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

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 & write back)

(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?

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

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 (non-blocking loads)
  - **out-of-order processors** can execute instructions after the load consumer

How do non-blocking caches improve memory system performance?

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?

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 sub-block were a block

\- less implicit prefetching

How does sub-block placement improve memory system performance?

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"
  - predict which is the fast-hit block
- \- increase in hit time (relative to 2-way associative) if always hit in the "slow-hit block"

How does pseudo-set associativity improve memory system performance?

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

How do pipelined caches improve memory system performance?

Mechanisms for Prefetching

Hardware-controlled prefetching

- overlap prefetching & execution
- issue of how close to put the data
- **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?

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 "I-cache" space
- trace is analogous to a cache block wrt accessing

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?

Trace Cache

Effect on performance?

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

Tiling Example

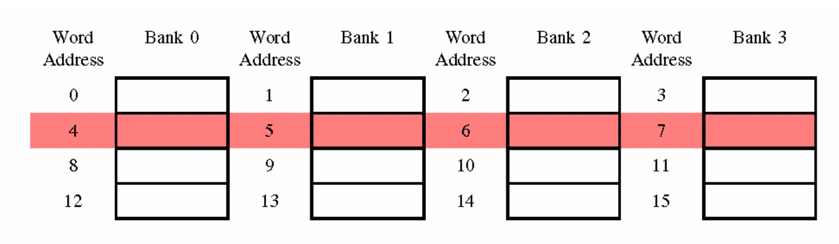
```
/* before */
for (i=0; i<n; i=i+1)
      for (j=0; j<n; j=j+1){
            r = 0;
            for (k=0; k<n; k=k+1) {
                  r = r + y[i,k] * z[k,j]; }
            x[i,j] = r;
            };
/* after */
for (jj=0; jj<n; jj=jj+T)
for (kk=0; kk<n; kk=kk+T)

  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;
            };
```

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



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?

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 critical word first	**32KB** **4-way** 32B block virtually indexed, virtual tags pipelined 2-cycle access	**12Kuop 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 (int) 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 replace-ment **32B block** **physical tags** 2-cycle access nonblocking critical 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	**external** up to 8MB direct-mapped 32B blocks write-back physical 12 cycles pipelined access	**onchip** 256KB **8-way** 128B block 64B "subblocks" write-back 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**

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)