Branch Prediction

Example: Comparing perfect branch prediction to 90%, 95%, 99% prediction accuracy, and to no branch prediction
- Processor has a 15-stage 6-wide pipeline, incorrectly predicted branch leads to pipeline flush
- Program can have an average of 4 instructions retire per cycle, has 100,000 conditional branches out of 1 million instructions
  - Perfect BP: IPC = 1,000,000/250,000 = 4.00
  - 90% BP accuracy: 1/10 branches incorrectly predicted
    - IPC = 1,000,000/(250,000 + 0.1x100,000x15) = 2.5 (60% slower)
  - 95% BP accuracy: 1/20 branches incorrectly predicted
    - IPC = 1,000,000/(250,000 + 0.05x100,000x15) = 3.08 (30% slower)
  - 99% BP accuracy: 1/100 branches incorrectly predicted
    - IPC = 1,000,000/(250,000 + 0.01x100,000x15) = 3.77 (6% slower)
- No BP: Fetch stalled until branch is resolved (4 pipeline stages)
  - IPC = 1,000,000/(250,000 + 100,000x4) = 1.53 (160% slower)

Reducing Branch Costs with Dynamic Hardware Prediction
- Branch prediction basics:
  - We need to predict conditional branch outcome to select the address for next instruction fetch
  - PC + 4
  - Or branch target address
  - Also we need to quickly determine the branch target address
  - Direct branches
  - Register indirect branches
  - Returns

Predicting Conditional Branch Outcomes
- Simplest dynamic branch prediction scheme uses a branch-prediction buffer or branch history table
  - Small memory indexed by the lower portion of the branch address
  - Stores previous branch outcomes to predict next outcome
  - Table is not tagged: Prediction may have been put in the entry by a different branch (Aliasing)

Predicting Conditional Branch Outcomes
- 2-bit saturating counter often used
  - Branch taken ==> increment state
    - Max state “11” stays at “11” when incremented
  - Branch not-taken ==> decrement state
    - Min state “00” stays at “00” when decremented
    - “11” and “10” are predict taken states
    - “00” and “01” are predict not-taken states
Predicting Conditional Branch Outcomes

- Assuming initial state to be “11”, i.e., 3, branch outcomes and corresponding predictions now look as follows:

<table>
<thead>
<tr>
<th>Outcomes</th>
<th>States</th>
<th>Predictions</th>
<th>Mispredictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1111</td>
<td>1111111111111111</td>
<td>1111111111111111</td>
<td>1111111111111111</td>
</tr>
<tr>
<td>01</td>
<td>3333333333333333</td>
<td>3333333333333333</td>
<td>3333333333333333</td>
</tr>
</tbody>
</table>

Correlating Branch Predictors

- 2-bit prediction schemes use the recent behavior of a single branch to predict the future behavior of that branch
- Behavior of longer sequence of branch execution history often provides more accurate prediction outcome
- Behavior of other branches rather than just the branch we are trying to predict is sometimes important
  - Because outcomes of different branches often correlate
  - Global branch history
- For some branches, prior history execution of the branch is important
  - Because of loops
  - Local branch history

Correlating Branch Predictors: Code Example

```c
if (aa == 2) {
    DSUBUI R3,R1,#2
    BNEZ R3,L1
    aa = 0;
    DADD R1,R0,R0
    if (bb == 2) {
        L1: DSUBUI R3,R2,#2
            BNEZ R3,L2
            bb = 0;
            DSUBU R3,R1,R2
        L2: BEQZ R3,L3
    }
    if (aa != bb) {
        DADD R2,R0,R0
        L1: DSUBUI R3,R2,#2
            BNEZ R3,L2
            bb = 0;
            DSUBU R3,R1,R2
        L2: BEQZ R3,L3
    }
}
```

Correlating Branch Predictor with 2-bit Global History Register

Two-Level Adaptive Branch Prediction

- Two main structures
  - Branch History Register (BHR) or Branch History Table (BHT)
  - Pattern History Table (PHT)
- Basic structure of the branch predictor: Yeh&Patt Figure 1
- Updating predictions using automata: Yeh&Patt Figure 2

- Three different flavors (Yeh&Patt Figure 3)
  - Global History Register and Global Pattern History Table (GAg)
  - Per-address Branch History Table and Global Pattern History Table (PAg)
  - Per-address Branch History Table and Per-address Pattern History Tables (PAp)
Two-Level Adaptive Branch Prediction: Discussion

- Cost-effectiveness of three flavors
  - GAg has too much branch interference, needs long history
  - PAp needs lots of space for Per-address PHT
  - PAg is the most cost-effective

- Context switch
  - GAg almost unaffected
  - PAg, PAp degraded
  - Pros and cons for saving branch history on a context switch?

Adaptively Combining Branch Predictors

- Some branches are predicted more accurately with global predictors
- Other branches are predicted better with local predictors
- It is possible to combine both types of predictors, and dynamically select the right predict for the right branch
- The selector is yet another predictor with 2-bit state machine per entry

State of the Art Branch Prediction: TAGE

- Tagged GEometric history length branch prediction (Seznec & Michaud, JILP 2006 – skim)
  - Variations of TAGE won the last three branch prediction championships (GBP)
  - History is tagged
  - Avoids aliasing (branch predicted using another branch’s history)
  - History length is geometric
  - Hard-to-predict branches use longer history than more predictable branches
  - Paper Figure 1

Branch Target Buffer (BTB)

- A cache that stores branch targets
- Accessed by the address of the instruction currently fetched
- Allows branch target to be read in the IF stage
  - When a branch is predicted taken, the fetch of the instruction at the branch target address can proceed immediately in the next cycle
  - Stall cycles that would have been needed to wait for the decoding of the branch and the computation of the target are saved

Branch Target Buffer
Predicting Return Address Using Return Address Stack (RAS)

- Indirect branches have multiple potential targets, since address comes from a register, which can have many possible values.
- Branch target buffers could be used for indirect branch target prediction.
  - However, many mispredictions can happen because the BTB can store only one target per branch.
- Most indirect branches come from return instructions.

Return Address Stack

- A small address buffer organized as a stack.
- When a Call is encountered, the Return address (which is Call address + 4) is pushed onto the RAS.
- When a Return instruction is encountered, the address from the top of the RAS is popped and used as the target.

Reading Assignment

- **Wednesday**
  - Simplescalar technical report (Read)
  - Tutorial (Skim)
  - Daniel Jimenez and Calvin Lin, “Dynamic Branch Prediction with Perceptrons,” HPCA 2001 (Skim)
  - No reviews due.
- **Monday**