Pipelines

Today's topics:

•Evidence suggests there is some rust on this topic

•hence spend a week and move on

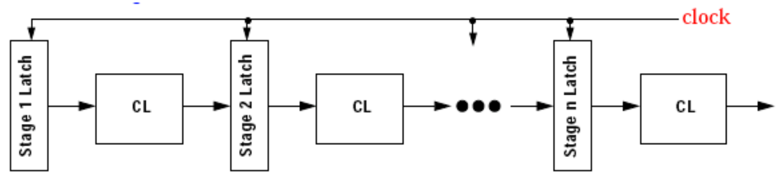
•also need some common terminology

•Attempt to present the ideal issues

•with some discussion on why ideal isn't reality.

Pipelining

- Computational assembly line
  - each step does a small fraction 1/pipeline_depth of the job
  - concurrent exectuion of pipeline_dept instructions
    - » performance is all about parallelism
- Vertical vs. Horizontal concurrency
- Pipeline stage – 1 step in an N step pipe
  - 1 cycle per stage
    - » synchronous design – slowest stage set clock rate
    - » laminar is the target
- Simple model



Pipeline Benefit = Performance

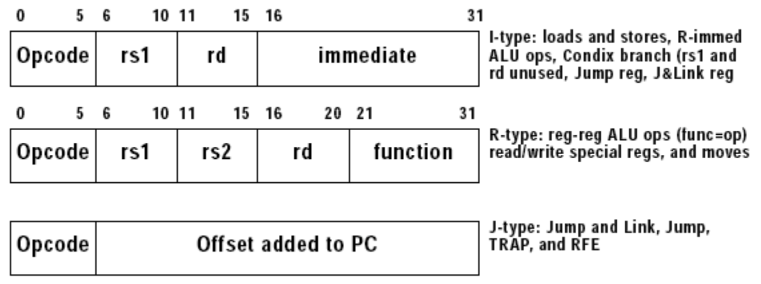
- Ideal performance
  - time-per-instruction = unpiped_instruction time/#stages
    - » asymptotic – overheads count
      - +10% typically achieved
- 2 ways to view this performance enhancement
  - logical
    - » work on several instructions at once
      - albeit in different stages of their execution
    - » parallelism
      - average IPC reduced
  - physical
    - » shorter stages = increased frequency

Other Pipeline Benefits

- HW mechanism
  - hidden from the SW so invisible to the user
  - just viewed as a benefit
- No programming impact
  - unless user needs the ultimate in performance
  - usually left up to compiler scheduling & optimization
- Pipelines are everywhere
  - key keep on Moore's law curve in the 80's
  - 90's just moved to multiple pipelines
  - frequency wars
    - » push pipeline depth to lunatic fringe
      - problems
        - – power α frequency
        - – overheads make ideal performance a bit optimistic

Consider MIPS64

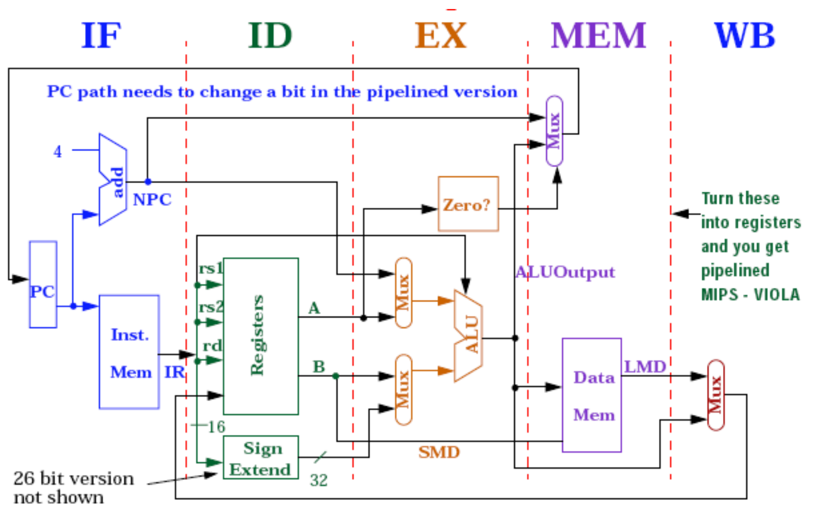
- 5 steps in instruction execution
  - fetch, decode, execute, mem, write-back
- Remember the ISA


0 5 6 10 11 15 16 31
Opcode
rs1
rd
immediate
I-type: loads and stores, R-immed ALU ops, Condix branch (rs1 and rd unused, Jump reg, J&Link reg
0 5 6 10 11 15 16 20 21 31
Opcode
rs1
rs2
rd
function
R-type: reg-reg ALU ops (func=op) read/write special regs, and moves
Opcode
Offset added to PC
J-type: Jump and Link, Jump, TRAP, and RFE

Stages vary by Instructions

- Stage 3
  - Xeq reg-reg or calculate effective address or branch target
    - » for any instruction
      - only one role
- Stage 4
  - only active on Load/Store/Jump/Branch
    - » LMD ← Mem[ALUoutput]
    - » Mem[ALUoutput] ← SMD
    - » next PC = ALUoutput w/ condition
      - JUMP – no condition
- Stage 5
  - Reg-Reg
    - » Regs[$IR_{16..20}$] ← ALUoutput
  - Reg – Immediate
    - » Regs[$IR_{11..15}$] ← ALUoutput
  - Load
    - » Regs[$IR_{11..15}$] ← memory data return

Example 5-stage Data-path



Inter_Stage Registers

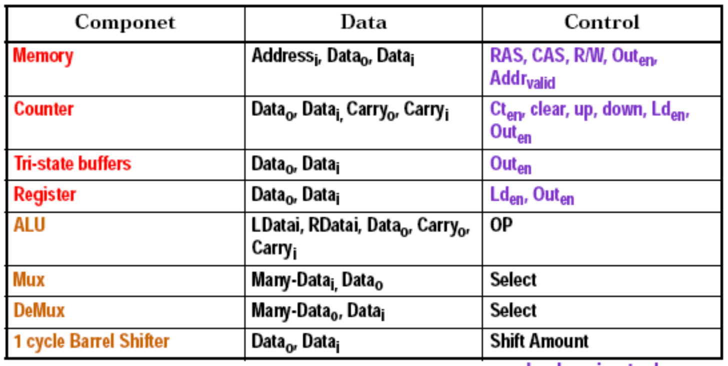
- **Pre-IF**
  - **Next PC**
- **IF:ID**
  - **PC+4**
  - **IR: opcode, RS1, RS2, RD, imm16, function**
  - **Wbmux value**
- **ID:EX**
  - **PC+4**
  - **IR1: Amux_sel, Bmux_sel, ALUop, Wbmux_sel, R/Wmem, Mmux_sel**
  - **immediate data: 16 or 26 bits**
- **EX:Mem**
  - **ALUout, SMD, mux selector indices, R vs. W command**
- **M:WB**
  - **ALUout, LMD**

How real was that?

- Depends
  - real for simple architectures
    - » woefully over simplified for higher performance architectures
  - not optimized
    - » 2 ALU's
      - IF and EX – but ALU's are cheap so who cares?
    - » Harvard architecture
      - separate instruction and data memories
        - – typical at L1 – but unified below that
    - » 5x frequency for five stages
      - slowed down by inter-stage register overhea
- Data-path is only part of the architecture
  - largest bit in terms of area
  - easiest bit in terms of getting it right
  - control path
    - » FSM or microcode or both?

Control vs. Data Example

- Look at a few typical components



Componet	Data	Control
Memory	Address_i, Data_o, Data_i	RAS, CAS, R/W, Out_{en}, Addr_{valid}
Counter	Data_o, Data_i, Carry_o, Carry_i	Ct_{en}, clear, up, down, Ld_{en}, Out_{en}
Tri-state buffers	Data_o, Data_i	Out_{en}
Register	Data_o, Data_i	Ld_{en}, Out_{en}
ALU	LDatai, RDatai, Data_o, Carry_o, Carry_i	OP
Mux	Many-Data_i, Data_o	Select
DeMux	Many-Data_o, Data_i	Select
1 cycle Barrel Shifter	Data_o, Data_i	Shift Amount

Sequential/Combinational   clock oriented

Control Path

- **Each component has control points**
  - register: load or output enable
  - mux/demux: select lines
  - memory: R vs. W
  - XU – optcode
- **What vs. When**
  - when controlled by a clock
    - » SDR vs. DDR
  - what controlled by FSM or uCode control point values
- **Note**
  - book ignores this for the most part
    - » fine in a way
      - tends to consume a small amount of area and power
      - BUT tends to be the major problem
        - – in terms of getting it right!!

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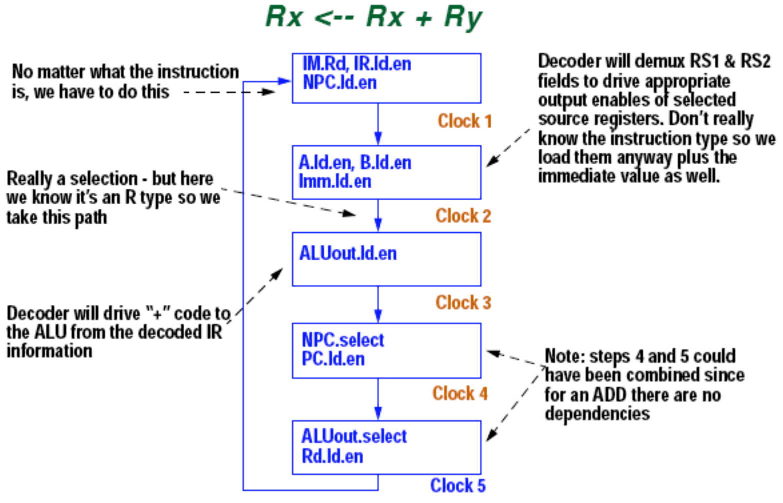
Example: FSM for a simple Add


Rx <-- Rx + Ry
No matter what the instruction is, we have to do this
IM.Rd, IR.ld.en
NPC.ld.en
Clock 1
Decoder will demux RS1 & RS2 fields to drive appropriate output enables of selected source registers. Don't really know the instruction type so we load them anyway plus the immediate value as well.
A.ld.en, B.ld.en
Imm.ld.en
Really a selection - but here we know it's an R type so we take this path
Clock 2
ALUout.ld.en
Decoder will drive "+" code to the ALU from the decoded IR information
Clock 3
NPC.select
PC.ld.en
Note: steps 4 and 5 could have been combined since for an ADD there are no dependencies
Clock 4
ALUout.select
Rd.ld.en
Clock 5

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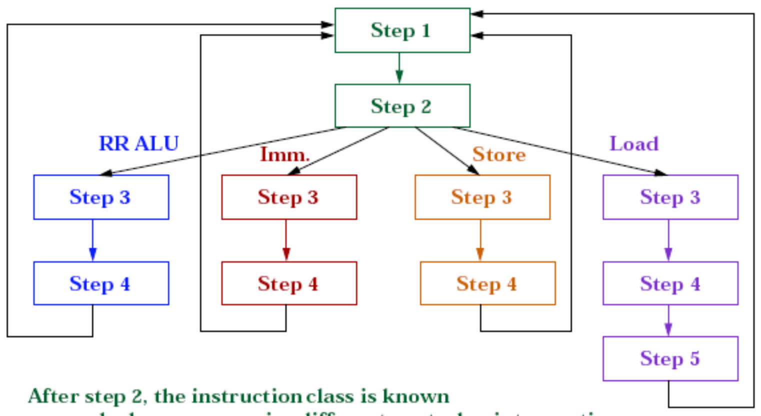
Full Control Scenario



After step 2, the instruction class is known
each class may require different control point assertions
Note that only the load requires all 5 cycles - dummy step 4 pads so all instructions finish at the same time.

Pipeline Parallelism

- **Best case – execute 5 instructions at once**
  - **Note pipeline fill and flush overhead**
  - **in stead state**
    - » **5x frequency → ideal speedup**

Instruction									
Clock #	1	2	3	4	5	6	7	8	9
i	IF	ID	EX	MEM	WB				
i+1		IF	ID	EX	MEM	WB			
i+2			IF	ID	EX	MEM	WB		
I+3				IF	ID	EX	MEM	WB	
i+4					IF	ID	EX	MEM	WB

- **Problem**
  - **consider single I & D memory**
    - » **step 4 & 5 have a resource conflict**

Pipeline Characteristics

- **Latency**
  - time it takes for an instruction to complete
    - » worse w/ pipeline since latch delay added to critical path
    - » dominant feature if lots of exceptions
      - steady state doesn't last for long
      - branch miss_predicts, cache misses, real exceptions
- **Throughput**
  - dominant feature if steady state is common
    - » compiler tries hard to make this true
  - e.g. no
    - » cache misses
    - » register misses
    - » speculation failures
    - » real exceptions

Example

- **Unpipelined**
  - 5 steps: 50, 50, 60, 50, 50 ns respectively
  - total 260 ns
- **Turn it into a pipelined design**
  - 10 ns of "laminarity" penalty
  - 5 ns delay due to latches
    - » set-up, hold, and fall through delays
- **Hence**
  - must run at slowest stage rate/clock = 65 ns
  - speedup 260/64 = 4x
    - » rather than idealized 5x

Pipeline Hair

- **Laminarity is hard**
  - **depends a lot on F04 budget**
    - » **20+ FO4 is somewhat easy**
    - » **13- has proven to be problematic**
- **Extra resources**
  - **each stage needs it's own**
    - » **design drill**
      - **list all possible instruction resource needs**
      - **separate by stage**
      - **each stage needs it's private set**
- **Example**
  - **PC modification can't use same ALU as arithmetic ops**
  - **IF & Mem can't access same memory**

Pipeline Memory Issues

- **More instructions on the fly**
  - **increased memory pressure & bandwidth requirements**
    - » **Nx for N stage pipeline**
- **Key issue w/ memory**
  - **it's slow**
    - » **bigger memories are slower and consume more power**
      - **tiled improves latency but not power**
- **Fixes**
  - **Harvard architecture**
    - » **independent roles**
    - » **access patterns are different**
      - **optimization opportunity**
  - **multi-level cache & memory hierarchy**
  - **speculative prefetch**
  - **pipeline the memory system**
    - » **works for both cache and main**

Hazards & Dependencies

- Consider a pair of instructions
  - R5 = R2 + R3; R3 = R5 + R6
    - » write back of R5 happens in stage 5
    - » R5 value needed by stage 3
    - » OOPS
- Enter bypass and stalls
  - value actually known at end of stage 3
  - used on next cycle in stage 3
  - send/bypass value to stage 4 and to beginning of stage 3
    - » more logic and more control
      - add mux delay → catch-22
    - » dependencies must be checked
      - time cash register goes KA-CHING
      - impact on both data and control paths

3 Types of Hazards

- Structural
  - resource contention of different pipeline stages
    - » register read in ID or register write in WB
      - 2 ported register file
        - – typical arith op is 2 reads and one write → 3 ports: 2R and IW
        - – superscalar makes this worse
- Data
  - dependency for either register source or destination
- Control
  - PC incremented or computed
    - » branch and jump effect
  - exceptions → go somewhere else
    - » e.g. exception handler
    - » not so bad with an in-order execution style
      - total pain with out-of-order execution
        - – more on this later

Example Pipeline Activity

- **From pipeline stage perspective**

Stage	PC Unit	Memory	Data Path
IF	PC <-- PC + 4	IR <-- Mem[PC]	
ID	PC1 <-- PC	IR1 <--IR	A <-- Rs1; B<--Rs2

EX			DMAR <--A + $(IR1_{16})^{16}$ ## $IR1_{16..31}$
			or
			ALUout <-- A op B
			or
			ALUout <-- A op $(IR1_{16})^{16}$ ## $IR1_{16..31}$
			or
			ALUout <-- PC1 + $(IR1_{16})^{16}$ ## $IR1_{16..31}$
			or
			cond <-- (Rs1 op 0); SMDR <-- B

MEM	if (cond) then
	PC <-- ALUout
		LMDR <-- MEM[DMAR]
		or
		MEM[DMAR] <-- SMDR
			ALUout1 <-- ALUout

WB			Rd <-- ALUout1 or Rd <-- LMDR

Pipeline Activity

- **From Instruction class perspective**

Stage	ALU instruction	Load or Store	Branch

IF	IR <-- MEM[PC];
	PC <-- PC+4
		IR <-- MEM[PC];
		PC <-- PC+4
			IR <-- MEM[PC];
			PC <-- PC+4

ID	A<--Rs1; B<--Rs2; PC1<--PC;
	IR1<--IR
		A<--Rs1; B<--Rs2; PC1<--PC;
		IR1<--IR
			A<--Rs1; B<--Rs2; PC1<--PC;
			IR1<--IR

EX	ALUout <-- A op B
	or
	ALUout<--A op $(IR1_{16})^{16}$ ##
	$IR1_{16..31}$
		DMAR<--A+$(IR1_{16})^{16}$ ##
		$IR1_{16..31:}$
		SMDR <-- B {if it's a store}
			ALUout <-- PC1+$(IR1_{16})^{16}$ ##
			$IR1_{16..31}$
			cond <-- Rs1 op 0

MEM	ALUout1 <-- ALUout	LMDR <-- MEM[DMAR]
		or
		MEM[DMAR] <-- SMDR
			if (cond) then PC<--ALUout

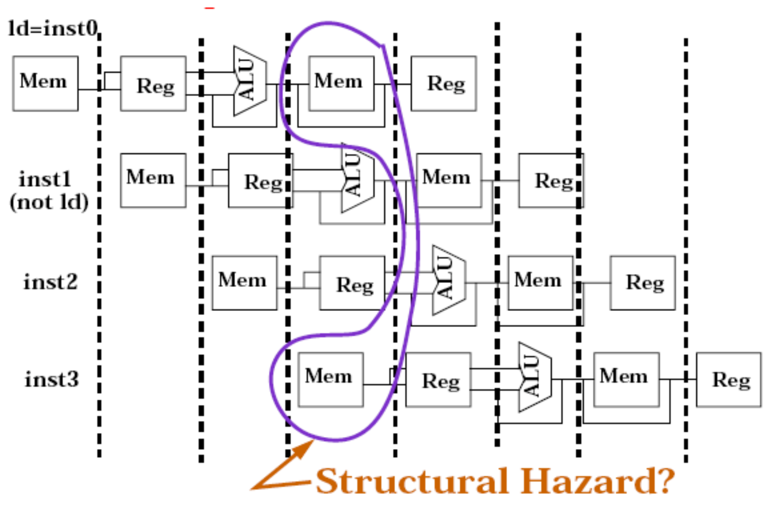
WB	Rd <-- ALUout1	RD <-- LMDR {if it's a load}	

- note potential stage holes where nothing much happens
- note pre-decode (stages 1 & 2) - same for all

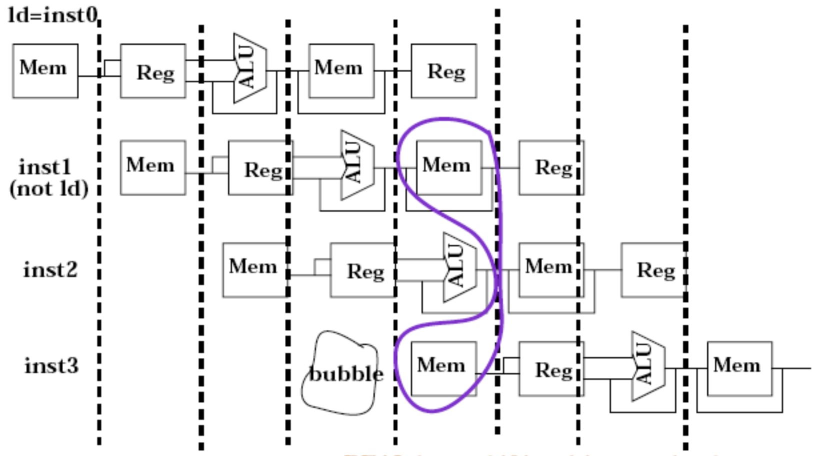
Hazards & Stalls

- Extra resources mitigate
  - data → bypass logic
  - structural → duplicate resources
  - control → predict and speculate
- When it fails
  - stall
    - » ideal pipeline speedup compromised
- More realistic scenario
  - not all stages are necessary for every instruction
    - » implementation increases control path complexity

Pipeline: Resource View



Stall Creates Pipeline Bubble



no REAL hazard if inst1 is not a load

Calculating Stall Effects

$$\text{Pipeline Speedup} = \frac{\text{Average instruction time without pipelining}}{\text{Average instruction time with pipelining}}$$

$$\text{Pipeline Speedup} = \frac{\text{unpiped cycle time}}{\text{piped cycle time}} \times \frac{\text{unpiped CPI}}{\text{piped CPI}}$$

$$\text{Ideal CPI} = \frac{\text{unpiped CPI}}{\text{Pipeline Depth}}$$

Therefore

$$\text{Pipeline Speedup} = \frac{\text{unpiped cycle time}}{\text{piped cycle time}} \times \frac{\text{Ideal CPI} \times \text{Pipeline Depth}}{\text{piped CPI}}$$

Calculating Further

However

$$\text{piped CPI} = \text{Ideal CPI} \times \text{Pipeline stall cycles} = 1 + \text{average stalls per instruction}$$

Then if perfect balance: no overhead and cycle times equal

$$\text{Speedup} = \frac{\text{CPI Unpiped}}{1 + \text{Pipeline stall cycles per instruction}}$$

If laminar then unpiped CPI = pipeline depth, hence

$$\text{Speedup} = \frac{\text{Pipeline Depth}}{1 + \text{Pipeline stalls per instruction}}$$

Similar derivations for clock cycles are also possible

Conclusion: Beware of Overhead

- **Cycle time**
  - **reduces w/ increased # of stages**
    - » **but latch insertion adds to latency**
    - » **size of inter-stage registers is large**
      - **increased power due to lots of bits moved and stored**
- **Stall effects**
  - **the deeper the pipeline**
    - » **reduced probability that nothing went wrong**
    - » **e.g. reduction from 1/N speedup ideal**
- **High frequency**
  - **active power linear w/ frequency**
  - **stall restart is a problem w/ very high frequencies**
    - » **e.g. Prescott and Northwood**
- **Amdahl's Law**
  - **not everything benefits**
    - » **no guessing – you have to run the sim's**