Data and Control Hazards

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CS 3410, Spring 2015
Computer Science
Cornell University

See P&H Chapter: 4.6-4.8
Announcements

Prelim next week
Tuesday at 7:30.
Go to location based on netid
[a-g]* → MRS146: Morrison Hall 146
[h-l]* → RRB125: Riley-Robb Hall 125
[m-n]* → RRB105: Riley-Robb Hall 105
[o-s]* → MVRG71: M Van Rensselaer Hall G71
[t-z]* → MVRG73: M Van Rensselaer Hall G73

Prelim reviews
Yesterday, Tue, Feb 24 @ 7:30pm in Olin 255
SATURDAY, Feb 28 @ 7:30pm in Upson B17

Prelim conflicts
Contact Deniz Altinbuken <deniz@cs.cornell.edu>
Announcements

Prelim1:
- Time: We will start at 7:30pm sharp, so come early
- Location: on previous slide
- Closed Book
  - Cannot use electronic device or outside material
- Practice prelims are online in CMS

Material covered everything up to end of this week
- Everything up to and including data hazards
- Appendix B (logic, gates, FSMs, memory, ALUs)
- Chapter 4 (pipelined [and non] MIPS processor with hazards)
- Chapters 2 (Numbers / Arithmetic, simple MIPS instructions)
- Chapter 1 (Performance)
- HW1, Lab0, Lab1, Lab2, C-Lab0, C-Lab1
Goals for Today

Data Hazards

• Data dependencies
• Problem, detection, and solutions
  – (delaying, stalling, forwarding, bypass, etc)
• Hazard detection unit
• Forwarding unit

Control Hazards

• What is the next instruction to execute if a branch is taken? Not taken?
• How to resolve control hazards
• Optimizations
Hazards

3 kinds

• Structural hazards
  – Multiple instructions want to use same unit

• Data hazards
  – Results of instruction needed before

• Control hazards
  – Don’t know which side of branch to take
How to handle data hazards

• What to do if data hazard detected?
  i.e. add \( r3, r1, r2 \)
  sub \( r5, r3, r4 \)

• Options
  • Nothing
  • Change the ISA to match implementation
  • Stall
    • Pause current and subsequent instructions till safe
      • Slow down the pipeline (add bubbles to pipeline)
  • Forward/bypass
    • Forward data value to where it is needed
Data Hazards

Data Hazards

• register file reads occur in stage 2 (ID)
• register file writes occur in stage 5 (WB)
• next instructions may read values about to be written
Data Hazards

Stall

• Pause current and all subsequent instructions

Forward/Bypass

• Try to steal correct value from elsewhere in pipeline
• Otherwise, fall back to stalling or require a delay slot

Tradeoffs?
Data Hazards

stall = If(IF/ID.Ra ≠ 0 &&
    (IF/ID.Ra == ID/Ex.Rd
    IF/ID.Ra == Ex/M.Rd
    IF/ID.Ra == M/W.Rd))
Three types of forwarding/bypass
• Forwarding from Ex/Mem registers to Ex stage (M→Ex)
• Forwarding from Mem/WB register to Ex stage (W → Ex)
• RegisterFile Bypass
Stalling

Pause current and all subsequent instructions

“slow down the pipeline”
r3 = 10
add r3, r1, r2
r3 = 20
sub r5, r3, r5
or r6, r3, r4
add r6, r3, r8

3 Stalls

Stalling
The diagram illustrates the pipeline stages of a processor, with emphasis on the stalling mechanisms. At the immediate stage, an instruction is fetched from memory, and its opcode is decoded. If the instruction is a NOP (no operation), which is represented as `nop`, it indicates that the pipeline is stalled.

The pipeline continues with the execution of operations such as `sub r5, r3, r5` and `add r0, r3, r1, r2`. The stalling condition is determined by the `MemWr=0` and `RegWr=0` flags, indicating that there is no memory write or register write to proceed.

The equation for determining if a NOP is executed is:

\[
\text{NOP = If(IF/ID.rA ≠ 0 \&\& (IF/ID.rA==ID/Ex.Rd \&\& (IF/ID.rA==Ex/M.Rd \&\& (IF/ID.rA==M/W.Rd)))}
\]

The diagram also shows the flow of data and control signals through the pipeline stages, such as D, B, A, and the data memory, indicating the sequence of instructions and their execution.
NOP = If(IF/ID.rA ≠ 0 &&
(IF/ID.rA==ID/Ex.Rd
IF/ID.rA==Ex/M.Rd
IF/ID.rA==M/W.Rd))

(MemWr=0
RegWr=0)

data
mem

inst
mem

rd

rA rB

D

A

B

WE

Op

Rd

NOP

sub r5,r3,r5

or r6,r3,r4

add r3,r1,r2

PC

+4

WE=0

stall

(MemWr=0
RegWr=0)
NOP = If(IF/ID.rA ≠ 0 &&
(If/ID.rA==ID/Ex.Rd
If/ID.rA==Ex/M.Rd
If/ID.rA==M/W.Rd))

/add r3,r1,r2

/sub r5,r3,r5

/nop

(MemWr=0
RegWr=0)

(op)

(MemWr=0
RegWr=0)

(MemWr=0
RegWr=0)
Stalling

How to stall an instruction in ID stage

• prevent IF/ID pipeline register update
  – stalls the ID stage instruction

• convert ID stage instr into nop for later stages
  – innocuous “bubble” passes through pipeline

• prevent PC update
  – stalls the next (IF stage) instruction
Forwarding

Alternative to stalling, we can forward Forwarding bypasses some pipelined stages forwarding a result to a dependent instruction operand (register)

Three types of forwarding/bypass

• Forwarding from Ex/Mem registers to Ex stage \((M\rightarrow Ex)\)
• Forwarding from Mem/WB register to Ex stage \((W\rightarrow Ex)\)
• RegisterFile Bypass
Forwarding Example

Clock cycle

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
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</tr>
</tbody>
</table>

- **r3 = 10**: add r3, r1, r2
- **r3 = 20**: sub r5, r3, r5
- **or r6, r3, r4**: or r6, r3, r4
- **add r6, r3, r8**: add r6, r3, r8
Forwarding

Alternative to stalling, we can forward
Forwarding bypasses some pipelined stages forwarding a result to a dependent instruction operand (register)

Three types of forwarding/bypass

- Forwarding from Ex/Mem registers to Ex stage (M→Ex)
- Forwarding from Mem/WB register to Ex stage (W→Ex)
- RegisterFile Bypass
Forwarding Datapath 1

```
add r3, r1, r2
sub r5, r3, r1
```
Three types of forwarding/bypass
- Forwarding from Ex/Mem registers to Ex stage (M→Ex)
- Forwarding from Mem/WB register to Ex stage (W → Ex)
- RegisterFile Bypass
Three types of forwarding/bypass

- Forwarding from Ex/Mem registers to Ex stage (M→Ex)
- Forwarding from Mem/WB register to Ex stage (W → Ex)
- RegisterFile Bypass
Forwarding Datapath 1

Ex/MEM to EX Bypass

• EX needs ALU result that is still in MEM stage
• Resolve:
  Add a bypass from EX/MEM.D to start of EX

How to detect? Logic in Ex Stage:

forward = (Ex/M.WE && EX/M.Rd != 0 &&
   ID/Ex.Ra == Ex/M.Rd)
   || (same for Rb)
<table>
<thead>
<tr>
<th>Instruction</th>
<th>IF</th>
<th>ID</th>
<th>Ex</th>
<th>M</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>add r3, r1, r2</td>
<td>IF</td>
<td>ID</td>
<td>Ex</td>
<td>M</td>
<td>W</td>
</tr>
<tr>
<td>sub r5, r3, r1</td>
<td>IF</td>
<td>ID</td>
<td>Ex</td>
<td>M</td>
<td>W</td>
</tr>
<tr>
<td>or r6, r3, r4</td>
<td>IF</td>
<td>ID</td>
<td>Ex</td>
<td>M</td>
<td>W</td>
</tr>
</tbody>
</table>
Forwarding Datapath 2

Mem/WB to EX Bypass

- EX needs value being written by WB
- Resolve:
  Add bypass from WB final value to start of EX

How to detect? Logic in Ex Stage:

```
forward = (M/WB.WE && M/WB.Rd != 0 &&
           ID/Ex.Ra == M/WB.Rd &&
           || (same for Rb)
```

Is this it?

Not quite!
Forwarding Datapath 2

add r3, r1, r2  add r3, r1, r2
sub r5, r3, r5  sub r3, r3, r5
or r6, r3, r4  or r6, r3, r4
add r6, r3, r8  add r6, r3, r8

How to detect? Logic in Ex Stage. Forward from M/WB reg if:
M/WB (WE on, Rd != 0) and (M/WB.Rd == ID/Ex.Ra)
also NOT(Ex/M.Rd == ID/Ex.Ra) and (WE, Rd!= 0))

Rb same as Ra

Check pg. 311
Register File Bypass

Register File Bypass

- Reading a value that is currently being written

Detect:

\(((Ra == MEM/WB.Rd) \text{ or } (Rb == MEM/WB.Rd)) \text{ and } (WB \text{ is writing a register})\)

Resolve:

Add a bypass around register file (WB to ID)

Better: just negate register file clock
- writes happen at end of first half of each clock cycle
- reads happen during second half of each clock cycle
add r3, r1, r2
sub r5, r3, r1
or r6, r3, r4
add r6, r3, r8
Are we done yet?

```
add r3, r1, r2
lw(r4, 20(r8)
or r6, r3, r4
add r6, r3, r8
```

Memory “Load-Use Data Hazard”
Memory Load Data Hazard

What happens if data dependency after a load word instruction?

Memory Load Data Hazard

• Value not available until after the M stage
• So: next instruction can’t proceed if hazard detected
Memory Load Data Hazard

```plaintext
lw r4, 20(r8)
or r6, r3, r4
```

Load-use stall
Memory Load Data Hazard

load-use stall

lw r4, 20(r8)
or r6, r3, r4

IF | ID | Ex | M | W
---|----|----|---|---
IF | ID | Ex | M | W

Inst mem

Data mem
Memory Load Data Hazard

Load-use stall
Memory Load Data Hazard

![Diagram of memory load data hazard with instruction flow and pipeline stages](image)

- Instruction memory (inst mem)
- Data memory (data mem)
- Load instruction (lw r4, 20(r8))
- OR instruction (or r6, r4, r1)
- NOP
- Load use stall

Pipelining stages:
- IF: Instruction Fetch
- ID: Instruction Decode
- Ex: Execution
- M: Memory Access
- W: Write Back

Load-use stall occurs due to the dependency between the load and the OR instruction.
Stall =
If(ID/Ex.MemRead &&
    IF/ID.Ra == ID/Ex.Rd)
Memory Load Data Hazard

Load Data Hazard

- Value not available until WB stage
- So: next instruction can’t proceed if hazard detected

Resolution:

- MIPS 2000/3000: one delay slot
  - ISA says results of loads are not available until one cycle later
  - Assembler inserts nop, or reorders to fill delay slot
- MIPS 4000 onwards: stall
  - But really, programmer/compiler reorders to avoid stalling in the load delay slot

For stall, how to detect? Logic in ID Stage

- Stall = ID/Ex.MemRead &&
  (IF/ID.Ra == ID/Ex.Rd || IF/ID.Rb == ID/Ex.Rd)
Quiz
Find all hazards, and say how they are resolved:

add   r3, r1, r2
nand  r5, r3, r4
add   r2, r6, r3
lw    r6, 24(r3)
sw    r6, 12(r2)
Quiz

Find all hazards, and say how they are resolved:

- `add r3, r1, r2`
- `nand r5, r3, r4`
- `add r2, r6, r3`
- `lw r6, 24(r3)`
- `sw r6, 12(r2)`

5 Hazards
Quiz
Find all hazards, and say how they are resolved:

add \( r3, r1, r2 \)
add \( r2, r6, r3 \)
\( \text{lw} \ r6, 24(r3) \)
\( \text{sw} \ r6, 12(r2) \)

- Forwarding from Ex/M→ID/Ex (M→Ex)
- Forwarding from M/W→ID/Ex (W→Ex)
- RegisterFile (RF) Bypass
- Forwarding from M/W→ID/Ex (W→Ex)

Stall
+ Forwarding from M/W→ID/Ex (W→Ex)

5 Hazards
Quiz

Find all hazards, and say how they are resolved:

add r3, r1, r2
sub r3, r2, r1
nand r4, r3, r1
or r0, r3, r4
xor r1, r4, r3
sb r4, 1(r0)
Quiz 2

Find all hazards, and say how they are resolved:

add r3, r1, r2
sub r3, r2, r1
nand r4, r3, r1
or r0, r3, r4
xor r4, r1, r4
sb r4, 1 r0

Hours and hours of debugging!
Data Hazard Recap

Delay Slot(s)
- Modify ISA to match implementation

Stall
- Pause current and all subsequent instructions

Forward/Bypass
- Try to steal correct value from elsewhere in pipeline
- Otherwise, fall back to stalling or require a delay slot
Why are we learning about this?

Logic and gates
Numbers & arithmetic
States & FSMs
Memory
A simple CPU
Performance
Pipelining
Hazards: Data and Control
Why are we learning about this?

Logic and gates
Numbers & arithmetic
States & FSMs
Memory
A simple CPU
Performance
Pipelining
Hazards: Data and Control
Computer Organization is fundamental to CS
Control Hazards

What about branches?

A control hazard occurs if there is a control instruction (e.g. BEQ) and the program counter (PC) following the control instruction is not known until the control instruction computes if the branch should be taken.

e.g.

0x10:        beq r1, r2, L
0x14:        add r3, r0, r3
0x18:        sub r5, r4, r6
0x1C: L:    or    r3, r2, r4
Control Hazards

Control Hazards

• instructions are fetched in stage 1 (IF)
• branch and jump decisions occur in stage 3 (EX)
• i.e. next PC is not known until 2 cycles after branch/jump

What happens to instr following a branch, if branch not taken?
A) Stall
B) Forward/Bypass
C) Zap/Flush
e.g.
D) All the above
0x10: beq r1, r2, L
0x14: add r3, r0, r3
0x18: sub r5, r4, r6
0x1C: L: or r3, r2, r4

E) None of the above
Control Hazards

Control Hazards

• instructions are fetched in stage 1 (IF)
• branch and jump decisions occur in stage 3 (EX)
• i.e. next PC is not known until 2 cycles after branch/jump

What happens to instr following a branch, if branch \textit{taken}?

A) Stall
B) Forward/Bypass
C) Zap/Flush \textbf{e.g.}
D) All the above
E) None of the above

\begin{tabular}{ll}
0x10: & beq r1, r2, L \\
0x14: & add r3, r0, r3 \\
0x18: & sub r5, r4, r6 \\
0x1C: & or r3, r2, r4 \\
\end{tabular}
Control Hazards

Control Hazards

• instructions are fetched in stage 1 (IF)
• branch and jump decisions occur in stage 3 (EX)
• i.e. next PC is not known until 2 cycles after branch/jump

What happens to instr following a branch, if branch taken?

Stall (+ Zap/Flush)

• prevent PC update
• clear IF/ID pipeline register
  – instruction just fetched might be wrong one, so convert to nop
• allow branch to continue into EX stage
### Control Hazards

- **beq r1, r2, L**
- **add r3, r0, r3**
- **sub r5, r4, r6**
- **or r3, r2, r4**

<table>
<thead>
<tr>
<th></th>
<th>IF</th>
<th>ID</th>
<th>Ex</th>
<th>M</th>
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<td>10</td>
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<tr>
<td>14</td>
<td>IF</td>
<td>ID</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
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<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
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<tr>
<td>1C</td>
<td>IF</td>
<td>ID</td>
<td>Ex</td>
<td>M</td>
<td>W</td>
</tr>
</tbody>
</table>
Control Hazards

10: beq r1, r2, L
   IF   ID   Ex   M   W

14: add r3, r0, r3
   IF   ID   NOP  NOP  NOP  NOP

18: sub r5, r4, r6
   IF   NOP  NOP  NOP  NOP  NOP

1C: or r3, r2, r4
   IF   ID   Ex   M   W
Control Hazards

14: add r3, r0, r3  
10: beq r1, r2, L
Control Hazards

18: sub r5, r4, r6
14: add r3, r0, r3
10: beq r1, r2, L
Control Hazards

1C: or r3, r2, r4

NOP

10: beq r1, r2, L

NOP

data mem

inst mem

PC

+4

D

B

A

branch calc
delete branch
Control Hazards

1C: or r3, r2, r4

NOP

NOP

NOP

10: beq r1, r2, L
Takeaway

Control hazards occur because the PC following a control instruction is not known until control instruction computes if branch should be taken or not.
If branch taken, then need to zap/flush instructions.
There is a performance penalty for branches:
Need to stall, then may need to zap (flush) subsequent instructions that have already been fetched.
Next Goal

Can we reduce the cost of a control hazard?
Reduce the cost of control hazard?

Can we forward/bypass values for branches?

• We can move branch calc from EX to ID
• will require new bypasses into ID stage; or can just zap the second instruction

What happens to instructions following a branch, if branch taken?

• Still need to zap/flush instructions

Is there still a performance penalty for branches

• Yes, need to stall, then may need to zap (flush) subsequent instructions that have already been fetched
Control Hazards

inst mem

+4

PC

branch calc
decide branch

D

B

A

data mem

mem
Control Hazards

inst mem → D → A → B → branch calc

PC +4 → branch decide branch

data mem
beq r1, r2, L
add r3, r0, r3
sub r5, r4, r6
or r3, r2, r4

Control Hazards

If branch Taken → Zap

If branch

10:
14:
18:
1C:
Control Hazards

10: beq r1, r2, L

14: add r3, r0, r3

18: sub r5, r4, r6

1C: or r3, r2, r4

If branch Taken → Zap

IF ID Ex M W

IF NOP NOP NOP NOP NOP

IF ID Ex M W
Control Hazards

10: beq r1, r2, L
14: add r3, r0, r3
10: beq r1, r2, L
Control Hazards

1C: or r3, r2, r4  NOP  10: beq r1, r2, L
Control Hazards

20:

1C: or r3, r2, r4

NOP

10: beq r1, r2, L
Control Hazards

Control Hazards

• instructions are fetched in stage 1 (IF)
• branch and jump decisions occur in stage 3 (EX)
  i.e. next PC is not known until \textbf{2 cycles after} branch/jump
• Can optimize and move branch and jump decision to stage 2 (ID)
  i.e. next PC is not known until \textbf{1 cycles after} branch/jump

Stall (+ Zap)

• prevent PC update
• clear IF/ID pipeline register
  – instruction just fetched might be wrong one, so convert to nop
• allow branch to continue into EX stage
Takeaway

Control hazards occur because the PC following a control instruction is not known until control instruction computes if branch should be taken or not.

If branch taken, then need to zap/flush instructions. There still a performance penalty for branches: Need to stall, then may need to zap (flush) subsequent instructions that have already been fetched.

We can reduce cost of a control hazard by moving branch decision and calculation from Ex stage to ID stage. This reduces the cost from flushing two instructions to only flushing one.
Reduce cost of Control Hazards More

Delay Slot

- ISA says N instructions after branch/jump *always* execute
  - MIPS has 1 branch delay slot

  - i.e. Whether branch taken or not, instruction following branch is *always* executed
Delay Slot

10: beq r1, r2, L
14: add r3, r0, r3
18: sub r5, r4, r6
1C: L: or r3, r2, r4

IF | ID | Ex | M | W
---|----|----|---|---
14 |    |    |   |   |
18 |    |    |   |   |
1C |    |    |   |   |

Delay Slot
If branch **taken** next instr still exec'd
beq r1, r2, L
add r3, r0, r3
sub r5, r4, r6
L: or r3, r2, r4

Delay Slot

If branch **not** taken next instr still exec’ed
Control Hazards

Control Hazards
• instructions are fetched in stage 1 (IF)
• branch and jump decisions occur in stage 3 (EX)
i.e. next PC is not known until 2 cycles after branch/jump
• Can optimize and move branch and jump decision to stage 2 (ID)
i.e. next PC is not known until 1 cycles after branch/jump

Stall (+ Zap)
• prevent PC update
• clear IF/ID pipeline register
  – instruction just fetched might be wrong one, so convert to nop
• allow branch to continue into EX stage

Delay Slot
• ISA says N instructions after branch/jump always executed
  – MIPS has 1 branch delay slot
Takeaway

Control hazards occur because the PC following a control instruction is not known until control instruction computes if branch should be taken or not. If branch taken, then need to zap/flush instructions. There still a performance penalty for branches: Need to stall, then may need to zap (flush) subsequent instructions that have already been fetched.

We can reduce cost of a control hazard by moving branch decision and calculation from Ex stage to ID stage. This reduces the cost from flushing two instructions to only flushing one.

Delay Slots can potentially increase performance due to control hazards by putting a useful instruction in the delay slot since the instruction in the delay slot will *always* be executed. Requires software (compiler) to make use of delay slot. Put nop in delay slot if not able to put useful instruction in delay slot.
Reduce cost of Ctrl Haz even further?

**Speculative Execution**

- “Guess” direction of the branch
  - Allow instructions to move through pipeline
  - Zap them later if wrong guess
- Useful for long pipelines
Speculative Execution: Loops

Pipeline so far

- “Guess” (predict) that the branch will not be taken

We can do better!

- Make prediction based on last branch
- Predict “take branch” if last branch “taken”
- Or Predict “do not take branch” if last branch “not taken”

- Need one bit to keep track of last branch
Speculative Execution: Loops

What is accuracy of branch predictor?
Wrong twice per loop!
Once on loop enter and exit
We can do better with 2 bits

While (r3 ≠ 0) {.... r3--;}
Top: BEQZ r3, End

End:

While (r3 ≠ 0) {.... r3--;}
Top2: BEQZ r3, End2

J Top

End2:
Speculative Execution: Branch Execution

- Predict Taken 2 (PT2)
- Branch Taken (T)
- Branch Not Taken (NT)
- Predict Not Taken 2 (PT2)
- Predict Taken 1 (PT1)
- Predict Not Taken 1 (PT1)
- Branch Taken (T)
- Branch Not Taken (NT)
Summary

Control hazards

- Is branch taken or not?
- Performance penalty: stall and flush

Reduce cost of control hazards

- Move branch decision from Ex to ID
  - 2 nops to 1 nop
- Delay slot
  - Compiler puts useful work in delay slot. ISA level.
- Branch prediction
  - Correct. Great!
  - Wrong. Flush pipeline. Performance penalty
Hazards Summary

Data hazards

Control hazards

Structural hazards

• resource contention
• so far: impossible because of ISA and pipeline design
Hazards Summary

Data hazards
- register file reads occur in stage 2 (IF)
- register file writes occur in stage 5 (WB)
- next instructions may read values soon to be written

Control hazards
- branch instruction may change the PC in stage 3 (EX)
- next instructions have already started executing

Structural hazards
- resource contention
- so far: impossible because of ISA and pipeline design