Chapter 2: Memory Hierarchy Design – Part 2

- Introduction (Section 2.1, Appendix B)
- Caches
  - Review of basics (Section 2.1, Appendix B)
  - Advanced methods (Section 2.3)
- Main Memory
- Virtual Memory

Fundamental Cache Parameters

- Cache Size
  - How large should the cache be?
- Block Size
  - What is the smallest unit represented in the cache?
- Associativity
  - How many entries must be searched for a given address?

Cache Size

- Cache size is the total capacity of the cache
  - Bigger caches exploit temporal locality better than smaller caches
  - But are *not always* better
  - Why?

Block Size

- Block (line) size is the data size that is both
  - (a) associated with an address tag, and
  - (b) transferred to/from memory
  - Advanced caches allow different (a) & (b)
- Problem with too small blocks
- Problem with large blocks

Set Associativity

Partition cache block frames & memory blocks in equivalence classes (usually w/ bit selection)

Number of sets, s, is the number of classes

Associativity (set size), n, is the number of block frames per class

Number of block frames in the cache is $s \times n$

Cache Lookup (assuming read hit)

- Select set
- Associatively compare stored tags to incoming tag
- Route data to processor

Associativity, cont.

Typical values for associativity

- 1 -- direct-mapped
- n = 2, 4, 8, 16 -- n-way set-associative
- All blocks – fully-associative

Larger associativity

Smaller associativity

Advanced Cache Design (Section 2.3)

Evaluation Methods

Two Levels of Cache

Getting Benefits of Associativity without Penalizing Hit Time

Reducing Miss Cost to Processor

Lockup-Free Caches

Beyond Simple Blocks

Prefetching

Pipelining and Banking for Higher Bandwidth

Software Restructuring

Handling Writes

Evaluation Methods

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?

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Method 1: Hardware Counters

Advantages
- +
- +

Disadvantages
- -
- -

Method 2: Analytic Models

Mathematical expressions

Advantages
- +
- +

Disadvantages
- -
- -

Method 3: Simulation

Software model of the system driven by model of program
- Can be at different levels of abstraction
  - Functional vs. timing
  - Trace-driven vs. execution-driven

Advantages

Disadvantages

Trace-Driven Simulation

Step 1:

Program + Input Data —*Execute and Trace*→ Trace File

Trace files may have only memory references or all instructions

Step 2:

Trace File + Input Cache Parameters

↓ Run simulator

Get miss ratio, tavg, execution time, etc.

Repeat Step 2 as often as desired

Trace-Driven Simulation: Limitation?

Average Memory Access Time and Performance

What About Non-Performance Metrics?

Area, power, detailed timing

- CACTI for caches
- McPAT: microarchitecture model for full multicore

Timing Data from CACTI

Y-axis unit incorrect

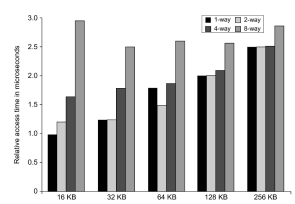

Figure 2.8 Relative access times generally increase as cache size and associativity are increased. These data come from the CACTI model 6.5 by Tarjan et al. (2005). The data assume typical embedded SRAM technology, a single bank, and 64-byte blocks. The assumptions about cache layout and the complex trade-offs between interconnect delays (that depend on the size of a cache block being accessed) and the cost of tag checks and multiplexing lead to results that are occasionally surprising, such as the lower access time for a 64 KiB with two-way set associativity versus direct mapping. Similarly, the results with eight-way set associativity generate unusual behavior as cache size is increased. Because such observations are highly dependent on technology and detailed design assumptions, tools such as CACTI serve to reduce the search space. These results are relative; nonetheless, they are likely to shift as we move to more recent and denser semiconductor technologies.

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Energy Data from CACTI

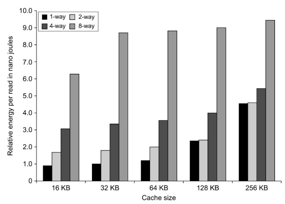

Figure 2.9 Energy consumption per read increases as cache size and associativity are increased. As in the previous figure, CACTI is used for the modeling with the same technology parameters. The large penalty for eight-way set associative caches is due to the cost of reading out eight tags and the corresponding data in parallel.

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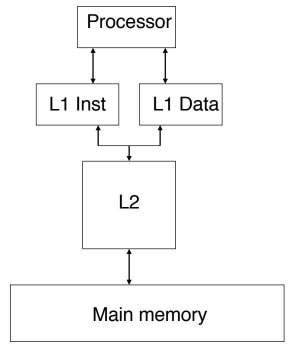
Multilevel Caches



Why Multilevel Caches?

Multilevel Inclusion

Multilevel inclusion holds if L2 cache always contains superset of data in L1 cache(s)

- Filter coherence traffic
- Makes L1 writes simpler

Example: Local LRU not sufficient

- Assume that L1 and L2 hold two and three blocks and both use local LRU
- Processor references: 1, 2, 1, 3, 1, 4
- Final contents of L1: 1, 4
- L1 misses: 1, 2, 3, 4
- Final contents of L2: 2, 3, 4, but not 1

Multilevel Inclusion, cont.

Multilevel inclusion takes effort to maintain

- (Typically L1/L2 cache line sizes are different)
- Make L2 cache have bits or pointers giving L1 contents
- Invalidate from L1 before replacing block from L2
- Number of pointers per L2 block is (L2 blocksize / L1 blocksize)

Multilevel Exclusion

What if the L2 cache is only slightly larger than L1?

Multilevel exclusion => A line in L1 is never in L2 (AMD Athlon)

Level Two Cache Design

L1 cache design similar to single-level cache design when main memories were ``faster''

Apply previous experience to L2 cache design?

What is ``miss ratio''?

- Global -- L2 misses after L1 / references
- Local -- L2 misses after L1 / L1 misses

BUT: L2 caches bigger than L1 experience (several MB)

BUT: L2 affects miss penalty, L1 affects clock rate

Benefits of Associativity W/O Paying Hit Time

Victim Caches

Pseudo-Associative Caches

Way Prediction

Victim Cache

Add a small fully associative cache next to main cache

On a miss in main cache

Pseudo-Associative Cache

To determine where block is placed

- Check one block frame as in direct mapped cache, but
- If miss, check another block frame
  - E.g., frame with inverted MSB of index bit
  - Called a pseudo-set
- Hit in first frame is fast

Placement of data

- Put most often referenced data in “first” block frame and the other in the “second” frame of pseudo-set

Way Prediction

Keep extra bits in cache to predict the “way” of the next access

Access predicted way first

If miss, access other ways like in set associative caches

Fast hit when prediction is correct

Reducing Miss Cost

If main memory takes M cycles before delivering two words per cycle, we previously assumed

$t_{memory} = t_{access} + B \times t_{transfer} = M + B \times 1/2$

where B is block size in words

How can we do better?

Reducing Miss Cost, cont.

$t_{memory} = t_{access} + B \times t_{transfer} = M + B \times 1/2$

$\Rightarrow$ the whole block is loaded before data returned

If main memory returned the reference first (requested-word-first) and the cache returned it to the processor before loading it into the cache data array (fetch-bypass, early restart),

$t_{memory} = t_{access} + W \times t_{transfer} = M + W \times 1/2$

where W is memory bus width in words

BUT ...

Reducing Miss Cost, cont.

What if processor references unloaded word in block being loaded?

Why not generalize?

- Handle other references that hit before any part of block is back?
- Handle other references to other blocks that miss?

Called ``lockupfree'' or ``nonblocking'' cache

Lockup-Free Caches

Normal cache stalls while a miss is pending

Lockup-Free Caches

- (a) Handle hits while first miss is pending
- (b) Handle hits & misses until K misses are pending

Potential benefit

- (a) Overlap misses with useful work & hits
- (b) Also overlap misses with each other

Only makes sense if

Lockup-Free Caches, cont.

Key implementation problems

- (1) Handling reads to pending miss
- (2) Handling writes to pending miss
- (3) Keep multiple requests straight

MSHRs -- miss status holding registers

What state do we need in MSHR?

Beyond Simple Blocks

Break block size into
- Address block associated with tag
- Transfer block transferred to/from memory

Larger address blocks
- Decrease address tag overhead
- But allow fewer blocks to be resident

Larger transfer blocks
- Exploit spatial locality
- Amortize memory latency
- But take longer to load
- But replace more data already cached
- But cause unnecessary traffic

Beyond Simple Blocks, cont.

Address block size > transfer block size
- Usually implies valid (& dirty) bit per transfer block
- Used in 360/85 to reduce tag comparison logic
  - 1K byte sectors with 64 byte subblocks

Transfer block size > address block size
- ``Prefetch on miss''
- E.g., early MIPS R2000 board

Prefetching

Prefetch instructions/data before processor requests them

Even ``demand fetching'' prefetches other words in the referenced block

Prefetching is useless unless a prefetch ``costs'' less than demand miss

Prefetches should
- ???

Prefetching Policy

Policy
- What to prefetch?
- When to prefetch?

Simplest Policy
- ?

Enhancements

Software Prefetching

Use compiler to
- Prefetch early
  - E.g., one loop iteration ahead
- Prefetch accurately

Software Prefetching Example

```
for (i = 0; i < N-1; i++) {
   … = A[i]
   /* computation */
}
```

Assume each iteration takes 10 cycles with a hit,
memory latency is 100 cycles

Software Prefetching Example

```
for (i = 0; i < N-1; i++) {
   … = A[i]
   /* computation */
}
```

Assume each iteration takes 10 cycles with a hit,
memory latency is 100 cycles, **cache block is two words**

Changes?

```
for (i = 0; i < N-1; i++) {
   prefetch(A[i+10])
   … = A[i]
   /* computation */
}
```

Software Restructuring

Restructure so that operations on a cache block done before going to next block

```
do i = 1 to rows
   do j = 1 to cols
      sum = sum + x[i,j]
```

What is the cache behavior?

Software Restructuring (Cont.)

```
do i = 1 to rows
   do j = 1 to cols
      sum = sum + x[i,j]
```

Column major order in memory

Code access pattern

Better code??

Called loop interchange

Many such optimizations possible (merging, fusion, blocking)

Pipelining and Banking for Higher Bandwidth

- Pipelining
  - Old: cache access = 1 cycle
  - New: 1 cycle caches would slow the whole processor
    - Pipeline: cache hit may take 4 cycles (affects misspeculation penalty)
- Multiple banks
  - Block based interleaving allows multiple accesses per cycle

Handling Writes - Pipelining

- Writing into a writeback cache
  - Read tags (1 cycle)
  - Write data (1 cycle)
- Key observation
  - Data RAMs unused during tag read
  - Could complete a previous write
- Add a special ``Cache Write Buffer'' (CWB)
  - During tag check, write data and address to CWB
  - If miss, handle in normal fashion
  - If hit, written data stays in CWB
  - When data RAMs are free (e.g., next write) store contents of CWB in data RAMs.
  - Cache reads must check CWB (bypass)
- Used in VAX 8800

Handling Writes - Write Buffers

- Writethrough caches are simple
  - But 5-15% of all instructions are stores
  - Need to buffer writes to memory
- Write buffer
  - Write result in buffer
  - Buffer writes results to memory
  - Stall only when buffer is full
  - Can combine writes to same line (Coalescing write buffer - Alpha)
  - Allow reads to pass writes
- What about data dependencies?
  - Could stall (slow)
  - Check address and bypass result

Handling Writes - Writeback Buffers

- Writeback caches need buffers too
  - 10-20% of all blocks are written back
  - 10-20% increase in miss penalty without buffer
- On a miss
  - Initiate fetch for requested block
  - Copy dirty block into writeback buffer
  - Copy requested block into cache, resume CPU
  - Now write dirty block back to memory
- Usually only need 1 or 2 writeback buffers