

Advanced Caching Techniques

Approaches to improving memory system performance

- eliminate memory operations
- decrease the number of misses
- decrease the miss penalty
- decrease the cache/memory access times
- hide memory latencies
- increase cache throughput
- increase memory bandwidth

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Handling a Cache Miss the Old Way

- (1) Send the address & read operation to the next level of the hierarchy
- (2) **Wait for the data to arrive**
- (3) Update the cache entry with data*, rewrite the tag, turn the valid bit on, clear the dirty bit (if data cache)
- (4) Resend the memory address; this time there will be a hit.

* There are variations:

- get data before replace the block
- send the requested word to the CPU as soon as it arrives at the cache (**early restart**)
- requested word is sent from memory first; then the rest of the block follows (**requested word first**)

How do the variations improve memory system performance?

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Non-blocking Caches

Non-blocking cache (lockup-free cache)

- allows the CPU to continue executing instructions while a miss is handled
- some processors allow only 1 outstanding miss ("hit under miss")
- some processors allow multiple misses outstanding ("miss under miss")
- **miss status holding registers (MSHR)**
 - hardware structure for tracking outstanding misses
 - physical address of the block
 - which word in the block
 - destination register number (if data)
 - mechanism to merge requests to the same block
 - mechanism to insure accesses to the same location execute in program order

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Non-blocking Caches

Non-blocking cache (lockup-free cache)

- can be used with both in-order and out-of-order processors
 - **in-order processors** stall when an instruction that uses the load data is the next instruction to be executed
 - **out-of-order processors** can execute instructions after the load consumer

How do non-blocking caches improve memory system performance?

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Victim Cache

Victim cache

- small fully-associative cache
 - contains the most recently replaced blocks of a direct-mapped cache
- check it on a cache miss
 - swap the direct-mapped block and victim cache block
- alternative to 2-way set-associative cache

How do victim caches improve memory system performance?

Why do victim caches work?

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Sub-block Placement

Divide a block into sub-blocks

tag	I	data	V	data	V	data	I	data
tag	I	data	V	data	V	data	V	data
tag	V	data	V	data	V	data	V	data
tag	I	data	I	data	I	data	I	data

- **sub-block** = unit of transfer on a cache miss
- **valid bit/sub-block**
- misses:
 - block-level miss: tags didn't match
 - sub-block-level miss: tags matched, valid bit was clear
- + the transfer time of a sub-block
- + fewer tags than if each block was the size of a block
- less implicit prefetching

How does sub-block placement improve memory system performance?

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Pseudo-set associative Cache

Pseudo-set associative cache

- access the cache
- if miss, invert the high-order index bit & access the cache again
- + miss rate of 2-way set associative cache
- + access time of direct-mapped cache if hit in the "fast-hit block"
- increase in hit time (relative to 2-way associative) if always hit in the "slow-hit block"
 - predict which is the fast-hit block

How does pseudo-set associativity improve memory system performance?

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Pipelined Cache Access

Pipelined cache access

- simple 2-stage pipeline
 - access the cache
 - data transfer back to CPU
 - tag check & hit/miss logic with the shorter of the two stages

How do pipelined caches improve memory system performance?

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Mechanisms for Prefetching

Stream buffers

- where prefetched instructions/data held
- if requested block in the stream buffer, then cancel the cache access

How do improve memory system performance?

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Trace Cache

Trace cache contents

- contains instructions from the *dynamic* instruction stream
 - + fetch statically noncontiguous instructions in a single cycle
 - + a more efficient use of "l-cache" space
- trace is analogous to a cache block wrt accessing

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Trace Cache

Assessing a trace cache

- trace cache state includes low bits of next addresses (target & fall-through code) for the last instruction in the currently executing trace, which is a branch
- trace cache tag is high branch address bits + predictions for all branches in the trace
- assess trace cache & branch predictor, BTB, I-cache in parallel
- compare high PC bits & prediction history of the current branch instruction to the trace cache tag
- hit: use trace cache & I-cache fetch ignored
- miss: use the I-cache
 - start constructing a new trace

Why does a trace cache work?

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Trace Cache

Effect on performance?

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Cache-friendly Compiler Optimizations

Exploit spatial locality

- **schedule for array misses**
 - hoist first load to each cache block

Improve spatial locality

- **group & transpose**
 - makes portions of vectors that are accessed together lie in memory together
- **loop interchange**
 - so inner loop follows memory layout

Improve temporal locality

- **loop fusion**
 - do multiple computations on the same portion of an array
- **tiling (also called blocking)**
 - do all computation on a small block of memory that will fit in the cache

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Tiling Example

```

/* before */
for (i=0; i<n; i=i+1)
  for (j=0; j<n; j=j+1) {
    r = 0;
    for (k=0; k<n; k=k+1) {
      r = r + y[i,k] * z[k,j]; }
    x[i,j] = r;
  };

/* after */
for (jj=0; jj<n; jj=jj+T)
for (kk=0; kk<n; kk=kk+T)

  for (i=0; i<n; i=i+1)
    for (j=jj; j<min(jj+T-1,n); j=j+1) {
      r = 0;
      for (k=kk; k<min(kk+T-1,n); k=k+1)
        { r = r + y[i,k] * z[k,j]; }
      x[i,j] = x[i,j] + r;
    };

```

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Memory Banks

Interleaved memory:

- multiple memory banks
 - word locations are assigned across banks
 - **interleaving factor**: number of banks
 - send a single address to all banks at once

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

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Memory Banks

Interleaved memory:

- + get more data for one transfer
 - data is probably used (*why?*)
- larger DRAM chip capacity means fewer banks
- power issue

Effect on performance?

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Memory Banks

Independent memory banks

- different banks can be accessed at once, with different addresses
- allows parallel access, possibly parallel data transfer
- multiple memory controllers & separate address lines, one for each access
 - different controllers cannot access the same bank
- less area than dual porting

Effect on performance?

	21264	R12000	UltraSparc-III	Pentium IV
L1 I onchip	64KB 2-way with set prediction 64B block virtually indexed	32KB 2-way 64B block 2-cycle access cr3/call word first	32KB 4-way 32B block virtually indexed, virtual tags pipelined 2-cycle access	12Kuoop trace cache (-8-16KB) 6 uops/line virtually indexed
L1 D onchip	64KB 2-way 64B block write-back virtually indexed, physical tags TLB in parallel 3 (tr) or 4 (FP) cycle reads phase-pipelined (read twice each cycle) miss under miss (32 loads or 8 blocks outstanding) victim cache	32KB 2-way, LRU replacement 32B block physical tags 2-cycle access nonblocking cr3/call word first	64KB 4-way 32B block write-through store compression virtually indexed TLB in parallel pipelined 2-cycle access nonblocking	8KB 4-way 64B block write-through virtually indexed 2 cycle latency pipelined nonblocking requested word first
L2	external 1MB-16MB direct-mapped 64B block write-back physical nonblocking 12 cycles	external 1MB-16MB 2-way pseudo, way prediction, LRU 128B blocks write-back nonblocking	external up to 8MB direct-mapped 32B blocks write-back physical 12 cycles pipelined access	onchip 256KB 8-way 128B block 64B "amblocks" physically indexed nonblocking pipelined
TLB	128 entries FA dual-ported multiple page sizes PAL code handling	64 entries, each maps to 2 pages FA 4KB - 16MB pages	multiple page sizes software handling	multiple page sizes hardware handling

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Today's Memory Subsystems

Look for designs in common:

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Wrap-up

Victim cache (reduce miss penalty)
TLB (reduce page fault time (penalty))
Hardware or compiler-based prefetching (reduce misses)
Cache-conscious compiler optimizations (reduce misses or hide miss penalty)
Coupling a write-through memory update policy with a write buffer (eliminate store ops/hide store latencies)
Handling the read miss before replacing a block with a write-back memory update policy (reduce miss penalty)
Sub-block placement (reduce miss penalty)
Non-blocking caches (hide miss penalty)
Merging requests to the same cache block in a non-blocking cache (hide miss penalty)
Requested word first or early restart (reduce miss penalty)
Cache hierarchies (reduce misses/reduce miss penalty)
Virtual caches (reduce miss penalty)
Pipelined cache accesses (increase cache throughput)
Pseudo-set associative cache (reduce misses)
Banked or interleaved memories (increase bandwidth)
Independent memory banks (hide latency)
Wider bus (increase bandwidth) techniques