If (aa == 2)
   aa = 0;
If (bb == 2)
   bb = 0;
If (aa != bb) {
   D SUBUI R3, R1, #2
   BNEZ R3, L1
   ANDI R1, R1, #0
   ; branch b1 (aa!=2)
   L1: SUBUI R3, R2, #2
   BNEZ R3, L2
   ANDI R2, R2, #0
   ; branch b2 (bb!=2)
   L2: SUBU R3, R1, R2
   BEQZ R3, L3
   ; R3=aa-bb
   ; branch b3 (aa==bb)

   The behavior of branch b3 is correlated with the behavior of b1 and b2
   Clearly of both branches b1 and b2 are untaken, then b3 will be taken
   A predictor that uses only the behavior of a single branch to predict the outcome of that branch can never capture this behavior
   Branch predictors that use the behavior of other branches to make a prediction are called correlating or two-level predictors

Hypothesis: recent branches are correlated; that is, behavior of recently executed branches affects prediction of current branch
(2,2) Correlating Predictors

- Record m most recently executed branches as taken or not taken, and use that pattern to select the proper branch history table
- (m,n) predictor means record last m branches to select between 2m history tables each with n-bit counters
  - Old 2-bit branch history table is a (0,2) predictor
- In a (2,2) predictor, the behavior of recent branches selects between, four predictions of next branch, updating just that prediction

Total size = $2^m \times n \times \#$ prediction entries selected by branch address
Accuracy of Different Schemes

- 4096 entries (2 bits/entry)
- Unlimited entries (2 bits/entry)
- 1024 entries (2,2)
Example

- Assume that \( d \) has values 0, 1, or 2 (alternating between 0, 2)
- Assume that the sequence will be executed repeatedly
- Ignore all other branches including those causing the sequence to repeat
- All branches are initially predicted to untaken state

\[
\begin{align*}
\text{if (d==0)} & \quad \text{BNEZ R1, L1} & \quad \text{; branch b1 (d!=0)} \\
\text{d=1;} & \quad \text{DADDI R1, R0, #1} & \quad \text{; d==0, sp d=1} \\
\text{if (d==1)} & \quad \text{L1: DSUBUI R3, R1, #1} & \quad \text{; branch b2 (d!=1)} \\
& \quad \text{BNEZ R3, L2} & \quad \text{; branch b2 (d!=1)} \\
\text{....} & & \\
\text{L2:} & &
\end{align*}
\]
Example

With a single bit predictor

<table>
<thead>
<tr>
<th>d=?</th>
<th>b1 prediction</th>
<th>b1 action</th>
<th>New b1 prediction</th>
<th>b2 prediction</th>
<th>b2 action</th>
<th>New b2 prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>NT</td>
<td>T</td>
<td>T</td>
<td>NT</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>0</td>
<td>T</td>
<td>NT</td>
<td>NT</td>
<td>T</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>2</td>
<td>NT</td>
<td>T</td>
<td>T</td>
<td>NT</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>0</td>
<td>T</td>
<td>NT</td>
<td>NT</td>
<td>T</td>
<td>NT</td>
<td>NT</td>
</tr>
</tbody>
</table>

• All branches are mispredicted

if (d==0)

d=1;

if (d==1)

BNEZ R1, L1 ; branch b1 (d!=0)
DADDI R1, R0, #1 ; d==0, sp d=1
L1: DSUBUI R3, R1, #1
BNEZ R3, L2 ; branch b2 (d!=1)

....

L2:
Example

With one bit predictor with one bit of correlation

<table>
<thead>
<tr>
<th>d=?</th>
<th>b1 prediction</th>
<th>b1 action</th>
<th>New b1 prediction</th>
<th>b2 prediction</th>
<th>b2 action</th>
<th>New b2 prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>NT/NT</td>
<td>T</td>
<td>T/NT</td>
<td>NT/NT</td>
<td>T</td>
<td>NT/T</td>
</tr>
<tr>
<td>0</td>
<td>T/NT</td>
<td>NT</td>
<td>T/NT</td>
<td>NT/NT</td>
<td>NT</td>
<td>NT/T</td>
</tr>
<tr>
<td>2</td>
<td>T/NT</td>
<td>T</td>
<td>T/NT</td>
<td>NT/NT</td>
<td>T</td>
<td>NT/T</td>
</tr>
<tr>
<td>0</td>
<td>T/NT</td>
<td>NT</td>
<td>T/NT</td>
<td>NT/NT</td>
<td>NT</td>
<td>NT/T</td>
</tr>
</tbody>
</table>

- Except for first iteration, all branches are correctly predicted

if (d==0) d=1;
if (d==1)

L1: DADDI R1, R0, #1
    DSUBUI R3, R1, #1
    BNEZ R1, L1

L2: BNEZ R3, L2

; branch b1 (d!=0)
; d==0, sp d=1

; branch b2 (d!=1)
Tournament Predictors

- Multilevel branch predictors use several levels of branch prediction tables together with an algorithm to choose among them.

- Tournament selectors are the most popular form of multilevel branch predictors (e.g. DEC Alpha 21264).

- Tournament predictors combines both local and global predictor.

- Selection between the two predictors are based on a selector (2-bit counter).

- Make a transition with two wrong prediction using the current table for which the correct prediction would have been possible using the other predictor.
Performance of Tournament Predictors

Based on SPEC 89 benchmark

Tournament predictors slightly outperform correlating predictors

Tournament predictors