Pipelining

Wei Wang

Optional Readings from Textbooks

- “Computer Organization and Design,” Chapters 4.5 to 4.10.
- “Computer Architecture: A Quantitative Approach,” Appendix C “Pipelining: Basic and Intermediate Concepts.”

Road Map

- Overview of Pipelining
- Structure Hazard
- Data Hazard
- Control Hazard
- Summary of Hazard Solutions
- Superscalar

Overview of Pipelining

Overview of Pipelining

- Pipelining is a processor implementation technique in which multiple instructions are overlapped in execution.
  - CPU pipelining is exactly the same like factory pipelines.
- In fact, one of the main reasons of breaking instruction execution into stages is to support pipelining.
  - Pipelining essentially overlaps different instructions working on different stages.
- Since 70’s, nearly all computers have been pipelined.

Pipelining vs No-pipelining

- For simplicity, we assume all instructions need 5 stages.
- Without pipelining, 3 instructions takes 15 cycles

Cycles:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
instr1:	IF	ID	EXE	MEM	WB										
instr2:						IF	ID	EXE	MEM	WB					
instr3:											IF	ID	EXE	MEM	WB

  - Average CPI is 15/3=5 cycles.
- With pipelining, 3 instructions take only 7 cycles
  - Average CPI is only 7/3= 2.33 cycles.

Cycles:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
instr1:	IF	ID	EXE	MEM	WB										
instr2:		IF	ID	EXE	MEM	WB									
instr3:			IF	ID	EXE	MEM	WB								

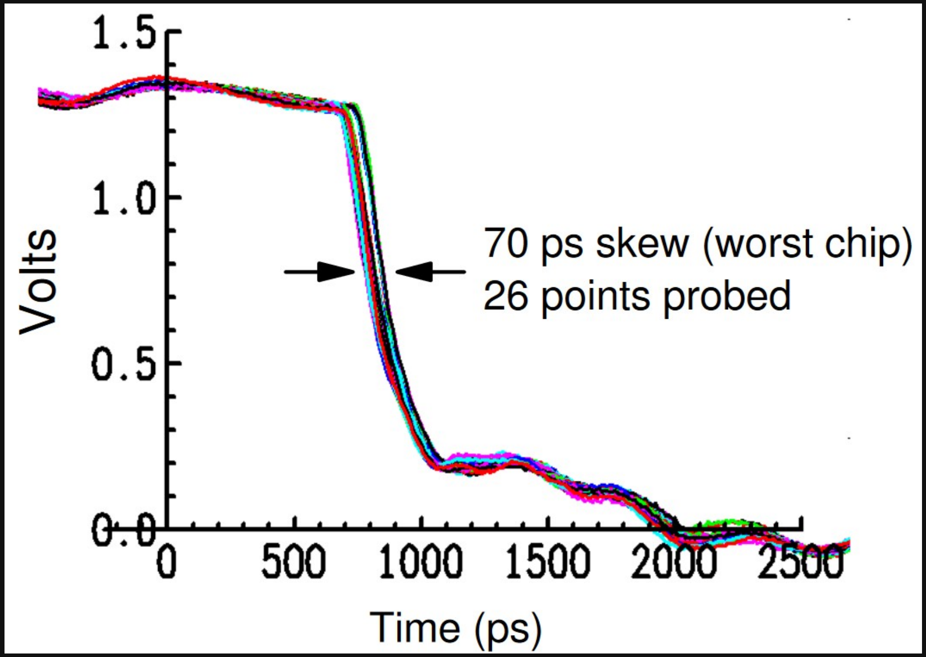
Next instr can be issued as soon as previous instr enters ID stage.

Ideal Pipelining Performance

- Without pipelining, assume instruction execution takes time `T`,
  - Single Instruction latency is `T`
  - Throughput = `1/T`
  - `M`-Instruction Latency = `M*T`
- If the execution is broken into an `N`-stage pipeline, ideally, a new instruction finishes each cycle
  - The time for each stage is `t = T/N`
  - Throughput = `1/t`
  - `M`-instruction Latency ≈ `M * t = M * T/N << M*T`
- Ideal CPI with pipelining is `1.`

Ideal is impossible

- Two reasons why ideal is impossible
  - Pipeline overhead
    - Latches, clock skew, jitters
      - Prolong the time each stage takes to execute
  - Hazards
    - Situations that prevent the next instruction from executing in its designated clock cycle
    - Hardware resource contention, data dependency, branch instructions and exceptions
    - The major hurdle of pipelining

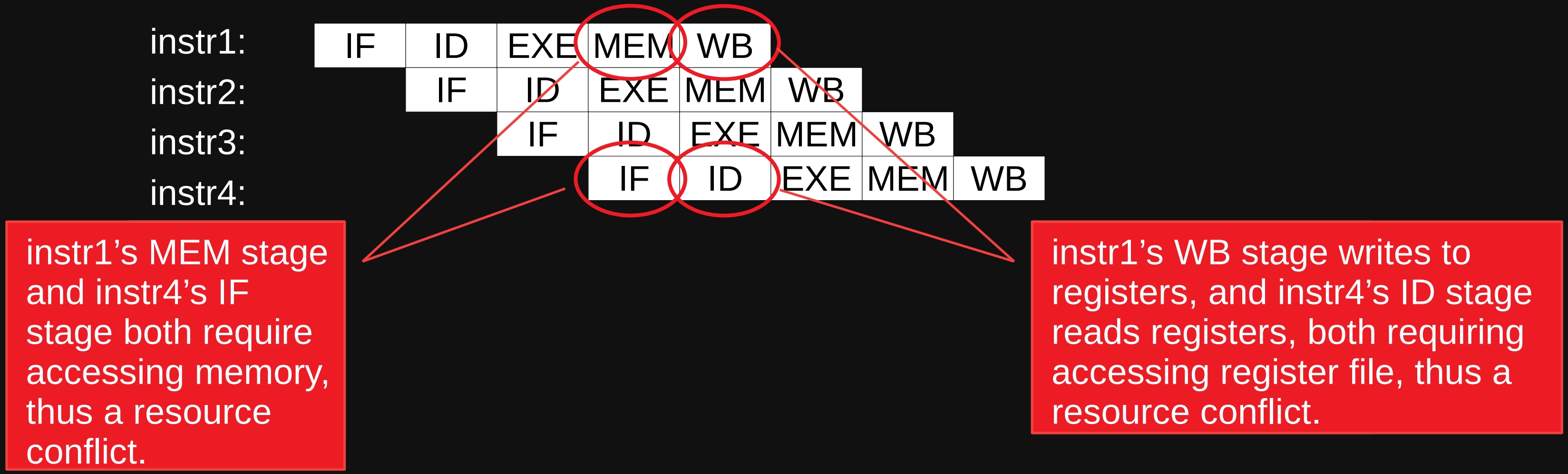


Clock Skew of IBM Power4
Taken from IBM Hot Chips 99 Presentation

Structural Hazard

Structural Hazards

- When two different instructions want to use the same hardware resource in the same cycle (resource conflict).
- For example, in the following execution, instr1 and instr4 have two structural hazards at memory and register file.



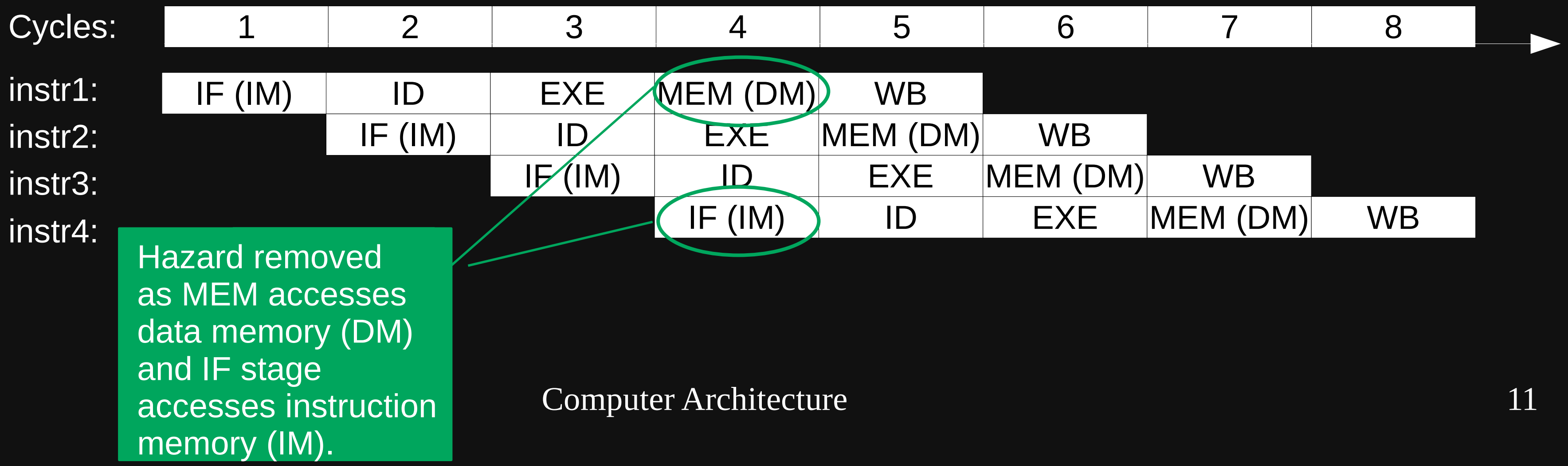
instr1:	IF	ID	EXE	MEM	WB			
instr2:		IF	ID	EXE	MEM	WB		
instr3:			IF	ID	EXE	MEM	WB	
instr4:				IF	ID	EXE	MEM	WB

instr1’s MEM stage and instr4’s IF stage both require accessing memory, thus a resource conflict.

instr1’s WB stage writes to registers, and instr4’s ID stage reads registers, both requiring accessing register file, thus a resource conflict.

Structural Hazards Solutions

- Solution 1: separate hardware resources
  - For example, for the contention of MEM and IF stages
    - IF stage only reads instructions
    - MEM stage only accesses (read/write) data
    - We can then separate memory for instructions and data
    - This structural hazard is the one of the motivations of using separated instruction and data L1 caches.

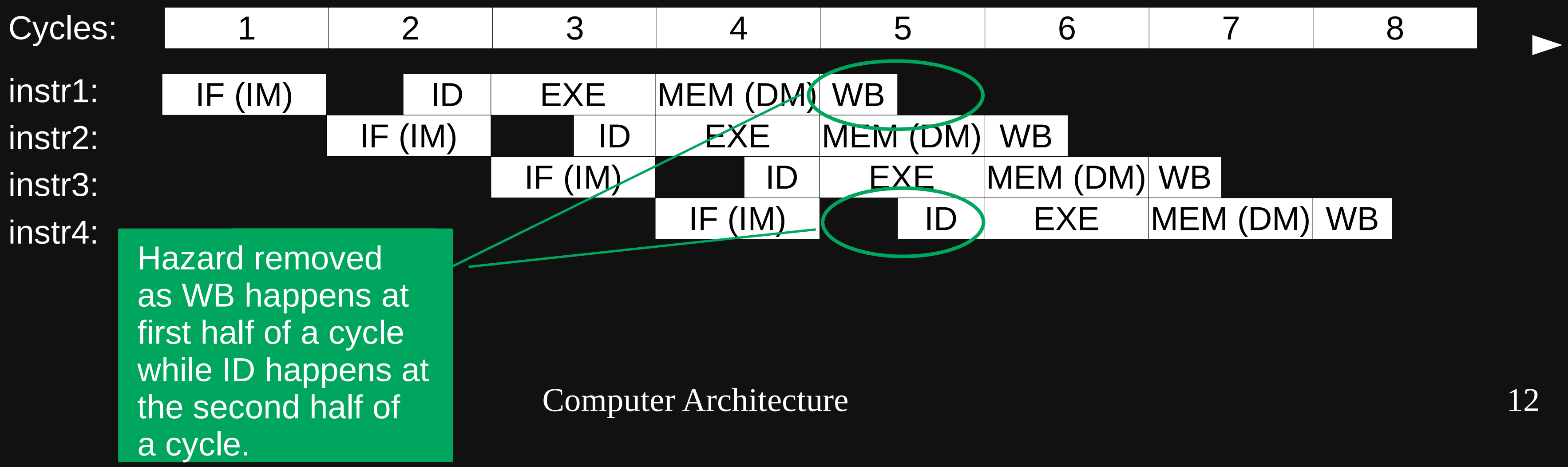


Cycles:	1	2	3	4	5	6	7	8
instr1:	IF (IM)	ID	EXE	MEM (DM)	WB			
instr2:		IF (IM)	ID	EXE	MEM (DM)	WB		
instr3:			IF (IM)	ID	EXE	MEM (DM)	WB	
instr4:				IF (IM)	ID	EXE	MEM (DM)	WB

Hazard removed as MEM accesses data memory (DM) and IF stage accesses instruction memory (IM).

Structural Solutions cont'd

- Solution 2: let the accesses to the same hardware component happen at a different part of a cycle
  - For example, for the contention of WB and ID stages
    - Let WB stage access registers at the first half of a cycle (e.g., at the falling edge of a cycle).
    - Let ID stage access registers at the second half of a cycle (e.g., at the rising edge of a cycle).
  - Alternatively, we can also make a stage multi-cycle and let the conflicted accesses happen at different cycles. This solution can accommodate more than two conflicting stages.



Cycles:	1	2	3	4	5	6	7	8
instr1:	IF (IM)	ID	EXE	MEM (DM)	WB			
instr2:		IF (IM)	ID	EXE	MEM (DM)	WB		
instr3:			IF (IM)	ID	EXE	MEM (DM)	WB	
instr4:				IF (IM)	ID	EXE	MEM (DM)	WB

Hazard removed as WB happens at first half of a cycle while ID happens at the second half of a cycle.

Structural Solutions cont’d

- Solution 3: Duplicate resources
  - Duplicate the contended resources. E.g., add more ALUs, if ALUs are contended.
  - Useful for cheap resources, frequent cases
    - Separate ALU/PC adders, Reg File Ports
  - Advantage: does not increase CPI
  - Disadvantage: increases cost, possibly increases cycle time.

Structural Solutions cont’d

- Good news
  - Structural hazards don’t occur as long as each instruction uses a resource
    - At most once
    - Always in the same pipeline stage
    - For one cycle
  - RISC ISAs are designed with this in mind, reduces structural hazards
  - For assignments and exams on simple pipelining (i.e., not OoO), always assume no structural hazards.

Data Hazards

Data Hazards

- Data hazards when an instruction depends on the result of a previous instruction that exposes overlapping of instructions
- Three types of Data Hazards
  - Read-After-Write (RAW)
    - True data-dependence (Most important)
  - Write-After-Read (WAR)
  - Write-After-Write (WAW)

Read-after-Write (RAW)

```
x = …
… = x
```

Write-after-Read (WAR)

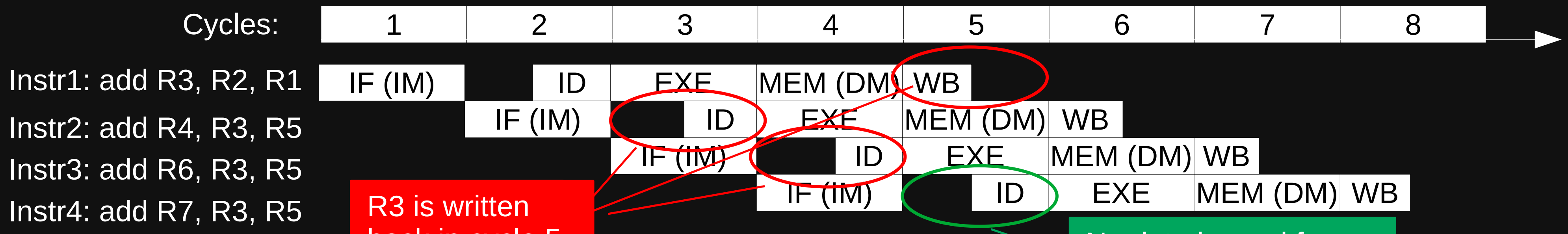
```
… = x
x = …
```

Write-after-Write (WAW)

```
x = …
x = …
```

Read-After-Write (RAW) Hazard

- For example, for the following code:
  - Instr1 writes R3 in cycle 5
  - However, instr2 needs R3 in cycle 3 and instr3 needs R3 in cycle 4, before the latest R3 is written.
  - Instr4 reads R3 at the second half of cycle 5. Therefore, there is no data hazard for instr4.



Cycles:	1	2	3	4	5	6	7	8
Instr1: add R3, R2, R1	IF (IM)	ID	EXE	MEM (DM)	WB			
Instr2: add R4, R3, R5		IF (IM)	ID	EXE	MEM (DM)	WB		
Instr3: add R6, R3, R5			IF (IM)	ID	EXE	MEM (DM)	WB	
Instr4: add R7, R3, R5				IF (IM)	ID	EXE	MEM (DM)	WB

R3 is written back in cycle 5, much later than when instr2 and instr3 need it.

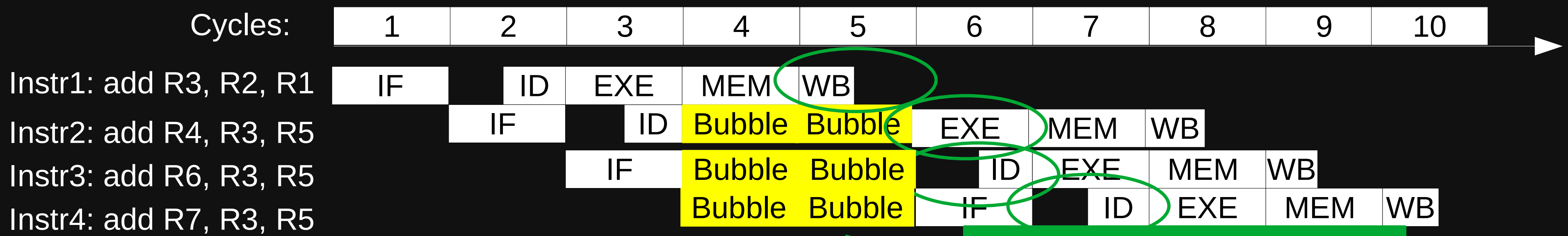
No data hazard for instr4, since its ID (register read) happens after instr1’s WB.

RAW Hazard Solutions

- Before solving RAW hazard, pipeline needs to be able to identify the data dependency that causes RAW hazard.
- The hardware component for detecting data hazards is called pipeline interlock
  - Need to keep register ID’s along with pipeling stages
  - Use comparators to check for hazards

RAW Hazard Solutions cont'd

- Solution 1 (simplest): Stall the pipeline
  - Stops some instructions from executing
  - Make them wait for older instructions to complete
  - Simple implementation to "freeze" (de-assert write-enable signals on pipeline latches)
  - Inserts a "bubble" into the pipe

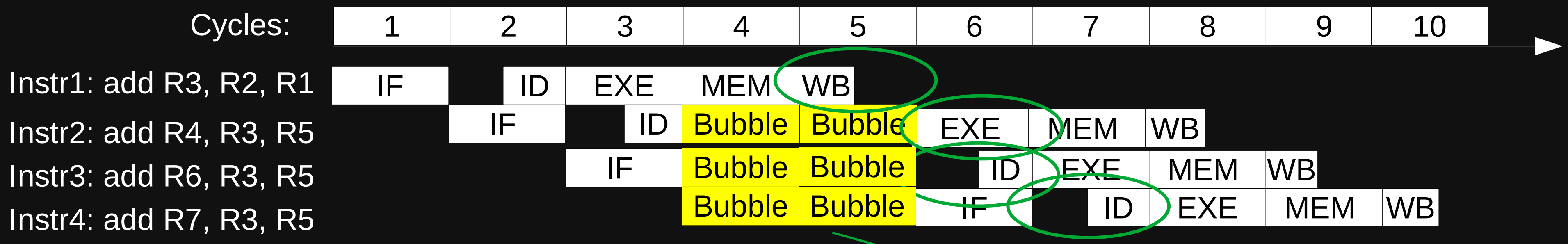


Cycles:	1	2	3	4	5	6	7	8	9	10
Instr1: add R3, R2, R1	IF	ID	EXE	MEM	WB					
Instr2: add R4, R3, R5		IF	ID	Bubble	Bubble	EXE	MEM	WB		
Instr3: add R6, R3, R5			IF	Bubble	Bubble	ID	EXE	MEM	WB	
Instr4: add R7, R3, R5				Bubble	Bubble	IF	ID	EXE	MEM	WB

After inserting two bubbles in to the pipeline (stalls the pipeline for two cycles), none of the instructions has data hazards.

RAW Hazard Solutions cont’d

- Solution 1 (simplest): Stall the pipeline
  - The downside of stalling is obviously the longer execution time. For example, for the following four instructions, stalling the pipeline prolongs the execution time from 8 cycles to 10 cycles.
    - Given that applications have a lot of internal dependencies, this performance penalty can be quite serious.
  - The advantages of stalling are
    - Easy and low cost to implement
    - Can solve nearly all pipeline hazards, including structural, data and control hazards.
      - Stalling is the last solution to any hazards that cannot solved by other solutions.

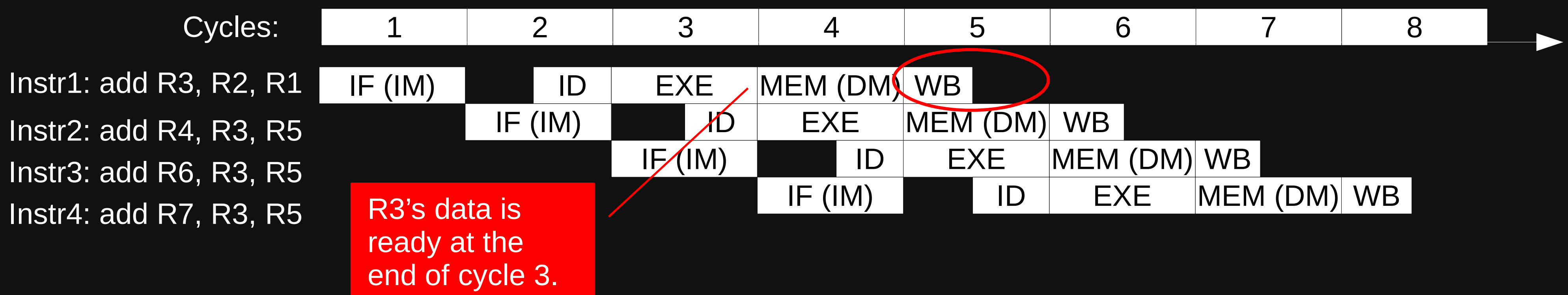


Cycles:	1	2	3	4	5	6	7	8	9	10
Instr1: add R3, R2, R1	IF	ID	EXE	MEM	WB					
Instr2: add R4, R3, R5		IF	ID	Bubble	Bubble	EXE	MEM	WB		
Instr3: add R6, R3, R5			IF	Bubble	Bubble	ID	EXE	MEM	WB	
Instr4: add R7, R3, R5				Bubble	Bubble	IF	ID	EXE	MEM	WB

After inserting two bubbles in to the pipeline (stalls the pipeline for two cycles), none of the instructions has data hazards.

RAW Hazard Solutions cont’d

- Solution 2: Bypass/forwarding
  - Data is usually ready at the end of EXE or MEM stages.
  - Basic idea,
    - add comparator for each combination of destination and source registers that can have RAW hazards.
    - Add muxes to datapath to select proper value instead of register file.
    - The forwarded data are from inter-stage registers.
    - Only stall when absolutely necessary
  - In the following example, R3’s data is ready at the end of cycle 3.

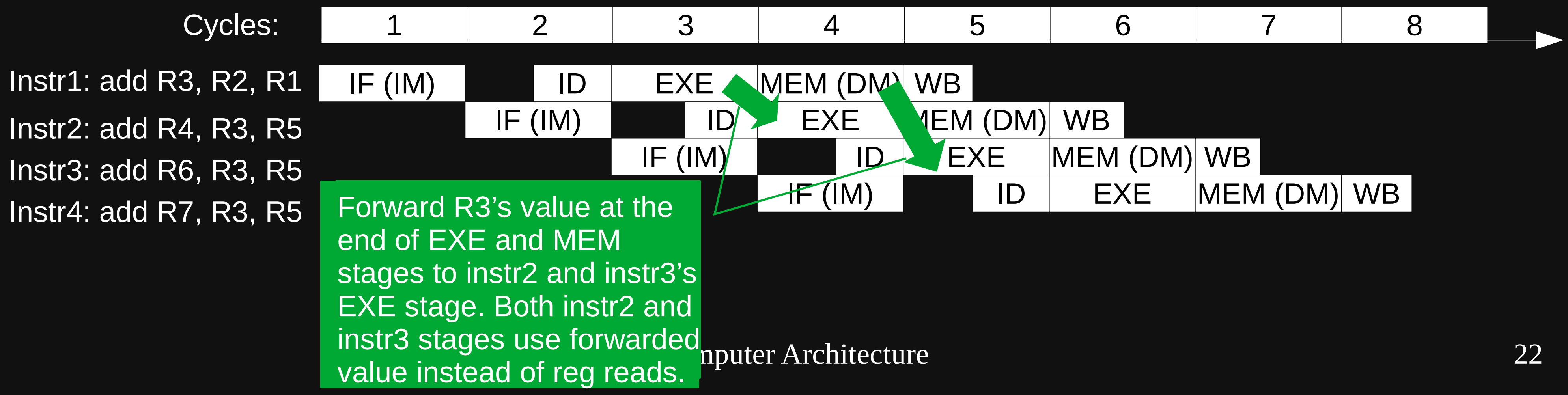


Cycles:	1	2	3	4	5	6	7	8
Instr1: add R3, R2, R1	IF (IM)	ID	EXE	MEM (DM)	WB			
Instr2: add R4, R3, R5		IF (IM)	ID	EXE	MEM (DM)	WB		
Instr3: add R6, R3, R5			IF (IM)	ID	EXE	MEM (DM)	WB	
Instr4: add R7, R3, R5				IF (IM)	ID	EXE	MEM (DM)	WB

R3’s data is ready at the end of cycle 3.

RAW Hazard Solutions cont’d

- Solution 2: Bypass/forwarding
  - In the following example, we can start forwarding the value of R3 at the end of cycle 3 to instr2 and instr3.
  - Advantage: no negative impact on performance. E.g., in the following example, it still takes 8 cycles to execute the four instructions.
  - Disadvantage:
    - Fairly complex change to the control unit and other pipeline resources
    - Cannot solve all RAW hazards (forwarding is only doable when the value is ready).

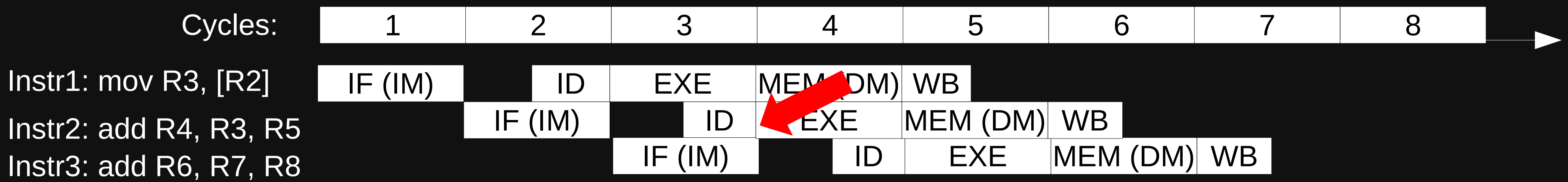


Cycles:	1	2	3	4	5	6	7	8
Instr1: add R3, R2, R1	IF (IM)	ID	EXE	MEM (DM)	WB			
Instr2: add R4, R3, R5		IF (IM)	ID	EXE	MEM (DM)	WB		
Instr3: add R6, R3, R5			IF (IM)	ID	EXE	MEM (DM)	WB	
Instr4: add R7, R3, R5				IF (IM)	ID	EXE	MEM (DM)	WB

Forward R3’s value at the end of EXE and MEM stages to instr2 and instr3’s EXE stage. Both instr2 and instr3 stages use forwarded value instead of reg reads.

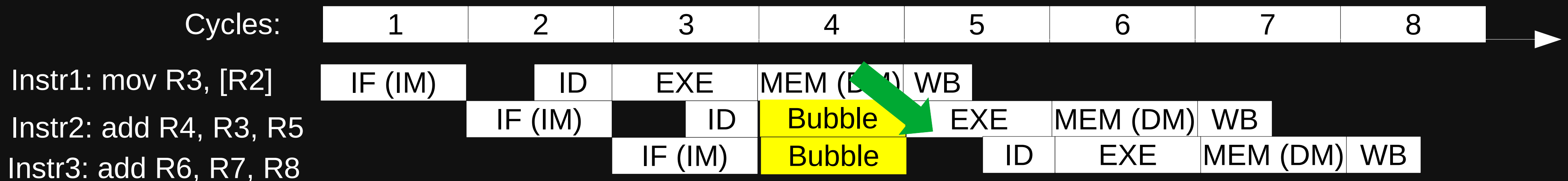
Load-Use Hazards

- Unfortunately, we can’t forward “backward in time.”



Cycles:	1	2	3	4	5	6	7	8
Instr1: mov R3, [R2]	IF (IM)	ID	EXE	MEM (DM)	WB			
Instr2: add R4, R3, R5		IF (IM)	ID	EXE	MEM (DM)	WB		
Instr3: add R6, R7, R8			IF (IM)	ID	EXE	MEM (DM)	WB	

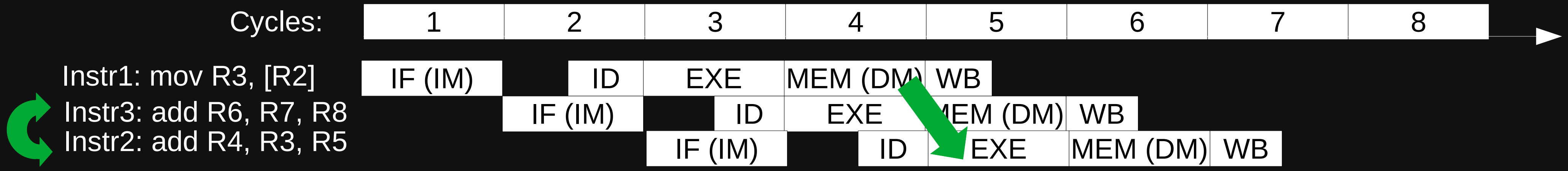
- Pipeline must be stalled to handle this dependency with forwarding.



Cycles:	1	2	3	4	5	6	7	8
Instr1: mov R3, [R2]	IF (IM)	ID	EXE	MEM (DM)	WB			
Instr2: add R4, R3, R5		IF (IM)	ID	Bubble	EXE	MEM (DM)	WB	
Instr3: add R6, R7, R8			IF (IM)	Bubble	ID	EXE	MEM (DM)	WB

Instruction Scheduling

- Alternatively, we can remove the bubble (i.e., avoid stalling) by rearranging the instructions.



Cycles:	1	2	3	4	5	6	7	8
Instr1: mov R3, [R2]	IF (IM)	ID	EXE	MEM (DM)	WB			
Instr3: add R6, R7, R8		IF (IM)	ID	EXE	MEM (DM)	WB		
Instr2: add R4, R3, R5			IF (IM)	ID	EXE	MEM (DM)	WB	

- Both compilers and CPU can perform instruction scheduling.
  - For compiler, it is more challenging to identify the opportunities of instruction scheduling due to unknown memory addresses at compilation time (hence unknown dependences)
  - CPU can performance dynamic instruction scheduling with out-of-order (OoO) execution.

Other Data Hazards: WARs and WAWs

- Write-After-Read (WAR) and Write-After-Write Hazards
  - Can’t happen in our simple 5-stage pipeline because the order of the instructions is always strictly followed
- But they may happen when the order of instructions are changed. E.g.,
  - in OoO executions,
  - if the stages require different execution time
  - When some instructions have cache misses
- Nonetheless, WAR and WAW can also be handled using stalls and forwarding.
- What about RARs?

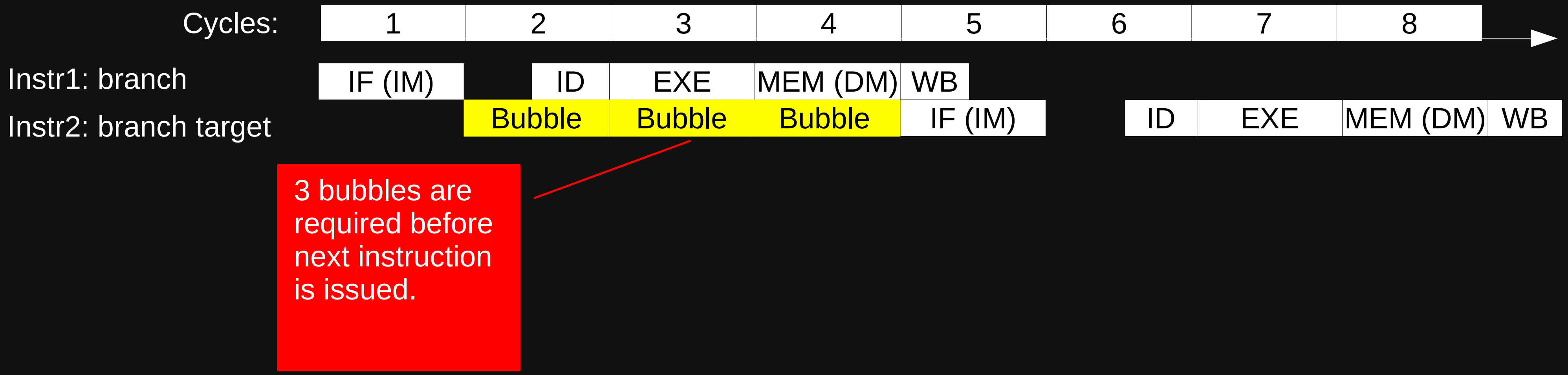
Control Hazards

Control Hazards

- Control hazards happen when there are PC-modifying instructions (branch, jump, etc) that prevent knowing which instruction to execute until branch target is computed and conditions are checked.
- In our simple model, the PC for the instruction after a branch is only known at the end of MEM stage.

An Example of Control Hazards

- Branch instruction prevents the issue of next instruction until MEM stage.
- Essentially, pipeline is stalled until next PC is known.

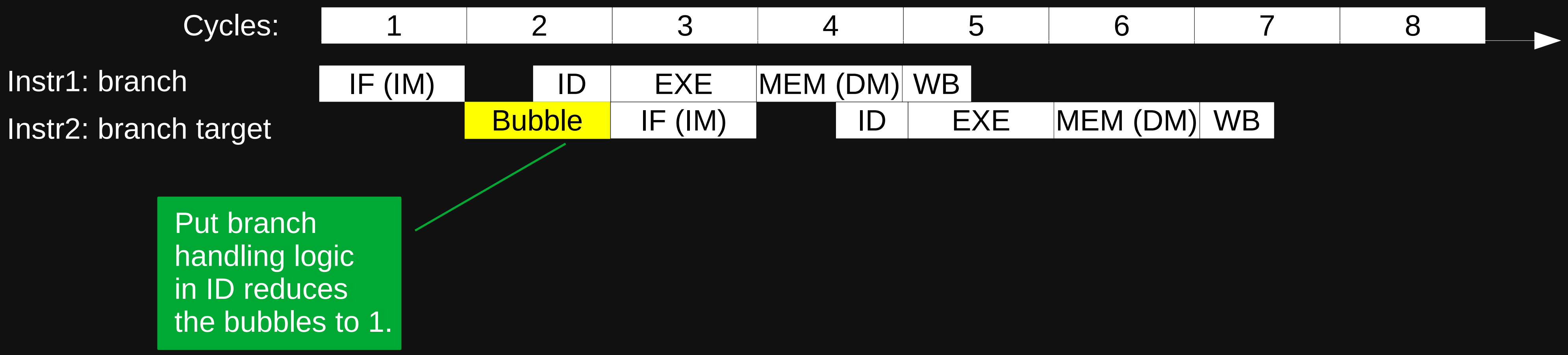


Cycles:	1	2	3	4	5	6	7	8	
Instr1: branch	IF (IM)	ID	EXE	MEM (DM)	WB				
Instr2: branch target		Bubble	Bubble	Bubble	IF (IM)	ID	EXE	MEM (DM)	WB

3 bubbles are required before next instruction is issued.

Control Hazard Solutions

- Solution 1: Fast branch resolution
  - Add extra adder to ID stage to compute branch target
  - Only works for simple conditional jump (compare to 0).
    - For some conditional jumps in CISC ISA that requires comparing two registers, the comparison can be slow.

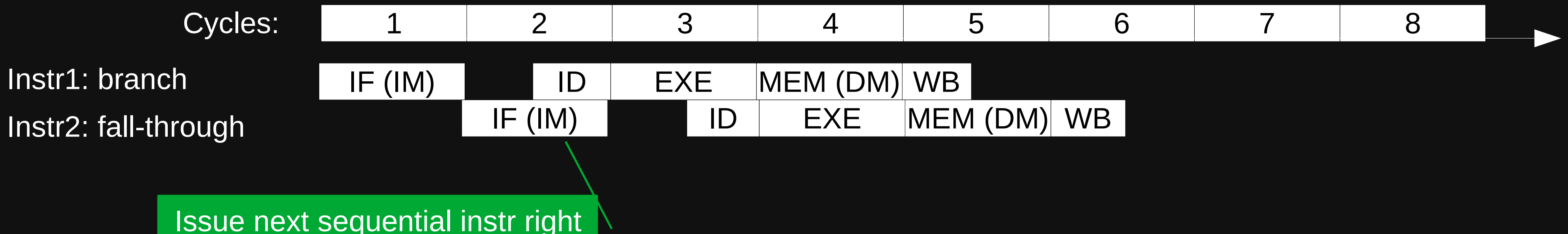


Cycles:	1	2	3	4	5	6	7	8
Instr1: branch	IF (IM)	ID	EXE	MEM (DM)	WB			
Instr2: branch target		Bubble	IF (IM)	ID	EXE	MEM (DM)	WB	

Put branch handling logic in ID reduces the bubbles to 1.

Control Hazard Solutions cont’d

- Solution 2: Assume not taken
  - Always assume branch is not taken, i.e., the next sequential instruction should be executed.
  - If this assumption is correct, not delay in the pipeline.



Cycles:	1	2	3	4	5	6	7	8
Instr1: branch	IF (IM)	ID	EXE	MEM (DM)	WB			
Instr2: fall-through		IF (IM)	ID	EXE	MEM (DM)	WB		

Issue next sequential instr right after a branch. If assumption is correct, no bubbles.

Control Hazard Solutions cont’d

- Solution 2: Assume not taken
  - Always assume branch is not taken, and the next sequential instruction is executed.
  - If the assumption is wrong, need to flush the pipeline to scratch all incorrectly issued instructions.
    - Instructions issued before the actual branch status is known are called speculatively issued instructions.
    - Speculatively issued instructions cannot write to registers and memory until the speculation is verified.

Cycles:	1	2	3	4	5	6	7	8	
Instr1: branch	IF (IM)	ID	EXE	MEM (DM)	WB				
Wrong Instr2		IF (IM)	ID	EXE	flush	flush			
Wrong Instr3			IF (IM)	ID	flush	flush	flush		
Wrong Instr4				IF (IM)	ID	flush	flush	flush	
Correct Instr2					IF (IM)	ID	EXE	MEM (DM)	WB

If assumption is wrong, the pipeline needs to be flushed to scratch all incorrectly issued instruction.

Control Hazard Solutions cont’d

- Solution 2: Assume not taken
  - Assume-not-taken may not help that much
    - Branch characteristics
      - Integer Benchmarks: 14-16% instructions are conditional branches
      - FP: 3-12%
      - On Average:
        - 67% of conditional branches are “taken”
        - 60% of forward branches are taken
        - 85% of backward branches are taken
      - Why? Because most branches are from loops!
  - Why not assume taken?
    - Branch target is not known when next instruction needs to be issued.

Control Hazard Solutions cont’d

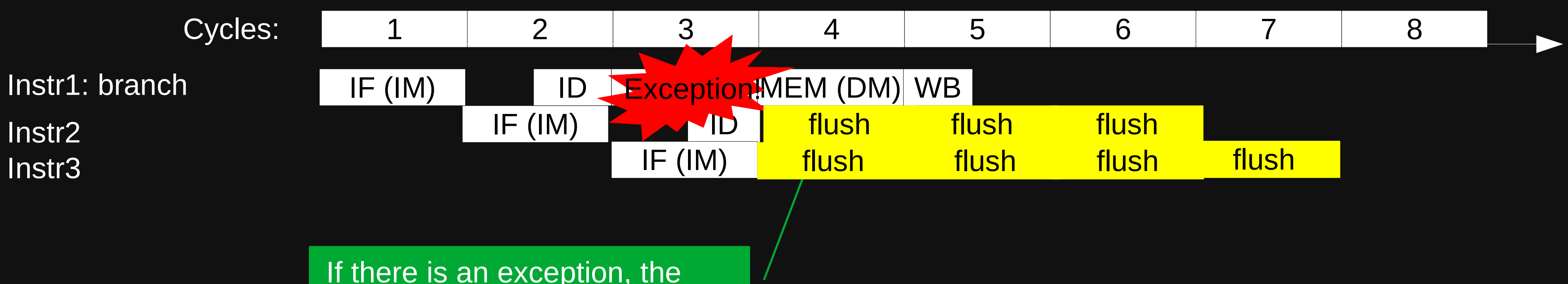
- Solution 3: Branch Delay Slots
  - Find one instruction that will be executed no matter which way the branch goes
  - Now we don’t care which way the branch goes!
    - Harder than it sounds to find instructions
  - What to put in the slot (80% of the time)
    - Instructions from before the branch (independent of branch)
    - Instructions that surely will be executed after the branch
      - Must be independent from the branch and the taken/non-taken path.
    - Instruction from taken or not-taken path
      - Similar to assume-not-taken or assume-taken.
      - Helps if you go the right way
  - Slots don’t help much with today’s machines
    - Interrupts are more difficult to handle because the order of the instruction changes

Control Hazard Solutions cont'd

- Solution 4: Branch Prediction
  - The actual solution for branches in modern processors is predicting whether the branch is taken and predicting what is the branch target.
  - Incorrect predictions still need flushing the pipeline.
  - We will discuss branch prediction in details in the lecture for speculative execution.

Control Hazards Due to Exceptions

- Instructions experiencing exceptions during execution also causes control hazards.
- For exceptions, the solution is to flush the pipeline.



Cycles:	1	2	3	4	5	6	7	8
Instr1: branch	IF (IM)	ID	Exception!	MEM (DM)	WB			
Instr2		IF (IM)	ID	flush	flush	flush		
Instr3			IF (IM)	flush	flush	flush	flush	

If there is an exception, the pipeline must be flushed with all instructions in the pipeline scratched.

Summary of Hazard Solutions

Hazard Solutions

- Generic solution for all hazards:
  - stall and/or flush the pipeline
    - A side note, NOP instructions are issued for stalls, while instructions are switched to NOPs for flushing.
- Solutions only for structural hazard
  - Separate hardware resources
  - Separate hardware access time
  - Duplicate resources
- Solutions only for data hazard
  - Bypass/forwarding
  - Instruction scheduling
- Solutions only for control hazard
  - Move branch logics to the ID stage.
  - Assume not taken
  - Branch delay slot
  - Branch prediction

Superscalar

Superscalar

- Modern processors usually have a number of pipeline hardware components.
  - Another benefit of Moore’s law.
- Therefore, modern processors usually can issue multiple instructions at each cycle.
  - Usually Superscalar is accompanied with OoO to ensure there are independent instructions that can be issued at the same time.
  - Obviously, multi-issue pipelines are more complex to implement and manage.

Illustration of A Two-issue Supersalar CPU

- Ideally, a two-issue Superscalar CPU has a CPI of 0.5 cycles, and IPC of 2.

IF	ID	EXE	MEM	WB				
IF	ID	EXE	MEM	WB				
	IF	ID	EXE	MEM	WB			
	IF	ID	EXE	MEM	WB			
		IF	ID	EXE	MEM	WB		
		IF	ID	EXE	MEM	WB		
			IF	ID	EXE	MEM	WB	
			IF	ID	EXE	MEM	WB	
				IF	ID	EXE	MEM	WB
				IF	ID	EXE	MEM	WB

Case Study: Intel Skylake Pipeline

- Maximum 8-issue per core.
- Pipeline stages: 14-19

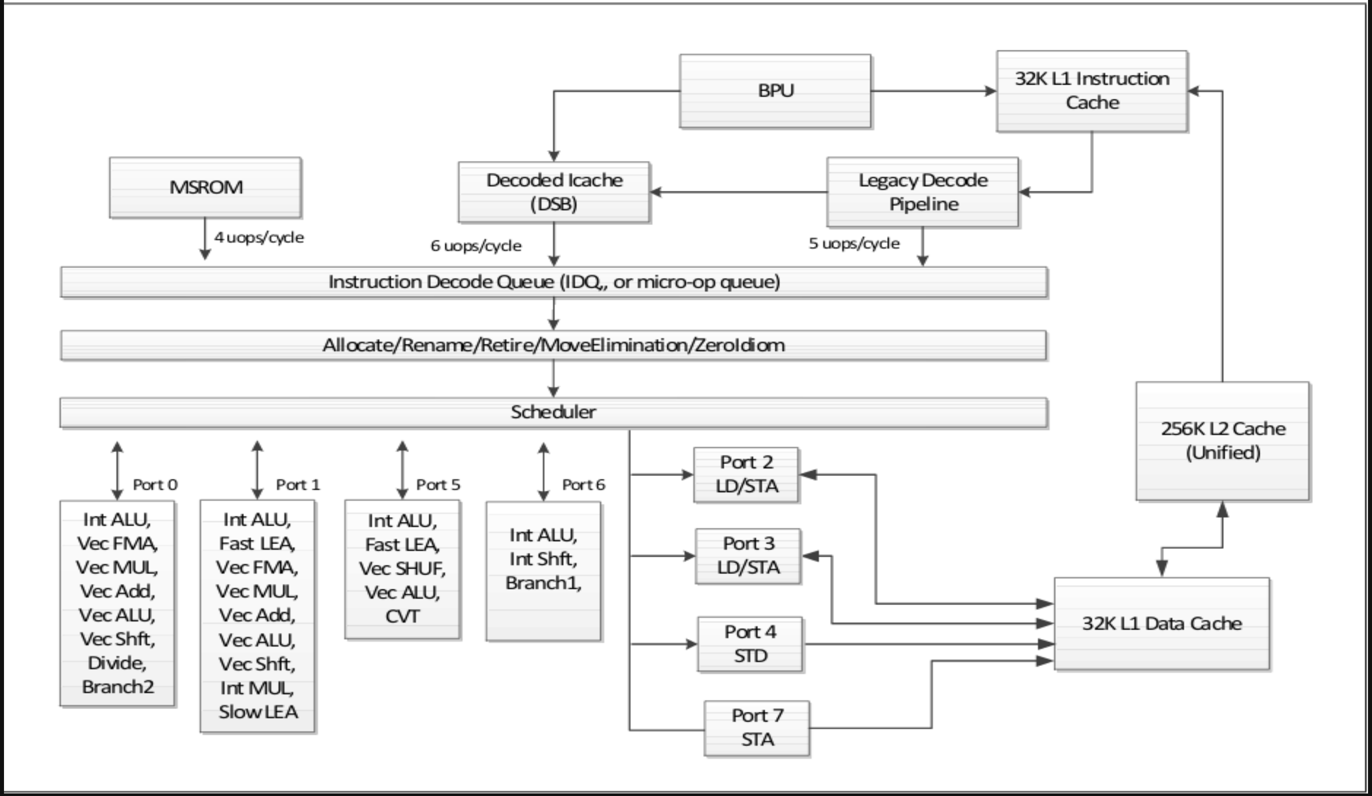

BPU
32K L1 Instruction Cache
MSROM
Decoded Icache (DSB)
Legacy Decode Pipeline
4 uops/cycle
6 uops/cycle
5 uops/cycle
Instruction Decode Queue (IDQ,, or micro-op queue)
Allocate/Rename/Retire/MoveElimination/ZeroIdiom
Scheduler
256K L2 Cache (Unified)
Port 0
Port 1
Port 5
Port 6
Int ALU, Vec FMA, Vec MUL, Vec Add, Vec ALU, Vec Shft, Divide, Branch2
Int ALU, Fast LEA, Vec FMA, Vec MUL, Vec Add, Vec ALU, Vec Shft, Int MUL, Slow LEA
Int ALU, Fast LEA, Vec SHUF, Vec ALU, CVT
Int ALU, Int Shft, Branch1,
Port 2 LD/STA
Port 3 LD/STA
Port 4 STD
Port 7 STA
32K L1 Data Cache

Figure from Intel Optimization Reference Manual.

Wikichip has a better figure.

Case Study: IBM Power9

- 4-8 Issue (maximum 8 fetch 6 decode)
  - Technically more of a SMT design than a Superscalar.
- 12-16 Pipeline stages

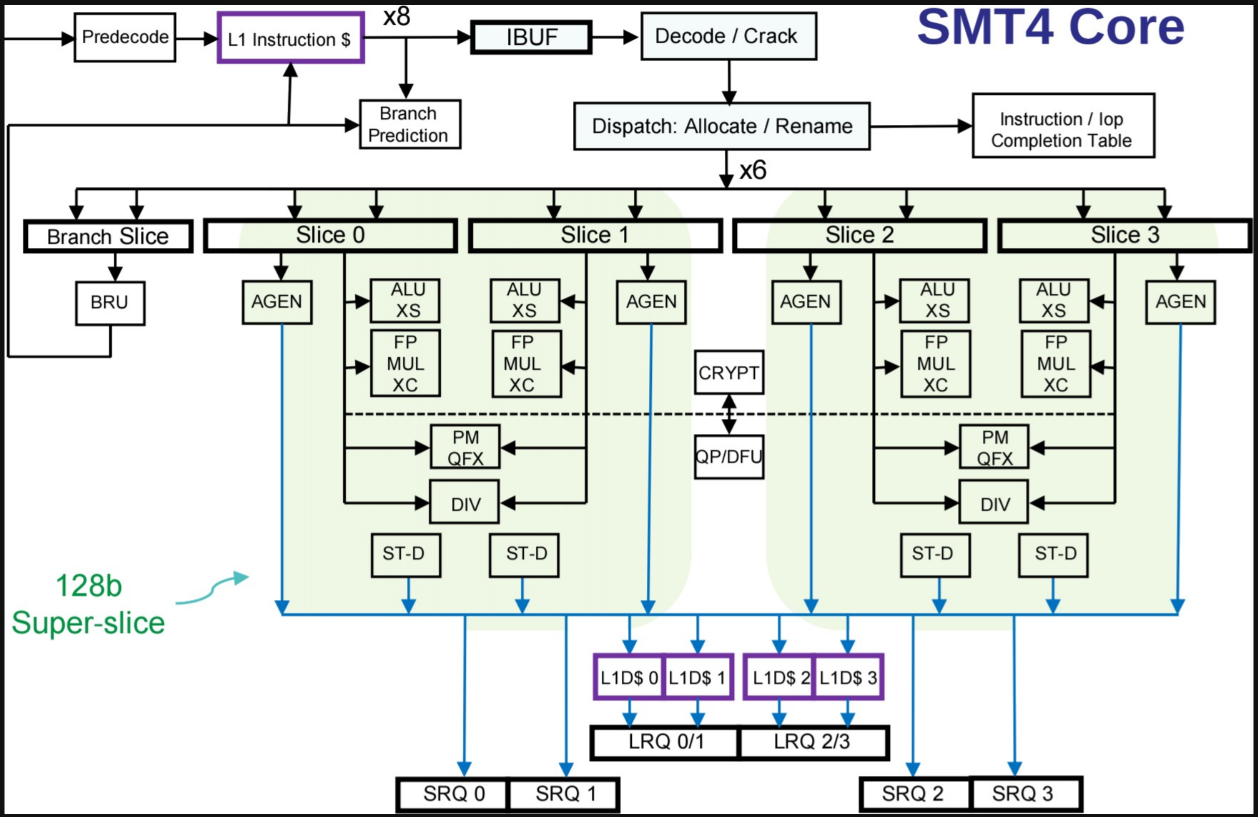


Figure from I
Wikichip.

Acknowledgment

- These slides are partially based on the lecture notes from Dr. David Brooks.