CSE 502: Computer Architecture

Branch Prediction
Fragmentation due to Branches

- Fetch group is aligned, cache line size > fetch group
  - Still limit fetch width if branch is “taken”
  - If we know “not taken”, width not limited
Toxonomy of Branches

• Direction:
  – Conditional vs. Unconditional

• Target:
  – PC-encoded
    • PC-relative
    • Absolute offset
  – Computed (target derived from register)

Need direction and target to find next fetch group
Branch Prediction Overview

• Use two hardware predictors
  – Direction predictor guesses if branch is taken or not-taken
  – Target predictor guesses the destination PC

• Predictions are based on history
  – Use previous behavior as indication of future behavior
  – Use historical context to disambiguate predictions
Where Are the Branches?

- To predict a branch, must find the branch
Simplistic Fetch Engine

Huge latency (reduces clock frequency)
Branch Identification

Predecode branches on fill from L2

Branch’s PC

Store 1 bit per inst, set if inst is a branch

partial-decode logic removed

High latency (L1-I on the critical path)
Line Granularity

- Predict fetch group without location of branches
  - With one branch in fetch group, does it matter where it is?

One predictor entry per instruction PC

One predictor entry per fetch group
Predicting by Line

Latency determined by branch predictor

This is still challenging: we may need to choose between multiple targets for the same cache line
Multiple Branch Prediction

- Target Pred
  - addr0
  - addr1
  - addr2
  - addr3

- Dir Pred
  - N
  - N
  - N
  - T

- Scan for 1st "T"

- no LSBs of PC

- LSBs of PC

- sizeof($-line)

- PC

- L1-I

- 0 1

- +
Direction vs. Target Prediction

- Direction: 0 or 1
- Target: 32- or 64-bit value
- Turns out targets are generally easier to predict
  - Don’t need to predict Not-taken target
  - Taken target doesn’t usually change
- Only need to predict taken-branch targets
- Prediction is really just a “cache”
  - Branch Target Buffer (BTB)
Branch Target Buffer (BTB)
Set-Associative BTB

Branch PC

\[ \text{Branch PC} \rightarrow \text{tag} \rightarrow \text{target} \rightarrow \text{tag} \rightarrow \text{target} \rightarrow \cdots \]

\[ \text{Next PC} \]
Making BTBs Cheaper

• Branch prediction is permitted to be wrong
  – Processor must have ways to detect mispredictions
  – Correctness of execution is always preserved
  – Performance may be affected

Can tune BTB accuracy based on cost
BTB w/Partial Tags

00000000cfff9810
00000000cfff9824
00000000cfff984c

00001111beef9810
00000000cfff9810
00000000cfff9824
00000000cfff984c

Fewer bits to compare, but prediction may alias
If target too far or PC rolls over, will mispredict
BTB Miss?

• Dir-Pred says “taken”
• Target-Pred (BTB) misses
  – Could default to fall-through PC (as if Dir-Pred said N-t)
    • But we know that’s likely to be wrong!
• Stall fetch until target known ... when’s that?
  – PC-relative: after decode, we can compute target
  – Indirect: must wait until register read/exec
Subroutine Calls

P: 0x1000: (start of printf)

A: 0xFC34: CALL printf

B: 0xFD08: CALL printf

C: 0xFFB0: CALL printf

BTB can easily predict target of calls
Subroutine Returns

P: 0x1000: ST $RA → [$sp]

0x1B98: LD $tmp ← [$sp]
0x1B9C: RETN $tmp

A: 0xFC34: CALL printf
A': 0xFC38: CMP $ret, 0

B: 0xFD08: CALL printf
B': 0xFD0C: CMP $ret, 0

BTB can’t predict return for multiple call sites
Return Address Stack (RAS)

- Keep track of call stack

A: 0xFC34: CALL printf
   FC38
P: 0x1000: ST $RA → [$sp]
   ...
0x1B9C: RETN $tmp

A': 0xFC38: CMP $ret, 0
Return Address Stack Overflow

1. Wrap-around and overwrite
   • Will lead to eventual misprediction after four pops

2. Do not modify RAS
   • Will lead to misprediction on next pop

64AC: CALL printf

64B0

FC90
421C
48C8
7300

top of stack
Branches Have Locality

• If a branch was previously taken...
  – There’s a good chance it’ll be taken again

```
for(i=0; i < 100000; i++)
{
    /* do stuff */
}
```

This branch will be taken 99,999 times in a row.
Simple Direction Predictor

• Always predict N-t
  – No fetch bubbles (always just fetch the next line)
  – Does horribly on loops

• Always predict T
  – Does pretty well on loops
  – What if you have if statements?

```c
p = calloc(num,sizeof(*p));
if(p == NULL) error_handler();
```

This branch is practically never taken
Last Outcome Predictor

- Do what you did last time

```c
for (i=0; i < 100000; i++) {
    if ( (i % 100) == 0 )
        tick();
    if ( (i & 1) == 1)
        odd();
}
```
Misprediction Rates?

How often is branch outcome != previous outcome?

- 0xDC08: TTTTTTTTTTTT ... TTTTTTTTTTTNTTTTTTTT ... 100,000 iterations
  - NT
  - TN

  2 / 100,000

- 0xDC44: TTTTT ... TNTTTTT ... TNTTTTT ... 100 iterations
  - 2 / 100

  99.998% Prediction Rate

  98.0%

- 0xDC50: TNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTNTN...
Saturating Two-Bit Counter

- Predict N-t
- Predict T
- Transition on T outcome
- Transition on N-t outcome

FSM for Last-Outcome Prediction

FSM for 2bC (2-bit Counter)
Example

Initial Training/Warm-up

1bC:

2bC:

Only 1 Mispredict per N branches now!
DC08: 99.999%  DC44: 99.0%

2x reduction in misprediction rate
Typical Organization of 2bC Predictor

- **PC**: 32 or 64 bits
- **hash**: 32 or 64 bits
- **log₂ n bits**: n entries/counters
- **table update**: FSM Update Logic
- **Prediction**: Actual outcome
Typical Branch Predictor Hash

- Take the $\log_2 n$ least significant bits of PC
- May need to ignore some bits
  - In RISC, insns. are typically 4 bytes wide
    - Low-order bits zero
  - In CISC (ex. x86), insns. can start anywhere
    - Probably don’t want to shift
Dealing with Toggling Branches

• Branch at 0xDC50 changes on every iteration
  – 1bc and 2bc don’t do too well (50% at best)
  – But it’s still obviously predictable

• Why?
  – It has a repeating pattern: (NT)*
  – How about other patterns? (TTNTN)*

• Use \textit{branch correlation}
  – Branch outcome is often related to previous outcome(s)
Track the **History** of Branches

- Previous Outcome:
  - prev = 1: 3 0, prediction = N
  - prev = 0: 3 0, prediction = T

- Counter if prev=0:
  - prev = 1: 3 2, prediction = T
  - prev = 0: 3 2, prediction = T

- Counter if prev=1:
  - prev = 1: 3 3, prediction = T
  - prev = 0: 3 3, prediction = T

- PC:
  - 1 3 0
  - 1 3 3

- Example:
  - prev = 1: 3 3, prediction = T (×)
  - prev = 0: 3 2, prediction = T

- Outcome:
  - prev = 1: 3 0, prediction = N
  - prev = 0: 3 0, prediction = T
Deeper History Covers More Patterns

- Counters learn “pattern” of prediction

001 → 1; 011 → 0; 110 → 0; 100 → 1
00110011001... (0011)∗
Predictor Organizations

Different pattern for each branch PC

Shared set of patterns

Mix of both
Branch Predictor Example (1/2)

• 1024 counters ($2^{10}$)
  – 32 sets (□)
    • 5-bit PC hash chooses a set
  – Each set has 32 counters
    • $32 \times 32 = 1024$
    • History length of 5 ($\log_2{32} = 5$)

• Branch collisions
  – 1000’s of branches collapsed into only 32 sets
Branch Predictor Example (2/2)

• 1024 counters ($2^{10}$)
  – 128 sets (■)
    • 7-bit PC hash chooses a set
  – Each set has 8 counters
    • $128 \times 8 = 1024$
    • History length of 3 ($\log_2 8 = 3$)

• Limited Patterns/Correlation
  – Can now only handle history length of three
Two-Level Predictor Organization

• **Branch History Table (BHT)**
  – $2^a$ entries
  – $h$-bit history per entry

• **Pattern History Table (PHT)**
  – $2^b$ sets
  – $2^h$ counters per set

• Total Size in bits
  – $h \times 2^a + 2^{(b+h)} \times 2$

Each entry is a 2-bit counter
Classes of Two-Level Predictors

• $h = 0$ or $a = 0$ (Degenerate Case)
  – Regular table of $2^b$C’s ($b = \log_2 \text{counters}$)

• $h > 0$, $a > 0$
  – “Local History” 2-level predictor
  – Predict branch from its own previous outcomes

• $h > 0$, $a = 0$
  – “Global History” 2-level predictor
  – Predict branch from previous outcomes of all branches
Why Global Correlations Exist

Example: related branch conditions

\[ p = \text{findNode}(\text{foo}); \]

**A:** \( \text{if ( p is parent )} \)
   
   \( \text{do something;} \)

\( \text{do other stuff;} \quad /* \text{may contain more branches */} \)

**B:** \( \text{if ( p is a child )} \)
   
   \( \text{do something else;} \)

Outcome of second branch is always opposite of the first branch.
A Global-History Predictor

Single global Branch History Register (BHR)
Tradeoff Between B and H

• For fixed number of counters
  – Larger h $\rightarrow$ Smaller b
    • Larger h $\rightarrow$ longer history
      – Able to capture more patterns
      – Longer warm-up/training time
    • Smaller b $\rightarrow$ more branches map to same set of counters
      – More interference
  – Larger b $\rightarrow$ Smaller h
    • Just the opposite...
Combined Indexing (1/2)

- “gshare” (S. McFarling)
Combined Indexing (2/2)

- Not all $2^h$ “states” are used
  - (TTNN)* uses $\frac{1}{4}$ of the states for a history length of 4
  - (TN)* uses two states regardless of history length

- Not all bits of the PC are uniformly distributed

- Not all bits of the history are uniformly correlated
  - More recent history more likely to be strongly correlated

PC Hash XOR

$k = \log_2 \text{counters}$
Combining Predictors

- Some branches exhibit local history correlations
  - ex. loop branches
- Some branches exhibit global history correlations
  - “spaghetti logic”, ex. if-elsif-elsif-elsif-else branches

- Global and local correlation often exclusive
  - Global history hurts locally-correlated branches
  - Local history hurts globally-correlated branches
Tournament Hybrid Predictors

If meta-counter MSB = 0, use \( \text{Pred}_0 \) else use \( \text{Pred}_1 \)

<table>
<thead>
<tr>
<th>Pred(_0)</th>
<th>Pred(_1)</th>
<th>Meta Update</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \times )</td>
<td>( \times )</td>
<td>---</td>
</tr>
<tr>
<td>( \times )</td>
<td>( \checkmark )</td>
<td>Inc</td>
</tr>
<tr>
<td>( \checkmark )</td>
<td>( \times )</td>
<td>Dec</td>
</tr>
<tr>
<td>( \checkmark )</td>
<td>( \checkmark )</td>
<td>---</td>
</tr>
</tbody>
</table>
Pros and Cons of Long Branch Histories

• Long global history provides context
  – More potential sources of correlation

• Long history incurs costs
  – PHT cost increases exponentially: $O(2^h)$ counters
  – Training time increases, possibly decreasing accuracy
Predictor Training Time

- Ex.: prediction equals opposite for 2\textsuperscript{nd} most recent
  - Hist Len = 2
  - 4 states to train:
    - NN $\rightarrow$ T
    - NT $\rightarrow$ T
    - TN $\rightarrow$ N
    - TT $\rightarrow$ N
  - Hist Len = 3
  - 8 states to train:
    - NNN $\rightarrow$ T
    - NNT $\rightarrow$ T
    - NTN $\rightarrow$ N
    - NTT $\rightarrow$ N
    - TNN $\rightarrow$ T
    - TNT $\rightarrow$ T
    - TTN $\rightarrow$ N
    - TTT $\rightarrow$ N
Branch Predictions Can Be Wrong

• How/when do we detect a misprediction?
• What do we do about it?
  – Re-steer fetch to correct address
  – Hunt down and squash instructions from the wrong path
Multiple speculatively fetched basic blocks may be in flight at the same time!
Branch Mispredictions in the Pipeline (2/2)

**IF**
- Direction prediction, target prediction
  - We know if branch is return, indirect jump, or phantom branch

**ID**
- If indirect target, can potentially read target from RF
  - Squash instructions in BP, L1-I-lookup
  - Re-steer BP to target from RF

**DP**
- Detect wrong direction or wrong target (indirect)
  - Squash instructions in BP, L1-I, ID and DP, *plus rest of pipeline*
  - Re-steer BP to correct next PC

**EX**
- Squash instructions in BP and L1-I-lookup
- Re-steer BP to new target from RAS/iBTB
Phantom Branches

- May occur when performing multiple bpreds

Fetch: ABCX… (C appears to be a branch)

After fetch, we discover C cannot be taken because it is not even a branch! This is a **phantom branch**.

Should have fetched: ABCDZ…
Front-End Hardware Organization

NPC → PC → L1-I → BPred → BTB → ID → RAS → iBTB → EX

- NPC: Next Program Counter
- PC: Program Counter
- L1-I: Level 1 Instruction Cache
- BPred: Branch Prediction
- BTB: Branch Target Buffer
- ID: Instruction Decode
- RAS: Register Addressing
- iBTB: Instruction Branch Target Buffer
- EX: Execution Unit

- Actual target: Branch prediction
- sizeof(L1-I-line): Size of L1-I line
- Push on call: Push on call instructions
- Pop on ret: Pop on return instructions
- Is indir: Indirect branch
- Is retn: Return
- Uncond br: Unconditional branch
- No branch: No branch instruction
Speculative Branch Update (1/3)

- **Ideal branch predictor operation**
  1. Given PC, predict branch outcome
  2. Given actual outcome, update/train predictor
  3. Repeat

- **Actual branch predictor operation**
  - Streams of predictions and updates proceed in parallel

  ![Diagram](image)

  - Predict: A B C D E F G
  - Update: A B C D E F G

  Can’t wait for update before making new prediction
Speculative Branch Update (2/3)

- BHR update cannot be delayed until commit
  - But outcome not known until commit

Predict: \[ \text{A B C D E F G} \]

Update: \[ \text{A B C D E F G} \]

BHR: \[
\begin{array}{cccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\end{array}
\]

Branches B-E all predicted with the same stale BHR value
Speculative Branch Update (3/3)

• Update branch history using predictions
  – *Speculative* update

• If predictions are correct, then BHR is correct

• What happens on a misprediction?
  – Commit-time BHR recovery
  – Execution-time BHR recovery
Commit-time BHR recovery

BPred Lookup → 0110100100100…

Speculative BHR

Mispredict!

BPred Update

Actual BHR
Execution-time BHR recovery

• Commit-time may delay misprediction recovery

  ![Diagram](image.png)

  - Cache miss to DRAM
  - Executed, but can’t recover until load is done

• Instead, “checkpoint” BHR at time of prediction
  - Roll back to checkpoint for recovery
  - Must track where to roll back to
  - In-flight branches limited by number of checkpoints
Overriding Branch Predictors (1/2)

• Use two branch predictors
  – 1\textsuperscript{st} one has single-cycle latency (fast, medium accuracy)
  – 2\textsuperscript{nd} one has multi-cycle latency, but more accurate
  – Second predictor can \textit{override} the 1\textsuperscript{st} prediction

Get speed without full penalty of low accuracy
Overriding Branch Predictors (2/2)

- **Fast 1st Pred**
  - Predict A
  - Predict A'

- **2-cycle Pipelined L1-I**
  - Fetch A
  - Predict B
  - Predict B'

- **Slower 2nd Pred**
  - Fetch B
  - Predict C
  - Predict A'

If A = A' (both preds agree), done

If A != A', flush A, B and C, restart fetch with A'