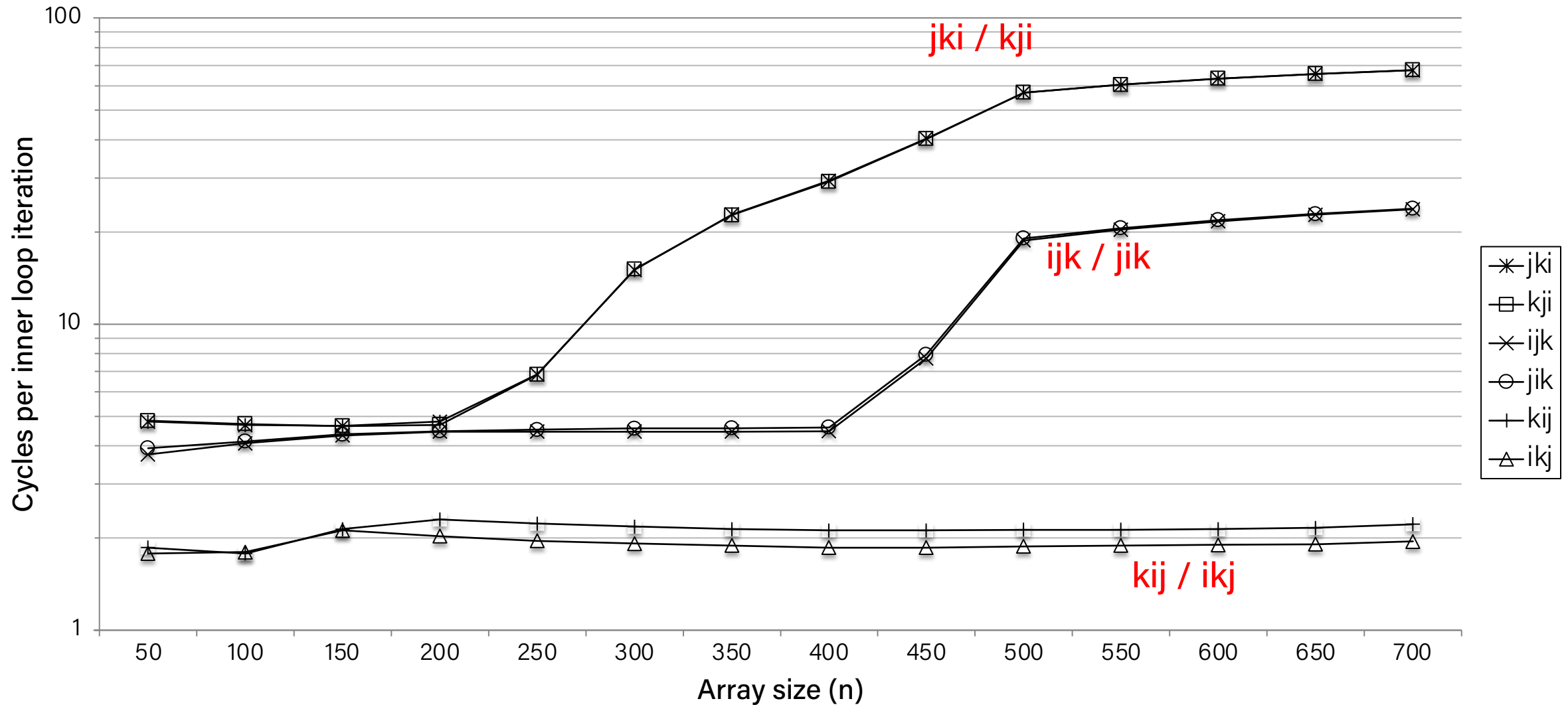
kij (& ikj):

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

jki (& kji):

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

Core i7 Matrix Multiply Performance



Question Break

Lecture Plan

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

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];  
}
```

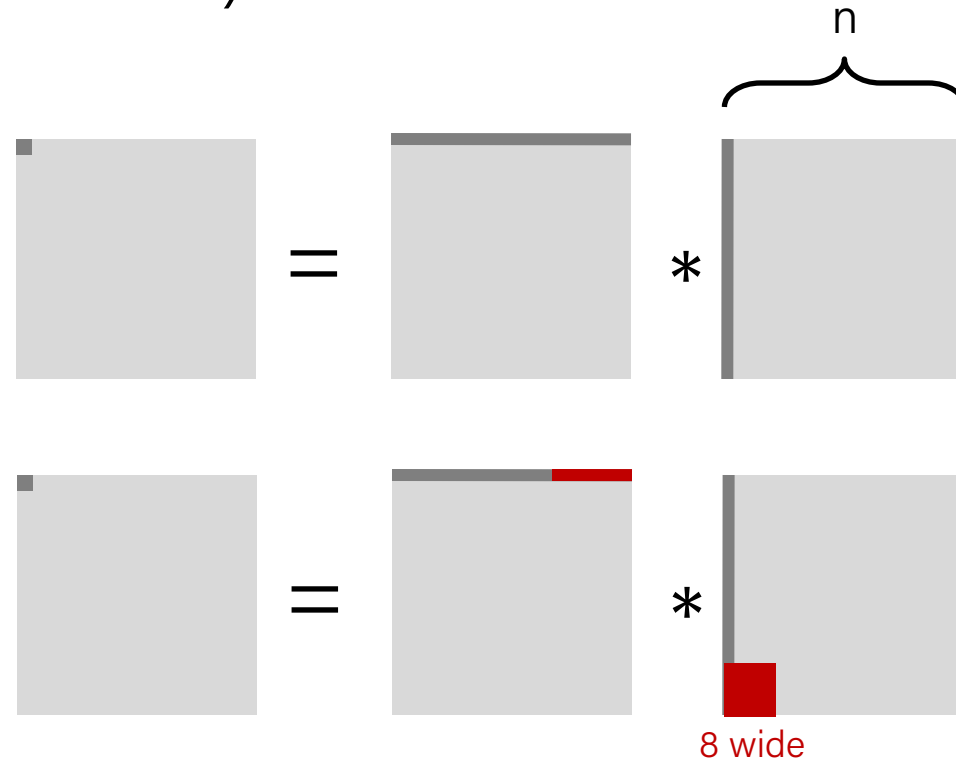


Cache Miss Analysis

- 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

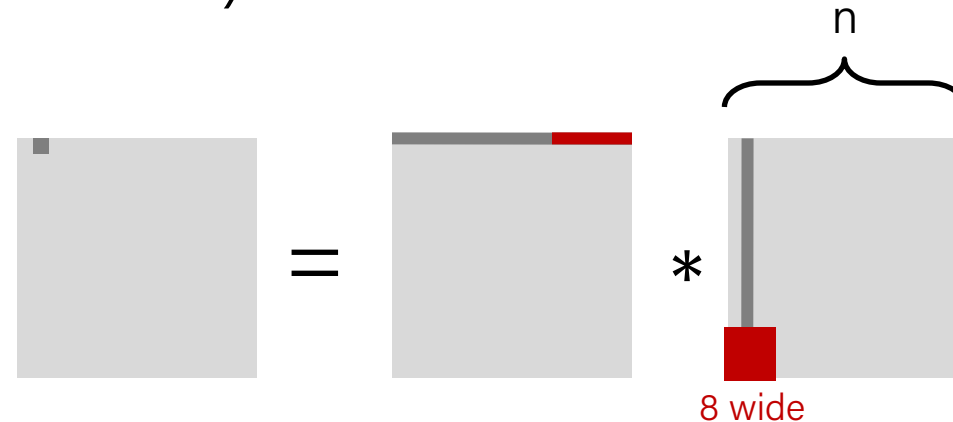
- Assume
 - Matrix elements are doubles
 - Cache block = 8 doubles
 - Cache size $C \ll n$ (much smaller than n)

- **Second iteration:**

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

- **Total misses:**

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

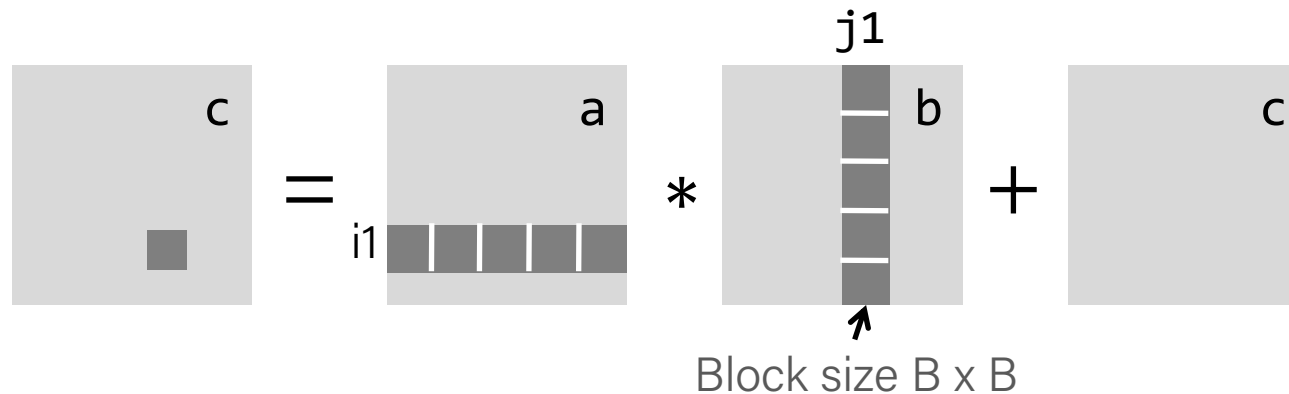


Blocked Matrix Multiplication


```
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; 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

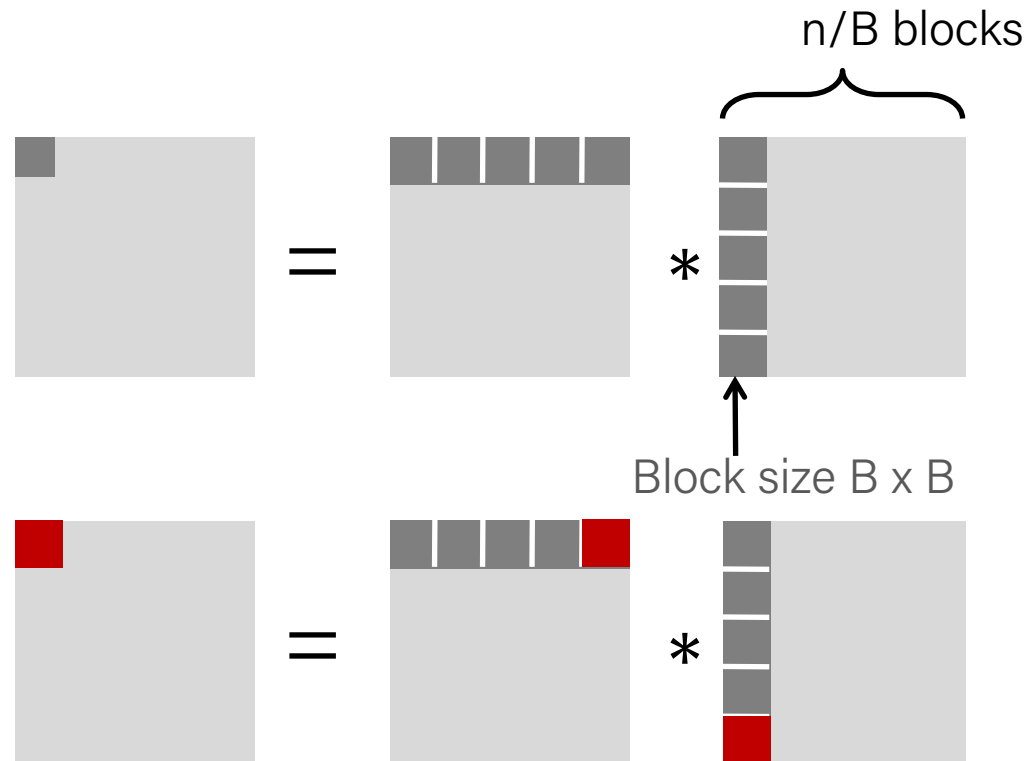


Cache Miss Analysis


- 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
- $2n/B * B^2/8 = nB/4$
(omitting matrix c)
- Afterwards in cache
(schematic)



Cache Miss Analysis

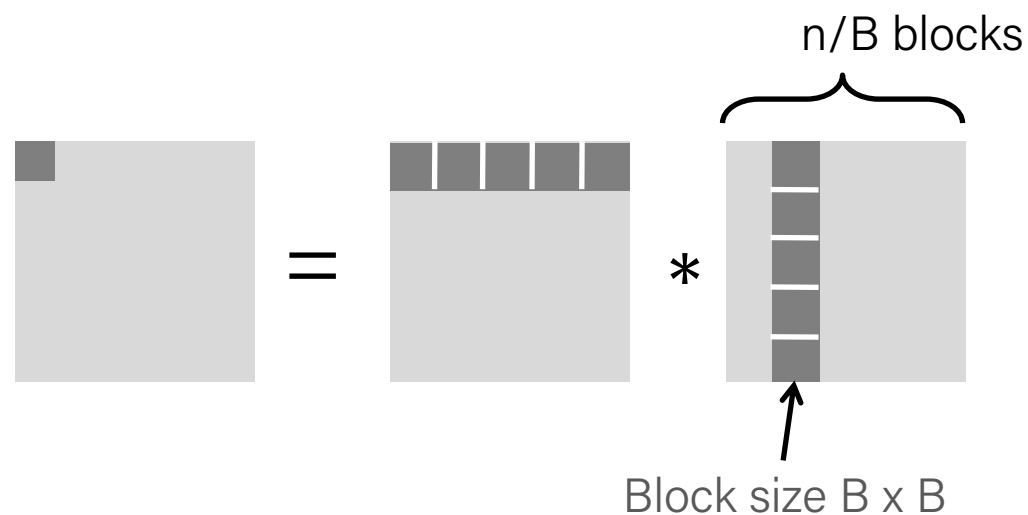
- Assume:
 - Cache block = 8 doubles
 - Cache size $C \ll n$ (much smaller than n)
 - Three blocks  fit into cache: $3B^2 < C$

- **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

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.

Next time: Debugging and Design