Design
of Pipelined MIPS Processor

Sept. 24 & 26, 1997

Topics

- Instruction processing
- Principles of pipelining
- Inserting pipe registers
- Data Hazards
- Control Hazards
- Exceptions

MIPS architecture subset

R-type instructions (add, sub, and, or, slt): rd <-- rs funct rt

0	rs	rt	rd	shamt	funct
31-26	25-21	20-16	15-11	10-6	5-0

RI-type instructions (addiu): rt <-- rs funct I16

0	rs	rt	I16
31-26	25-21	20-16	15-0

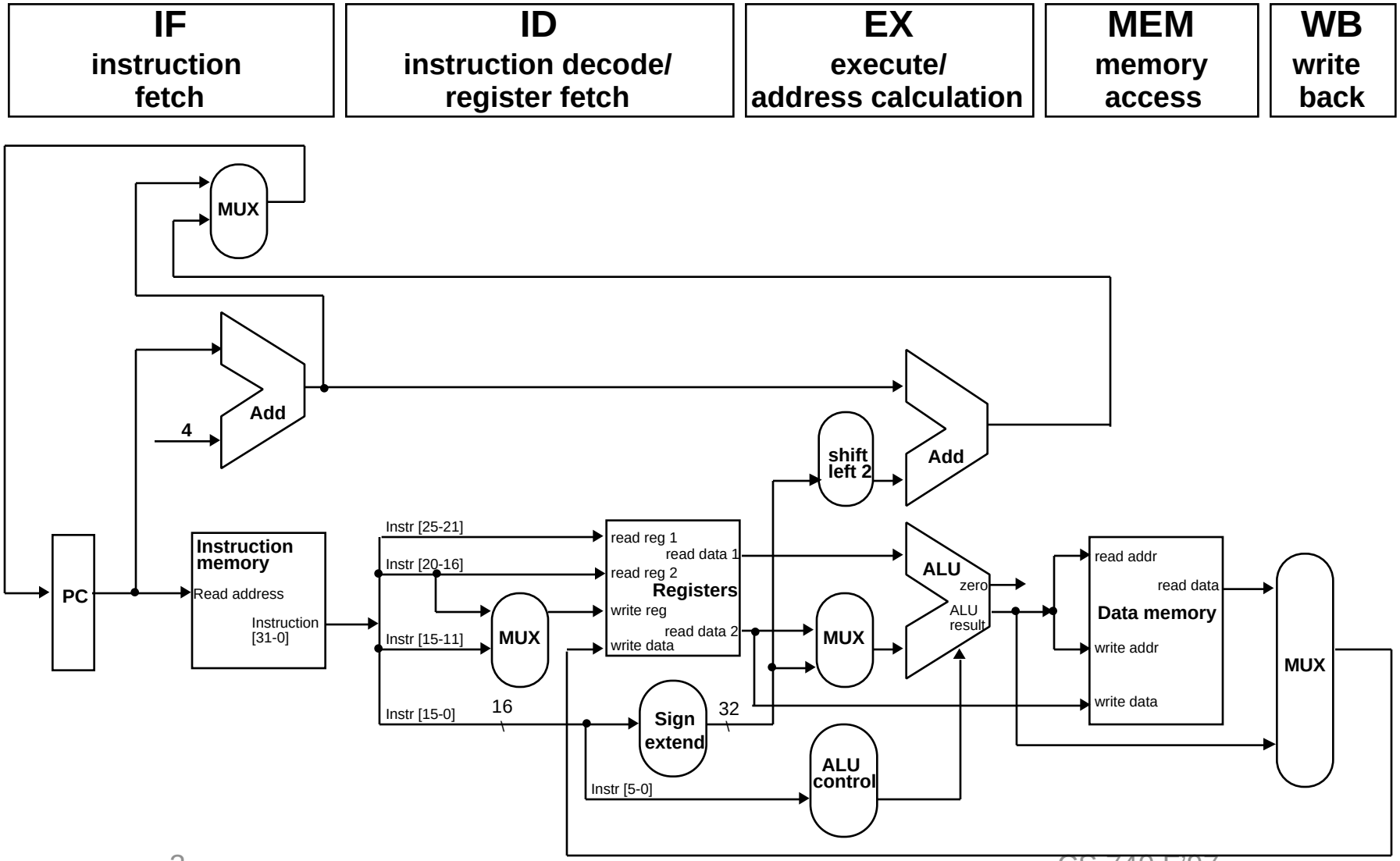
Load: rt <-- Mem[rs + I16] **Store:** Mem[rs + I16] <-- rt

35 or 43	rs	rt	I16
31-26	25-21	20-16	15-0

Branch equal: PC <-- (rs == rt) ? PC + 4 + I16 <<2 : PC + 4

4	rs	rt	I16
31-26	25-21	20-16	15-0

Datapath


IF
instruction fetch
ID
instruction decode/ register fetch
EX
execute/ address calculation
MEM
memory access
WB
write back
MUX
Add
4
shift left 2
Add
PC
Instruction memory
Read address
Instruction [31-0]
Instr [25-21]
Instr [20-16]
Instr [15-11]
Instr [15-0]
MUX
16
read reg 1
read data 1
read reg 2
Registers
write reg
read data 2
write data
Sign extend
32
ALU
zero
ALU result
MUX
read addr
read data
Data memory
write addr
write data
MUX
ALU control
Instr [5-0]

R-type instructions

IF: Instruction fetch

- IR <-- IMemory[PC]
- PC <-- PC + 4

ID: Instruction decode/register fetch

- A <-- Register[IR[25:21]]
- B <-- Register[IR[20:16]]

Ex: Execute

- ALUOutput <-- A op B

MEM: Memory

- nop

WB: Write back

- Register[IR[15:11]] <-- ALUOutput

Load instruction

IF: Instruction fetch

- IR <-- IMemory[PC]
- PC <-- PC + 4

ID: Instruction decode/register fetch

- A <-- Register[IR[25:21]]
- B <-- Register[IR[20:16]]

Ex: Execute

- ALUOutput <-- A + SignExtend(IR[15:0])

MEM: Memory

- Mem-Data <-- DMemory[ALUOutput]

WB: Write back

- Register[IR[20:16]] <-- Mem-Data

Store instruction

IF: Instruction fetch

- IR <-- IMemory[PC]
- PC <-- PC + 4

ID: Instruction decode/register fetch

- A <-- Register[IR[25:21]]
- B <-- Register[IR[20:16]]

Ex: Execute

- ALUOutput <-- A + SignExtend(IR[15:0])

MEM: Memory

- DMemory[ALUOutput] <-- B

WB: Write back

- nop

Branch on equal

IF: Instruction fetch

- **IR <-- IMemory[PC]**
- **PC <-- PC + 4**

ID: Instruction decode/register fetch

- **A <-- Register[IR[25:21]]**
- **B <-- Register[IR[20:16]]**

Ex: Execute

- **Target <-- PC + SignExtend(IR[15:0]) << 2**
- **Z <-- (A - B == 0)**

MEM: Memory

- **If (Z) PC <-- target**

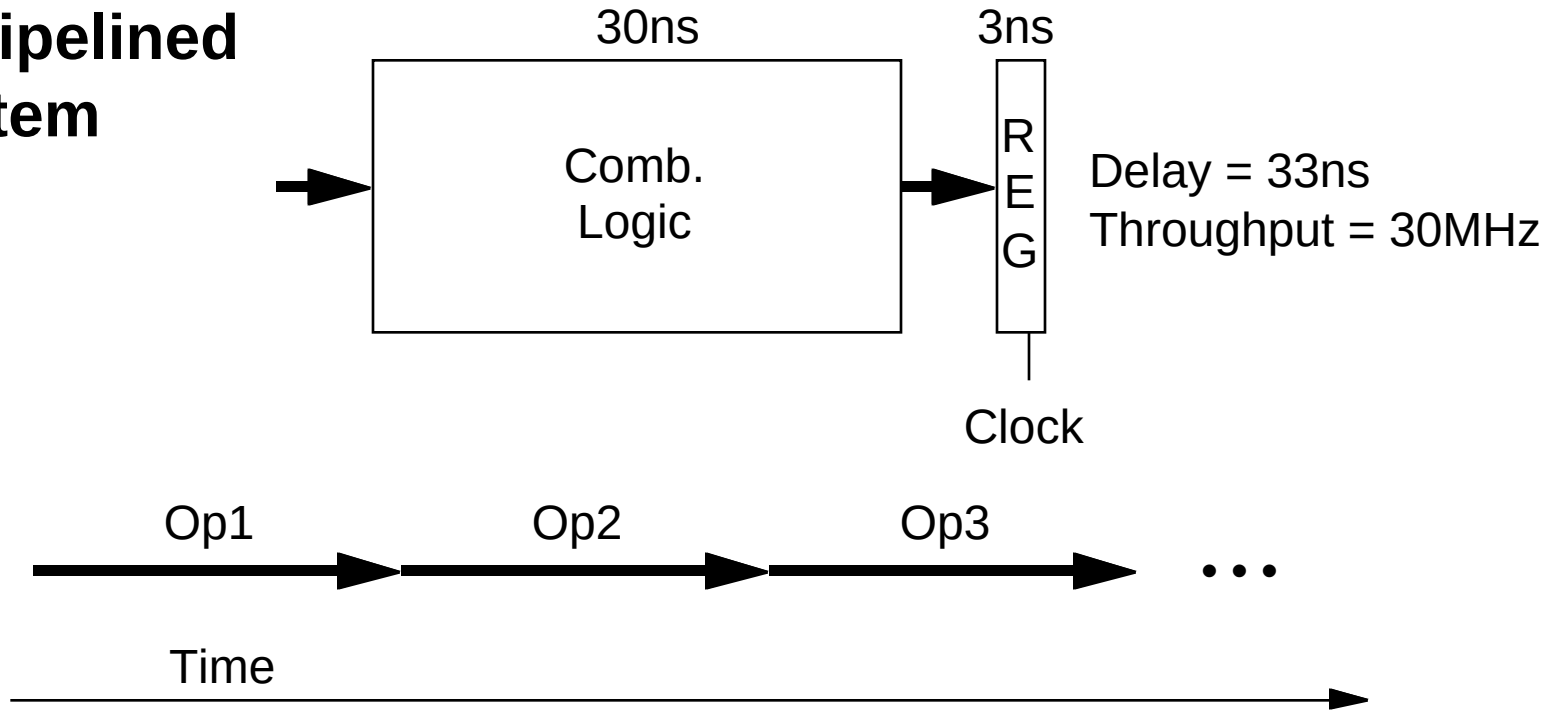
Is this a delayed branch?

WB: Write back

- **nop**

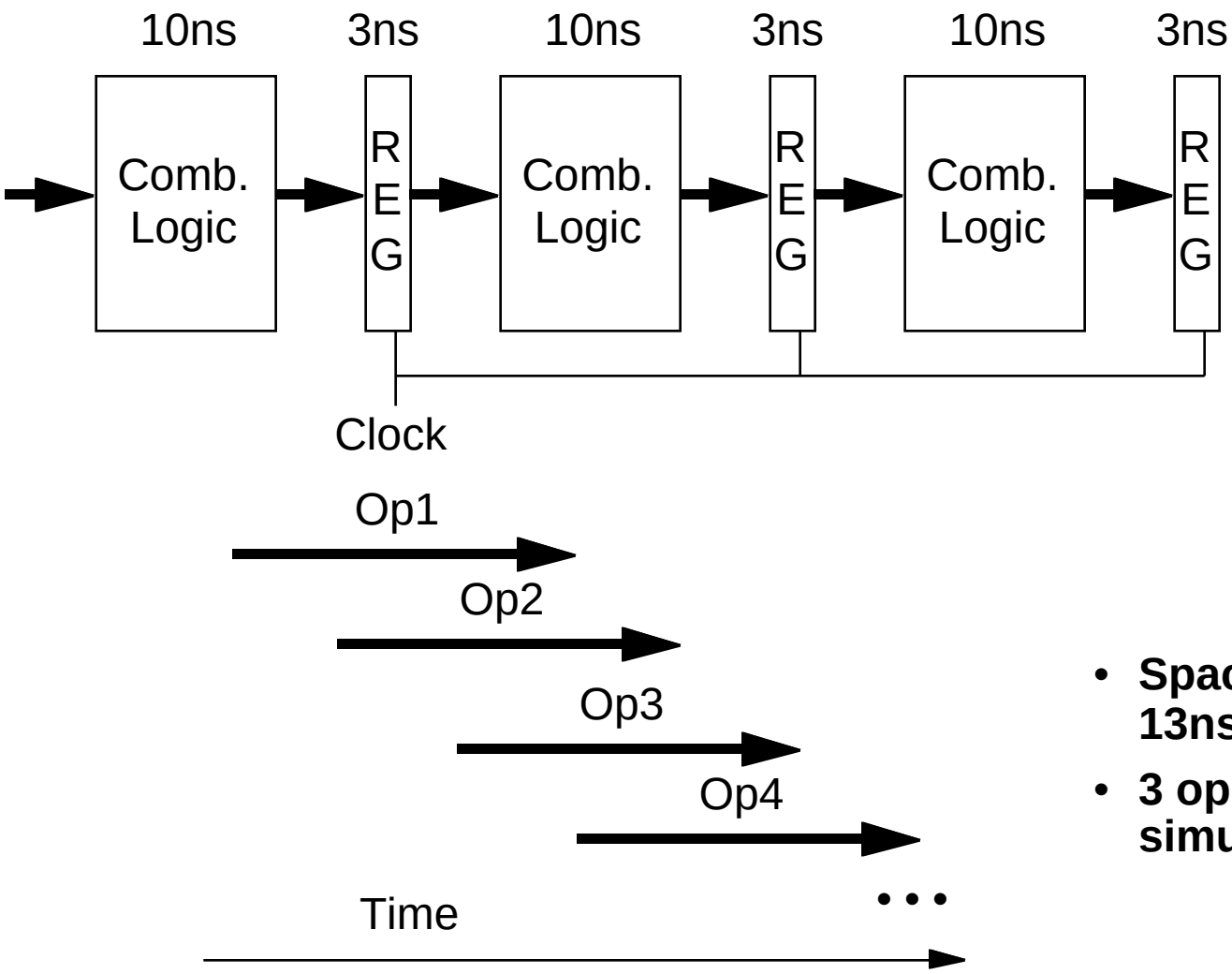
Pipelining Basics

Unpipelined System



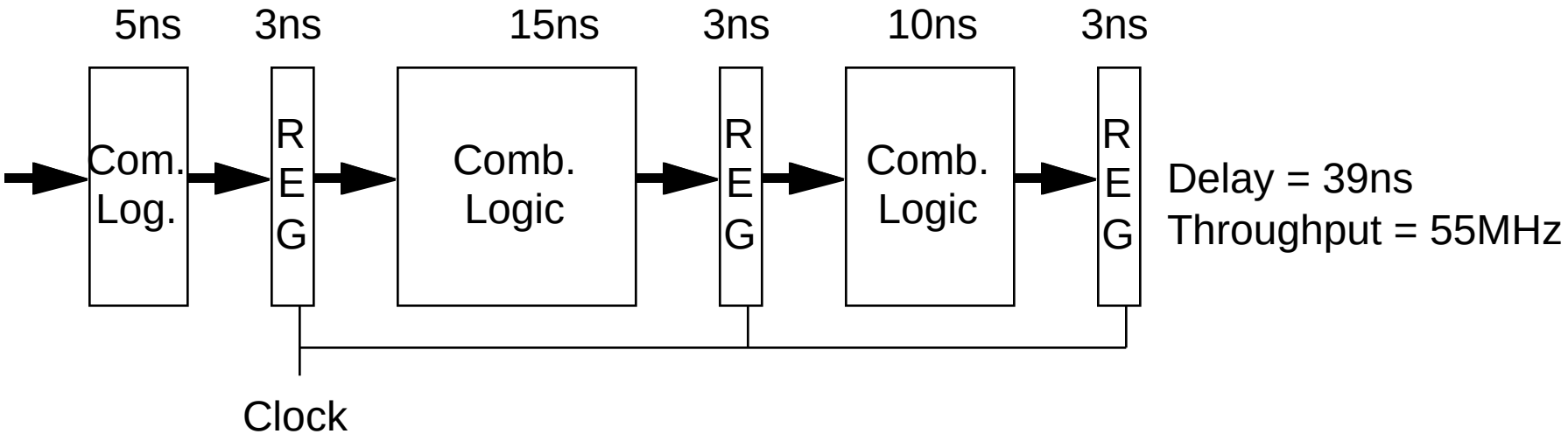
- **One operation must complete before next can begin**
- **Operations spaced 33ns apart**

3 Stage Pipelining



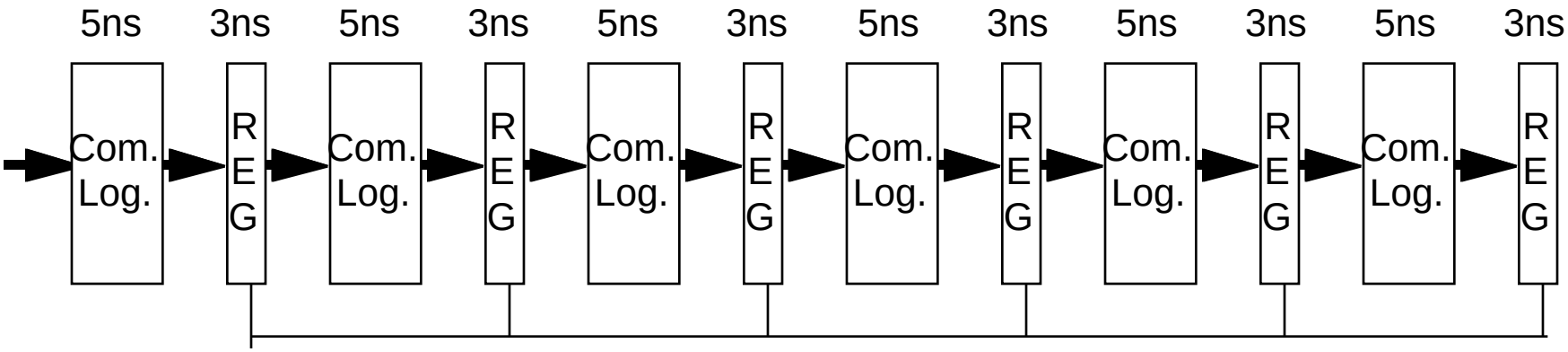
- **Space operations 13ns apart**
- **3 operations occur simultaneously**

Limitation: Nonuniform Pipelining



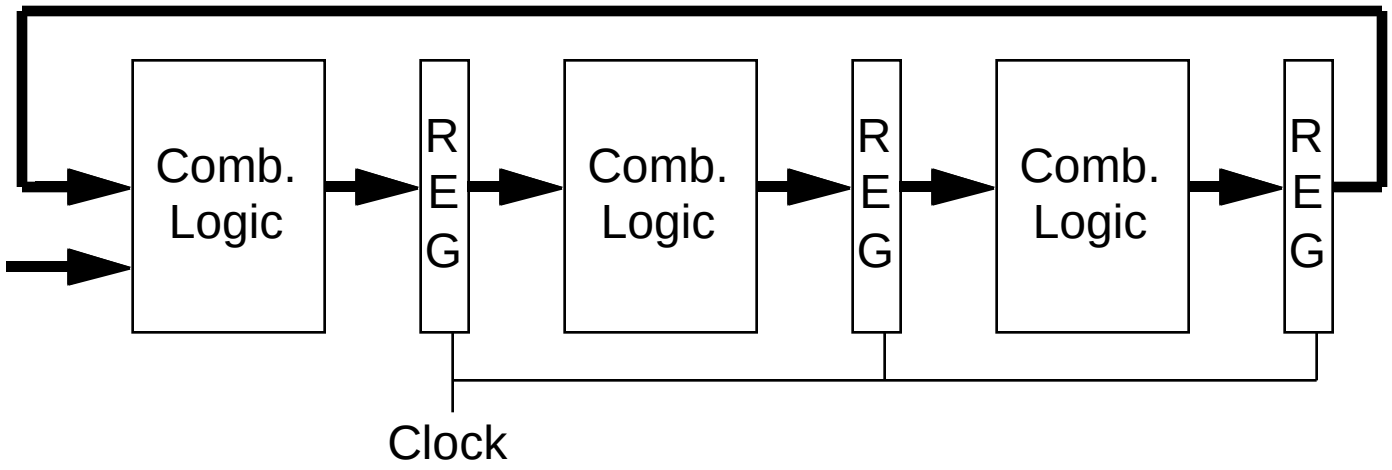
- **Throughput limited by slowest stage**
- **Must attempt to balance stages**

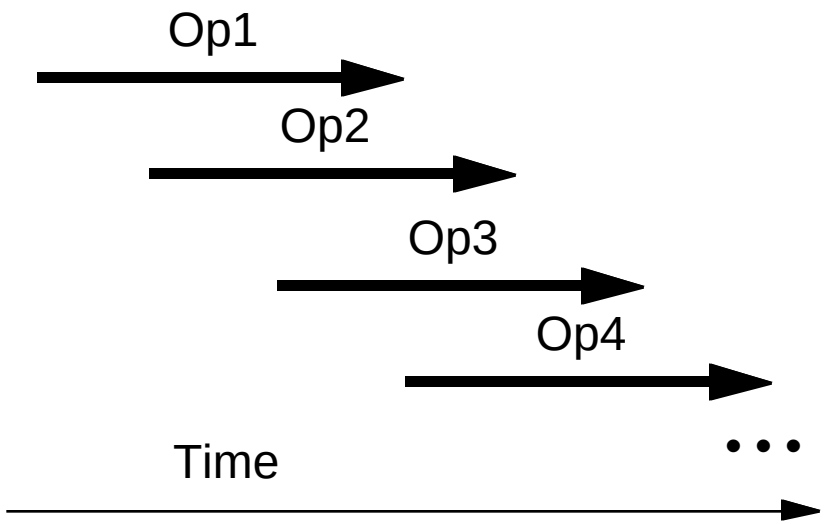
Limitation: Deep Pipelines



- **Diminishing returns as add more pipeline stages**
- **Register delays become limiting factor**
  - Increased latency
  - Small througput gains

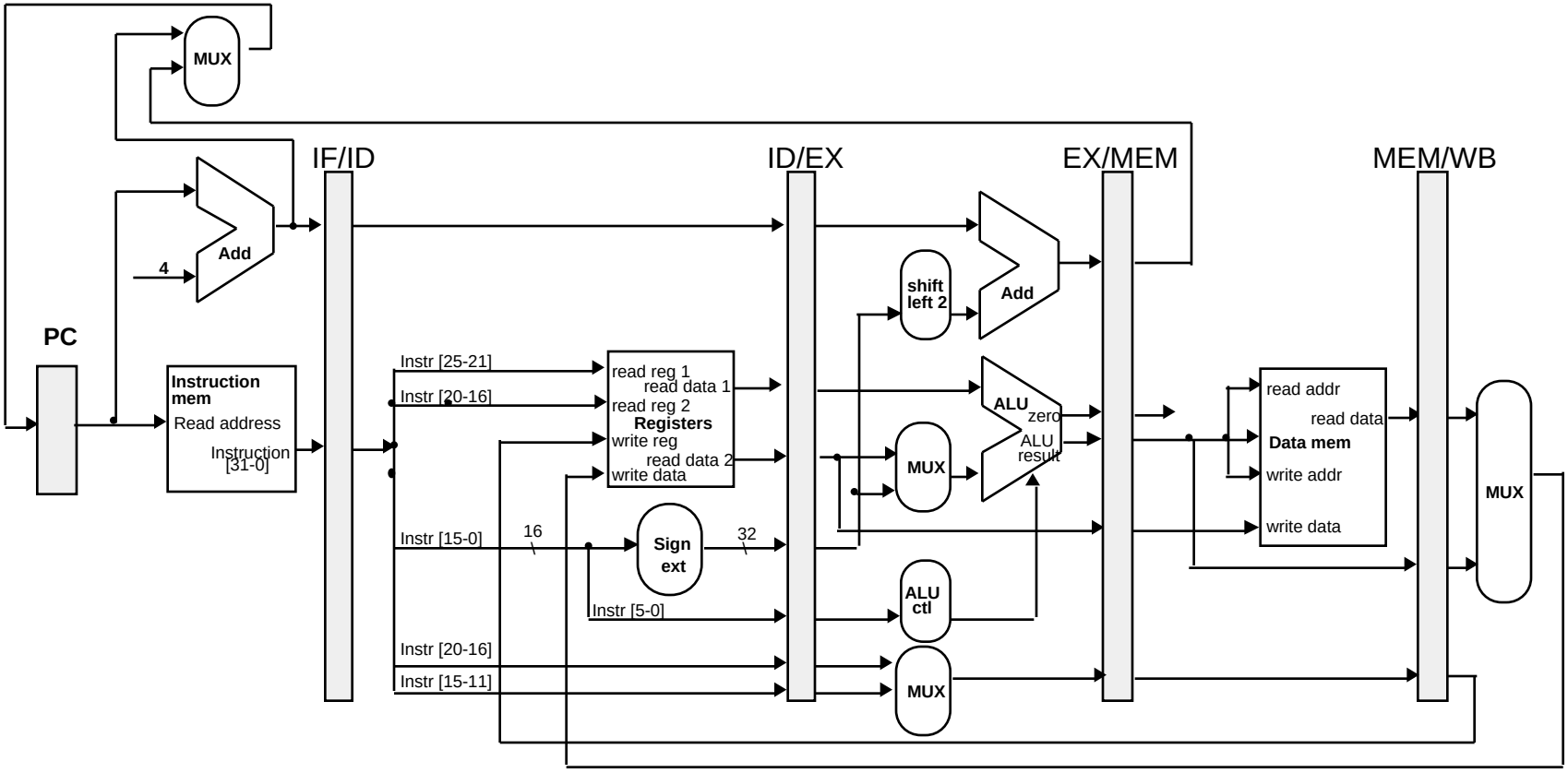
Limitation: Sequential Dependencies



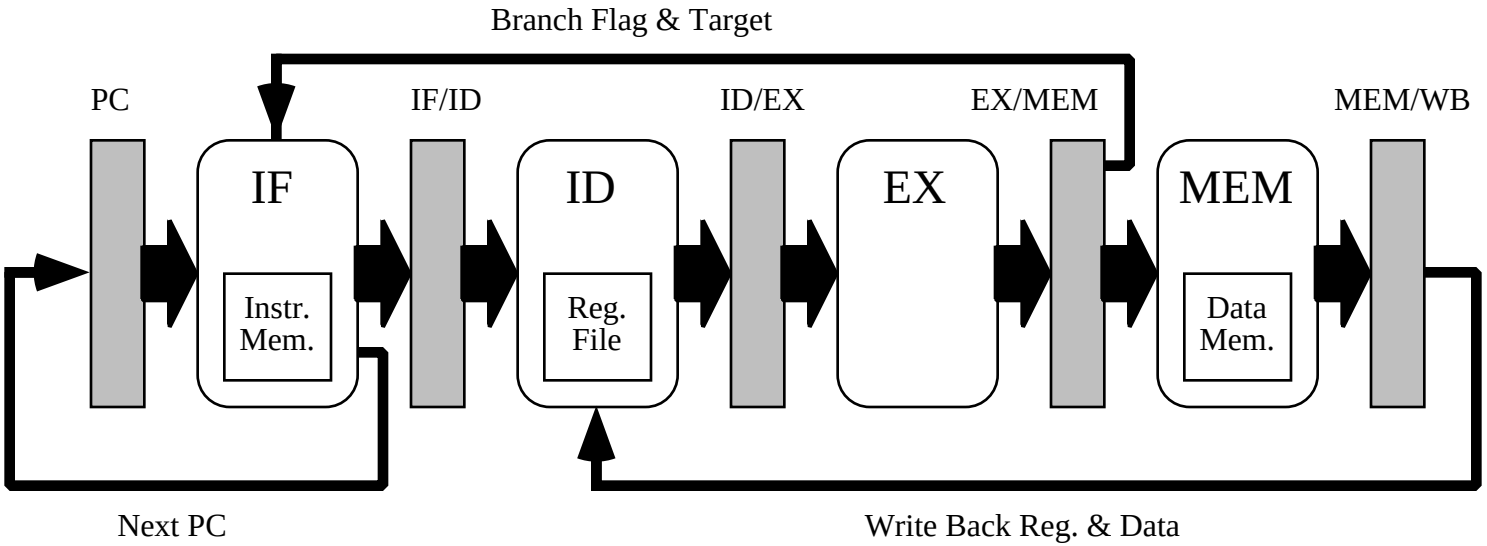


- **Op4 gets result from Op1 !**
- ***Pipeline Hazard***

Pipelined datapath



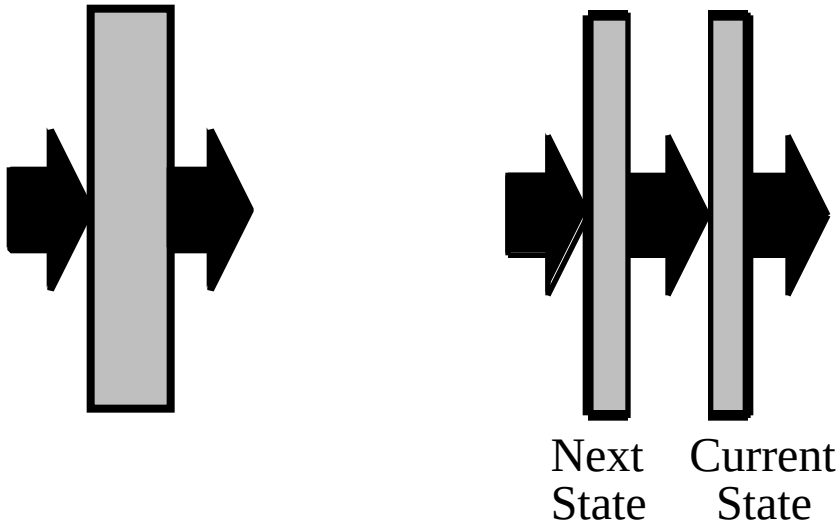
Pipeline Structure



Notes

- **Each stage consists of operate logic connecting pipe registers**
- **WB logic merged into ID**
- **Additional paths required for forwarding**

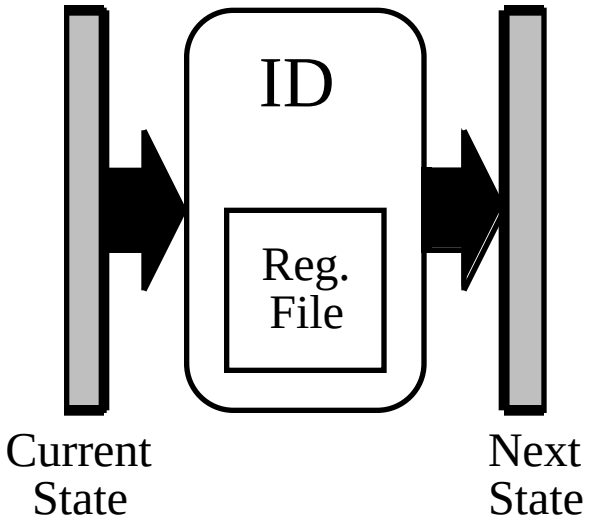
Pipe Register



Operation

- **Current State stays constant while Next State being updated**
- **Update involves transferring Next State to Current**

Pipeline Stage



Operation

- **Computes next state based on current**
  - From/to one or more pipe registers
- **May have embedded memory elements**
  - Low level timing signals control their operation during clock cycle
  - Writes based on current pipe register state
  - Reads supply values for Next state

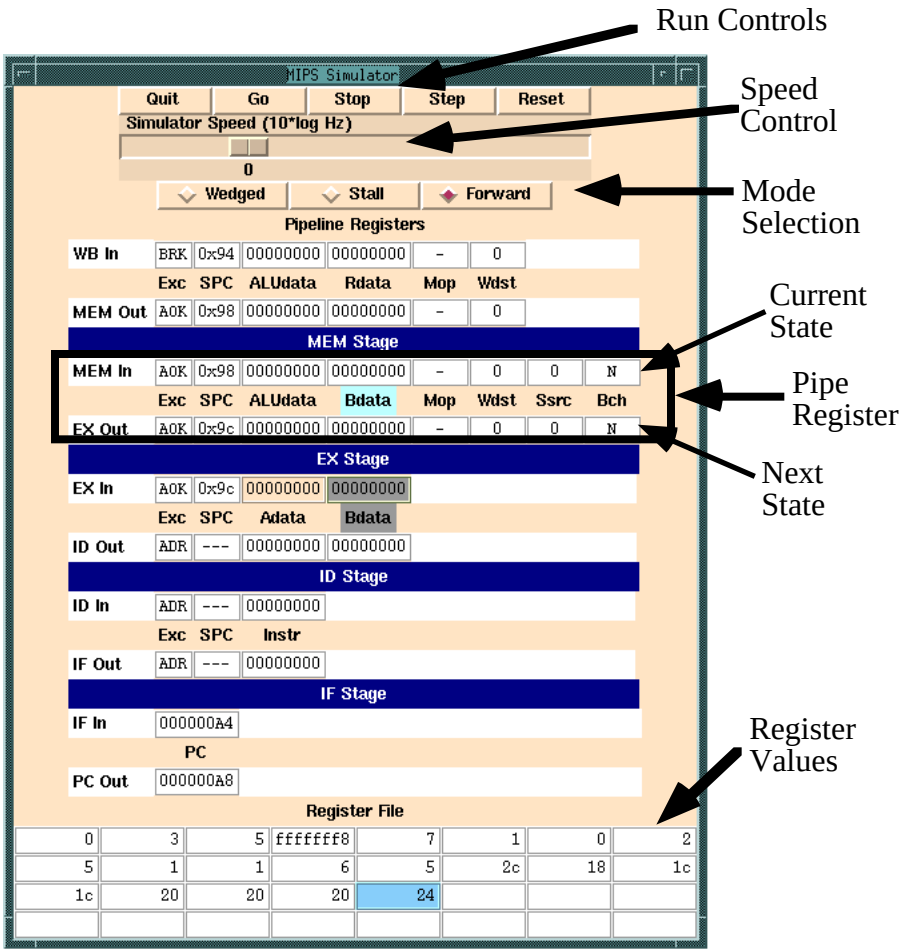
MIPS Simulator

Features

- **Based on MIPS subset**
  - Code generated by `dis`
  - Hexadecimal instruction code
- **Executable available**
  - *HOME*/public/sim/solve_tk

Demo Programs

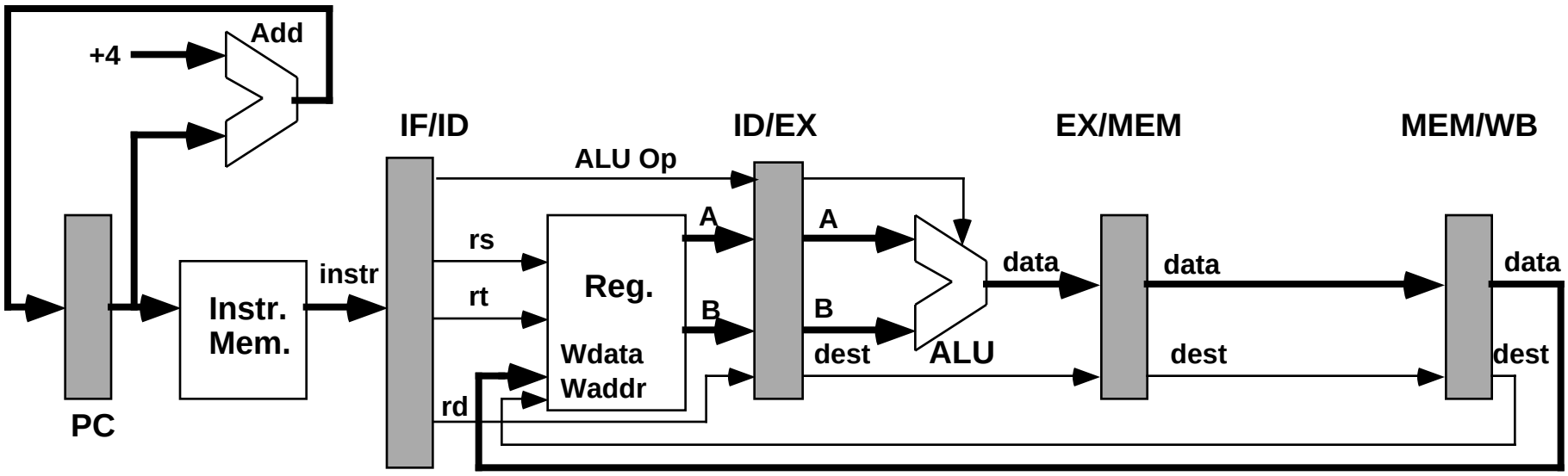
- *HOME*/public/sim/solve_tk/demos



Reg-Reg Instructions

R-type instructions (add, sub, and, or, slt): rd <-- rs funct rt

0	rs	rt	rd	shamt	funct
31-26	25-21	20-16	15-11	10-6	5-0



Simulator ALU Example

IF

- **Fetch instruction**

ID

- **Fetch operands**

EX

- **Compute ALU result**

MEM

- **Nothing**

WB

- **Store result in destination reg.**

demo1.O

```
0x0: 24020003   li      r2,3
0x4: 24030004   li      r3,4
0x8: 00000000   nop
0xc: 00000000   nop
0x10:00432021   addu    r4,r2,r3  # --> 7
0x14:00000000   nop
0x18:0000000d   break   0
0x1c:00000000   nop
```

demo1.s

```
.set noreorder
        addiu $2, $0, 3
        addiu $3, $0, 4
        nop
        nop
        addu $4, $2, $3
        nop
        break 0
.set reorder
```

Simulator Store/Load Examples

IF

- **Fetch instruction**

ID

- **Get addr reg**
- **Store: Get data**

EX

- **Compute EA**

MEM

- **Load: Read**
- **Store: Write**

WB

- **Load: Update reg.**

demo2.O

```
0x0: 24020003  li     r2,3 # Store/Load -->3
0x4: 24030004  li     r3,4 # --> 4
0x8: 00000000  nop
0xc: 00000000  nop
0x10:ac430005  sw     r3,5(r2) # 4 at 8
0x14:00000000  nop
0x18:00000000  nop
0x1c:8c640004  lw     r4,4(r3) # --> 4
0x20:00000000  nop
0x24:0000000d  break  0
0x28:00000000  nop
0x2c:00000000  nop
```

Simulator Branch Examples

IF

- **Fetch instruction**

ID

- **Fetch operands**

EX

- **Subtract operands**
  - test if 0
- **Compute target**

MEM

- **Taken: Update PC to target**

WB

- **Nothing**

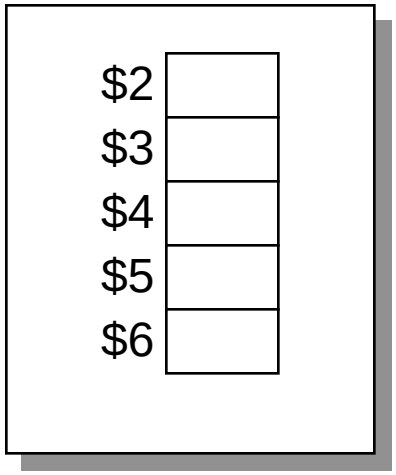
demo3.O

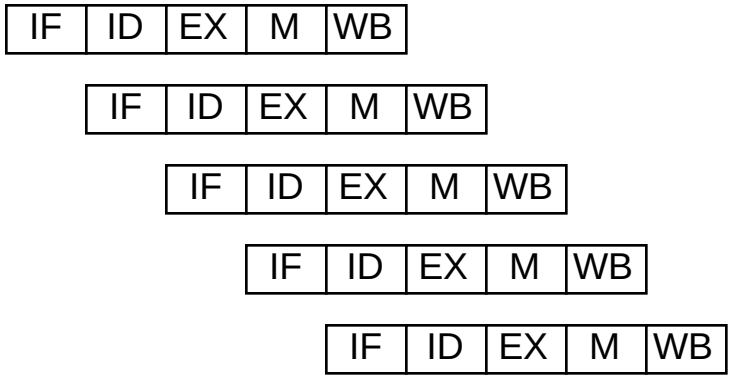
```
0x0: 24020003  li     r2,3
0x4: 24030004  li     r3,4
0x8: 00000000  nop
0xc: 00000000  nop
0x10:10430008  beq    r2,r3,0x34 # Don't take
0x14:00000000  nop
0x18:00000000  nop
0x1c:00000000  nop
0x20:14430004  bne    r2,r3,0x34 # Take
0x24:00000000  nop
0x28:00000000  nop
0x2c:00000000  nop
0x30:00432021  addu   r4,r2,r3 # skip
0x34:00632021  addu   r4,r3,r3 # Target
...
```

Data Hazards in MIPS Pipeline

Problem

- **Registers read in ID, and written in WB**
- **Must resolve conflict between instructions competing for register array**
  - Generally do write back in first half of cycle, read in second
- **But what about intervening instructions?**
- **E.g., suppose initially $2 is zero:**






```
addiu $2, $0, 63
addiu $3, $2, 0
addiu $4, $2, 0
addiu $5, $2, 0
addiu $6, $2, 0
```

Simulator Data Hazard Example

Operation

- **Read in ID**
- **Write in WB**
- **Write-before-read register file**

demo4.O

```
0x0: 2402003f  li    r2,63
0x4: 00401821  move  r3,r2 # --> 0x3F?
0x8: 00402021  move  r4,r2 # --> 0x3f?
0xc: 00402821  move  r5,r2 # --> 0x3f?
0x10:00403021  move  r6,r2 # --> 0x3f?
0x14:00000000  nop
0x18:0000000d  break 0
0x1c:00000000  nop
```

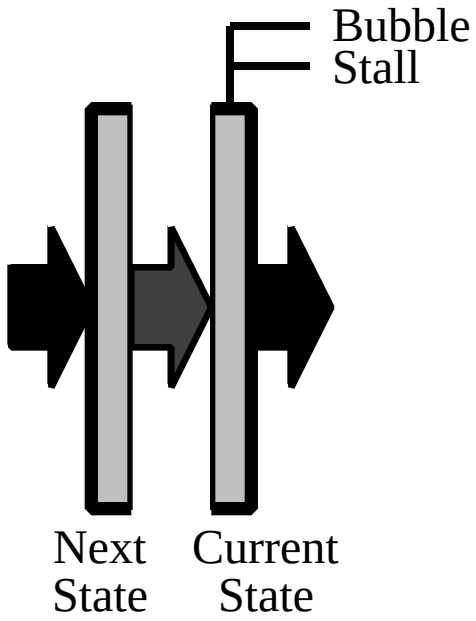
Handling Hazards by Stalling

Idea

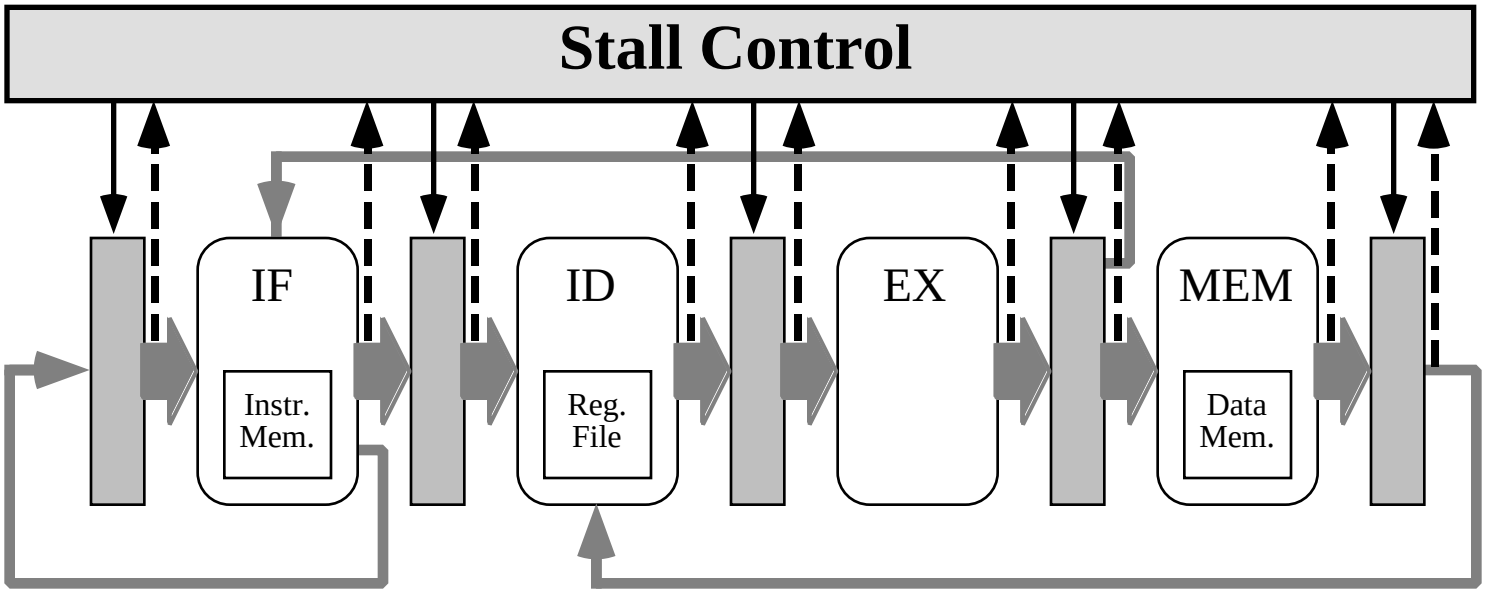
- **Delay instruction until hazard eliminated**
- **Put "bubble" into pipeline**
  - Dynamically generated NOP

Pipe Register Operation

- **Normally transfer next state to current**
- **"Stall" indicates that current state should not be changed**
- **"Bubble" indicates that current state should be set to 0**
  - Stage logic designed so that 0 is like NOP
  - [Other conventions possible]



Stall Control



Stall Logic

- **Determines which stages to stall or bubble on next update**

Observations on Stalling

Good

- **Relatively simple hardware**
- **Only penalizes performance when hazard exists**

Bad

- **As if placed NOP's in code**
  - Except that does not waste instruction memory

Reality

- **Some problems can only be dealt with by stalling**
- **E.g., instruction cache miss**
  - Stall PC, bubble IF/ID
- **Data cache miss**
  - Stall PC, IF/ID, ED/EX, EX/MEM, bubble MEM/WB

Forwarding (Bypassing)

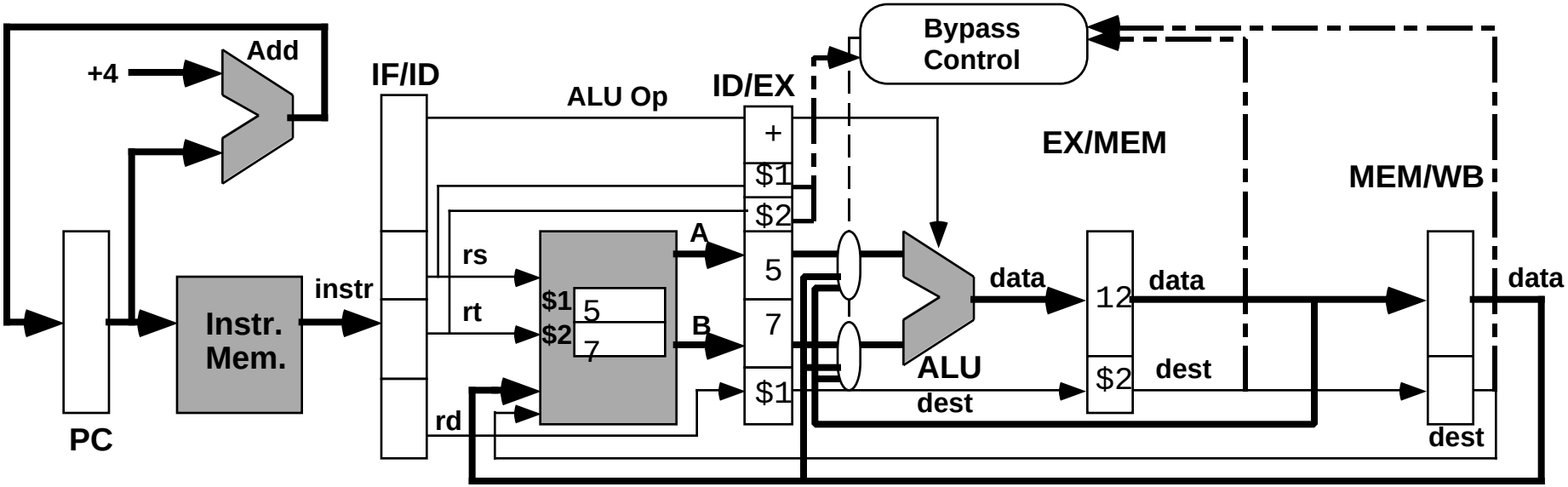
Observation

- **ALU data generated at end of EX**
  - Steps through pipe until WB
- **ALU data consumed at beginning of EX**

Idea

- **Expedite passing of previous instruction result to ALU**
- **By adding extra data pathways and control**

Forwarding for ALU-ALU Hazard



Program:

```
0x18:      add $2, $1, $2
0x1c:      add $1, $1, $2
```

Some Hazards with Loads & Stores

Data Generated by Load

Load-ALU

```
lw $1, 8($2)
add $2, $1, $2
```

Load-Store Data

```
lw $1, 8($2)
sw $1, 12($2)
```

Load-Store (or Load) Addr.

```
lw $1, 8($2)
sw $1, 12($1)
```

Data Generated by Store

Store-Load Data

```
sw $1, 8($2)
lw $3, 8($2)
```

Analysis of Data Transfers

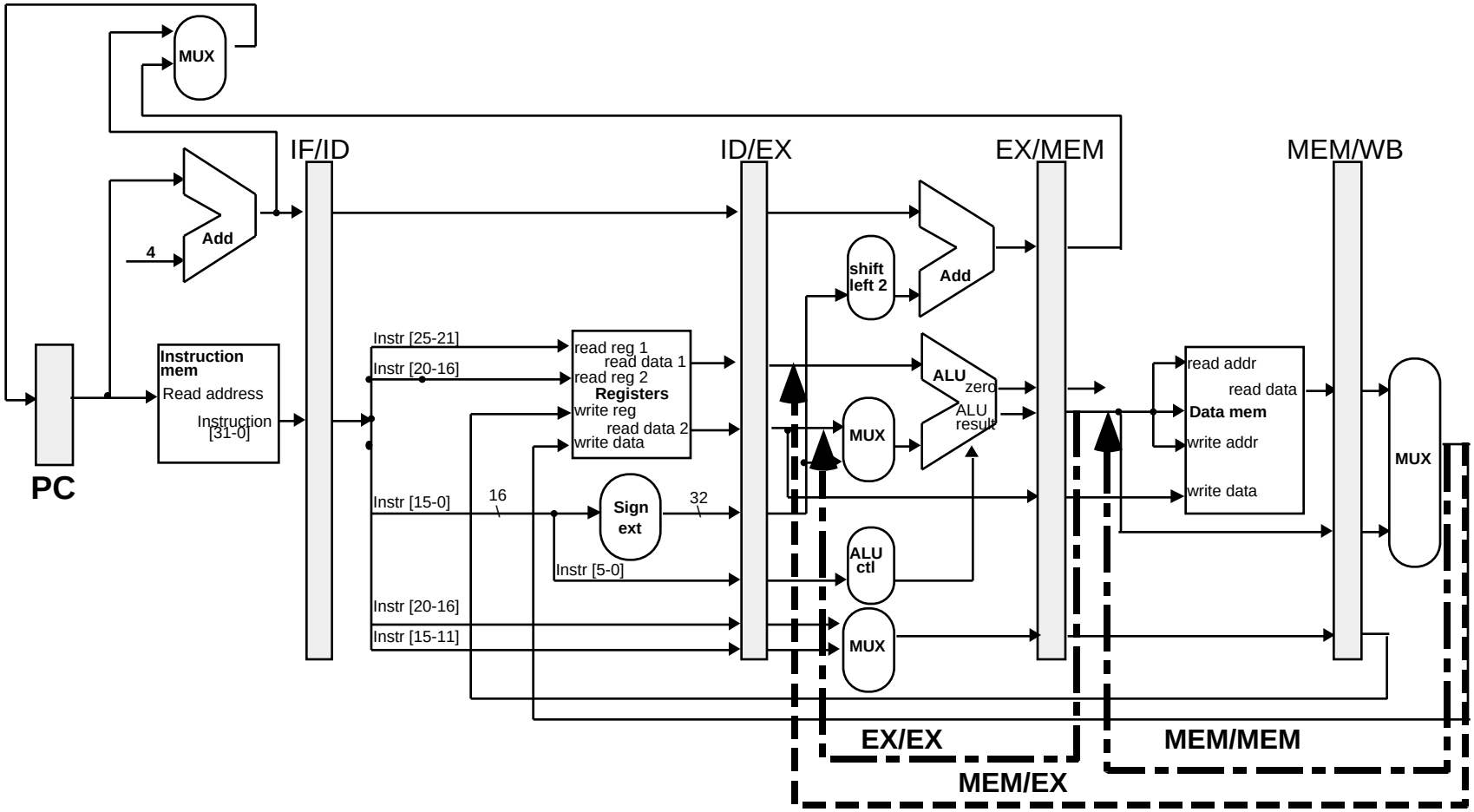
Data Sources

- **Available after EX**
  - ALU Result Reg-Reg Result
- **Available after MEM**
  - Read Data Load result
  - ALU Data Reg-Reg Result passing through MEM stage

Data Destinations

- **ALU A input Need in EX**
  - Reg-Reg Operand
  - Load/Store Base
- **ALU B input Need in EX**
  - Reg-Reg Operand
- **Write Data Need in MEM**
  - Store Data

Complete Bypassing



Simulator Data Hazard Examples

- **demo5.O**

```
0x0:   2402003f li    r2,  63 # --> 0x3F
0x4:   00401821 move  r3,  r2 # --> EX-EX 0x3F
0x8:   00000000 nop
0xc:   00000000 nop
0x10:  2402000f li    r2,  15 # --> 0xF
0x14:  00000000 nop
0x18:  00401821 move  r3,  r2 # --> MEM-EX 0xF
0x1c:  00000000 nop
0x20:  2402000c li    r2,  12 # --> 0xC
0x24:  24020010 li    r2,  16 # --> 0x10
0x28:  ac430000 sw    r3,  0(r2) # EX-EX 0xF at 0x10
0x2c:  00000000 nop
0x30:  8c440000 lw    r4,  0(r2) # --> 0xF
0x34:  00822821 addu  r5,  r4,  r2 # (Stall) --> 0x1F
0x38:  00000000 nop
0x3c:  0000000d break 0
0x40:  00000000 nop
0x44:  00000000 nop
```

Impact of Forwarding

Single Remaining Hazard Class

- **Load followed by ALU operation**
  - Including address calculation

MIPS I Architecture

- **Programmer may not put instruction after load that uses loaded register**
  - Not even allowed to assume it will be old value
  - "Load delay slot"
- **Can force with `.set noreorder`**

MIPS II Architecture

- **No restriction on programs**
- **Stall following instruction one cycle**
- **Then pick up with MEM/EX bypass**

Load-ALU

```
lw $1, 8($2)
add $2, $1, $2
```

Load-Store (or Load) Addr.

```
lw $1, 8($2)
lw $4, 12($1)
```

Methodology for characterizing and Enumerating Data Hazards

OP	writes	reads
R	rd	rs,rt
RI	rt	rs
LW	rt	rs
SW		rs,rt
Bx		rs,rt
JR		rs
JAL	$31	
JALR	rd	rs

The space of data hazards (from a program-centric point of view) can be characterized by 3 independent axes:

5 possible write regs (axis 1):

R.rd, RI.rt, LW.rt, JAL.$31, JALR.rd

10 possible read regs (axis 2):

R.rs, R.rt, RI.rs, RI.rs, SW.rs, SW.rt
Bx.rs, Bx.rt, JR.rs, JALR.rs

A dependent read can be a distance of either 1 or 2 from the corresponding write (axis 3):

distance 2 hazard: R.rd/R.rs/2

addiu **$2**, $0, 63
addu $3, $0, **$2**
addu $4, **$2**, $0

distance 1 hazard: R.rd/R.rt/1

Enumerating data hazards

distance = 1

writes \ reads	R.rs	R.rt	RI.rs	LW.rs	SW.rs	SW.rt	Bx.rs	Bx.rt	JR.rs	JALR.rs
R.rd										
RI.rt										
LW.rt										
JAL.$31							n/a	n/a	n/a	n/a
JALR.rd							n/a	n/a	n/a	n/a

distance = 2

writes \ reads	R.rs	R.rt	RI.rs	LW.rs	SW.rs	SW.rt	Bx.rs	Bx.rt	JR.rs	JALR.rs
R.rd										
RI.rt										
LW.rt										
JAL.$31										
JALR.rd										

Simulator Microtest Example

```
0x0:   24020010    li      r2,16
0x4:   00000000    nop
0x8:   00000000    nop
0xc:   00022821    addu    r5,r0,r2
0x10:  00a00821    move    r1,r5
0x14:  00000000    nop
0x18:  00000000    nop
0x1c:  24040010    li      r4,16
0x20:  00000000    nop
0x24:  00000000    nop
0x28:  1024000b    beq     r1,r4,0x58
0x2c:  00000000    nop
0x30:  00000000    nop
0x34:  00000000    nop
0x38:  00000000    nop
0x3c:  00000000    nop
0x40:  0000000d    break   0
0x44:  00000000    nop
```

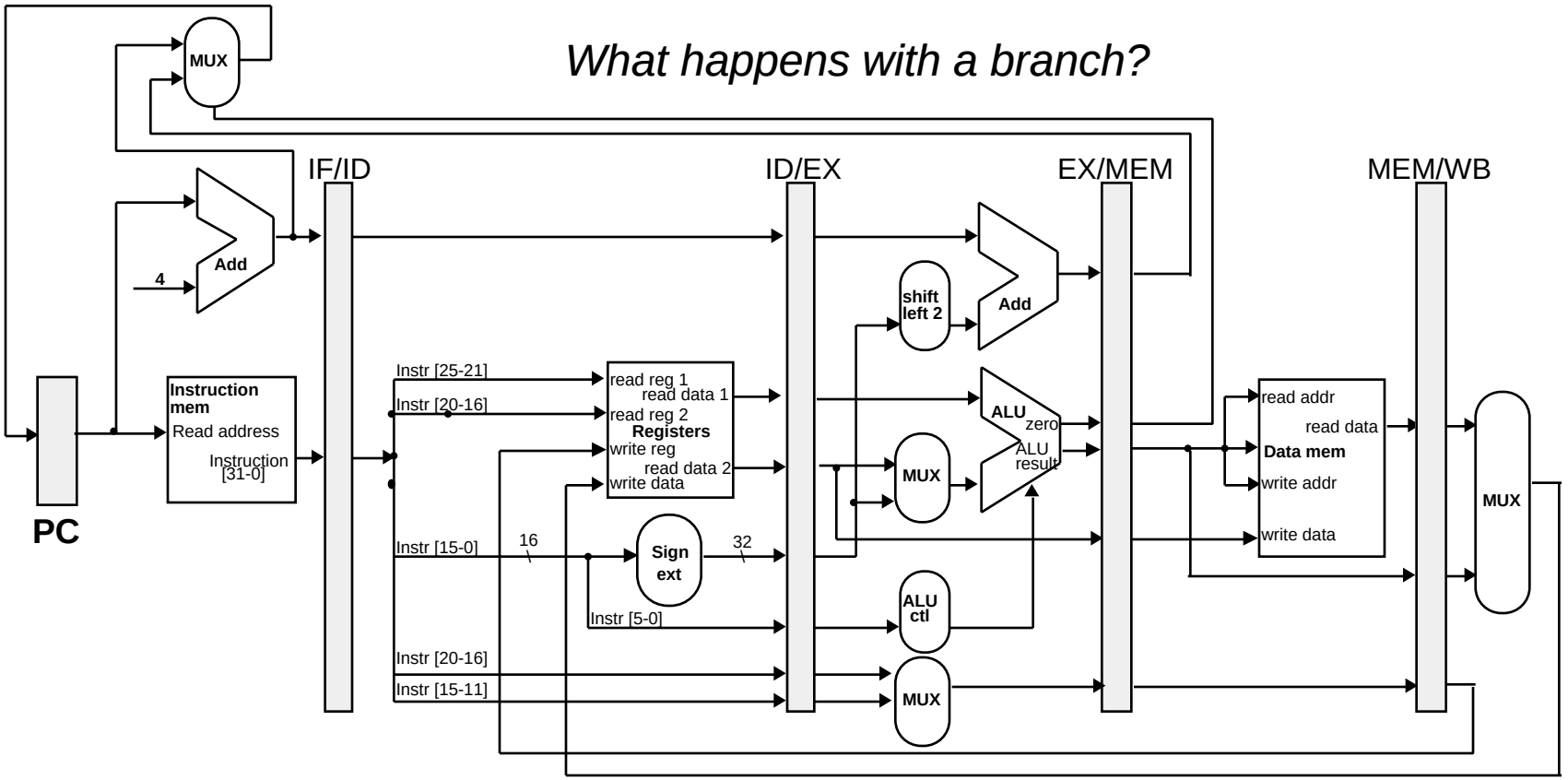
demo7.O

```
0x48:  00000000    nop
0x4c:  00000000    nop
0x50:  00000000    nop
0x54:  00000000    nop
0x58:  0001000d    break   1
0x5c:  00000000    nop
0x60:  00000000    nop
0x64:  00000000    nop
0x68:  00000000    nop
0x6c:  00000000    nop
```

- **Tests for single failure mode**
  - ALU Rd --> ALUI Rs, dist 1
- **Hits `break 0` when error**
- **Jumps to `break 1` when OK**
  - Grep for ERROR or `break 0`

Pipelined datapath

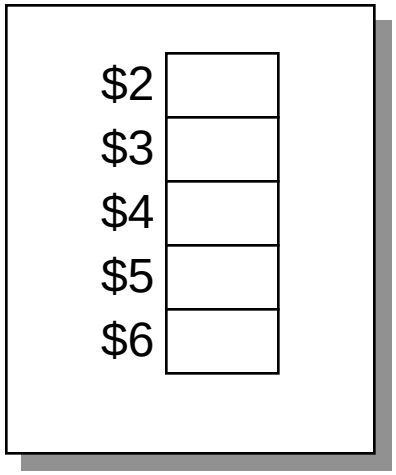
IF	ID	EX	MEM	WB
instruction fetch	instruction decode/ register fetch	execute/ address calc	memory access	write back

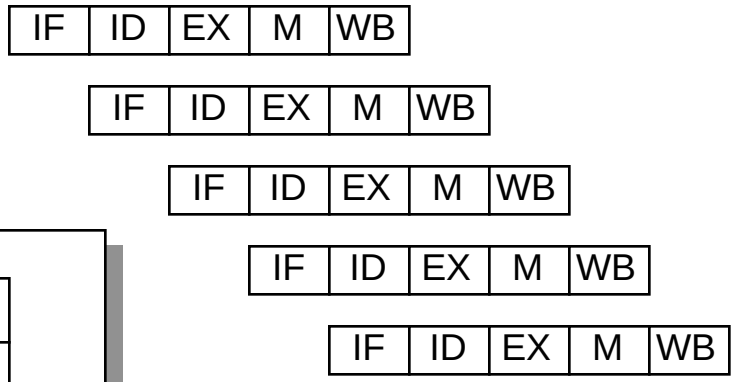


Control Hazards in MIPS Pipeline

Problem

- **Instruction fetched in IF, branch condition set in MEM**
- **When does branch take effect?**
- **E.g.: assume initially that all registers = 0**





beq $0, $0, target

addiu $2, $0, 63

addiu $3, $0, 63

addiu $4, $0, 63

addiu $5, $0, 63

target: addiu $6, $0, 63

Branch Example

Assume

- **All registers initially 0**

Desired Behavior

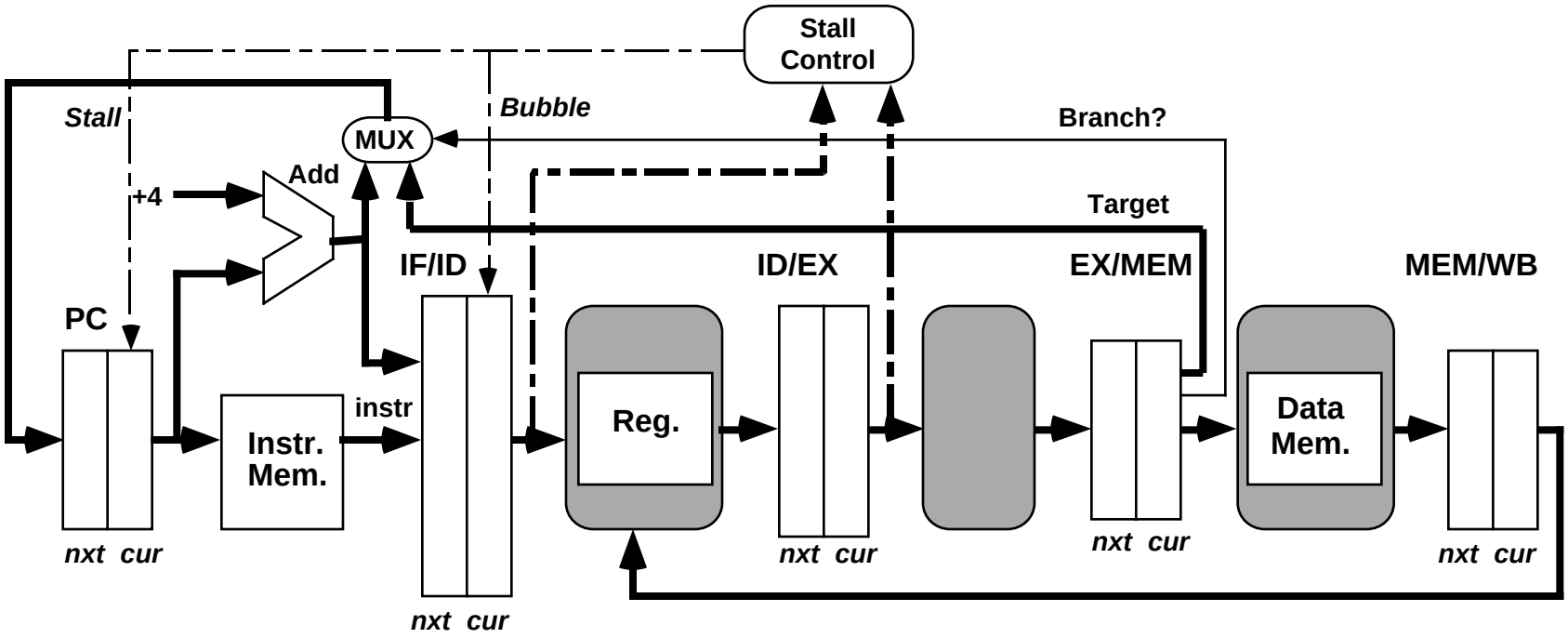
- **Take branch at 0x00**
- **Execute delay slot 0x04**
- **Execute target 0x18**
  - PC + 4 + I16<<2
  - PC = 0x00
  - I16 = 5

Branch Code (demo8.O)

```
0x00:  BEQ  $0, $0, 5
0x04:  li $2, 63  # Slot
0x08:  li $3, 63  # Xtra1
0x0c:  li $4, 63  # Xtra2
0x10:  li $5, 63  # Xtra3
0x14:  nop
0x18:  li $6, 63  # Target
```

Stall Until Resolve Branch

- **Detect when branch in stages ID or EX**
- **Stop fetching until resolve**
- **Delay slot instruction just before target**



Branch Not Taken Example

Assume

- **All registers initially 0**

Desired Behavior

- **Execute entire sequence**

Effect of Stalling

- **Wastes 2 cycles waiting for branch decision**

Branch Code (demo9.O)

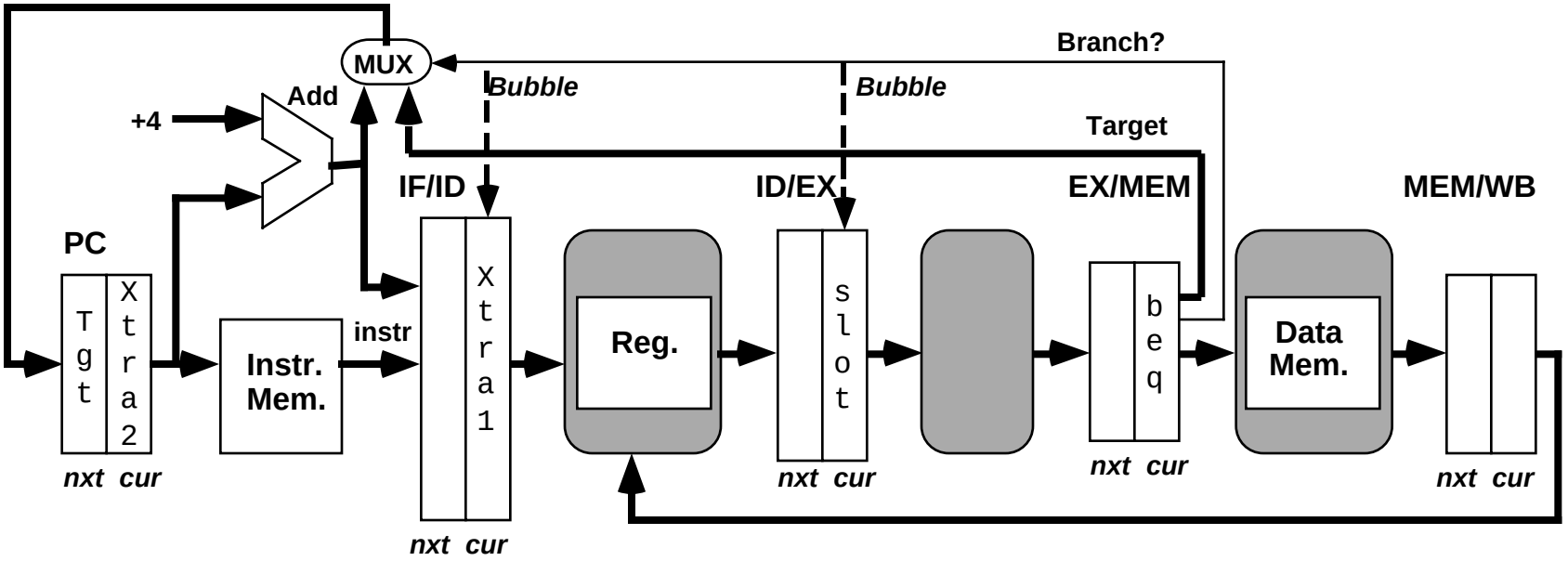
```
0x00:  BNE  $0, $0, 5
0x04:  li $2, 63  # Slot
0x08:  li $3, 63  # Xtra1
0x0c:  li $4, 63  # Xtra2
0x10:  li $5, 63  # Xtra3
0x14:  nop
0x18:  li $6, 63  # Target
```

Fetch & Cancel When Taken

- **Instruction does not cause any updates until MEM or WB stages**
- **Instruction can be "cancelled" from pipe up through EX stage**
  - Replace with bubble

Strategy

- **Continue fetching under assumption that branch not taken**
- **If decide to take branch, cancel undesired ones**



Branch Prediction Analysis

Our Scheme Implements “Predict Not Taken”

- **But 67% of branches are taken**
- **Would give CPI ≥ 1.0 + 0.16 * 0.67 * 2.0 = 1.22**

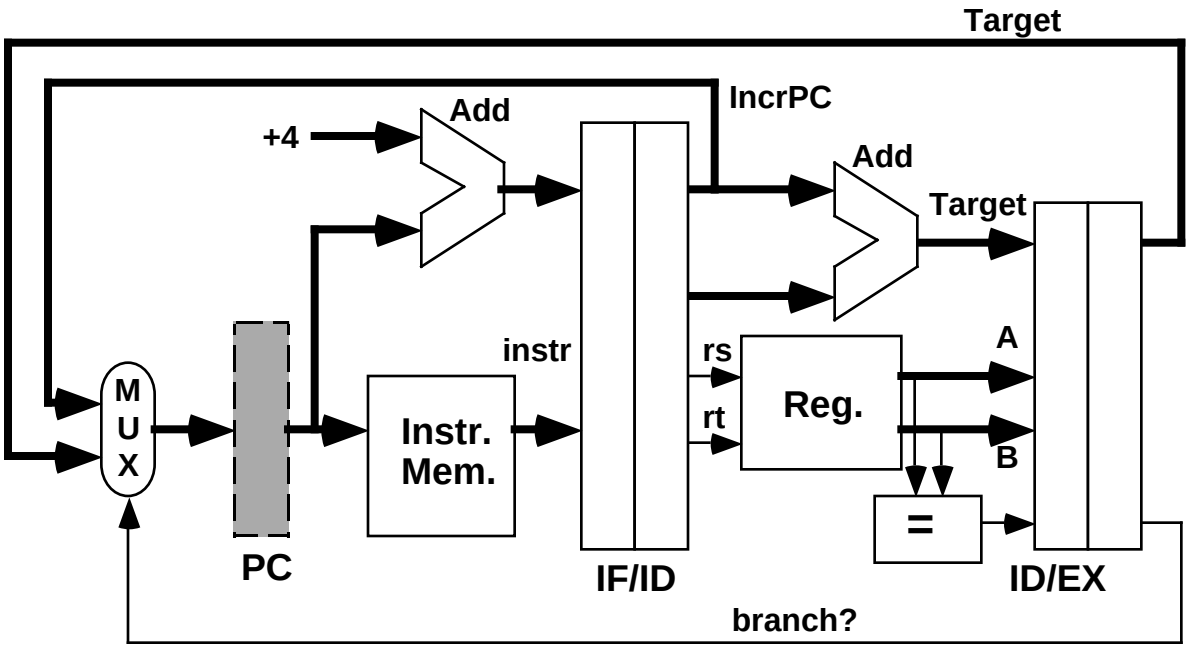
Alternative Schemes

- **Predict taken**
  - Would be hard to squeeze into our pipeline
    - » Can’t compute target until ID
  - In principle, would give CPI ≥ 1.11
- **Backwards taken, forwards not taken**
  - Predict based on sign of I16
  - Exploits fact that loops usually closed with backward branches

How Does Real MIPS Handle Branches?

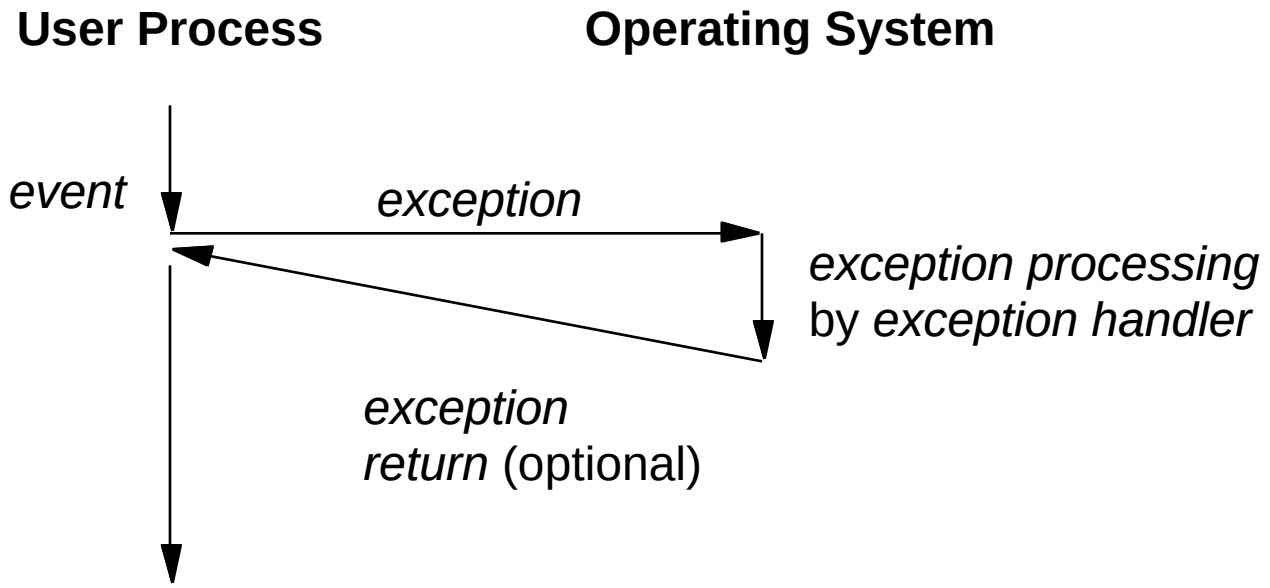
Avoids any Branch Penalty!

- **Do not treat PC as pipe register**
  - Loaded at beginning of IF
- **Compute branch target & branch condition in ID**
  - Can fetch at target in following cycle



Exceptions

An *exception* is a transfer of control to the OS in response to some *event* (i.e. change in processor state)



Internal (CPU) exceptions

Internal exceptions occur as a result of events generated by executing instructions.

Execution of a SYSCALL instruction.

- **allows a program to ask for OS services (e.g., timer updates)**

Execution of a BREAK instruction

- **used by debuggers**

Errors during instruction execution

- **arithmetic overflow, address error, parity error, undefined instruction**

Events that require OS intervention

- **virtual memory page fault**

External (I/O) exceptions

External exceptions occur as a result of events generated by devices external to the processor.

I/O interrupts

- **hitting ^C at the keyboard**
- **arrival of a packet**
- **arrival of a disk sector**

Hard reset interrupt

- **hitting the reset button**

Soft reset interrupt

- **hitting ctl-alt-delete on a PC**

Exception handling (hardware tasks)

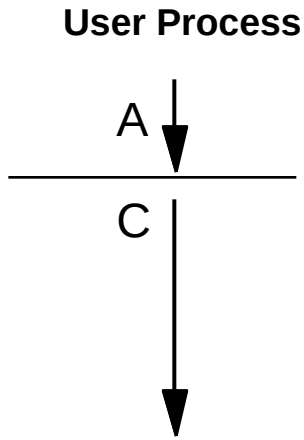
Recognize event(s)

Associate one event with one instruction.

- external event: pick any instruction
- multiple internal events: typically choose the earliest instruction.
- multiple external events: prioritize
- multiple internal and external events: prioritize

Create Clean Break in Instruction Stream

- Complete all instructions before excepting instruction
- Abort excepting and all following instructions



Exception handling (hardware tasks)

Set status registers

- **EPC register: exception program counter**
  - external exception: address of instruction about to be executed.
  - internal exception (not in the delay slot): address of instruction causing the exception
  - internal exception (in delay slot): address of preceding branch or jump
- **Cause register**
  - records the event that caused the exception
- **Others**
  - 15 other registers! Which get set depends on CPU and exception type

Disable interrupts and switch to kernel mode

Jump to common exception handler location

Exception handling (software tasks)

Deal with event

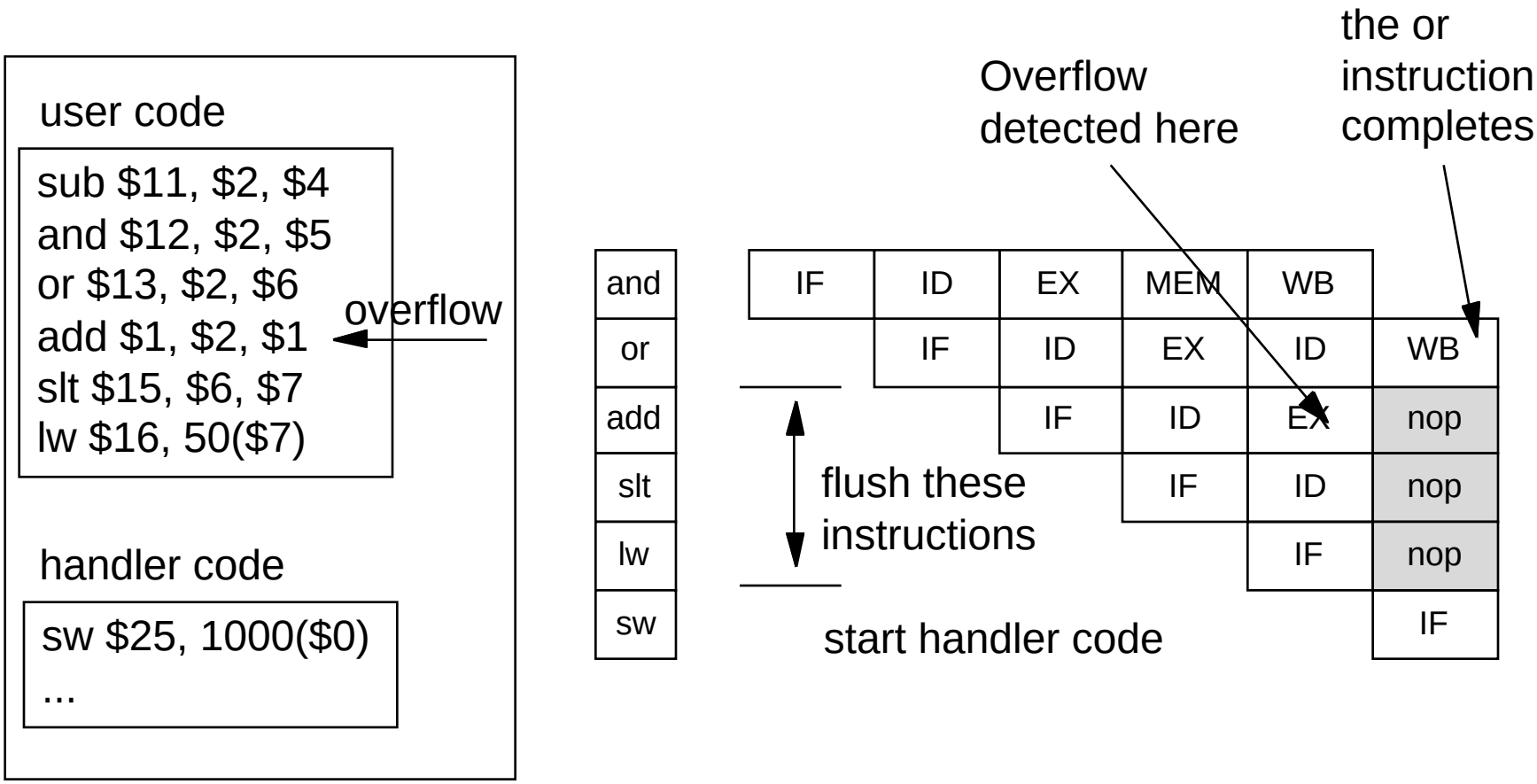
(Optionally) Resume execution

- **using special `rfe` (return from exception) instruction**
- **similar to `jr` instruction, but restores processor to user mode as a side effect.**

Where to resume execution?

- **usually re-execute the instruction causing exception**
- **unless instruction was in branch delay slot, in which case re-execute the branch instruction immediately preceding the delay slot**
  - EPC points here anyhow
- **Also, what about `syscall` or `break`?**

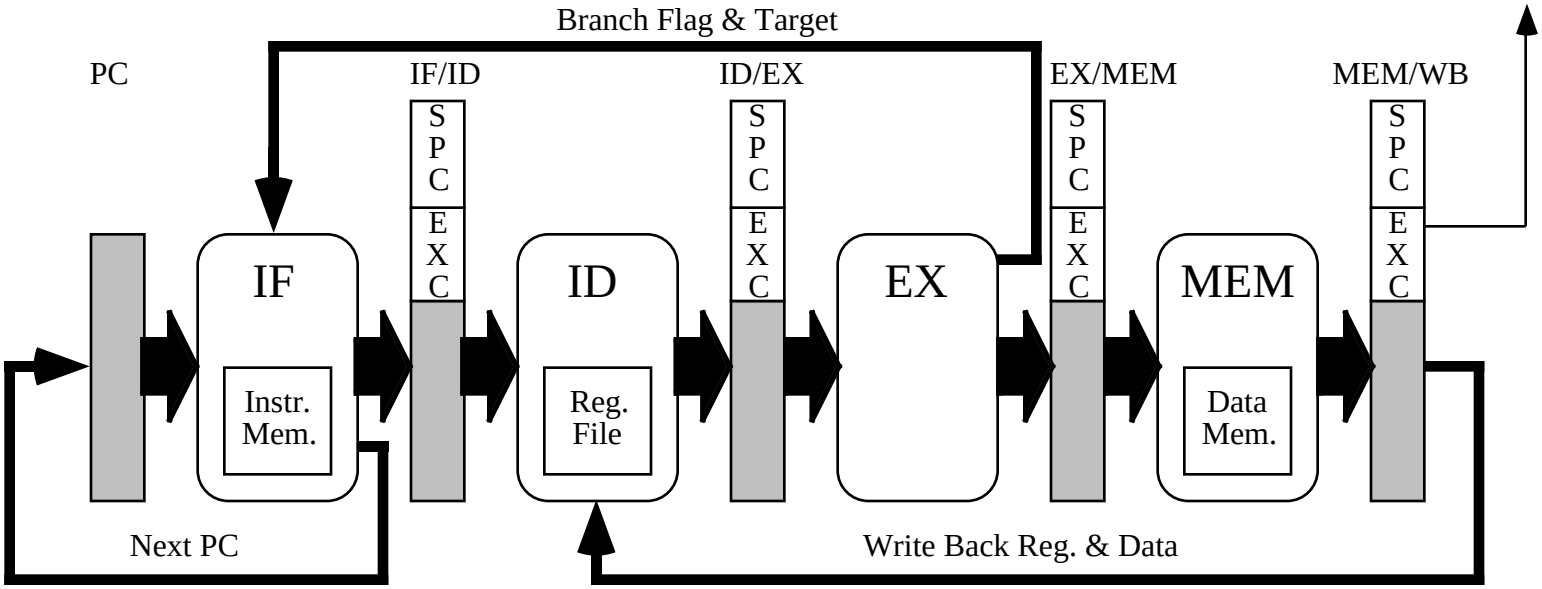
Example: Integer overflow (EX)



Exception Handling In pMIPS Simulator

Relevant Pipeline State

- **Address of instruction in pipe stage (SPC)**
- **Exception condition (EXC)**
  - Set in stage when problem encountered
    - » IF for fetch problems, EX for instr. problems, MEM for data probs.
  - Triggers special action once hits WB



MIPS Exception Examples

- **In directory *HOME*/public/sim/exc**

Illegal Instruction (exc1.O)

```
0x0: srl  r3,r2,4  # Unimplemented
0x4: li   r2,4     # Should cancel
```

Illegal Instruction followed by store (exc2.O)

```
0x0:  li   r2,15    # --> 0xf
0x4:  srl  r3,r2,4  # Unimplemented
0x8:  sw   r2,4(r0) # Should cancel
```

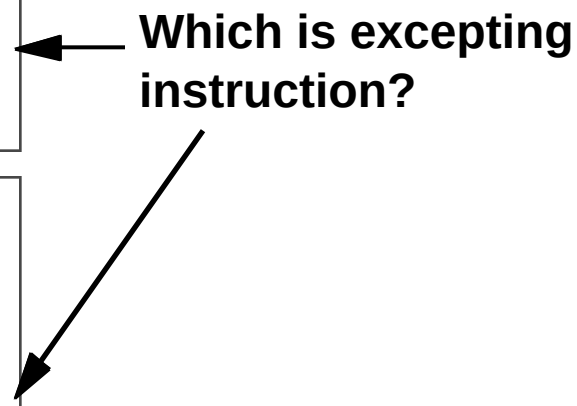
More MIPS Exception Examples

Good instruction in delay slot (exc3.O)

```
0x0: li   r3,3
0x4: jr   r3        # Bad address
0x8: li   r3,5      # Should execute
```

Bad instruction in delay slot (exc4.O)

```
0x0: li   r3,3
0x4: jr   r3        # Bad address
0x8: sw   r3,0(r3) # Bad address
```



Final MIPS Exception Example

Avoiding false alarms (exc5.O)

```
  0x0:  beq  r2,r2,0x10
  0x4:  nop
  0x8:  srl  r2,r4,4   # Should cancel
  0xc:  nop
  0x10: li   r2,1      # --> 1
  0x14: break          0
```

Implementation Features

Correct

- **Detects excepting instruction (exc4.O)**
  - Furthest one down pipeline = Earliest one in program order
- **Completes all preceding instructions (exc3.O)**
- **Usually aborts excepting instruction & beyond (exc1.O)**
- **Prioritizes exception conditions**
  - Earliest stage where instruction ran into problems
- **Avoids false alarms (exc5.O)**
  - Problematic instructions that get canceled anyhow

Shortcomings

- **Store following excepting instruction (exc2.O)**
- **EPC ≠ SPC for delay slot instruction**