18-447 Lecture 8: Data Hazard and Resolution

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Housekeeping

• Your goal today
  – detect and resolve data hazards in in-order instruction pipelines
  – control dependence next time

• Notices
  – HW 2, due Mon 2/21
  – Lab 2, status check wk6, due wk7 (Handout #7)
  – HW 3, due Mon 2/28 (Handout #8)

• Readings
  – P&H Ch 4
Instruction Pipeline Reality

- Not identical tasks
  - coalescing instruction types into one “multi-function” pipe
  - external fragmentation (some idle stages)

- Not uniform suboperations
  - group or sub-divide steps into stages to minimize variance
  - internal fragmentation (some too-fast stages)

- Not independent tasks
  - dependency detection and resolution
  - next lecture(s)

Even more messy if not RISC
Data Dependence

Data dependence

Read-after-Write (RAW)
\[
x_3 \leftarrow x_1 \text{ op } x_2
\]
\[
\ldots
\]
\[
x_5 \leftarrow x_3 \text{ op } x_4
\]

Anti-dependence

Write-after-Read (WAR)
\[
x_3 \leftarrow x_1 \text{ op } x_2
\]
\[
\ldots
\]
\[
x_1 \leftarrow x_4 \text{ op } x_5
\]

Output-dependence

Write-after-Write (WAW)
\[
x_3 \leftarrow x_1 \text{ op } x_2
\]
\[
\ldots
\]
\[
x_3 \leftarrow x_6 \text{ op } x_7
\]

false dependence

Don’t forget memory instructions
Dependency vs Hazard: e.g. RAW

Dependence is property of program; hazards specific to microarchitecture
### Register Data Hazard Analysis

For a given pipeline, when is there a register data hazard between 2 dependent instructions?
- dependence type: RAW, WAR, WAW?
- instruction types involved?
- distance between the two instructions?

<table>
<thead>
<tr>
<th>R/I-Type</th>
<th>LW</th>
<th>SW</th>
<th>Bxx</th>
<th>Jal</th>
<th>Jalr</th>
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<tbody>
<tr>
<td>IF</td>
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<td>ID</td>
<td>read RF</td>
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<td>EX</td>
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<td>WB</td>
<td>write RF</td>
<td>write RF</td>
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<td>write RF</td>
<td>write RF</td>
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</tbody>
</table>

- For a given pipeline, when is there a register data hazard between 2 dependent instructions?
Hazard in In-order Pipeline

\[
\text{dist}_{\text{dependence}}(i,j) \leq \text{dist}_{\text{hazard}}(X,Y) \implies \text{Hazard!!}
\]

\[
\text{dist}_{\text{dependence}}(i,j) > \text{dist}_{\text{hazard}}(X,Y) \implies \text{Safe}
\]
RAW Hazard Analysis Example

<table>
<thead>
<tr>
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<tr>
<td>ID</td>
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<td>read RF</td>
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<td>EX</td>
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<td>MEM</td>
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<tr>
<td>WB</td>
<td>write RF</td>
<td>write RF</td>
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<td></td>
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</tbody>
</table>

- Older $I_A$ and younger $I_B$ have RAW hazard iff
  - $I_B$ (R/I, LW, SW, Bxx or JALR) reads a register written by $I_A$ (R/I, LW, or JAL/R)
  - $\text{dist}(I_A, I_B) \leq \text{dist}(ID, WB) = 3$

What about WAW and WAR hazard?
What about memory data hazard?
Pipeline Stall: universal hazard resolution

Inst_h
Inst_i
Inst_j
Inst_k
Inst_l

i: x1 ← _
bubble
bubble
bubble
j: _ ← x1  dist(i,j)=4

Stall==make younger instruction
wait until hazard passes
1. stop all up-stream stages
2. drain all down-stream stages
Pop Quiz: What happens in this case?

Inst_h

Inst_i

Inst_j

Inst_k

Inst_l

i: x1 ← _
j: x3 ← x2
k: _ ← x1  dist(i,k)=2

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# Pipeline Stall

<table>
<thead>
<tr>
<th></th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$t_3$</th>
<th>$t_4$</th>
<th>$t_5$</th>
<th>$t_6$</th>
<th>$t_7$</th>
<th>$t_8$</th>
<th>$t_9$</th>
<th>$t_{10}$</th>
<th>$t_{11}$</th>
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<tr>
<td><strong>IF</strong></td>
<td>i</td>
<td>j</td>
<td>k</td>
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<td><strong>ID</strong></td>
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<tr>
<td><strong>EX</strong></td>
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<td>i</td>
<td>bub</td>
<td>bub</td>
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<td>j</td>
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<tr>
<td><strong>MEM</strong></td>
<td>h</td>
<td>i</td>
<td>bub</td>
<td>bub</td>
<td>bub</td>
<td>j</td>
<td>k</td>
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</tr>
<tr>
<td><strong>WB</strong></td>
<td>h</td>
<td>i</td>
<td>bub</td>
<td>bub</td>
<td>bub</td>
<td>j</td>
<td>k</td>
<td>l</td>
<td></td>
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</tr>
</tbody>
</table>

\[ i: x_1 \leftarrow \_ \]
\[ j: \_ \leftarrow x_1 \]
Stall

- Stall
  - disable PC and IR latching
  - set \( \text{RegWrite}_{\text{ID}} = 0 \) and \( \text{MemWrite}_{\text{ID}} = 0 \)
When to Stall

• Older $I_A$ and younger $I_B$ have RAW hazard iff
  – $I_B$ (R/I, LW, SW, Bxx or JALR) reads a register written by $I_A$ (R/I, LW, or JAL/R)
  – $\text{dist}(I_A, I_B) \leq \text{dist}(\text{ID}, \text{WB}) = 3$

  Above is about existence of hazard

• Operationally, to detect hazard in time to prevent:
  – before $I_B$ in ID reads a register, $I_B$ needs to check if any $I_A$ in EX, MEM or WB is going to update it

  (if so, value in RF is “stale”)

Watch out for x0!!
Stall Condition

- Helper function
  - `waitForRs1(I)` returns true if I uses `rs1` && `rs1! = x0`

- Stall IF and ID when
  - `(rs1_{ID} == rd_{EX}) && RegWrite_{EX} && waitForRs1(\text{IR}_{ID})` or
  - `(rs1_{ID} == rd_{MEM}) && RegWrite_{MEM} && waitForRs1(\text{IR}_{ID})` or
  - `(rs1_{ID} == rd_{WB}) && RegWrite_{WB} && waitForRs1(\text{IR}_{ID})` or
  - `(rs2_{ID} == rd_{EX}) && RegWrite_{EX} && waitForRs2(\text{IR}_{ID})` or
  - `(rs2_{ID} == rd_{MEM}) && RegWrite_{MEM} && waitForRs2(\text{IR}_{ID})` or
  - `(rs2_{ID} == rd_{WB}) && RegWrite_{WB} && waitForRs2(\text{IR}_{ID})`

It is crucial that EX, MEM and WB continue to advance during stall
Impact of Stall on Performance

• Each stall cycle corresponds to 1 lost ALU cycle
• A program with \( N \) instructions and \( S \) stall cycles:
  \[
  \text{average IPC} = \frac{N}{N+S}
  \]
• \( S \) depends on
  – frequency of hazard-causing dependencies
  – distance between hazard-causing instruction pairs
  – distance between hazard-causing dependencies
    (suppose \( i_1, i_2 \) and \( i_3 \) all depend on \( i_0 \), once \( i_1 \)'s hazard is resolved by stalling, \( i_2 \) and \( i_3 \) do not stall)
Sample Assembly [P&H]

for (j=i-1; j>=0 && v[j] > v[j+1]; j-=1) { ...... }

addi $s1, $s0, -1

for2tst:

slti $t0, $s1, 0
bne $t0, $zero, exit2
sll $t1, $s1, 2
add $t2, $a0, $t1
lw $t3, 0($t2)
lw $t4, 4($t2)
slt $t0, $t4, $t3
beq $t0, $zero, exit2

........

addi $s1, $s1, -1

exit2:
j for2tst
Data Forwarding (or Register Bypassing)

- What does “ADD \( r_x \ r_y \ r_z \)” mean? Get inputs from \( RF[r_y] \) and \( RF[r_z] \) and put result in \( RF[r_x] \)?
- But, \( RF \) is just a part of an abstraction
  - a way to connect dataflow between instructions
    “operands to ADD are resulting values of the last instructions to assign to \( RF[r_y] \) and \( RF[r_z] \)”
  - \( RF \) doesn’t have to exist/behave as a literal object!!!
- If only dataflow matters, don’t wait for WB . . .

```
addi x1, x0, 0  IF  ID  EX  MEM  WB  
addi x2, x1, 0  IF  ID  EX  MEM  WB  
```
Resolving RAW Hazard by Forwarding

- Older $I_A$ and younger $I_B$ have RAW hazard iff
  - $I_B$ (R/I, LW, SW, Bxx or JALR) reads a register written by $I_A$ (R/I, LW, or JAL/R)
  - $\text{dist}(I_A, I_B) \leq \text{dist(ID, WB)} = 3$

- To detect hazard in time to prevent, before $I_B$ in ID reads a register, $I_B$ needs to check if any $I_A$ in EX, MEM or WB is going to update it

- Before: $I_B$ need to stall for $I_A$ to update RF
- Now: $I_B$ need to stall for $I_A$ to produce result
  - retrieve $I_A$ result from datapath when ready
  - must retrieve from youngest if multiple hazards
Forwarding Paths (v1)

- **dist(i,j)=3**
  - Registers
  - Internal forward?
  - **dist(i,j)=3**

- **dist(i,j)=2**
  - Data memory
  - **dist(i,j)=1**

- Forwarding Paths (v1)

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Forwarding Paths (v2)

better if EX is the fastest stage
Forwarding Logic (for v1)

if \( \text{rs1}_{ID} \neq 0 \) && \( \text{rs1}_{ID} == \text{rd}_{EX} \) && \( \text{RegWrite}_{EX} \) then
  forward writeback value from EX // dist=1
else if \( \text{rs1}_{ID} \neq 0 \) && \( \text{rs1}_{ID} == \text{rd}_{MEM} \) && \( \text{RegWrite}_{MEM} \) then
  forward writeback value from MEM // dist=2
else if \( \text{rs1}_{ID} \neq 0 \) && \( \text{rs1}_{ID} == \text{rd}_{WB} \) && \( \text{RegWrite}_{WB} \) then
  forward writeback value from WB // dist=3
else
  use \( A_{ID} \) // dist > 3

Must prioritize young-to-old
Why doesn’t \textit{waitForRs1}() appear?
Isn’t it bad to forward from LW in EX?
## Data Hazard Analysis (with Forwarding)

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<td>EX</td>
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<td>use</td>
<td>use</td>
<td>use</td>
<td>produce</td>
<td>use produce</td>
</tr>
<tr>
<td>MEM</td>
<td></td>
<td>produce</td>
<td>(use)</td>
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</tbody>
</table>

- Even with forwarding, RAW dependence on immediate preceding LW results in hazard
- \( \text{Stall} = \left\{ \left[ \left( rs_{1_{ID}} == \text{rd}_{EX} \right) \&\& \text{waitForRs1}(IR_{ID}) \right] \right\} \| \left[ \left( rs_{2_{ID}} == \text{rd}_{EX} \right) \&\& \text{waitForRs2}(IR_{ID}) \right] \} \&\& \text{MemRead}_{EX} \)
  - i.e., \( \text{op}_{EX} = Lx \)
Historical: MIPS Load “Delay Slot”

- R2000 defined LW with arch. latency of 1 inst
  - invalid for $l_2$ (in LW’s delay slot) to ask for LW’s result
  - any dependence on LW at least distance 2

- Delay slot vs dynamic stalling
  - fill with an independent instruction (no difference)
  - if not, fill with a NOP (no difference)

- Can’t lose on 5-stage ... good idea?

Hint: 1. non-atomic instruction; 2. µarch influence
Sample Assembly [P&H]

for (j=i-1; j>=0 && v[j] > v[j+1]; j--=1) { ...... }

addi $s1, $s0, -1

for2tst: slti $t0, $s1, 0
bne $t0, $zero, exit2
sll $t1, $s1, 2
add $t2, $a0, $t1
lw $t3, 0($t2)
lw $t4, 4($t2)
slt $t0, $t4, $t3
beq $t0, $zero, exit2

.......... addi $s1, $s1, -1

exit2: j for2tst

1 stall or 1 nop (MIPS)
Why not very deep pipelines?

- With only 5 stages, still plenty of combinational logic between registers
- “Superpipelining” \(\Rightarrow\) increase pipelining such that even intrinsic operations (e.g. ALU, RF access, memory access) require multiple stages
- What’s the problem?  
  \(\text{Inst}_0: \text{addi} \ x1, \ x0, \ 0\)  
  \(\text{Inst}_1: \text{addi} \ x2, \ x1, \ 0\)
Intel P4’s Superpipelined Adder Hack

32-bit addition pipelined over 2 stages, BW=1/latency
No stall between back-to-back dependencies
Terminology

• Dependency
  – property of program
  – ordering requirement between instructions

• Pipeline Hazard:
  – property of uarch when interacting with program
  – (potential) violation of dependencies in program

• Hazard Resolution:
  – static ⇒ schedule instructions at compile time to avoid hazards
  – dynamic ⇒ detect hazard and adjust pipeline operation

  Stall, Flush or Forward
Dependencies and Pipelining
(architecture vs. microarchitecture)

Sequential and atomic instruction semantics

True dependence between two instructions may only require ordering of certain sub-operations

Defines what is correct; doesn’t say do it this way