# Pipelining Wrap-Up

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Jae W. Lee (jaewlee@snu.ac.kr)
Computer Science and Engineering
Seoul National University

***Slide credits***: *[CS:APP3e] slides from CMU; [COD5e] slides from Elsevier Inc.*

# Today

**Textbook: [CS:APP3e] 4.5.6, 4.5.9, and 5.7**

- **Wrap-Up of PIPE Design**
  - Exceptional conditions
  - Performance analysis
- **Modern High-Performance Processors**
  - Out-of-order execution

# Exceptions

- Conditions under which processor cannot continue normal operation

- **Causes**
  - Halt instruction (Current)
  - Bad address for instruction or data (Previous)
  - Invalid instruction (Previous)
- **Typical Desired Action**
  - Complete some instructions
    - Either current or previous (depends on exception type)
  - Discard others
  - Call exception handler
    - Like an unexpected procedure call
- **Our Implementation**
  - Halt when instruction causes exception

# Exception Examples

- **Detect in Fetch Stage**

```
jmp $-1                        # Invalid jump target

.byte 0xFF                     # Invalid instruction code

halt                           # Halt instruction
```

- **Detect in Memory Stage**

```
irmovq $100,%rax
rmmovq %rax,0x10000(%rax) # invalid address
```

# Exceptions in Pipeline Processor #1

```
# demo-exc1.ys
irmovq $100,%rax
rmmovq %rax,0x10000(%rax) # Invalid address
nop
.byte 0xFF                # Invalid instruction code
```

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 0x000: irmovq $100,%rax | F | D | E | M | W |
| 0x00a: rmmovq %rax,0x1000(%rax) | | F | D | E | M |
| 0x014: nop | | | F | D | E |
| 0x015: .byte 0xFF | | | | F | D |

Exception detected

Exception detected

- **Desired Behavior**
  - `rmmovq` should cause exception
  - Following instructions should have no effect on processor state

# Exceptions in Pipeline Processor #2

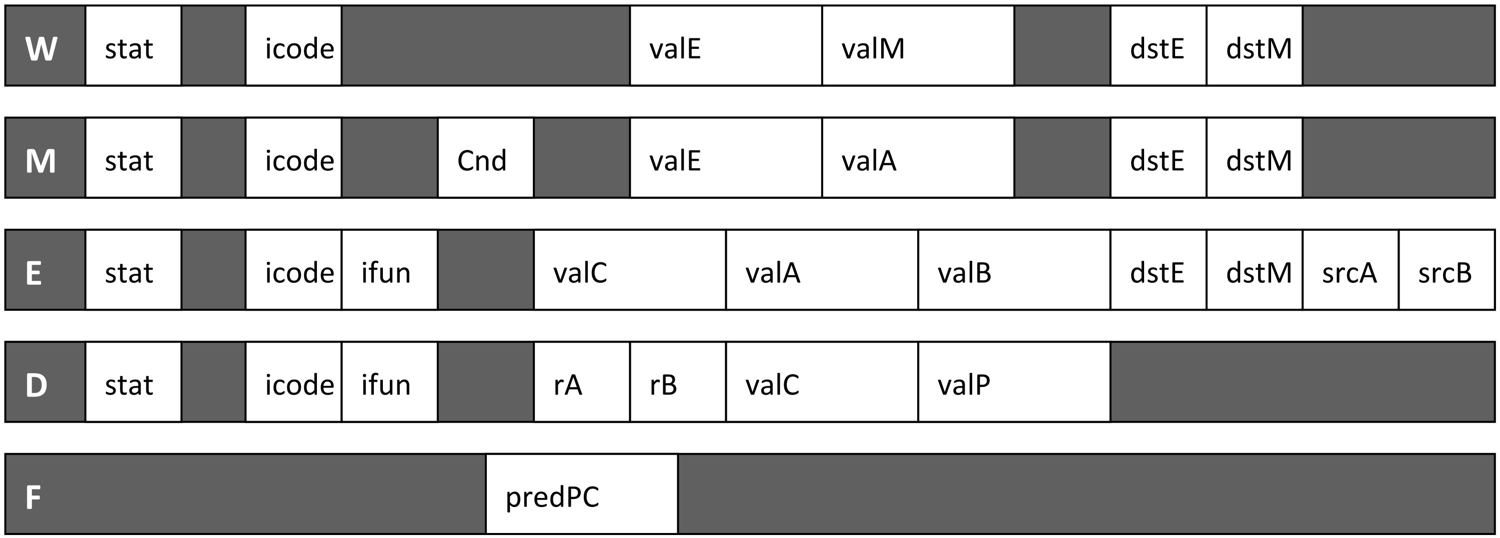
```
 # demo-exc2.ys
0x000:     xorq %rax,%rax   # Set condition codes
0x002:     jne t            # Not taken
0x00b:     irmovq $1,%rax
0x015:     irmovq $2,%rdx
0x01f:     halt
0x020: t: .byte 0xFF        # Target
```

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| `0x000:     xorq %rax,%rax` | F | D | E | M | W | | | | |
| `0x002:     jne t` | | F | D | E | M | | | | |
| `0x020: t: .byte 0xFF` | | | F | D | E | M | W | | |
| `0x???: (I'm lost!)` | | | | F | D | E | M | W | |
| `0x00b:     irmovq $1,%rax` | | | | | F | D | E | M | W |

**Exception detected**

- **Desired Behavior**
  - No exception should occur

# Maintaining Exception Ordering




- Add status field to pipeline registers
- Fetch stage sets to either “AOK,” “ADR” (when bad fetch address), “HLT” (halt instruction) or “INS” (illegal instruction)
- Decode & execute pass values through
- Memory either passes through or sets to “ADR”
- Exception triggered only when instruction hits write back

# Exception Handling Logic

- **Fetch Stage**

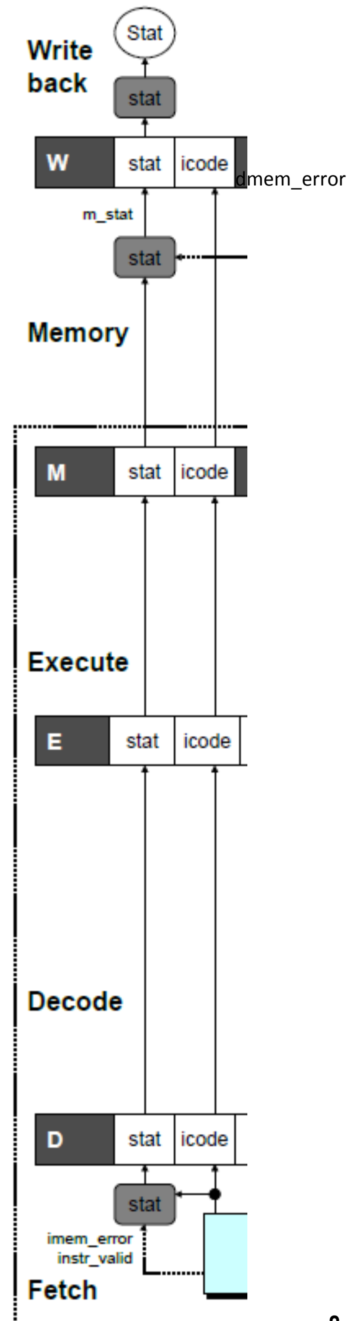
```
# Determine status code for fetched instruction
int f_stat = [
        imem_error: SADR;
        !instr_valid : SINS;
        f_icode == IHALT : SHLT;
        1 : SAOK;
];
```

- **Memory Stage**

```
# Update the status
int m_stat = [
        dmem_error : SADR;
        1 : M_stat;
];
```

- **Writeback Stage**

```
int Stat = [
        # SBUB in earlier stages indicates bubble
        W_stat == SBUB : SAOK;
        1 : W_stat;
];
```



# Side Effects in Pipeline Processor

```
# demo-exc3.ys
irmovq $100,%rax
rmmovq %rax,0x10000(%rax) # invalid address
addq %rax,%rax            # Sets condition codes
```

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| `0x000: irmovq $100,%rax` | F | D | E | M | W |
| `0x00a: rmmovq %rax,0x1000(%rax)` | | F | D | E | M |
| `0x014: addq %rax,%rax` | | | F | D | E |

**Exception detected**

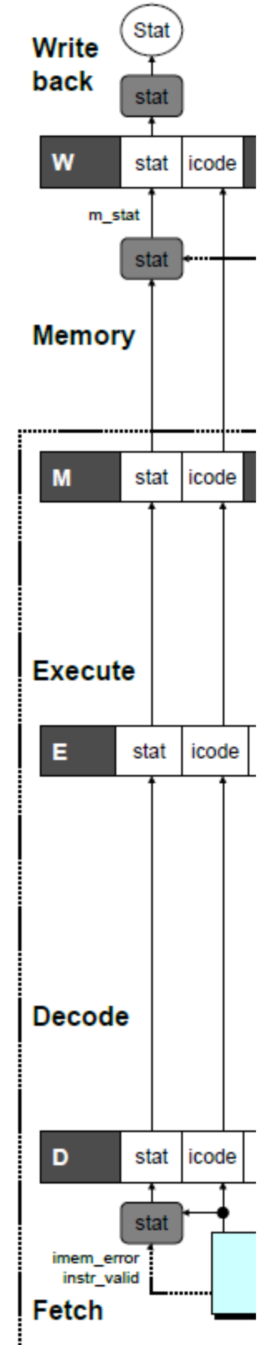
**Condition code set**

- **Desired Behavior**
  - `rmmovq` should cause exception
  - No following instruction should have any effect

# Avoiding Side Effects

- **Presence of Exception Should Disable State Update**
  - Invalid instructions are converted to pipeline bubbles
    - Except have stat indicating exception status
  - Data memory will not write to invalid address
  - Prevent invalid update of condition codes
    - Detect exception in memory stage
    - Disable condition code setting in execute
    - Must happen in same clock cycle
  - Handling exception in final stages
    - When detect exception in memory stage
      - Start injecting bubbles into memory stage on next cycle
    - When detect exception in write-back stage
      - Stall excepting instruction

# Control Logic for State Changes




## ■ Setting Condition Codes

```
# Should the condition codes be updated?
bool set_cc = E_icode == IOPQ &&
        # State changes only during normal operation
        !m_stat in { SADR, SINS, SHLT }
        && !W_stat in { SADR, SINS, SHLT };
```

## ■ Stage Control

- Also controls updating of memory

```
# Start injecting bubbles as soon as exception passes
through memory stage
bool M_bubble = m_stat in { SADR, SINS, SHLT }
        || W_stat in { SADR, SINS, SHLT };

# Stall pipeline register W when exception encountered
bool W_stall = W_stat in { SADR, SINS, SHLT };
```

# Rest of Real-Life Exception Handling

- **Call Exception Handler**
  - Push PC onto stack
    - Either PC of faulting instruction or of next instruction
    - Usually pass through pipeline along with exception status
  - Jump to handler address
    - Usually fixed address
    - Defined as part of ISA

# Performance Metrics

- **Clock rate**
  - Measured in Gigahertz
  - Function of stage partitioning and circuit design
    - Keep amount of work per stage small
- **Rate at which instructions executed**
  - CPI: cycles per instruction
  - On average, how many clock cycles does each instruction require?
  - Function of pipeline design and benchmark programs
    - E.g., how frequently are branches mispredicted?

# CPI for PIPE

- **CPI ≈ 1.0**
  - Fetch instruction each clock cycle
  - Effectively process new instruction almost every cycle
    - Although each individual instruction has latency of 5 cycles
- **CPI > 1.0**
  - Sometimes must stall or cancel branches
- **Computing CPI**
  - C clock cycles
  - I instructions executed to completion
  - B bubbles injected (C = I + B)

$$CPI = C/I = (I+B)/I = 1.0 + B/I$$

  - Factor B/I represents average penalty due to bubbles

# CPI for PIPE (Cont.)

**Typical Values**

B/I = LP + MP + RP

- LP: Penalty due to load/use hazard stalling
  - Fraction of instructions that are loads — 0.25
  - Fraction of load instructions requiring stall — 0.20
  - Number of bubbles injected each time — 1

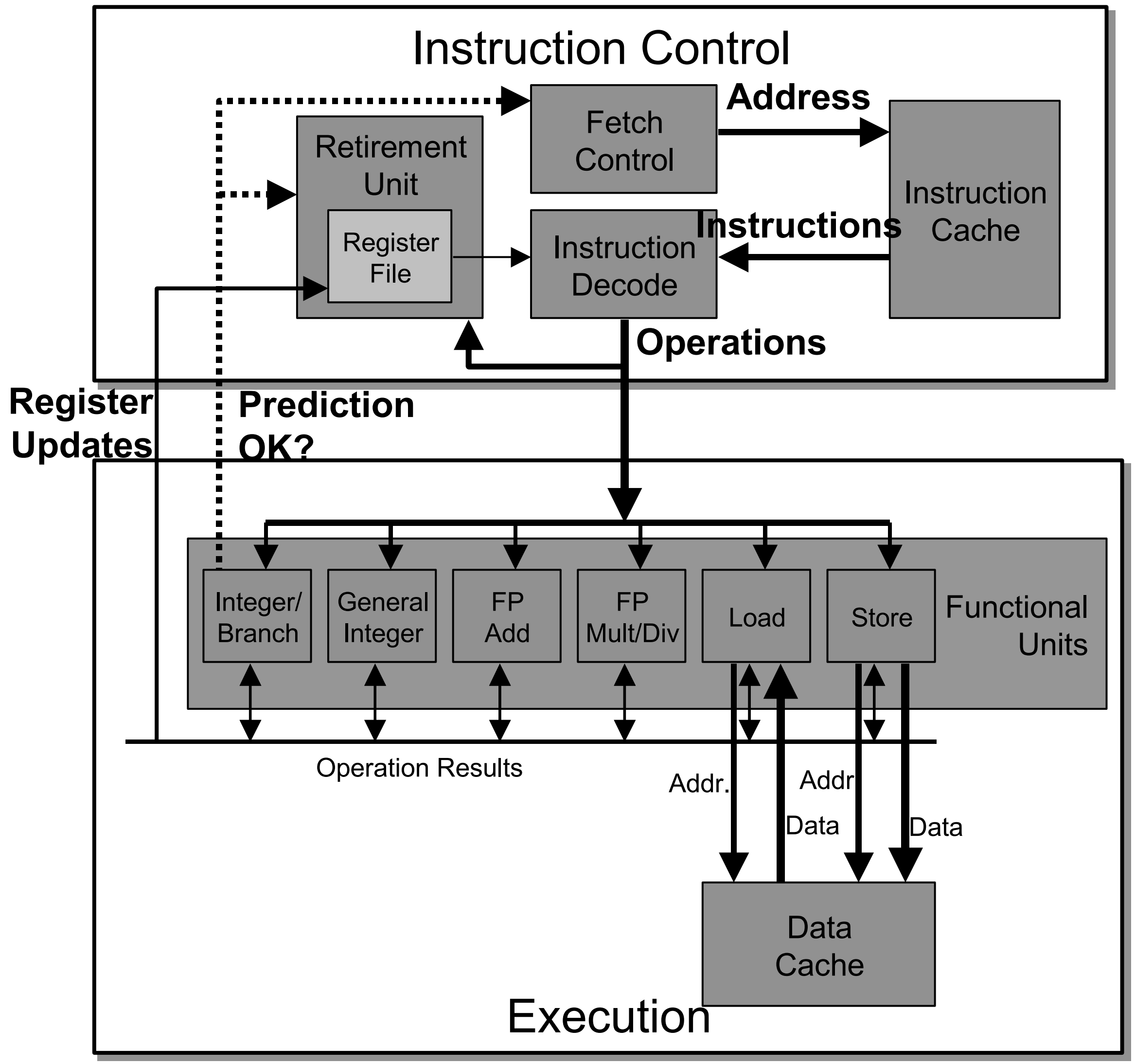
  ⇒ LP = 0.25 * 0.20 * 1 = 0.05
- MP: Penalty due to mispredicted branches
  - Fraction of instructions that are cond. jumps — 0.20
  - Fraction of cond. jumps mispredicted — 0.40
  - Number of bubbles injected each time — 2

  ⇒ MP = 0.20 * 0.40 * 2 = 0.16
- RP: Penalty due to `ret` instructions
  - Fraction of instructions that are returns — 0.02
  - Number of bubbles injected each time — 3

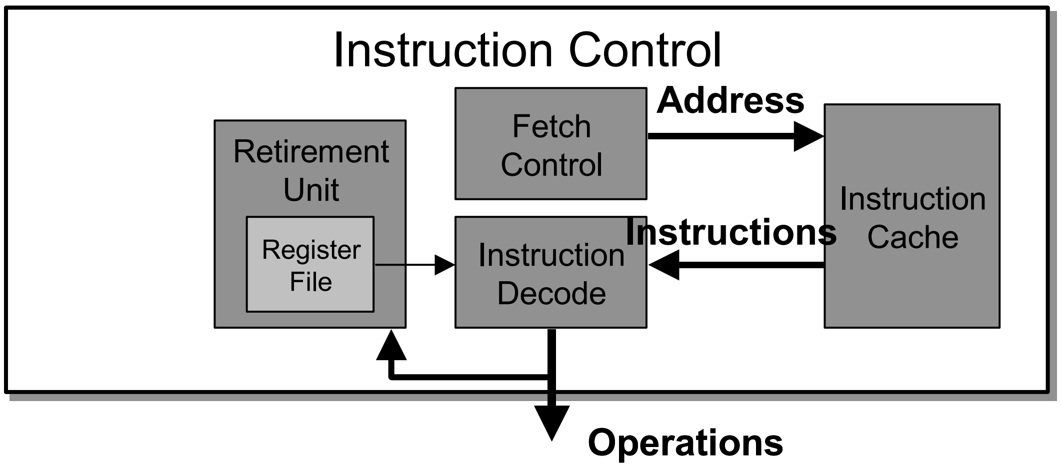
  ⇒ RP = 0.02 * 3 = 0.06
- Net effect of penalties 0.05 + 0.16 + 0.06 = 0.27

  ⇒ CPI = 1.27 (Not bad!)

# Modern CPU Design

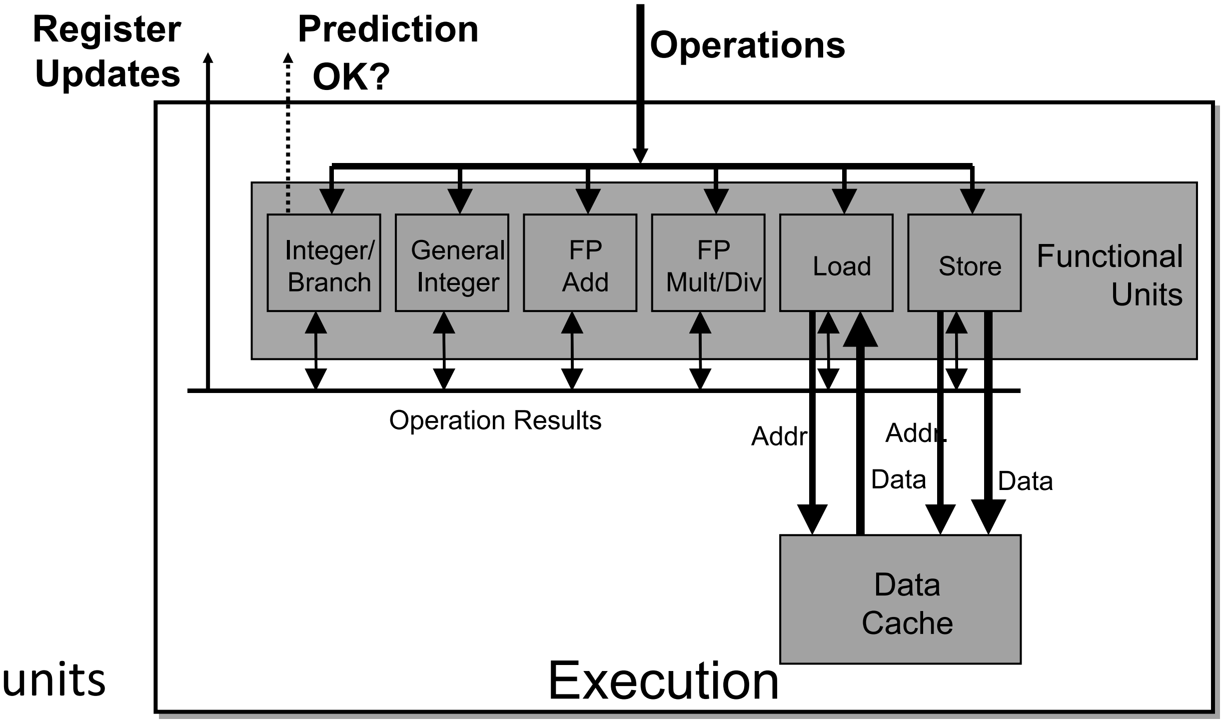


# Instruction Control




- **Grabs Instruction Bytes From Memory**
  - Based on Current PC + Predicted Targets for Predicted Branches
  - Hardware dynamically guesses whether branches taken/not taken and (possibly) branch target
- **Translates Instructions Into *Operations***
  - Primitive steps required to perform instruction
  - Typical instruction requires 1–3 operations
- **Converts Register References Into *Tags***
  - Abstract identifier linking destination of one operation with sources of later operations

# Execution Units




- Multiple functional units
  - Each can operate in independently
- Operations performed as soon as operands available
  - Not necessarily in program order
  - Within limits of functional units
- Control logic
  - Ensures behavior equivalent to sequential program execution

# CPU Capabilities of Intel Haswell

- **Multiple Instructions Can Execute in Parallel**
  - 2 load
  - 1 store
  - 4 integer
  - 2 FP multiply
  - 1 FP add / divide
- **Some Instructions Take > 1 Cycle, but Can be Pipelined**

| Instruction | Latency | Cycles/Issue |
|---|---:|---:|
| Load / Store | 4 | 1 |
| Integer Multiply | 3 | 1 |
| Integer Divide | 3—30 | 3—30 |
| Double/Single FP Multiply | 5 | 1 |
| Double/Single FP Add | 3 | 1 |
| Double/Single FP Divide | 10—15 | 6—11 |

# Haswell Operation

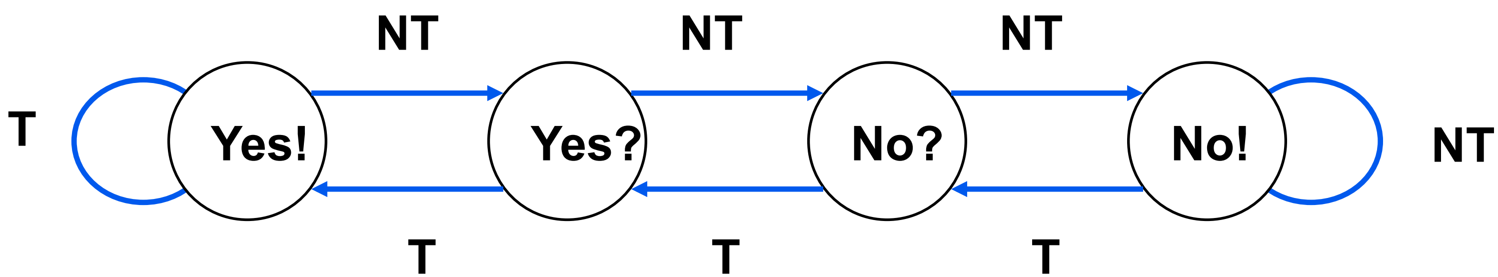
- **Translates instructions dynamically into "Uops"**
  - ~118 bits wide
  - Holds operation, two sources, and destination
- **Executes Uops with "Out of Order" engine**
  - Uop executed when
    - Operands available
    - Functional unit available
  - Execution controlled by "Reservation Stations"
    - Keeps track of data dependencies between uops
    - Allocates resources

# High-Perforamnce Branch Prediction

- **Critical to Performance**
  - Typically 11–15 cycle penalty for misprediction
- **Branch Target Buffer**
  - 512 entries
  - 4 bits of history
  - Adaptive algorithm
    - Can recognize repeated patterns, e.g., alternating taken–not taken
- **Handling BTB misses**
  - Detect in ~cycle 6
  - Predict taken for negative offset, not taken for positive
    - Loops vs. conditionals

# Example Branch Prediction

- **Branch History**
  - Encode information about prior history of branch instructions
  - Predict whether or not branch will be taken




- **State Machine**
  - Each time branch taken, transition to right
  - When not taken, transition to left
  - Predict branch taken when in state Yes! or Yes?

# Processor Summary

- **Design Technique**
  - Create uniform framework for all instructions
    - Want to share hardware among instructions
  - Connect standard logic blocks with bits of control logic
- **Operation**
  - State held in memories and clocked registers
  - Computation done by combinational logic
  - Clocking of registers/memories sufficient to control overall behavior
- **Enhancing Performance**
  - Pipelining increases throughput and improves resource utilization
  - Must make sure to maintain ISA behavior