CS 61C: Great Ideas in Computer
Architecture (Machine Structures)
Caches Part 3

Instructors:
Krste Asanovic & Vladimir Stojanovic
http://inst.eecs.berkeley.edu/~cs61c/

You Are Here!

Software   *Hardware*

- Parallel Requests
  Assigned to computer
  e.g., Search "Katz"
- Parallel Threads
  Assigned to core
  e.g., Lookup, Ads

  Harness Parallelism & Achieve High Performance
- Parallel Instructions
  >1 instruction @ one time
  e.g., 5 pipelined instructions
- Parallel Data
  >1 data item @ one time
  e.g., Add of 4 pairs of words
- Hardware descriptions
  All gates @ one time
- Programming Languages

Warehouse Scale Computer

Smart Phone

Computer

Today's Lecture

Core   ...   Core

Memory   (Cache)

Input/Output

Core

Instruction Unit(s)   Functional Unit(s)

A_0+B_0 A_1+B_1 A_2+B_2 A_3+B_3

Main Memory

Logic Gates

2

Caches Review

- Direct-Mapped vs. Set-Associative vs. Fully Associative
- AMAT = Hit Time + Miss Rate * Miss Penalty
- 3 Cs of cache misses: Compulsory, Capacity, Conflict
- Effect of cache parameters on performance

3

Primary Cache Parameters

- Block size (aka line size)
  - how many bytes of data in each cache entry?
- Associativity
  - how many ways in each set?
  - Direct-mapped => Associativity = 1
  - Set-associative => 1 < Associativity < #Entries
  - Fully associative => Associativity = #Entries
- Capacity (bytes) = Total #Entries * Block size
- #Entries = #Sets * Associativity

4

Other Cache Parameters

- Write Policy
- Replacement policy

5

Write Policy Choices

- Cache hit:
  - **write through**: writes both cache & memory on every access
    - Generally higher memory traffic but simpler pipeline & cache design
  - **write back**: writes cache only, memory `written only when dirty entry evicted
    - A dirty bit per line reduces write-back traffic
    - Must handle 0, 1, or 2 accesses to memory for each load/store
- Cache miss:
  - **no write allocate**: only write to main memory
  - **write allocate** (aka fetch on write): fetch into cache

- Common combinations:
  - write through and no write allocate
  - write back with write allocate

6

Replacement Policy

In an associative cache, which line from a set should be evicted when the set becomes full?

- Random
- Least-Recently Used (LRU)
  - LRU cache state must be updated on every access
  - True implementation only feasible for small sets (2-way)
  - Pseudo-LRU binary tree often used for 4-8 way
- First-In, First-Out (FIFO) a.k.a. Round-Robin
  - Used in highly associative caches
- Not-Most-Recently Used (NMRU)
  - FIFO with exception for most-recently used line or lines

This is a second-order effect. Why?

Replacement only happens on misses

7

Sources of Cache Misses (3 C's)

- *Compulsory* (cold start, first reference):
  - 1st access to a block, "cold" fact of life, not a lot you can do about it.
    - If running billions of instructions, compulsory misses are insignificant
- *Capacity*:
  - Cache cannot contain all blocks accessed by the program
    - Misses that would not occur with infinite cache
- *Conflict* (collision):
  - Multiple memory locations mapped to same cache set
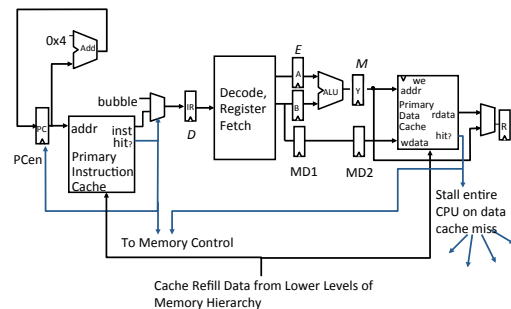   - Misses that would not occur with ideal fully associative cache

8

Impact of Cache Parameters on Performance

- AMAT = Hit Time + Miss Rate * Miss Penalty
  - Note, we assume always first search cache, so must charge hit time for both hits and misses!
- For misses, characterize by 3Cs

9

CPU-Cache Interaction
(5-stage pipeline)

10

Increasing Block Size?

- Hit time as block size increases?
  - Hit time unchanged, but might be slight hit-time reduction as number of tags is reduced, so faster to access memory holding tags
- Miss rate as block size increases?
  - Goes down at first due to spatial locality, then increases due to increased conflict misses due to fewer blocks in cache
- Miss penalty as block size increases?
  - Rises with longer block size, but with fixed constant initial latency that is amortized over whole block

11

Increasing Associativity?

- Hit time as associativity increases?
  - Increases, with large step from direct-mapped to >=2 ways, as now need to mux correct way to processor
  - Smaller increases in hit time for further increases in associativity
- Miss rate as associativity increases?
  - Goes down due to reduced conflict misses, but most gain is from 1->2->4-way with limited benefit from higher associativities
- Miss penalty as associativity increases?
  - Unchanged, replacement policy runs in parallel with fetching missing line from memory

12

Increasing #Entries?

- Hit time as #entries increases?
  - Increases, since reading tags and data from larger memory structures
- Miss rate as #entries increases?
  - Goes down due to reduced capacity and conflict misses
  - *Architects rule of thumb: miss rate drops ~2x for every ~4x increase in capacity (only a gross approximation)*
- Miss penalty as #entries increases?
  - Unchanged

13

Administrivia

- Project 2, Part 2 due 3/22
- No assigned work over spring break
- Next assignment, HW5, due 04/05
- Midterm II is 04/09
  - Conflict? Email Sagar
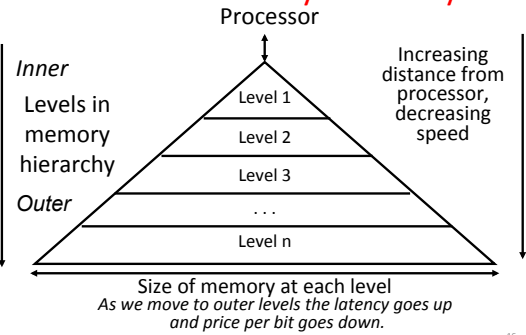 - DSP will receive email about accommodations soon

14

How to Reduce Miss Penalty?

- Could there be locality on misses from a cache?
- Use multiple cache levels!
- With Moore's Law, more room on die for bigger L1 caches and for second-level (L2) cache
- And in some cases even an L3 cache!
- IBM mainframes have ~1GB L4 cache off-chip.

15

Review: Memory Hierarchy

Processor

Inner

Levels in memory hierarchy

Outer

Increasing distance from processor, decreasing speed

Level 1
Level 2
Level 3
. . .
Level n

Size of memory at each level
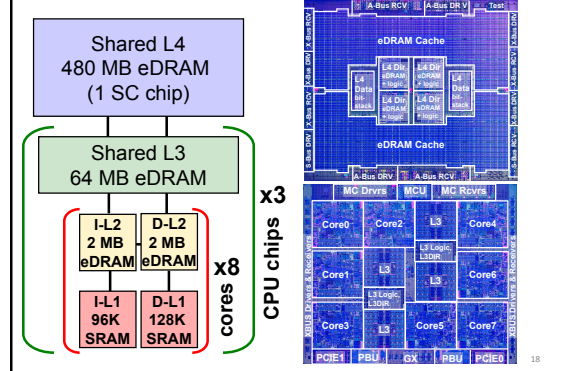*As we move to outer levels the latency goes up and price per bit goes down.*

16

From Lecture 11: In the News

- At ISSCC 2015 in San Francisco yesterday, latest IBM mainframe chip details
- z13 designed in 22nm SOI technology with seventeen metal layers, 4 billion transistors/chip
- 8 cores/chip, with 2MB L2 cache, 64MB L3 cache, and 480MB L4 off-chip cache.
- 5GHz clock rate, 6 instructions per cycle, 2 threads/core
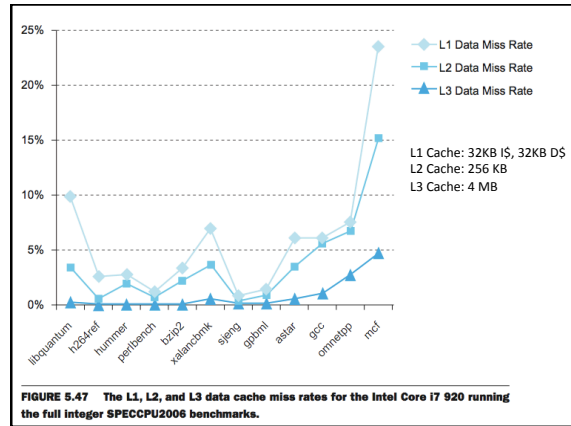- Up to 24 processor chips in shared memory node

17

IBM z13 Memory Hierarchy

Shared L4
480 MB eDRAM
(1 SC chip)

Shared L3
64 MB eDRAM

x3 CPU chips

I-L2
2 MB
eDRAM

D-L2
2 MB
eDRAM

I-L1
96K
SRAM

D-L1
128K
SRAM

x8 cores

18

3

Local vs. Global Miss Rates

- *Local miss rate* – the fraction of references to one level of a cache that miss
- Local Miss rate L2$ = $L2 Misses / L1$ Misses
- *Global miss rate* – the fraction of references that miss in all levels of a multilevel cache
  - L2$ local miss rate >> than the global miss rate

19

FIGURE 5.47 The L1, L2, and L3 data cache miss rates for the Intel Core i7 920 running the full integer SPECCPU2006 benchmarks.

Local vs. Global Miss Rates

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  - L2$ local miss rate >> than the global miss rate
- Global Miss rate = L2$ Misses / Total Accesses
  = L2$ Misses / L1$ Misses x L1$ Misses / Total Accesses
  = Local Miss rate L2$ x Local Miss rate L1$
- AMAT = Time for a hit + Miss rate x Miss penalty
- AMAT = Time for a L1$ hit + (local) Miss rate L1$ x
  (Time for a L2$ hit + (local) Miss rate L2$ x L2$ Miss penalty)

21

Clickers/Peer Instruction

- Overall, what are L2 and L3 local miss rates?

A: L2 > 50%, L3 > 50%
B: L2 ~ 50%, L3 < 50%
C: L2 ~ 50%, L3 ~ 50%
D: L2 < 50%, L3 < 50%
E: L2 > 50%, L3 ~50%
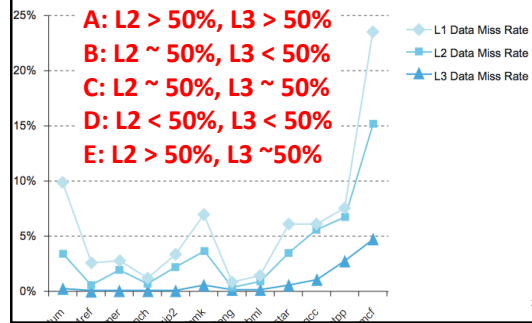
22

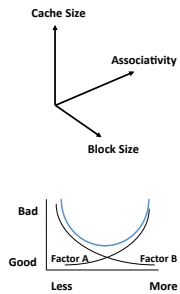| Characteristic	Intel Nehalem	AMD Opteron X4 (Barcelona)
L1 cache organization	Split instruction and data caches	Split instruction and data caches
L1 cache size	32 KB each for instructions/data per core	64 KB each for instructions/data per core
L1 block size	64 bytes	64 bytes
L1 write policy	Write-back, Write-allocate	Write-back, Write-allocate
L1 hit time (load-use)	Not Available	3 clock cycles
L2 cache organization	Unified (instruction and data) per core	Unified (instruction and data) per core
L2 cache size	256 KB (0.25 MB)	512 KB (0.5 MB)
L2 block size	64 bytes	64 bytes
L2 write policy	Write-back, Write-allocate	Write-back, Write-allocate
L2 hit time	Not Available	9 clock cycles
L3 cache organization	Unified (instruction and data)	Unified (instruction and data)
L3 cache size	8192 KB (8 MB), shared	2048 KB (2 MB), shared
L3 block size	64 bytes	64 bytes
L3 write policy	Write-back, Write-allocate	Write-back, Write-allocate
L3 hit time	Not Available	38 (?)clock cycles

23

CPI/Miss Rates/DRAM Access SpecInt2006

		Data Only	Data Only	Instructions and Data
Name	**CPI**	**L1 D cache** misses/1000 instr	**L2 D cache** misses/1000 instr	**DRAM** accesses/1000 instr
perl	0.75	3.5	1.1	1.3
bzip2	0.85	11.0	5.8	2.5
gcc	1.72	24.3	13.4	14.8
mcf	10.00	106.8	88.0	88.5
go	1.09	4.5	1.4	1.7
hmmer	0.80	4.4	2.5	0.6
sjeng	0.96	1.9	0.6	0.8
libquantum	1.61	33.0	33.1	47.7
h264avc	0.80	8.8	1.6	0.2
omnetpp	2.94	30.9	27.7	29.8
astar	1.79	16.3	9.2	8.2
xalancbmk	2.70	38.0	15.8	11.4
Median	1.35	13.6	7.5	5.4

In Conclusion, Cache Design Space

- Several interacting dimensions
  - Cache size
  - Block size
  - Associativity
  - Replacement policy
  - Write-through vs. write-back
  - Write-allocation
- Optimal choice is a compromise
  - Depends on access characteristics
    - Workload
    - Use (I-cache, D-cache)
  - Depends on technology / cost
- Simplicity often wins

Cache Size

Associativity

Block Size

Bad

Good   Factor A   Factor B

Less   More

25