Static Conditional Branch Prediction

• Branch prediction schemes can be classified into static and dynamic schemes. Static methods are usually carried out by the compiler. They are static because the prediction is already known before the program is executed. Some of the static prediction schemes include:
  – Predict all branches to be taken. This makes use of the observation that the majority of branches are taken. This primitive mechanism yields 60% to 70% accuracy.
  – Use the direction of a branch to base the prediction on. Predict backward branches (branches which decrease the PC) to be taken and forward branches (branches which increase the PC) not to be taken. This mechanism can be found as a secondary mechanism in some commercial processors.
  – Profiling can also be used to predict the outcome of a branch. A previous run of the program is used to collect information if a given branch is likely to be taken or not, and this information is included in the opcode of the branch (one bit branch direction hint).

(Static Prediction in Chapter 4.2  Dynamic Prediction in Chapter 3.4, 3.5)
Dynamic Conditional Branch Prediction

- Dynamic branch prediction schemes are different from static mechanisms because they use the run-time behavior of branches to make more accurate predictions than possible using static prediction.

- Usually information about outcomes of previous occurrences of a given branch (branching history) is used to predict the outcome of the current occurrence. Some of the proposed dynamic branch prediction mechanisms include:
  - One-level or Bimodal: Uses a Branch History Table (BHT), a table of usually two-bit saturating counters which is indexed by a portion of the branch address (low bits of address).
  - Two-Level Adaptive Branch Prediction.
  - MCFarling’s Two-Level Prediction with index sharing (gshare).
  - Hybrid or Tournament Predictors: Uses a combinations of two or more (usually two) branch prediction mechanisms.

- To reduce the stall cycles resulting from correctly predicted taken branches to zero cycles, a Branch Target Buffer (BTB) that includes the addresses of conditional branches that were taken along with their targets is added to the fetch stage.
Branch Target Buffer (BTB)

- Effective branch prediction requires the target of the branch at an early pipeline stage.
- One can use additional adders to calculate the target, as soon as the branch instruction is decoded. This would mean that one has to wait until the ID stage before the target of the branch can be fetched, taken branches would be fetched with a one-cycle penalty (this was done in the enhanced MIPS pipeline Fig A.24).
- To avoid this problem one can use a Branch Target Buffer (BTB). A typical BTB is an associative memory where the addresses of taken branch instructions are stored together with their target addresses.
- Some designs store $n$ prediction bits as well, implementing a combined BTB and Branch history Table (BHT).
- Instructions are fetched from the target stored in the BTB in case the branch is predicted-taken and found in BTB. After the branch has been resolved the BTB is updated. If a branch is encountered for the first time a new entry is created once it is resolved.
- Branch Target Instruction Cache (BTIC): A variation of BTB which caches also the code of the branch target instruction in addition to its address. This eliminates the need to fetch the target instruction from the instruction cache or from memory.
Basic Branch Target Buffer (BTB)

PC of instruction to fetch

Look up

Predicted PC

Number of entries in branch-target buffer

No: instruction is not predicted to be branch. Proceed normally

Yes: then instruction is branch and predicted PC should be used as the next PC

A branch-target buffer.

Branch predicted taken or untaken
The steps involved in handling an instruction with a branch-target buffer:

1. Send PC to memory and branch-target buffer.
2. If entry found in branch-target buffer:
   - Send out predicted PC.
3. Check if instruction is a branch:
   - Yes: Go to step 4.
   - No: Normal instruction execution.
4. If taken branch:
   - Yes: Branch correctly predicted; continue execution with no stalls.
   - No: Mispredicted branch; kill fetched instruction; restart fetch at other target; delete entry from target buffer.
5. Enter branch and next PC into branch target buffer.

IF  +  ID  +  EX
Branch-Target Buffer Penalties
Using A Branch-Target Buffer

<table>
<thead>
<tr>
<th>Instruction in buffer</th>
<th>Prediction</th>
<th>Actual branch</th>
<th>Penalty cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Taken</td>
<td>Taken</td>
<td>0</td>
</tr>
<tr>
<td>Yes</td>
<td>Taken</td>
<td>Not taken</td>
<td>2</td>
</tr>
<tr>
<td>No</td>
<td>Taken</td>
<td>Taken</td>
<td>2</td>
</tr>
</tbody>
</table>

Penalties for all possible combinations of whether the branch is in the buffer and what it actually does, assuming we store only taken branches in the buffer.
Hardware Dynamic Branch Prediction

- Simplest method:
  - A branch prediction buffer or Branch History Table (BHT) indexed by low address bits of the branch instruction.
  - Each buffer location (or BHT entry) contains one bit indicating whether the branch was recently taken or not.
  - Always mispredicts in first and last loop iterations.

- To improve prediction accuracy, two-bit prediction is used:
  - A prediction must miss twice before it is changed.
  - Two-bit prediction is a specific case of n-bit saturating counter incremented when the branch is taken and decremented otherwise.
  - Two-bit prediction counters are usually always used based on observations that the performance of two-bit BHT prediction is comparable to that of n-bit predictors.
One-Level Bimodal Branch Predictors

- One-level or bimodal branch prediction uses only one level of branch history.
- These mechanisms usually employ a table which is indexed by lower bits of the branch address.
- The table entry consists of $n$ history bits, which form an $n$-bit automaton or saturating counters.
- Smith proposed such a scheme, known as the Smith algorithm, that uses a table of two-bit saturating counters.
- One rarely finds the use of more than 3 history bits in the literature.
- Two variations of this mechanism:
  - Decode History Table: Consists of directly mapped entries.
  - Branch History Table (BHT): Stores the branch address as a tag. It is associative and enables one to identify the branch instruction during IF by comparing the address of an instruction with the stored branch addresses in the table (similar to BTB).
One-Level Bimodal Branch Predictors
Decode History Table (DHT)

N Low Bits of Branch Address

Table has $2^N$ entries.

Example:
For $N=12$
Table has $2^{12} = 4096 = 4k$ entries

Number of bits needed = $2 \times 4k = 8k$ bits

High bit determines branch prediction
$0 =$ Not Taken
$1 =$ Taken

Prediction Bits

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
</table>
| 0 | 0 | Not Taken
| 0 | 1 |
| 1 | 0 | Taken
| 1 | 1 |

EECC551 - Shaaban
One-Level Bimodal Branch Predictors

Branch History Table (BHT)

High bit determines branch prediction
0 = Not Taken
1 = Taken

Prediction Bits
Basic Dynamic Two-Bit Branch Prediction:

Two-bit Predictor State Transition Diagram

The states in a two-bit prediction scheme.
Prediction Accuracy of A 4096-Entry Basic Dynamic Two-Bit Branch Predictor

Integer

SPEC89 benchmarks

Integer average 11%
FP average 4%

Prediction accuracy of a 4096-entry two-bit prediction buffer for the SPEC89 benchmarks.
From The Analysis of Static Branch Prediction:
MIPS Performance Using Canceling Delay Branches

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>% conditional branches</th>
<th>% conditional branches with empty slots</th>
<th>% conditional branches that are cancelling</th>
<th>% cancelling branches that are cancelled</th>
<th>% branches with cancelled delay slots</th>
<th>Total % branches with empty or cancelled delay slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>compress</td>
<td>14%</td>
<td>18%</td>
<td>31%</td>
<td>43%</td>
<td>13%</td>
<td>31%</td>
</tr>
<tr>
<td>eqntott</td>
<td>24%</td>
<td>24%</td>
<td>50%</td>
<td>24%</td>
<td>12%</td>
<td>36%</td>
</tr>
<tr>
<td>espresso</td>
<td>15%</td>
<td>29%</td>
<td>19%</td>
<td>21%</td>
<td>4%</td>
<td>33%</td>
</tr>
<tr>
<td>gcc</td>
<td>15%</td>
<td>16%</td>
<td>33%</td>
<td>34%</td>
<td>11%</td>
<td>27%</td>
</tr>
<tr>
<td>li</td>
<td>15%</td>
<td>20%</td>
<td>55%</td>
<td>48%</td>
<td>26%</td>
<td>46%</td>
</tr>
<tr>
<td>Integer average</td>
<td>17%</td>
<td>21%</td>
<td>38%</td>
<td>34%</td>
<td>13%</td>
<td>35%</td>
</tr>
<tr>
<td>doduc</td>
<td>8%</td>
<td>33%</td>
<td>12%</td>
<td>62%</td>
<td>8%</td>
<td>41%</td>
</tr>
<tr>
<td>ear</td>
<td>10%</td>
<td>37%</td>
<td>36%</td>
<td>14%</td>
<td>5%</td>
<td>42%</td>
</tr>
<tr>
<td>hydro2d</td>
<td>12%</td>
<td>0%</td>
<td>69%</td>
<td>24%</td>
<td>16%</td>
<td>17%</td>
</tr>
<tr>
<td>mdljdp2</td>
<td>9%</td>
<td>0%</td>
<td>86%</td>
<td>10%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>su2cor</td>
<td>3%</td>
<td>7%</td>
<td>17%</td>
<td>57%</td>
<td>10%</td>
<td>17%</td>
</tr>
<tr>
<td>FP average</td>
<td>8%</td>
<td>16%</td>
<td>44%</td>
<td>34%</td>
<td>9%</td>
<td>25%</td>
</tr>
<tr>
<td>Overall average</td>
<td>12%</td>
<td>18%</td>
<td>41%</td>
<td>34%</td>
<td>11%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Delayed and cancelling delay branches for DLX allow branch hazards to be hidden 70% of the time on average for these 10 SPEC benchmarks.
Prediction Accuracy of Basic Two-Bit Branch Predictors:

4096-entry buffer Vs. An Infinite Buffer Under SPEC89
Recent branches are possibly correlated: The behavior of recently executed branches affects prediction of current branch.

Example:

B1  if (aa==2)  
    aa=0;  

B2  if (bb==2)  
    bb=0;  

B3  if (aa!==bb){

Branch B3 is correlated with branches B1, B2. If B1, B2 are both not taken, then B3 will be taken. Using only the behavior of one branch cannot detect this behavior.
Correlating Two-Level Dynamic GAp Branch Predictors

- Improve branch prediction by looking not only at the history of the branch in question but also at that of other branches using two levels of branch history.
- Uses two levels of branch history:
  - First level (global):
    - Record the global pattern or history of the m most recently executed branches as taken or not taken. Usually an m-bit shift register.
  - Second level (per branch address):
    - $2^m$ prediction tables, each table entry has n bit saturating counter.
    - The branch history pattern from first level is used to select the proper branch prediction table in the second level.
    - The low N bits of the branch address are used to select the correct prediction entry within a the selected table, thus each of the $2^m$ tables has $2^N$ entries and each entry is 2 bits counter.
    - Total number of bits needed for second level = $2^m \times n \times 2^N$ bits
- In general, the notation: (m,n) GAp predictor means:
  - Record last m branches to select between $2^m$ history tables.
  - Each second level table uses n-bit counters (each table entry has n bits).
- Basic two-bit single-level Bimodal BHT is then a (0,2) predictor.
Organization of A Correlating Two-level GAp (2,2) Branch Predictor

First Level
(2 bit shift register)

Second Level

High bit determines branch prediction
0 = Not Taken
1 = Taken

m = # of branches tracked in first level = 2
Thus $2^m = 2^2 = 4$ tables in second level

N = # of low bits of branch address used = 4
Thus each table in 2nd level has $2N = 24 = 16$ entries

n = # number of bits of 2nd level table entry = 2

Number of bits for 2nd level = $2^m \times n \times 2^N$
= $4 \times 2 \times 16 = 128$ bits

A (2,2) branch-prediction buffer uses a two-bit global history to choose from among four predictors for each branch address.
Dynamic Branch Prediction: Example

If \((d==0)\), then \(d=1;\)

If \((d==1)\),

\[
\begin{align*}
\text{BNEZ} & \quad \text{R1, L1} & \quad \text{branch b1 (d!=0)} \\
\text{DADDIU} & \quad \text{R1, R0, #1} & \quad d==0, \text{ so } d=1 \\
\text{L1:} & \quad \text{DADDIU} & \quad \text{R3, R1, # -1} \\
\text{BNEZ} & \quad \text{R3, L2} & \quad \text{branch b2 (d!=1)}
\end{align*}
\]

Possible execution sequences for a code fragment.

<table>
<thead>
<tr>
<th>Initial value of (d)</th>
<th>(d==0?)</th>
<th>(b1)</th>
<th>Value of (d) before (b2)</th>
<th>(d==1?)</th>
<th>(b2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Yes</td>
<td>Not taken</td>
<td>1</td>
<td>Yes</td>
<td>Not taken</td>
</tr>
<tr>
<td>1</td>
<td>No</td>
<td>Taken</td>
<td>1</td>
<td>Yes</td>
<td>Not taken</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>Taken</td>
<td>2</td>
<td>No</td>
<td>Taken</td>
</tr>
</tbody>
</table>

Behavior of a one-bit predictor initialized to not taken.

<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>
Dynamic Branch Prediction: Example

(continued)

```asm
if (d==0)
  d=1;
if (d==1)
  ...
L1:
  BNEZ R1, L1 ; branch b1 (d!=0)
  DADDIU R1, R0, #1 ; d==0, so d=1
L2:
  DADDIU R3, R1, # -1
  BNEZ R3, L2 ; branch b2 (d!=1)
```

<table>
<thead>
<tr>
<th>Initial value of d</th>
<th>d==0?</th>
<th>b1</th>
<th>Value of d before b2</th>
<th>d==1?</th>
<th>b2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Yes</td>
<td>Not taken</td>
<td>1</td>
<td>Yes</td>
<td>Not taken</td>
</tr>
<tr>
<td>1</td>
<td>No</td>
<td>Taken</td>
<td>1</td>
<td>Yes</td>
<td>Not taken</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>Taken</td>
<td>2</td>
<td>No</td>
<td>Taken</td>
</tr>
</tbody>
</table>

Combination and meaning of the taken/not taken prediction bits.

<table>
<thead>
<tr>
<th>d=2</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/T</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/T</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/T</td>
<td>NT</td>
<td>NT/T</td>
</tr>
</tbody>
</table>
Prediction Accuracy of Two-Bit Dynamic Predictors Under SPEC89

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>4096 entries: 2 bits per entry</th>
<th>Unlimited entries: 2 bits per entry</th>
<th>1024 entries (2,2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nasa7</td>
<td>1%</td>
<td>0%</td>
<td>1%</td>
</tr>
<tr>
<td>matrix300</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>tomcatv</td>
<td>1%</td>
<td>0%</td>
<td>1%</td>
</tr>
<tr>
<td>doduc</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>spice</td>
<td>9%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>fpopp</td>
<td>5%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>gcc</td>
<td>12%</td>
<td>11%</td>
<td>11%</td>
</tr>
<tr>
<td>espresso</td>
<td>5%</td>
<td>5%</td>
<td>4%</td>
</tr>
<tr>
<td>eqntott</td>
<td>6%</td>
<td>18%</td>
<td>18%</td>
</tr>
<tr>
<td>li</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>

**Basic**

**Correlating Two-level GAp**
MCFarling's gshare Predictor

- McFarling notes that using global history information might be less efficient than simply using the address of the branch instruction, especially for small predictors.
- He suggests using both global history and branch address by hashing them together. He proposes using the XOR of global branch history and branch address since he expects that this value has more information than either one of its components. The result is that this mechanism outperforms a GAp scheme by a small margin.
- This mechanism uses less hardware than GAp, since both branch (first level) and pattern history (second level) are kept globally.
- The hardware cost for k history bits is \( k + 2 \times 2^k \) bits, neglecting costs for logic.
gshare Predictor

Branch and pattern history are kept globally. History and branch address are XORed and the result is used to index the pattern history table.
gshare Performance

![Graph showing gshare Performance with predictor size (bytes) on the x-axis and conditional branch prediction accuracy (%) on the y-axis. The graph compares gshare-best, gselect-best, and global performance.]
Hybrid or Tournament Predictors

- Hybrid predictors are simply combinations of two or more branch prediction mechanisms.
- This approach takes into account that different mechanisms may perform best for different branch scenarios.
- McFarling presented a number of different combinations of two branch prediction mechanisms.
- He proposed to use an additional 2-bit counter selector array which serves to select the appropriate predictor for each branch.
- One predictor is chosen for the higher two counts, the second one for the lower two counts.
- If the first predictor is wrong and the second one is right the counter is decremented, if the first one is right and the second one is wrong, the counter is incremented. No changes are carried out if both predictors are correct or wrong.
A Generic Hybrid Predictor

Diagram showing a decision process involving branch history and branch address, leading to multiple predictors (Predictor 1, Predictor 2, Predictor n) followed by a selection process.
The hybrid predictor contains an additional counter array with 2-bit up/down saturating counters. Which serves to select the best predictor to use. Each counter keeps track of which predictor is more accurate for the branches that share that counter. Specifically, using the notation $P_1c$ and $P_2c$ to denote whether predictors $P_1$ and $P_2$ are correct respectively, the counter is incremented or decremented by $P_1c - P_2c$ as shown below.

<table>
<thead>
<tr>
<th>$P_1c$</th>
<th>$P_2c$</th>
<th>$P_1c - P_2c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

(no change)  (decrement counter)  (increment counter)  (no change)
MCFarling’s Hybrid Predictor Performance by Benchmark

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>bimodal</th>
<th>gshare</th>
<th>bimodal/gshare</th>
</tr>
</thead>
<tbody>
<tr>
<td>doduc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eqntott</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>espress</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fpPPP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gcc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>li</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mat300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>nasa7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>spice</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tomcatv</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conditional Branch Prediction Accuracy (%)
## Processor Branch Prediction Comparison

<table>
<thead>
<tr>
<th>Processor</th>
<th>Released</th>
<th>Accuracy</th>
<th>Prediction Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyrix 6x86</td>
<td>early '96</td>
<td>ca. 85%</td>
<td>BHT associated with BTB</td>
</tr>
<tr>
<td>Cyrix 6x86MX</td>
<td>May '97</td>
<td>ca. 90%</td>
<td>BHT associated with BTB</td>
</tr>
<tr>
<td>AMD K5</td>
<td>mid '94</td>
<td>80%</td>
<td>BHT associated with I-cache</td>
</tr>
<tr>
<td>AMD K6</td>
<td>early '97</td>
<td>95%</td>
<td>2-level adaptive associated with BTIC and ALU</td>
</tr>
<tr>
<td>Intel Pentium</td>
<td>late '93</td>
<td>78%</td>
<td>BHT associated with BTB</td>
</tr>
<tr>
<td>Intel P6</td>
<td>mid '96</td>
<td>90%</td>
<td>2-level adaptive with BTB</td>
</tr>
<tr>
<td>PowerPC750</td>
<td>mid '97</td>
<td>90%</td>
<td>BHT associated with BTIC</td>
</tr>
<tr>
<td>MC68060</td>
<td>mid '94</td>
<td>90%</td>
<td>BHT associated with BTIC</td>
</tr>
<tr>
<td>DEC Alpha</td>
<td>early '97</td>
<td>95%</td>
<td>2-level adaptive associated with I-cache</td>
</tr>
<tr>
<td>HP PA8000</td>
<td>early '96</td>
<td>80%</td>
<td>BHT associated with BTB</td>
</tr>
<tr>
<td>SUN UltraSparc</td>
<td>mid '95</td>
<td>88% int</td>
<td>BHT associated with I-cache</td>
</tr>
<tr>
<td></td>
<td></td>
<td>94% FP</td>
<td></td>
</tr>
</tbody>
</table>
The Cyrix 6x86/6x86MX

- Both use a single-level 2-bit Smith algorithm BHT associated with BTB.
- BTB (512-entry for 6x86MX and 256-entry for 6x86) and the BHT (1024-entry for 6x86MX).
- The Branch Target Buffer is organized 4-way set-associative where each set contains the branch address, the branch target addresses for taken and not-taken and 2-bit branch history information.
- Unconditional branches are handled during the fetch stage by either fetching the target address in case of a BTB hit or continuing sequentially in case of a BTB miss.
- For conditional branch instructions that hit in the BTB the target address according to the history information is fetched immediately. Branch instructions that do not hit in the BTB are predicted as not taken and instruction fetching continues with the next sequential instruction.
- Whether the branch is resolved in the EX or in the WB stage determines the misprediction penalty (4 cycles for the EX and 5 cycles for the WB stage).
- Both the predicted and the unpredicted path are fetched. avoiding additional cycles for cache access when a misprediction occurs.
- Return addresses for subroutines are cached in an eight-entry return stack on which they are pushed during CALL and popped during the corresponding RET.
Intel Pentium

- Similar to 6x86, it uses a single-level 2-bit Smith algorithm BHT associated with a four way associative BTB which contains the branch history information.
- However, Pentium does not fetch non-predicted targets and does not employ a return stack.
- It also does not allow multiple branches to be in flight at the same time.
- However, due to the shorter Pentium pipeline (compared with 6x86) the misprediction penalty is only three or four cycles, depending on what pipeline the branch takes.
Intel P6,II,III

- Like Pentium, the P6 uses a BTB that retains both branch history information and the predicted target of the branch. However the BTB of P6 has 512 entries reducing BTB misses. Since the
- The average misprediction penalty is 15 cycles. Misses in the BTB cause a significant 7 cycle penalty if the branch is backward.
- To improve prediction accuracy a two-level branch history algorithm is used.
- Although the P6 has a fairly satisfactory accuracy of about 90%, the enormous misprediction penalty should lead to reduced performance. Assuming a branch every 5 instructions and 10% mispredicted branches with 15 cycles per misprediction the overall penalty resulting from mispredicted branches is 0.3 cycles per instruction. This number may be slightly lower since BTB misses take only seven cycles.
AMD K6

• Uses a two-level adaptive branch history algorithm implemented in a BHT with 8192 entries (16 times the size of the P6).

• However, the size of the BHT prevents AMD from using a BTB or even storing branch target address information in the instruction cache. Instead, the branch target addresses are calculated on-the-fly using ALUs during the decode stage. The adders calculate all possible target addresses before the instruction is fully decoded and the processor chooses which addresses are valid.

• A small branch target cache (BTC) is implemented to avoid a one cycle fetch penalty when a branch is predicted taken.

• The BTC supplies the first 16 bytes of instructions directly to the instruction buffer.

• Like the Cyrix 6x86 the K6 employs a return address stack for subroutines.

• The K6 is able to support up to 7 outstanding branches.

• With a prediction accuracy of more than 95% the K6 outperforms all other microprocessors (except the Alpha).
The K6 Instruction Buffer

32-K byte Level-One Instruction Cache

16 Bytes

Branch Target Cache 16x16 Bytes

Branch Target Address Adders

Return Address Stack 16x16 Bytes

2:1

Fetch Unit

16 Instruction Bytes
plus
16 Sets of Predecode Bits

Instruction Buffer
Motorola PowerPC 750

- A dynamic branch prediction algorithm is combined with static branch prediction which enables or disables the dynamic prediction mode and predicts the outcome of branches when the dynamic mode is disabled.
- Uses a single-level Smith algorithm 512-entry BHT and a 64-entry Branch Target Instruction Cache (BTIC), which contains the most recently used branch target instructions, typically in pairs. When an instruction fetch does not hit in the BTIC the branch target address is calculated by adders.
- The return address for subroutine calls is also calculated and stored in user-controlled special purpose registers.
- The PowerPC 750 supports up to two branches, although instructions from the second predicted instruction stream can only be fetched but not dispatched.
The HP PA 8000

- The HA PA 8000 uses static branch prediction combined with dynamic branch prediction.
- The static predictor can turn the dynamic predictor on and off on a page-by-page basis. It usually predicts forward conditional branches as not taken and backward conditional branches as taken.
- It also allows compilers to use profile based optimization and heuristic methods to communicate branch probabilities to the hardware.
- Dynamic bench prediction is implemented by a 256-entry BHT where each entry is a three bit shift register which records the outcome of the last three branches instead of saturated up and down counters. The outcome of a branch (taken or not taken) is shifted in the register as the branch instruction retires.
- To avoid a taken branch penalty of one cycle the PA 8000 is equipped with a Branch Target Address Cache (BTAC) which has 32 entries.
The HP PA 8000 Branch Prediction Algorithm
The SUN UltraSparc

- Uses a single-level BHT Smith algorithm.
- It employs a static prediction which is used to initialize the state machine (saturated up and down counters).
- However, the UltraSparc maintains a large number of branch history entries (up to 2048 or every other line of the I-cache).
- To predict branch target addresses a branch following mechanism is implemented in the instruction cache. The branch following mechanism also allows several levels of speculative execution.
- The overall performance of UltraSparc is 94% for FP applications and 88% for integer applications.
The Alpha 21264

- The Alpha 21264 uses a two-level adaptive hybrid method combining two algorithms (a global history and a per-branch history scheme) and chooses the best according to the type of branch instruction encountered.
- The prediction table is associated with the lines of the instruction cache. An I-cache line contains 4 instructions along with a next line and a set predictor.
- If an I-cache line is fetched that contains a branch the next line will be fetched according to the line and set predictor. For lines containing no branches or unpredicted branches the next line predictor point simply to the next sequential cache line.
- This algorithm results in zero delay for correct predicted branches but wastes I-cache slots if the branch instruction is not in the last slot of the cache line or the target instruction is not in the first slot.
- The misprediction penalty for the alpha is 11 cycles on average and not less than 7 cycles.
- The resulting prediction accuracy is about 95% very good.
- Supports up to 6 branches in flight and employs a 32-entry return address stack for subroutines.
The Basic Alpha 21264 Pipeline

- **Fetch**: Access I-cache
- **Transit**: Send to decoder
- **Map**: Rename registers
- **Queue**: Insert in queue
- **Register**: Read operands
- **Execute**: Integer calc
- **Write**: Write result

Mispredicted branch penalty: 7 cycles minimum
Possible delay in instr queue
Load-use penalty: 2 cycles minimum
Alpha 21264 Branch Prediction

Program Counter

Local History Table
1,024 × 10 bits

Local Predict
1,024 × 3 bits

Global Predict
4,096 × 2 bits

Global History

Choice Predict
4,096 × 2 bits

Local Prediction

Global Prediction

Final Prediction