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?

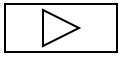
Associativity

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?



Cache Size**

Cache size is the total capacity of the cache

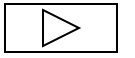
- Bigger caches exploit temporal locality better than smaller caches
- But are *not always* better

Too large a cache size

- Smaller means faster $\Rightarrow$ bigger means slower
- Access time may degrade critical path

Too small a cache size

- Don't exploit temporal locality well
- Useful data is prematurely replaced



Block Size

Block (line) size is the data size that is both

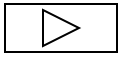
(a) associated with an address tag, and

(b) transferred to/from memory

Advanced caches allow different (a) & (b)

Problem with too small blocks

Problem with large blocks



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Don't amortize memory access time well

Have inordinate address tag overhead

Too large blocks cause

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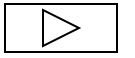
Too large blocks cause

- Unused data to be transferred
- Useful data to be prematurely replaced



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

*Associativity, cont. ***

Typical values for associativity

- 1 -- direct-mapped
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Larger associativities

- Lower miss ratios
- Less variance

Smaller associativities

- Lower cost
- Faster access (hit) time (perhaps)

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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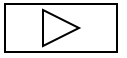
*Evaluation Methods***

Hardware Counters

Analytic Models

Simulation



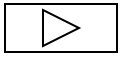
Method 1: Hardware Counters

Advantages

- +
- +

Disadvantages

- -
- -



*Method 1: Hardware Counters***

Count hits & misses in hardware

Advantages

- +
- +

Disadvantages

- -
- -

Many recent processors have hardware counters

*Method 1: Hardware Counters***

Count hits & misses in hardware

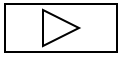
Advantages

+ Accurate
+ Realistic workload

Disadvantages

- Requires machine to exist
- Hard to vary cache parameters
- Experiments not deterministic

Many recent processors have hardware counters



Method 2: Analytic Models

Mathematical expressions

Advantages

+

+

Disadvantages

-

-

*Method 2: Analytic Models***

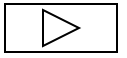
Mathematical expressions

Advantages

+ Insight -- can vary parameters
+ Fast

Disadvantages

- (Absolute) accuracy?
- Hard/time-consuming to determine many parameter values



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

*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

+ Experiments repeatable
+ Can be accurate for many detailed metrics

Disadvantages

- Slow
- Still a model, can be inaccurate
- Only provides insight for the input programs simulated

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:

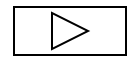
Trace File + Input Cache Parameters

↓ Run simulator

Get miss ratio, tavg, execution time, etc.

Repeat Step 2 as often as desired

Trace-Driven Simulation: Limitation?



*Trace-Driven Simulation: Limitation?***

Impact of aggressive processor?

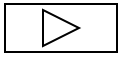
- Does not model mispredicted paths, actual order of accesses

Reasonable traces are very large

- (Can integrate step 1 and step 2)

Alternative: Execution-driven simulation

- Simulate entire application execution
- Model full impact of processor
  - Mispredicted paths, reordering of accesses



Average Memory Access Time and Performance

*Average Memory Access Time and Performance***

Old: Avg memory time = Hit time + Miss rate * Miss penalty

But what is miss penalty in an out of order processor?

Hit time is no longer one cycle, hits can stall the processor

*Average Memory Access Time and Performance***

Old: Avg memory time = Hit time + Miss rate * Miss penalty

But what is miss penalty in an out of order processor?

Hit time is no longer one cycle, hits can stall the processor

Execution cycles = Busy cycles + Cycles due to CPU stalls + Cycles due to memory stalls

Cycles from memory stalls = stalls from misses + stalls from hits

Stalls from misses = # misses *

(Total miss latency – overlapped latency)

*Average Memory Access Time and Performance***

Stalls from misses = # misses *

(Total miss latency – overlapped latency)

What is a stall?

- Processor is stalled if it does not retire at its full rate
- Charge stall to first instruction that cannot retire

Where do you start measuring latency?

- From time instruction is queued in instruction window, or when address is generated, or when sent to memory system?
- Anything works as long as is consistent

Miss latency is also made of latency due to and w/o contention

Hit stalls are analogous

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

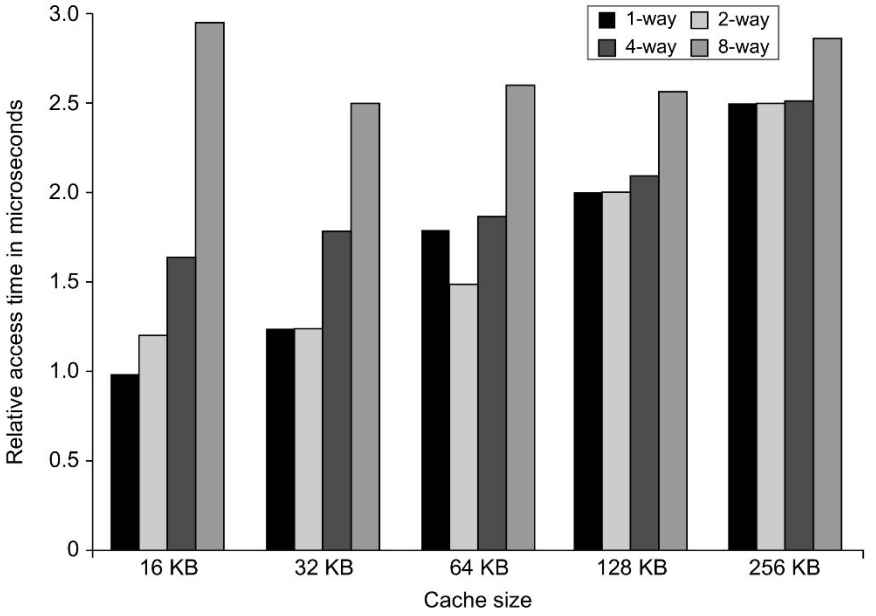


Figure 2.8 Relative access times generally increase as cache size and associativity are increased. These data come from the CACTI model 6.5 by Tarjan et al. (2005). The data assume typical embedded SRAM technology, a single bank, and 64-byte blocks. The assumptions about cache layout and the complex 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.

Energy Data from CACTI

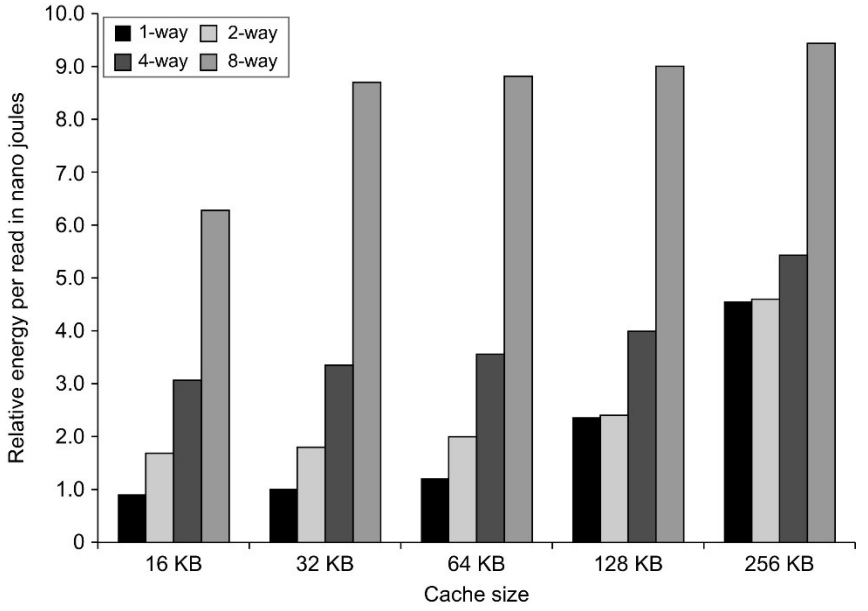
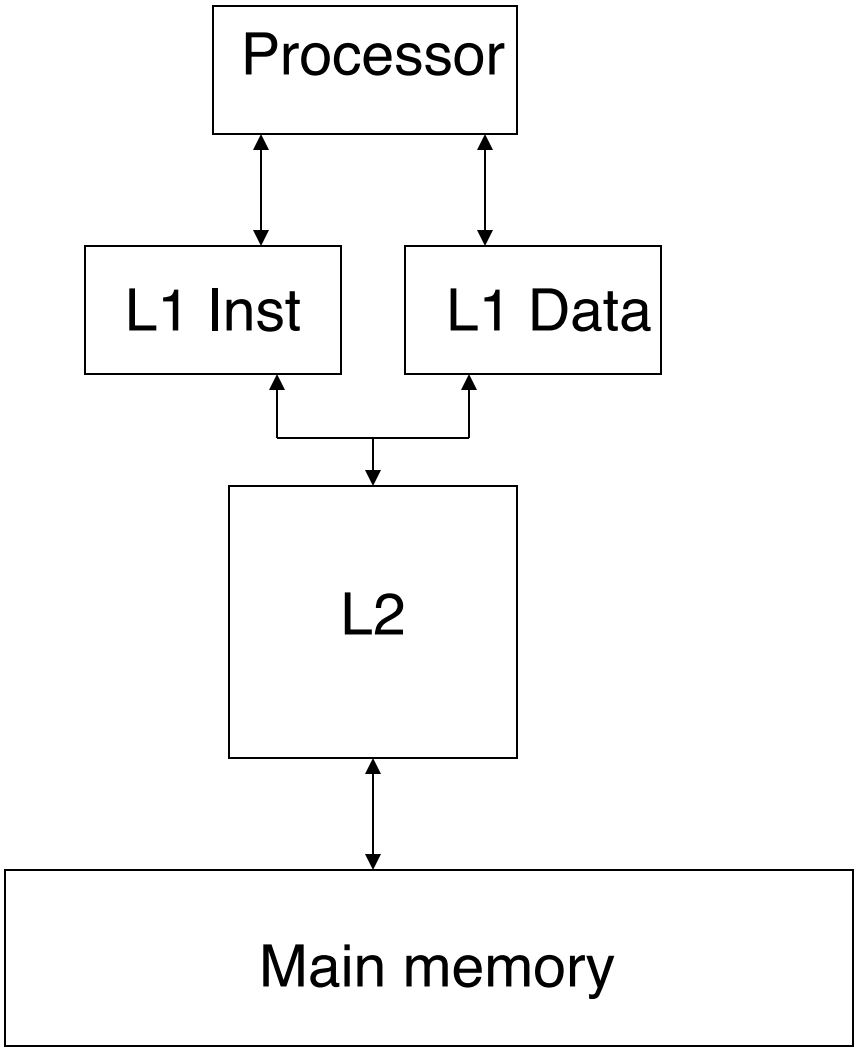
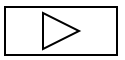


Figure 2.9 Energy consumption per read increases as cache size and associativity are increased. As in the previous figure, CACTI is used for the modeling with the same technology parameters. The large penalty for eight-way set associative caches is due to the cost of reading out eight tags and the corresponding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

Multilevel Caches



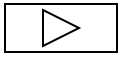
Why Multilevel Caches?



*Why Multilevel Caches?***

Processors getting faster w.r.t. main memory

- Want larger caches to reduce frequency of more costly misses
- But larger caches are too slow for processor
- Solution: reduce the cost of misses with a second (and third!) level of cache instead



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

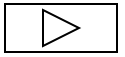
Pseudo-Associative Caches

Way Prediction

Victim Cache

Add a small fully associative cache next to main cache

On a miss in main cache

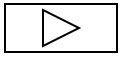


*Victim Cache***

Add a small fully associative cache next to main cache

On a miss in main cache

- Search in victim cache
- Put any replaced data in victim 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 ...

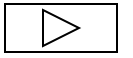
Reducing Miss Cost, cont.

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



*Reducing Miss Cost, cont.***

What if processor references unloaded word in block being loaded?

- Must add (equivalent to) ``word'' valid bits

Why not generalize?

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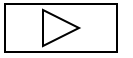
Called ``lockup-free'' or ``non-blocking'' cache



Lockup-Free Caches

Normal cache stalls while a miss is pending

Lockup-Free Caches

(a) Handle hits while first miss is pending

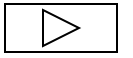
(b) Handle hits & misses until K misses are pending

Potential benefit

(a) Overlap misses with useful work & hits

(b) Also overlap misses with each other

Only makes sense if



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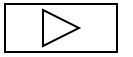
Only makes sense if processor

- Handles pending references correctly
- Often can do useful work with references pending (Tomasulo, etc.)
- Has misses that can be overlapped (for (b))



Lockup-Free Caches, cont.

Key implementation problems

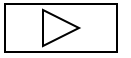
(1) Handling reads to pending miss

(2) Handling writes to pending miss

(3) Keep multiple requests straight

MSHRs -- miss status holding registers

What state do we need in MSHR?



*Lockup-Free Caches, cont. ***

Key implementation problems

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MSHRs -- miss status holding registers

For every MSHR – Valid bit

Block request address

For every word – Destination register?

Valid bit

Format (byte load, etc.)

Comparator (for later miss requests)

Limitation?

*Lockup-Free Caches, cont.***

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MSHRs -- miss status holding registers

For every MSHR – Valid bit

Block request address

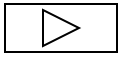
For every word – Destination register?

Valid bit

Format (byte load, etc.)

Comparator (for later miss requests)

Limitation: Must block on next access to same word



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

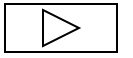
Beyond Simple Blocks, cont.

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

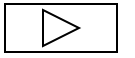
Prefetch instructions/data before processor requests them

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

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

Prefetches should

???



*Prefetching***

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

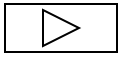
(a) Always get data back before it is referenced

(b) Never get data not used

(c) Never prematurely replace other data

(d) Never interfere with other cache activity

Item (a) conflicts with (b), (c) and (d)



Prefetching Policy

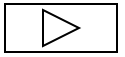
Policy

- What to prefetch?
- When to prefetch?

Simplest Policy

- ?

Enhancements



*Prefetching Policy***

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- What to prefetch?
- When to prefetch?

Simplest Policy

- One block (spatially) ahead on every access

Enhancements

*Prefetching Policy ***

Policy

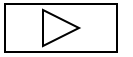
- What to prefetch?
- When to prefetch?

Simplest Policy

- One block (spatially) ahead on every access

Enhancements

- On every miss
  - Because hard to determine on every reference whether block to be prefetched is already in cache
- Detect stride and prefetch on stride
- Prefetch into prefetch buffer
- Prefetch more than 1 block (for instruction caches, when block small)



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***

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memory latency is 100 cycles

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

*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

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

This is good with one word cache blocks

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 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**

```
for (i = 0; i < N-1; i+=2) {
    prefetch(A[i+10])
    … = A[i]
    … = A[i+1]
    /* computation for two iterations */
}
```

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]
```

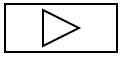
Column major order in memory

Code access pattern

Better code??

Called loop interchange

Many such optimizations possible (merging, fusion, blocking)



Software Restructuring (Cont.) **

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

Column major order in memory

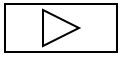
x[i,j], x[i+1,j], x[i+2,j], ...

Code access pattern

Better code??

Called loop interchange

Many such optimizations possible (merging, fusion, blocking)



Software Restructuring (Cont.) **

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

Column major order in memory

x[i,j], x[i+1,j], x[i+2,j], ...

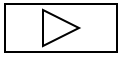
Code access pattern

x[1,1], x[1,2], x[1,3], ...

Better code??

Called loop interchange

Many such optimizations possible (merging, fusion, blocking)



Software Restructuring (Cont.) **

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

Column major order in memory

x[i,j], x[i+1,j], x[i+2,j], ...

Code access pattern

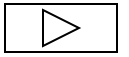
x[1,1], x[1,2], x[1,3], ...

Better code

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

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