Pipeline Hazards

or

Danger! Danger! Danger!

Data Hazards

ADD R1, R2, R3
SUB R4, R5, R1
AND R6, R1, R7
OR R8, R1, R9
XOR R10, R1, R11

Data ___________ may result in data ____________.

Data Hazards

lw R8, 10000(R3)  add R6, R2, R1  addi R3, R1, #35

Data Hazard
**Data Dependence**

- Data hazards are caused by data dependences
- Data dependences, and thus data hazards, come in 3 flavors (not all of which apply to this pipeline).
  - (read-after-write)
  - (write-after-write)
  - (write-after-read)

**RAW Hazard**

- later instruction tries to read an operand before earlier instruction writes it
- The dependence
  
  ```
  add R1, R2, R3
  sub R5, R1, R4
  ```

- The hazard
  
  ```
  IF | ID | EX | MEM | WB
  --|----|----|-----|-----
  IF | ID | EX | MEM | WB
  ```

- RAW hazard is extremely common

**WAW Hazard**

- later instruction tries to write an operand before earlier instruction writes it
- The dependence
  
  ```
  add R1, R2, R3
  sub R1, R2, R4
  ```

- The hazard
  
  ```
  lw R1, R2, R3
  sub R1, R2, R4
  ```

- WAW hazard possible in a reasonable pipeline, but not in the very simple pipeline we’re assuming.

**WAR Hazard**

- later instruction tries to write an operand before earlier instruction reads it
- The dependence
  
  ```
  add R1, R2, R3
  sub R2, R5, R4
  ```

- The hazard
  
  ```
  IF | ID | EX | MEM | WB
  --|----|----|-----|-----
  IF | ID | EX | MEM | WB
  ```

- WAR hazard is uncommon/impossible in a reasonable (in-order) pipeline
Dealing with Data Hazards through Forwarding

Forwarding Options

- ADD -> ADD
- ADD -> LW
- ADD -> SW (2 operands)
- LW -> ADD
- LW -> LW
- LW -> SW (2 operands)

(I’m letting ADD stand in for all ALU operations)
More Forwarding

DM
ALU
ALU
ALU
DM
CC
CC
CC
CC
CC
CSE 240A
Dean Tullsen

Forwarding and Stalling

DM
ALU
ALU
ALU
DM
Reg
Reg
Reg
Reg
Reg
RegIM
RegIM
RegIM
Reg
Reg
Reg
Reg
Reg
RegIM
Reg
RegIM
Reg
RegIM
Reg
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
RegIM
How big a problem are these pipeline stalls?

- 13% of the loads in FP programs
- 25% of the loads in integer programs

Detecting ALU Input Hazards

Inserting Bubbles

- Set all control values in the EX/MEM register to safe values (equivalent to a nop)
- Keep same values in the ID/EX register and IF/ID register
- Keep PC from incrementing

Adding Datapaths
Control Hazards

- Result from branch or control __________
- Instructions are not only dependent on instructions that produce their operands, but also on all previous control flow (branch, jump) instructions that lead to that instruction.

Branch Hazards

<table>
<thead>
<tr>
<th>Branch</th>
<th>IF</th>
<th>ID</th>
<th>EX</th>
<th>MEM</th>
<th>WB</th>
</tr>
</thead>
<tbody>
<tr>
<td>l2</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
</tr>
<tr>
<td>l3</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
</tr>
<tr>
<td>l4</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
</tr>
<tr>
<td>correct instruction</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
</tr>
</tbody>
</table>

Old Datapath

Branch Stall Impact

- If CPI = 1, 30% branch, Stall 3 cycles => new CPI = ???
- Two part solution:
  - Determine branch taken or not sooner, AND
  - Compute taken branch address earlier
- (limited MIPS) branch tests if register = 0 or \( \neq \) 0
- MIPS Solution:
  - Move Zero test to ID/RF stage
  - Adder to calculate new PC in ID/RF stage
  - 1 clock cycle penalty for branch versus 3
New Datapath

Branch Hazards

What We Know About Branches

- more conditional branches than unconditional
- more forward than backward
- 67% of branches taken
- backward branches taken 80%

Four Branch Hazard Alternatives

- 4 – delayed branch
______ until branch direction clear

- Problems?

- Execute successor instructions in sequence
- “Squash” instructions in pipeline if branch actually taken
- Advantage of late pipeline state update
- 33% MIPS branches not taken on average
- PC+4 already calculated, so use it to get next instruction
- This is what the pipeline is doing, anyway

- 67% MIPS branches taken on average
- But haven’t calculated branch target address in this MIPS architecture
  - MIPS still incurs 1 cycle branch penalty
  - Other machines: branch target known before outcome

Fourth Branch Hazard Alternatives – Delayed Branch

- Define branch to take place AFTER a following instruction
  - Branch instruction
  - sequential successor₁
  - sequential successor₂
  - ...........
  - sequential successorₙ
  - branch target if taken
  - 1 slot delay allows proper decision and branch target address in 5 stage pipeline
  - MIPS uses this
Delayed Branch

- Where to get instructions to fill branch delay slot?
  - Before branch instruction
  - From the target address: only valuable when branch taken
  - From fall through: only valuable when branch not taken
  - Cancelling branches allow more slots to be filled

- Compiler effectiveness for single branch delay slot:
  - Fills about 60% of branch delay slots
  - About 80% of instructions executed in branch delay slots useful in computation
  - About 50% (60% x 80%) of slots usefully filled

Key Points

- Hard to keep the pipeline completely full
- Data Hazards require dependent instructions to wait for the producer instruction
  - Most of the problem handled with forwarding (bypassing)
  - Sometimes stall still required (especially in modern processors)
- Control hazards require control-dependent (post-branch) instructions to wait for the branch to be resolved