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)
Dynamic Branch Prediction

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

```
Prediction bit

1
1
0
1
0
1
```

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

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(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

(1st entry for previous branch taken, 2nd for not taken)

Direction of b1:

Direction of b2:

History at b2:

Prediction entries of b2:

Prediction for b2:
Tournament Predictor

Combine multiple predictors with a selector
Selector typically two bit saturating counter
   Increment when predicted predictor correct, other incorrect
Tournament Predictor Example - Alpha 21264

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?
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

**Reorder Buffer**

<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>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<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>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>ADD</td>
<td>6</td>
<td>75</td>
<td>Compl</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
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<td></td>
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<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<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:

```
LF F6,34(R2)
LF F2,45(R3)
MULTF F0,F2,F4
SUBF F8,F6,F2
DIVF F10,F0,F6
ADDF F6,F8,F2
```

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)