Computer Architecture

Unit 6: Pipelining

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with sources that included University of Wisconsin slides
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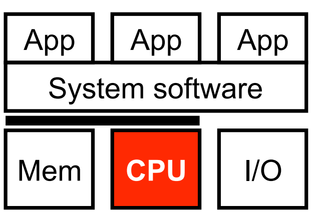
This Unit: Pipelining



- Single-cycle & multi-cycle datapaths
- Latency vs throughput & performance
- Basic pipelining
- Data hazards
  - Bypassing
  - Load-use stalling
- Pipelined multi-cycle operations
- Control hazards
  - Branch prediction

In-Class Exercise

- You have a washer, dryer, and "folder"
  - Each takes 30 minutes per load
  - How long for one load in total?
  - How long for two loads of laundry?
  - How long for 100 loads of laundry?

- Now assume:
  - Washing takes 30 minutes, drying 60 minutes, and folding 15 min
  - How long for one load in total?
  - How long for two loads of laundry?
  - How long for 100 loads of laundry?

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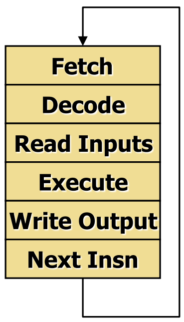
In-Class Exercise Answers

- You have a washer, dryer, and "folder"
  - Each takes 30 minutes per load
  - How long for one load in total? **90 minutes**
  - How long for two loads of laundry? 90 + 30 = **120 minutes**
  - How long for 100 loads of laundry? 90 + 30*99 = **3060 min**

- Now assume:
  - Washing takes 30 minutes, drying 60 minutes, and folding 15 min
  - How long for one load in total? **105 minutes**
  - How long for two loads of laundry? 105 + 60 = **165 minutes**
  - How long for 100 loads of laundry? 105 + 60*99 = **6045 min**

Datapath Background

Recall: The Sequential Model



- **Basic structure of all modern ISAs**
  - Often called VonNeuman, but in ENIAC before
- **Program order**: total order on dynamic insns
  - Order and **named storage** define computation
- Convenient feature: **program counter (PC)**
  - Insn itself stored in memory at location pointed to by PC
  - Next PC is next insn unless insn says otherwise
- Processor logically executes loop at left
- **Atomic**: insn finishes before next insn starts
  - Implementations can break this constraint physically
  - **But must maintain illusion to preserve correctness**

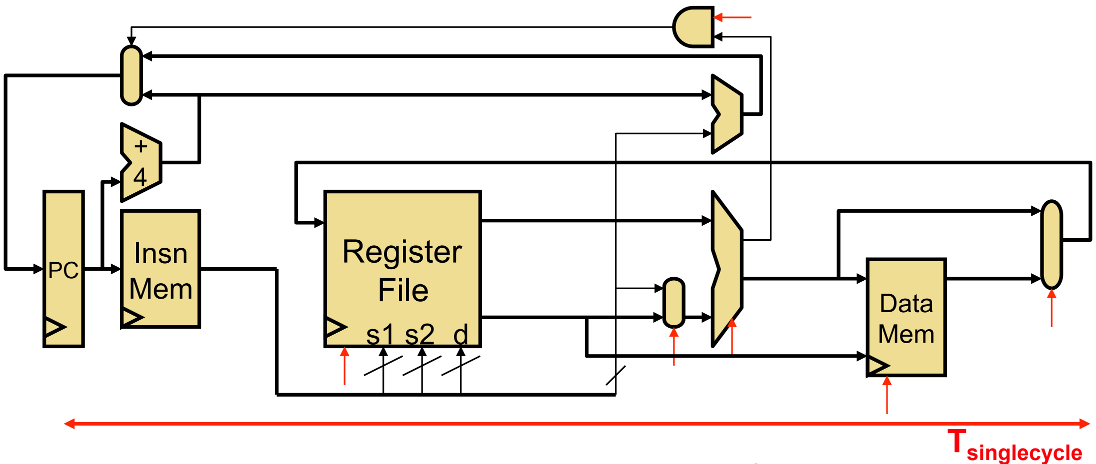
Recall: Maximizing Performance

Execution time =
(instructions/program) * (seconds/cycle) * (cycles/instruction)

(1 billion instructions) * (1ns per cycle) * (1 cycle per insn)
= 1 second

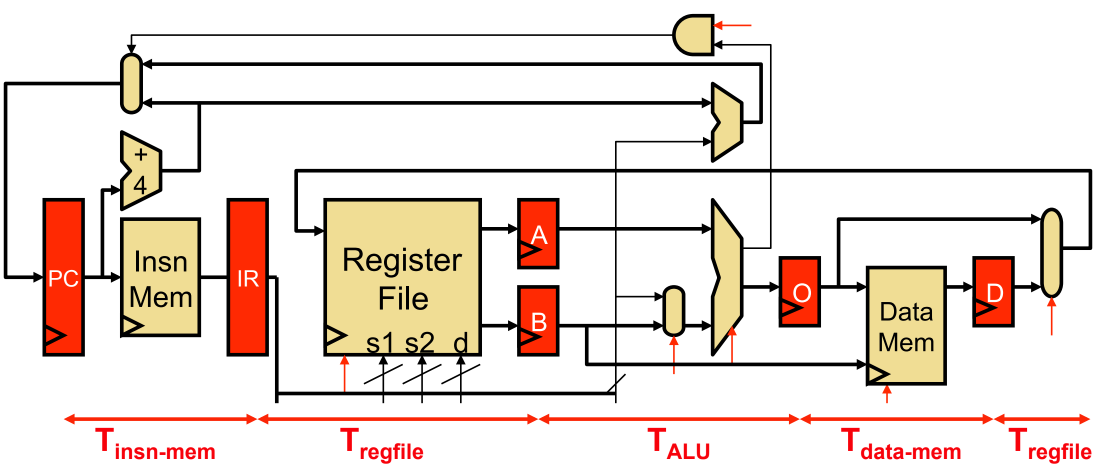
- Instructions per program:
  - Determined by program, compiler, instruction set architecture (ISA)
- **Cycles per instruction: "CPI"**
  - Typical range today: 2 to 0.5
  - Determined by program, compiler, ISA, micro-architecture
- **Seconds per cycle: "clock period" - same each cycle**
  - Typical range today: 2ns to 0.25ns
  - Reciprocal is frequency: 0.5 Ghz to 4 Ghz (1 Htz = 1 cycle per sec)
  - Determined by micro-architecture, technology parameters
- For minimum execution time, minimize each term
  - Difficult: ***often pull against one another***

Single-Cycle Datapath



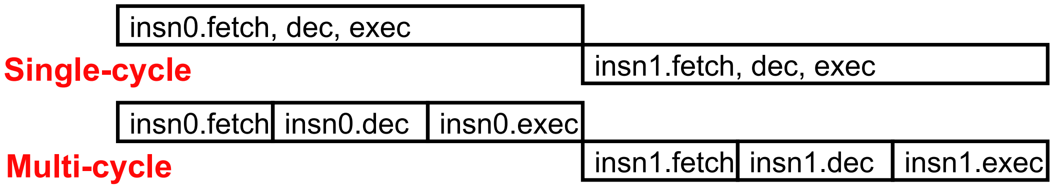
- **Single-cycle datapath**: true "atomic" fetch/execute loop
  - Fetch, decode, execute one complete instruction every cycle
  - \+ Takes 1 cycle to execution any instruction by definition ("CPI" is 1)
  - – Long clock period: to accommodate slowest instruction (worst-case delay through circuit, must wait this long *every* time)

Multi-Cycle Datapath



- **Multi-cycle datapath**: attacks slow clock
  - Fetch, decode, execute one complete insn over multiple cycles
  - **Allows insns to take different number of cycles**
  - \+ Opposite of single-cycle: short clock period (less "work" per cycle)
  - – Multiple cycles per instruction (higher "CPI")

Recap: Single-cycle vs. Multi-cycle



- **Single-cycle datapath**:
  - Fetch, decode, execute one complete instruction every cycle
  - \+ Low CPI: 1 by definition
  - – Long clock period: to accommodate slowest instruction

- **Multi-cycle datapath**: attacks slow clock
  - Fetch, decode, execute one complete insn over multiple cycles
  - **Allows insns to take different number of cycles**
  - ± Opposite of single-cycle: short clock period, high CPI (think: CISC)

Single-cycle vs. Multi-cycle Performance

- Single-cycle
  - Clock period = 50ns, CPI = 1
  - Performance = **50ns/insn**

- Multi-cycle has opposite performance split of single-cycle
  - \+ Shorter clock period
  - – Higher CPI

- Multi-cycle
  - Branch: 20% (**3** cycles), load: 20% (**5** cycles), ALU: 60% (**4** cycles)
  - Clock period = **11ns**, CPI = (20%*3)+(20%*5)+(60%*4) = 4
    - Why is clock period 11ns and not 10ns? overheads
  - Performance = **44ns/insn**

- Aside: CISC makes perfect sense in multi-cycle datapath

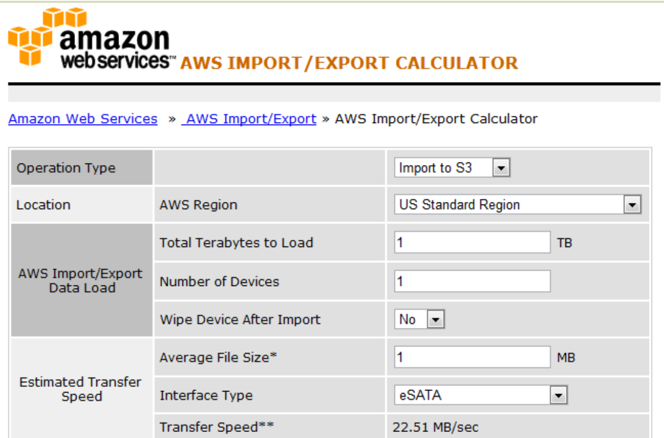
Pipelined Datapath

Performance: Latency vs. Throughput

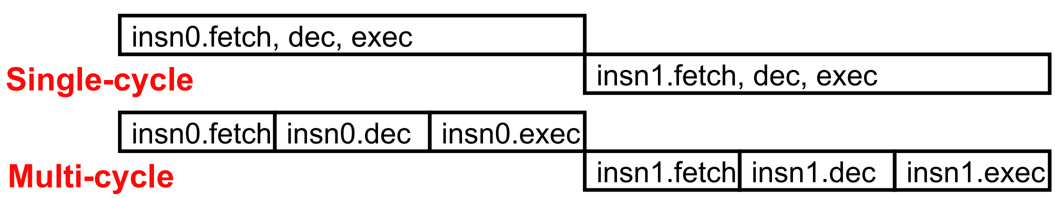
- **Latency (execution time)**: time to finish a fixed task
- **Throughput (bandwidth)**: number of tasks in fixed time
  - Different: exploit parallelism for throughput, not latency (e.g., bread)
  - Often contradictory (latency **vs.** throughput)
    - Will see many examples of this
  - Choose definition of performance that matches your goals
    - Scientific program? Latency, web server: throughput?
- Example: move people 10 miles
  - Car: capacity = 5, speed = 60 miles/hour
  - Bus: capacity = 60, speed = 20 miles/hour
  - Latency: **car = 10 min**, bus = 30 min
  - Throughput: car = 15 PPH (count return trip), **bus = 60 PPH**
- Fastest way to send 10TB of data? (at 1+ gbits/second)

Amazon Does This…

Available Internet Connection	Theoretical Min. Number of Days to Transfer 1TB at 80% Network Utilization	When to Consider AWS Import/Export?
T1 (1.544Mbps)	82 days	100GB or more
10Mbps	13 days	600GB or more
T3 (44.736Mbps)	3 days	2TB or more
100Mbps	1 to 2 days	5TB or more
1000Mbps	Less than 1 day	60TB or more



Latency versus Throughput



- Can we have both low CPI and short clock period?
  - Not if datapath executes only one insn at a time
- Latency and throughput: two views of performance …
  - (1) at the program level and (2) at the instructions level
- Single instruction latency
  - Doesn't matter: programs comprised of billions of instructions
  - Difficult to reduce anyway
- Goal is to make programs, not individual insns, go faster
  - Instruction throughput → program latency
  - Key: **exploit inter-insn parallelism**

Pipelining

Multi-cycle

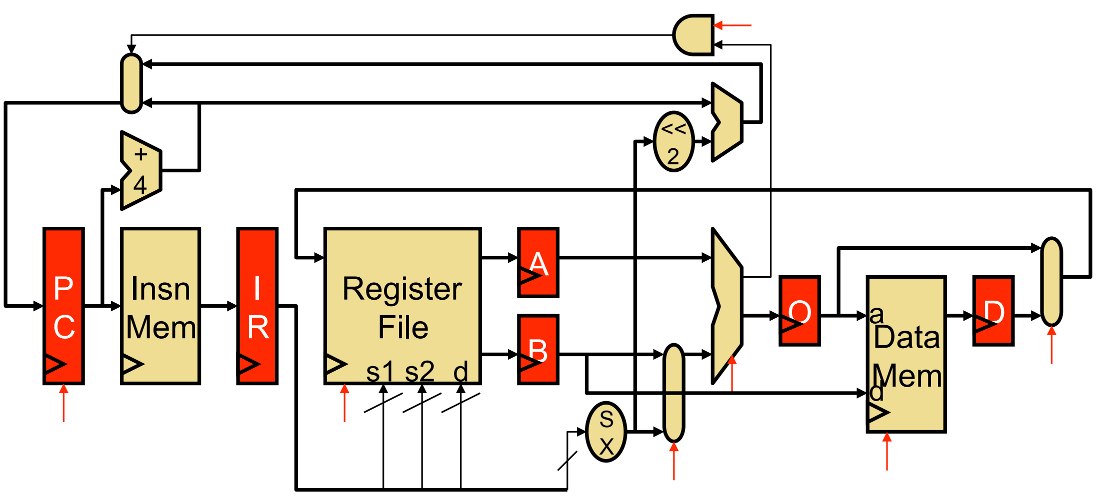
insn0.fetch	insn0.dec	insn0.exec			
			insn1.fetch	insn1.dec	insn1.exec

Pipelined

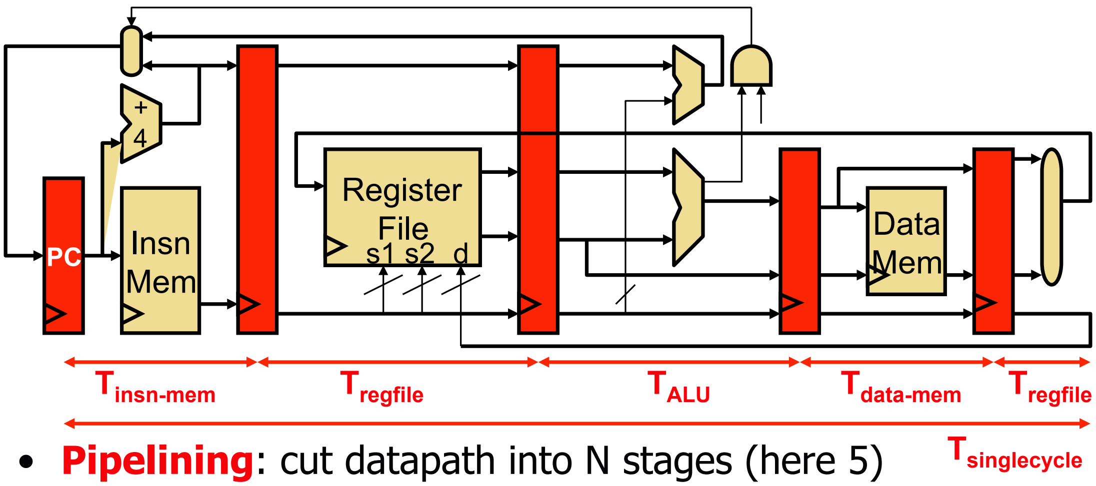
insn0.fetch	insn0.dec	insn0.exec	
	insn1.fetch	insn1.dec	insn1.exec

- Important performance technique
  - **Improves instruction throughput rather instruction latency**
- Begin with multi-cycle design
  - When insn advances from stage 1 to 2, next insn enters at stage 1
  - Form of parallelism: "insn-stage parallelism"
  - Maintains illusion of sequential fetch/execute loop
  - Individual instruction takes the same number of stages
  - \+ **But instructions enter and leave at a much faster rate**
- Laundry analogy

5 Stage Multi-Cycle Datapath

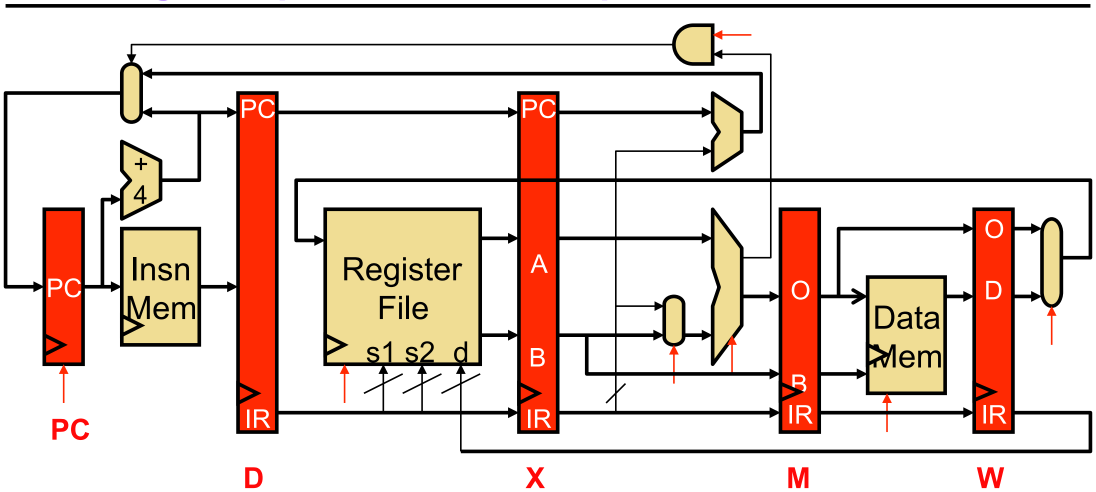


5 Stage Pipeline: Inter-Insn Parallelism



- **Pipelining**: cut datapath into N stages (here 5)
  - One insn in each stage in each cycle
  - + Clock period = MAX($T_{insn\text{-}mem}$, $T_{regfile}$, T_{ALU}, $T_{data\text{-}mem}$)
  - + Base CPI = 1: insn enters and leaves every cycle
  - – Actual CPI > 1: pipeline must often "stall"
  - Individual insn latency increases (pipeline overhead), not the point

5 Stage Pipelined Datapath



- Five stage: **F**etch, **D**ecode, e**X**ecute, **M**emory, **W**riteback
  - Nothing magical about 5 stages (Pentium 4 had 22 stages!)
- Latches (pipeline registers) named by stages they begin
  - **PC**, **D**, **X**, **M**, **W**

More Terminology & Foreshadowing

- **Scalar pipeline**: one insn per stage per cycle
  - Alternative: "superscalar" (later)
- **In-order pipeline**: insns enter execute stage in order
  - Alternative: "out-of-order" (later)
- **Pipeline depth**: number of pipeline stages
  - Nothing magical about five
  - Contemporary high-performance cores have ~15 stage pipelines

Instruction Convention

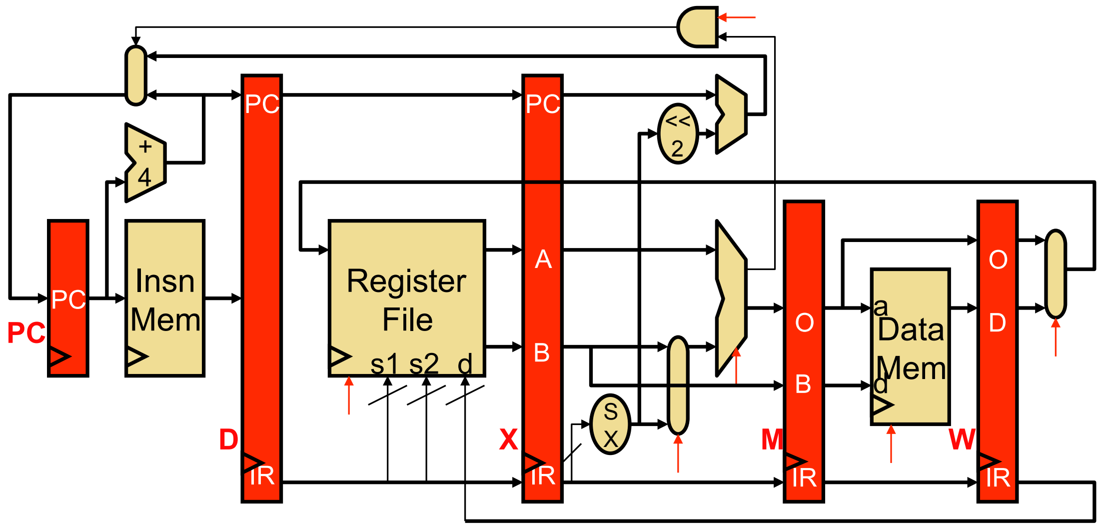
- Different ISAs use inconsistent register orders
- Some ISAs (for example MIPS)
  - Instruction destination (i.e., output) **on the left**
  - add $1, $2, $3 means $1←$2+$3
- Other ISAs
  - Instruction destination (i.e., output) **on the right**

  `add r1,r2,r3` means `r1+r2→r3`

  `ld 8(r5),r4` means `mem[r5+8]→r4`

  `st r4,8(r5)` means `r4→mem[r5+8]`
- Will try to specify to avoid confusion, next slides MIPS style

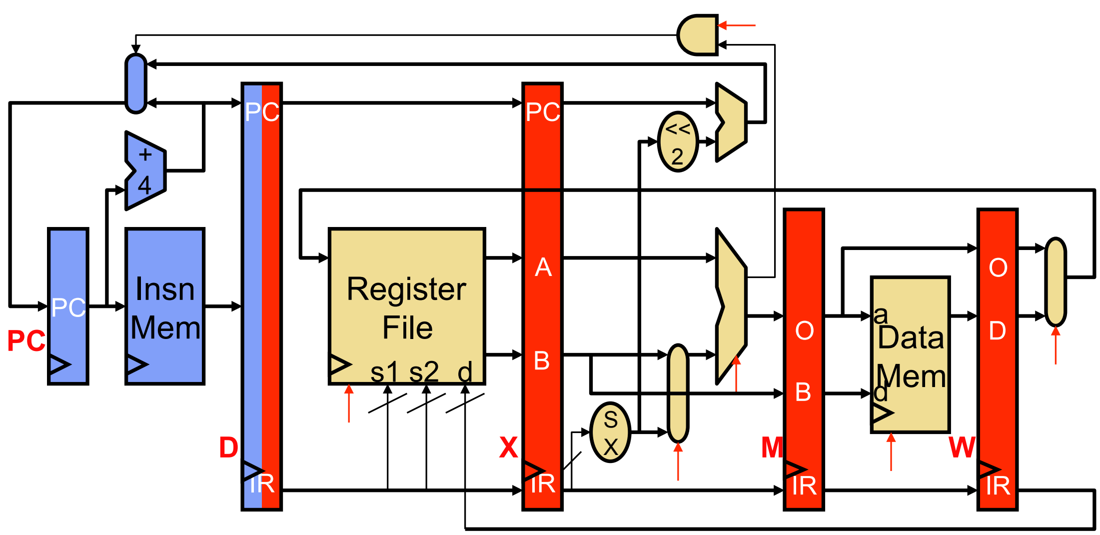
Pipeline Example: Cycle 1



add $3,$2,$1

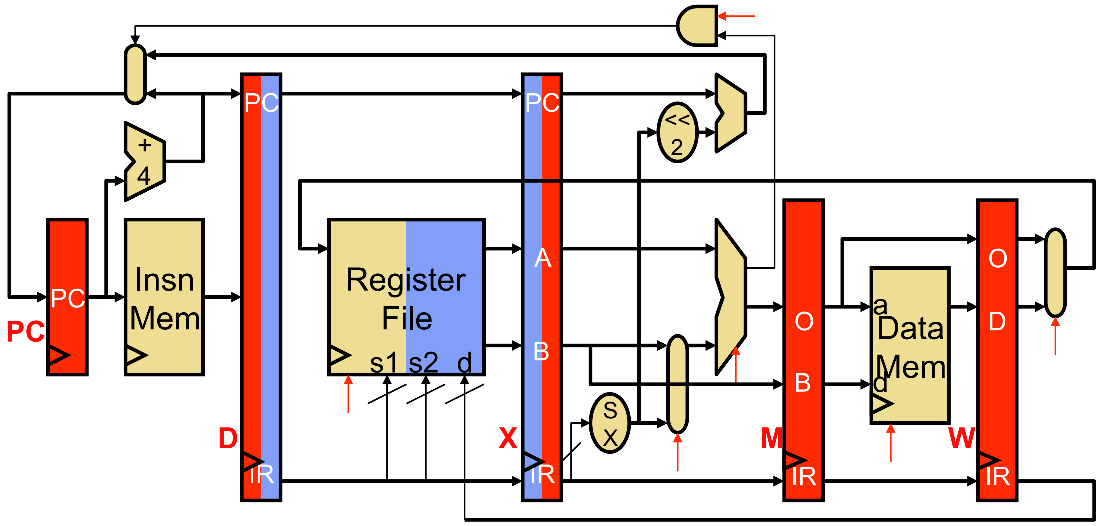
- 3 instructions

Pipeline Example: Cycle 2



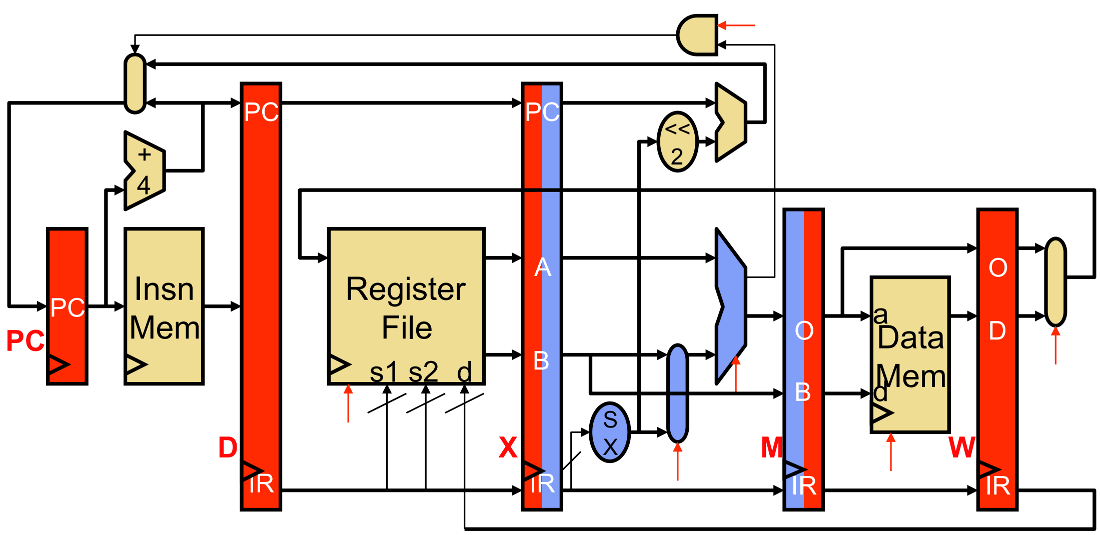
lw $4,8($5)   add $3,$2,$1

Pipeline Example: Cycle 3



`sw $6,4($7)` `lw $4,8($5)` `add $3,$2,$1`

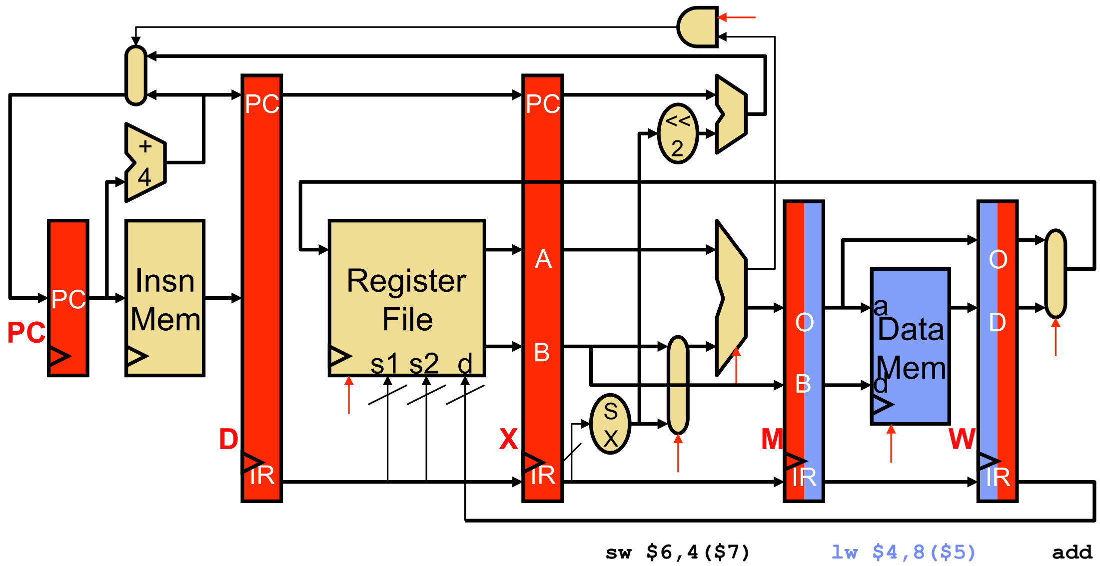
Pipeline Example: Cycle 4



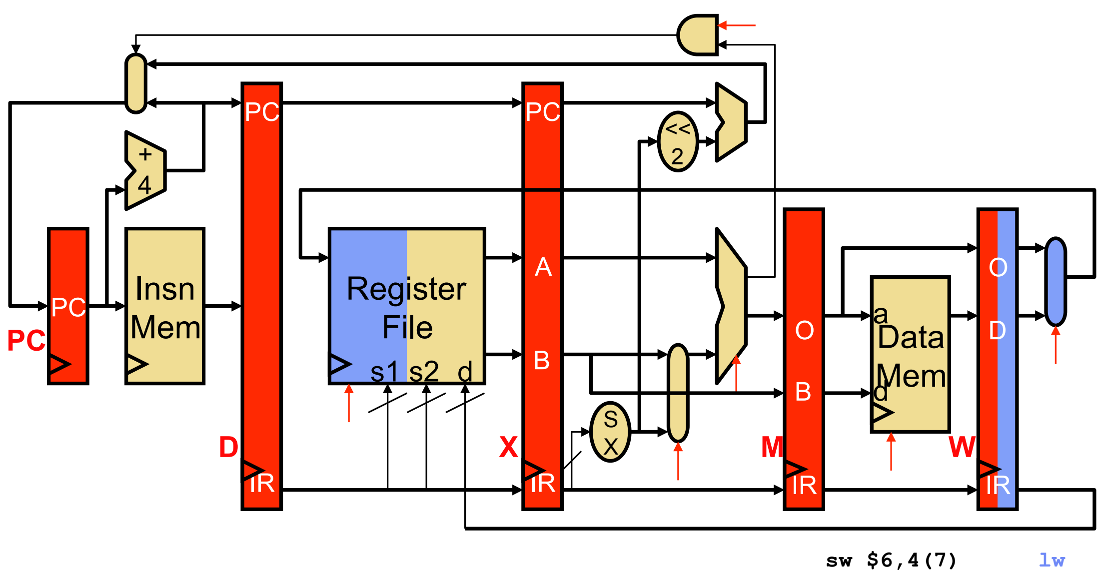
`sw $6,4($7)` `lw $4,8($5)` `add $3,$2,$1`

- 3 instructions

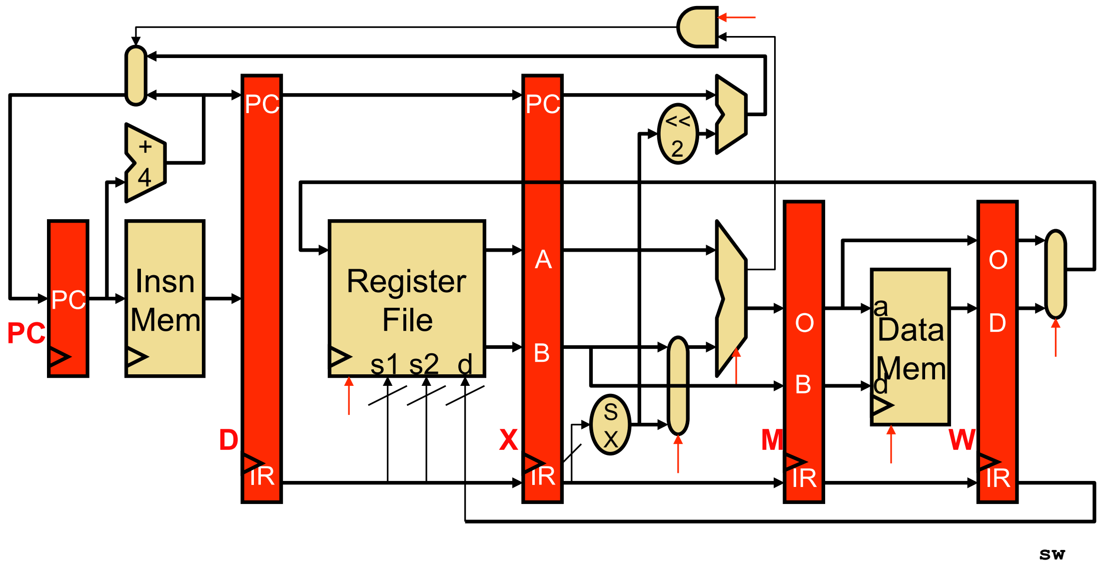
Pipeline Example: Cycle 5



Pipeline Example: Cycle 6



Pipeline Example: Cycle 7



Pipeline Diagram

- **Pipeline diagram**: shorthand for what we just saw
  - Across: cycles
  - Down: insns
  - Convention: **X** means `lw $4,8($5)` finishes execute stage and writes into M latch at end of cycle 4

	1	2	3	4	5	6	7	8	9
`add $3,$2,$1`	F	D	X	M	W				
`lw $4,8($5)`		F	D	**X**	M	W			
`sw $6,4($7)`			F	D	X	M	W		

Example Pipeline Perf. Calculation

- Single-cycle
  - Clock period = 50ns, CPI = 1
  - Performance = 50ns/insn
- Multi-cycle
  - Branch: 20% (3 cycles), load: 20% (5 cycles), ALU: 60% (4 cycles)
  - Clock period = 11ns, CPI = (20%*3)+(20%*5)+(60%*4) = 4
  - Performance = 44ns/insn
- 5-stage pipelined
  - Clock period = **12ns** approx. (50ns / 5 stages) + overheads
  - \+ CPI = **1** (each insn takes 5 cycles, but 1 completes each cycle)
    - \+ Performance = **12ns/insn**
  - – Well actually … CPI = 1 + some penalty for pipelining (next)
    - CPI = **1.5** (on average insn completes every 1.5 cycles)
    - Performance = **18ns/insn**
    - Much higher performance than single-cycle or multi-cycle

Q1: Why Is Pipeline Clock Period …

- … > (delay thru datapath) / (number of pipeline stages)?
  - Three reasons:
    - Latches add delay
    - Pipeline stages have different delays, clock period is max delay
    - Extra datapaths for pipelining (bypassing paths)
  - These factors have implications for ideal number pipeline stages
    - Diminishing clock frequency gains for longer (deeper) pipelines

Q2: Why Is Pipeline CPI…

- … > 1?
  - CPI for scalar in-order pipeline is 1 **+ stall penalties**
  - Stalls used to resolve hazards
    - **Hazard**: condition that jeopardizes sequential illusion
    - **Stall**: pipeline delay introduced to restore sequential illusion
- Calculating pipeline CPI
  - **Frequency of stall** * **stall cycles**
  - Penalties add (stalls generally don't overlap in in-order pipelines)
  - 1 + (stall-$freq_1$*stall-cyc_1) + (stall-$freq_2$*stall-cyc_2) + …
- Correctness/performance/make common case fast
  - Long penalties OK if they are rare, e.g., 1 + (0.01 * 10) = 1.1
  - Stalls also have implications for ideal number of pipeline stages

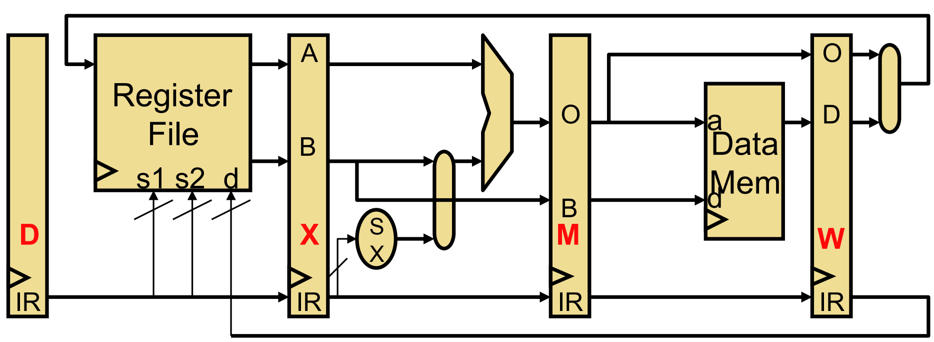
Data Dependences, Pipeline Hazards, and Bypassing

Dependences and Hazards

- **Dependence**: relationship between two insns
  - **Data**: two insns use same storage location
  - **Control**: one insn affects whether another executes at all
  - Not a bad thing, programs would be boring without them
  - Enforced by making older insn go before younger one
    - Happens naturally in single-/multi-cycle designs
    - But not in a pipeline

- **Hazard**: dependence & possibility of wrong insn order
  - Effects of wrong insn order cannot be externally visible
    - **Stall**: for order by keeping younger insn in same stage
  - Hazards are a bad thing: stalls reduce performance

Data Hazards



- Let's forget about branches and the control for a while
- The three insn sequence we saw earlier executed fine…
  - But it wasn't a real program
  - Real programs have **data dependences**
    - They pass values via registers and memory

Dependent Operations

- Independent operations

```
add $3,$2,$1
add $6,$5,$4
```

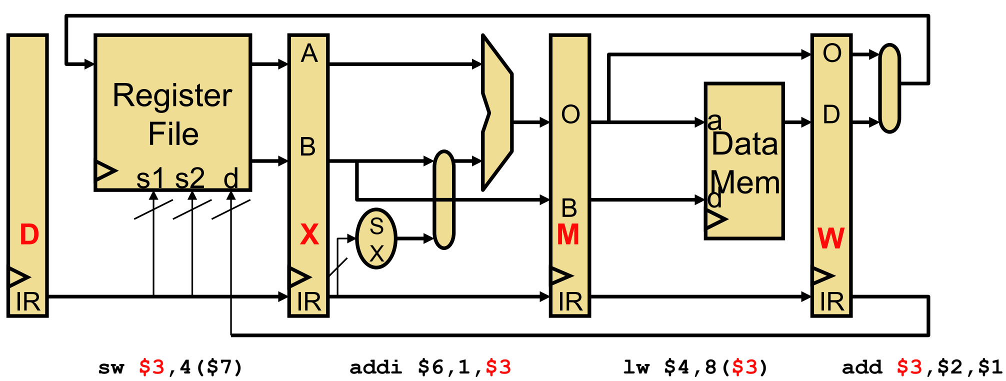
- Would this program execute correctly on a pipeline?

```
add $3,$2,$1
add $6,$5,$3
```

- What about this program?

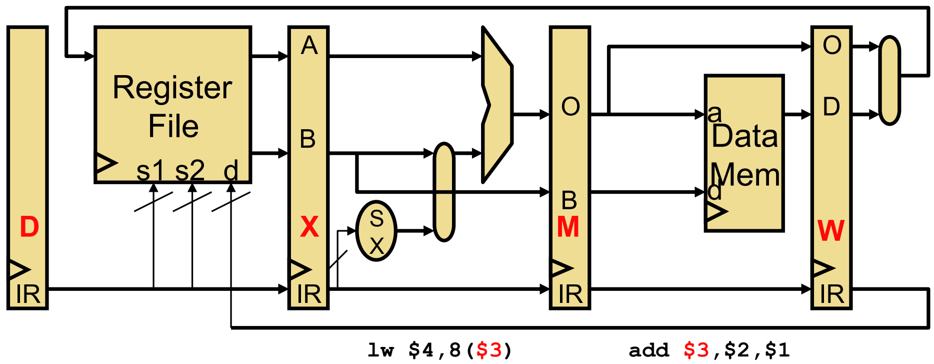
```
add $3,$2,$1
lw $4,8($3)
addi $6,1,$3
sw $3,8($7)
```


Data Hazards



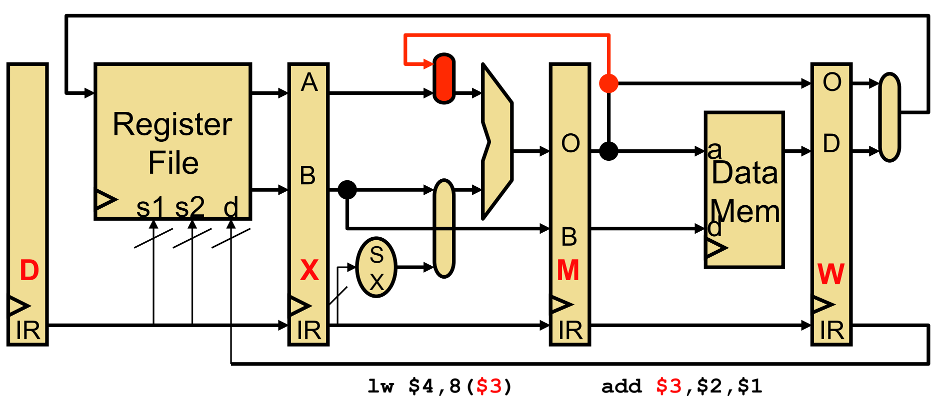
- Would this "program" execute correctly on this pipeline?
  - Which insns would execute with correct inputs?
  - **add** is writing its result into **$3** in current cycle
  - – **lw** read **$3** two cycles ago → got wrong value
  - – **addi** read **$3** one cycle ago → got wrong value
  - **sw** is reading **$3** this cycle → maybe (depending on regfile design)

Observation!



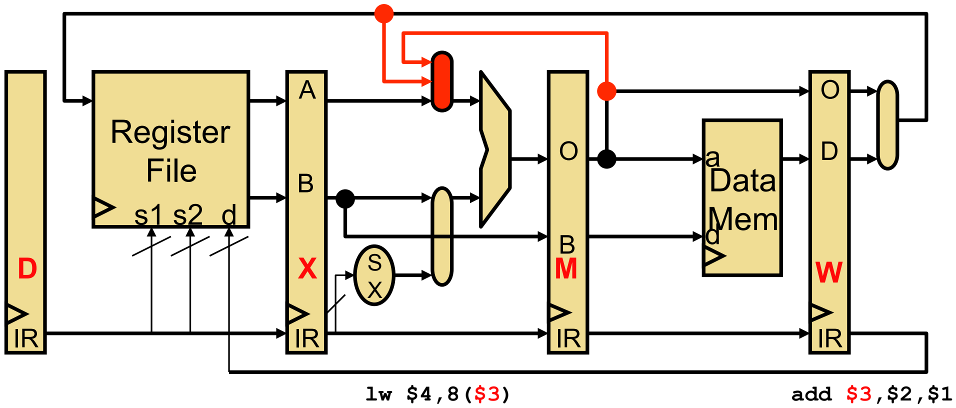
- Technically, this situation is broken
  - **`lw $4,8($3)`** has already read **$3** from regfile
  - **`add $3,$2,$1`** hasn't yet written **$3** to regfile
- But fundamentally, everything is OK
  - **`lw $4,8($3)`** hasn't actually used **$3** yet
  - **`add $3,$2,$1`** has already computed **$3**

Bypassing



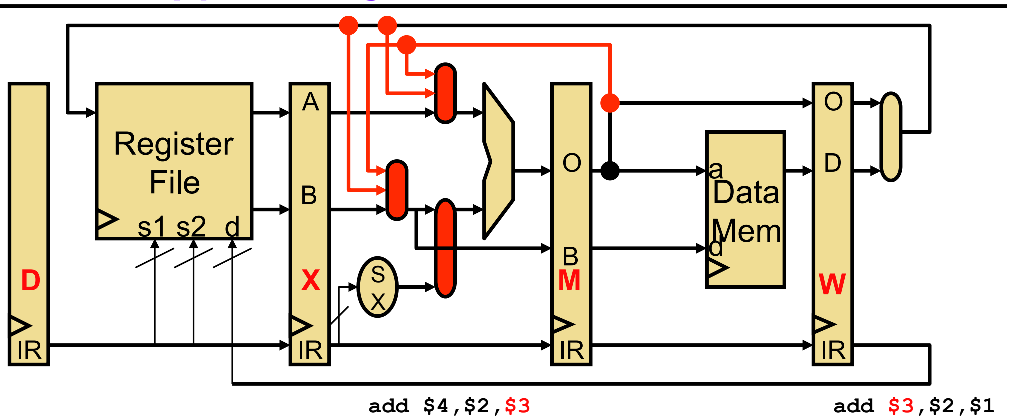
- **Bypassing**
  - Reading a value from an intermediate (μarchitectural) source
  - Not waiting until it is available from primary source
  - Here, we are bypassing the register file
  - Also called **forwarding**

WX Bypassing



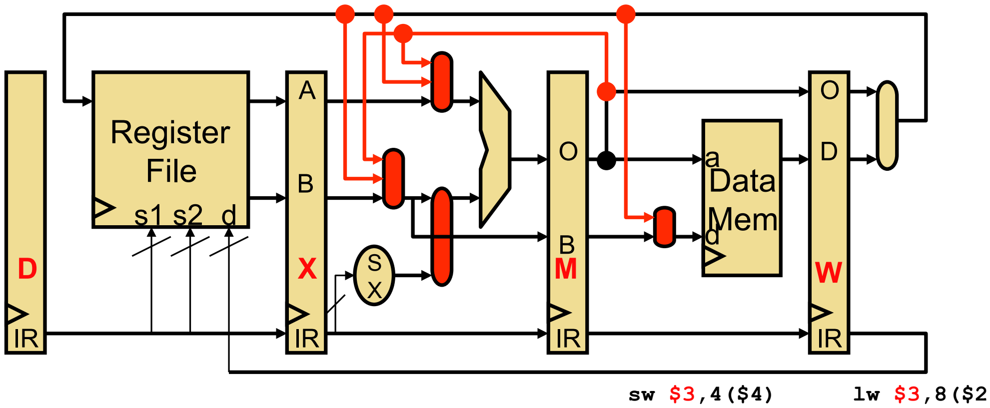
- What about this combination?
  - Add another bypass path and MUX (multiplexor) input
  - First one was an **MX** bypass
  - This one is a **WX** bypass

ALUinB Bypassing

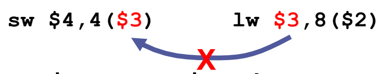


- Can also bypass to ALU input B

WM Bypassing?

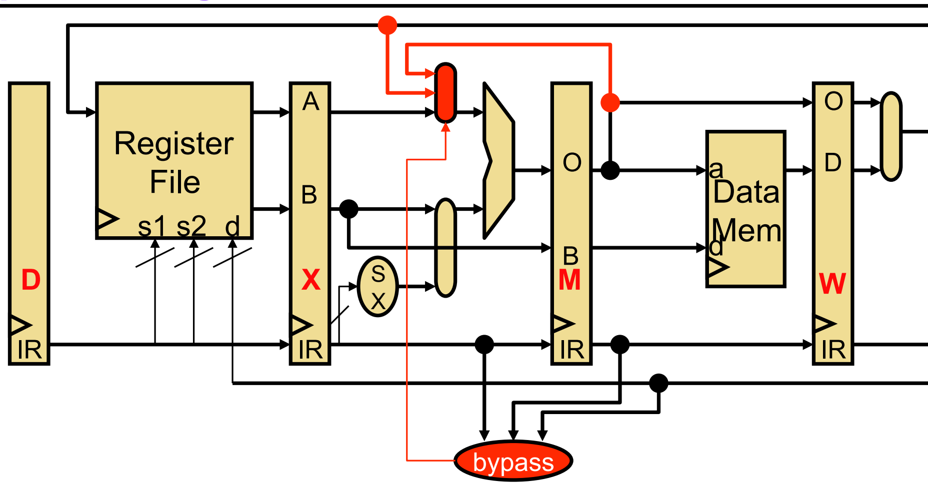


- Does WM bypassing make sense?
  - Not to the address input (why not?)



  - But to the store data input, yes

Bypass Logic



- Each multiplexor has its own, here it is for "ALUinA"

  (X.IR.RegSrc1 == M.IR.RegDest) => 0
  (X.IR.RegSrc1 == W.IR.RegDest) => 1
  Else => 2

Pipeline Diagrams with Bypassing

- If bypass exists, "from"/"to" stages execute in same cycle
  - Example: MX bypass

	1	2	3	4	5	6	7	8	9	10
`add r2,r3→r1`	F	D	X	**M**	W					
`sub r1,r4→r2`		F	D	**X**	M	W				

  - Example: WX bypass

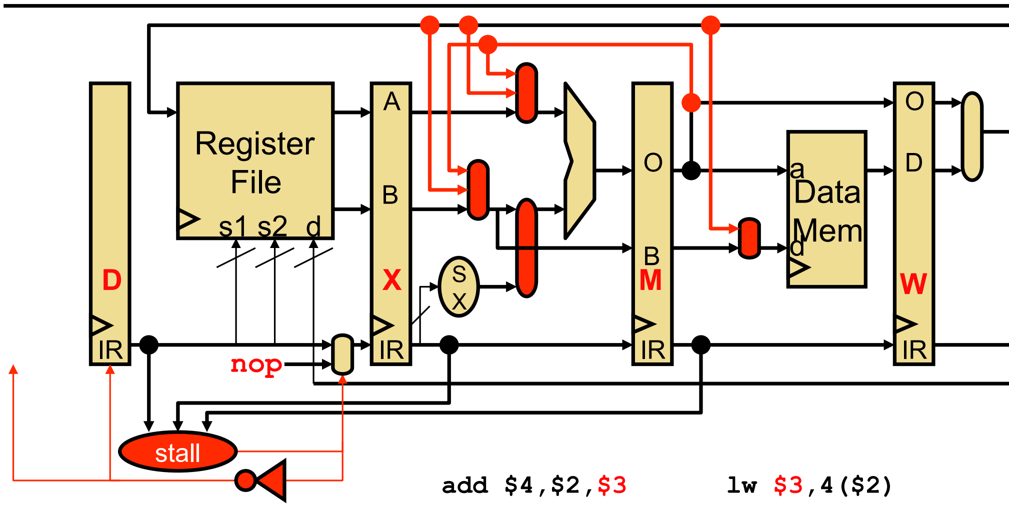
	1	2	3	4	5	6	7	8	9	10
`add r2,r3→r1`	F	D	X	M	**W**					
`ld [r7+4]→r5`		F	D	X	M	W				
`sub r1,r4→r2`			F	D	**X**	M	W			

  - Example: WM bypass

	1	2	3	4	5	6	7	8	9	10
`add r2,r3→r1`	F	D	X	M	**W**					
`?`		F	D	X	**M**	W				

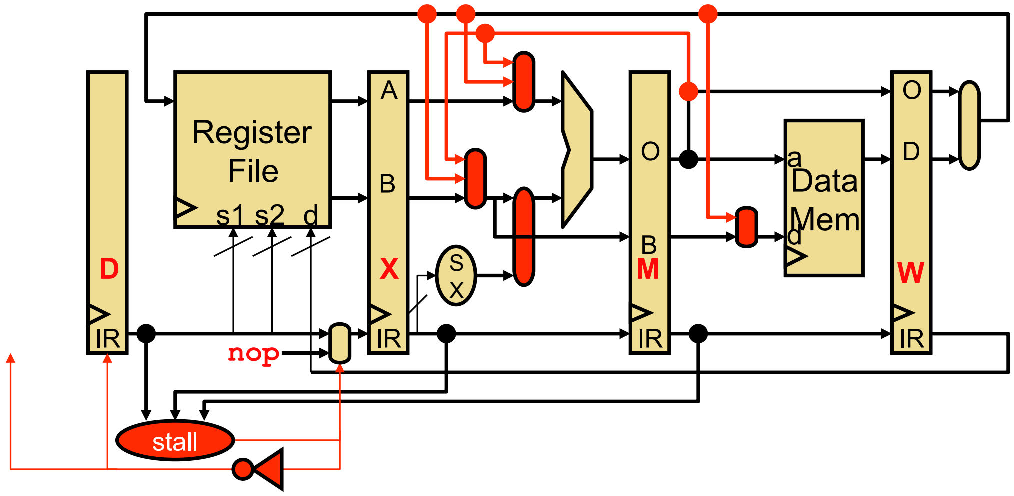
    - Can you think of a code example that uses the WM bypass?

Have We Prevented All Data Hazards?



- No. Consider a "load" followed by a dependent "add" insn
- Bypassing alone isn't sufficient!
- Hardware solution: detect this situation and inject a stall cycle
- Software solution: ensure compiler doesn't generate such code

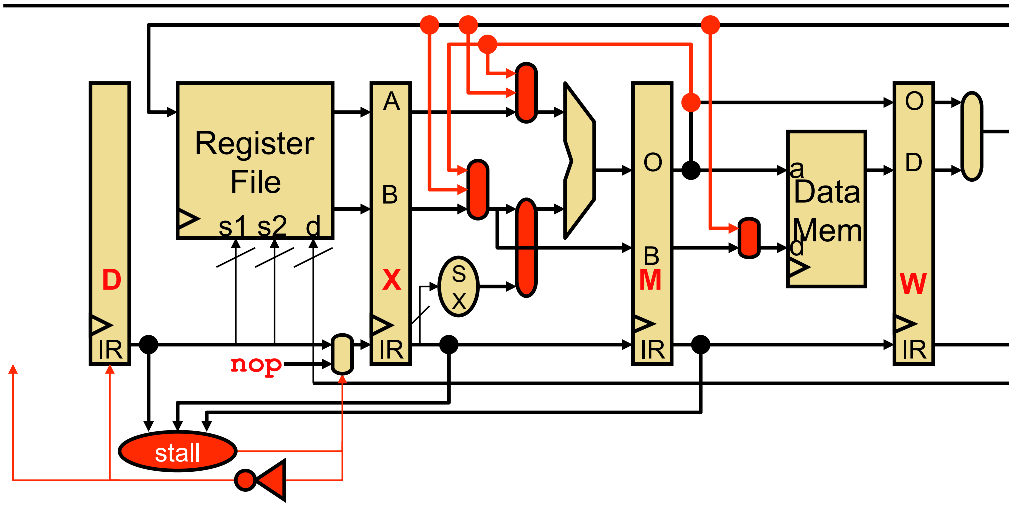
Stalling on Load-To-Use Dependences



`add $4,$2,$3`   `lw $3,4($2)`

- Prevent "D insn" from advancing this cycle
  - Write **nop** into X.IR (effectively, insert **nop** in hardware)
  - Keep same "D insn", same PC next cycle
- Re-evaluate situation next cycle

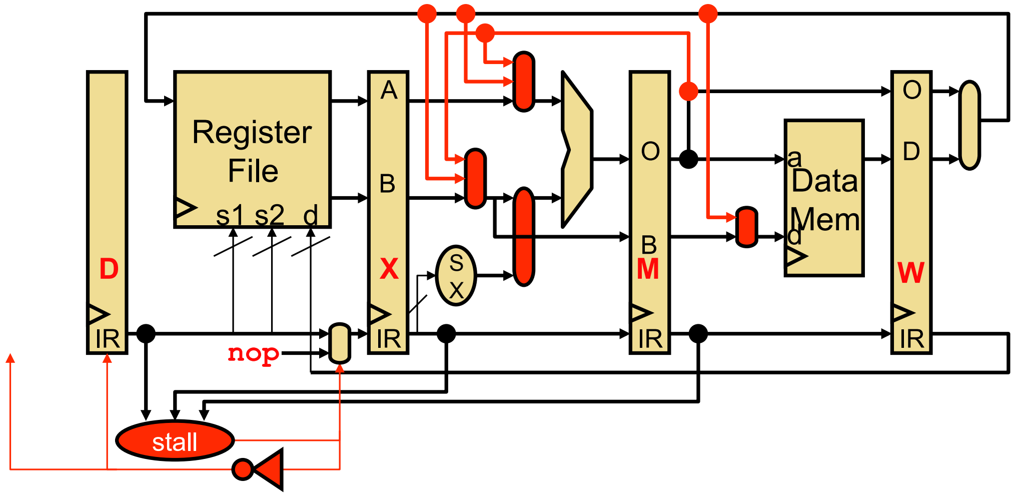
Stalling on Load-To-Use Dependences



`add $4,$2,$3`   `lw $3,4($2)`

Stall = (X.IR.Operation == LOAD) &&
((D.IR.RegSrc1 == X.IR.RegDest) ||
((D.IR.RegSrc2 == X.IR.RegDest) && (D.IR.Op != STORE))
)

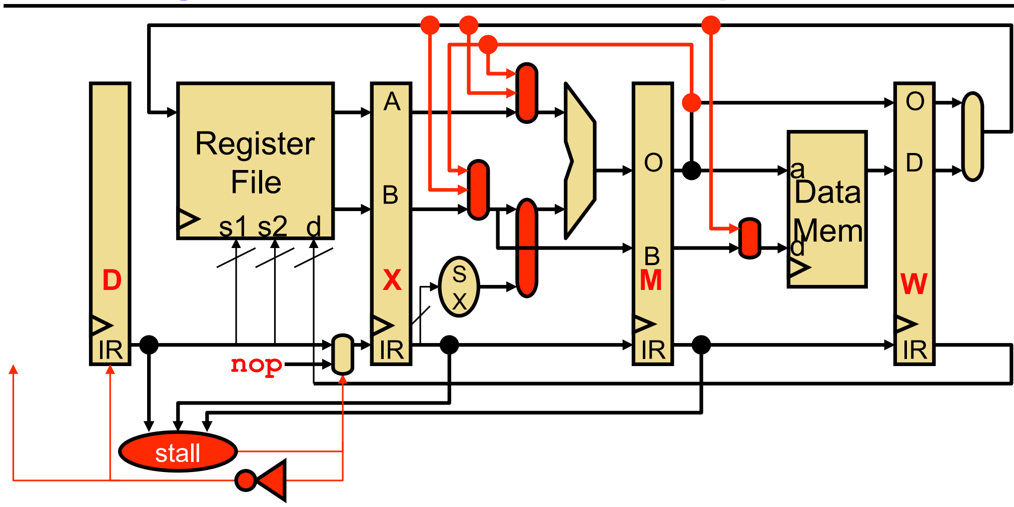
Stalling on Load-To-Use Dependences



`add $4,$2,$3`   `(stall bubble)`   `lw $3,4($2)`

Stall = (X.IR.Operation == LOAD) &&
((D.IR.RegSrc1 == X.IR.RegDest) ||
((D.IR.RegSrc2 == X.IR.RegDest) && (D.IR.Op != STORE))
)

Stalling on Load-To-Use Dependences



`add $4,$2,$3`   `(stall bubble)`   `lw $3,…`

Stall = (X.IR.Operation == LOAD) &&
((D.IR.RegSrc1 == X.IR.RegDest) ||
((D.IR.RegSrc2 == X.IR.RegDest) && (D.IR.Op != STORE))
)

Performance Impact of Load/Use Penalty

- Assume
  - Branch: 20%, load: 20%, store: 10%, other: 50%
  - 50% of loads are followed by dependent instruction
    - require 1 cycle stall (I.e., insertion of 1 **`nop`**)

- Calculate CPI
  - CPI = 1 + (1 * 20% * 50%) = **1.1**

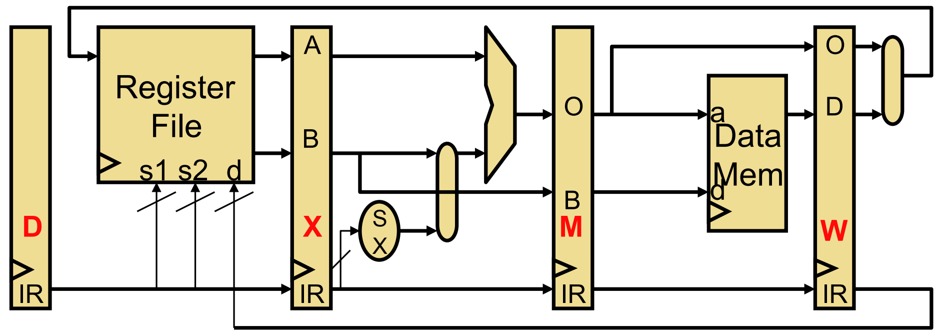
Reducing Load-Use Stall Frequency

	1	2	3	4	5	6	7	8	9
`add $3,$2,$1`	F	D	X	M	W				
`lw $4,4($3)`		F	D	X	M	W			
`addi $6,$4,1`			F	D	**d***	X	M	W	
`sub $8,$3,$1`				F	**d***	D	X	M	W

- Use compiler scheduling to reduce load-use stall frequency
  - More on compiler scheduling later

	1	2	3	4	5	6	7	8	9
`add $3,$2,$1`	F	D	X	M	W				
`lw $4,4($3)`		F	D	X	M	W			
`sub $8,$3,$1`			F	D	X	M	W		
`addi $6,$4,1`				F	D	X	M	W	

Dependencies Through Memory



`lw $4,8($1)` `sw $5,8($1)`

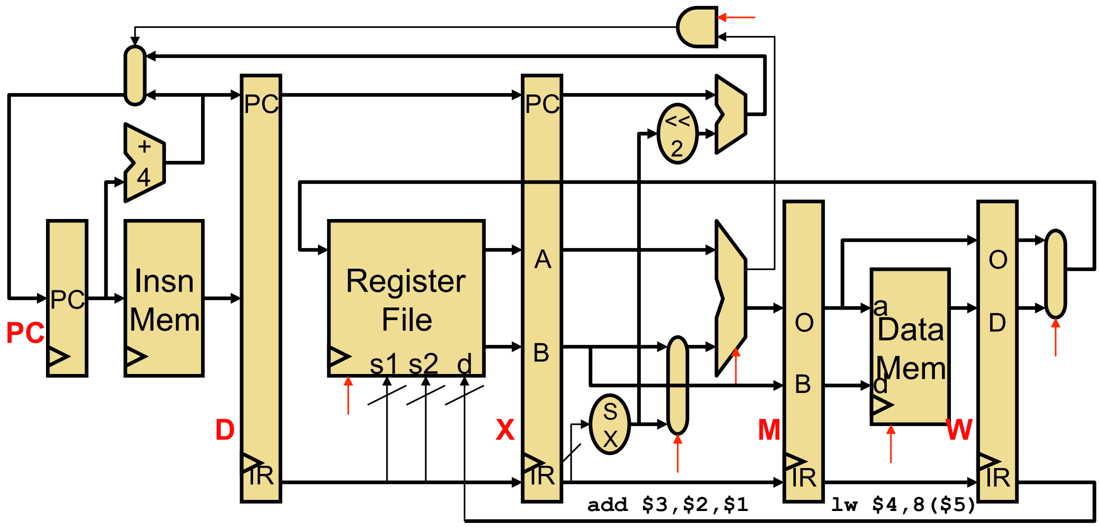
- Are “load to store” memory dependencies a problem? No
  - **`lw`** following **`sw`** to same address in next cycle, gets right value
  - Why? Data mem read/write always take place in same stage

- Are there any other sort of hazards to worry about?

Structural Hazards

- **Structural hazards**
  - Two insns trying to use same circuit at same time
    - E.g., structural hazard on register file write port
- **To avoid structural hazards**
  - Avoided if:
    - Each insn uses every structure exactly once
    - For at most one cycle
    - All instructions travel through all stages
  - Add more resources:
    - Example: two memory accesses per cycle (Fetch & Memory)
    - Split instruction & data memories allows simultaneous access
- **Tolerate structure hazards**
  - Add stall logic to stall pipeline when hazards occur

Why Does Every Insn Take 5 Cycles?

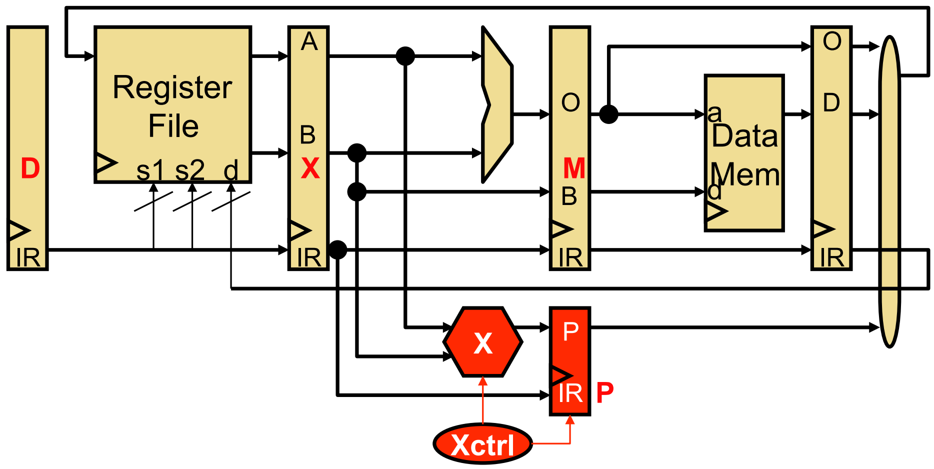


- Could/should we allow **`add`** to skip M and go to W? No
  - It wouldn't help: peak fetch still only 1 insn per cycle
  - **Structural hazards**: imagine **`add`** after **`lw`** (only 1 reg. write port)

Multi-Cycle Operations

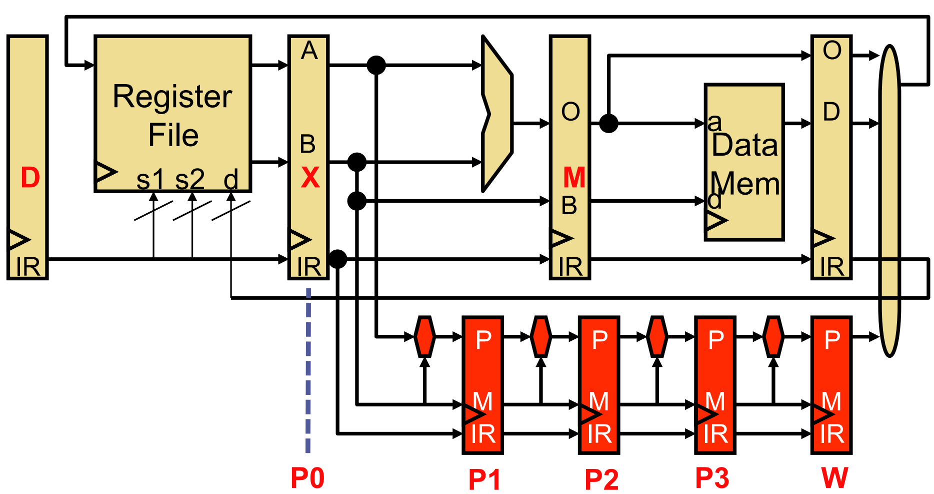
(if time permits)

Pipelining and Multi-Cycle Operations



- What if you wanted to add a multi-cycle operation?
  - E.g., 4-cycle multiply
  - **P**: separate output latch connects to W stage
  - Controlled by pipeline control finite state machine (FSM)

A Pipelined Multiplier



- Multiplier itself is often pipelined, what does this mean?
  - Product/multiplicand register/ALUs/latches replicated
  - Can start different multiply operations in consecutive cycles
  - **But still takes 4 cycles to generate output value**

Pipeline Diagram with Multiplier

- Allow independent instructions

	1	2	3	4	5	6	7	8	9
`mul $4,$3,$5`	F	D	P0	P1	P2	P3	W		
`addi $6,$7,1`		F	D	X	M	W			

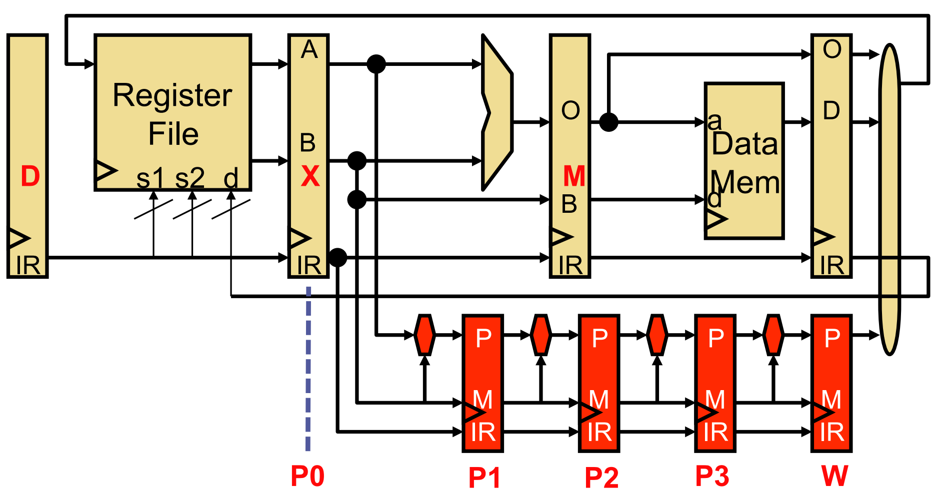
- Even allow independent multiplies

	1	2	3	4	5	6	7	8	9
`mul $4,$3,$5`	F	D	P0	P1	P2	P3	W		
`mul $6,$7,$8`		F	D	P0	P1	P2	P3	W	

- But must stall subsequent dependent instructions:

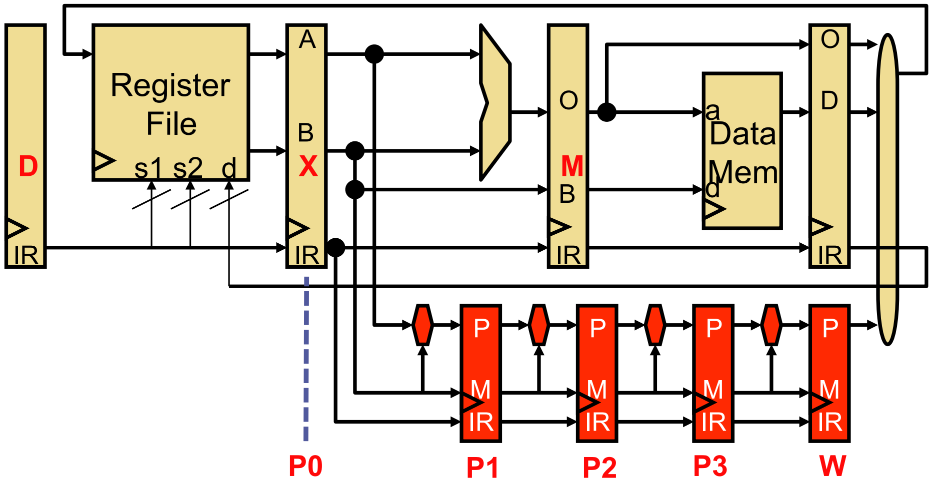
	1	2	3	4	5	6	7	8	9
`mul $4,$3,$5`	F	D	P0	P1	P2	P3	W		
`addi $6,$4,1`		F	D	**d***	**d***	**d***	X	M	W

What about Stall Logic?



	1	2	3	4	5	6	7	8	9
`mul $4,$3,$5`	F	D	P0	P1	P2	P3	W		
`addi $6,$4,1`		F	D	**d***	**d***	**d***	X	M	W

What about Stall Logic?



Stall = (OldStallLogic) ||
(D.IR.RegSrc1 == P0.IR.RegDest) || (D.IR.RegSrc2 == P0.IR.RegDest) ||
(D.IR.RegSrc1 == P1.IR.RegDest) || (D.IR.RegSrc2 == P1.IR.RegDest) ||
(D.IR.RegSrc1 == P2.IR.RegDest) || (D.IR.RegSrc2 == P2.IR.RegDest)

Multiplier Write Port Structural Hazard

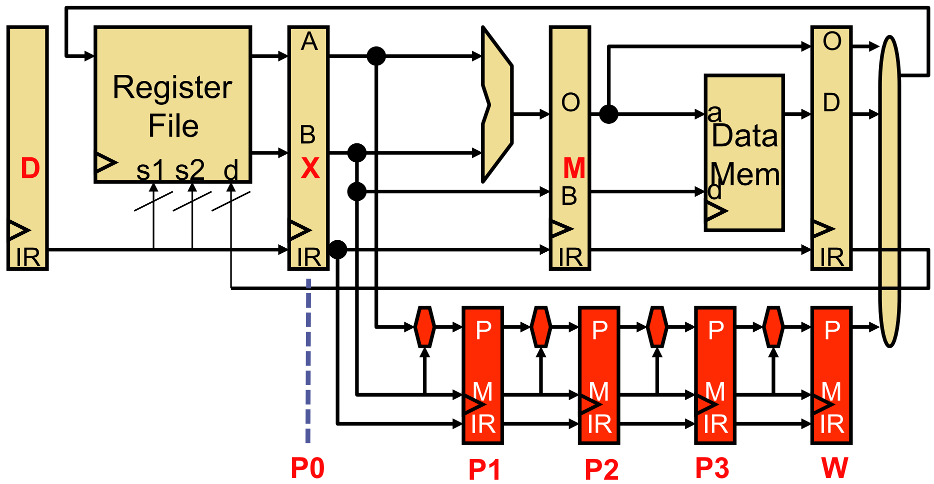
- What about…
  - Two instructions trying to write register file in same cycle?
  - Structural hazard!
- Must prevent:

	1	2	3	4	5	6	7	8	9
`mul $4,$3,$5`	F	D	P0	P1	P2	P3	W		
`addi $6,$1,1`		F	D	X	M	W			
`add $5,$6,$10`			F	D	X	M	**W**		

- Solution? stall the subsequent instruction

	1	2	3	4	5	6	7	8	9
`mul $4,$3,$5`	F	D	P0	P1	P2	P3	W		
`addi $6,$1,1`		F	D	X	M	W			
`add $5,$6,$10`			F	**d***	D	X	M	**W**	

Preventing Structural Hazard



- Fix to problem on previous slide:

  Stall = (OldStallLogic) ||

  (**D.IR.RegDest "is valid" &&**

  D.IR.Operation != MULT && P0.IR.RegDest "is valid")

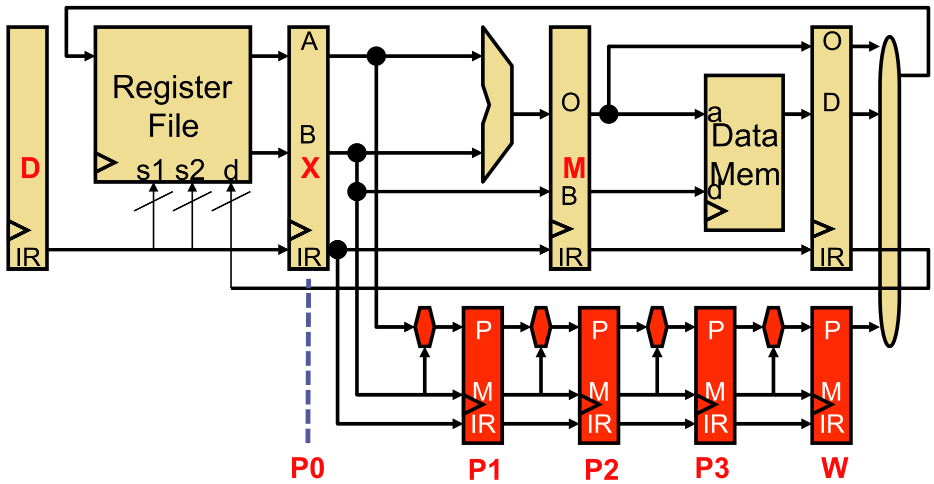
More Multiplier Nasties

- What about…
  - Mis-ordered writes to the same register
  - Software thinks **add** gets **$4** from **addi**, actually gets it from **mul**

	1	2	3	4	5	6	7	8	9
mul $4,$3,$5	F	D	P0	P1	P2	P3	W		
addi $4,$1,1		F	D	X	M	**W**			
…									
…									
add $10,$4,$6					F	D	X	M	W

- Common? Not for a 4-cycle multiply with 5-stage pipeline
  - More common with deeper pipelines
  - In any case, must be correct

Preventing Mis-Ordered Reg. Write



- Fix to problem on previous slide:
  Stall = (OldStallLogic) ||
  ((**D.IR.RegDest == X.IR.RegDest) && (X.IR.Operation == MULT)**)

Corrected Pipeline Diagram

- With the correct stall logic
  - Prevent mis-ordered writes to the same register
  - Why two cycles of delay?

	1	2	3	4	5	6	7	8	9
`mul $4,$3,$5`	F	D	P0	P1	P2	P3	W		
`addi $4,$1,1`		F	**d***	**d***	D	X	M	**W**	
…									
…									
`add $10,$4,$6`					F	D	X	M	W

- **Multi-cycle operations complicate pipeline logic**

Pipelined Functional Units

- Almost all multi-cycle functional units are pipelined
  - Each operation takes N cycles
  - But can start initiate a new (independent) operation every cycle
  - Requires internal latching and some hardware replication
  + A cheaper way to add bandwidth than multiple non-pipelined units

	1	2	3	4	5	6	7	8	9	10	11
`mulf f0,f1,f2`	F	D	E*	E*	E*	E*	W				
`mulf f3,f4,f5`		F	D	E*	E*	E*	E*	W			

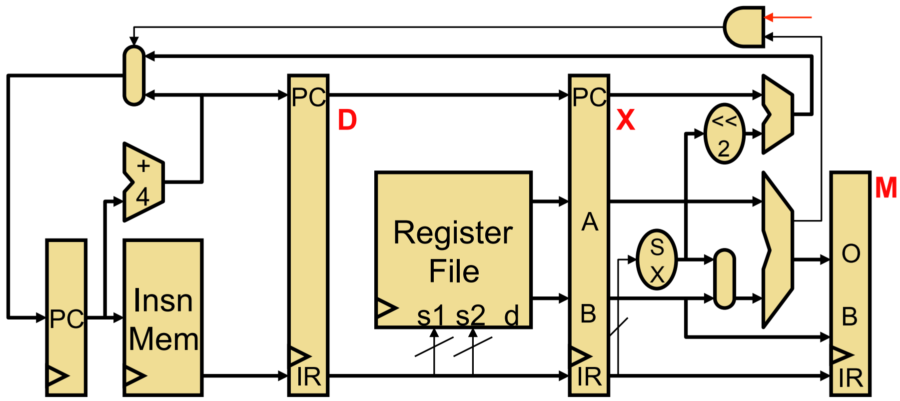
- One exception: int/FP divide: difficult to pipeline and not worth it

	1	2	3	4	5	6	7	8	9	10	11
`divf f0,f1,f2`	F	D	E/	E/	E/	E/	W				
`divf f3,f4,f5`		F	D	**s***	**s***	**s***	E/	E/	E/	E/	W

- **s* = structural hazard, two insns need same structure**
  - ISAs and pipelines designed to have few of these
  - Canonical example: all insns forced to go through M stage

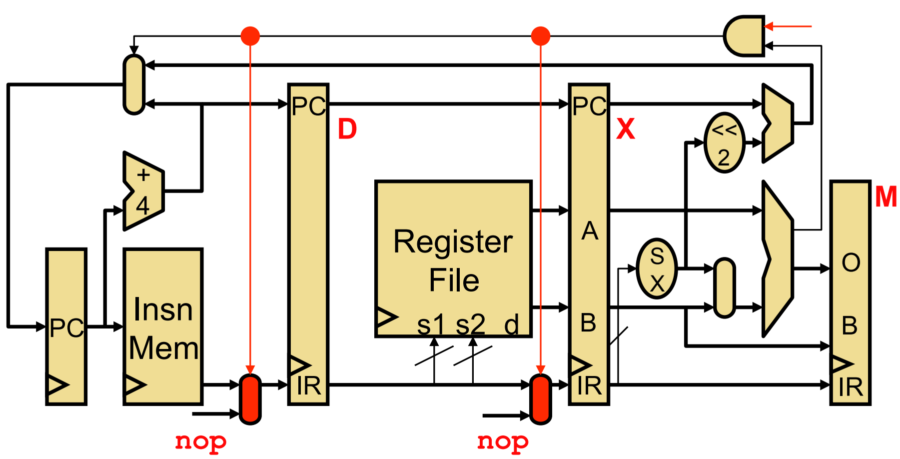
Control Dependences and Branch Prediction

What About Branches?



- **Branch speculation**
  - Could just stall to wait for branch outcome (two-cycle penalty)
  - **Fetch past branch insns before branch outcome is known**
    - Default: assume "**not-taken**" (at fetch, can't tell it's a branch)

Branch Recovery



- **Branch recovery**: what to do when branch is actually taken
  - Insns that will be written into D and X are wrong
  - **Flush them**, i.e., replace them with `nops`

  \+ They haven't had written permanent state yet (regfile, DMem)

  – Two cycle penalty for taken branches

Branch Speculation and Recovery

Correct:

	1	2	3	4	5	6	7	8	9
`addi r1,1→r3`	F	D	X	M	W				
`bnez r3,targ`		F	D	X	M	W			
`st r6→[r7+4]`			**F**	**D**	X	M	W		
`mul r8,r9→r10`				**F**	D	X	M	W	

speculative

- **Mis-speculation recovery**: what to do on wrong guess
  - Not too painful in an short, in-order pipeline
  - Branch resolves in X
  - \+ Younger insns (in F, D) haven't changed permanent state
  - **Flush** insns currently in D and X (i.e., replace with `nops`)

Recovery:

	1	2	3	4	5	6	7	8	9
`addi r1,1→r3`	F	D	X	M	W				
`bnez r3,targ`		F	D	**X**	M	W			
~~`st r6→[r7+4]`~~			**F**	**D**	--	--	--		
~~`mul r8,r9→r10`~~				**F**	--	--	--	--	
`targ:add r4,r5→r4`					**F**	D	X	M	W

Branch Performance

- Back of the envelope calculation
  - **Branch: 20%**, load: 20%, store: 10%, other: 50%
  - Say, **75% of branches are taken**

- CPI = 1 + 20% * 75% * 2 =
  1 + **0.20 * 0.75 * 2** = 1.3
  - – **Branches cause 30% slowdown**
    - Worse with deeper pipelines (higher mis-prediction penalty)

- Can we do better than assuming branch is not taken?

Big Idea: Speculative Execution

- Speculation: "risky transactions on chance of profit"

- **Speculative execution**
  - Execute before all parameters known with certainty
  - **Correct speculation**
    + Avoid stall, improve performance
  - **Incorrect speculation (mis-speculation)**
    – Must abort/flush/squash incorrect insns
    – Must undo incorrect changes (recover pre-speculation state)

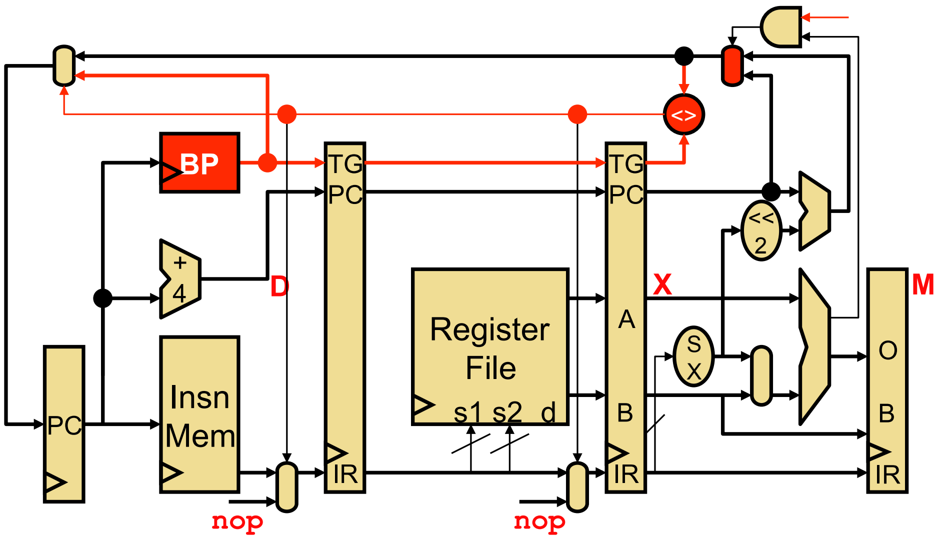
- **Control speculation**: speculation aimed at control hazards
  - Unknown parameter: are these the correct insns to execute next?

Control Speculation Mechanics

- Guess branch target, start fetching at guessed position
  - Doing nothing is implicitly guessing target is PC+4
  - Can actively guess other targets: **dynamic branch prediction**

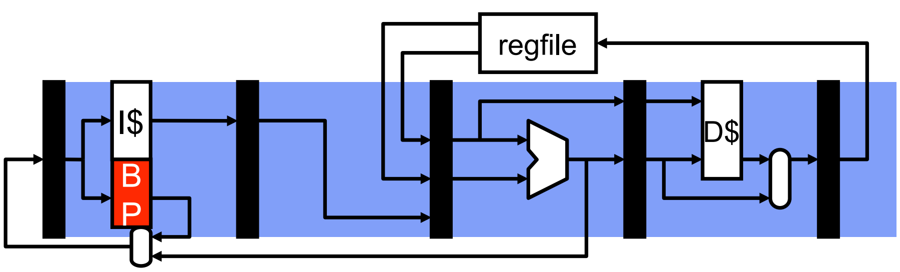
- Execute branch to verify (check) guess
  - Correct speculation? keep going
  - Mis-speculation? Flush mis-speculated insns
    - Hopefully haven't modified permanent state (Regfile, DMem)
    + Happens naturally in in-order 5-stage pipeline

Dynamic Branch Prediction



- **Dynamic branch prediction**: hardware guesses outcome
  - Start fetching from guessed address
  - Flush on **mis-prediction**

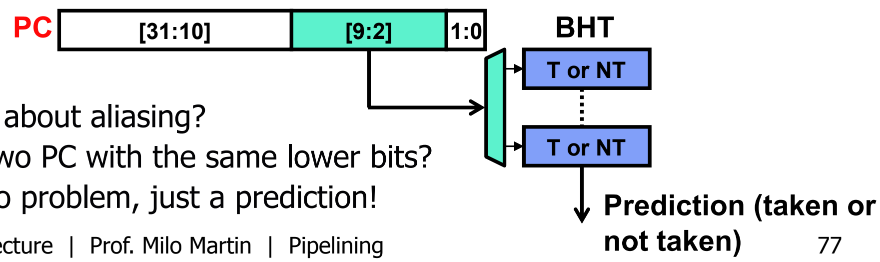
Dynamic Branch Prediction Components



- Step #1: is it a branch?
  - Easy after decode...
- Step #2: is the branch taken or not taken?
  - **Direction predictor** (applies to conditional branches only)
  - Predicts taken/not-taken
- Step #3: if the branch is taken, where does it go?
  - Easy after decode…

Branch Direction Prediction

- **Learn from past, predict the future**
  - Record the past in a hardware structure
- **Direction predictor (DIRP)**
  - Map conditional-branch PC to taken/not-taken (T/N) decision
  - Individual conditional branches often biased or weakly biased
    - 90%+ one way or the other considered **"biased"**
    - Why? Loop back edges, checking for uncommon conditions
- **Branch history table (BHT)**: simplest predictor
  - PC indexes table of bits (0 = N, 1 = T), no tags
  - Essentially: branch will go same way it went last time



- What about aliasing?
  - Two PC with the same lower bits?
  - No problem, just a prediction!

Branch History Table (BHT)

- **Branch history table (BHT)**: simplest direction predictor
  - PC indexes table of bits (0 = N, 1 = T), no tags
  - Essentially: branch will go same way it went last time
  - Problem: **inner loop branch** below

```
for (i=0;i<100;i++)
  for (j=0;j<3;j++)
    // whatever
```

  – Two "built-in" mis-predictions per inner loop iteration

  – Branch predictor "changes its mind too quickly"

Time	State	Prediction	Outcome	Result?
1	N	N	T	Wrong
2	T	T	T	Correct
3	T	T	T	Correct
4	T	T	N	Wrong
5	N	N	T	Wrong
6	T	T	T	Correct
7	T	T	T	Correct
8	T	T	N	Wrong
9	N	N	T	Wrong
10	T	T	T	Correct
11	T	T	T	Correct
12	T	T	N	Wrong

Two-Bit Saturating Counters (2bc)

- **Two-bit saturating counters (2bc)** [Smith 1981]
  - Replace each single-bit prediction
    - (0,1,2,3) = (N,n,t,T)
  - Adds "hysteresis"
    - Force predictor to mis-predict twice before "changing its mind"
  - One mispredict each loop execution (rather than two)
    - + Fixes this pathology (which is not contrived, by the way)
    - Can we do even better?

Time	State	Prediction	Outcome	Result?
1	N	N	T	Wrong
2	n	N	T	Wrong
3	t	T	T	Correct
4	T	T	N	Wrong
5	t	T	T	Correct
6	T	T	T	Correct
7	T	T	T	Correct
8	T	T	N	Wrong
9	t	T	T	Correct
10	T	T	T	Correct
11	T	T	T	Correct
12	T	T	N	Wrong

Correlated Predictor

- **Correlated (two-level) predictor** [Patt 1991]
  - Exploits observation that branch outcomes are correlated
  - Maintains separate prediction per (PC, BHR) pairs
    - **Branch history register (BHR)**: recent branch outcomes
  - Simple working example: assume program has one branch
    - BHT: one 1-bit DIRP entry
    - BHT+**2BHR**: 2^2 = **4** 1-bit DIRP entries
  - – Why didn't we do better?
    - BHT not long enough to capture pattern

Time	"Pattern"	State NN	State NT	State TN	State TT	Prediction	Outcome	Result?
1	NN	N	N	N	N	N	T	Wrong
2	NT	T	N	N	N	N	T	Wrong
3	TT	T	T	N	N	N	T	Wrong
4	TT	T	T	N	T	T	N	Wrong
5	TN	T	T	N	N	N	T	Wrong
6	NT	T	T	T	N	T	T	Correct
7	TT	T	T	T	N	N	T	Wrong
8	TT	T	T	T	T	T	N	Wrong
9	TN	T	T	T	N	T	T	Correct
10	NT	T	T	T	N	T	T	Correct
11	TT	T	T	T	N	N	T	Wrong
12	TT	T	T	T	T	T	N	Wrong

Correlated Predictor – 3 Bit Pattern

- **Try 3 bits of history**
- 2^3 DIRP entries per pattern

Time	"Pattern"	NNN	NNT	NTN	NTT	TNN	TNT	TTN	TTT	Prediction	Outcome	Result?
1	NNN	**N**	N	N	N	N	N	N	N	**N**	**T**	Wrong
2	NNT	T	**N**	N	N	N	N	N	N	**N**	**T**	Wrong
3	NTT	T	T	N	**N**	N	N	N	N	**N**	**T**	Wrong
4	TTT	T	T	N	T	N	N	N	**N**	**N**	**N**	Correct
5	TTN	T	T	N	T	N	N	**N**	N	**N**	**T**	Wrong
6	TNT	T	T	N	T	N	**N**	T	N	**N**	**T**	Wrong
7	NTT	T	T	N	**T**	N	T	T	N	**T**	**T**	Correct
8	TTT	T	T	N	T	N	T	T	**N**	**N**	**N**	Correct
9	TTN	T	T	N	T	N	T	**T**	N	**T**	**T**	Correct
10	TNT	T	T	N	T	N	**T**	T	N	**T**	**T**	Correct
11	NTT	T	T	N	**T**	N	T	T	N	**T**	**T**	Correct
12	TTT	T	T	N	T	N	T	T	**N**	**N**	**N**	Correct

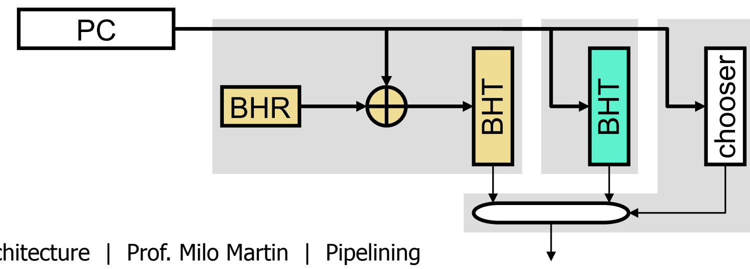
\+ No mis-predictions after predictor learns all the relevant patterns!

Correlated Predictor Design

- Design choice: how many history bits (BHR size)?
  - Tricky one
  - \+ Given unlimited resources, longer BHRs are better, but…
  - – BHT utilization decreases
    - – Many history patterns are never seen
    - – Many branches are history independent (don't care)
    - PC xor BHR allows multiple PCs to dynamically share BHT
    - BHR length < $\log_2$(BHT size)
  - – Predictor takes longer to train
  - Typical length: 8–12

Hybrid Predictor

- **Hybrid (tournament) predictor** [McFarling 1993]
  - Attacks correlated predictor BHT capacity problem
  - Idea: combine two predictors
    - **Simple BHT** predicts history independent branches
    - **Correlated predictor** predicts only branches that need history
    - **Chooser** assigns branches to one predictor or the other
    - Branches start in simple BHT, move mis-prediction threshold
  - \+ Correlated predictor can be made **smaller**, handles fewer branches
  - \+ 90–95% accuracy



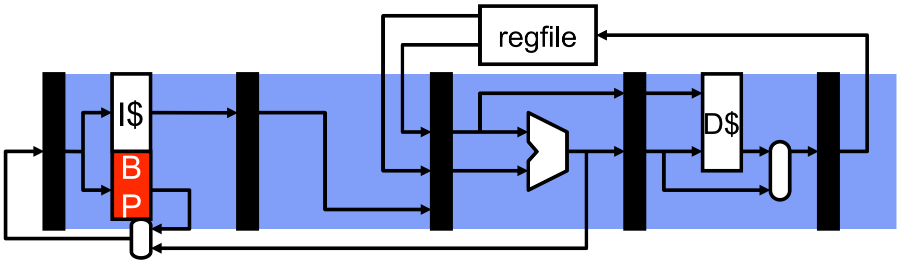
When to Perform Branch Prediction?

- Option #1: During Decode
  - Look at instruction opcode to determine branch instructions
  - Can calculate next PC from instruction (for PC-relative branches)
  - – One cycle "mis-fetch" penalty **even if branch predictor is correct**

	1	2	3	4	5	6	7	8	9
`bnez r3,targ`	F	**D**	X	M	W				
`targ:add r4,r5,r4`			**F**	D	X	M	W		

- Option #2: During Fetch?
  - How do we do that?

Revisiting Branch Prediction Components



- Step #1: is it a branch?
  - Easy after decode... during fetch: **predictor**
- Step #2: is the branch taken or not taken?
  - **Direction predictor** (as before)
- Step #3: if the branch is taken, where does it go?
  - **Branch target predictor (BTB)**
  - Supplies target PC if branch is taken

Branch Target Buffer (BTB)

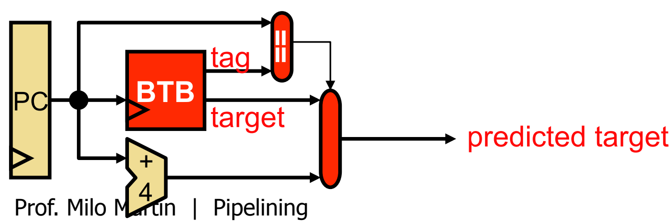
- As before: learn from past, predict the future
  - Record the past branch targets in a hardware structure

- **Branch target buffer (BTB)**:
  - "guess" the future PC based on past behavior
  - "Last time the branch X was taken, it went to address Y"
    - "So, in the future, if address X is fetched, fetch address Y next"

- Operation
  - A small RAM: address = PC, data = target-PC
  - Access at Fetch *in parallel* with instruction memory
    - predicted-target = BTB[hash(PC)]
  - Updated at X whenever target != predicted-target
    - BTB[hash(PC)] = target
  - Hash function is just typically just extracting lower bits (as before)
  - Aliasing? No problem, this is only a prediction

Branch Target Buffer (continued)

- At Fetch, how does insn know it's a branch & should read BTB? It doesn't have to…
  - **…all insns access BTB in parallel with Imem Fetch**
- Key idea: **use BTB to predict which insn are branches**
  - Implement by "tagging" each entry with its corresponding PC
  - Update BTB on every taken branch insn, record target PC:
    - BTB[PC].tag = PC, BTB[PC].target = target of branch
  - All insns access at Fetch *in parallel* with Imem
    - Check for tag match, signifies insn at that PC is a branch
    - Predicted PC = (BTB[PC].tag == PC) ? BTB[PC].target : PC+4

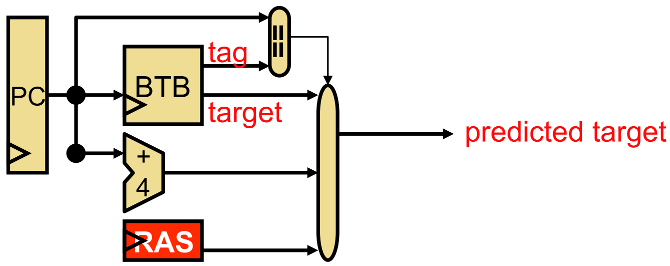


Why Does a BTB Work?

- Because most control insns use **direct targets**
  - Target encoded in insn itself → same "taken" target every time

- What about **indirect targets**?
  - Target held in a register → can be different each time
  - Two indirect call idioms
    - \+ Dynamically linked functions (DLLs): target always the same
    - Dynamically dispatched (virtual) functions: hard but uncommon
  - Also two indirect unconditional jump idioms
    - Switches: hard but uncommon
    - – Function returns: hard and common but…

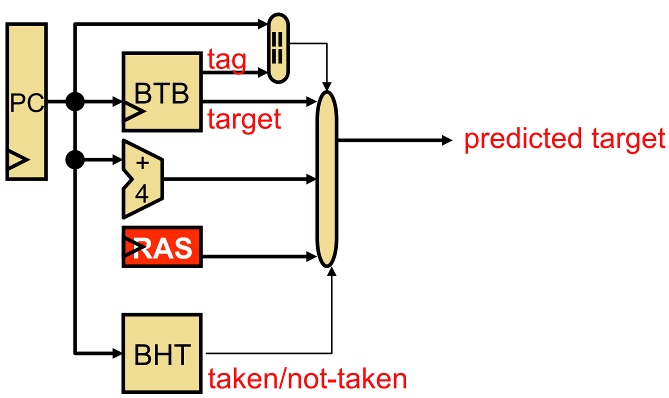
Return Address Stack (RAS)



- **Return address stack (RAS)**
  - Call instruction? RAS[TopOfStack++] = PC+4
  - Return instruction? Predicted-target = RAS[--TopOfStack]

Putting It All Together

- BTB & branch direction predictor during fetch



- If branch prediction correct, no taken branch penalty

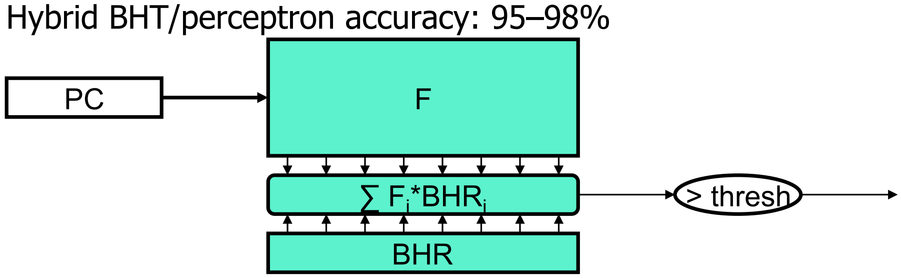
Branch Prediction Performance

- Dynamic branch prediction
  - 20% of instruction branches
  - Simple predictor: branches predicted with 75% accuracy
    - CPI = 1 + (20% * **25%** * 2) = **1.1**
  - More advanced predictor: 95% accuracy
    - CPI = 1 + (20% * **5%** * 2) = **1.02**

- Branch mis-predictions still a big problem though
  - Pipelines are long: typical mis-prediction penalty is 10+ cycles
  - For cores that do more per cycle, predictions more costly (later)

Research: Perceptron Predictor

- **Perceptron predictor** [Jimenez]
  - Attacks predictor size problem using machine learning approach
  - History table replaced by table of function coefficients F_i (signed)
  - Predict taken if $\sum(BHR_i*F_i)$> threshold
  + Table size #PC*|BHR|*|F| (can use long BHR: ~60 bits)
    – Equivalent correlated predictor would be $\#PC*2^{|BHR|}$
  - How does it learn? Update F_i when branch is taken
    - BHR_i == 1 ? F_i++ : F_i– –;
    - "don't care" F_i bits stay near 0, important F_i bits saturate
  + Hybrid BHT/perceptron accuracy: 95–98%



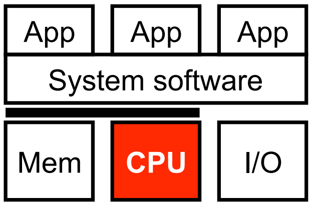
More Research: GEHL Predictor

- Problem with both correlated predictor and perceptron
  - Same predictor area dedicated to 1st history bit (1 column) …
  - … as to 2nd, 3rd, 10th, 60th…
  - Not a good use of space: 1st bit much more important than 60th
- **GEometric History-Length predictor** [Seznec, ISCA'05]
  - Multiple predictors, indexed with geometrically longer history (0, 4, 16, 32)
    - Predictors are (partially) tagged, no separate "chooser"
    - Predict: use *matching* entry from predictor with longest history
    - Mis-predict: create entry in predictor with next-longest history
    - Only 25% of predictor area used for bits 16-32 (not 50%)
    - Helps amortize cost of tagging
  - \+ Trains quickly
  - 95-97% accurate

Pipeline Depth

- Trend had been to deeper pipelines
  - 486: 5 stages (50+ gate delays / clock)
  - Pentium: 7 stages
  - Pentium II/III: 12 stages
  - Pentium 4: 22 stages (~10 gate delays / clock) **"super-pipelining"**
  - Core1/2: 14 stages
- Increasing **pipeline depth**
  - \+ Increases clock frequency (reduces period)
    - But double the stages reduce the clock period by less than 2x
  - – Decreases IPC (increases CPI)
    - Branch mis-prediction penalty becomes longer
    - Non-bypassed data hazard stalls become longer
  - At some point, actually causes performance to decrease, but when?
    - 1GHz Pentium 4 was slower than 800 MHz PentiumIII
  - "Optimal" pipeline depth is program and technology specific

Summary



- Single-cycle & multi-cycle datapaths
- Latency vs throughput & performance
- Basic pipelining
- Data hazards
  - Bypassing
  - Load-use stalling
- Pipelined multi-cycle operations
- Control hazards
  - Branch prediction