Software Restructuring: Data

- Capacity misses: poor spatial or temporal locality
  - Several code restructuring techniques to improve both
  - – Compiler must know that restructuring preserves semantics

Loop interchange: spatial locality

- Example: row-major matrix: `X[i][j]` followed by `X[i][j+1]`
- Poor code: `X[i][j]` followed by `X[i+1][j]`

```
for (j = 0; j<NCOLS; j++)
   for (i = 0; i<NROWS; i++)
      sum += X[i][j];    // say
```

- Better code

```
for (i = 0; i<NROWS; i++)
   for (j = 0; j<NCOLS; j++)
      sum += X[i][j];
```

93

Software Restructuring: Data

- **Loop blocking**: temporal locality
  - Poor code

```
for (k=0; k<NITERATIONS; k++)
   for (i=0; i<NELEMS; i++)
      sum += X[i];    // say
```

  - Better code
    - Cut array into CACHE_SIZE chunks
    - Run all phases on one chunk, proceed to next chunk

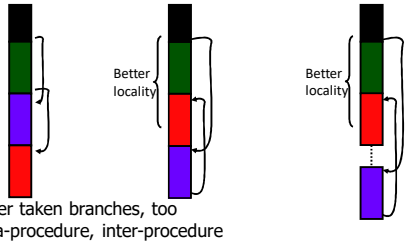
```
for (i=0; i<NELEMS; i+=CACHE_SIZE)
   for (k=0; k<NITERATIONS; k++)
      for (ii=0; ii<i+CACHE_SIZE-1; ii++)
         sum += X[ii];
```

  - – Assumes you know `CACHE_SIZE`, do you?
  - Loop fusion: similar, but for multiple consecutive loops

94

Software Restructuring: Code

- Compiler can layout code for temporal and spatial locality
  - If (a) { **code1;** } else { **code2;** } **code3;**
  - But, code2 case never happens (say, error condition)



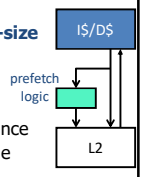
- Fewer taken branches, too
- Intra-procedure, inter-procedure

95

Prefetching

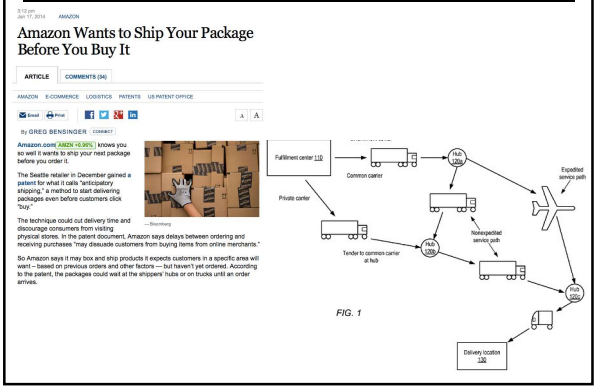
Prefetching: put blocks in cache proactively/speculatively

- Key: anticipate upcoming miss addresses accurately
  - Can do in software or hardware
- Simple example: **next block prefetching**
  - Miss on addr **X** → anticipate miss on **X+block-size**
  - + Works for insns: sequential execution
  - + Works for data: arrays
- **Timeliness**: initiate prefetches sufficiently in advance
- **Coverage**: prefetch for as many misses as possible
- **Accuracy**: don't pollute with unnecessary data
  - It evicts useful data



96

Prefetching in the Real World!



Amazon Wants to Ship Your Package Before You Buy It

FIG. 1

97

Software Prefetching

- Use a special "prefetch" instruction
  - Tells the hardware to bring in data, doesn't actually read it
  - Just a hint
- Inserted by programmer or compiler

  Example:

```
for (i = 0; i<NROWS; i++)
   for (j = 0; j<NCOLS; j+=BLOCK_SIZE) {
      __builtin_prefetch(&X[i][j]+BLOCK_SIZE);
      for (jj=j; jj<j+BLOCK_SIZE-1; jj++)
         sum += x[i][jj];
   }
```

- Multiple prefetches bring multiple blocks in parallel
  - Using lockup-free caches
  - "Memory-level" parallelism

98

Hardware Prefetching

- What to prefetch?
  - **Stride-based sequential prefetching**
    - Can also do N blocks ahead to hide more latency
    - + Simple, works for sequential things: insns, array data
    - + Works better than doubling the block size
  - **Address-prediction**
    - Needed for non-sequential data: lists, trees, etc.
    - Use a hardware table to detect strides, common patterns
- When to prefetch?
  - On every reference?
  - On every miss?

99

More Advanced Address Prediction

- "Next-block" prefetching is easy, what about other options?
- **Correlating predictor**
  - Large table stores (miss-addr → next-miss-addr) pairs
  - On miss, access table to find out what will miss next
    - It's OK for this table to be large and slow
- Content-directed or dependence-based prefetching
  - Greedily chases pointers from fetched blocks
- Jump pointers
  - Augment data structure with prefetch pointers
- Make it easier to prefetch: cache-conscious layout/malloc
  - Lays lists out serially in memory, so they look like arrays
- Active area of research

100

Write Issues

- So far we have looked at reading from cache
  - Instruction fetches, loads
- What about writing into cache
  - Stores, not an issue for instruction caches (why they are simpler)
- Several new issues
  - Tag/data access
  - Write-through vs. write-back
  - Write-allocate vs. write-not-allocate
  - Hiding write miss latency

101

Tag/Data Access

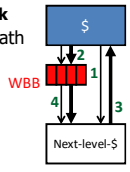
- Reads: read tag and data in parallel
  - Tag mis-match → data is garbage (OK, stall until good data arrives)
- Writes: read tag, write data in parallel?
  - Tag mis-match → clobbered data (oops)
  - For associative caches, which way was written into?
- Writes are a pipelined two step (multi-cycle) process
  - Step 1: match tag
  - Step 2: write to matching way
  - Bypass (with address check) to avoid load stalls
  - May introduce structural hazards

102

Write Propagation

When to propagate new value to (lower level) memory?

- **Option #1: Write-through**: immediately
  - On hit, update cache
  - Immediately send the write to the next level
- **Option #2: Write-back**: when block is replaced
  - Requires additional "dirty" bit per block
    - Replace **clean** block: **no extra traffic**
    - Replace **dirty** block: **extra "writeback" of block**
  - + **Writeback-buffer (WBB)**: keep it off critical path
    1. Send "fill" request to next-level
    2. While waiting, write dirty block to buffer
    3. When new blocks arrives, put it into cache
    4. Write buffer contents to next-level



103

Write Propagation Comparison

- **Write-through**
  - – Requires additional bus bandwidth
    - Consider repeated write hits
  - – Next level must handle small writes (1, 2, 4, 8-bytes)
  - + No need for dirty bits in cache
  - + No need to handle "writeback" operations
    - Simplifies miss handling (no write-back buffer)
  - Sometimes used for L1 caches (for example, by IBM)
- **Write-back**
  - + Key advantage: uses less bandwidth
  - Reverse of other pros/cons above
  - Used by Intel and AMD
  - 2nd-level and beyond are generally write-back caches

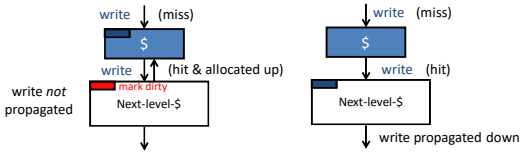
104

Write Miss Handling

How is a write miss handled?

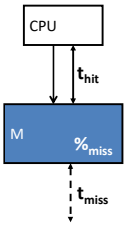
Write-allocate: fill block from next level, then write it
+ Decreases read misses (next read to block will hit)
– Requires additional bandwidth
• Commonly used (especially with **write-back** caches)

Write-non-allocate: just write to next level, no allocate
– Potentially more read misses
+ Uses less bandwidth
• Use with **write-through**



105

Memory Performance Equation



- **Access**: read or write to M
- **Hit**: desired data found in M
- **Miss**: desired data not found in M
  - Must get from another (slower) component
- **Fill**: action of placing data in M

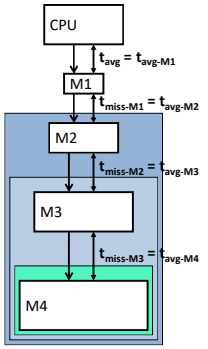
- **$\%_{miss}$** (miss-rate): #misses / #accesses
- **t_{hit}**: time to read data from (write data to) M
- **t_{miss}**: time to read data into M

- Performance metric
  - **t_{avg}**: average access time

$$t_{avg} = t_{hit} + \%_{miss} \times t_{miss}$$

106

Hierarchy Performance



t_{avg} =
t_{avg-M1}
$t_{hit-M1} + (\%_{miss-M1} \times t_{miss-M1})$
$t_{hit-M1} + (\%_{miss-M1} \times t_{avg-M2})$
$t_{hit-M1} + (\%_{miss-M1} \times (t_{hit-M2} + (\%_{miss-M2} \times t_{miss-M2})))$
$t_{hit-M1} + (\%_{miss-M1} \times (t_{hit-M2} + (\%_{miss-M2} \times t_{avg-M3})))$
…

107

Performance Calculation with $ Hierarchy

- **Parameters**
  - Reference stream: all loads
  - D$: t_{hit} = 1ns, $\%_{miss}$ = 5%
  - L2: t_{hit} = 10ns, $\%_{miss}$ = 20% (local miss rate)
  - Main memory: t_{hit} = 50ns
- **What is $t_{avgD\$}$ without an L2?**
  - $t_{missD\$}$ =
  - $t_{avgD\$}$ =
- **What is $t_{avgD\$}$ with an L2?**
  - $t_{missD\$}$ =
  - t_{avgL2} =
  - $t_{avgD\$}$ =

108

Performance Calculation with $ Hierarchy

- **Parameters**
  - Reference stream: all loads
  - D$: t_{hit} = 1ns, $\%_{miss}$ = 5%
  - L2: t_{hit} = 10ns, $\%_{miss}$ = 20% (local miss rate)
  - Main memory: t_{hit} = 50ns
- **What is $t_{avgD\$}$ without an L2?**
  - $t_{missD\$} = t_{hitM}$
  - $t_{avgD\$} = t_{hitD\$} + \%_{missD\$} \times t_{hitM}$ = 1ns+(0.05x50ns) = 3.5ns
- **What is $t_{avgD\$}$ with an L2?**
  - $t_{missD\$} = t_{avgL2}$
  - $t_{avgL2} = t_{hitL2} + \%_{missL2} \times t_{hitM}$ = 10ns+(0.2x50ns) = 20ns
  - $t_{avgD\$} = t_{hitD\$} + \%_{missD\$} \times t_{avgL2}$ = 1ns+(0.05x20ns) = 2ns

109

Designing a Cache Hierarchy

- For any memory component: t_{hit} vs. $\%_{miss}$ tradeoff

- Upper components (I$, D$) emphasize low t_{hit}
  - Frequent access → t_{hit} important
  - t_{miss} is not bad → $\%_{miss}$ less important
  - Low capacity/associativity (to reduce t_{hit})
  - Small-medium block-size (to reduce conflicts)

- Moving down (L2, L3) emphasis turns to $\%_{miss}$
  - Infrequent access → t_{hit} less important
  - t_{miss} is bad → $\%_{miss}$ important
  - High capacity/associativity/block size (to reduce $\%_{miss}$)

110

Memory Hierarchy Parameters

Parameter	I$/D$	L2	L3	Main Memory
t_{hit}	2ns	10ns	30ns	100ns
t_{miss}	**10ns**	**30ns**	**100ns**	**10ms (10M ns)**
Capacity	8KB–64KB	256KB–8MB	2–16MB	1-8GBs
Block size	16B–64B	32B–128B	32B-256B	NA
Associativity	1–4	4–16	4-16	NA

- Some other design parameters
  - Split vs. unified insns/data
  - Inclusion vs. exclusion vs. nothing
  - On-chip, off-chip, or partially on-chip?

111

Split vs. Unified Caches

Split I$/D$: insns and data in different caches
- To minimize structural hazards and t_{hit}
- Larger unified I$/D$ would be slow, 2nd port even slower
- Optimize I$ for wide output (superscalar), no writes

Unified L2, L3: insns and data together
- To minimize $\%_{miss}$

\+ Fewer capacity misses: unused insn capacity used for data

– More conflict misses: insn/data conflicts
  - A much smaller effect in large caches
- Insn/data structural hazards are rare: simultaneous I$/D$ miss
- Go even further: unify L2, L3 of multiple cores in a multi-core

112

Hierarchy: Inclusion versus Exclusion

- **Inclusion**
  - A block in the L1 is always in the L2
  - Good for write-through L1s (why?)
- **Exclusion**
  - Block is either in L1 or L2 (never both)
  - Good if L2 is small relative to L1
    - Example: AMD's Duron 64KB L1s, 64KB L2
- **Non-inclusion**
  - No guarantees

113

Summary

- **Average access time** of a memory component
  - $latency_{avg} = latency_{hit} + \%_{miss} \times latency_{miss}$
  - low $latency_{hit}$ and $\%_{miss}$ in one structure = hard → hierarchy
- **Memory hierarchy**
  - Cache (SRAM) → memory (DRAM) → swap (Disk)
  - Smaller, faster, more expensive → bigger, slower, cheaper
- Cache ABCs (**associativity, block size, capacity**)
  - 3C miss model: compulsory, capacity, conflict
- **Performance optimizations**
  - $\%_{miss}$: prefetching
  - $latency_{miss}$: victim buffer, critical-word-first, lockup-free design
- **Write issues**
  - Write-back vs. write-through
  - write-allocate vs. write-no-allocate

114