COMPUTER ORGANIZATION AND DESIGN
The Hardware/Software Interface
ARM Edition

Chapter 4

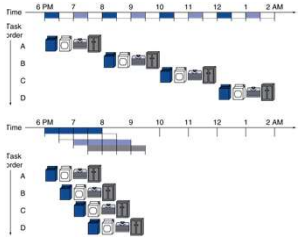
The Processor

Performance Issues

- Longest delay determines clock period
  - Critical path: load instruction
  - Instruction memory → register file → ALU → data memory → register file
- Not feasible to vary period for different instructions
- Violates design principle
  - Making the common case fast
- We will improve performance by pipelining

Pipelining Analogy

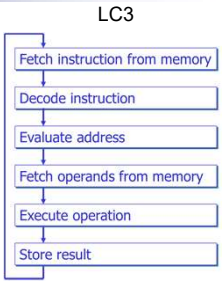
- Pipelined laundry: overlapping execution
  - Parallelism improves performance



- Four loads:
  - Speedup = 8/3.5 = 2.3
- Non-stop:
  - Speedup = 2n/0.5n + 1.5 ≈ 4 = number of stages

LEGv8 Pipeline

- Five stages, one step per stage
  1. IF: Instruction fetch from memory
  2. ID: Instruction decode & register read
  3. EX: Execute operation or calculate address
  4. MEM: Access memory operand
  5. WB: Write result back to register



Pipeline Performance

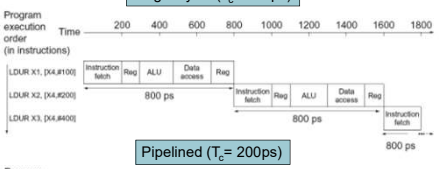
- Assume time for stages is
  - 100ps for register read or write
  - 200ps for other stages
- Compare pipelined datapath with single-cycle datapath

Instr	Instr fetch	Register read	ALU op	Memory access	Register write	Total time
LDUR	200ps	100 ps	200ps	200ps	100 ps	800ps
STUR	200ps	100 ps	200ps	200ps		700ps
R-format	200ps	100 ps	200ps		100 ps	600ps
CBZ	200ps	100 ps	200ps			500ps

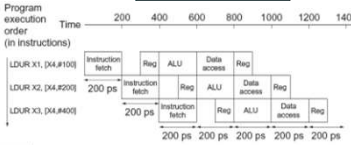
LDUR = LD STUR = ST R-format = ADD, AND CBZ = BRz

Pipeline Performance

Single-cycle (T_c= 800ps)



Pipelined (T_c= 200ps)



Pipeline Speedup

- If all stages are balanced
  - i.e., all take the same time
  - Time between instructions$_{pipelined}$ = $\frac{\text{Time between instructions}_{nonpipelined}}{\text{Number of stages}}$
- If not balanced, speedup is less
- Speedup due to increased throughput
  - Latency (time for each instruction) does not decrease

Pipelining and ISA Design

- LEGv8 ISA designed for pipelining
  - All instructions are 32-bits
    - Easier to fetch and decode in one cycle
    - c.f. x86: 1- to 17-byte instructions
  - Few and regular instruction formats
    - Can decode and read registers in one step
  - Load/store addressing
    - Can calculate address in 3rd stage, access memory in 4th stage
  - Alignment of memory operands
    - Memory access takes only one cycle

Hazards

- Situations that prevent starting the next instruction in the next cycle
- Structure hazards
  - A required resource is busy
- Data hazard
  - Need to wait for previous instruction to complete its data read/write
- Control hazard
  - Deciding on control action depends on previous instruction

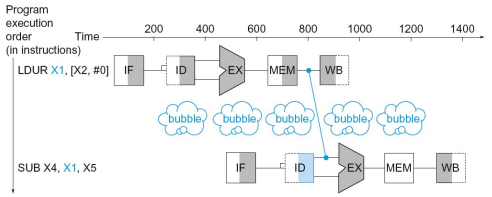
Structure Hazards

- Conflict for use of a resource
- In LEGv8 pipeline with a single memory
  - Load/store requires data access
  - Instruction fetch would have to *stall* for that cycle
    - Would cause a pipeline “bubble”
- Hence, pipelined datapaths require separate instruction/data memories
  - Or separate instruction/data caches

Data Hazards

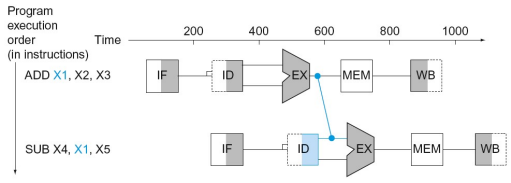
- An instruction depends on completion of data access by a previous instruction

```
ADD  X19, X0, X1
SUB  X2, X19, X3
```



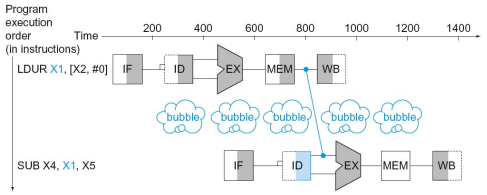
Forwarding (aka Bypassing)

- Use result when it is computed
  - Don’t wait for it to be stored in a register
  - Requires extra connections in the datapath



Load-Use Data Hazard

- Can't always avoid stalls by forwarding
  - If value not computed when needed
  - Can't forward backward in time!



Code Scheduling to Avoid Stalls

- Reorder code to avoid use of load result in the next instruction
- C code for `A = B + E; C = B + F;`

```
LDUR   X1, [X0,#0]
LDUR   X2, [X0,#8]
stall → ADD   X3, X1, X2
STUR   X3, [X0,#24]
LDUR   X4, [X0,#16]
stall → ADD   X5, X1, X4
STUR   X5, [X0,#32]
```

13 cycles

```
LDUR   X1, [X0,#0]
LDUR   X2, [X0,#8]
LDUR   X4, [X0,#16]
ADD    X3, X1, X2
STUR   X3, [X0,#24]
ADD    X5, X1, X4
STUR   X5, [X0,#32]
```

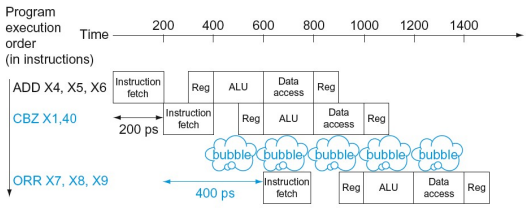
11 cycles

Control Hazards

- Branch determines flow of control
  - Fetching next instruction depends on branch outcome
  - Pipeline can't always fetch correct instruction
    - Still working on ID stage of branch
- In LEGv8 pipeline
  - Need to compare registers and compute target early in the pipeline
  - Add hardware to do it in ID stage

Stall on Branch

- Wait until branch outcome determined before fetching next instruction



Branch Prediction

- Longer pipelines can't readily determine branch outcome early
  - Stall penalty becomes unacceptable
- Predict outcome of branch
  - Only stall if prediction is wrong
- In LEGv8 pipeline
  - Can predict branches not taken
  - Fetch instruction after branch, with no delay

More-Realistic Branch Prediction

- Static branch prediction
  - Based on typical branch behavior
  - Example: loop and if-statement branches
    - Predict backward branches taken
    - Predict forward branches not taken
- Dynamic branch prediction
  - Hardware measures actual branch behavior
    - e.g., record recent history of each branch
  - Assume future behavior will continue the trend
    - When wrong, stall while re-fetching, and update history

Pipeline Summary

The BIG Picture

- Pipelining improves performance by increasing instruction throughput
  - Executes multiple instructions in parallel
  - Each instruction has the same latency
- Subject to hazards
  - Structure, data, control
- Instruction set design affects complexity of pipeline implementation