ILP: CONTROL FLOW

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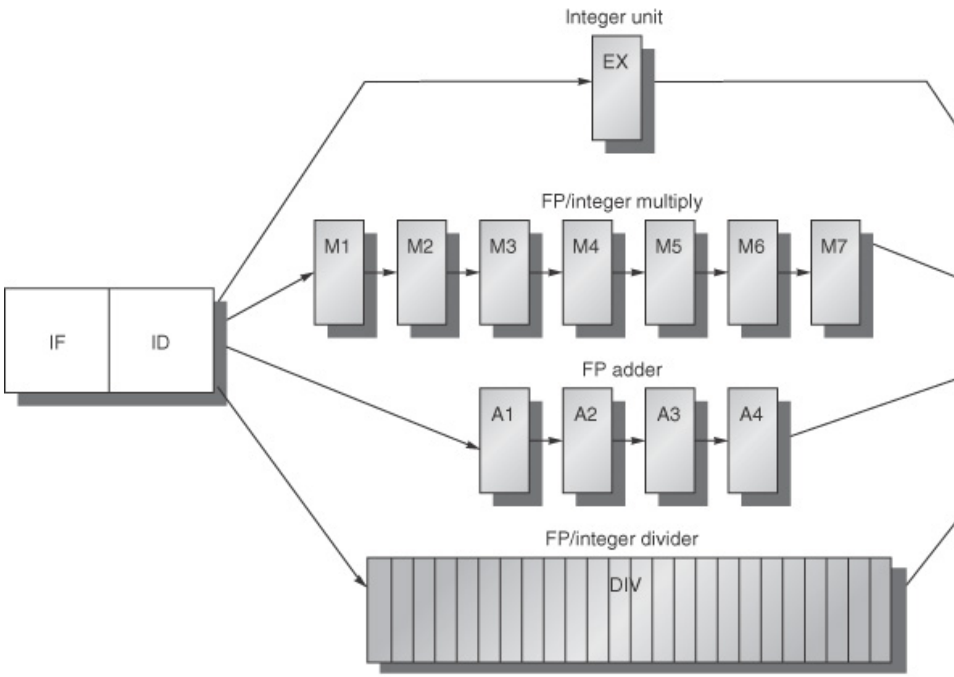
Overview

- Announcement
  - Homework 2 is due tonight (11:59PM)

- This lecture
  - Performance bottleneck
  - Program flow
  - Branch instructions
  - Branch prediction

Performance Bottleneck

- Key performance limitation
  - Number of instructions fetched per second is limited



Performance Bottleneck

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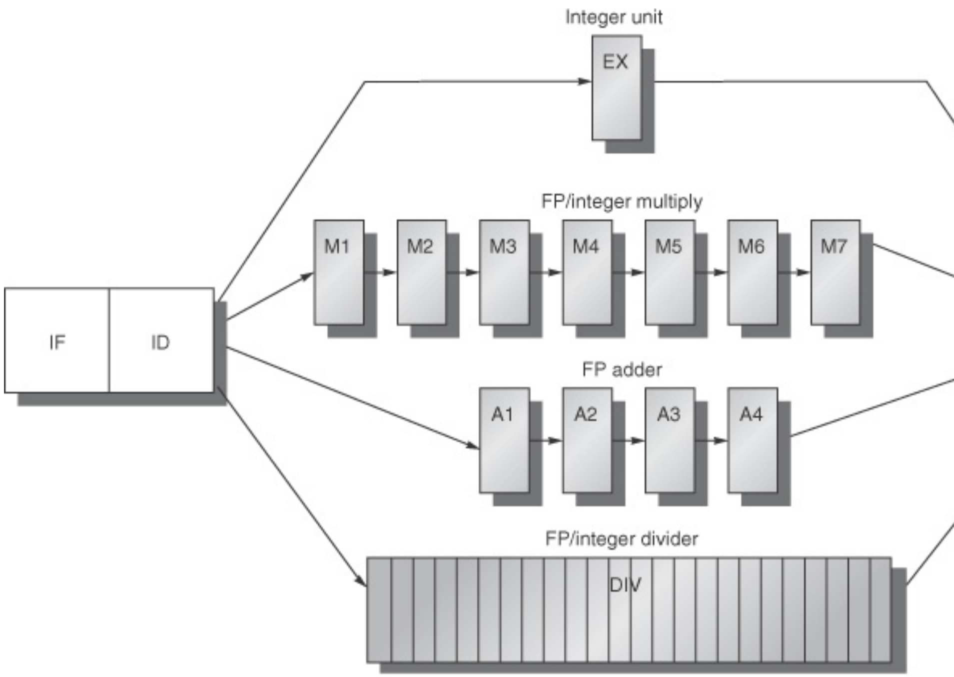
- How to increase fetch performance?



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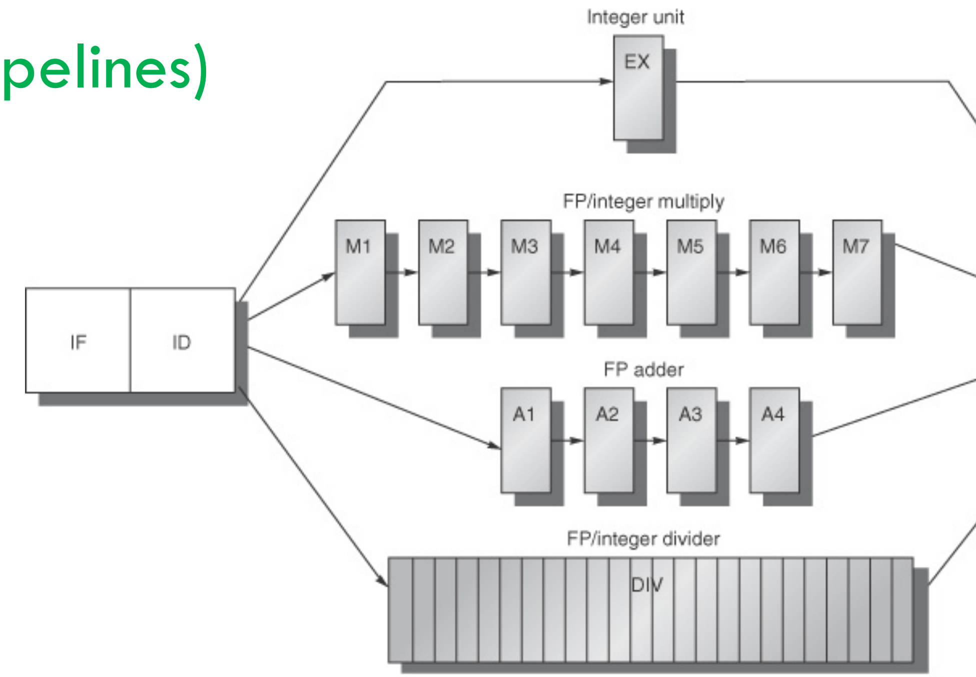
  - Wider fetch (multiple pipelines)



Performance Bottleneck

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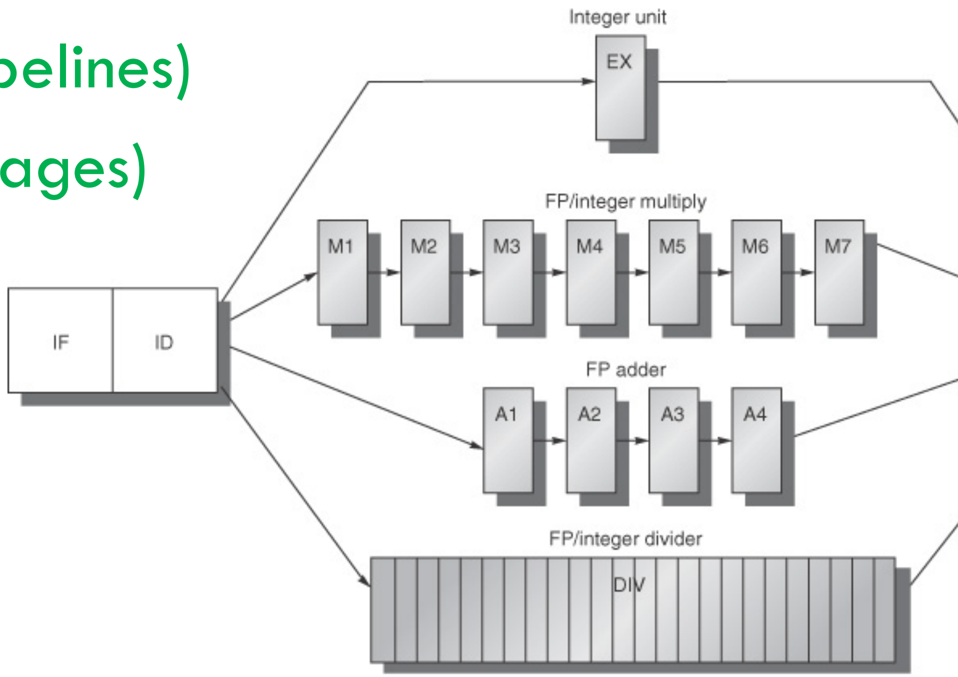
  - Wider fetch (multiple pipelines)
  - Deeper fetch (multiple stages)



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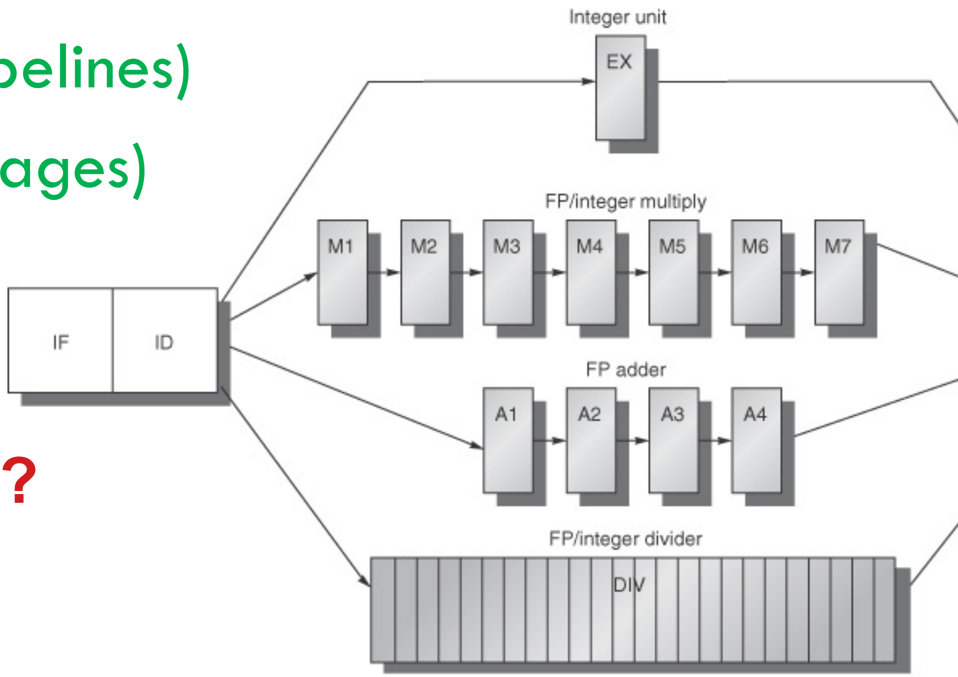

How to handle branches?

Impact of Branches

- Example C code
  - No structural hazards
  - What is fetch rate (IPS)?

```
do {
    sum = sum + i;
    i = i – 1;
} while(i != j);
```

Impact of Branches

- Example C code
  - No structural hazards
  - What is fetch rate (IPS)?

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do {
    sum = sum + i;
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```

- Five-stage pipeline
  - Cycle time = 10ns

Assembly code:

```
Loop:  ADD   R1, R1, R2
       ADDI  R2, R2, #-1
       BNEQ  R2, R0, Loop
       stall
```

Impact of Branches

- Example C code
  - No structural hazards
  - What is fetch rate (IPS)?

```
do {
    sum = sum + i;
    i = i – 1;
} while(i != j);
```

- Ten-stage pipeline
  - Cycle time = 5ns

Assembly code:

```
Loop:  ADD   R1, R1, R2
       ADDI  R2, R2, #-1
       BNEQ  R2, R0, Loop
       stall
       stall
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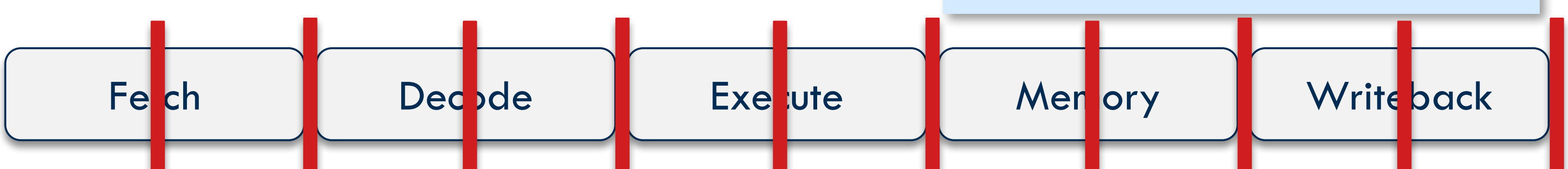
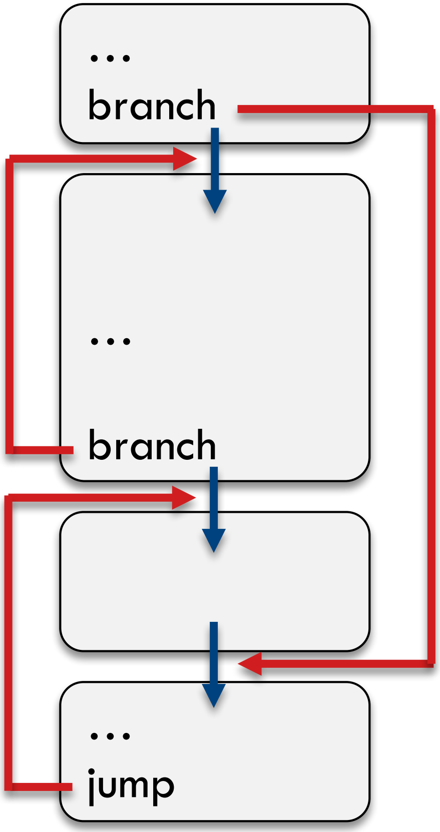
```



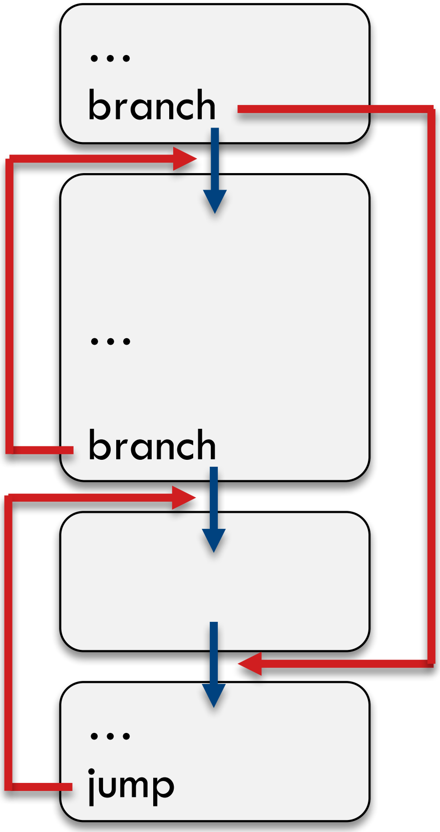
Program Flow

- A program contains basic blocks
  - Only one entry and one exit point per basic block



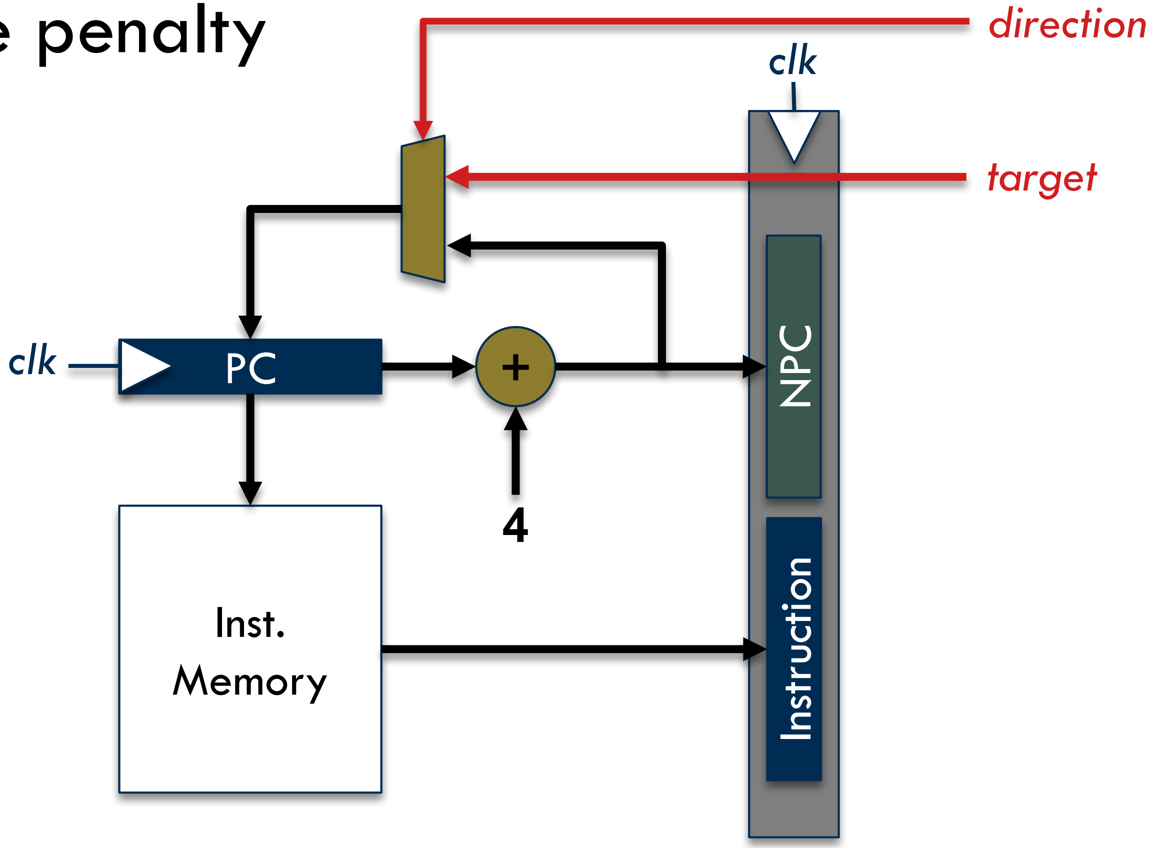
Program Flow

- A program contains basic blocks
  - Only one entry and one exit point per basic block
- Branches
  - Conditional vs. unconditional
    - How to check conditions
    - Jumps, calls, and returns
  - Target address
    - Absolute address
    - Relative to the program counter



Branch Instructions

- Branch penalty due to unknown outcome
  - Direction and target
- How to reduce penalty



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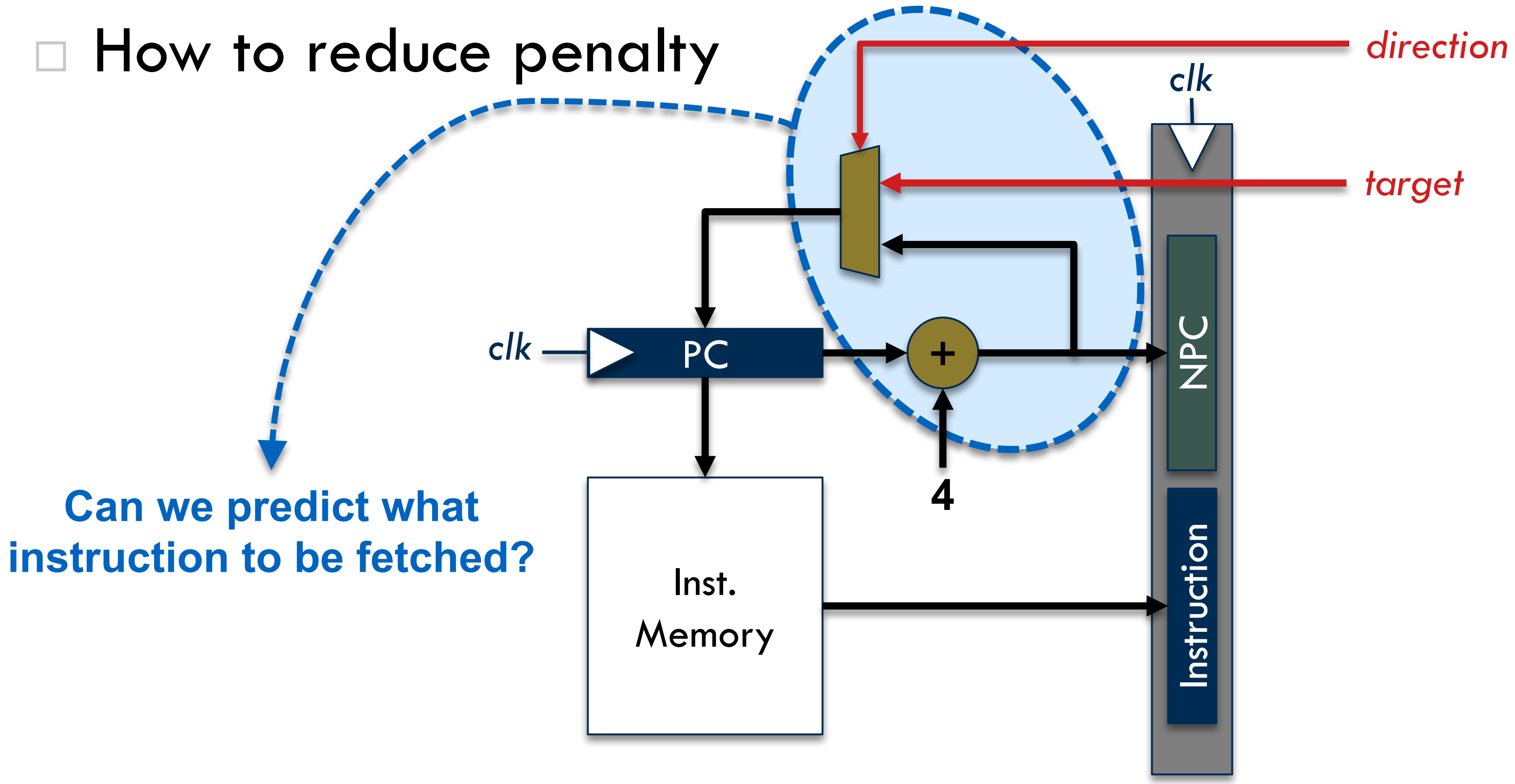

Branch Prediction

- How to predict the outcome of a branch
  - Profiling the entire program
  - Predict based on common cases

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Example C/C++ code:

```
i = 10000;
do {
    r = i%4;
    if(r != 0) {
        sum = sum + i;
    }
    i = i – 1;
} while(i != 0);
```

How many branches?

Branch Prediction

- How to predict the outcome of a branch
  - Profiling the entire program
  - Predict based on common cases

Example C/C++ code:

```
    i = 10000;
    do {
        r = i%4;
=>      if(r != 0) {
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        }
        i = i – 1;
=>  } while(i != 0);
```

How many branches?

Branch Prediction

- How to predict the outcome of a branch
  - Profiling the entire program
  - Predict based on common cases

Assembly code:

```
        ADDI  R1, R0, #10000
do:
        ANDI  R2, R1, #3
        BEQ   R2, R0, skp
        ADD   R3, R3, R1
skp:    ADDI  R1, R1, #-1
        BNEQ  R1, R0, do
```

Branch Prediction

- How to predict the outcome of a branch
  - Profiling the entire program
  - Predict based on common cases

Assembly code:

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        ADDI  R1, R0, #10000
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```

	TAKEN	NOT-TAKEN
branch-1		
branch-2		

Branch Prediction

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  - Profiling the entire program
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        ADD   R3, R3, R1
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        BNEQ  R1, R0, do
```

	TAKEN	NOT-TAKEN
branch-1	2500	7500
branch-2	9999	1

Branch Prediction

- The goal of branch prediction
  - To avoid stall cycles in fetch stage
- Types
  - Static prediction (based on direction or profile)
    - Always not-taken
      - Target = next PC
    - Always taken
      - Target = unknown
  - Dynamic prediction
    - Special hardware using PC

Branch Prediction

- The goal of branch prediction
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    - Always taken
      - Target = unknown
  - Dynamic prediction
    - Special hardware using PC

Which ones are influenced

a. Performance

b. Energy

c. Power

Branch Prediction/Misprediction

- Prediction accuracy?
  - A: always not-taken
  - B: always taken

```
i = 100;
do {
    sum = sum + i;
    i = i – 1;
} while(i != 0);
```

Branch Prediction/Misprediction

- Prediction accuracy?
  - A: always not-taken

    0.01

  - B: always taken

    0.99

```
i = 100;
do {
    sum = sum + i;
    i = i – 1;
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Problem

- Compute IPC of a scalar processor when there are
  - no data/structural hazards, only control hazards,
  - every 5th instruction is a branch, and
  - 90% branch prediction accuracy

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- Compute IPC of a scalar processor when there are
  - no data/structural hazards, only control hazards,
  - every 5th instruction is a branch, and
  - 90% branch prediction accuracy
- IPC = 1/ (1 + stalls per instruction)
- = 1/(1 + 0.2x0.1x1) = 0.98

Dynamic Branch Prediction

- Hardware unit capable of learning at runtime
  - 1. Prediction logic
    - Direction (taken or not-taken)
    - Target address (where to fetch next)
  - 2. Outcome validation and training
    - Outcome is computed regardless of prediction
  - 3. Recovery from misprediction
    - Nullify the effect of instructions on the wrong path

Simple Dynamic Predictors

- One-bit branch predictor
  - Keep track of and use the outcome of last executed branch
- Prediction accuracy

```
while(1) {
    for(i=0; i<10; i++) {        branch-1
    }
    for(j=0; j<20; j++) {        branch-2
    }
}
```

Simple Dynamic Predictors

- One-bit branch predictor
  - Keep track of and use the outcome of last executed branch

```
while:
        ADDI   R3, R0, #10
        JMP    chk1
for1:   ...
chk1:   BNQ    R1, R3, for1
        ADDI   R3, R0, #20
        JMP    chk2
for2:   ...
chk2:   BNQ    R2, R3, for2
        JMP    while
```

*** Loop implementation suggested by an student ***

```
while(1) {
    for(i=0; i<10; i++) {      branch-1
    }
    for(j=0; j<20; j++) {      branch-2
    }
}
```

Simple Dynamic Predictors

- One-bit branch predictor
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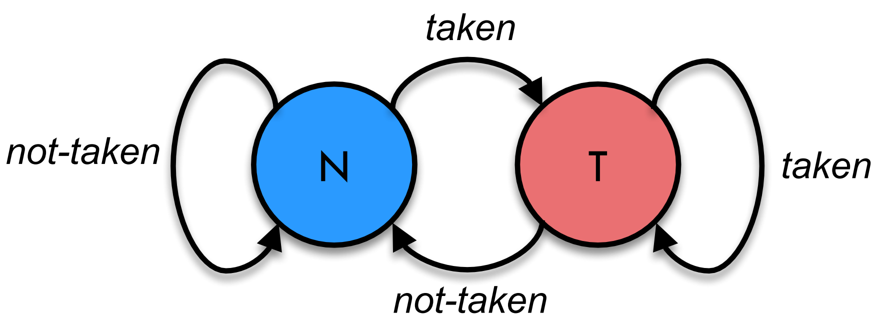

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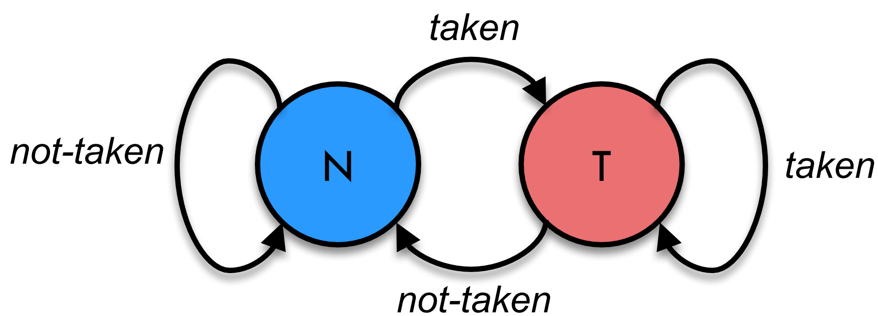

- Prediction accuracy
  - A single predictor shared by multiple branches
  - Two mispredictions for loops (1 entry and 1 exit)

```
while(1) {
    for(i=0; i<10; i++) {      branch-1
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```
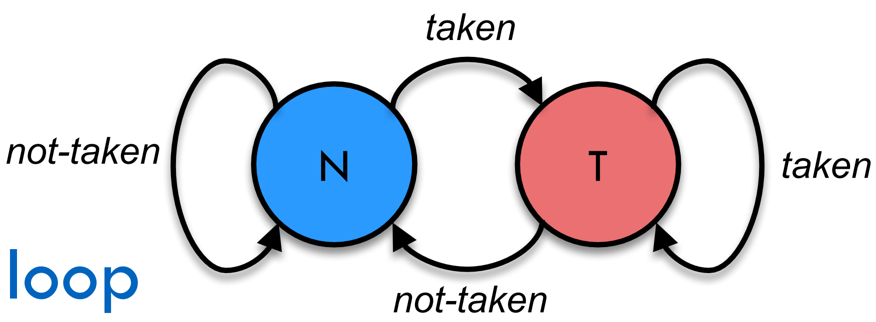

Bimodal Branch Predictors

- One-bit branch predictor
  - Keep track of and use the outcome of last executed branch
- Shared predictor
- Two mispredictions per loop

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    }
}
```

Accuracy = 26/30 = 0.86

How to improve?

Bimodal Branch Predictors

- Two-bit branch predictor
  - Increment if taken
  - Decrement if untaken

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    for(i=0; i<10; i++) {      branch-1
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}
```

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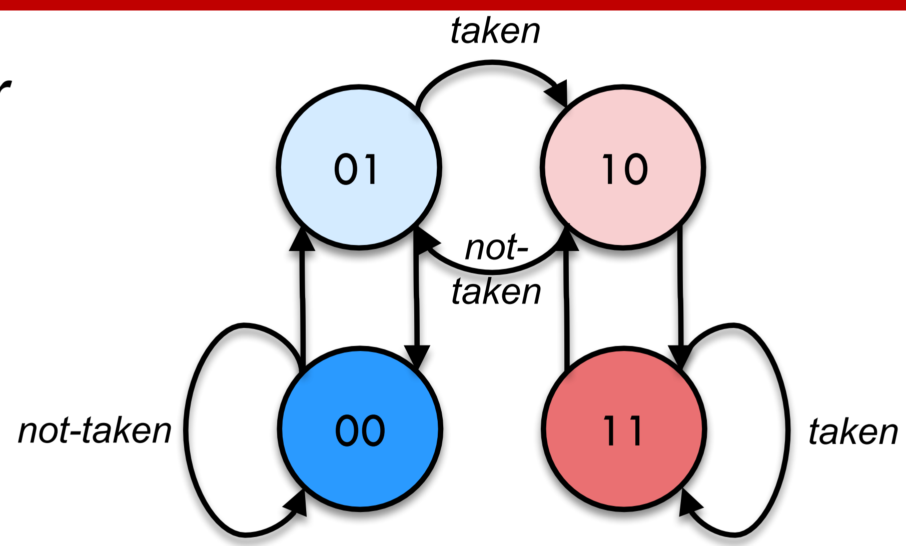


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Bimodal Branch Predictors

- Two-bit branch predictor
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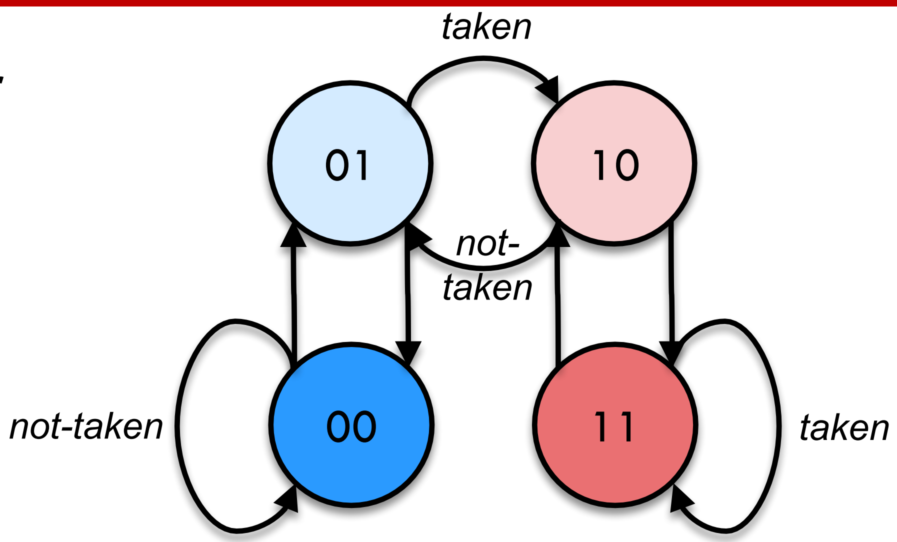
- One misprediction on loop exit
- Accuracy = 28/30 = 0.93

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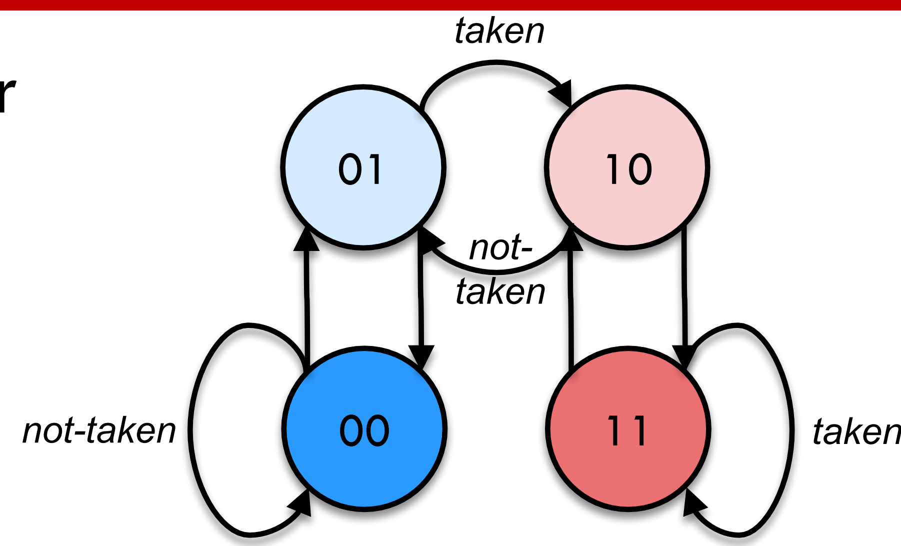

- One misprediction on loop exit
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- **How to improve?**
  - 3-bit predictor?
- **Problem?**
  - A single predictor shared by many branches

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