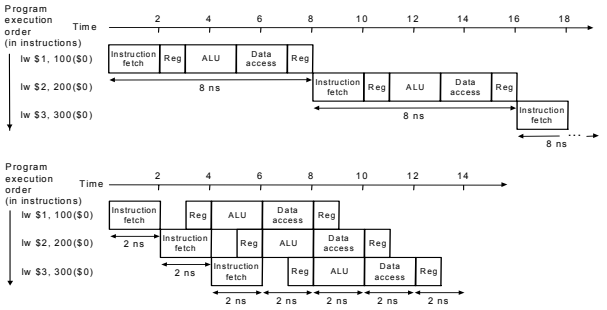
Pipelining

- Reconsider the data path we just did
- Each instruction takes from 3 to 5 clock cycles
- However, there are parts of hardware that are idle many time
- We can reorganize the operation
- Make each hardware block independent
  - 1. Instruction Fetch Unit
  - 2. Register Read Unit
  - 3. ALU Unit
  - 4. Data Memory Read/Write Unit
  - 5. Register Write Unit
- Units in 3 and 5 cannot be independent, but operations can be
- Let each unit just do its required job for each instruction
- If for some instruction, a unit need not do anything, it can simply perform a noop

Gain of Pipelining

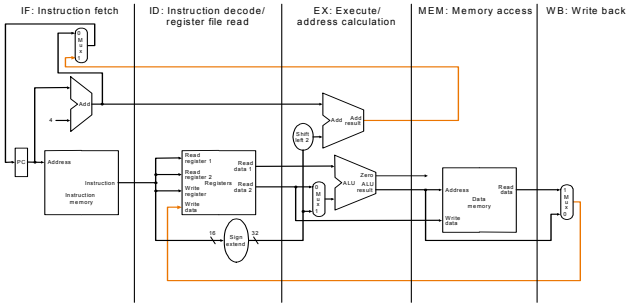
- Improve performance by increasing instruction throughput
- Ideal speedup is number of stages in the pipeline
- Do we achieve this? No, why not?



Pipelining

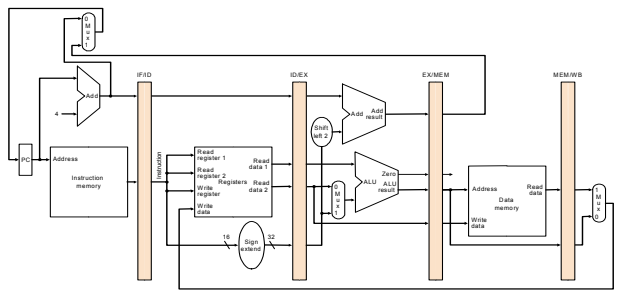
- What makes it easy
  - all instructions are the same length
  - just a few instruction formats
  - memory operands appear only in loads and stores
- What makes it hard?
  - structural hazards: suppose we had only one memory
  - control hazards: need to worry about branch instructions
  - data hazards: an instruction depends on a previous instruction
- We'll study these issues using a simple pipeline
- Other complication:
  - exception handling
  - trying to improve performance with out-of-order execution, etc.

Basic Idea



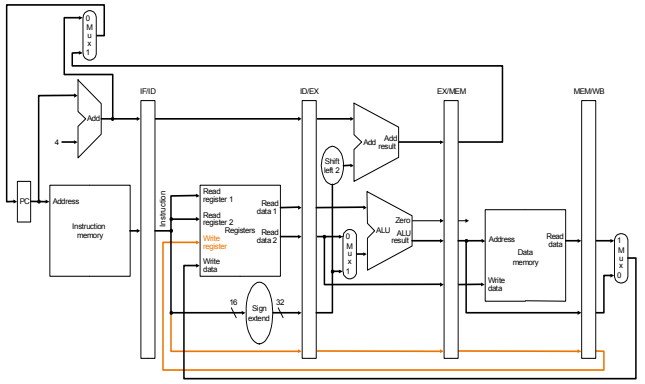
- What do we need to add to actually split the datapath into stages?

Pipelined Data Path



Can you find a problem even if there are no dependencies?
What instructions can we execute to manifest the problem?

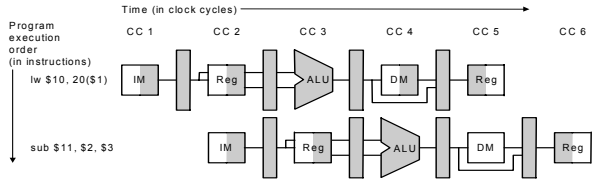
Corrected Data Path



Pipeline Operation

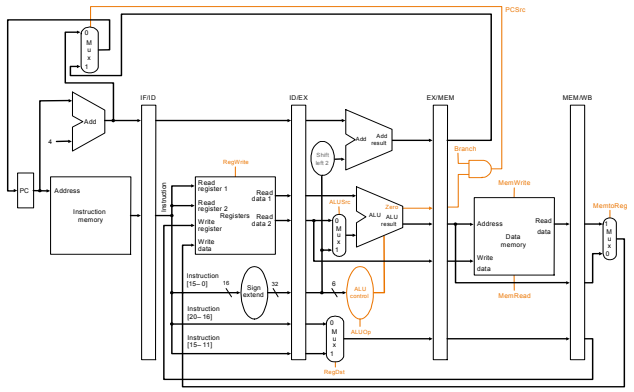
- In pipeline one operation begins in every cycle
- Also, one operation completes in each cycle
- Each instruction takes 5 clock cycles (k cycles in general)
- When a stage is not used, no control needs to be applied
- In one clock cycle, several instructions are active
- Different stages are executing different instructions
- How to generate control signals for them is an issue

Graphically Representing Pipelines



- Can help with answering questions like:
  - how many cycles does it take to execute this code?
  - what is the ALU doing during cycle 4?
  - use this representation to help understand datapaths

Pipeline Control



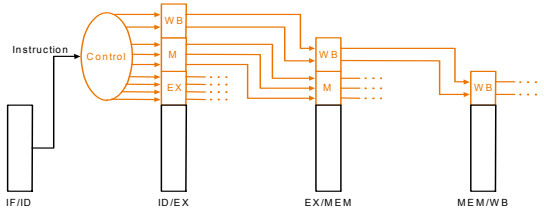
Pipeline control

- We have 5 stages. What needs to be controlled in each stage?
  - Instruction Fetch and PC Increment
  - Instruction Decode / Register Fetch
  - Execution
  - Memory Stage
  - Write Back
- How would control be handled in an automobile plant?
  - a fancy control center telling everyone what to do?
  - should we use a finite state machine?

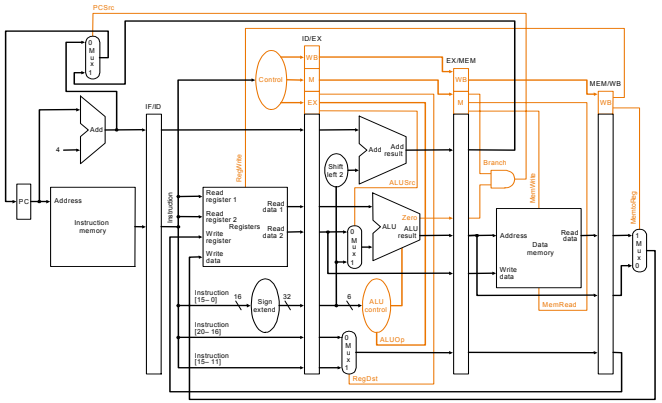
Pipeline Control

- Pass control signals along just like the data

Instruction	Execution/Address Calculation stage control lines				Memory access stage control lines			stage control lines	
	Reg Dst	ALU Op1	ALU Op0	ALU Src	Branch	Mem Read	Mem Write	Reg write	Mem to Reg
R-format	1	1	0	0	0	0	0	1	0
lw	0	0	0	1	0	1	0	1	1
sw	X	0	0	1	0	0	1	0	X
beq	X	0	1	0	1	0	0	0	X

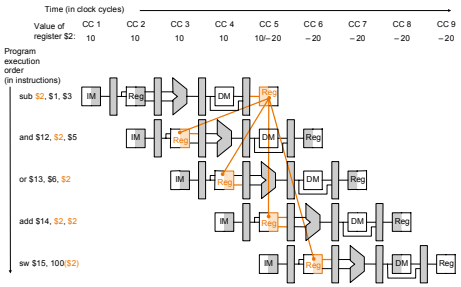


Data Path with Control



Dependencies

- Problem with starting next instruction before first is finished
  - dependencies that "go backward in time" are data hazards



Solution: Software No-ops/Hardware Bubbles

- Have compiler guarantee no hazards
- Where do we insert the "no-ops" ?

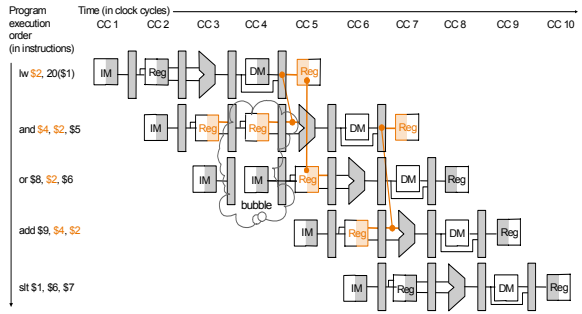
```
sub    $2, $1, $3
and    $12, $2, $5
or     $13, $6, $2
add    $14, $2, $2
sw     $15, 100($2)
```

Problem: this really slows us down!
  - Also, the program will always be slow even if a techniques like forwarding is employed afterwards in newer version

- Hardware can detect dependencies and insert no-ops in hardware by not accepting a new instruction
  - This is a bubble in pipeline and waste one cycle at all stages
  - Need two or three bubbles between write and read of a register

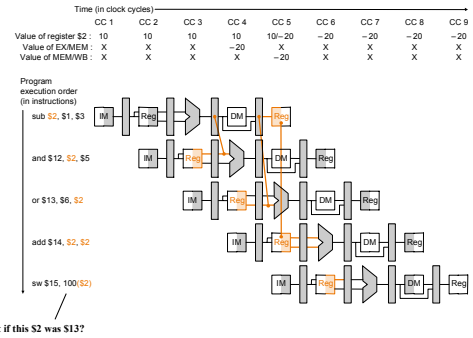
Stalling

- Hardware detection and no-op insertion is called stalling
- We stall the pipeline by keeping an instruction in the same stage

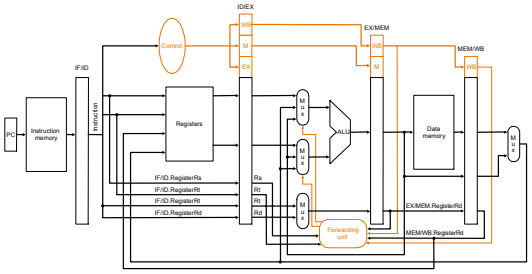


Forwarding

- Use temporary results, don't wait for them to be written
  - register file forwarding to handle read/write to same register
  - ALU forwarding

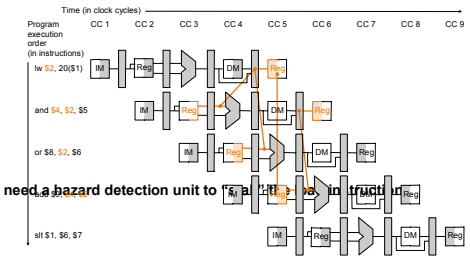


Forwarding



Can't always forward

- **Load word can still cause a hazard:**
  - **an instruction tries to read a register following a load instruction that writes to the same register.**
  -



- **Thus, we need a hazard detection unit to "stall" the load instruction**