Systems I

Pipelining V

Topics

- Branch prediction
- State machine design

Branch Prediction

- **Until now - we have assumed a “predict taken” strategy for conditional branches**
  - Compute new branch target and begin fetching from there
  - If prediction is incorrect, flush pipeline and begin refetching
- **However, there are other strategies**
  - Predict not-taken
  - Combination (quasi-static)
    - Predict taken if branch backward (like a loop)
    - Predict not taken if branch forward

Branching Structures

Predict not taken works well for “top of the loop” branching structures

```
Loop: cmpl %eax, %edx
      je Out
      1nd loop instr
           .
           .
      last loop instr
      jmp  Loop
Out:  fall out instr
```

- But such loops have jumps at the bottom of the loop to return to the top of the loop – and incur the jump stall overhead

Predict not taken doesn’t work well for “bottom of the loop” branching structures

```
Loop: 1st loop instr
      2nd loop instr
           .
           .
      last loop instr
      cmpl %eax, %edx
      jne Loop
      fall out instr
```

Branch Prediction Algorithms

Static Branch Prediction

- Prediction (taken/not-taken) either assumed or encoded into program

Dynamic Branch Prediction

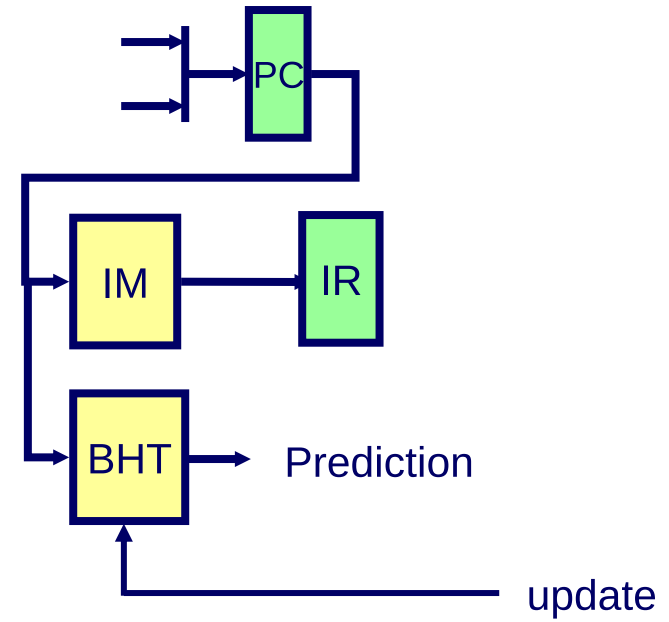
- Uses forms of machine learning (in hardware) to predict branches
  - Track branch behavior
- Past history of individual branches
- Learn branch biases
- Learn patterns and correlations between different branches
- Can be very accurate (95% plus) as compared to less than 90% for static

Simple Dynamic Predictor

Predict branch based on past history of branch

Branch history table

- Indexed by PC (or fraction of it)
- Each entry stores last direction that indexed branch went (1 bit to encode taken/not-taken)
- Table is a cache of recent branches
- Buffer size of 4096 entries are common (track 4K different branches)



Multi-bit predictors

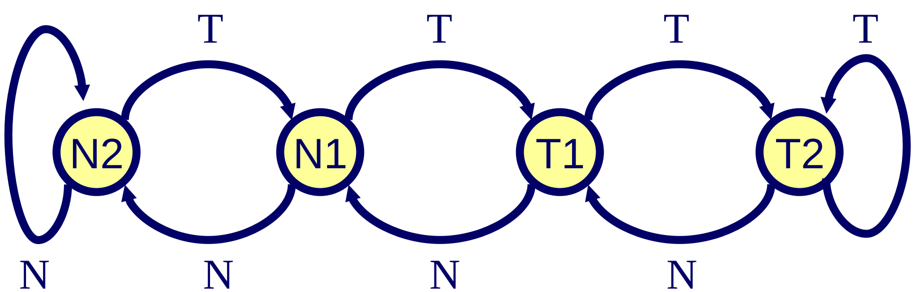
A ‘predict same as last’ strategy gets two mispredicts on each loop

- Predict NTTTT…TTT
- Actual TTTT…TTN

```
for(j=0;j<30;j++) {
    …
}
```

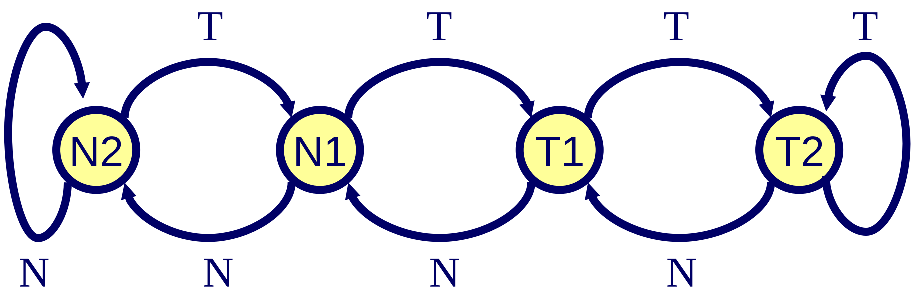
Can do much better by adding *inertia* to the predictor

- e.g., two-bit saturating counter
- Predict TTTT…TTT
- Use two bits to encode:
  - Strongly taken (T2)
  - Weakly taken (T1)
  - Weakly not-taken (N1)
  - Strongly not-taken (N2)



State diagram to representing states and transitions

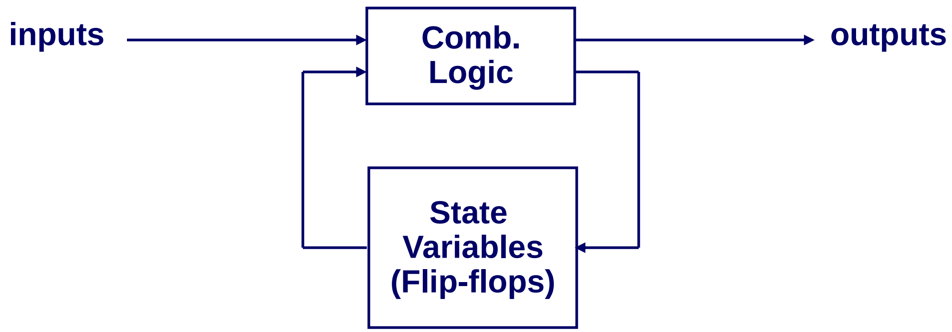
How do we build this in Hardware?



This is a sequential logic circuit that can be formulated as a state machine

- **4 states (N2, N1, T1, T2)**
- **Transitions between the states based on action "b"**

General form of state machine:



State Machine for Branch Predictor

4 states - can encode in two state bits <S1, S0>

- N2 = 00, N1 = 01, T1 = 10, T2 = 11
- Thus we only need 2 storage bits (flip-flops in last slide)

Input: b = 1 if last branch was taken, 0 if not taken

Output: p = 1 if predict taken, 0 if predict not taken

Now - we just need combinational logic equations for:

- p, $S1_{new}$, $S0_{new}$, based on b, S1, S0

Combinational logic for state machine

p =1 if state is T2 or T1

thus p = S1 (according to encodings)

The state variables S1, S0 are governed by the truth table that implements the state diagram

- $S1_{new}$ = S1*S0 + S1*b + S0*b
- $S0_{new}$ = S1*S0’ + S0’*S1’*b + S0*S1*b

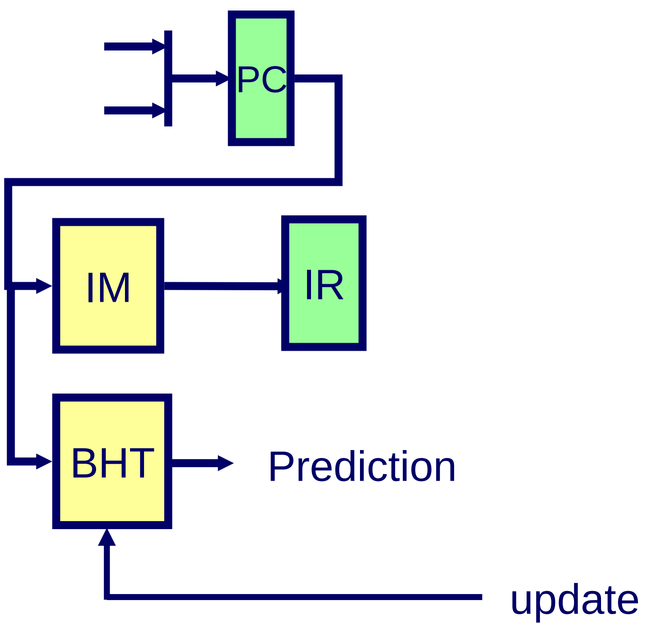
S1	S0	b	$S1_{new}$	$S0_{new}$	p
0	0	0	0	0	0
0	0	1	0	1	0
0	1	0	0	0	0
0	1	1	1	0	0
1	0	0	0	1	1
1	0	1	1	1	1
1	1	0	1	0	1
1	1	1	1	1	1

Enhanced Dynamic Predictor

Replace simple table of 1 bit histories with table of 2 bit state bits

State transition logic can be shared across all entries in table

- Read entry out
- Apply combinational logic
- Write updated state bits back into table



YMSBP

Yet more sophisticated branch predictors

Predictors that recognize patterns

- eg. if last three instances of a given branches were NTN, then predict taken

Predictors that correlate between multiple branches

- eg. if the last three instances of any branch were NTN, then predict taken

Predictors that correlate weight different past branches differently

- e.g. if the branches 1, 4, and 8 ago were NTN, then predict taken

Hybrid predictors that are composed of multiple different predictors

- e.g. two different predictors run in parallel and a third predictor predicts which one to use

More sophisticated learning algorithms

Summary

Today

- Branch mispredictions cost a lot in performance
- CPU Designers willing to go to great lengths to improve prediction accuracy
- Predictors are just state machines that can be designed using combinational logic and flip-flops