Master Informatics Eng.

2020/21

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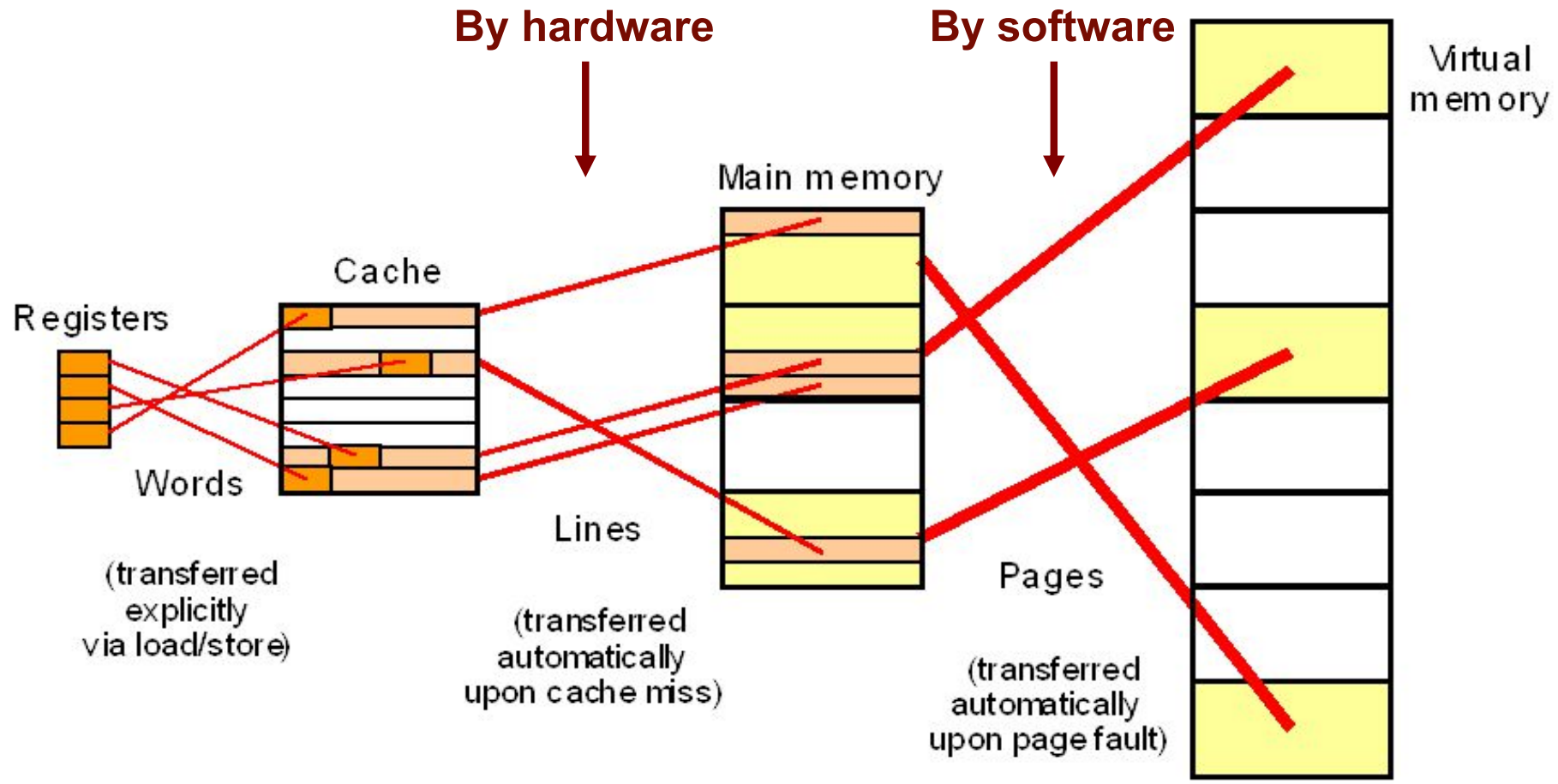
Memory Hierarchy (online)

(most slides are borrowed)

Memory hierarchy: the big picture



Data movement in a memory hierarchy.

Exercise 1 on memory hierarchy

Consider the following study case:

- execution of a piece of code in the SeARCH node with the **Xeon Skylake (Gold 6130)**; detailed info on this Intel microarchitetcure in https://en.wikichip.org/wiki/intel/microarchitectures/skylake_(server) ;
- execution of the **same 2 instructions** (that are already in the instruction cache) **in all cores** of a single chip: load in register a double followed by a multiplication by another double in a memory distant location;
- Skylake cores are **6-way superscalar** and each core has 2 load units;
- these instructions are executed with a **cold data cache**.

Compute:

a) **The max required bandwidth** to access the external RAM when executing these 2 instructions (to simplify, consider **clock rate = 2 GHz**).

b) **The peak bandwidth** available in this Xeon device to access the installed DRAM-4 using **all memory channels**.

Resolution

Exercise 1 on memory hierarchy

- each clock cycle needs 2 mem accesses to fetch 2 doubles
- **max required bandwidth** to fetch a cache line
  for each double (cache is cold & doubles are far away):

  ???? GB/s
- note: the following 7 pairs of doubles are already in cache
- RAM in each Skylake Gold 6130: 6x DDR4-2666 (6x8 GiB)
- **peak bandwidth** of 6x DDR4-2666 in 6 memory channels:
  ??? GB/s

Resolution

Exercise 1 on memory hierarchy

- each clock cycle needs 2 mem accesses to fetch 2 doubles
- **max required bandwidth** to fetch a cache line
  for each double (cache is cold & doubles are far away):
  (16 cores x 2 lines x 64 B/line) x clock_frequency =
  2048 B x 2 GHz = **4096 GB/s**
- note: the following 7 pairs of doubles are already in cache
- RAM in each Skylake Gold 6130: 6x DDR4-2666 (6x8 GiB)
- **peak bandwidth** of 6x DDR4-2666 in 6 memory channels:
  6 mem_chan x 2.666 GT/s x 64 b/chan = **128 GB/s**

Exercise 2 on memory hierarchy

Similar to exercise 1 (same node/chip in the cluster), but consider now:

- execution of code taking advantage of the **AVX-512** facilities;
- execution of the same **2 vector instructions** (that are already in the instruction cache) **in all cores**: load in register a vector of doubles followed by a multiplication by another vector of doubles in memory;
- the Skylake cores are **6-way superscalar** and **2-way MT**, and each core supports 2 simultaneous vector loads;
- the Skylake 6130 base clock rate with **AVX-512** code is **1.3 GHz**;
- these instructions are executed with a **cold data cache**.

Compute/estimate:

The **max required bandwidth** to access the external RAM when executing these 2 vector instructions.
Compare with the **peak bandwidth** computed before.

* https://en.wikichip.org/wiki/intel/xeon_gold/6130

Resolution

Exercise 2 on memory hierarchy

- each clock cycle needs 2 mem accesses to fetch 2 vectors with 8 doubles each (512 bits)
- **max required bandwidth** to fetch a cache line for each vector with 8 doubles (cache is cold):

  ???? GB/s

- note: same max required bandwidth as exercise 1, but this **mem access is required at each clock cycle**
- RAM in each Skylake Gold 6130: 6x DDR4-2666 (6x8 GiB)
- **peak bandwidth** of 6x DDR4-2666 in 6 memory channels: **??? GB/s**

Resolution

Exercise 2 on memory hierarchy

- each clock cycle needs 2 mem accesses to fetch 2 vectors with 8 doubles each (512 bits)
- **max required bandwidth** to fetch a cache line for each vector with 8 doubles (cache cold, AVX-512 clock rate lower*):
  (16 cores x 2 lines x 64 B/line) x clock_rate =
  2048 B x **1.3** GHz = **2662.4 GB/s**
- note: same max required bandwidth as exercise 1,
  but this **mem access is required at each clock cycle**
- RAM in each Skylake Gold 6130: 6x DDR4-2666 (6x8 GiB)
- **peak bandwidth** of 6x DDR4-2666 in 6 memory channels:
  6 mem_chan x 2.666 GT/s x 64 b/chan = **128 GB/s**

* https://en.wikichip.org/wiki/intel/xeon_gold/6130

Memory Hierarchy Basics

$$CPU_{exec\text{-}time} = (CPU_{clock\text{-}cycles} + Mem_{stall\text{-}cycles}) \times \text{Clock cycle time}$$

$$CPU_{exec\text{-}time} = (IC \times CPI_{CPU} + Mem_{stall\text{-}cycles}) \times \text{Clock cycle time}$$

With introduction of a single-level cache:

$$Mem_{stall\text{-}cycles} = IC \times \text{... Miss rate ... Mem accesses ... Miss penalty...}$$

$$Mem_{stall\text{-}cycles} = IC \times \text{Misses/Instruction} \times \text{Miss Penalty}$$

$$\frac{\text{Misses}}{\text{Instruction}} = \frac{\text{Miss rate} \times \text{Memory accesses}}{\text{Instruction count}} = \text{Miss rate} \times \frac{\text{Memory accesses}}{\text{Instruction}}$$

For each additional cache-level `i` (including LLC to memory):

$$Mem\_accesses_{level\_i} = Misses/Instruction_{level\_i-1}$$

$$Miss\_penalty_{level\_i} = (Hit\_rate \times Hit\_time + Miss\_rate \times Miss\_penalty)_{level\_i+1}$$

Exercise 3 on Cache Performance

- Given
  - I-cache miss rate = 2%
  - D-cache miss rate = 4%
  - Miss penalty = 100 cycles
  - Base CPI (ideal cache) = **2**
  - Load & stores are 36% of instructions
- Miss cycles per instruction
  - I-cache: 0.02 x 100 = 2
  - D-cache: 0.36 x 0.04 x 100 = 1.44
- Actual CPI = 2 + 2 + 1.44 = **5.44**

Exercise 4 on Multilevel Cache

- **CPU**: base CPI = 1, clock rate = 4GHz
- **L1 cache**: L1 miss rate/instruction = 2%
- **L2 cache**: access time = **5ns**, L2 miss rate/instruction = 25%, global miss rate = 2% x 25% = **0.5%**
- **Main memory**: access time = **100ns**
- **With just primary cache**
  - Miss penalty = 100ns / 0.25ns = 400 cycles
  - Effective CPI = 1 + 0.02 × 400 = **9**
- **With L1 & L2 cache**
  - L1 miss penalty, L2 hit = **?? cycles**
  - L2 miss penalty = **?? cycles**
- **CPI** = 1 + **2%** × **??** cycles + **0.5%** × **???** cycles = **???**
- **Performance ratio** = 9 / **???** = **???**

Exercise 4 on Multilevel Cache

- **CPU**: base CPI = 1, clock rate = 4GHz
- **L1 cache**: L1 miss rate/instruction = 2%
- **L2 cache**: access time = **5ns**, L2 miss rate/instruction = 25%, global miss rate = 2% x 25% = **0.5%**
- **Main memory**: access time = **100ns**
- **With just primary cache**
  - Miss penalty = 100ns / 0.25ns = 400 cycles
  - Effective CPI = 1 + 0.02 × 400 = **9**
- **With L1 & L2 cache**
  - L1 miss penalty, L2 hit = 99.5% × 5ns / 0.25ns ≈ **20 cycles**
  - L2 miss penalty = 100ns / 0.25ns = **400 cycles**
- **CPI** = 1 + **2%** × **20** cycles + **0.5%** × **400** cycles = **3.4**
- **Performance ratio** = 9 / **3.4** = **2.6**

Exercise 5 on multilevel performance

Similar to problem 1 (same node/chip in the cluster, code), but consider now:

- execution of scalar code in a **2 GHz** single-core (already in L1 I-cache);
- code already takes advantage of all data cache levels (**L1, L2 & L3**), where 50% of data is placed on the RAM modules in the memory channels of the other PU chip (**NUMA architecture**);
- remember: the Skylake cores are **6-way superscalar** and **2-way MT**, and each core supports **2 simultaneous loads**;
- **cache latency time on hit**: take the average of the specified values;
- **memory latency**: 80 nsec (**NUMA local**), 120 nsec (**NUMA remote**);
- **miss rate per instruction** :
  - at **L1: 2%;** at **L2: 50%;** at **L3: 80%** (these are not global values!).

Compute/estimate:

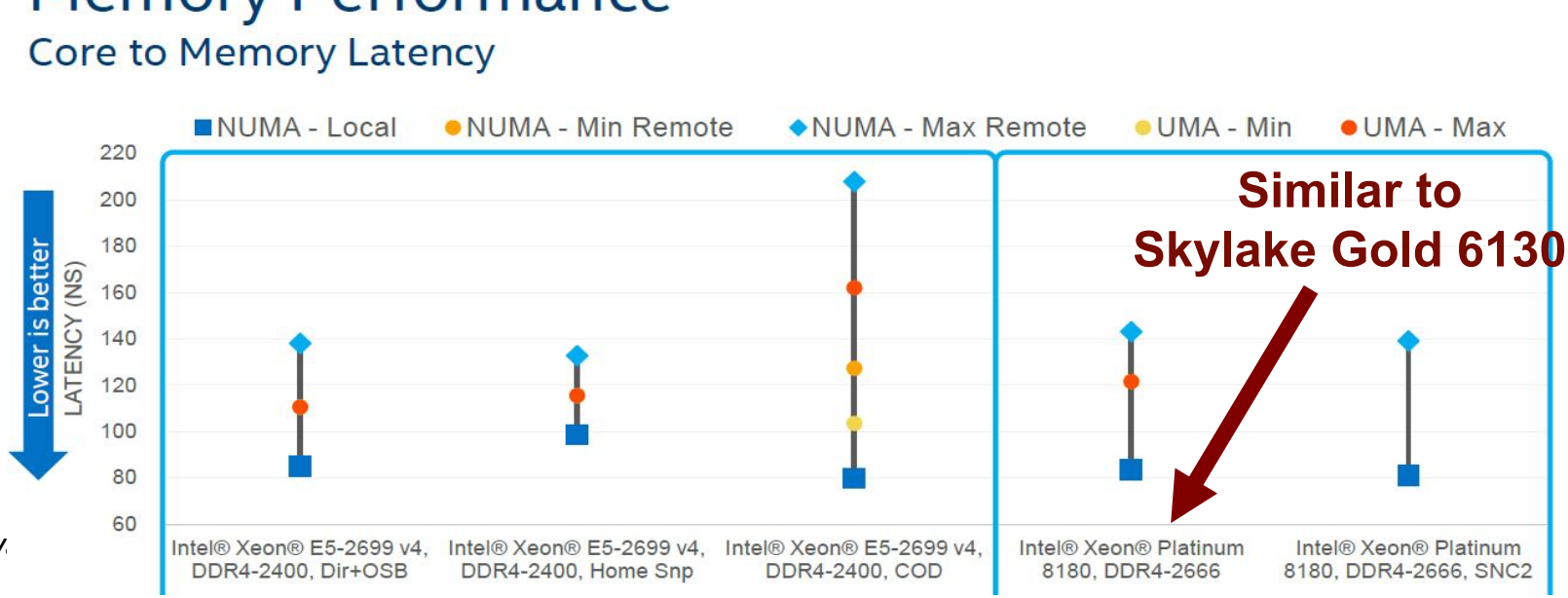
1. **The miss penalty** per instruction at each cache level.
2. **The average memory stall cycles** per instruction that degrades CPI.

Resolution

Exercise 5 on memory hierarchy

- **PU**: base CPI = 1, clock rate = 2 GHz
- **L1 cache**: L1 miss rate/instruction = 2%;
- **L2 cache**: access time = **14** cycles, global miss rate = 2% x 50% = **1%**
- **L3 cache**: access time = **60** cycles, L3 miss rate = 80%,
  global miss rate = 1% x 80% = **0.8%**
- **Main memory**: NUMA local access time = **80ns**, NUMA remote = **120ns**
  average memory access = ((80ns+120ns)/2) / 0.5ns = **200 cycles**

- **CPI?**

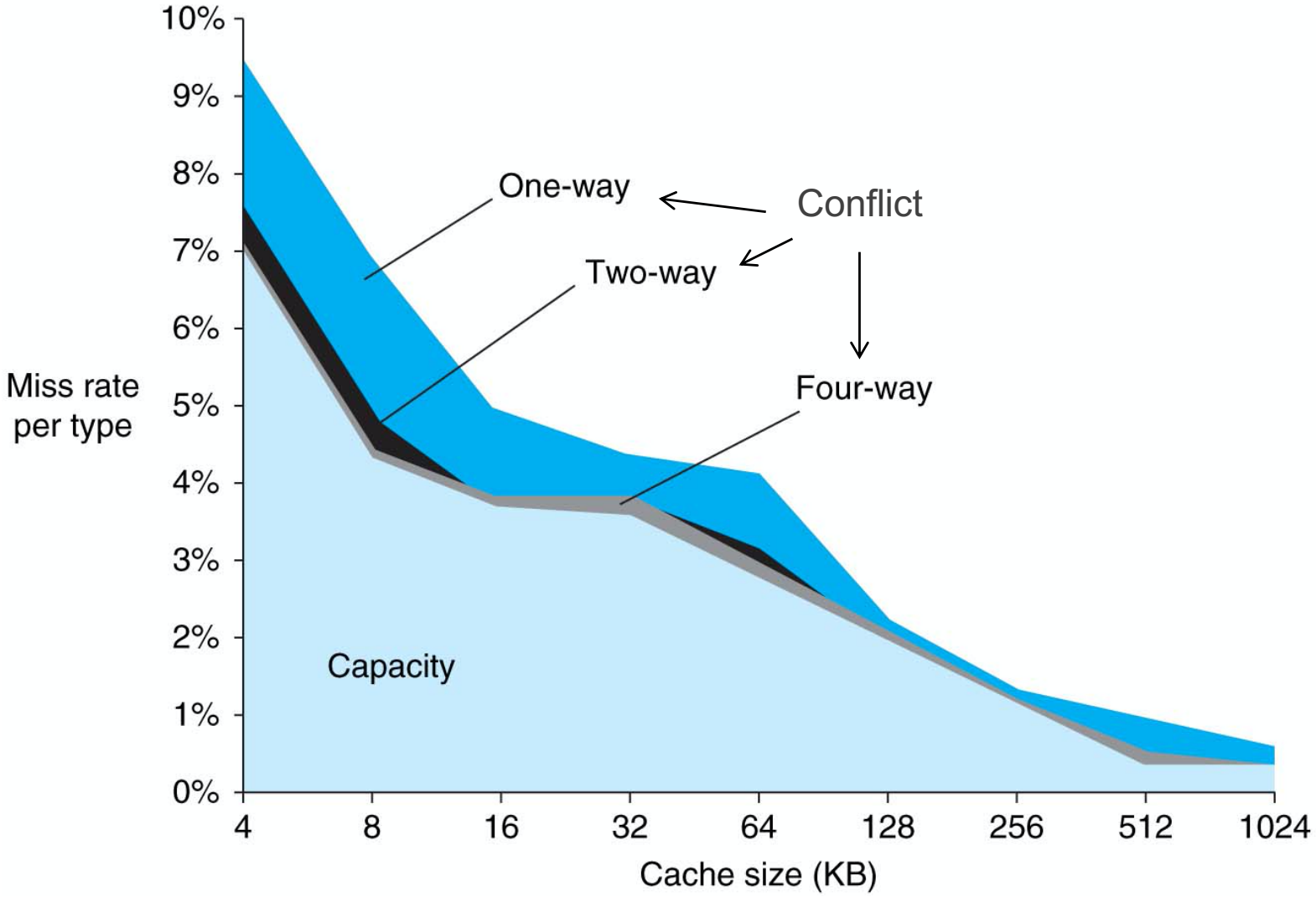


AJProença, Adv

Memory Hierarchy Basics

- Miss rate
  - Fraction of cache access that result in a miss
- Causes of misses (3C's +1)
  - Compulsory
    - First reference to a block
  - Capacity
    - Blocks discarded and later retrieved
  - Conflict
    - Program makes repeated references to multiple addresses from different blocks that map to the same location in the cache
  - **Coherency**
    - **Different processors should see same value in same location**

The 3C's in different cache sizes



The cache coherence pb

- Processors may see different values through their caches:

Time	Event	Cache contents for processor A	Cache contents for processor B	Memory contents for location X
0				1
1	Processor A reads X	1		1
2	Processor B reads X	1	1	1
3	Processor A stores 0 into X	0	1	0

Cache Coherence

- Coherence
  - All reads by any processor must return the most recently written value
  - Writes to the same location by any two processors are seen in the same order by all processors

    (Coherence defines the behaviour of reads & writes to the same memory location)

- Consistency
  - When a written value will be returned by a read
  - If a processor writes location A followed by location B, any processor that sees the new value of B must also see the new value of A

    (Consistency defines the behaviour of reads & writes with respect to accesses to other memory locations)

Enforcing Coherence

- Coherent caches provide:
  - *Migration*: movement of data
  - *Replication*: multiple copies of data

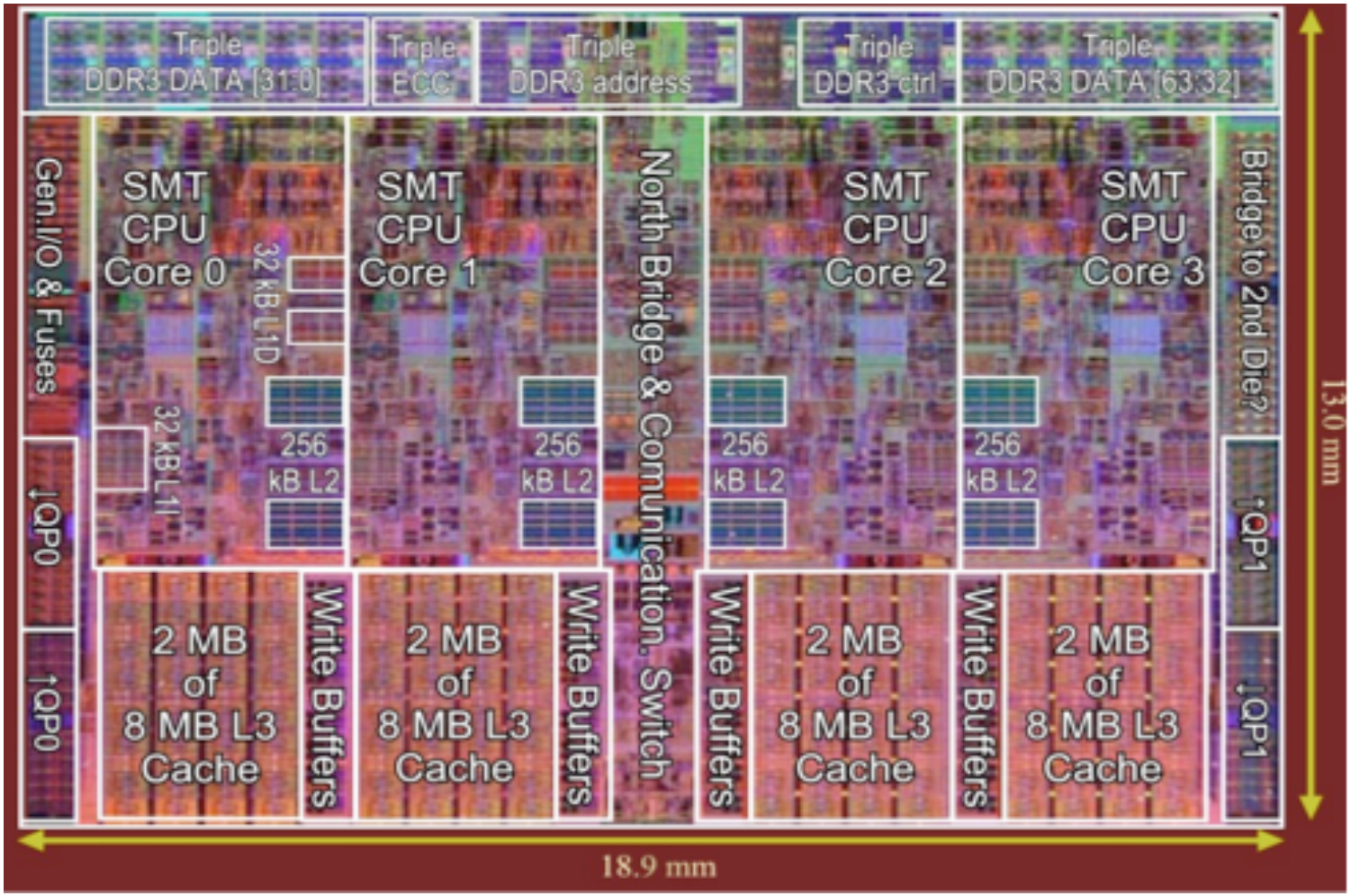
- Cache coherence protocols
  - Directory based
    - Sharing status of each block kept in one location
  - Snooping
    - Each core tracks sharing status of each block

Memory Hierarchy Basics

- Six basic cache optimizations:
  - Larger block size
    - Reduces compulsory misses
    - Increases capacity and conflict misses, increases miss penalty
  - Larger total cache capacity to reduce miss rate
    - Increases hit time, increases power consumption
  - Higher associativity
    - Reduces conflict misses
    - Increases hit time, increases power consumption
  - Multilevel caches to reduce miss penalty
    - Reduces overall memory access time
  - Giving priority to read misses over writes
    - Reduces miss penalty
  - Avoiding address translation in cache indexing
    - Reduces hit time

Multilevel On-Chip Caches

Intel Nehalem 4-core processor



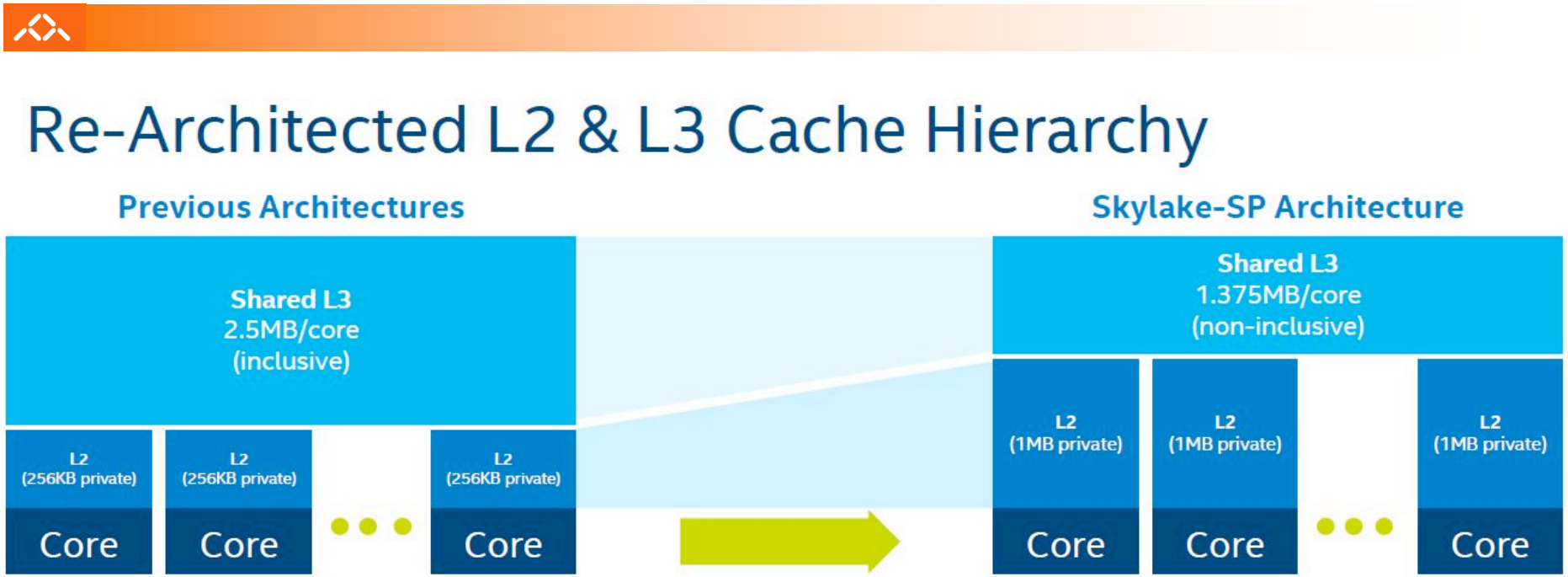
Per core: 32KB L1 I-cache, 32KB L1 D-cache, 512KB L2 cache

3-Level Cache Organization

	Intel Nehalem	AMD Opteron X4
L1 caches (per core)	L1 I-cache: 32KB, 64-byte blocks, 4-way, approx LRU replacement, hit time n/a L1 D-cache: 32KB, 64-byte blocks, 8-way, approx LRU replacement, write-back/allocate, hit time n/a	L1 I-cache: 32KB, 64-byte blocks, 2-way, approx LRU replacement, hit time 3 cycles L1 D-cache: 32KB, 64-byte blocks, 2-way, approx LRU replacement, write-back/allocate, hit time 9 cycles
L2 unified cache (per core)	256KB, 64-byte blocks, 8-way, approx LRU replacement, write-back/allocate, hit time n/a	512KB, 64-byte blocks, 16-way, approx LRU replacement, write-back/allocate, hit time n/a
L3 unified cache (shared)	8MB, 64-byte blocks, 16-way, replacement n/a, write-back/allocate, hit time n/a	2MB, 64-byte blocks, 32-way, replace block shared by fewest cores, write-back/allocate, hit time 32 cycles

n/a: data not available

Intel new cache approach with Skylake



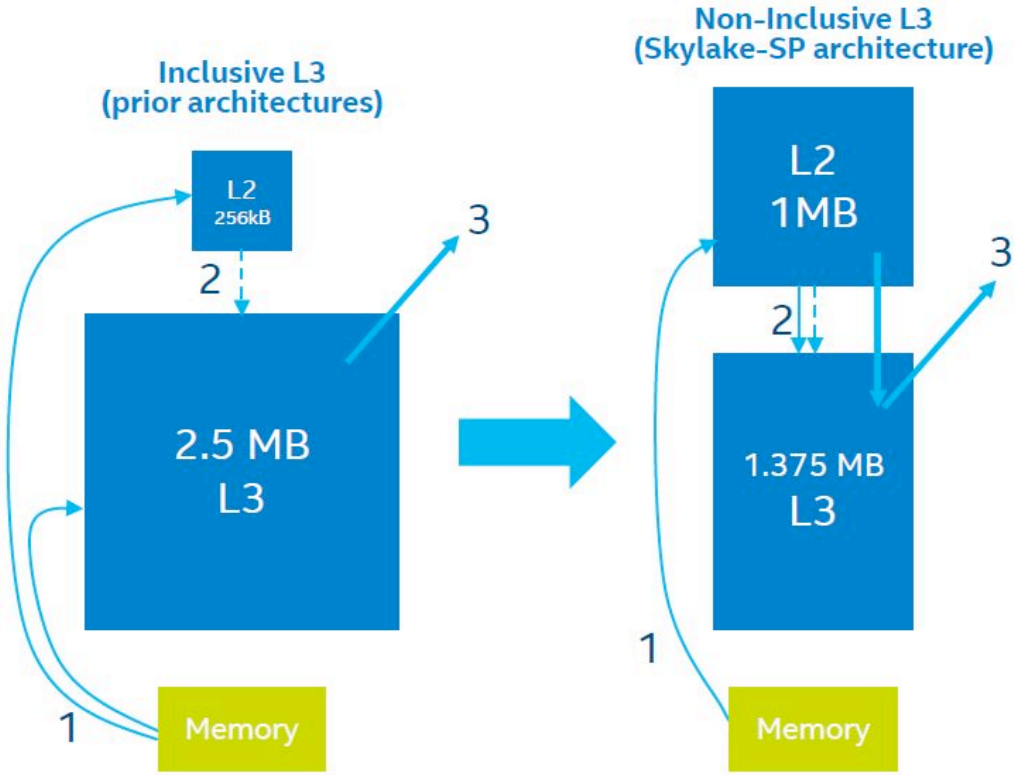
- On-chip cache balance shifted from shared-distributed (prior architectures) to private-local (Skylake architecture):
  - Shared-distributed ➔ shared-distributed L3 is primary cache
  - Private-local ➔ private L2 becomes primary cache with shared L3 used as overflow cache
- Shared L3 changed from inclusive to non-inclusive:
  - Inclusive (prior architectures) ➔ L3 has copies of all lines in L2
  - Non-inclusive (Skylake architecture) ➔ lines in L2 ***may not*** exist in L3

SKYLAKE-SP CACHE HIERARCHY ARCHITECTED SPECIFICALLY FOR DATA CENTER USE CASE

https://www.servethehome.com/intel-xeon-scalable-processor-family-microarchitecture-overview/

Intel new cache approach with Skylake

Inclusive vs Non-Inclusive L3



1. Memory reads fill directly to the L2, no longer to both the L2 and L3
2. When a L2 line needs to be removed, both modified and unmodified lines are written back
3. Data shared across cores are copied into the L3 for servicing future L2 misses

Cache hierarchy architected and optimized for data center use cases:

- Virtualized use cases get larger private L2 cache free from interference
- Multithreaded workloads can operate on larger data per thread (due to increased L2 size) and reduce uncore activity

https://www.servethehome.com/intel-xeon-scalable-processor-family-microarchitecture-overview/

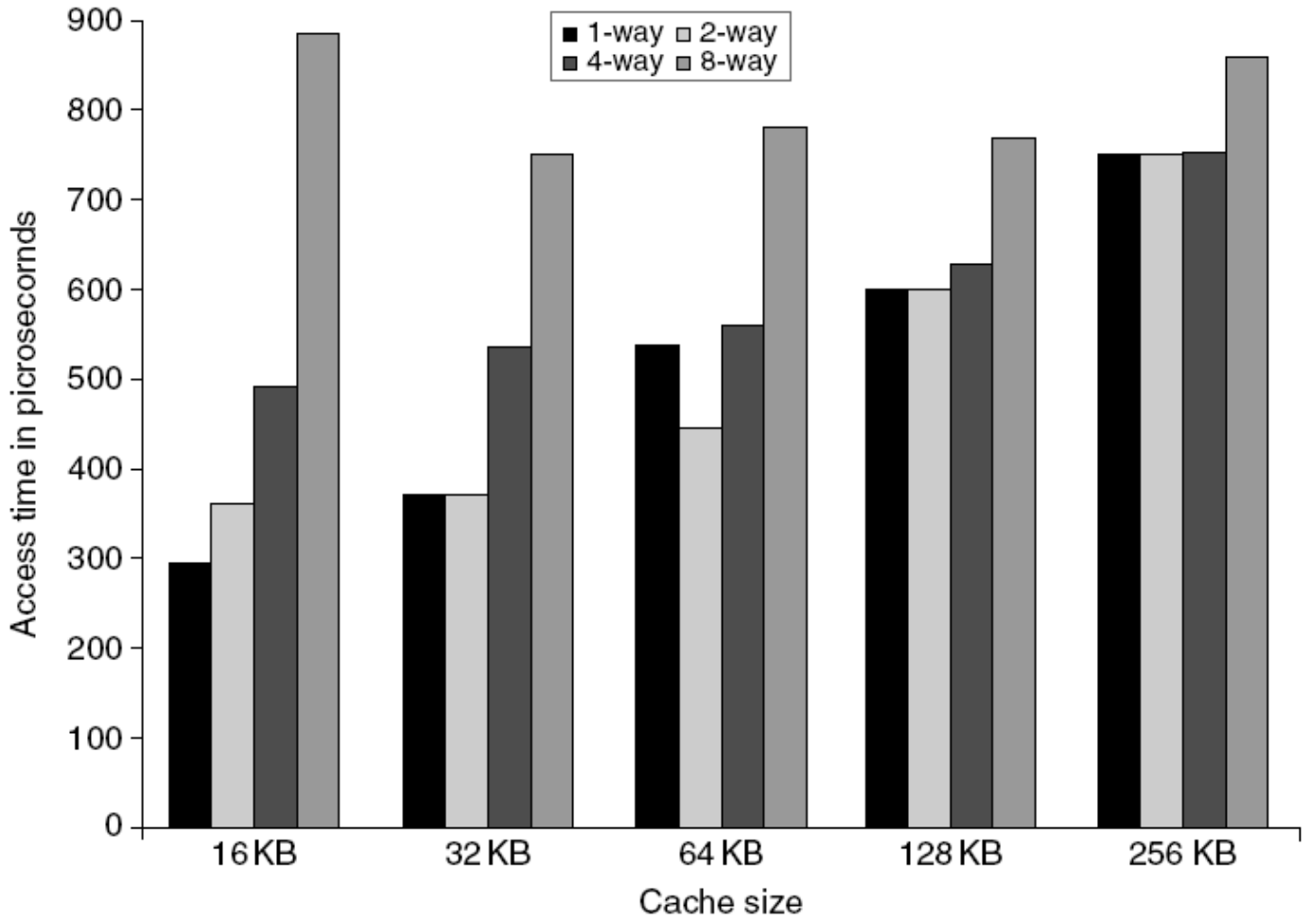
Ten Advanced Optimizations

- Reducing the hit time
  1. Small & simple first-level caches
  2. Way-prediction
- Increase cache bandwidth
  3. Pipelined cache access
  4. Nonblocking caches
  5. Multibanked caches
- Reducing the miss penalty
  6. Critical word first
  7. Merging write buffers
- Reducing the miss rate
  8. Compiler optimizations
- Reducing the miss penalty or miss rate via parallelism
  9. Hardware prefetching of instructions and data
  10. Compiler-controlled prefetching

1. Small and simple 1st level caches

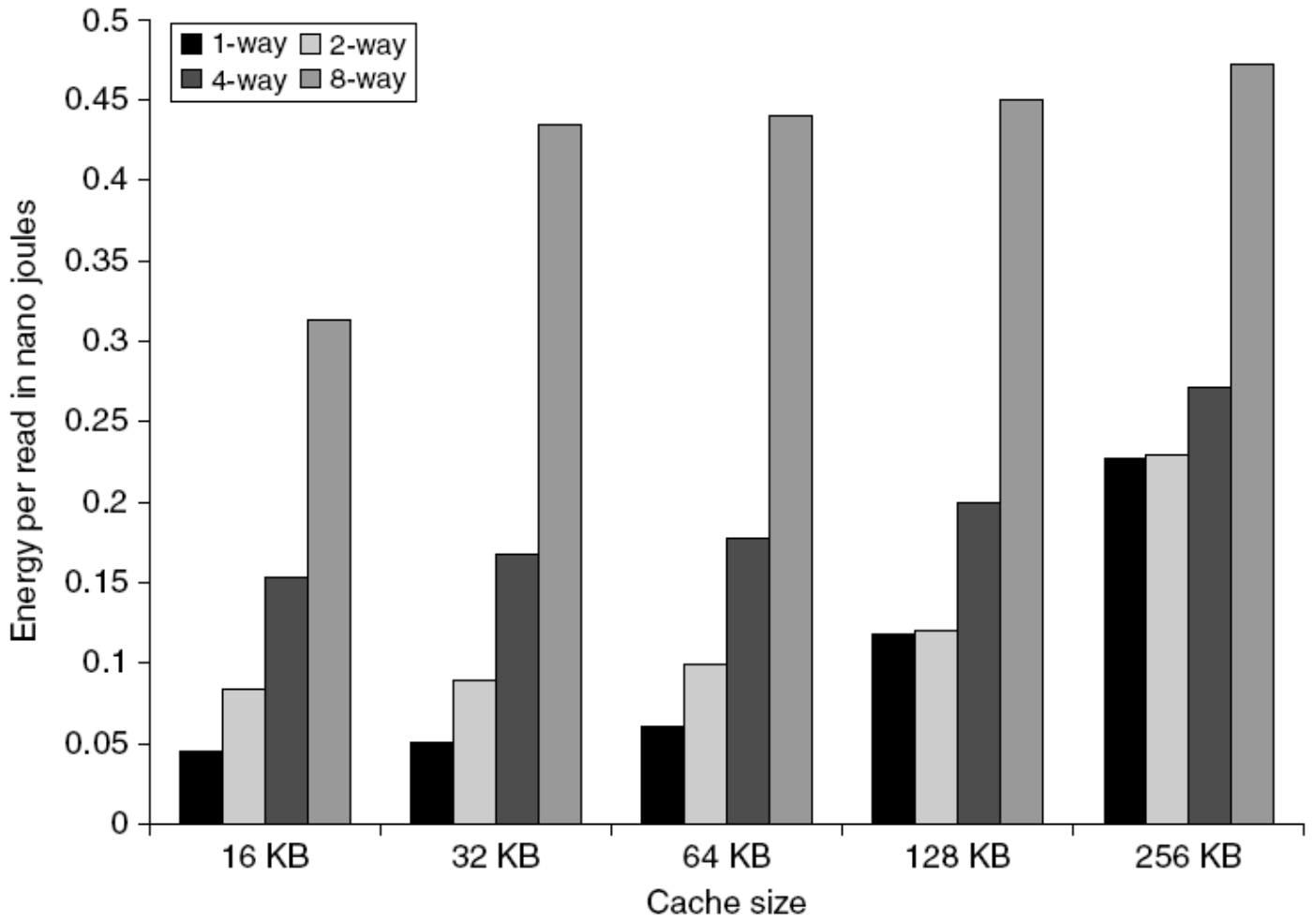
- Small and simple first level caches
  - Critical timing path:
    - addressing tag memory, then
    - comparing tags, then
    - selecting correct set
  - Direct-mapped caches can overlap tag compare and transmission of data
  - Lower associativity reduces power because fewer cache lines are accessed

L1 Size and Associativity



Access time vs. size and associativity

L1 Size and Associativity



Energy per read vs. size and associativity

2. Way Prediction

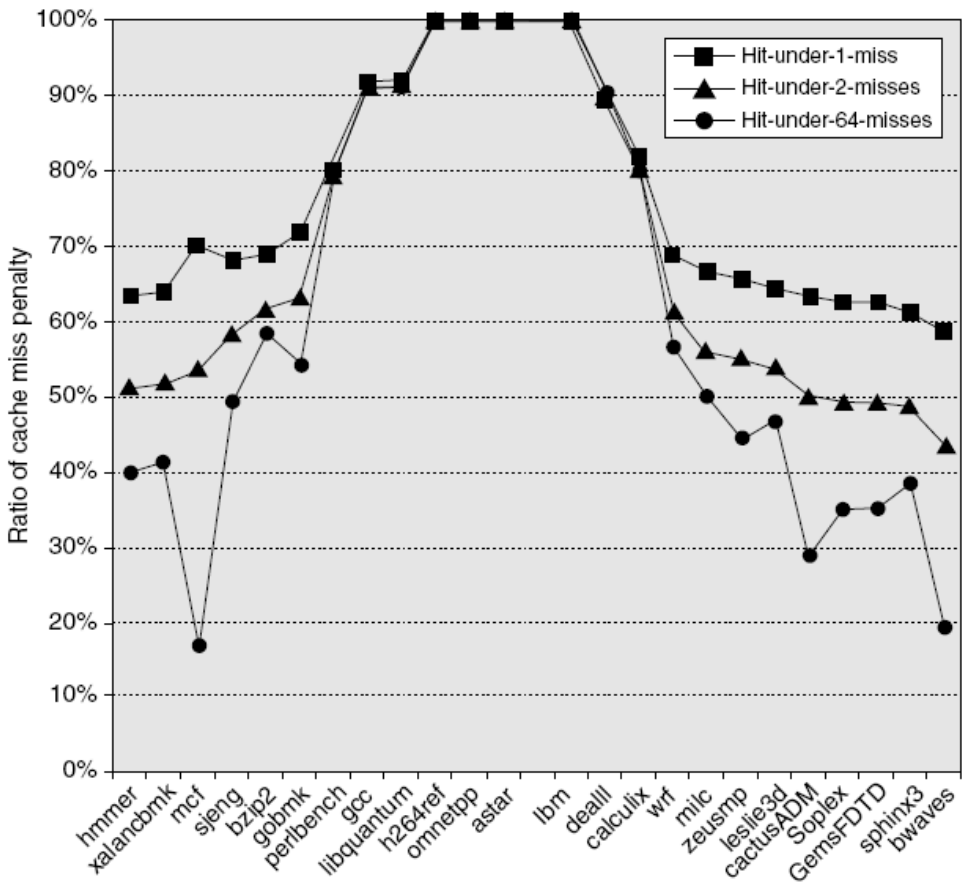
- To improve hit time, predict the way to pre-set mux
  - Mis-prediction gives longer hit time
  - Prediction accuracy
    - > 90% for two-way
    - > 80% for four-way
    - I-cache has better accuracy than D-cache
  - First used on MIPS R10000 in mid-90s
  - Used on ARM Cortex-A8
- Extend to predict block as well
  - “Way selection”
  - Increases mis-prediction penalty

3. Pipelining Cache

- Pipeline cache access to improve bandwidth
  - Examples:
    - Pentium: 1 cycle
    - Pentium Pro – Pentium III: 2 cycles
    - Pentium 4 – Core i7: 4 cycles
- Increases branch mis-prediction penalty
- Makes it easier to increase associativity

4. Nonblocking Caches

- Allow hits before previous misses complete
  - "Hit under miss"
  - "Hit under multiple miss"
- L2 must support this
- In general, processors can hide L1 miss penalty but not L2 miss penalty



5. Multibanked Caches

- Organize cache as independent banks to support simultaneous access
  - ARM Cortex-A8 supports 1-4 banks for L2
  - Intel i7 supports 4 banks for L1 and 8 banks for L2

- Interleave banks according to block address

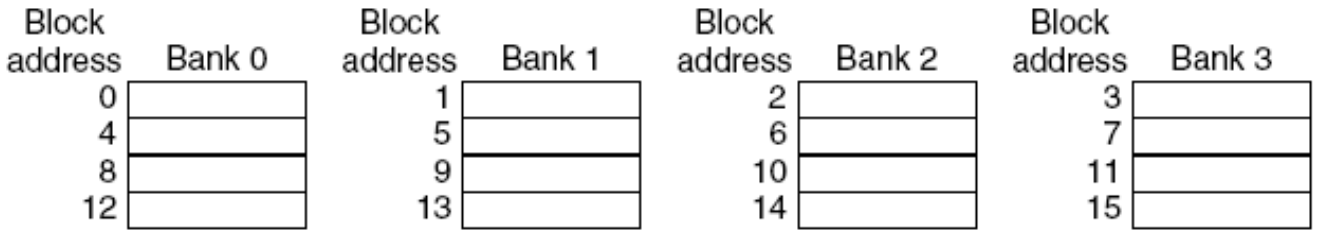


Figure 2.6 Four-way interleaved cache banks using block addressing. Assuming 64 bytes per blocks, each of these addresses would be multiplied by 64 to get byte addressing.

6. Critical Word First, Early Restart

- Critical word first
  - Request missed word from memory first
  - Send it to the processor as soon as it arrives
- Early restart
  - Request words in normal order
  - Send missed work to the processor as soon as it arrives

- Effectiveness of these strategies depends on block size and likelihood of another access to the portion of the block that has not yet been fetched

7. Merging Write Buffer

- When storing to a block that is already pending in the write buffer, update write buffer
- Reduces stalls due to full write buffer
- Do not apply to I/O addresses

Write address	V		V		V		V	
100	1	Mem[100]	0		0		0	
108	1	Mem[108]	0		0		0	
116	1	Mem[116]	0		0		0	
124	1	Mem[124]	0		0		0	

No write buffering

Write address	V		V		V		V	
100	1	Mem[100]	1	Mem[108]	1	Mem[116]	1	Mem[124]
	0		0		0		0	
	0		0		0		0	
	0		0		0		0	

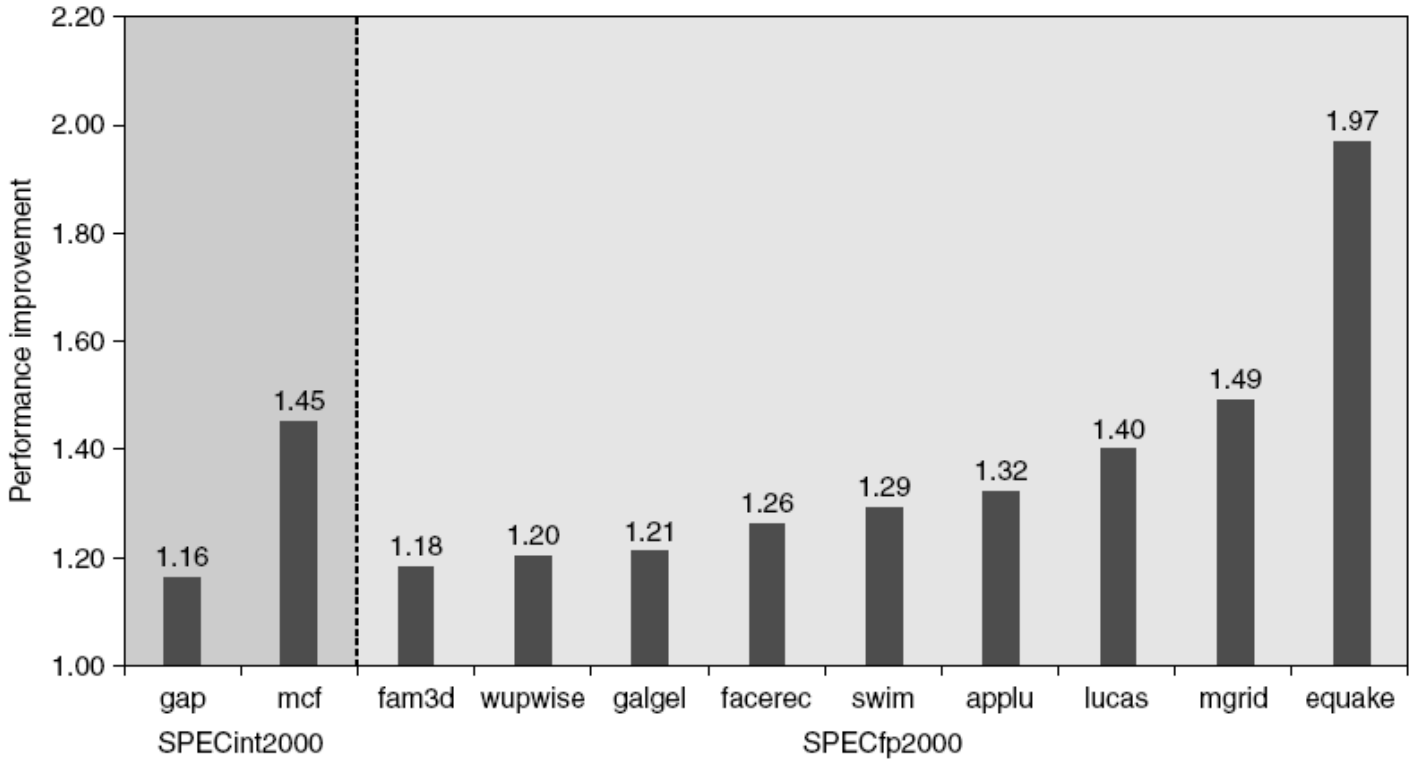
Write buffering

8. Compiler Optimizations

- Loop Interchange
  - Swap nested loops to access memory in sequential order
- Blocking
  - Instead of accessing entire rows or columns, subdivide matrices into blocks
  - Requires more memory accesses but improves locality of accesses

9. Hardware Prefetching

- Fetch two blocks on miss (include next sequential block)



Pentium 4 Pre-fetching

10. Compiler Prefetching

- Insert prefetch instructions before data is needed
- Non-faulting: prefetch doesn't cause exceptions

- Register prefetch
  - Loads data into register
- Cache prefetch
  - Loads data into cache

- Combine with loop unrolling and software pipelining

Summary

Technique	Hit time	Band-width	Miss penalty	Miss rate	Power consumption	Hardware cost/ complexity	Comment
Small and simple caches	+			–	+	0	Trivial; widely used
Way-predicting caches	+				+	1	Used in Pentium 4
Pipelined cache access	–	+				1	Widely used
Nonblocking caches		+	+			3	Widely used
Banked caches		+			+	1	Used in L2 of both i7 and Cortex-A8
Critical word first and early restart			+			2	Widely used
Merging write buffer			+			1	Widely used with write through
Compiler techniques to reduce cache misses				+		0	Software is a challenge, but many compilers handle common linear algebra calculations
Hardware prefetching of instructions and data			+	+	–	2 instr., 3 data	Most provide prefetch instructions; modern high-end processors also automatically prefetch in hardware.
Compiler-controlled prefetching			+	+		3	Needs nonblocking cache; possible instruction overhead; in many CPUs