Lecture #2: Branch Prediction

Parallel Computer Systems

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Instruction fetch

- Goal is to fetch as many insns per cycle as possible
- Branch prediction is super important to fill the pipeline with correct-path instructions (useful work)
- Importance increases with deeper pipelines

Branch prediction

- Goal is to predict the branch direction and target address, and start fetching and executing insns along the predicted path
- Key observation:
  - Branches exhibit temporal locality
  - Predicting branch behavior
    - Keep track of past history
    - Predict the future based on the past
  - Branch behavior is predictable
    - typically over 90%, 95% or 99% of all dynamically executed branches are correctly predicted

Overview

- Branch direction prediction
  - Static
  - Dynamic
- Branch target prediction
- How to handle mispredictions?

Branch Direction Prediction

- Applies to conditional branches
- Static prediction
  - Static = before program execution
  - One prediction (taken/not-taken) per static branch in the program binary
  - Via software: compiler or programmer
- Dynamic prediction
  - Dynamic = during program execution
  - Multiple predictions per static branch, depending on history (= outcomes of prior branch executions) of that particular branch or even other branches
  - Done in hardware

Branch address vs. branch target address

```
000000012002e530 <__start>:
   12002e530:   f0 ff de 23    lda     sp,-16(sp)
   12002e534:   08 00 fe b7    stq     zero,8(sp)
   12002e538:   00 00 20 c0    br      t0,12002e53c <__start+0xc>
   12002e53c:   10 00 1e a2    ldl     a0,16(sp)
   12002e540:   18 00 3e 22    lda     a1,24(sp)
   12002e544:   00 20 a1 27    ldah    gp,8192(t0)
   12002e548:   52 06 11 42    s8addq  a0,a1,a2
   12002e54c:   12 14 41 42    addq    a2,0x8,a2
   12002e550:   24 28 bd 23    lda     gp,10276(gp)
   12002e554:   13 04 52 46    mov     a2,a3
   12002e558:   00 00 33 a4    ldq     t0,0(a3)
   12002e55c:   13 14 61 42    addq    a3,0x8,a3
   12002e560:   fd ff 3f f4    bne     t0,12002e558 <__start+0x28>
```

onder Linux/UNIX/OS X: `objdump -d a.out`

Static Branch Prediction

- Advantages
  - Easy to implement
  - Little HW is needed
- Disadvantages
  - Provides the same prediction regardless of input and/or dynamic execution behavior
- Three flavors
  - rule-based
  - program-based
  - profile-based

Rule-based

- Always not-taken
  – Simple HW: sequential fetch
- Always taken
  – HW is more complex because of unknown branch target
  – Branch target is known at the decode stage
  – May lead to a *bubble* ('lost cycle') in the pipeline
- BTFNT
  – *Backward taken - forward not-taken*
  – Branches to smaller addresses are typically backward loop branches and are typically taken

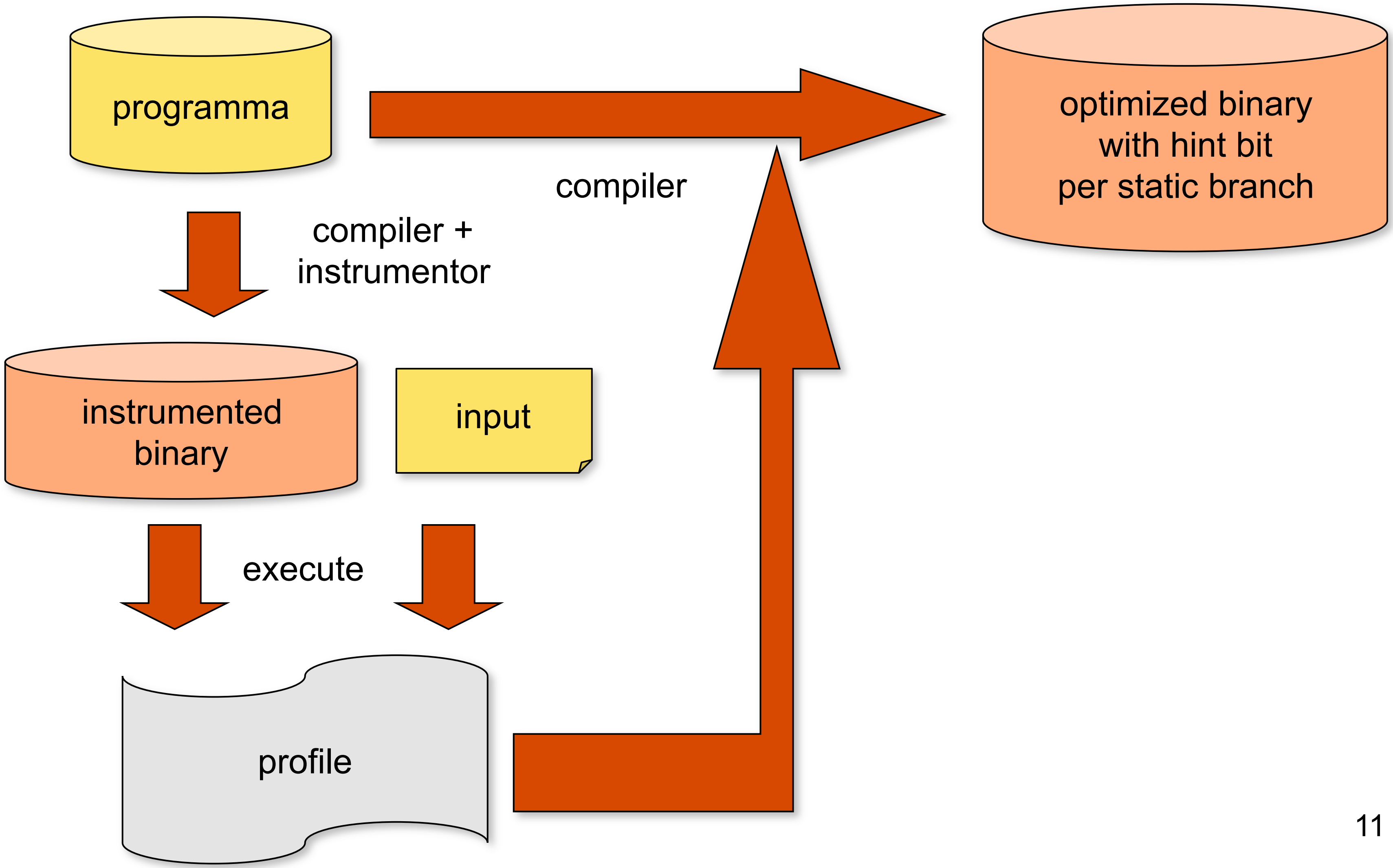
Program-based

- Ball en Larus heuristics (1993)
  - Requires a hint bit in instruction opcode
  - Branch direction is estimated based on program structure
  - Examples:
    - Predict loop branches to be taken
    - When comparing a pointer to NULL, predict branch direction to non-NULL path
    - When comparing two pointers, predict branch direction to path representing pointer inequality
  - Typically more accurate than rule-based

Profile-based

- Execute instrumented binary with a given training input to collect profile information
  - Count how often a static branch is taken/not-taken
- Use profile information during recompilation and add hint bits
  - Predict taken if branch has higher probability than 50% to be taken; predict not-taken otherwise
- Typically more accurate than rule- and program based

Profile-based



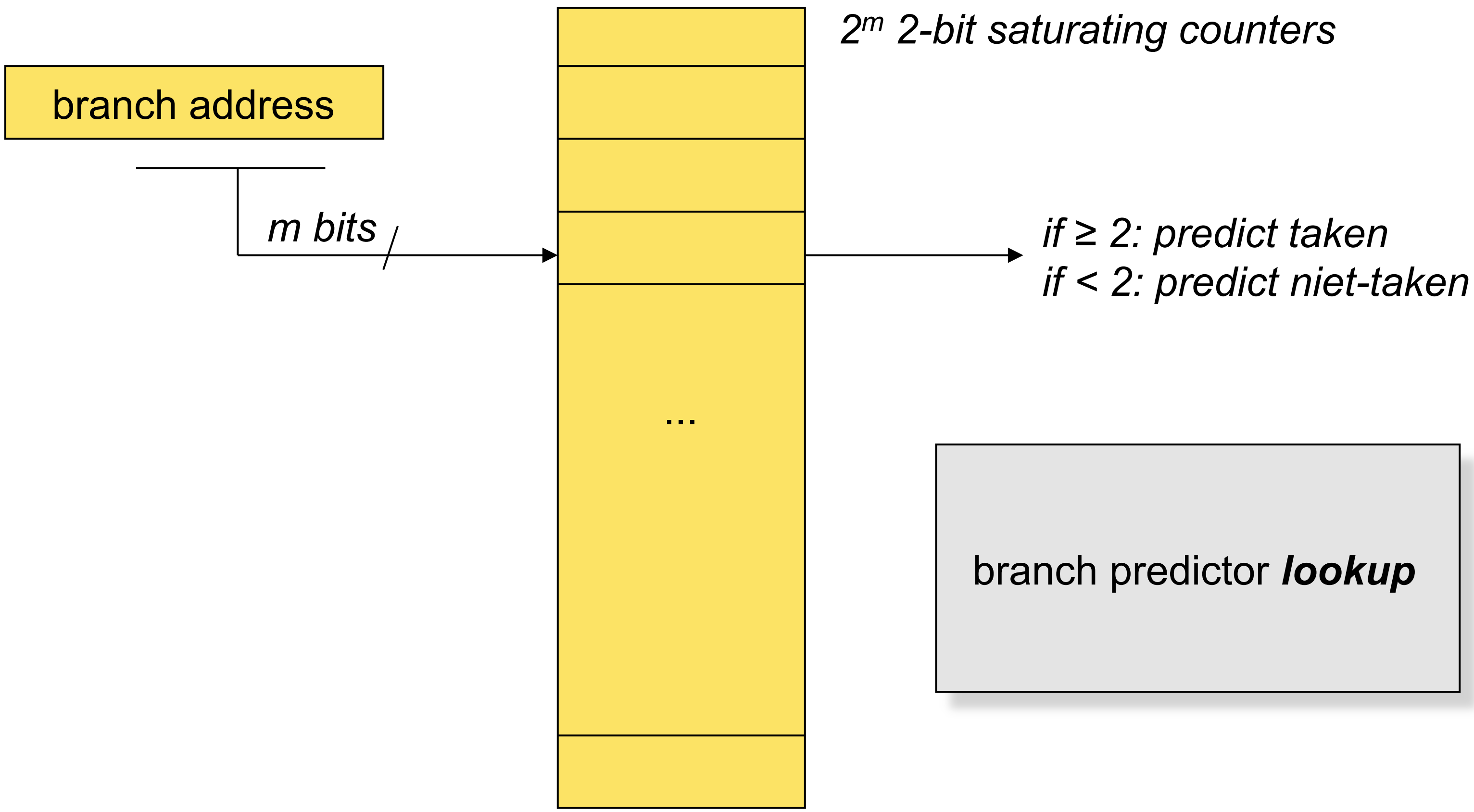
Overview

- Branch direction prediction
  - Static
  - Dynamic
- Branch target prediction
- How to handle mispredictions?

Dynamic branch prediction

- More accurate than static branch prediction
  - 80%-97% (dynamic) vs. 50%-80% (static)
- Some branches are hard to predict statically, but are easily predicted dynamically
  - Some examples
    - Not-taken during first half of execution, and taken during second half
    - Alternating taken/not-taken
- Takes into account branch context!
  - the branch's own history (***local history***)
  - other branches' histories (***global history***)

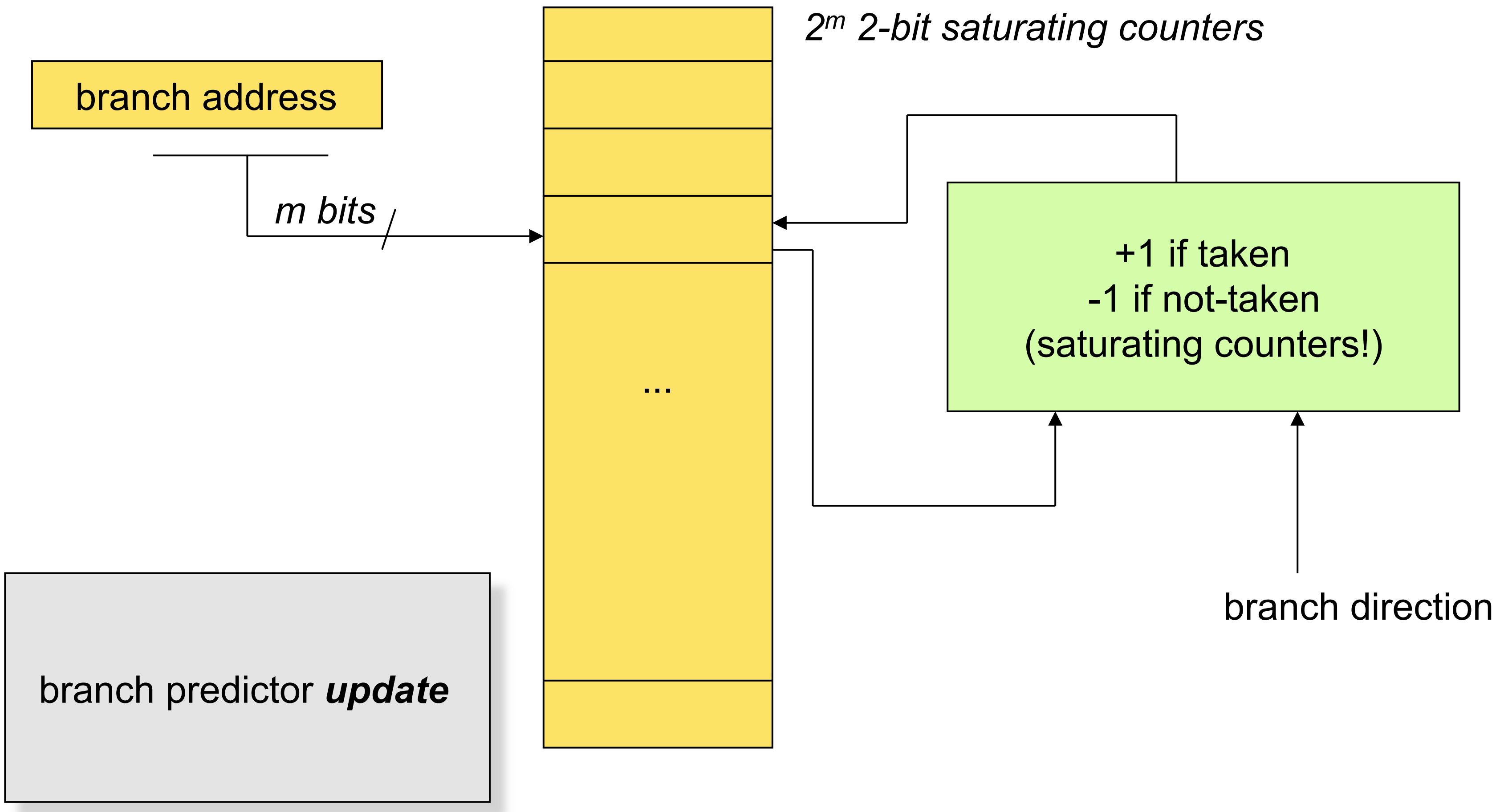
Bimodal predictor



branch predictor ***lookup***

James E. Smith (1981)

Bimodal predictor



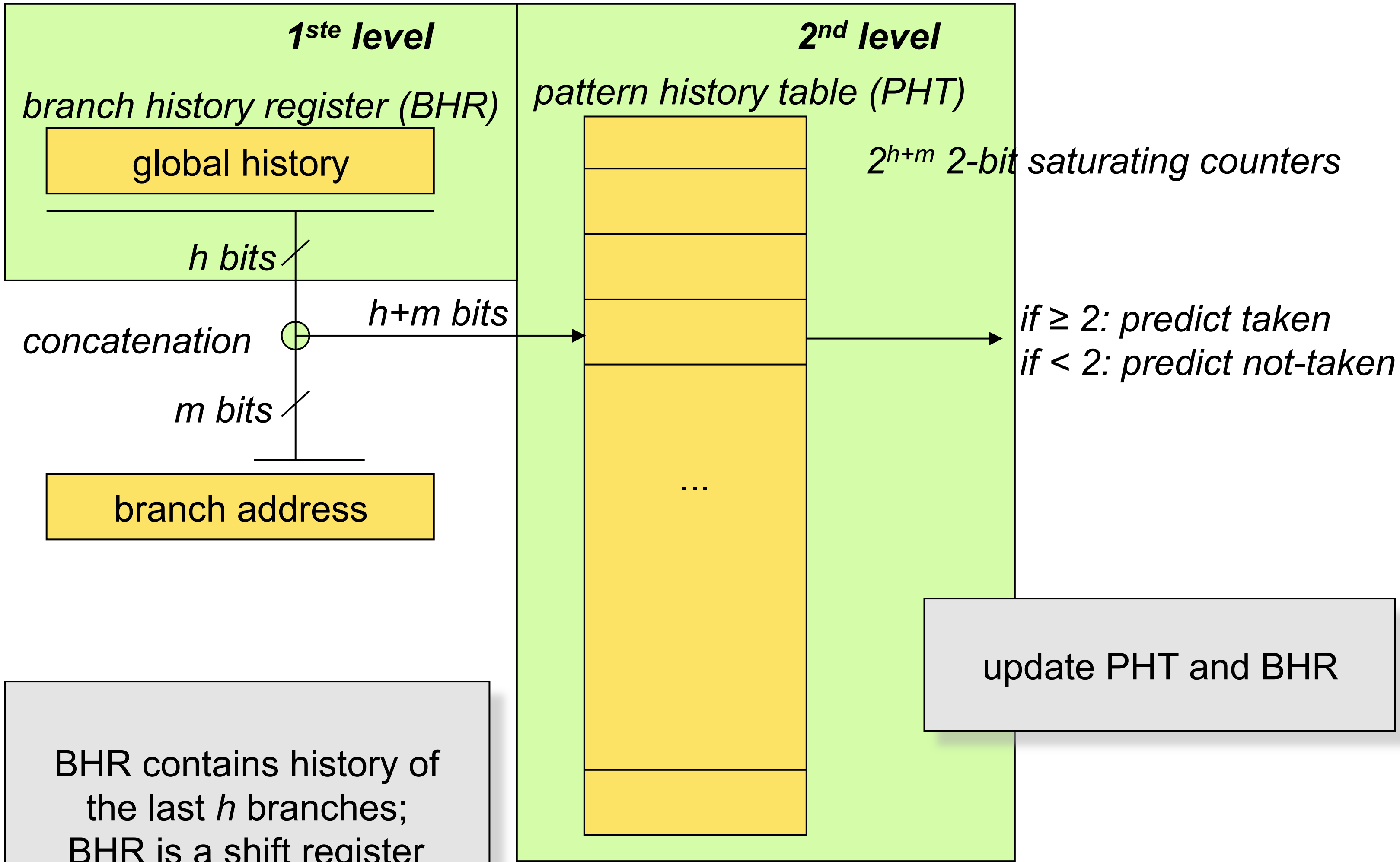
Example bimodal predictor

old state	*prediction*	*branch direction*	*new state*
00	**0**	0	00
00	**0**	0	00
00	**0**	1	01
01	**0**	1	10
10	**1**	1	11
11	**1**	1	11
11	**1**	0	10
10	**1**	1	11
11	**1**	1	11
11	**1**	0	10
10	**1**	0	01

Two-level predictors

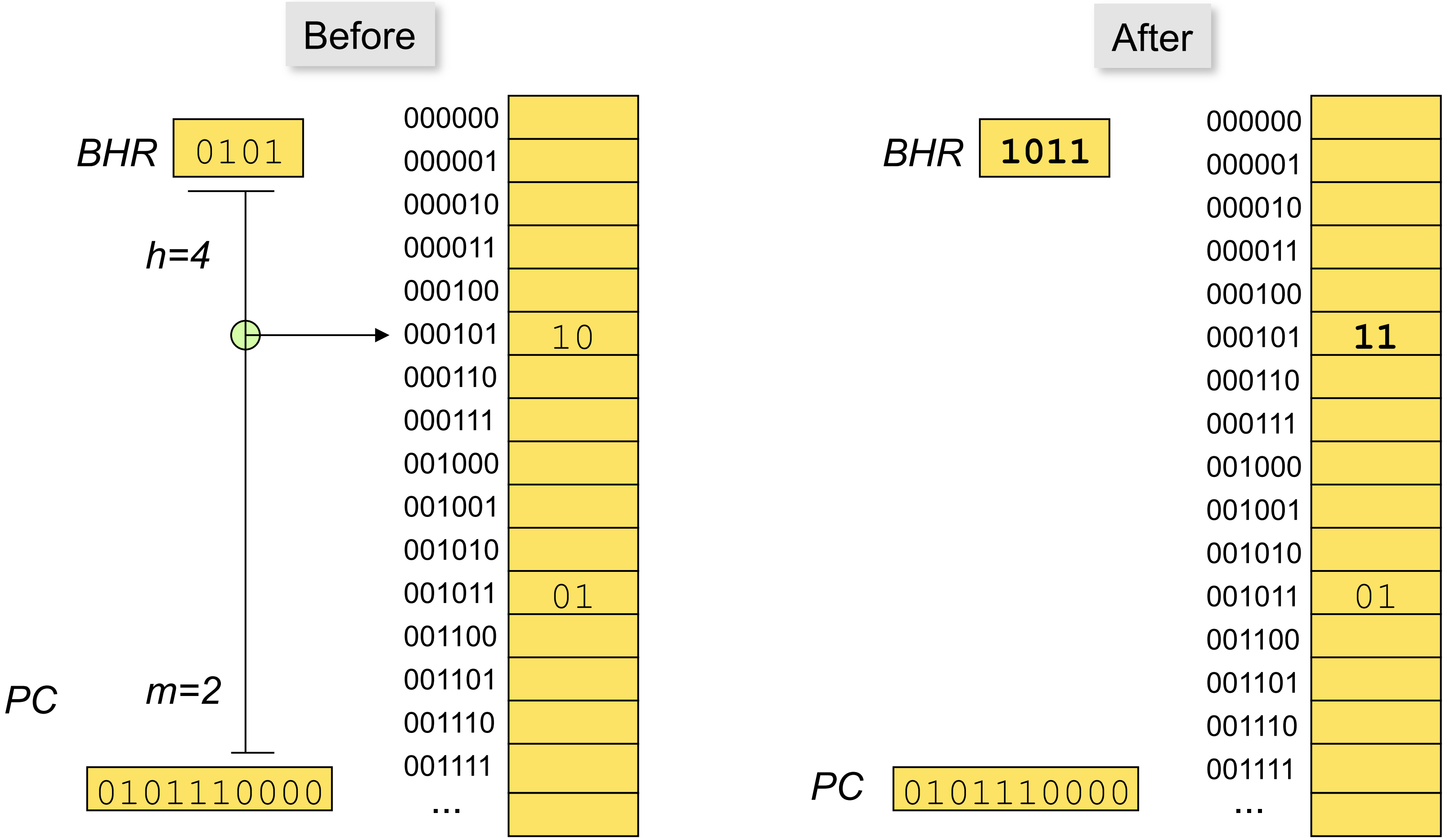
- *Correlating branch predictor*
- Uses (two levels of) branch history to make a prediction
  - Bimodal predictor uses the branch address only
  - Two-level predictors also use
    - *Local history* of that particular branch, or
    - *Global history* of all prior branches
    - history = outcome of prior branch executions
    - history acts as a shift register: newest branch outcome is inserted; oldest branch outcome is discarded
- Proposed by Tse-Yu Yeh and Yale N. Patt in 1991

… using global history



BHR contains history of the last *h* branches;
BHR is a shift register

Example



Assume: branch direction is taken

Why does this work?

- Correlation among branches
  - For example, if a particular branch is taken (not-taken), probability may be high that next branches are also taken (not-taken), or vice versa
- Concrete examples
  - Branch conditions that depend on the same variable
  - A variable is control dependent on branch; a subsequent branch is data dependent on the variable; both branches will be correlated

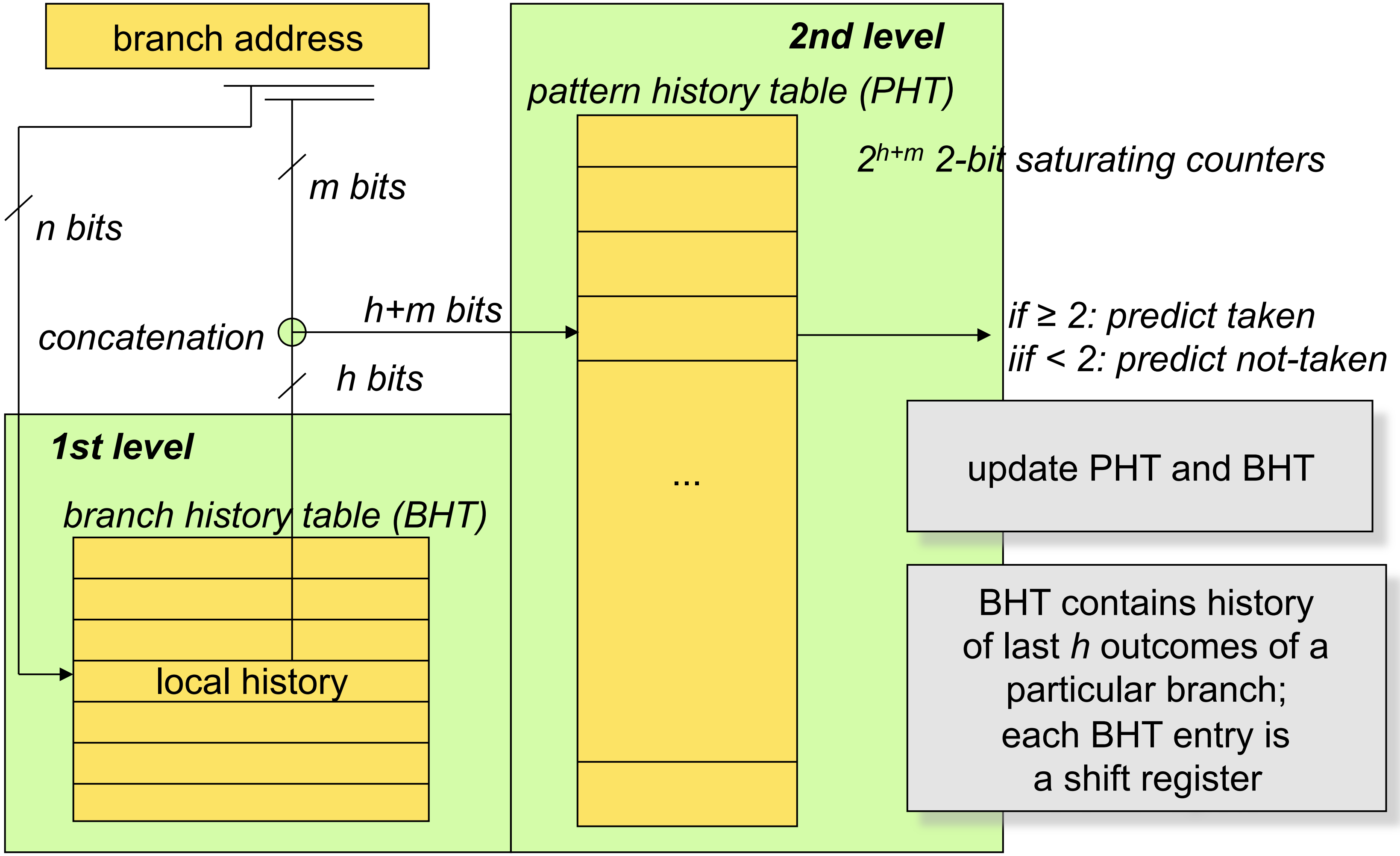
Example

```
x = 0;
if (some_condition) {
  x = 3;
}
if (another_condition) {
  y += 19;
}
if (x <= 0) {
  do_something ();
}
```

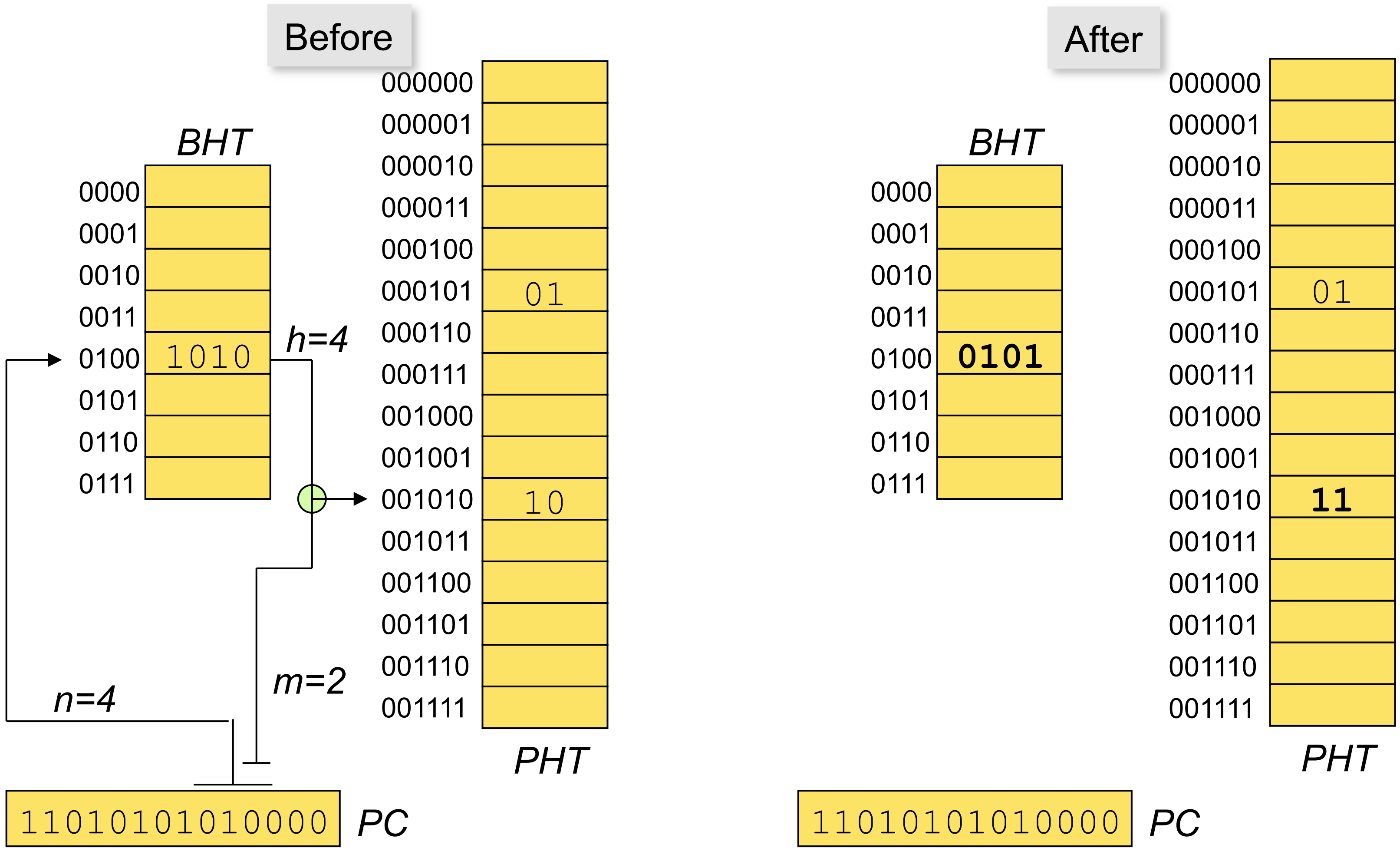
strong correlation
between 1st and 3rd branch

Note: there is no correlation between the 2nd and 3rd branch → branch prediction needs to learn!

… using local history



Example



Assume: branch direction is taken

Why does this work?

- Local behavior of a branch
- Examples
  - Alternating: 01010101…
  - Loops with limited number of iterations: 111011101110…

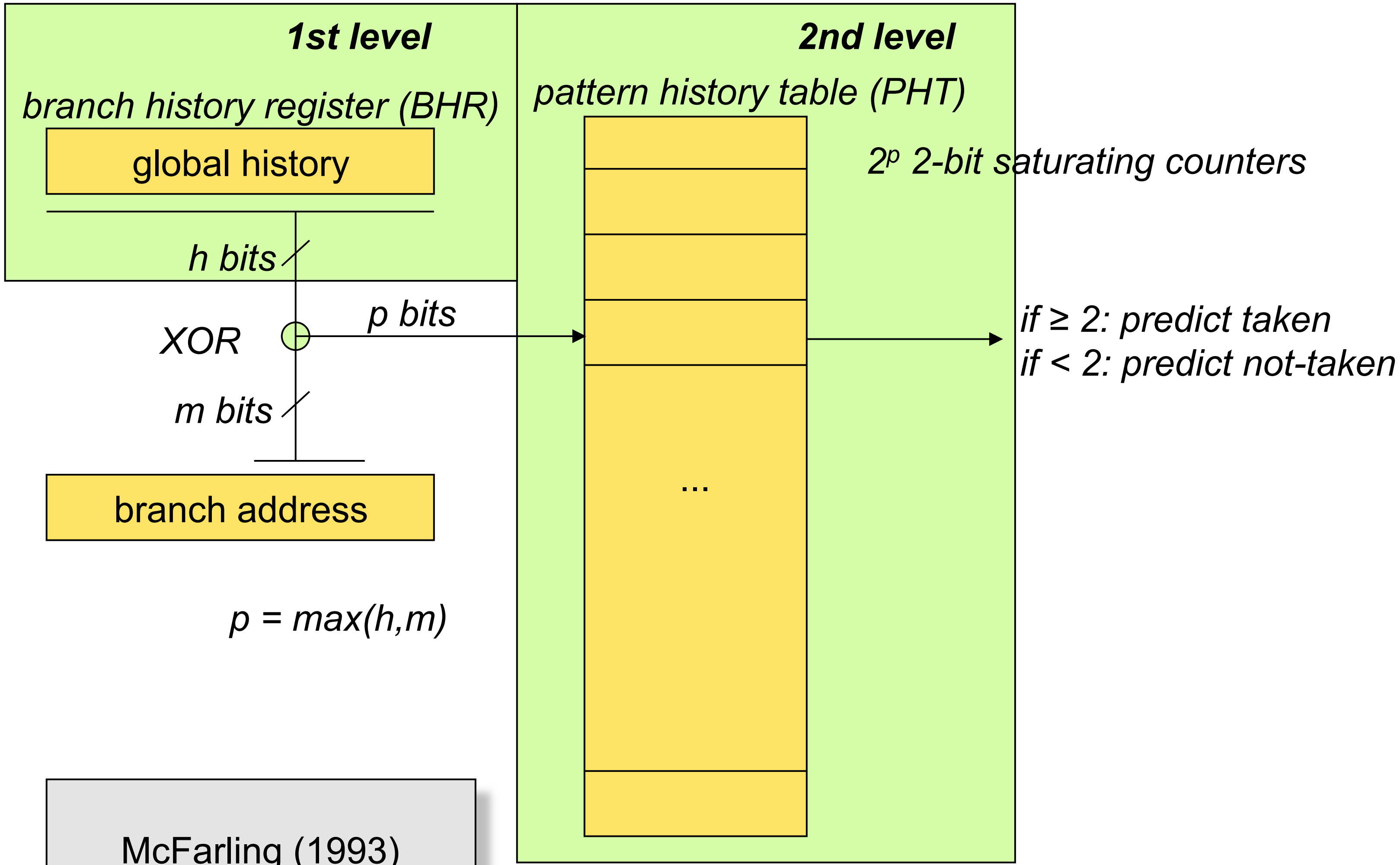
Two-level predictor implementations

- If *m=0*
  - *Global pattern history table (gPHT)*
  - All branches share the same PHT
- If *m≠0*
  - *Per-address pattern history table (pPHT)*
  - PHT is partitioned based on branch address bits
- Four variations: GAg, GAp, PAg, PAp
  - ‘G’ global history, ‘P’ per-address (local)
  - ‘A’ adaptive
  - ‘g’ → gPHT and ‘p’ → pPHT

Good configurations

- Obtained through experimental evaluation by Yeh/Patt (1991)
- GAg
  - BHR: 18 bits
  - PHT: 2^{18} x 2 bits
- PAg
  - BHT: 2^{11} x 12 bits
  - PHT: 2^{12} x 2 bits
- PAp
  - BHT: 2^{11} x 6 bits
  - PHT: 2^{9} x 2^{6} x 2 bits
- Prediction accuracy of 97%

gshare



McFarling (1993)

GAp vs. gshare

- GAp needs to make a choice
  - How many bits to concatenate from BHR vs. branch address?
  - e.g., 5 bits from BHR and 5 bits from branch address
- gshare doesn’t need to make this choice
  - e.g., 10 bits from BHR and 10 bits from branch address
  - More information is used to index the PHT

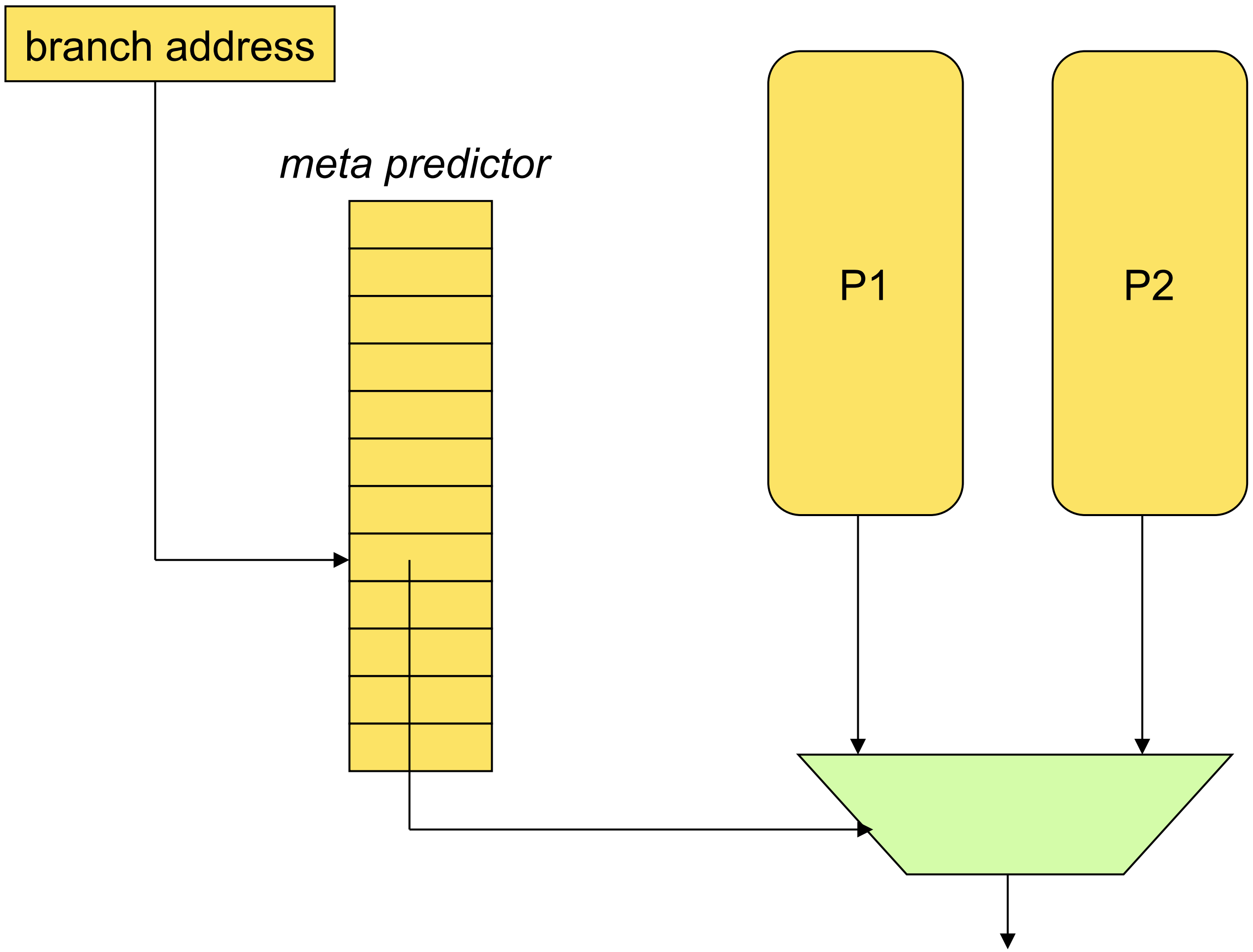
Towards hybrid branch prediction

- Reasons for mispredictions?
- Branches may be hard to predict
  - During training phase of the branch predictor, e.g., after a context switch
- Interference or aliasing
  - Mostly negative interference
    - Branch predictor is of too limited size for the number of branches
    - Hence, branches with different behavior may be mapped onto the same PHT entry
- Branch behavior doesn’t match branch predictor type

Hybrid branch prediction

- Idea: Combine different types of branch predictors and learn which one is most accurate for which branch

Tournament predictor



McFarling in 1993

Tournament predictor

- Meta predictor determines which predictor will be followed
  - If < 2 → P1; If ≥ 2 → P2
- Update meta predictor
  - If both correct or incorrect: do nothing
  - If P1 is correct and P2 incorrect: decrement
  - If P1 is incorrect and P2 is correct: increment
- Both predictors are updated
  - irrespective of whether P1 or P2 was followed

Tournament predictor (cont.)

- Various flavors exist
- Any predictor can be part of a hybrid predictor
- Indexing of meta predictor is to be chosen
- Hybrid predictor typically combines local and global history based predictors

Alpha 21264

- Hybrid predictor
  - PAg
    - 1st level: 1K 10-bit entries
    - 2nd level: 1K 3-bit saturating counters
  - GAg
    - 4K 2-bit saturating counters
    - 12-bit global history
  - Meta predictor
    - 4K 2-bit saturating counters
    - Indexed using 12-bit global history

IBM POWER4

- Hybrid predictor
  - Bimodal predictor
    - 16K 1-bit saturating counters
  - Gshare
    - 16K 1-bit saturating counters
    - 11-bit global history
  - Meta predictor
    - 16K 1-bit saturating counters
    - gshare indexing

Overview

- Branch direction prediction
  - Static
  - Dynamic

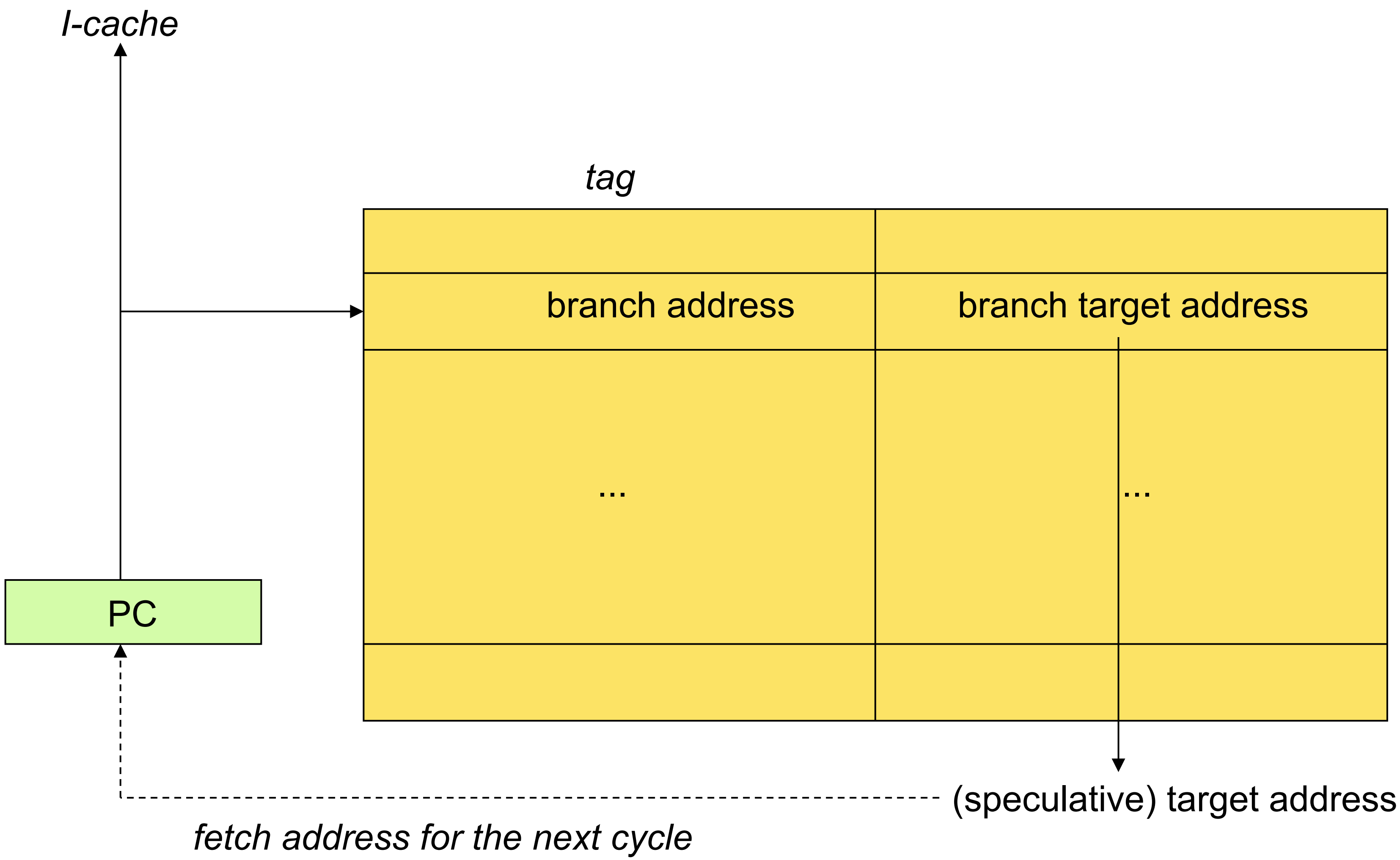
- Branch target prediction

- How to handle mispredictions?

Branch target prediction

- Branch target buffer (BTB) or Branch target address cache (BTAC)
- Small (set-associative) cache
- Idea:
  - Input = branch address
  - Output = branch target address
  - Accessed in the same cycle as the I-cache access
  - Branch target address is the fetch address in the next cycle
- Done for both conditional as well as non-conditional branches

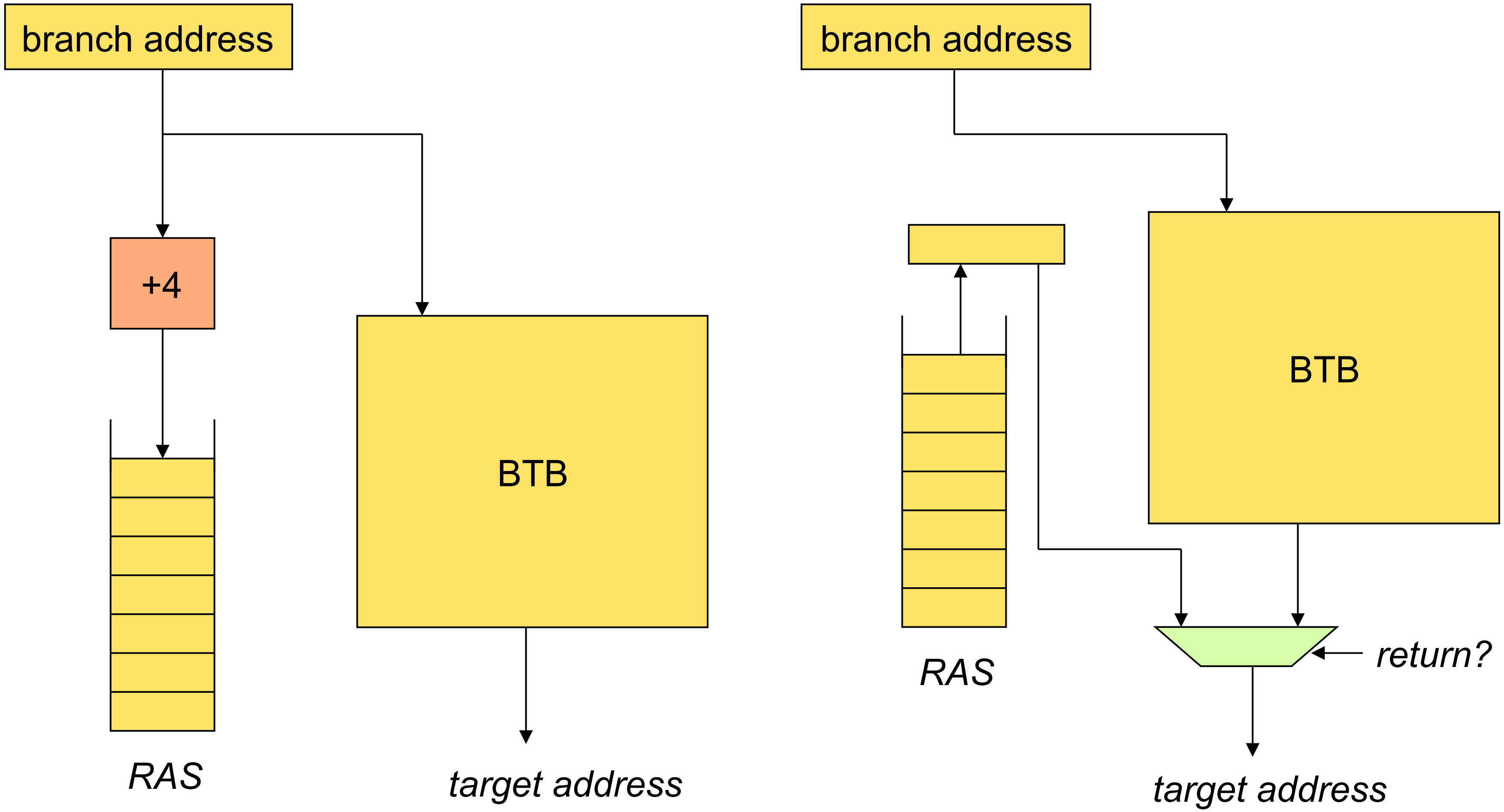
Branch Target Buffer



Return Address Stack

- Function calls are easy to predict
- Function returns are much more complicated to predict
- Solution: Return Address Stack (RAS)
  - by Kaeli and Emma in 1991
  - In Pentium 4: 16 elementen
  - Circular buffer
    - Push function return address on RAS; pop the address upon a return
    - If depth of function call stack > RAS size: incorrect predictions

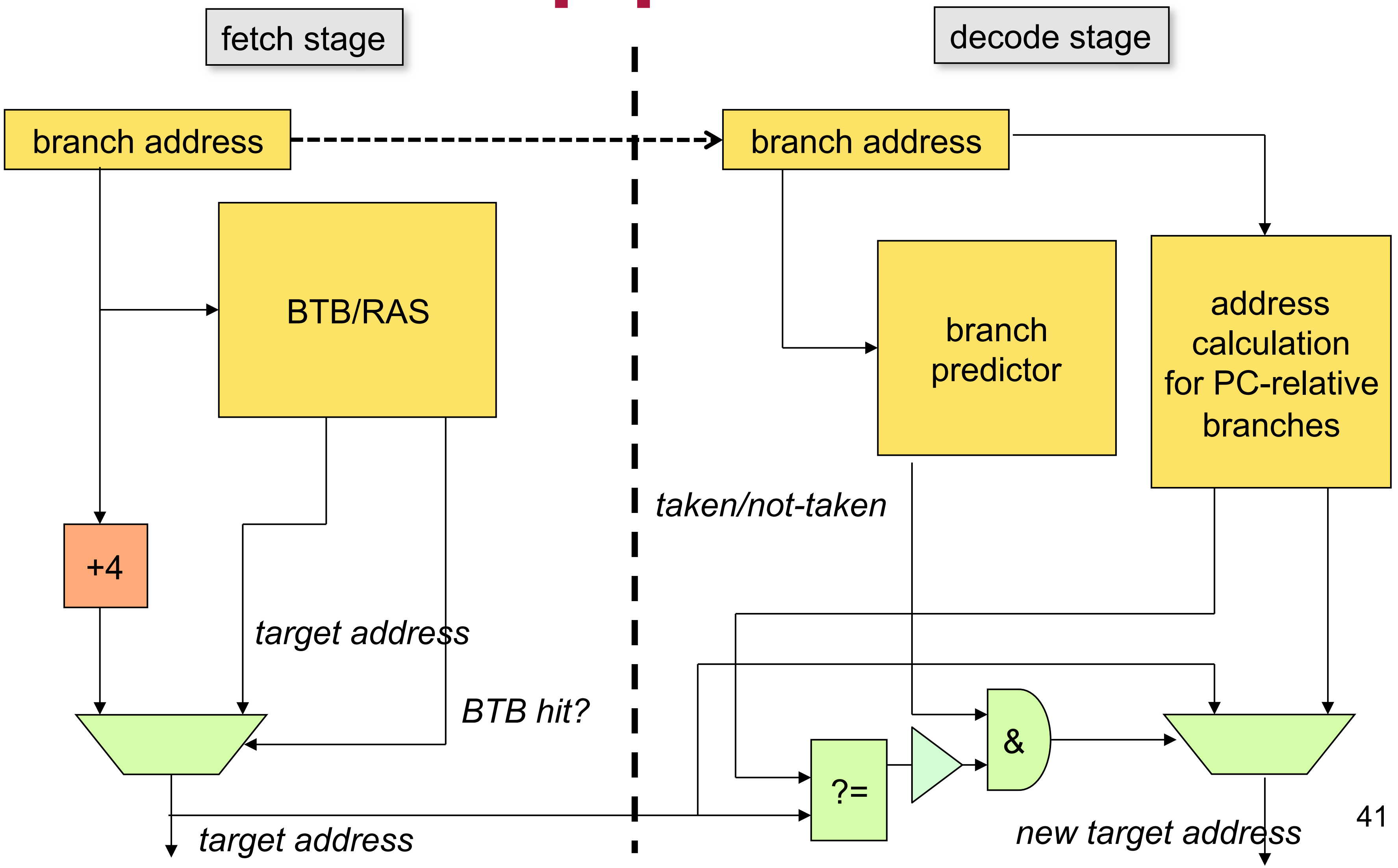
Return Address Stack



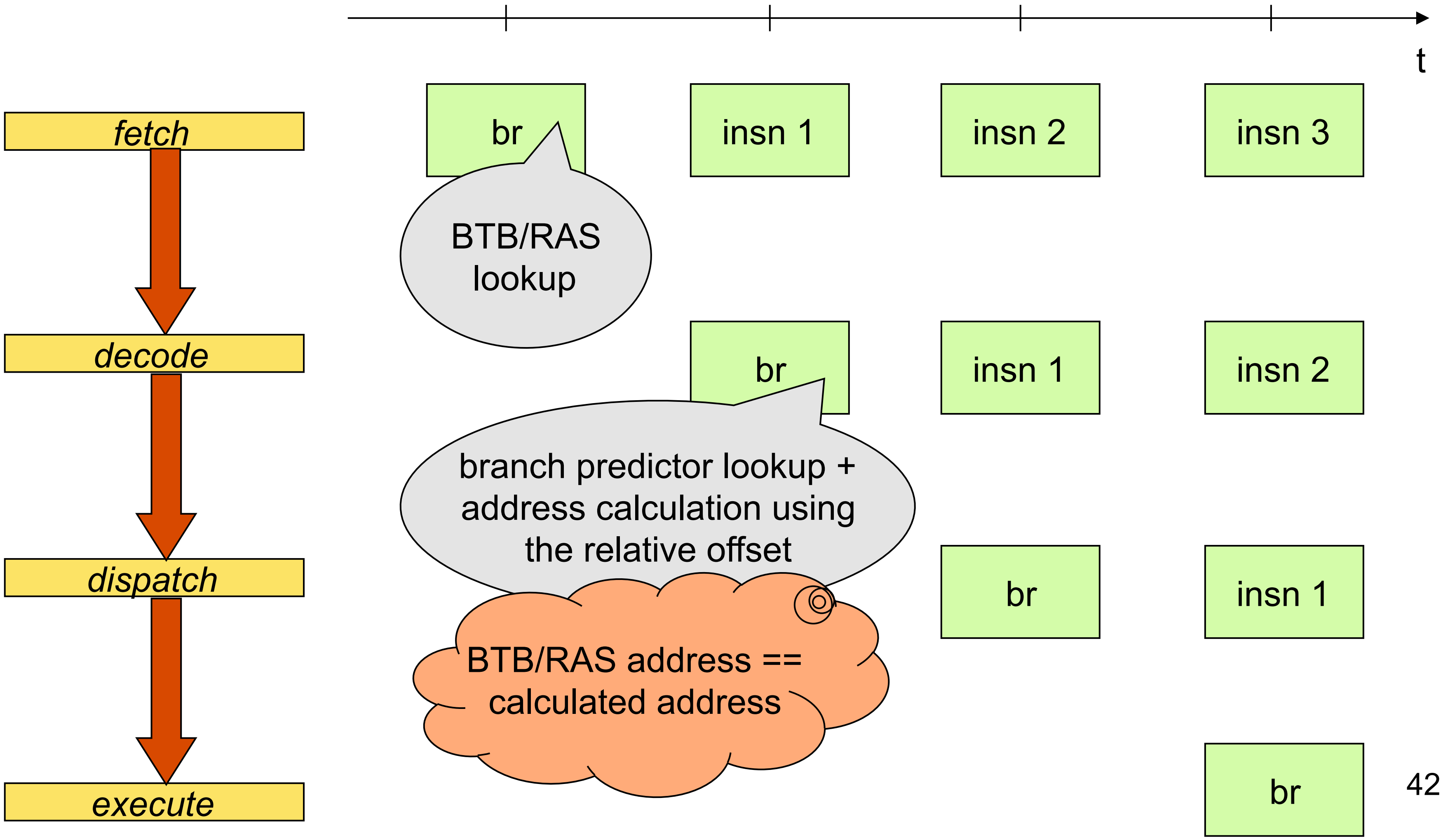
In case of a function call

In case of a return

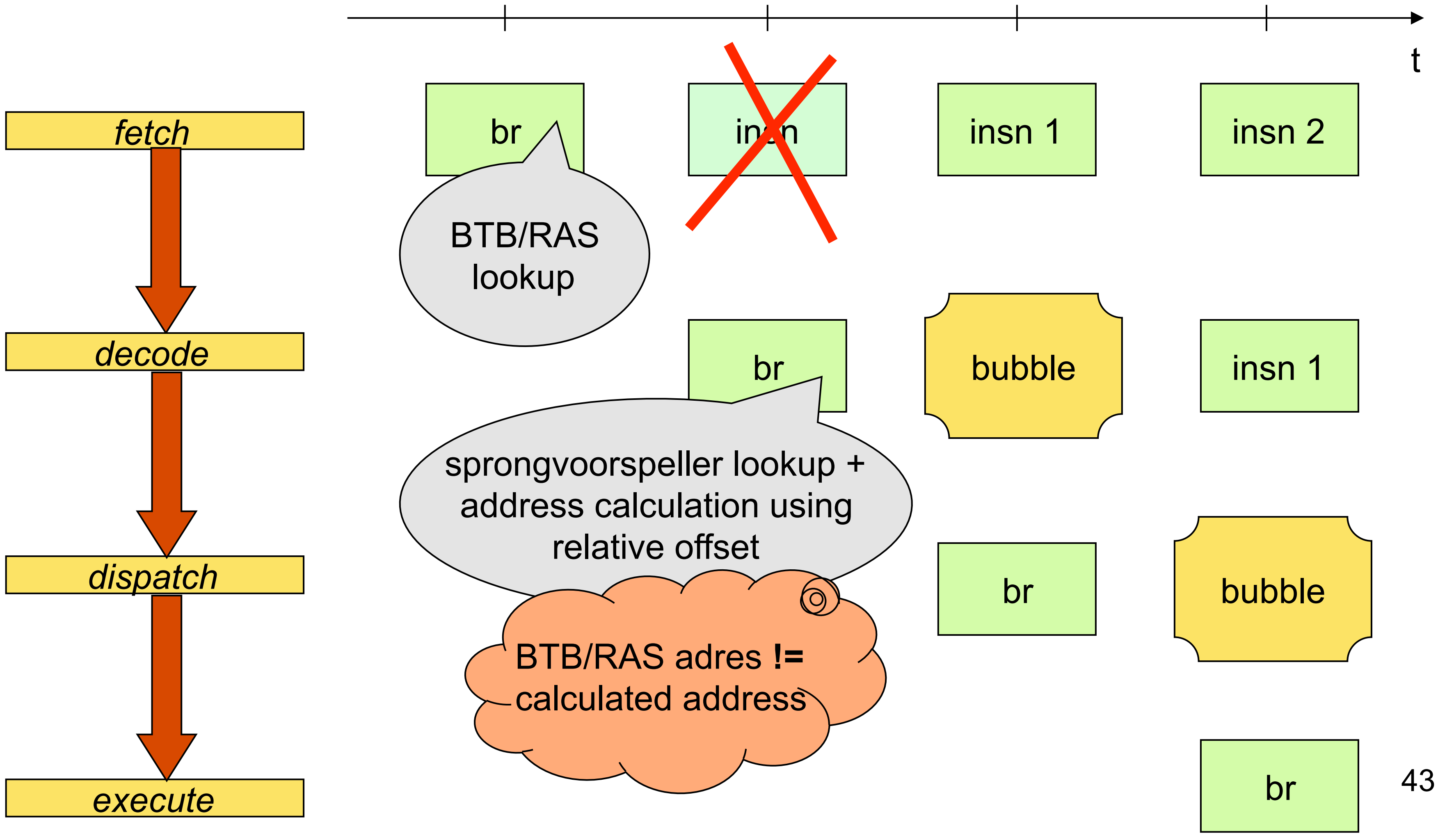
Branch prediction in the pipeline



Branch prediction predicts taken and target address is correct



Branch predictor predicts taken but target address is incorrect



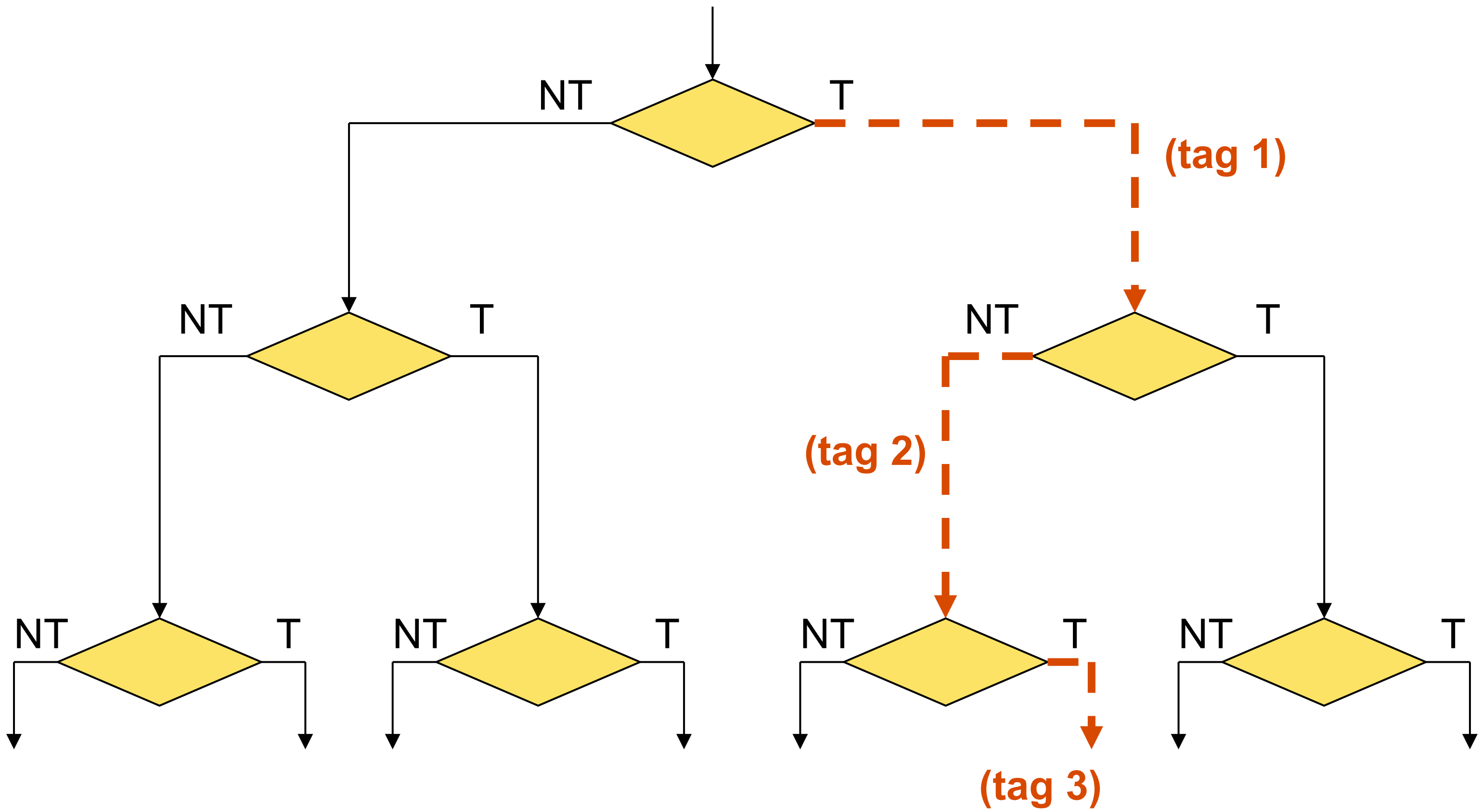
Overview

- Branch direction prediction
  - Static
  - Dynamic
- Branch target prediction
- Branch misprediction recovery

Speculative execution

- Predict branch target address and start fetching and executing instructions along the predicted path
  – no completion of speculative insns!
- There might be multiple branches in flight along the predicted path
  – tags are added

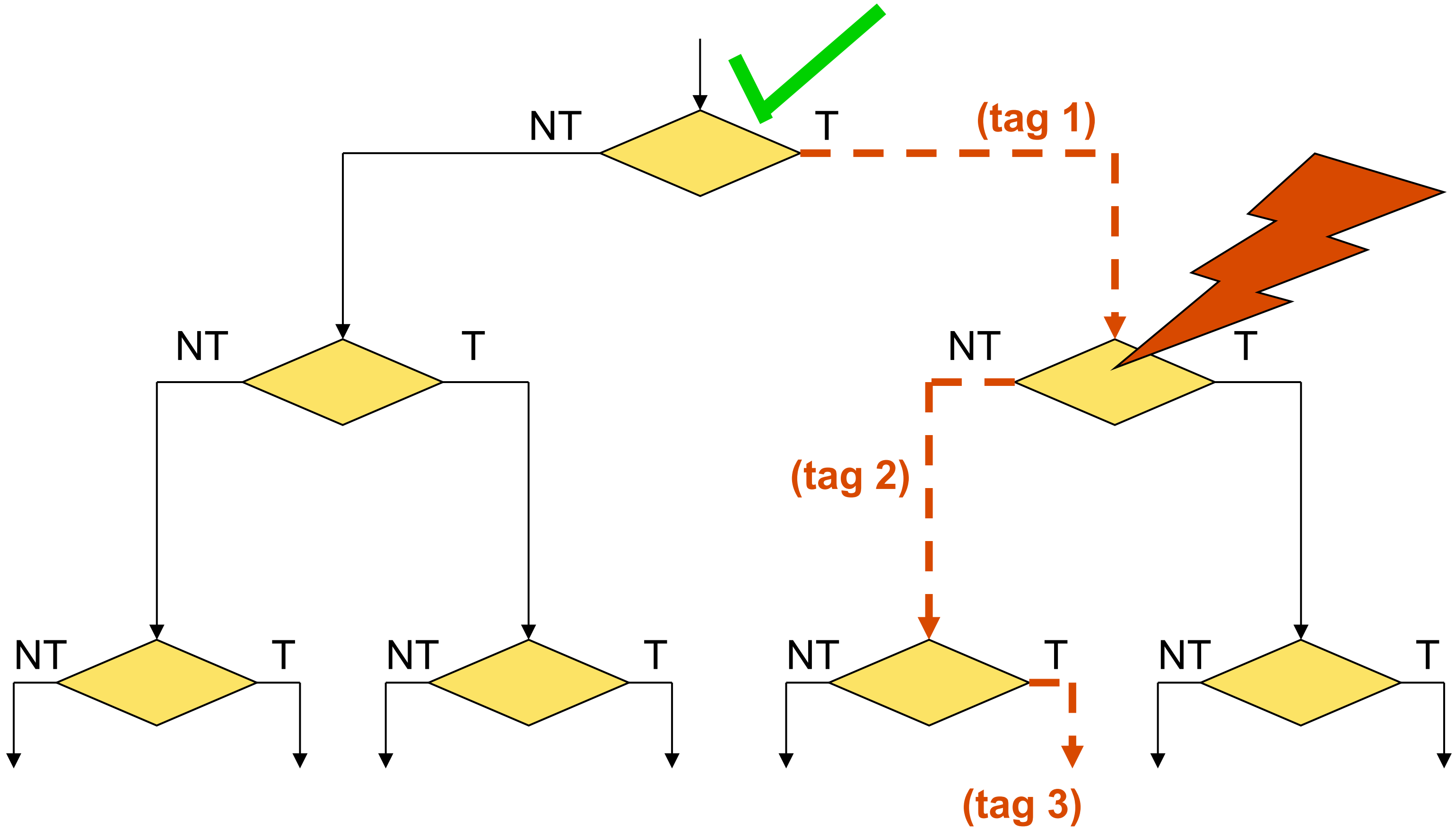
Speculative execution



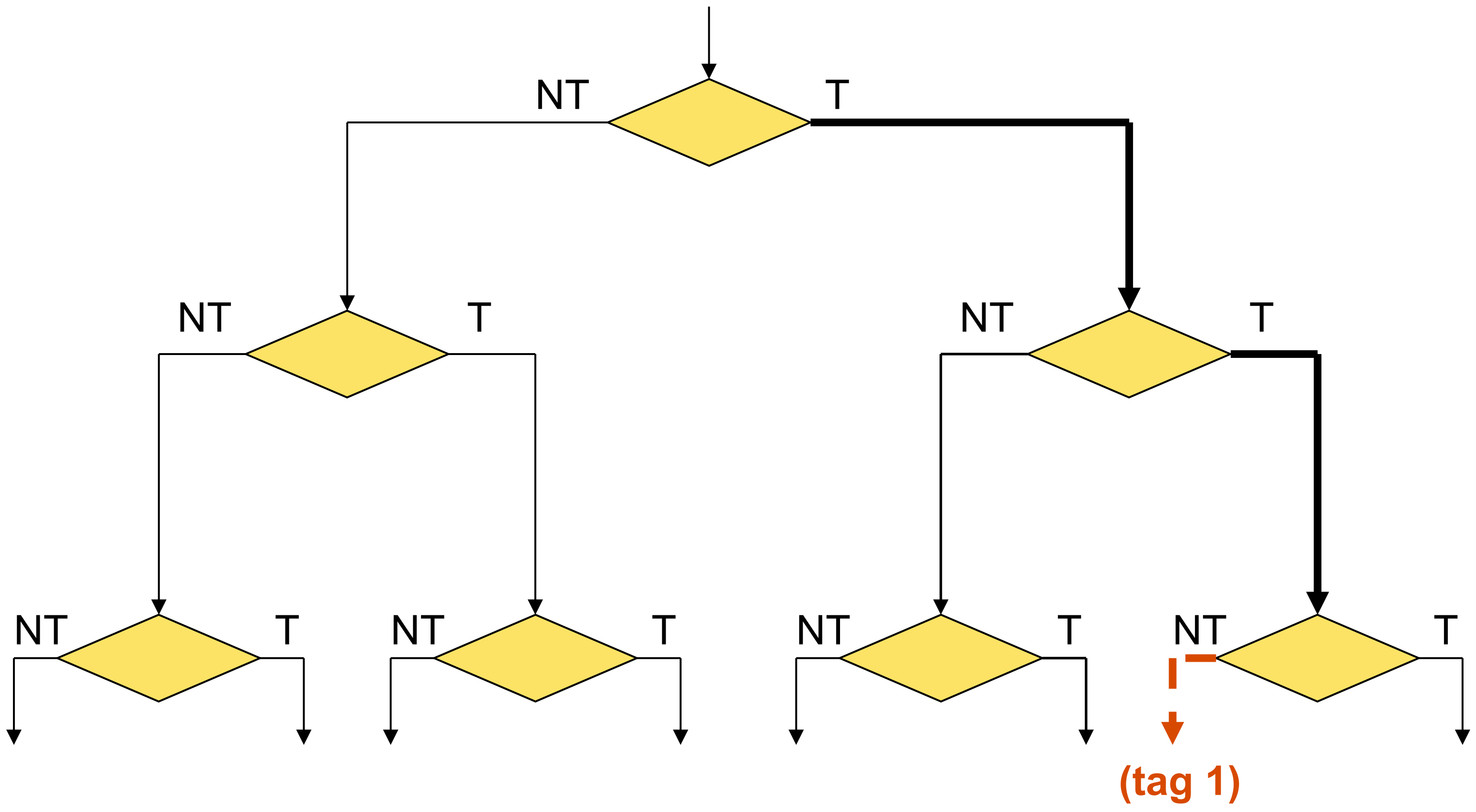
Pipeline squashing

- Branch outcome is known at execution
- If correctly predicted
  - Corresponding tags are deallocated
  - Instructions become non-speculative
- If mispredicted
  - Wrong-path instructions are nullified
  - Start fetching instructions along correct path

Speculative execution



Squash wrong-path insns and fetch insns along correct path



Literature

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“An Analysis of Correlation and Predictability: What Makes Two-Level Branch Predictors Work” –
M. Evers, S. J. Patel, R. S. Chappell, and Y. N. Patt
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