MSc Informatics Eng.

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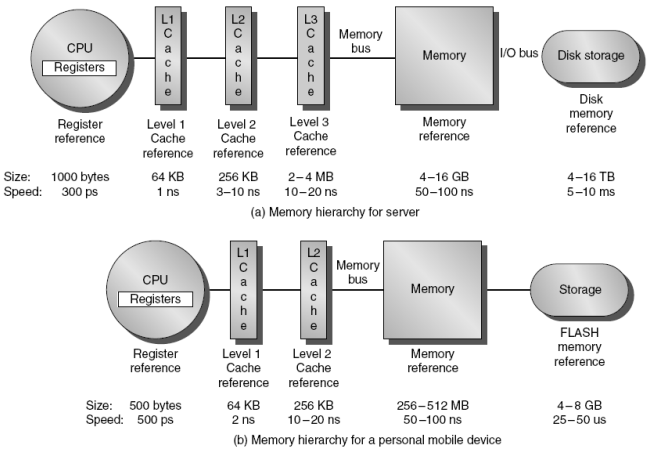
Memory Hierarchy

(most slides are borrowed)

Memory Hierarchy



Memory Hierarchy Design

- Memory hierarchy design becomes more crucial with recent multi-core processors:
  - Aggregate peak bandwidth grows with # cores:
    - Intel Core i7 can generate two references per core per clock
    - Four cores and 3.2 GHz clock
      - 25.6 *10^9 64-bit data references/second +
      - 12.8 *10^9 128-bit instruction references
      - = 409.6 GB/s!
    - DRAM bandwidth is only 6% of this (25 GB/s)
    - Requires:
      - Multi-port, pipelined caches
      - Two levels of cache per core
      - Shared third-level cache on chip

Memory Hierarchy Basics

- When a word is not found in the cache, a *miss* occurs:
  - Fetch word from lower level in hierarchy, requiring a higher latency reference
  - Lower level may be another cache or the main memory
  - Also fetch the other words contained within the *block*
    - Takes advantage of spatial locality
  - Place block into cache in any location within its *set*, determined by address
    - block address MOD number of sets

Memory Hierarchy Basics

- *n* sets => *n-way set associative*
  - *Direct-mapped cache* => one block per set
  - *Fully associative* => one set
- Writing to cache: two strategies
  - *Write-through*
    - Immediately update lower levels of hierarchy
  - *Write-back*
    - Only update lower levels of hierarchy when an updated block is replaced
  - Both strategies use *write buffer* to make writes asynchronous

Memory Hierarchy Basics

- Miss rate
  - Fraction of cache access that result in a miss
- Causes of misses
  - 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

Memory Hierarchy Basics

$$\text{CPU}_{\text{exec-time}} = (\text{CPU}_{\text{clock-cycles}} + \text{Mem}_{\text{stall-cycles}}) \times \text{Clock cycle time}$$

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

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

- Note1: miss rate/penalty are often different for reads and writes

$$\text{Average memory access time} = \text{Hit time} + \text{Miss rate} \times \text{Miss penalty}$$

- Note2: speculative and multithreaded processors may execute other instructions during a miss
  - Reduces performance impact of misses

Cache Performance Example

- 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 × 100 = 2
  - D-cache: 0.36 × 0.04 × 100 = 1.44
- Actual CPI = 2 + 2 + 1.44 = 5.44
  - Ideal CPU is 5.44/2 =2.72 times faster

Multilevel Caches

- Primary cache attached to CPU
  - Small, but fast
- Level-2 cache services misses from primary cache
  - Larger, slower, but still faster than main memory
- Main memory services L-2 cache misses
- Some high-end systems include L-3 cache

Multilevel Cache Example

- Given
  - CPU base CPI = 1, clock rate = 4GHz
  - Miss rate/instruction = 2%
  - Main memory access time = 100ns
- With just primary cache
  - Miss penalty = 100ns/0.25ns = 400 cycles
  - Effective CPI = 1 + 0.02 × 400 = 9
- Now add L-2 cache …

Example (cont.)

- Now add L-2 cache
  - Access time = 5ns
  - Global miss rate to main memory = 0.5%
- Primary miss with L-2 hit
  - Penalty = 5ns/0.25ns = 20 cycles
- Primary miss with L-2 miss
  - Extra penalty = 500 cycles
- CPI = 1 + 0.02 × 20 + 0.005 × 400 = 3.4
- Performance ratio = 9/3.4 = 2.6

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

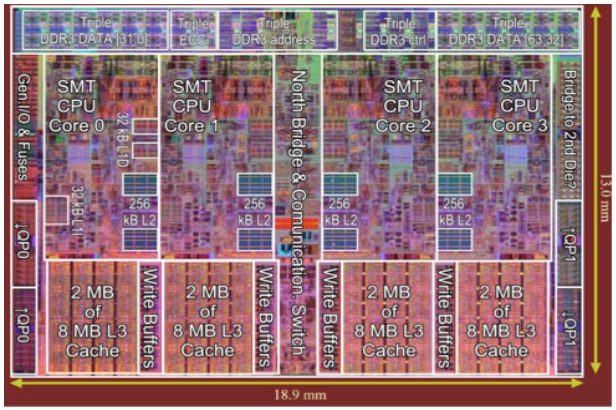
3-Level Cache Organization

	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, LRU replacement, hit time 3 cycles L1 D-cache: 32KB, 64-byte blocks, 2-way, 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

Multilevel On-Chip Caches

Intel Nehalem 4-core processor



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

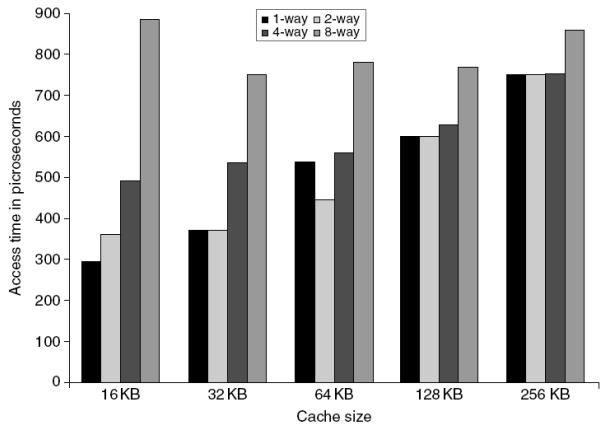
Ten Advanced Optimizations

- Reducing the hit time
  - small & simple first-level caches
  - way-prediction
- Increase cache bandwidth
  - pipelined cache access
  - nonblocking caches
  - multibanked caches
- Reducing the miss penalty
  - critical word first
  - merging write buffers
- Reducing the miss rate
  - compiler optimizations
- Reducing the miss penalty or miss rate via parallelism
  - hardware prefetching of instructions and data
  - compiler-controlled prefetching

1. Small and simple 1st level caches

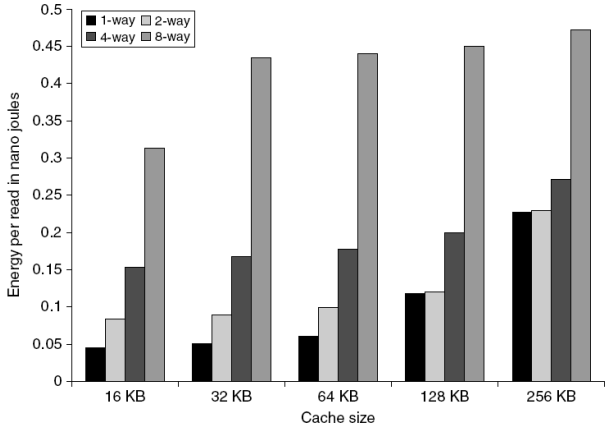
- Small and simple first level caches
  - Critical timing path:
    - addressing tag memory, then
    - comparing tags, then
    - selecting correct set
  - Direct-mapped caches can overlap tag compare and transmission of data
  - Lower associativity reduces power because fewer cache lines are accessed

L1 Size and Associativity



Access time vs. size and associativity

L1 Size and Associativity



Energy per read vs. size and associativity

2. Way Prediction

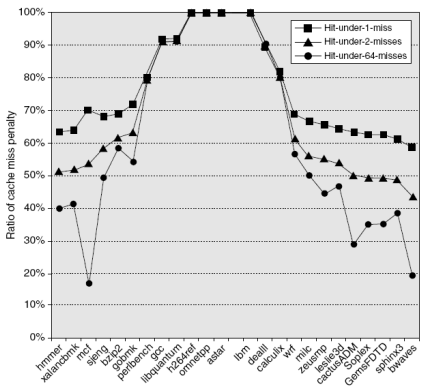
- To improve hit time, predict the way to pre-set mux
  - Mis-prediction gives longer hit time
  - Prediction accuracy
    - > 90% for two-way
    - > 80% for four-way
    - I-cache has better accuracy than D-cache
  - First used on MIPS R10000 in mid-90s
  - Used on ARM Cortex-A8
- Extend to predict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

Block address	Bank 0	Block address	Bank 1	Block address	Bank 2	Block address	Bank 3
0		1		2		3	
4		5		6		7	
8		9		10		11	
12		13		14		15	

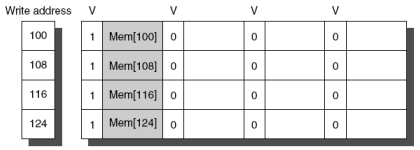
Figure 2.6 Four-way interleaved cache banks using block addressing. Assuming 64 bytes per blocks, each of these addresses would be multiplied by 64 to get byte addressing.

6. Critical Word First, Early Restart

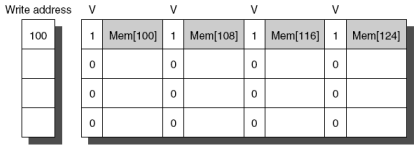
- Critical word first
  - Request missed word from memory first
  - Send it to the processor as soon as it arrives
- Early restart
  - Request words in normal order
  - Send missed work to the processor as soon as it arrives
- Effectiveness of these strategies depends on block size and likelihood of 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



No write buffering



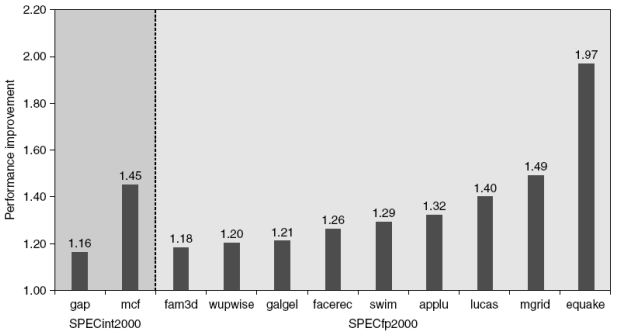
Write buffering

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