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 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

Now we just have to make it work
Single Cycle vs. Pipeline

Single Cycle Implementation:

<table>
<thead>
<tr>
<th>Load</th>
<th>Store</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle 1</td>
<td>Cycle 2</td>
<td>Cycle 3</td>
</tr>
<tr>
<td>Cycle 4</td>
<td>Cycle 5</td>
<td>Cycle 6</td>
</tr>
<tr>
<td>Cycle 7</td>
<td>Cycle 8</td>
<td>Cycle 9</td>
</tr>
<tr>
<td>Cycle 10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pipeline Implementation:

<table>
<thead>
<tr>
<th>Load</th>
<th>Ifetch</th>
<th>Reg</th>
<th>Exec</th>
<th>Mem</th>
<th>Wr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Store</td>
<td>Ifetch</td>
<td>Reg</td>
<td>Exec</td>
<td>Mem</td>
<td>Wr</td>
</tr>
<tr>
<td>R-type</td>
<td>Ifetch</td>
<td>Reg</td>
<td>Exec</td>
<td>Mem</td>
<td>Wr</td>
</tr>
</tbody>
</table>
Why Pipeline?

Suppose we execute 100 instructions

Single Cycle Machine
45 ns/cycle x 1 CPI x 100 inst = ____ ns

Ideal pipelined machine
10 ns/cycle x (1 CPI x 100 inst + 4 cycle drain) = ____ 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
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
Structural Hazard

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

<table>
<thead>
<tr>
<th>Clock</th>
<th>Cycle 1</th>
<th>Cycle 2</th>
<th>Cycle 3</th>
<th>Cycle 4</th>
<th>Cycle 5</th>
<th>Cycle 6</th>
<th>Cycle 7</th>
<th>Cycle 8</th>
<th>Cycle 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-type</td>
<td>Ifetch</td>
<td>Reg/Dec</td>
<td>Exec</td>
<td>Wr</td>
<td>R-type</td>
<td>Ifetch</td>
<td>Reg/Dec</td>
<td>Exec</td>
<td>Wr</td>
</tr>
</tbody>
</table>
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
- R-type uses Register File’s Write Port during its 4th stage

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.
Pipelining the R-type Instruction
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.

<table>
<thead>
<tr>
<th>Cycle 1</th>
<th>Cycle 2</th>
<th>Cycle 3</th>
<th>Cycle 4</th>
<th>Cycle 5</th>
<th>Cycle 6</th>
<th>Cycle 7</th>
<th>Cycle 8</th>
<th>Cycle 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-type</td>
<td>Ifetch</td>
<td>Reg/Dec</td>
<td>Exec</td>
<td>Mem</td>
<td>Wr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBZ</td>
<td>Ifetch</td>
<td>Reg/Dec</td>
<td>Exec</td>
<td>Mem</td>
<td>Wr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>load</td>
<td>Ifetch</td>
<td>Reg/Dec</td>
<td>Exec</td>
<td>Mem</td>
<td>Wr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-type</td>
<td>Ifetch</td>
<td>Reg/Dec</td>
<td>Exec</td>
<td>Mem</td>
<td>Wr</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Accelerate Branches

When can we compute branch target address?
When can we compute the CBZ condition?
Branch updates the PC at the end of the Reg/Dec stage.
Solution #1: Stall

Delay loading next instruction, load no-op instead

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

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
CBZ X2, FOO       ADD X1, X0, X4
ADD X1, X0, X4    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
Design Register File Carefully

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

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

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

Forward the ALU output to later instructions

ADD $X0$, $X1$, $X2$
SUB $X3$, $X0$, $X4$
AND $X5$, $X0$, $X6$
ORR $X7$, $X0$, $X8$
EOR $X9$, $X0$, $X10$
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 \(X9, X0, X10\)
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>
</tr>
</thead>
<tbody>
<tr>
<td>ALU</td>
<td></td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td></td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>Store</td>
<td></td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Branch</td>
<td></td>
<td>20%</td>
<td></td>
</tr>
</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