Chapter 3 – Instruction-Level Parallelism and its Exploitation (Part 2)

ILP vs. Parallel Computers
Dynamic Scheduling (Section 3.4, 3.5)
Dynamic Branch Prediction (Section 3.3)
Hardware Speculation and Precise Interrupts (Section 3.6)
Multiple Issue (Section 3.7)
Static Techniques (Section 3.2, Appendix H)
Limitations of ILP (Section 3.10)
Multithreading (Section 3.12)
Putting it Together (Mini-projects)
Reducing penalties from control dependences

Basic idea

Hardware guesses

* Whether branch will be taken/not taken
* Where the branch will go

Especially important for multiple issue processors

Desirable properties

Good prediction rate
Make correct prediction fast
Don't slow too much on misprediction
Maintain a buffer with prediction bits
Index buffer with LSBs of branch instruction PC

Predict based on indexed bit, change bit on misprediction

Accessed in ID stage (not useful for simple 5-stage pipeline)

Limitation of 1-bit predictor?
Variations on Branch Prediction Buffer

Variations

- n-bit predictor
- Correlating predictors
- Tournament predictors
N-bit Predictor

Contains n-bit saturating counter
Count up if taken, down if not taken
Predict taken if $\geq 2^{(n-1)}$; predict not taken if $< 2^{(n-1)}$
2-bit good for loops
Correlating Predictors: \((m,n)\) Predictor

Use outcome of previous \(m\) branches and \(n\)-bit predictors

For each branch, the prediction buffer contains

- An entry for each possible history of previous \(m\) branches
- Each entry is an \(n\)-bit predictor

\* This figure has been taken from Computer Architecture, A Quantitative Approach, 3rd Edition Copyright 2003 by Elsevier Inc. All rights reserved. It has been used with permission by Elsevier Inc.
(1,1) predictor
   Prediction based on 1 previous branch,
   1 bit predictor

Number of prediction entries per branch = ??

Number of bits per prediction entry = ??
Correlating Predictors Example

Loop:

If a == 1            /* b1 */
  a = 0
If a == 0            /* b2 */

...

Let a = 1, 3, 1, 3, 1, 3, ...

Notation: N=not taken; T=taken

Initialize (1,1) prediction buffer entries of b2 to NT

  (1\textsuperscript{st} entry for previous branch taken, 2\textsuperscript{nd} for not taken)

Direction of b1:

Direction of b2:

History at b2:

Prediction entries of b2:

Prediction for b2:
Combining multiple predictors with a selector:

Selector typically a two-bit saturating counter:

Increment when the predicted predictor is correct, other incorrect.
Uses 4K 2-bit counters to choose from global and local predictor

Global predictor

- 4K entries of 2-bit predictors
- Indexed by history of last 12 branches

Local predictor is a two-level predictor

- History table with 1K 10-bit entries (for that branch)
  - Each entry gives 10 most recent branch outcomes
- Indexes table of 1K entries with 3-bit counters

Total of 29K bits

Misprediction rate

- SPECfp95 – 1 per 1000
- SPECint95 – 11.5 per 1000
Limitations

- May use bit from wrong PC
- Target must be known when branch resolved
Branch Target Buffer or Cache

Store target PC along with prediction

Accessed in IF stage

Next IF stage uses target PC
  - No bubbles on correctly predicted taken branch

Must store tag

More state

Can remove not-taken branches?
Branch Target Cache With Target Instruction

Store target instruction along with prediction
Send target instruction instead of branch into ID
Zero cycle branch - branch folding
Used for unconditional jumps
**Return Address Stack**

Hardware stack for addresses for returns

Call pushes return address in stack

Return pops the address

Perfect prediction if stack length \( \geq \) call depth
Speculative Execution

How far can we go with branch prediction?

Speculative fetch?
Speculative issue?
Speculative execution?
Speculative write?
Speculative Execution

Allows instructions after branch to execute before knowing if branch will be taken

Must be able to undo if branch is not taken

Often try to combine with dynamic scheduling

Key insight: Split Write stage into Complete and Commit

  Complete out of order
    No state update
  Commit in order
    State updated (instruction no longer speculative)

Use reorder buffer
Overview

Instructions complete out-of-order
Reorder buffer reorganizes instructions
Modify state in-order

<table>
<thead>
<tr>
<th>Entry</th>
<th>Busy</th>
<th>Type</th>
<th>Dest</th>
<th>Result</th>
<th>State</th>
<th>Excep</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1</td>
<td>LD</td>
<td>4</td>
<td></td>
<td>Exec</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>BR</td>
<td></td>
<td></td>
<td>Exec</td>
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</tr>
<tr>
<td>4</td>
<td>1</td>
<td>ADD</td>
<td>6</td>
<td>75</td>
<td>Compl</td>
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<td></td>
<td></td>
</tr>
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<td>N</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Instruction tag now is reorder buffer entry
Re-order Buffer Pipeline

Issue:

Execute:

Complete:

Commit:
Precise Interrupts Again

Precise interrupts hard with dynamic scheduling

Consider our canonical code fragment:

\[
\begin{align*}
\text{LF } F6,34 (R2) \\
\text{LF } F2,45 (R3) \\
\text{MULTF } F0,F2,F4 \\
\text{SUBF } F8,F6,F2 \\
\text{DIVF } F10,F0,F6 \\
\text{ADDF } F6,F8,F2
\end{align*}
\]

What happens if DIVF causes an interrupt?

- ADDF has already completed

Out-of-order completion makes interrupts hard

But reorder buffer can help!
Reorder Buffer for Precise Interrupts
Re-order Buffer Drawback

Operands need to be read from reorder buffer or registers
Alternative: Rename registers
Many current machines
More physical registers than logical registers
Reorder buffer does not have values
Read all values from registers

Rename mechanism
Rename map stores mapping from logical to physical registers
(Logical register Ri mapped to physical register Rp)
On issue, Ri mapped to Rp-new
On completion, write to Rp-new
On commit, old mapping of Ri discarded (free Rp-old)
On misprediction, new mapping of Ri discarded (free Rp-new)