Hazards

Why pipelines don’t complete an instruction each cycle

- **structural hazards**
  - instructions in different stages want to use the same resource in the same cycle
  - if not solved, one instruction has to stall
  - example: one memory (early SPARC)

- **data hazards**
  - an instruction needs the result produced by a previous instruction before it has been written to the register file
    - the second instruction is data dependent on the first
  - if not solved, the second instruction has to stall
  - example: \texttt{lw \$8, 12($9)} \texttt{add \$4, \$8, \$10} \texttt{sub \$5, \$4, \$10}

- **control hazards**
  - the instruction after a branch needs to be fetched before the result of the branch condition is determined
    - the second instruction is control dependent on the first
  - if not solved, the instruction after the branch has to stall
  - example: \texttt{beq}

All occur because pipelines overlap instruction execution

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Structural Hazards

**Cause** of the hazard:

- hardware resource conflicts
  - instructions in different stages want to use the same resource in the same cycle
  - rarely, one instruction wants to use the same resource twice in the same cycle

**Solutions:**

- **more hardware**
  - separate ALUs for arithmetic, target address calculation, PC incrementing
  - dual-ported register file
  - write/read registers on different phases in the same cycle
  - separate memory (caches) for instructions & data
  - better performance with a little more hardware --- it's worth it!

- **just stall**
  - 1 port to memory: service the data access (the older instruction) before the instruction access
  - logic in the MEM stage: is this a load? if yes, stall the instruction fetch if the next instruction uses the loaded value
  - less hardware, but much lower performance
Data Hazards

Cause of the hazard:
- producer-consumer conflict over data values
  - an instruction needs data that is produced by a previous instruction
  - the data has not yet been written into a register
- code causes a data dependence
- the implementation causes the data hazard

Solutions:
- compiler code scheduling
  - nops (on a processor without pipeline interlocks, aka R2000)
  - reordering instructions
  - this is an example of where the pipeline is exposed to the architecture
- hardware
  - forwarding
    output of one stage (result in that stage’s pipeline register) sent to the input of a previous stage
  - pipelined interlock (stall the pipeline)
    hardware stalls the following instructions

Dependences vs. Hazards

sub $2, $1, $3
and $12, $2, $5
or $13, $6, $2
add $14, $2, $2
sw $15, 100 ($2)
Code Scheduling

add $4, $5, $6
sub $7, $8, $4
add $15, $16, $17
addi $18, $19, 256

inserting nops
   add $4, $5, $6
   nop
   nop
   sub $7, $8, $4
   add $15, $16, $17
   addi $18, $19, 256

reordering instructions
   add $4, $5, $6
   add $15, $16, $17
   addi $18, $19, 256
   sub $7, $8, $4

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Code Scheduling

add $4, $5, $6

nop

nop

sub $7, $8, $4

add $15, $16, $17

addi $18, $19, $16

addi $18, $19, 256

sub $7, $8, $4

data dependence
no hazard
Code Scheduling

Forwarding

Forwarding (also called bypassing):
- output of one stage (the result in that stage’s pipeline register) is bused (bypassed) to the input of a previous stage
- why forwarding is possible: results are computed 1 or more stages before they are written to a register
  - at the end of the EX stage for computational instructions
  - at the end of MEM for a load
- if you forward a result to an ALU input as soon as it has been computed, you can eliminate or reduce stalling
Forwarding Example

Forwarding unit checks to see if values must be forwarded:
- between instructions in ID and EX
  - compare the R-type write register number in EX/MEM pipeline register to each read register number in ID/EX
- between instructions in ID and MEM
  - compare the R-type write register number in MEM/WB to each read register number in ID/EX
- it’s a little more complicated than this

If a match, then forward the appropriate result values to an ALU source
- bus a value from EX/MEM or MEM/WB to an ALU source
Forwarding Hardware

Hardware to implement forwarding:

- destination register number in pipeline registers
  (but need it anyway because we need to know which register to
  write when storing an ALU or load result)
- source register numbers
  (only rs is extra)
- a comparator for each source-destination register pair
- buses to ship data and register numbers --- the BIG cost
- larger ALU MUXes (+ 2 ALU bypass values)

Delayed Loads

Delayed load:

- data hazard caused by a load instruction & an immediate use of
  the loaded value
- forwarding won’t eliminate the hazard
  data not back from memory until the end of the MEM stage
- solutions
  - if processor has no hardware interlocks
    must schedule independent instructions or nops into the
    delay slot: R2000
    (hazard exposed to the compiler)
  - pipelined interlocks: everyone else
Delayed Loads

lw $2, 20($1)

and $4, $2, $5

$2 is available here

$2 is needed here

$2 is written here

data dependence

hazard

no hazard

Stalling

lw $2, 20($1)

and $4, $2, $5

or $8, $2, $6

add $9, $4, $2

data dependence

no hazard

the bubble
Pipelined Interlocks

How pipelined stalls are implemented

**Hazard detection unit:** stalls the use after a load

- is the instruction in EX a load?
  - is the MemRead signal in ID/EX set?
- does the destination register number of the load = either source register number in the next instruction?
  - compare the load write register number in ID/EX to each read register number in IF/ID

⇒ if yes, stall the pipe 1 cycle

Pipelined Interlocks

How stalling is implemented:

- **nullify the instruction in the ID stage**, the one that uses the loaded value
  - change EX, MEM, WB control signals in ID/EX pipeline register to 0
  - the instruction in the ID stage will have no side effects as it passes down the pipeline
- **repeat the instructions in ID & IF stages**
  - disable writing the PC --- the same instruction will be fetched again
  - disable writing the IF/ID pipeline register --- the load use instruction will be decoded & its registers read again
Implementing Stalls

Hardware to implement stalling:

- rt register number in ID/EX pipeline register  
  (but need it anyway because we need to know what register  
  to write when storing load data)
- both source register numbers in IF/ID pipeline register  
  (already there)
- a comparator for each source-destination register pair
- buses to ship register numbers
- write enable/disable for PC
- write enable/disable for the IF/ID pipeline register
- a MUX to the ID/EX pipeline register (+ 0s)

Code Scheduling vs. Pipelined Interlocks

Pipeline interlocks preferred

- trivial amount of hardware  
  stall logic needed for cache misses anyway
- smaller code size  
  no nops when no independent instructions
- higher performance processors can have shorter clock cycles & more stages  
  therefore it could have more than one delay slot

MIPS now uses pipeline interlocks!