Pipelining

Implementation technique

- overlaps execution of different instructions
- increases instruction throughput by executing several instructions “in parallel”
- abstract model: an assembly line

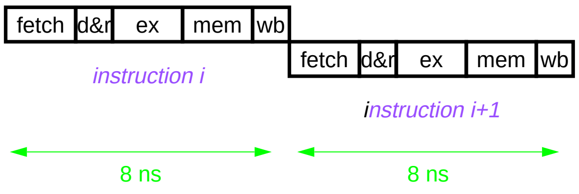
Pipelining

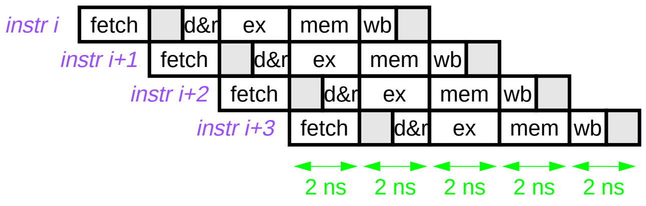
Divide the execution cycle into **stages**

- each stage takes one clock cycle
    - cycle time limited by the longest stage
    - want each stage to do equal work
- instructions advance down the pipeline together
    - want all instructions to do the same amount of total work

In what ways has a RISC architecture been designed for pipelining?

Pipelining





Pipelining Performance

Pipelining increases instruction throughput

- new instruction can start & complete each cycle (once you fill the pipeline & if there are no pipeline stalls)
- therefore execution time of a program decreases
- does not improve the latency of an individual instruction
  - slightly increases instruction latency
    - each stage is the length of the longest
    - pipeline registers

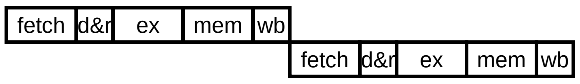
$$T_{\text{without pipeline}} = \text{instructions} \bullet \text{n cycles per instruction}$$

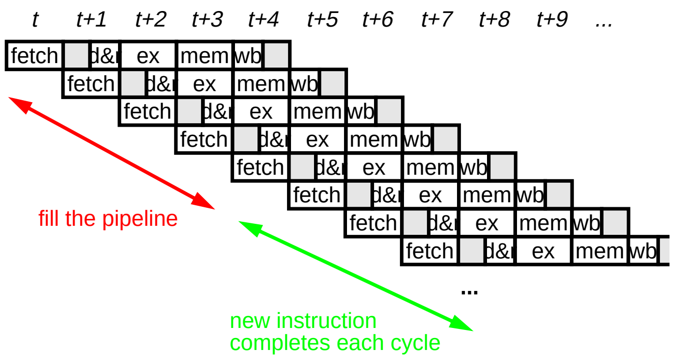
$$T_{\text{pipelining}} = \text{instructions} + n - 1 \text{ cycles}$$

$$\text{Speedup} = \frac{T_{\text{without pipeline}}}{T_{\text{pipelining}}} = \text{\# of pipe stages}$$

- assumes:
  - no pipeline stalls
  - no pipeline overhead

Pipelining





Pipeline Datapath

Stages are independent & isolated from each other

- information generated or retained at stage *i* that is needed in stage *i+1* must be stored in **pipeline registers** that separate each stage
- otherwise subsequent instruction will overwrite information
- examples of information stored in pipeline registers:
  - the destination register number for an ALU result
  - the source register number for the **sw** data
  - offset of immediate value
  - the updated PC
  - control lines

All 5 stages are active at the same time

- cannot share resources among stages
  - similar to the single-cycle datapath
- need pipeline registers to hold the results of one stage for the next stage
  - similar to the multiple-cycle datapath

Tracing an Instruction Through the Pipeline

Stage 1: instruction fetch & PC increment

- PC is used to access memory
  fetch instruction
  put instruction into IF/ID (equivalent to IR)
- increment PC
  put incremented PC into IF/ID

Main resources needed:

- instruction memory
- an ALU

IF/ID (64 bits) contains:

- instruction
- incremented PC

Tracing an Instruction Through the Pipeline

Stage 2: instruction decode & register read

- decode instruction & read source registers
  put register values into ID/EX (equivalent to registers A & B)
- sign-extend immediate field & put into ID/EX

Main resources needed:

- register file

ID/EX (147 bits) contains:

- 2 register values
- sign-extended immediate
- rt, rd
- incremented PC
- control for the next 3 stages
  - ALUop (which ALU operation)
    ALUsrc (which operand for the second ALU source)
    RegDst (which destination register)
  - Branch (in case this is a **beq**)
    MemRead (read from memory)
    MemWrite (write to memory)
  - RegWrite (write the register file)
    MemtoReg (where the value comes from)

Tracing an Instruction Through the Pipeline

Stage 3: execute

- do an ALU operation
  put result & Zero into EX/MEM
- calculate the target address
  put target into EX/MEM

Main resources needed:

- 2 ALUs

EX/MEM (139 bits) contains:

- ALU result
- target address
- store value
- destination register # (which one has been chosen)
- Zero line
- incremented PC *(for exceptions: later)*
- control for the next 2 stages
    - Branch (in case this is a **`beq`**)
      MemRead (read from memory)
      MemWrite (write to memory)
    - RegWrite (write the register file)
      MemtoReg (where the value comes from)

Tracing an Instruction Through the Pipeline

Stage 4: data memory access

- use effective address in EX/MEM to access memory
  store data from EX/MEM if **`sw`**
  put loaded value into MEM/WB if **`lw`**
- determine if branch should be taken
- R-type instructions do nothing

Main resources needed:

- data memory

MEM/WB (34 bits) contains:

- ALU or **`lw`** result
- control for the last stage
    - RegWrite (write the register file)
      MemtoReg (where the value comes from)

Tracing an Instruction Through the Pipeline

Stage 5: register write

- write loaded value or ALU result
- **`sw`** instruction does nothing

Main resources needed:

- register file

No pipeline register

More on Control Signals

No control signals needed to

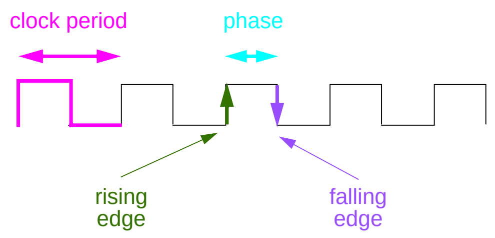
- write PC
- read instruction memory
- write pipeline registers

Control signals are computed in ID & propagated to later stages in the pipeline registers

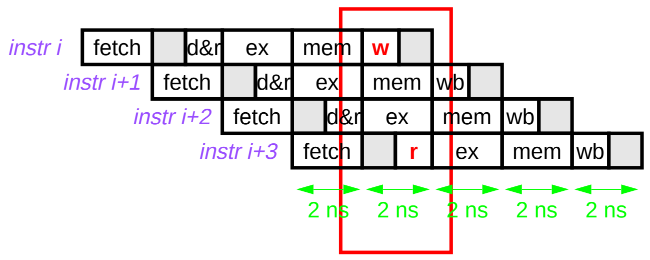
Clocking

Clock: free-running signal with a fixed cycle time

- typically divided into 2 **clock phases**
  - clock signal high
  - clock signal low
- **edge-triggered clocking**
  - state changes occur on a clock edge
  - write registers on a rising edge
  - read registers on a falling edge



Register Reading & Writing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fetch
d&r
ex
mem
w
instr i+1
fetch
d&r
ex
mem
wb
instr i+2
fetch
d&r
ex
mem
wb
instr i+3
fetch
r
ex
mem
wb
2 ns
2 ns
2 ns
2 ns
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