**Pipelining**

Readings: 4.5-4.8

Example: Doing the laundry

Ann, Brian, Cathy, & Dave each have one load of clothes to wash, dry, and fold

- Washer takes 30 minutes
- Dryer takes 40 minutes
- "Folder" takes 20 minutes

---

**Sequential Laundry**

Sequential laundry takes 6 hours for 4 loads

If they learned pipelining, how long would laundry take?
**Pipelined Laundry: Start work ASAP**

Pipelined laundry takes 3.5 hours for 4 loads

**Pipelining Lessons**

Pipelining doesn’t help latency of single task, it helps throughput of entire workload

Pipeline rate limited by slowest pipeline stage

Multiple tasks operating simultaneously using different resources

Potential speedup = Number pipe stages

Unbalanced lengths of pipe stages reduces speedup

Time to “fill” pipeline and time to “drain” it reduces speedup

Stall for Dependences
Pipelined Execution

Program Flow

Now we just have to make it work

Single Cycle vs. Pipeline

Clk

Single Cycle Implementation:

Load | Store | Waste

Cycle 1 | Cycle 2 | Cycle 3 | Cycle 4 | Cycle 5

Clk

Pipeline Implementation:

Load | Ifetch | Reg | Exec | Mem | Wr

Store | Ifetch | Reg | Exec | Mem | Wr

R-type | Ifetch | Reg | Exec | Mem | Wr

Now we just have to make it work
Why Pipeline?

Suppose we execute 100 instructions

Single Cycle Machine
45 ns/cycle \times 1 \text{ CPI} \times 100 \text{ inst} = ____ \text{ ns}

Ideal pipelined machine
10 \text{ ns/cycle} \times (1 \text{ CPI} \times 100 \text{ inst} + 4 \text{ cycle drain}) = ____ \text{ ns}

CPI for Pipelined Processors

Ideal pipelined machine
10 \text{ ns/cycle} \times (1 \text{ CPI} \times 100 \text{ inst} + 4 \text{ cycle drain}) = ____ \text{ ns}

CPI in pipelined processor is “issue rate”. Ignore fill/drain, ignore latency.

Example: A processor wastes 2 cycles after every branch, and 1 after every load, during which it cannot issue a new instruction. If a program has 10% branches and 30% loads, what is the CPI on this program?
Pipelined Datapath

Divide datapath into multiple pipeline stages

Pipelined Control

The Main Control generates the control signals during Reg/Dec
Control signals for Exec (ALUOp, ALUSrc, …) are used 1 cycle later
Control signals for Mem (MemWE, Mem2Reg, …) are used 2 cycles later
Control signals for Wr (RegWE, …) are used 3 cycles later
Can pipelining get us into trouble?

Yes: Pipeline Hazards

structural hazards: attempt to use the same resource two different ways at the same time
  E.g., combined washer/dryer would be a structural hazard or folder busy doing something else (watching TV)

data hazards: attempt to use item before it is ready
  E.g., one sock of pair in dryer and one in washer; can’t fold until get sock from washer through dryer
  instruction depends on result of prior instruction still in the pipeline

control hazards: attempt to make decision before condition evaluated
  E.g., washing football uniforms and need to get proper detergent level; need to see after dryer before next load in branch instructions

Can always resolve hazards by waiting
  pipeline control must detect the hazard
  take action (or delay action) to resolve hazards

Pipelining the Load Instruction

The five independent functional units in the pipeline datapath are:
  Instruction Memory for the Ifetch stage
  Register File’s Read ports (bus A and busB) for the Reg/Dec stage
  ALU for the Exec stage
  Data Memory for the Mem stage
  Register File’s Write port (bus W) for the Wr stage

Clock

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<thead>
<tr>
<th>Cycle 1</th>
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</table>

1st LDUR
  Ifetch | Reg/Dec | Exec | Mem | Wr |

2nd LDUR
  Ifetch | Reg/Dec | Exec | Mem | Wr |

3rd LDUR
  Ifetch | Reg/Dec | Exec | Mem | Wr |
The Four Stages of R-type

Ifetch: Fetch the instruction from the Instruction Memory
Reg/Dec: Register Fetch and Instruction Decode
Exec: ALU operates on the two register operands
Wr: Write the ALU output back to the register file

Cycle 1 | Cycle 2 | Cycle 3 | Cycle 4
R-type Ifetch | Reg/Dec | Exec | Wr

Structural Hazard

Interaction between R-type and loads causes structural hazard on writeback

Cycle 1 | Cycle 2 | Cycle 3 | Cycle 4 | Cycle 5 | Cycle 6 | Cycle 7 | Cycle 8 | Cycle 9
R-type Ifetch | Reg/Dec | Exec | Wr

Clock

R-type Ifetch | Reg/Dec | Exec | Mem | Wr
Load Ifetch | Reg/Dec | Exec | Mem | Wr
R-type Ifetch | Reg/Dec | Exec | Wr
R-type Ifetch | Reg/Dec | Exec | Wr
**Important Observation**

Each functional unit can only be used once per instruction. Each functional unit must be used at the same stage for all instructions:

Load uses Register File’s Write Port during its 5th stage.

<table>
<thead>
<tr>
<th>Load</th>
<th>Ifetch</th>
<th>Reg/Dec</th>
<th>Exec</th>
<th>Mem</th>
<th>Wr</th>
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</thead>
</table>

R-type uses Register File’s Write Port during its 4th stage.

<table>
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<tr>
<th>R-type</th>
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<th>Wr</th>
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</table>

Solution: Delay R-type’s register write by one cycle:

Now R-type instructions also use Reg File’s write port at Stage 5.

Mem stage is a NOOP stage: nothing is being done.

<table>
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**Pipelining the R-type Instruction**

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</table>

| R-type  | Ifetch  | Reg/Dec | Exec    | Mem     | Wr      |

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The Four Stages of Store

Ifetch: Fetch the instruction from the Instruction Memory
Reg/Dec: Register Fetch and Instruction Decode
Exec: Calculate the memory address
Mem: Write the data into the Data Memory
Wr: NOOP

Compatible with Load & R-type instructions

The Stages of Conditional Branch

Ifetch: Fetch the instruction from the Instruction Memory
Reg/Dec: Register Fetch and Instruction Decode, compute branch target
Exec: Test condition & update the PC
Mem: NOOP
Wr: NOOP
**Control Hazard**

Branch updates the PC at the end of the Exec stage.

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**Accelerate Branches**

When can we compute branch target address?
When can we compute the CBZ condition?
Control Hazard 2

Branch updates the PC at the end of the Reg/Dec stage.

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Solution #1: Stall

Delay loading next instruction, load no-op instead

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CPI if all other instructions take 1 cycle, and branches are 20% of instructions?
Solution #2: Branch Prediction

Guess all branches not taken, squash if wrong

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</table>

CPI if 50% of branches actually not taken, and branch frequency 20%?

Solution #3: Branch Delay Slot

Redefine branches: Instruction directly after branch always executed
Instruction after branch is the delay slot

Compiler/assembler fills the delay slot

ADD X1, X0, X4  SUB X2, X0, X3  ADD X1, X0, X4  ADD X1, X0, X4
CBZ X2, FOO  ADD X1, X0, X4  CBZ X1, FOO  CBZ X1, FOO
CBZ X1, FOO  ADD X1, X3, X3

FOO:
ADD X1, X2, X0
### Data Hazards

Consider the following code:

```
ADD X0, X1, X2
SUB X3, X0, X4
AND X5, X0, X6
ORR X7, X0, X8
EOR X9, X0, X10
```

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### Design Register File Carefully

What if reads see value after write during the same cycle?

```
ADD X0, X1, X2
SUB X3, X0, X4
AND X5, X0, X6
ORR X7, X0, X8
EOR X9, X0, X10
```

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Forwarding

Add logic to pass last two values from ALU output to ALU input(s) as needed. 

*Forward* the ALU output to later instructions.

ADD \( X_0, X_1, X_2 \)

SUB \( X_3, X_0, X_4 \)

AND \( X_5, X_0, X_6 \)

ORR \( X_7, X_0, X_8 \)

EOR \( X_9, X_0, X_{10} \)

Forwarding (cont.)

Requires values from last two ALU operations. 
Remember destination register for operation. 
Compare sources of current instruction to destinations of previous 2.
### Data Hazards on Loads

LDUR X0, [X31, 0]
SUB X3, X0, X4
AND X5, X0, X6
ORR X7, X0, X8
EOR X9, X0, X10

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### Data Hazards on Loads (cont.)

Solution:

Use same forwarding hardware & register file for hazards 2+ cycles later
Force compiler to not allow register reads within a cycle of load
  Fill delay slot, or insert no-op.
Pipelined CPI, cycle time

CPI, assuming compiler can fill 50% of delay slots

<table>
<thead>
<tr>
<th>Instruction Type</th>
<th>Type Cycles</th>
<th>Type Frequency</th>
<th>Cycles * Freq</th>
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<tbody>
<tr>
<td>ALU</td>
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<td>Load</td>
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<tr>
<td>Store</td>
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<tr>
<td>Branch</td>
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<td>20%</td>
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</tbody>
</table>

CPI:

Pipelined: cycle time = 1ns.  Delay for 1M instr:

Single cycle: CPI = 1.0, cycle time = 4.5ns.  Delay for 1M instr:

Pipelined CPU Summary