CS:APP Chapter 4
Computer Architecture
Pipelined Implementation
Part I

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Overview

General Principles of Pipelining

- Goal
- Difficulties

Creating a Pipelined Y86 Processor

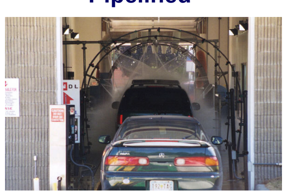
- Rearranging SEQ
- Inserting pipeline registers
- Problems with data and control hazards

Real-World Pipelines: Car Washes

Sequential

Parallel

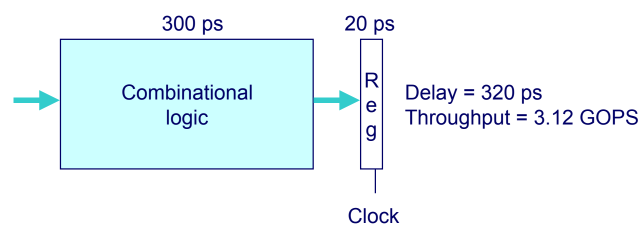
Pipelined



Idea

- Divide process into independent stages
- Move objects through stages in sequence
- At any given times, multiple objects being processed

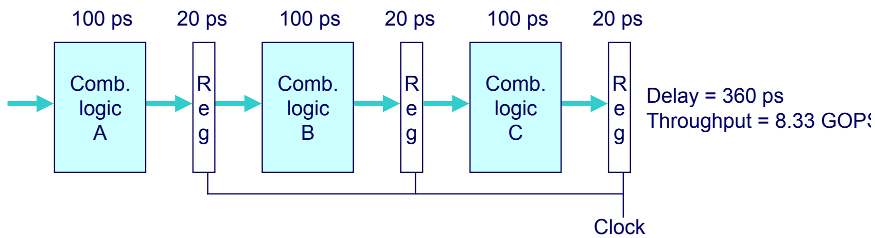
Computational Example



System

- Computation requires total of 300 picoseconds
- Additional 20 picoseconds to save result in register
- Can must have clock cycle of at least 320 ps

3-Way Pipelined Version

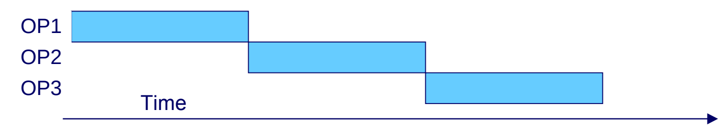


System

- Divide combinational logic into 3 blocks of 100 ps each
- Can begin new operation as soon as previous one passes through stage A.
  - Begin new operation every 120 ps
- Overall latency increases
  - 360 ps from start to finish

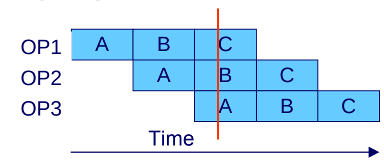
Pipeline Diagrams

Unpipelined



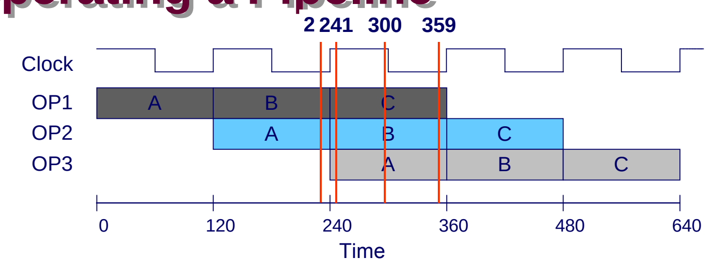
- Cannot start new operation until previous one completes

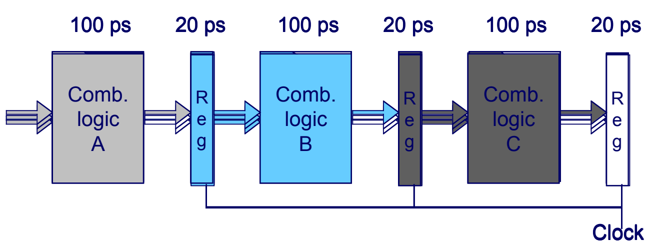
3-Way Pipelined



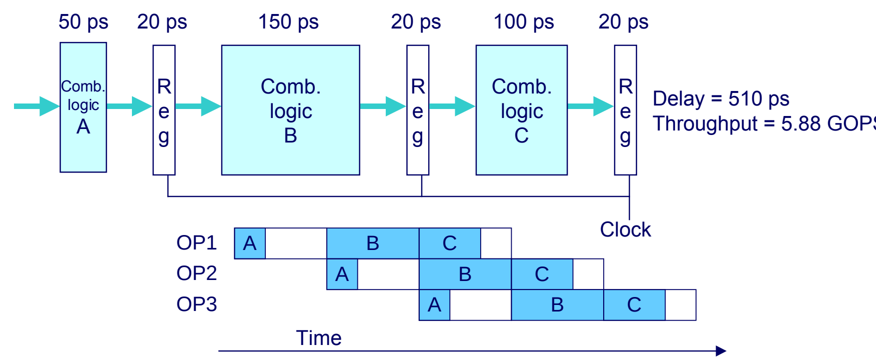
- Up to 3 operations in process simultaneously

Operating a Pipeline



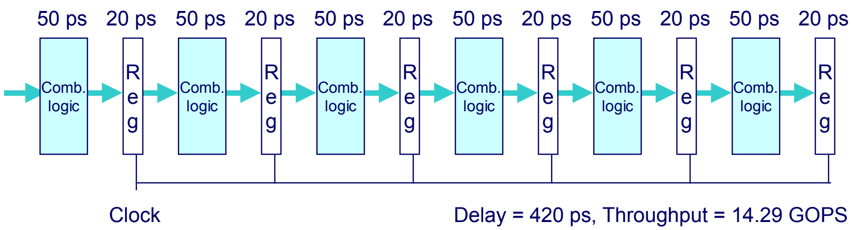


Limitations: Nonuniform Delays



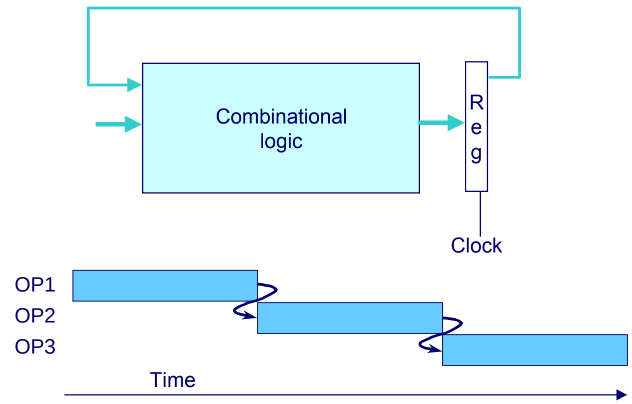
- Throughput limited by slowest stage
- Other stages sit idle for much of the time
- Challenging to partition system into balanced stages

Limitations: Register Overhead



- As try to deepen pipeline, overhead of loading registers becomes more significant
- Percentage of clock cycle spent loading register:
  - 1-stage pipeline: 6.25%
  - 3-stage pipeline: 16.67%
  - 6-stage pipeline: 28.57%
- High speeds of modern processor designs obtained through very deep pipelining

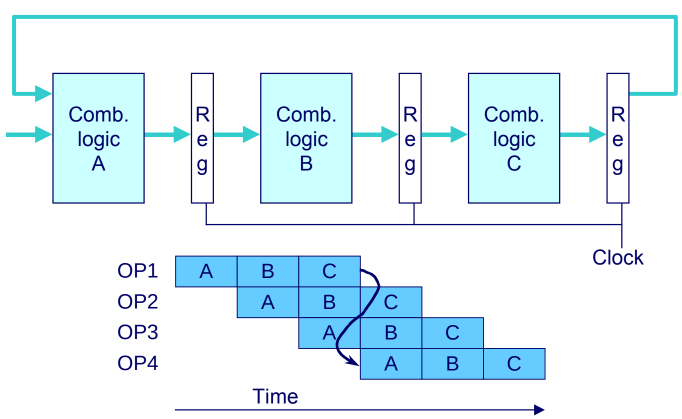
Data Dependencies



System

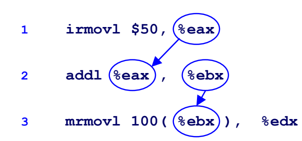
- Each operation depends on result from preceding one

Data Hazards



- Result does not feed back around in time for next operation
- Pipelining has changed behavior of system

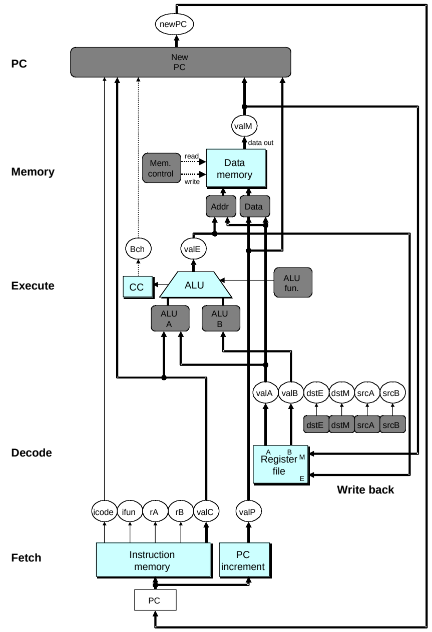
Data Dependencies in Processors



- Result from one instruction used as operand for another
  - Read-after-write (RAW) dependency
- Very common in actual programs
- Must make sure our pipeline handles these properly
  - Get correct results
  - Minimize performance impact

SEQ Hardware

- Stages occur in sequence
- One operation in process at a time



SEQ+ Hardware

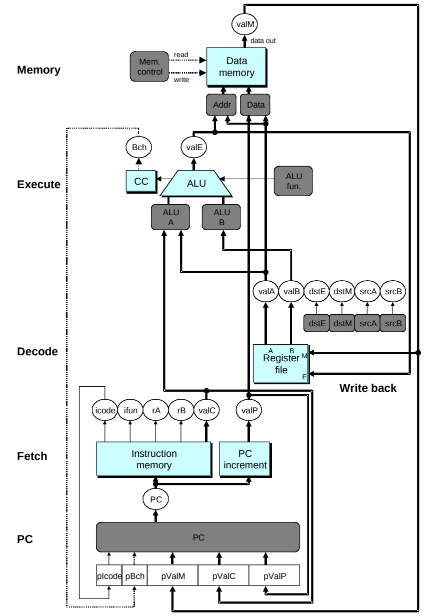
- Still sequential implementation
- Reorder PC stage to put at beginning

PC Stage

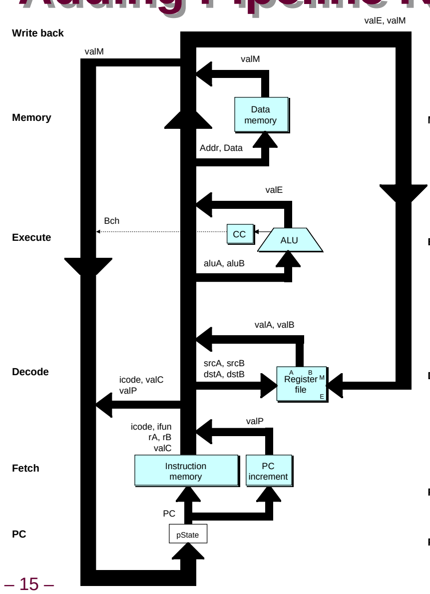
- Task is to select PC for current instruction
- Based on results computed by previous instruction

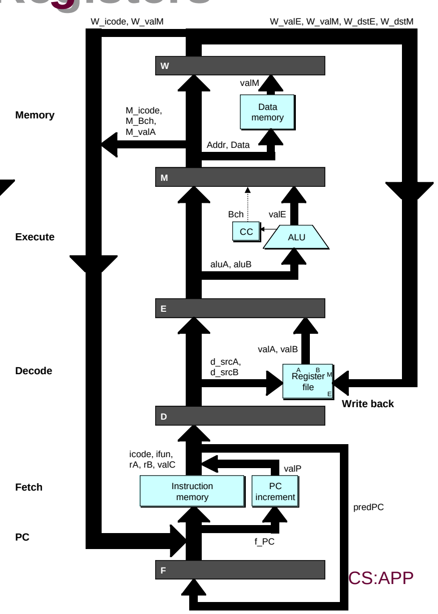
Processor State

- PC is no longer stored in register
- But, can determine PC based on other stored information



Adding Pipeline Registers





Pipeline Stages

Fetch

- Select current PC
- Read instruction
- Compute incremented PC

Decode

- Read program registers

Execute

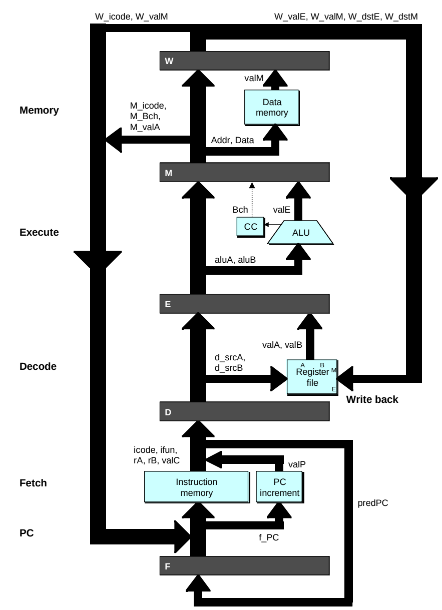
- Operate ALU

Memory

- Read or write data memory

Write Back

- Update register file

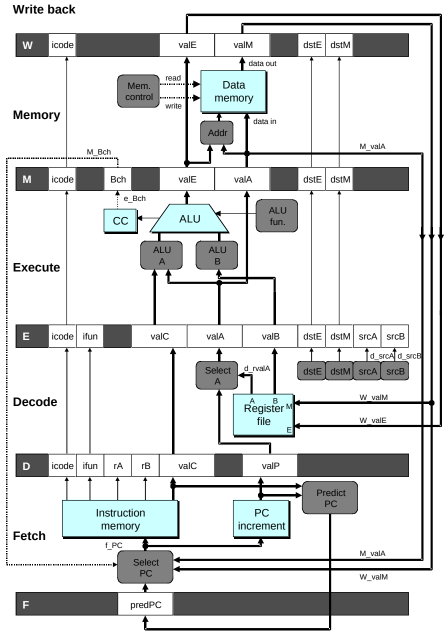


PIPE- Hardware

- Pipeline registers hold intermediate values from instruction execution

Forward (Upward) Paths

- Values passed from one stage to next
- Cannot jump past stages
  - e.g., valC passes through decode



Feedback Paths

Predicted PC

- Guess value of next PC

Branch information

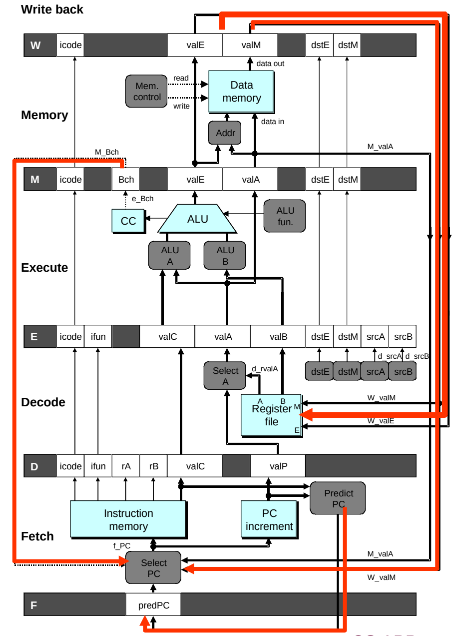
- Jump taken/not-taken
- Fall-through or target address

Return point

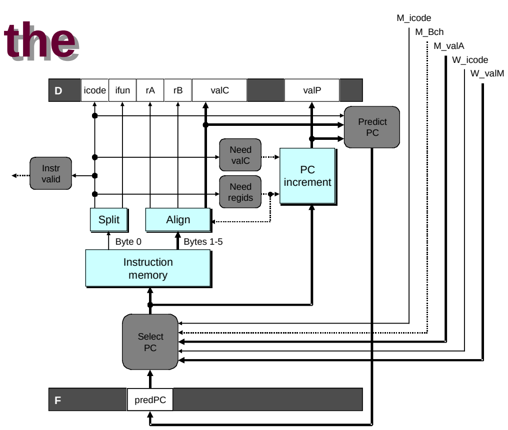
- Read from memory

Register updates

- To register file write ports



Predicting the PC



- Start fetch of new instruction after current one has completed fetch stage
  - Not enough time to reliably determine next instruction
- Guess which instruction will follow
  - Recover if prediction was incorrect

Our Prediction Strategy

Instructions that Don’t Transfer Control

- Predict next PC to be valP
- Always reliable

Call and Unconditional Jumps

- Predict next PC to be valC (destination)
- Always reliable

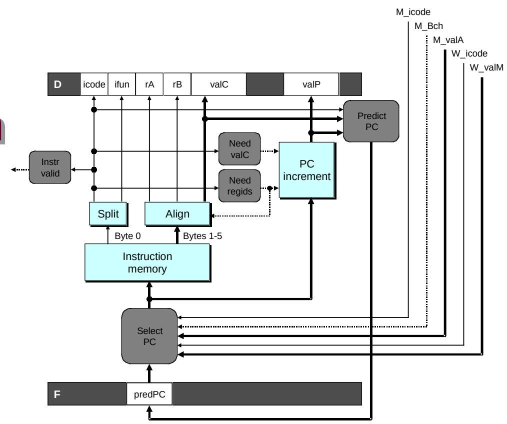
Conditional Jumps

- Predict next PC to be valC (destination)
- Only correct if branch is taken
  - Typically right 60% of time

Return Instruction

- Don’t try to predict

Recovering from PC Misprediction

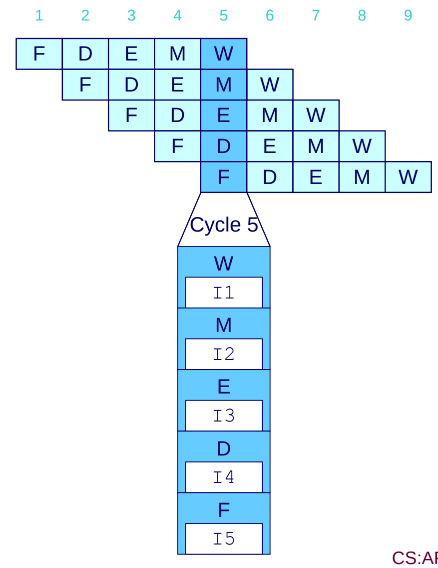


- Mispredicted Jump
  - Will see branch flag once instruction reaches memory stage
  - Can get fall-through PC from valA
- Return Instruction
  - Will get return PC when `ret` reaches write-back stage

Pipeline Demonstration

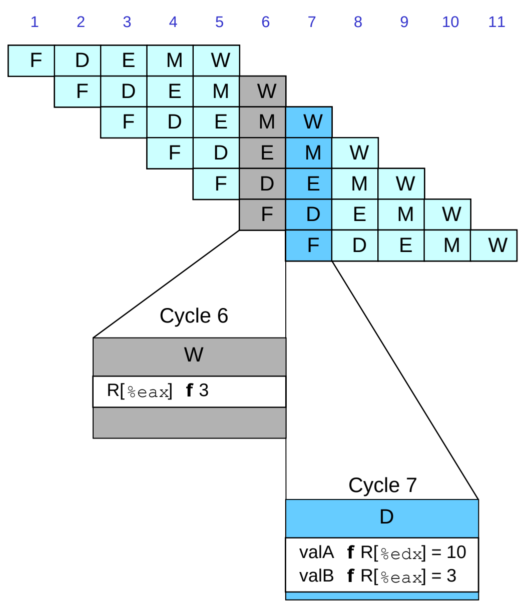
```
irmovl  $1,%eax  #I1
irmovl  $2,%ecx  #I2
irmovl  $3,%edx  #I3
irmovl  $4,%ebx  #I4
halt             #I5
```

File: `demo-basic.ys`



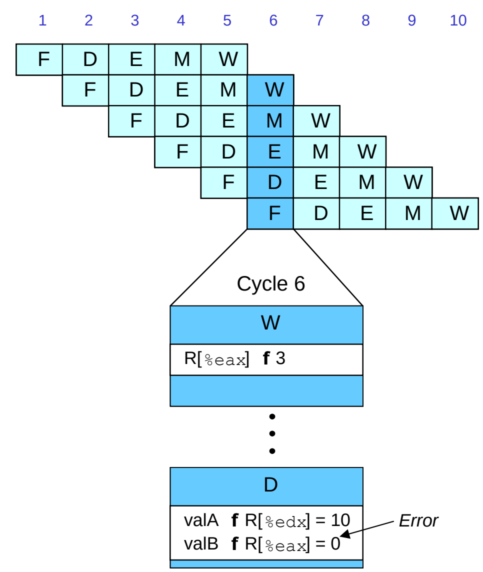
Data Dependencies: 3 Nop's

```
# demo-h3.ys
0x000: irmovl $10,%edx
0x006: irmovl  $3,%eax
0x00c: nop
0x00d: nop
0x00e: nop
0x00f: addl %edx,%eax
0x011: halt
```



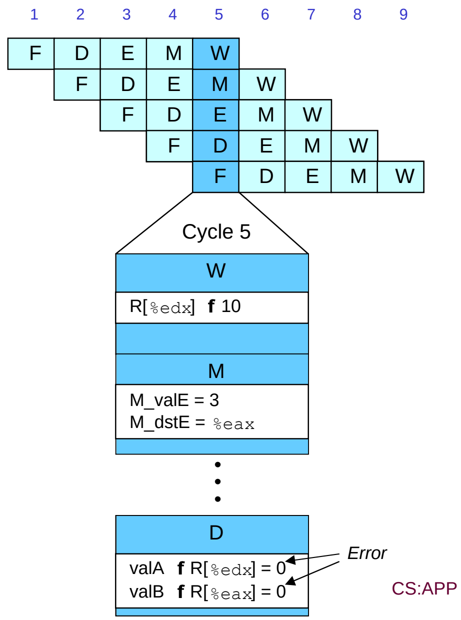
Data Dependencies: 2 Nop's

```
# demo-h2.ys
0x000: irmovl $10,%edx
0x006: irmovl  $3,%eax
0x00c: nop
0x00d: nop
0x00e: addl %edx,%eax
0x010: halt
```



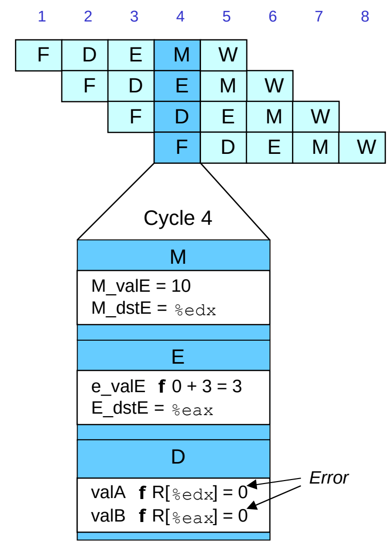
Data Dependencies: 1 Nop

```
# demo-h1.ys
0x000: irmovl $10,%edx
0x006: irmovl  $3,%eax
0x00c: nop
0x00d: addl %edx,%eax
0x00f: halt
```



Data Dependencies: No Nop

```
# demo-h0.ys
0x000: irmovl $10,%edx
0x006: irmovl  $3,%eax
0x00c: addl %edx,%eax
0x00e: halt
```



Branch Misprediction Example

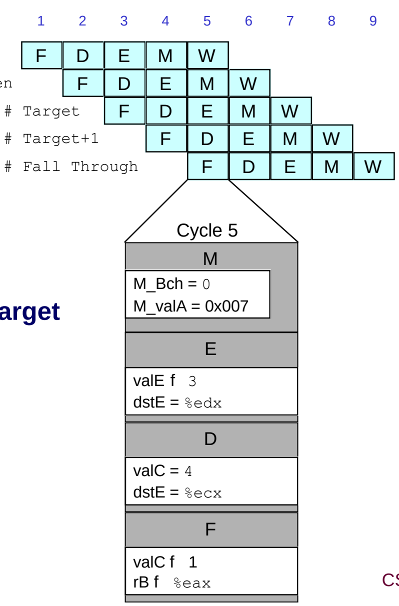
demo-j.ys

```
0x000:    xorl %eax,%eax
0x002:    jne  t              # Not taken
0x007:    irmovl $1, %eax     # Fall through
0x00d:    nop
0x00e:    nop
0x00f:    nop
0x010:    halt
0x011: t: irmovl $3, %edx     # Target (Should not execute)
0x017:    irmovl $4, %ecx     # Should not execute
0x01d:    irmovl $5, %edx     # Should not execute
```

- **Should only execute first 8 instructions**

Branch Misprediction Trace

```
# demo-j
0x000:    xorl %eax,%eax
0x002:    jne t # Not taken
0x011: t: irmovl $3, %edx # Target
0x017:    irmovl $4, %ecx # Target+1
0x007:    irmovl $1, %eax # Fall Through
```



- **Incorrectly execute two instructions at branch target**

Return Example

demo-ret.ys

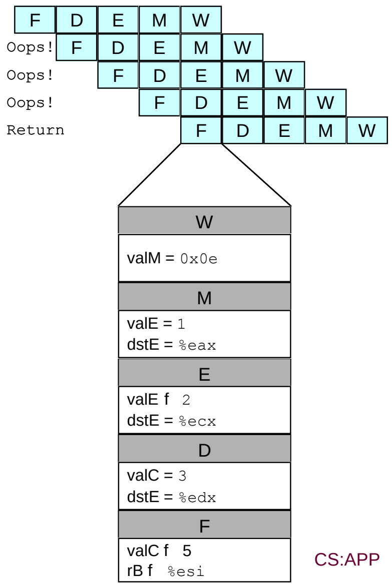
```
0x000:    irmovl Stack,%esp  # Intialize stack pointer
0x006:    nop                # Avoid hazard on %esp
0x007:    nop
0x008:    nop
0x009:    call p             # Procedure call
0x00e:    irmovl $5,%esi     # Return point
0x014:    halt
0x020: .pos 0x20
0x020: p: nop                 # procedure
0x021:    nop
0x022:    nop
0x023:    ret
0x024:    irmovl $1,%eax      # Should not be executed
0x02a:    irmovl $2,%ecx      # Should not be executed
0x030:    irmovl $3,%edx      # Should not be executed
0x036:    irmovl $4,%ebx      # Should not be executed
0x100: .pos 0x100
0x100: Stack:                 # Stack: Stack pointer
```

- Require lots of nops to avoid data hazards

Incorrect Return Example

```
# demo-ret

0x023:    ret
0x024:    irmovl $1,%eax # Oops!
0x02a:    irmovl $2,%ecx # Oops!
0x030:    irmovl $3,%edx # Oops!
0x00e:    irmovl $5,%esi # Return
```



- Incorrectly execute 3 instructions following `ret`

Pipeline Summary

Concept

- Break instruction execution into 5 stages
- Run instructions through in pipelined mode

Limitations

- Can't handle dependencies between instructions when instructions follow too closely
- Data dependencies
  - One instruction writes register, later one reads it
- Control dependency
  - Instruction sets PC in way that pipeline did not predict correctly
  - Mispredicted branch and return

Fixing the Pipeline

- We'll do that next time