Code Generation for Branch Prediction: a review

Quinn Pham

You

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ChatGPT

As of my last knowledge update in January 2022, there might be new research papers and developments in the field of code generation for branch prediction. However, I can provide you with a list of seminal academic papers up to that point that you might consider including in a literature review on this topic:

1. **"Two-Level Adaptive Training Branch Prediction"**

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"Free Access" ACM article

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Static Branch Prediction

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- Program-based
  - Prediction made based on static analysis

Predicting Conditional Branch Directions From Previous Runs of a Program

Joseph A. Fisher and Stefan M. Freudenberger

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Can we get accurate static branch prediction by feeding information about previous runs of a program to the compiler?

Fisher & Freudenberger (1992)

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  - ie. branches that can be effectively predicted at compile-time

Improving the Accuracy of Static Branch Prediction Using Branch Correlation

Cliff Young and Michael D. Smith
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Improving Semi-static Branch Prediction by Code Replication

Andreas Krall
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A-1040 Wien
andi@mips.complang.tuwien.ac.at

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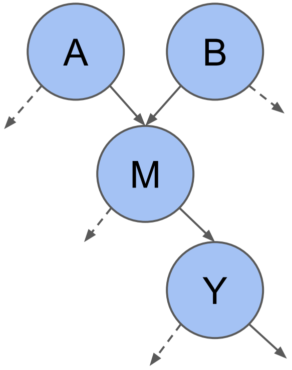

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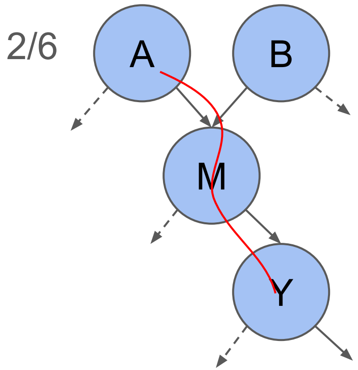

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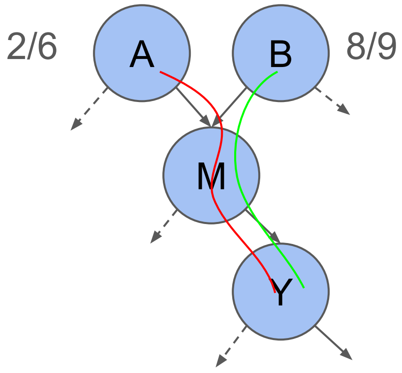

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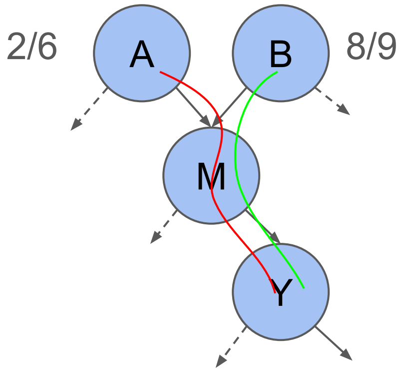

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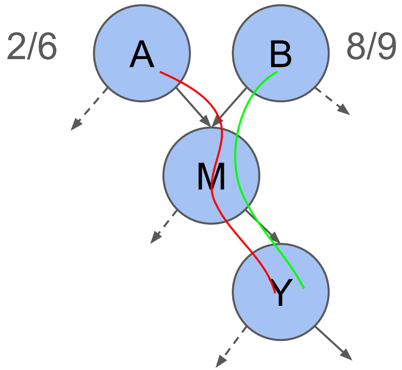

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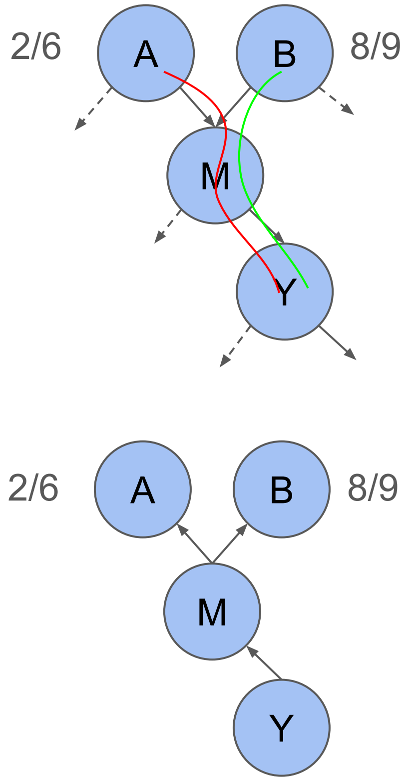

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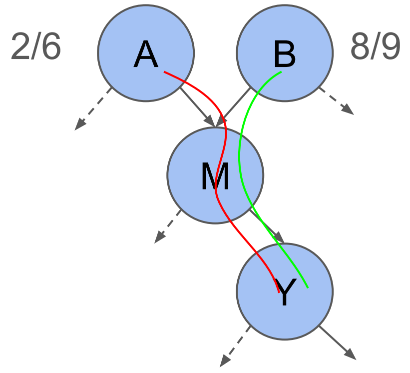

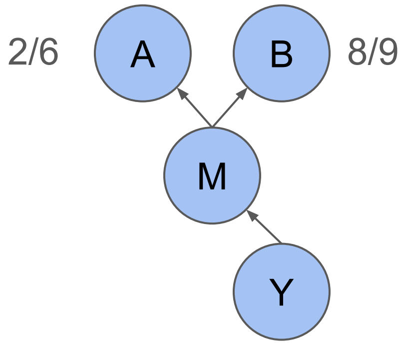

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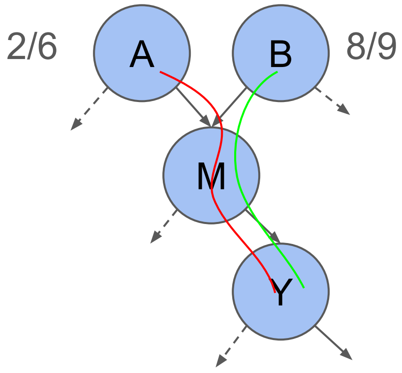

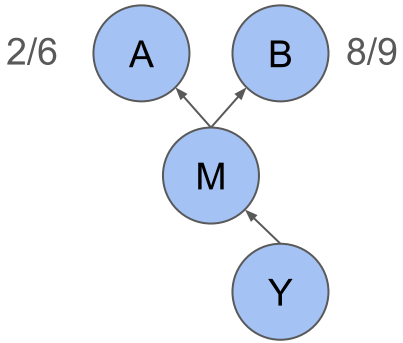

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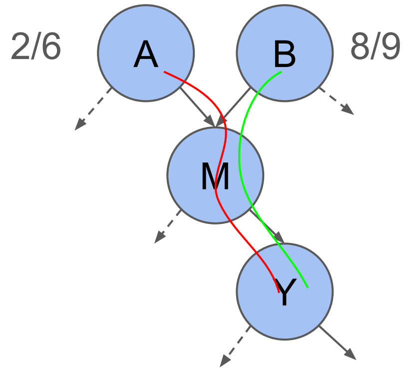

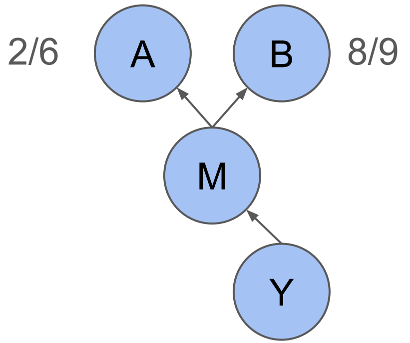

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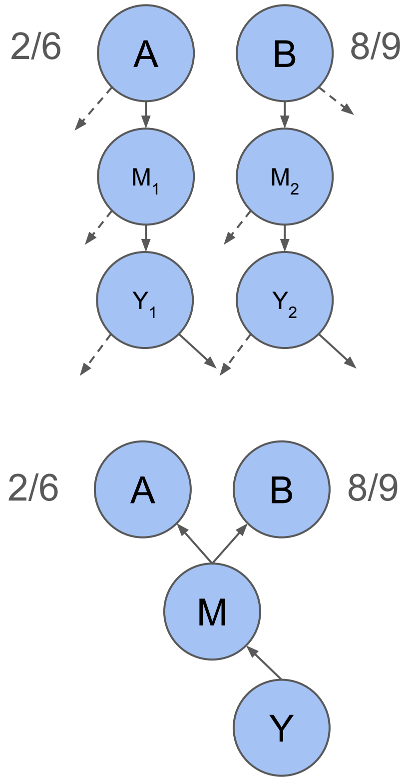

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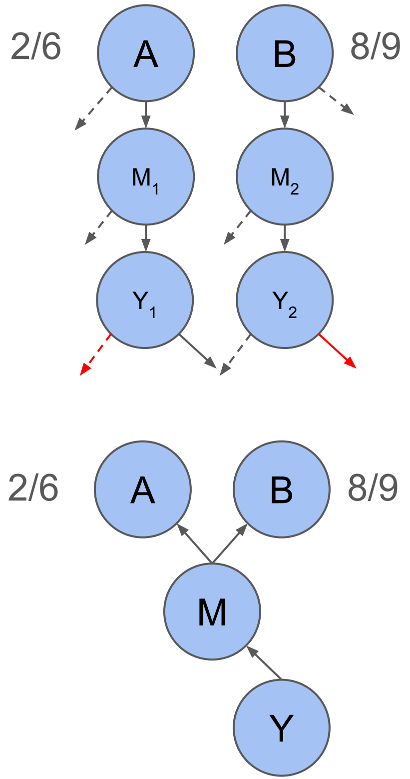

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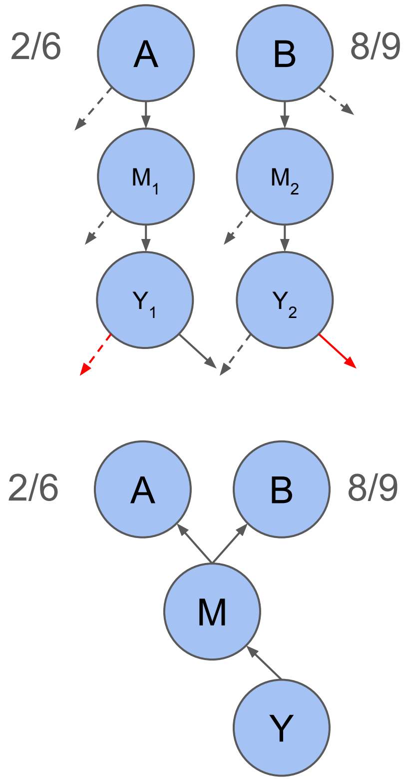

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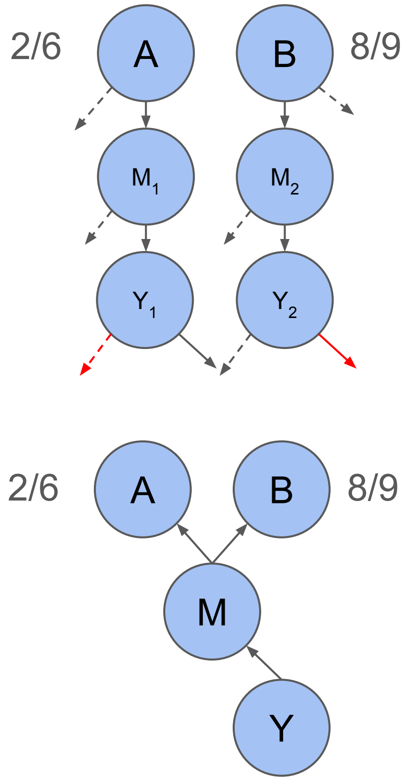

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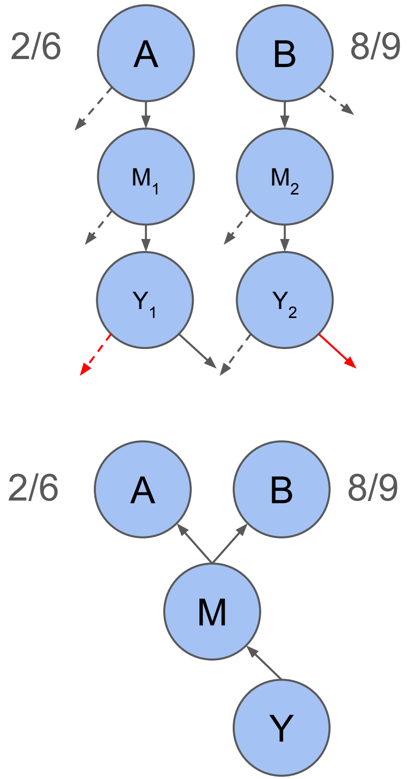

Profile Guided Code Positioning

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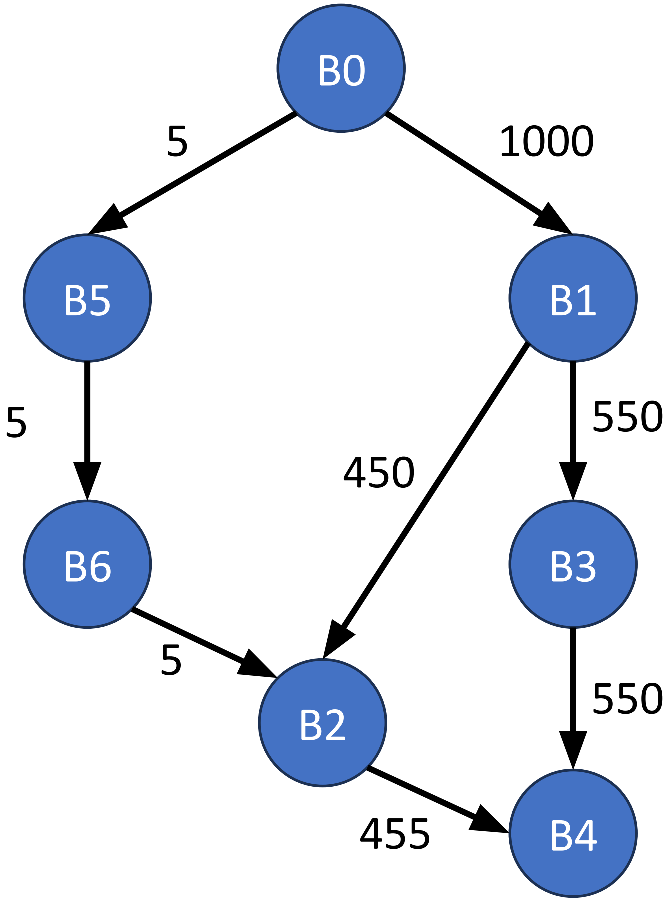

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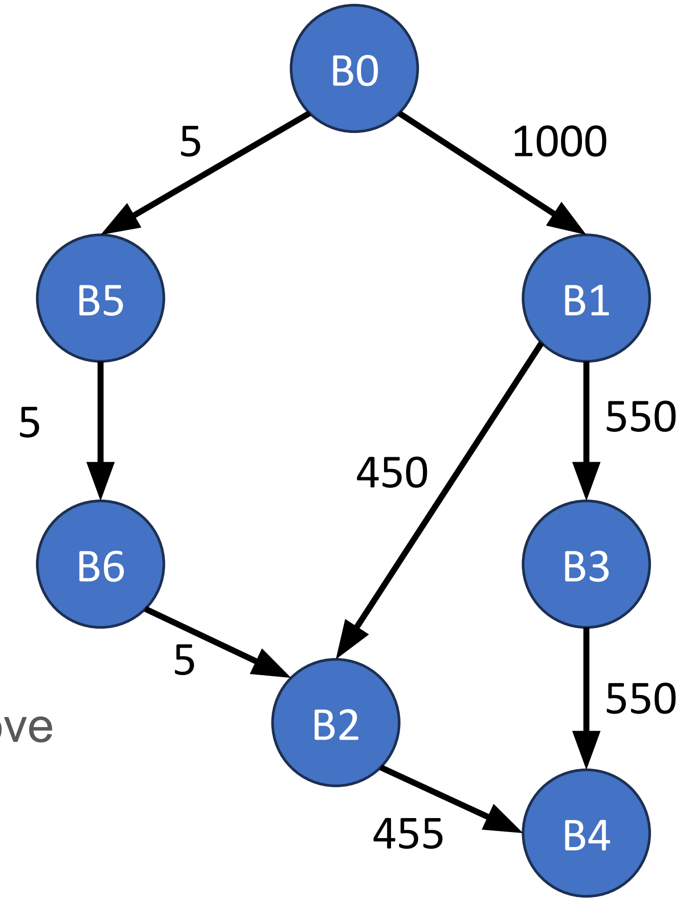

Reposition basic blocks using profile data to improve static branch prediction for a PA-RISC CPU

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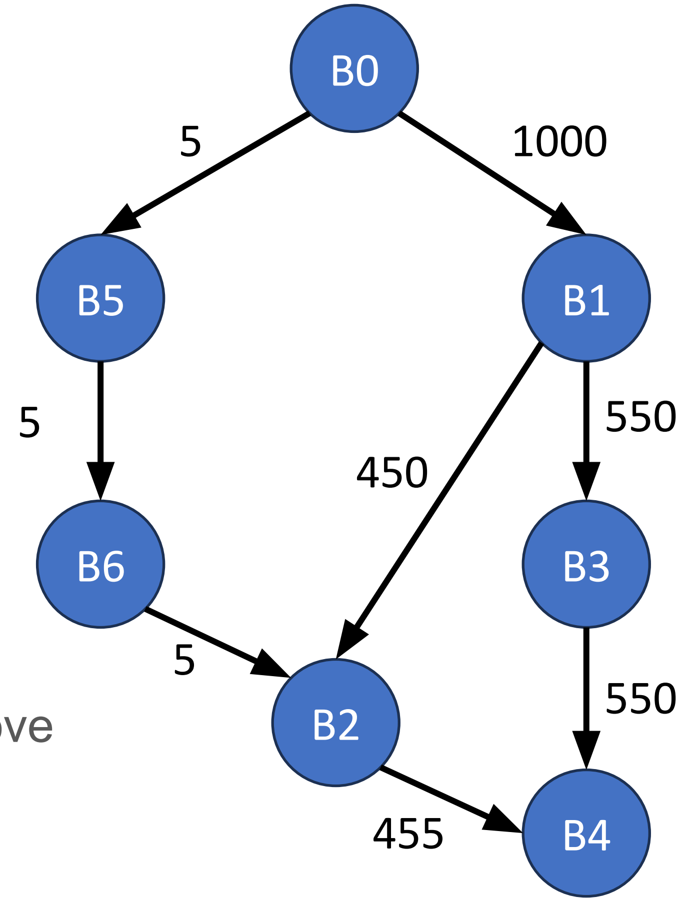

Reposition basic blocks using profile data to improve static branch prediction for a PA-RISC CPU

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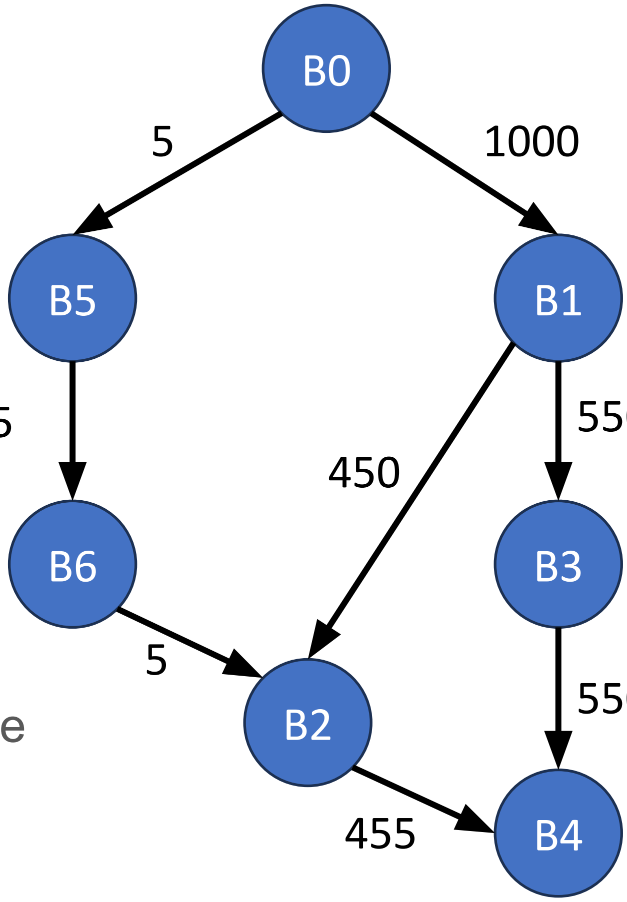

Reposition basic blocks using profile data to improve static branch prediction for a PA-RISC CPU

- Backward branches taken
- Forward branches not taken

Reducing the Cost of Branches

Scott McFarling and John Hennessy
Computer Systems Laboratory
Stanford University

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Introduces the concept of the delayed branch

McFarling & Hennessey (1986)

Delayed branch

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  - After branch / From target: must be safe to execute the instruction whether the branch is taken or not
    - Beneficial if the instruction is along the correct path
- Difficult to find safe instructions to fill the “delay” slots

McFarling & Hennessey (1986)

Delayed branch with squashing

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Delayed branch with squashing

- Use a bit to indicate the predicted direction
  - Delay slots filled by instructions from that direction
    - Squash when incorrect
- Use a bit to specify if squashing is needed on a misprediction
  - Machine does not need to squash if the compiler can fill the delay slots with safe instructions

Branch Prediction For Free

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- Program-based static branch prediction
- Uses natural loop analysis to predict loop branches

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- Program-based static branch prediction
- Uses natural loop analysis to predict loop branches
- Uses heuristics to predict non-loop branches

Ball & Larus (1993): Predicting loop branches

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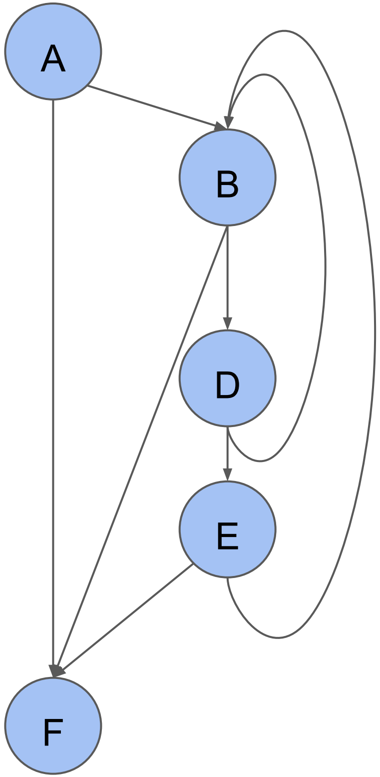
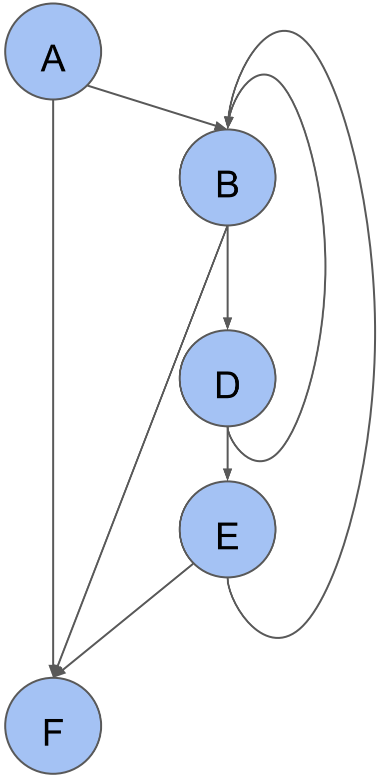


Ball & Larus (1993): Predicting loop branches

- Find back-edges and natural loops in the CFG



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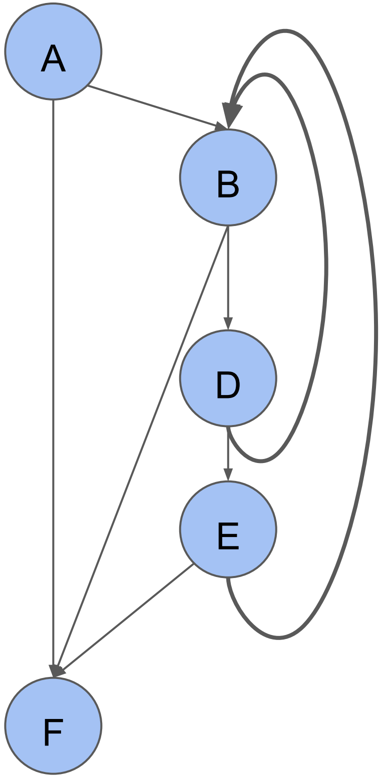

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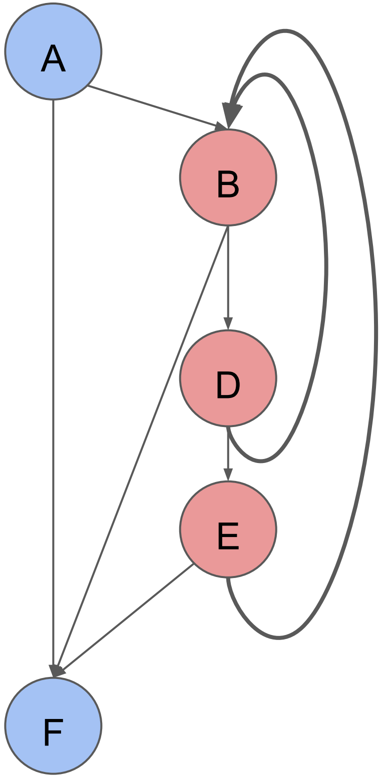

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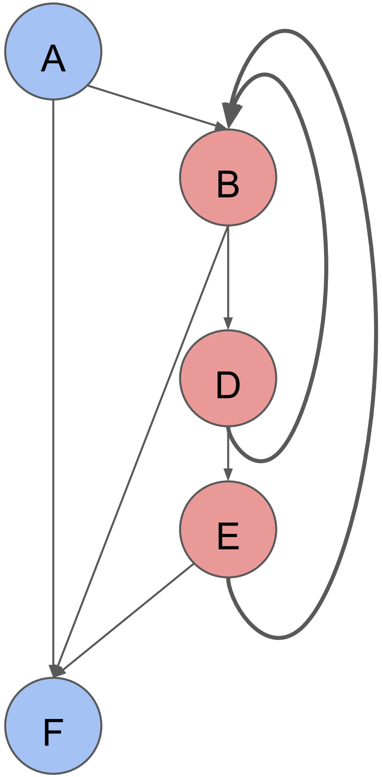

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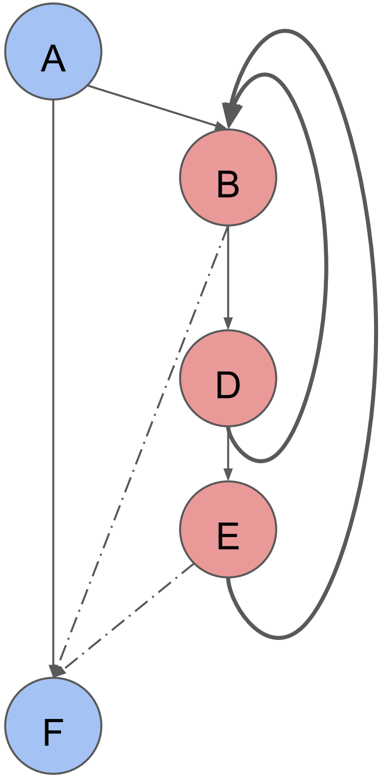

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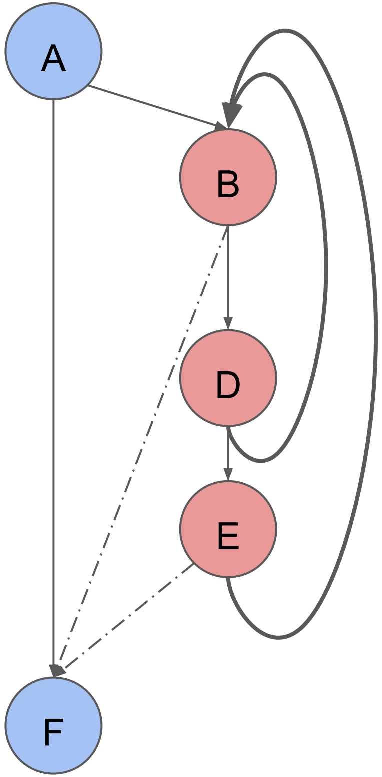

Ball & Larus (1993): Predicting loop branches

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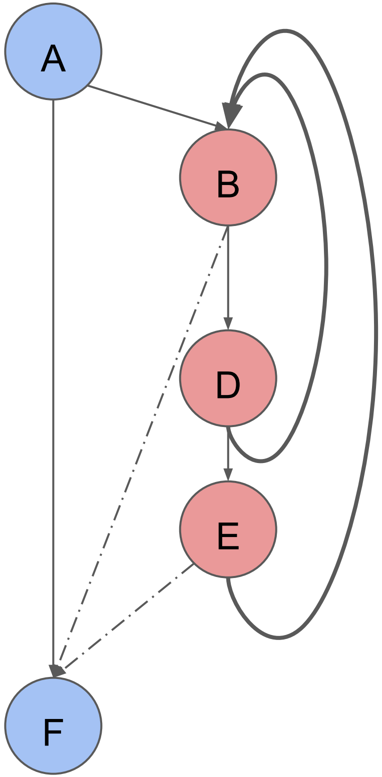
  - Either of its outgoing edges is an exit-edge or back-edge



Ball & Larus (1993): Predicting loop branches

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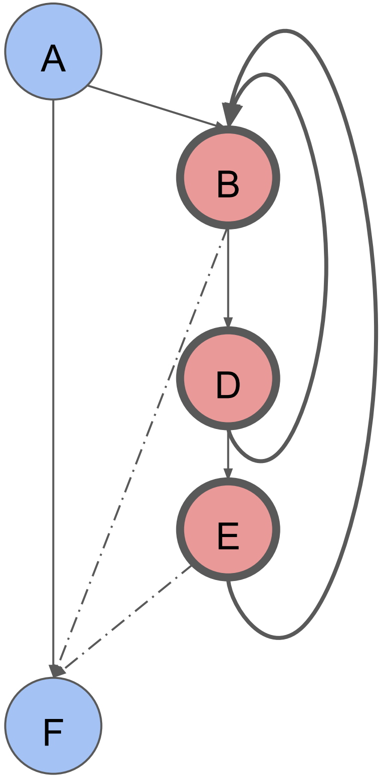

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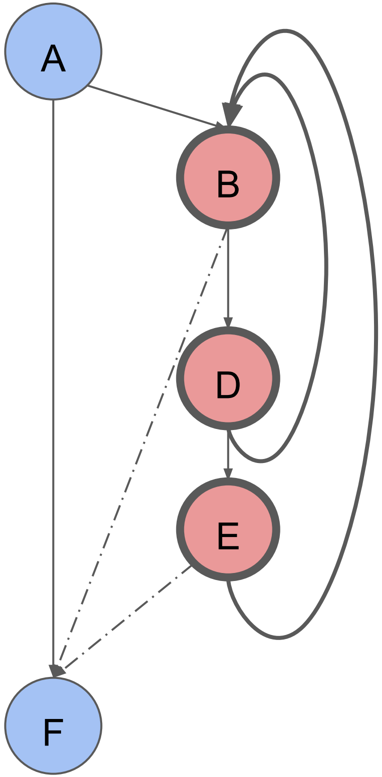

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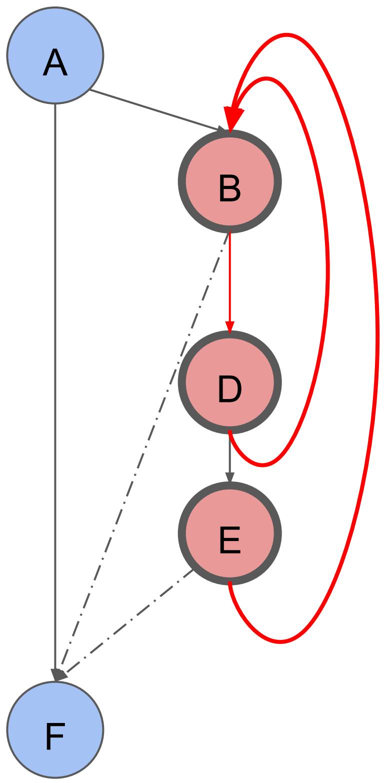

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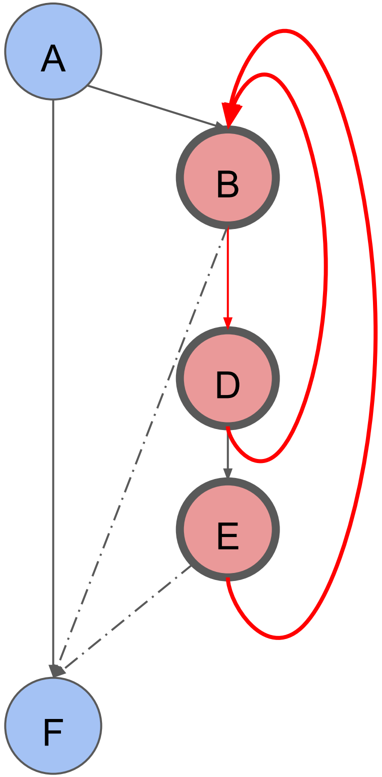

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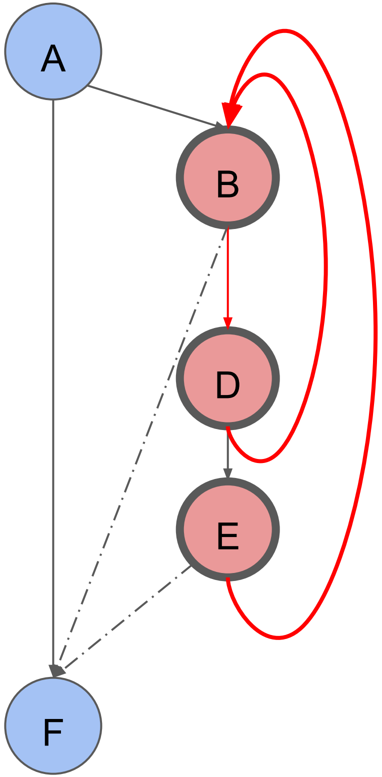

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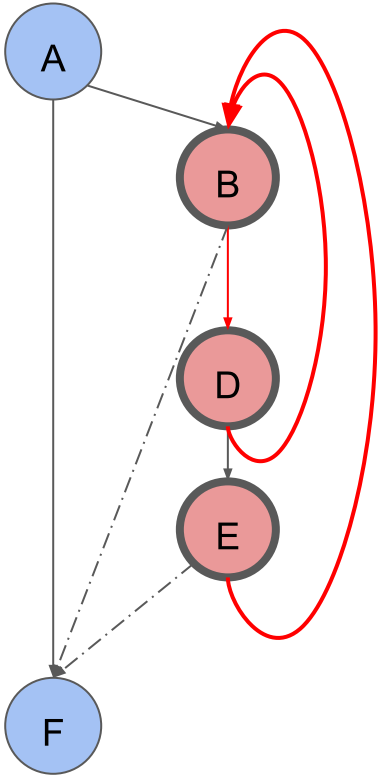

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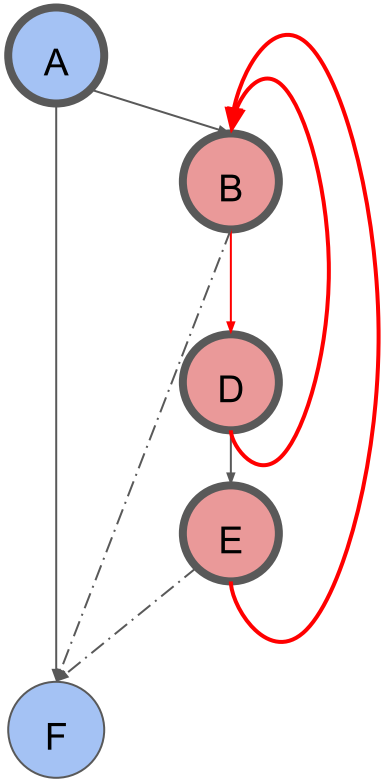

Ball & Larus (1993): Predicting non-loop branches

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Many programs use negative integers to denote error values

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Floating point numbers are rarely equal

Ball & Larus (1993): Predicting non-loop branches

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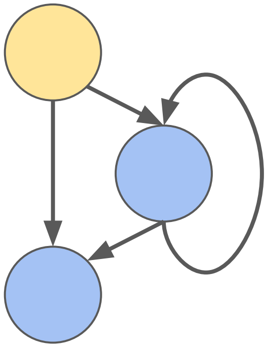

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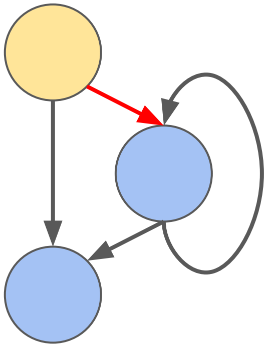

Ball & Larus (1993): Predicting non-loop branches

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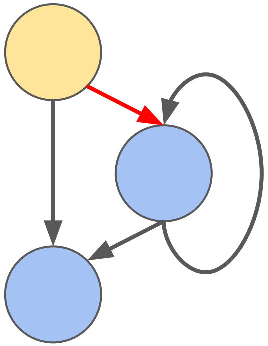
```
while(i < n) {
  …
}
```



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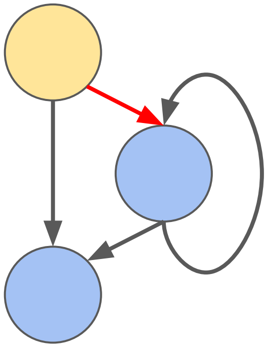

```
while(i < n) {
  …
}
```

```
  if (i >= n) goto skip
body:
  …
  if (i < n) goto body
skip:
```

Ball & Larus (1993): Predicting non-loop branches

3. Call Heuristic

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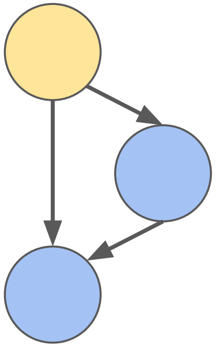

```
…
call f()
…
```

Ball & Larus (1993): Predicting non-loop branches

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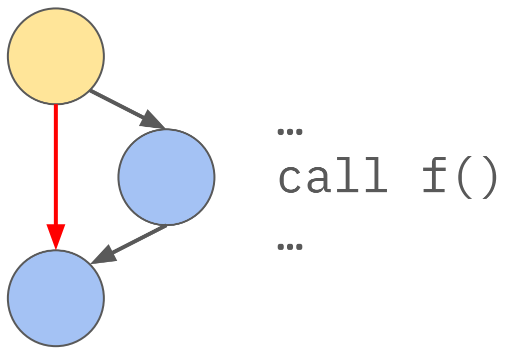

Ball & Larus (1993): Predicting non-loop branches

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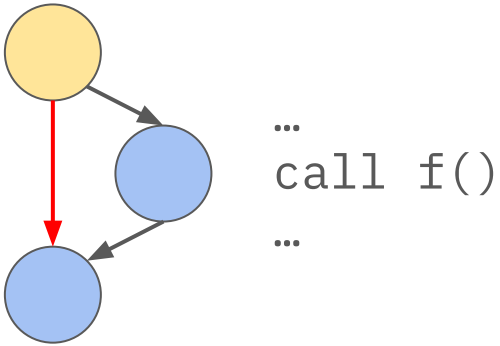

Many conditional calls are to handle rare situations

Ball & Larus (1993): Predicting non-loop branches

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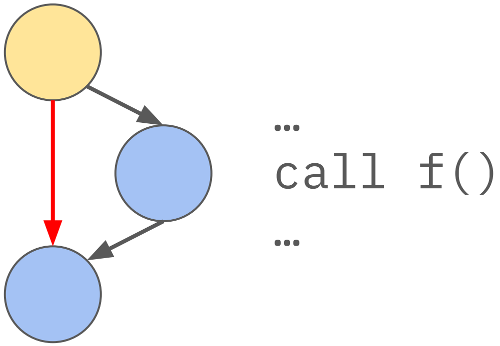

Many conditional calls are to handle rare situations

eg: printing output

Ball & Larus (1993): Predicting non-loop branches

4. Return Heuristic

Ball & Larus (1993): Predicting non-loop branches

4. Return Heuristic

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Ball & Larus (1993): Predicting non-loop branches

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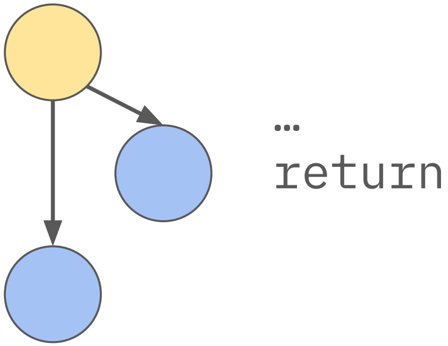

Ball & Larus (1993): Predicting non-loop branches

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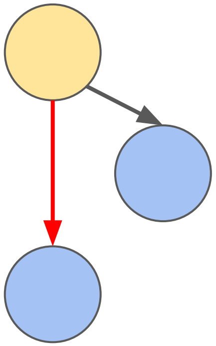

…
```
return
```

Ball & Larus (1993): Predicting non-loop branches

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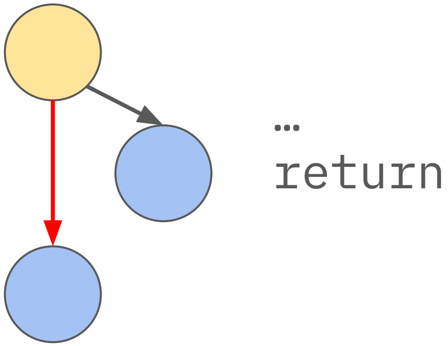
Many conditional returns handle rare situations



Ball & Larus (1993): Predicting non-loop branches

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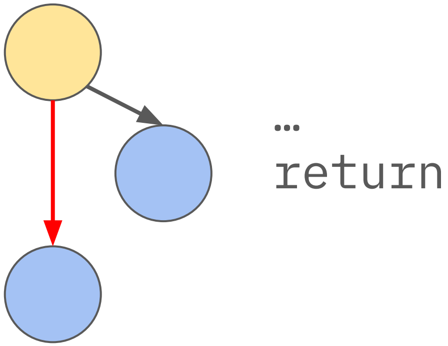

Many conditional returns handle rare situations

eg: base case in recursion

Ball & Larus (1993): Predicting non-loop branches

5. Guard Heuristic

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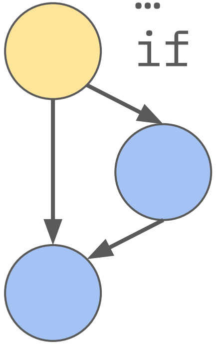
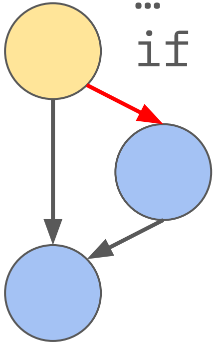


```
…
if x != 0 goto
    …
    use x
    …
```

Ball & Larus (1993): Predicting non-loop branches

5. Guard Heuristic

- Prefer branch direction to successor block that uses an operand of the branch instruction



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Ball & Larus (1993): Predicting non-loop branches

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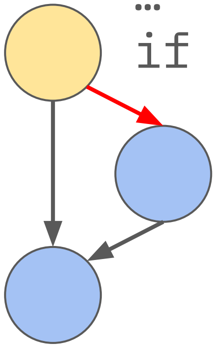
Many guard conditionals usually allow the guarded value to flow to its use



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Ball & Larus (1993): Predicting non-loop branches

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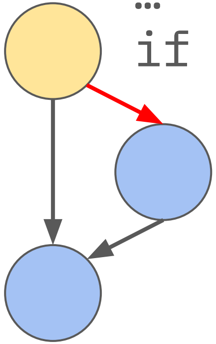

```
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```

```
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```

Many guard conditionals usually allow the guarded value to flow to its use

eg: guarding for existence

Ball & Larus (1993): Predicting non-loop branches

6. Store Heuristic

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- Prefer branch direction to successor block that does **not** contain a store instruction

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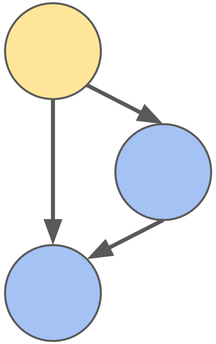

```
…
*x = 1
…
```

Ball & Larus (1993): Predicting non-loop branches

6. Store Heuristic

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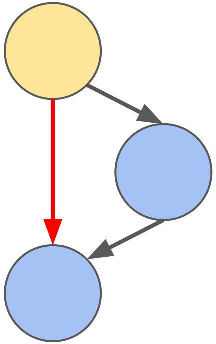

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Ball & Larus (1993): Predicting non-loop branches

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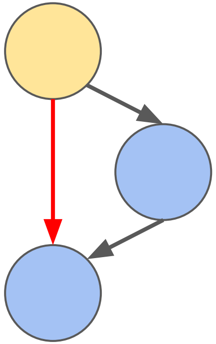
Many conditional stores are to handle rare situations



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Ball & Larus (1993): Predicting non-loop branches

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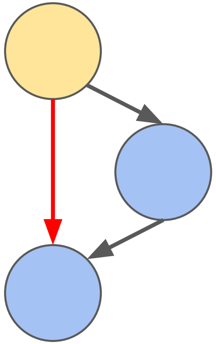

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Many conditional stores are to handle rare situations

eg: updating a maximum

Ball & Larus (1993): Predicting non-loop branches

7. Point Heuristic

Ball & Larus (1993): Predicting non-loop branches

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- Predict pointer comparisons as false

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Ball & Larus (1993): Predicting non-loop branches

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- Predict pointer comparisons as false
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Both cases are rarely true

Ball & Larus (1993): Predicting non-loop branches

1. **Opcode**
2. **Loop**
3. **Call**
4. **Return**
5. **Guard**
6. **Store**
7. **Point**

Ball & Larus (1993): Predicting non-loop branches

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Ball & Larus (1993): Predicting non-loop branches

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- How to prioritize?

Ball & Larus (1993): Predicting non-loop branches

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Dynamic Branch Prediction

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Reducing Branch Costs via Branch Alignment

Brad Calder and Dirk Grunwald

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Reducing Branch Costs via Branch Alignment

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- Use PH's algorithm to minimize the number of taken branches by placing the hot path in a straight line of fall through execution

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- Use PH’s algorithm to minimize the number of taken branches by placing the hot path in a straight line of fall through execution
- Show that branch alignment improves dynamic branch prediction accuracy

Code Placement for Improving Dynamic Branch Prediction Accuracy

Daniel A. Jiménez

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Jiménez (2005)

- Introduces PHT Partitioning

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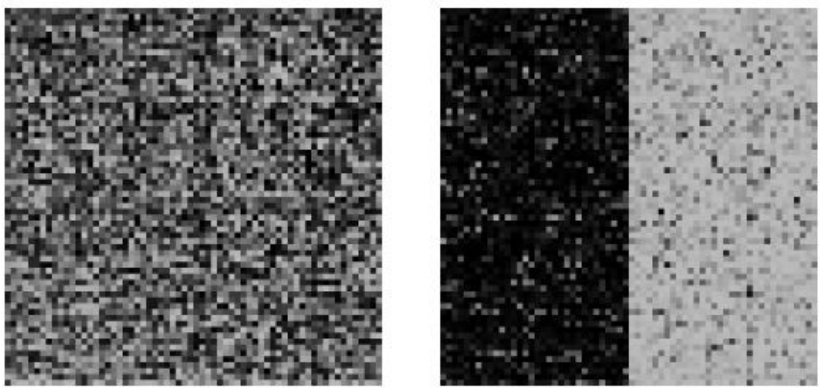

Figure 1. Average PHT entries before and after compiler-based alignment.

Branchless Code Generation for Modern Processor Architectures

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No need to predict a branch that isn’t there

Angelou et al. (2021)

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- Remove branches in a program using code transformations

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$$result = condition \times case\_true + \neg condition \times case\_false$$

$$mask(c) = integer(\neg c) - 1$$

$$result = (mask(c) \wedge value1) \vee (mask(\neg c) \wedge value2)$$

Angelou et al. (2021)

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- Remove branches in a program using code transformations
  - Use the condition as the data or as a mask to generate the desired data
  - May be able to remove unpredictable branches
- 3 methods
  - Multiplication and addition
    - Very slow
  - BitMasking
    - Slow
  - Conditional move and predication

$$result = condition \times case\_true + \neg condition \times case\_false$$

$$mask(c) = integer(\neg c) - 1$$

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Thank you :)

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