Prefetching

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Lecture notes based on notes by John P. Shen and Mark Hill
Updated by Mikko Lipasti
Prefetching

• Even “demand fetching” prefetches other words in block
  – Spatial locality

• Prefetching is useless
  – Unless a prefetch costs less than demand miss

• Ideally, prefetches should
  – Always get data before it is referenced
  – Never get data not used
  – Never prematurely replace data
  – Never interfere with other cache activity
Software Prefetching

• Use compiler to try to
  – Prefetch early
  – Prefetch accurately

• Prefetch into
  – Register (binding)
    • Use normal loads? Stall-on-use (Alpha 21164)
    • What about page faults? Exceptions?
  – Caches (non-binding) – preferred
    • Needs ISA support
Software Prefetching

• For example:

\[
\begin{align*}
do \ j = 1, \ cols \\
& do \ ii = 1 \ to \ rows \ by \ BLOCK \\
& \quad \text{prefetch} \ (\&(x[i,j])+\text{BLOCK}) \quad \# \text{prefetch one block ahead} \\
& \quad do \ i = ii \ to \ ii + \text{BLOCK}-1 \\
& \quad \quad \text{sum} = \text{sum} + x[i,j]
\end{align*}
\]

• How many blocks ahead should we prefetch?
  – Affects timeliness of prefetches
  – Must be scaled based on miss latency
Hardware Prefetching

• What to prefetch
  – One block spatially ahead
  – N blocks spatially ahead
  – Based on observed stride, track/prefetch multiple strides

• Training hardware prefetcher
  – On every reference (expensive)
  – On every miss (information loss)
  – Misses at what level of cache?
  – Prefetchers at every level of cache?

• Pressure for nonblocking miss support (MSHRs)
Prefetching for Pointer-based Data Structures

• What to prefetch
  – Next level of tree: n+1, n+2, n+?
    • Entire tree? Or just one path
  – Next node in linked list: n+1, n+2, n+?
  – Jump-pointer prefetching

• How to prefetch
  – Software places jump pointers in data structure
  – Hardware scans blocks for pointers
    • Content-driven data prefetching
Stream or Prefetch Buffers

• Prefetching causes capacity and conflict misses (pollution)
  – Can displace useful blocks
• Aimed at compulsory and capacity misses
• Prefetch into buffers, NOT into cache
  – On miss start filling stream buffer with successive lines
  – Check both cache and stream buffer
    • Hit in stream buffer => move line into cache (promote)
    • Miss in both => clear and refill stream buffer
• Performance
  – Very effective for I-caches, less for D-caches
  – Multiple buffers to capture multiple streams (better for D-caches)
• Can use with any prefetching scheme to avoid pollution
Example: Global History Buffer

  - [slides from conference talk follow]
- Hardware prefetching scheme
- Monitors miss stream
- Learns correlations
- Issues prefetches for likely next address
Markov Prefetching

- Markov prefetching forms address correlations
  - Joseph and Grunwald (ISCA ‘97)
- Uses global memory addresses as states in the Markov graph
- Correlation Table *approximates* Markov graph

**Miss Address Stream**

\[ A \ B \ C \ A \ B \ C \ B \ C \ldots \]

**Markov Graph**

- Node A with self-transition probability 1
- Node B with self-transition probability 1, transition to C probability 0.5, and to A probability 0.5
- Node C with self-transition probability 1, transition to B probability 0.5, and to A probability 0.5

**Correlation Table**

<table>
<thead>
<tr>
<th>Address</th>
<th>1st predict.</th>
<th>2nd predict.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
</tbody>
</table>
Correlation Prefetching

- Distance Prefetching forms *delta* correlations
  - Kandiraju and Sivasubramaniam (ISCA ‘02)
- Delta-based prefetching leads to much smaller table than “classical” Markov Prefetching
- Delta-based prefetching can remove compulsory misses

**Markov Prefetching**

**Miss Address Stream**

<table>
<thead>
<tr>
<th>27</th>
<th>28</th>
<th>29</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>28</th>
<th>29</th>
</tr>
</thead>
</table>

**Distance Prefetching**

**Global Delta Stream**

| 1 | 1 | -2 | 1 | 1 | -1 | 1 |

**Miss Address Table**

<table>
<thead>
<tr>
<th>miss address</th>
<th>1st predict.</th>
<th>2nd predict.</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>28</td>
<td>29</td>
</tr>
</tbody>
</table>

**Global Delta Table**

<table>
<thead>
<tr>
<th>global delta</th>
<th>1st predict.</th>
<th>2nd predict.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>-2</td>
</tr>
</tbody>
</table>
Global History Buffer (GHB)

- Holds miss address history in FIFO order
- Linked lists within GHB connect related addresses
  - Same static load
  - Same global miss address
  - Same global delta
  - Linked list walk is short compared with L2 miss latency

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GHB - Example

Miss Address Stream

27 28 29 27 28 29 28 29

Index Table

pointer

Global Miss
Address

Global History Buffer

miss address

pointer

27
28
29
27
29
28
29
28
29

head pointer

Key

Æ Current
Æ Prefetches

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GHB – Deltas

Miss Address Stream
27 28 36 44 45 49 53 54 62 70

Global Delta Stream
1 8 8 1 4 4 1 8 8

Markov Graph

<table>
<thead>
<tr>
<th>Key</th>
<th>Prefetches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purple</td>
<td>Current</td>
</tr>
<tr>
<td>Blue</td>
<td>Prefetches</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prefetches</th>
</tr>
</thead>
<tbody>
<tr>
<td>71 + 8 =&gt; 79</td>
</tr>
<tr>
<td>71 + 4 =&gt; 75</td>
</tr>
<tr>
<td>79 + 8 =&gt; 87</td>
</tr>
<tr>
<td>79 + 4 =&gt; 79</td>
</tr>
</tbody>
</table>
GHB – Hybrid Delta

• Width prefetching suffers from poor accuracy and short look-ahead
• Depth prefetching has good look-ahead, but may miss prefetch opportunities when a number of “next” addresses have similar probability
• The hybrid method combines depth and width
GHB - Hybrid Example

**Miss Address Stream**
27 28 36 44 45 49 53 54 62 70 71

**Global Delta Stream**
1 8 8 1 4 4 1 8 8 1

**Index Table**

- Global Delta pointer
- Head pointer

**Global History Buffer**

- Global history buffer
- Miss address pointer

**Prefetches**
- 71 + 8 => 79
- 79 + 8 => 89

**Key**
- Current
- Prefetches
Summary

• Prefetching anticipates future memory references
  – Software prefetching
  – Next-block, stride prefetching
  – Global history buffer prefetching

• Issues/challenges
  – Accuracy
  – Timeliness
  – Overhead (bandwidth)
  – Conflicts (displace useful data)