

Reduction of Data Hazards Stalls with Dynamic Scheduling

i.e Current pipeline: In-order
Single issue with FP support

- So far we have dealt with data hazards in instruction pipelines by:

- Result forwarding (register bypassing) to reduce or eliminate stalls needed to prevent RAW hazards as a result of true data dependence.
- Hazard detection hardware to stall the pipeline starting with the instruction that uses the result. *i.e forward + stall (if needed)*
- Compiler-based static pipeline scheduling to separate the dependent instructions minimizing actual hazard-prevention stalls in scheduled code.
 - Loop unrolling to increase basic block size: More ILP exposed.

Dynamic = Done at runtime by CPU

i.e Start of instruction execution is not in program order

- Dynamic scheduling: (out-of-order execution)

- Uses a hardware-based mechanism to reorder or rearrange instruction execution order to reduce stalls dynamically at runtime.
 - Better dynamic exploitation of instruction-level parallelism (ILP).

Why?

- Enables handling some cases where instruction dependencies are unknown at compile time (ambiguous dependencies).
- Similar to the other pipeline optimizations above, a dynamically scheduled processor cannot remove true data dependencies, but tries to avoid or reduce stalling.

Fourth Edition: Appendix A.7, Chapter 2.4, 2.5
(Third Edition: Appendix A.8, Chapter 3.2, 3.3)

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Dynamic Pipeline Scheduling: *The Concept*

Dynamic = Done at runtime by CPU

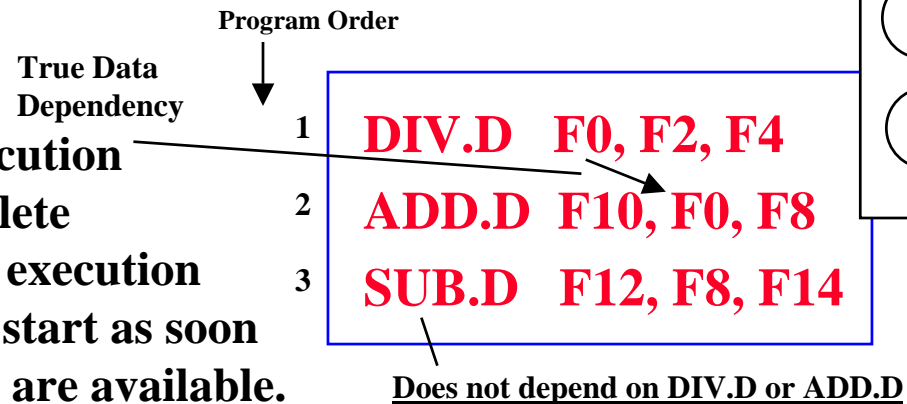
(Out-of-order execution)

i.e Start of instruction execution is not in program order

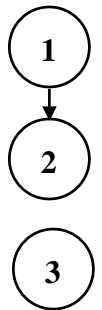
- **Dynamic pipeline scheduling overcomes the limitations of in-order pipelined execution by allowing out-of-order instruction execution.**
- **Instruction are allowed to start executing out-of-order as soon as their operands are available.**
 - **Better dynamic exploitation of instruction-level parallelism (ILP).**

Example:

In the case of in-order pipelined execution SUB.D must wait for DIV.D to complete which stalled ADD.D before starting execution
In out-of-order execution SUB.D can start as soon as the values of its operands F8, F14 are available.



Dependency Graph



- **This implies allowing out-of-order instruction commit (completion).**
- **May lead to imprecise exceptions if an instruction issued earlier raises an exception.**
 - **This is similar to pipelines with multi-cycle floating point units.**

In Fourth Edition: Appendix A.7, Chapter 2.4
(In Third Edition: Appendix A.8, Chapter 3.2)

Order = Program Instruction Order

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#2 lec # 4 Spring 2018 2-7-2018

Dynamic Pipeline Scheduling

- Dynamic instruction scheduling is accomplished by:

- Dividing the Instruction Decode ID stage into two stages:

Always done in program order

1. **Issue:** Decode instructions, check for structural hazards.

- + – A record of data dependencies is constructed as instructions are issued
- This creates a dynamically-constructed dependency graph for the window of instructions in-flight (being processed) in the CPU.

Can be done out of program order

2. **Read operands:** Wait until data hazard conditions, if any, are resolved, then read operands when available (then start execution)

(All instructions pass through the issue stage 1 in order but can be stalled or pass each other in the read operands stage 2).

- In the instruction fetch stage IF, fetch an additional instruction every cycle into a latch or several instructions into an instruction queue.
- Increase the number of functional units to meet the demands of the additional instructions in their EX stage.

- Two approaches to dynamic scheduling:

FYI

1

- Dynamic scheduling with the Scoreboard used first in CDC6600 (1963)

2

- The Tomasulo approach pioneered by the IBM 360/91 (1966)

(Control Data Corp.)

Fourth Edition: Appendix A.7, Chapter 2.4
(Third Edition: Appendix A.8, Chapter 3.2)

CDC660 is the world's first
"Supercomputer" Cost: \$7 million in 1963

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Dynamic Scheduling With A Scoreboard

- The scoreboard is a centralized hardware mechanism that maintains an execution rate of one instruction per cycle by executing an instruction as soon as its operands are available in registers and no hazard conditions prevent it.

No Forwarding

– e.g. Forming a single-issue out-of-order pipeline

EX Includes MEM

- It replaces ID, EX, WB with four stages: ID1, ID2, EX, WB

Includes MEM

Issue

Read Operands

No changes to Instruction Fetch (IF)

- Every instruction goes through the scoreboard where a record of data dependencies is constructed (ID1 corresponds to instruction issue).

In ID1 (Issue) In-Order

– In effect dynamically constructing the dependency graph by hardware for a window of instructions as they are issued one at a time in program order.

- A system with a scoreboard is assumed to have several functional units with their status information reported to the scoreboard.
- If the scoreboard determines that an instruction cannot execute immediately it executes another waiting instruction and keeps monitoring hardware units status and decide when the instruction can proceed to execute.
- The scoreboard also decides when an instruction can write its results to registers (hazard detection and resolution is centralized in the scoreboard).

Instruction Fetch (IF) is not changed

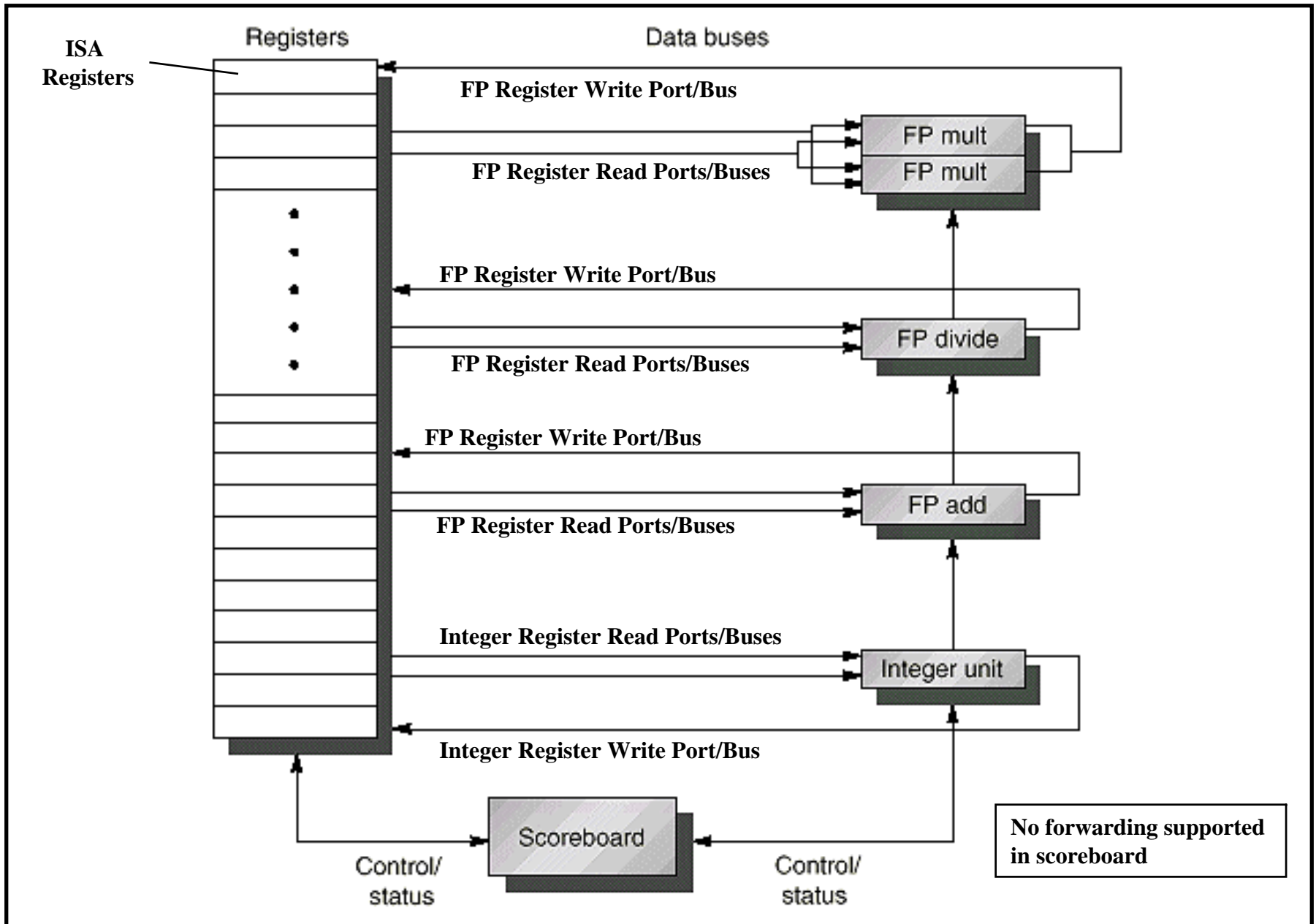
Order = Program Instruction Order

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In Fourth Edition: Appendix A.7
(In Third Edition: Appendix A.8)

Introduced in CDC6600 (1963)

#4 lec # 4 Spring 2018 2-7-2018



The basic structure of a MIPS processor with a scoreboard

In Fourth Edition: Appendix A.7
 (In Third Edition: Appendix A.8)

FP units are not pipelined similar to CDC6600

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Instruction Execution Stages with A Scoreboard

1 Issue (ID1): An instruction is issued if:

Stage 0 Instruction Fetch (IF): No changes, in-order

1
Always
done in
program
order

2 • A functional unit for the instruction is available (No structural hazard).

3 • The instruction result destination register is not marked for writing by an earlier active instruction (No WAW hazard, i.e no output dependence)

- If the above conditions are satisfied, the scoreboard issues the instruction to a functional unit and updates its internal data structures. As indicated by instruction issue requirements, structural and WAW hazards are resolved here by stalling the instruction issue. (this stage replaces part of **ID** stage in the conventional MIPS pipeline).

Can be
done
out of
program
order

2 Read operands (ID2): The scoreboard monitors the availability of the source operands. A source operand is available when no earlier active instruction will write it. When all source operands are available the scoreboard tells the functional unit to *read* all operands from the registers at once (no forwarding supported) and start execution (RAW hazards resolved here dynamically). This completes **ID**.

From registers (No forwarding)

3 Execution (EX): The functional unit starts execution upon receiving operands. When the results are ready it notifies the scoreboard (replaces **EX**, **MEM** in MIPS).

4 Write result (WB): Once the scoreboard senses that a functional unit completed execution, it checks for WAR hazards and stalls the completing instruction if needed otherwise the write back is completed. The functional unit issued to the instruction is marked as available (not busy) after WB is completed.

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In Fourth Edition: Appendix A.7
(In Third Edition: Appendix A.8)

Stage 0: Fetch, no changes, in-order

Three Parts of the Scoreboard

- 1 Instruction status:** Which of 4 steps the instruction is in.
- 2 Functional unit status:** Indicates the state of the functional unit (FU).

Nine fields for each functional unit:

Busy = Issued an instruction

- **Busy** Indicates whether the unit is busy or not
- **Op** Operation to perform in the unit (e.g., + or -)
- **Fi** Destination register
- **Fj, Fk** Source-register numbers i.e. Operand Registers If Any
- **Qj, Qk** Functional units producing source (operand) registers Fj, Fk
- **Rj, Rk** Flags indicating when Fj, Fk are ready Yes or = 1 means ready
(set to Yes after operand is available to read
both operands read at once from registers) i.e. when both Rj, Rk are set to yes
 (both operands are ready)

Used/Needed
To Track Data
Dependencies

- 3 Register result status:** Indicates which functional unit will write to each register, if one exists. Blank when no pending instructions will write that register.

Needed to check for possible WAW hazard and stall issue

e.g.

F0	F1	F2	F3	F31
Add1	--	Mult1	--	--

In Fourth Edition: Appendix A.7
(In Third Edition: Appendix A.8)

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The Scoreboard: Detailed Pipeline Control

Instruction status	Wait until	Bookkeeping
Issue	Not busy (FU) and not result(D)	$Busy(FU) \leftarrow \text{yes}; Op(FU) \leftarrow op;$ $Fi(FU) \leftarrow 'D'; Fj(FU) \leftarrow 'S1';$ $Fk(FU) \leftarrow 'S2'; Qj \leftarrow \text{Result}('S1');$ $Qk \leftarrow \text{Result}('S2'); Rj \leftarrow \text{not } Qj;$ $Rk \leftarrow \text{not } Qk; \text{Result}('D') \leftarrow FU;$
Read operands	Rj and Rk	$Rj \leftarrow \text{Yes}$ $Rk \leftarrow \text{Yes}$
Execution complete	Functional unit done	
Write result	$\forall f((Fj(f) \neq Fi(FU)$ or $Rj(f) = \text{No}) \&$ $(Fk(f) \neq Fi(FU)$ or $Rk(f) = \text{No}))$	$\forall f(\text{if } Qj(f) = FU \text{ then } Rj(f) \leftarrow \text{Yes});$ $\forall f(\text{if } Qk(f) = FU \text{ then } Rj(f) \leftarrow \text{Yes});$ $\text{Result}(Fi(FU)) \leftarrow 0; Busy(FU) \leftarrow \text{No}$

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In Fourth Edition: Appendix A.7
(In Third Edition: Appendix A.8)

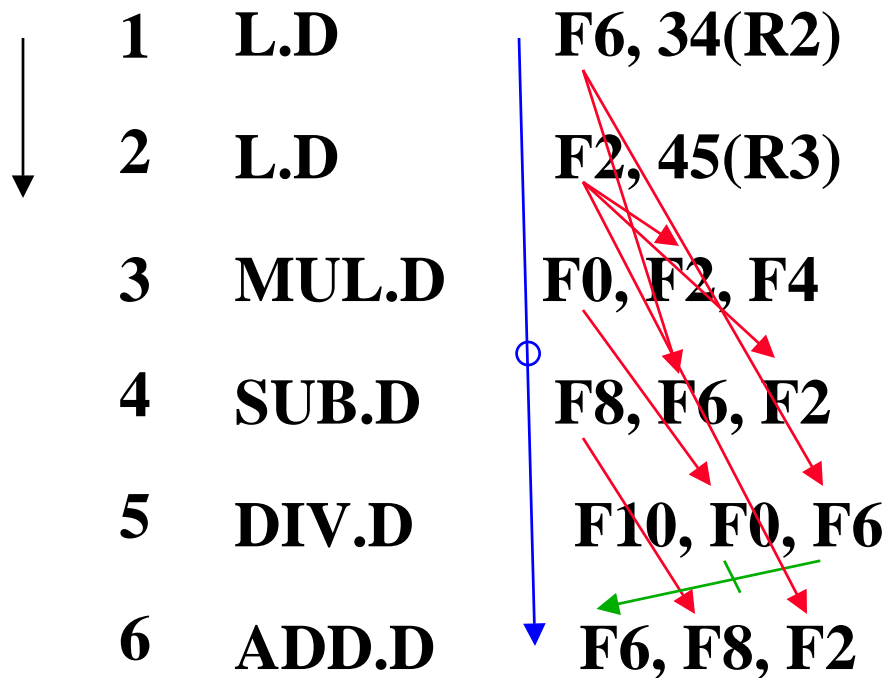
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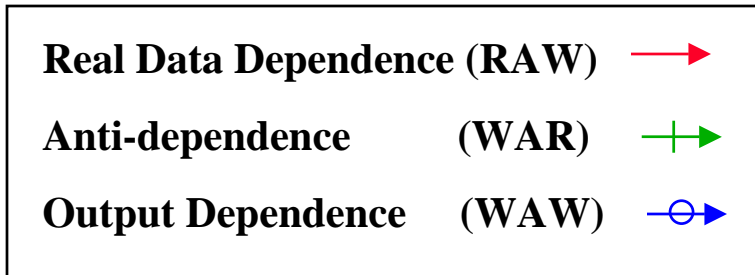
A Scoreboard Example

The following code is run on the MIPS with a scoreboard given earlier with:

Functional Unit (FU)	# of FUs	EX cycles
Integer	1	1
Floating Point Multiply	2	10
Floating Point add/sub	1	2
Floating point Divide	1	40



All functional units
are not pipelined
(similar to CDC6600)



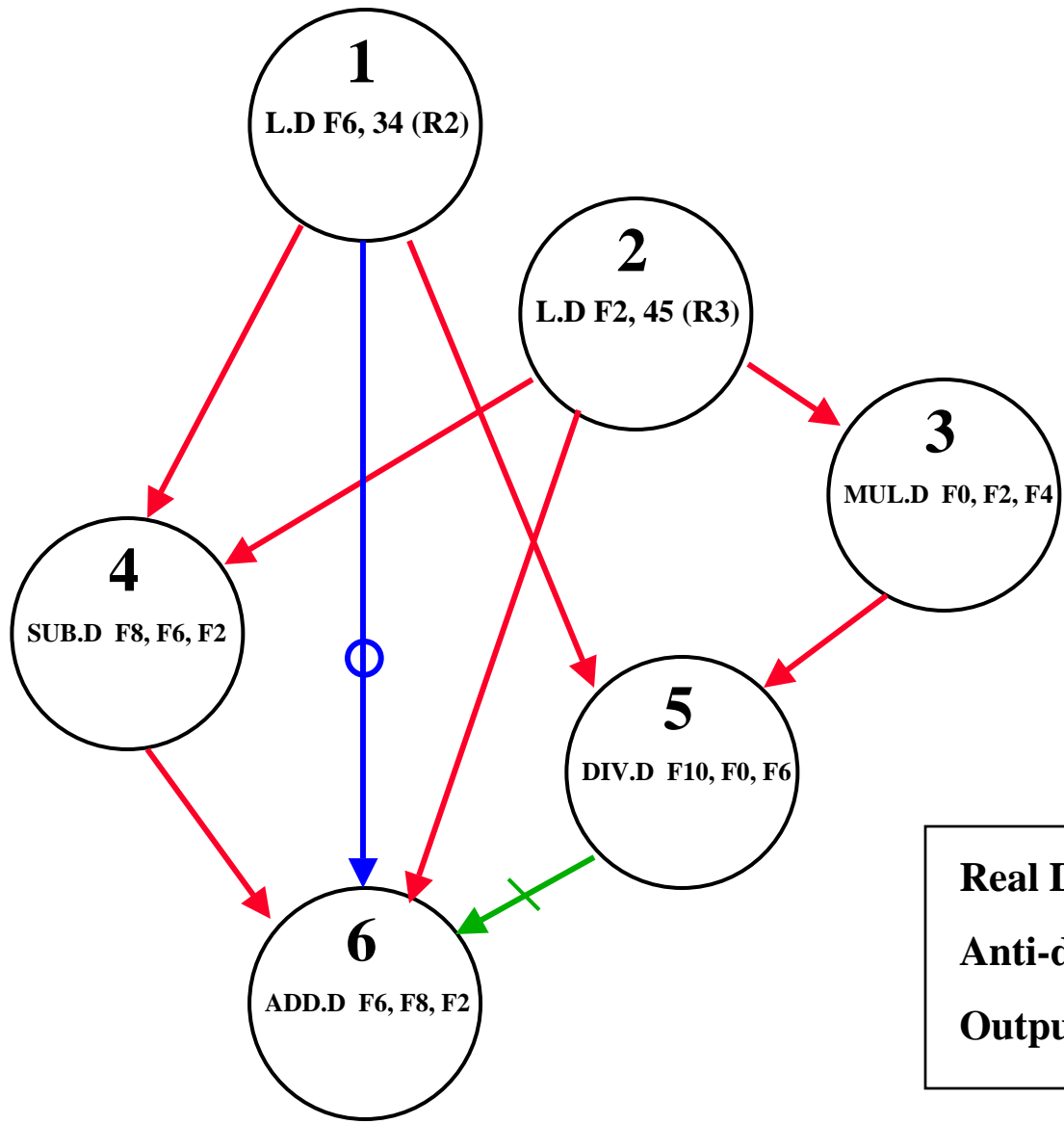
Assume EX and MEM
for L.D. done in one cycle ←

In Fourth Edition: Appendix A.7
(In Third Edition: Appendix A.8)

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Dependency Graph For Example Code

∅ →



Example Code

1	L.D	F6, 34(R2)
2	L.D	F2, 45(R3)
3	MUL.D	F0, F2, F4
4	SUB.D	F8, F6, F2
5	DIV.D	F10, F0, F6
6	ADD.D	F6, F8, F2

Date Dependence:

(1, 4) (1, 5) (2, 3) (2, 4)
(2, 6) (3, 5) (4, 6)

Output Dependence:

(1, 6)

Anti-dependence:

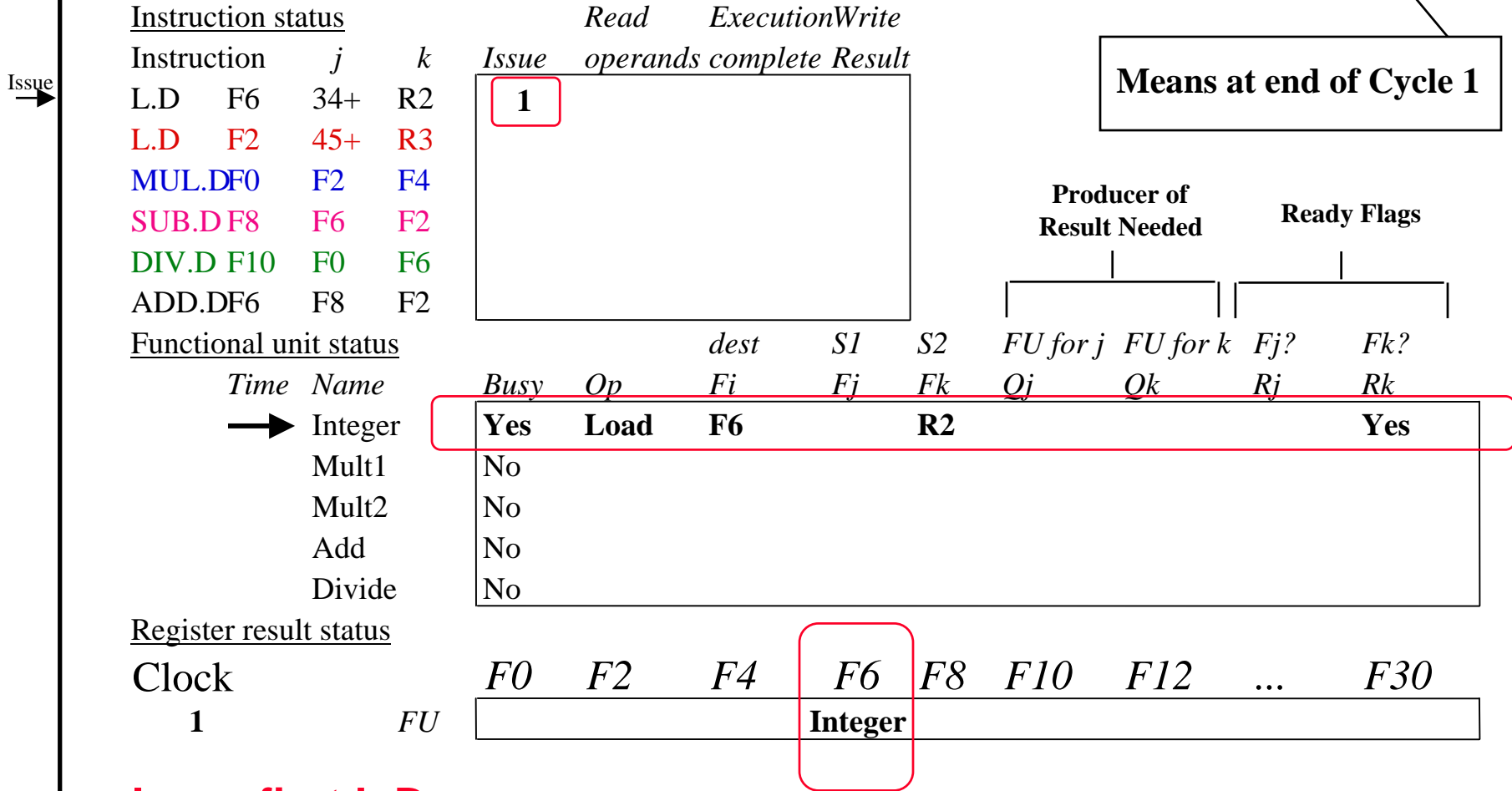
(5, 6)

Real Data Dependence (RAW)	→
Anti-dependence (WAR)	+→
Output Dependence (WAW)	⊙→

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Scoreboard Example: Cycle 1

FP EX Cycles: Add = 2 cycles, Multiply = 10, Divide = 40



Issue first L.D

Scoreboard Example: Cycle 2

FP EX Cycles : Add = 2 cycles, Multiply = 10, Divide = 40

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands complete</i>	<i>Result</i>	
L.D F6	34+	R2	1	2		
L.D F2	45+	R3	?			
MUL.D F0	F2	F4				
SUB.D F8	F6	F2				
DIV.D F10	F0	F6				
ADD.D F6	F8	F2				

Issue ? →

<u>Functional unit status</u>		<i>Busy</i>	<i>Op</i>	<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU for j</i>	<i>FU for k</i>	<i>Fj?</i>	<i>Fk?</i>
<i>Time</i>	<i>Name</i>			<i>Fi</i>	<i>Fj</i>	<i>Fk</i>	<i>Qj</i>	<i>Qk</i>	<i>Rj</i>	<i>Rk</i>
	Integer	Yes	Load	F6		R2				Yes
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status

<u>Clock</u>	<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
2									Integer

? **Issue second L.D? No, stall on structural hazard. Single integer functional unit is busy.**

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Scoreboard Example: Cycle 3

Instruction status

Instruction	<i>j</i>	<i>k</i>
L.D F6 34+ R2		
L.D F2 45+ R3		
MUL.D F0 F2 F4		
SUB.D F8 F6 F2		
DIV.D F10 F0 F6		
ADD.D F6 F8 F2		

Issue ? →

Issue	Read operands	Execution complete	Write Result
1	2	3	
?			

From Assumption
EX, MEM
for L.D. in one cycle

Functional unit status

Time	Name	Busy	Op	dest <i>Fi</i>	<i>S1</i> <i>Fj</i>	<i>S2</i> <i>Fk</i>	<i>FU for j</i> <i>Qj</i>	<i>FU for k</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	Yes	Load	F6		R2				Yes
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status

Clock	<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
3									
	FU Integer								

- Issue MUL.D? No, cannot issue out of order (second L.D not issued yet)

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Scoreboard Example: Cycle 4

Instruction status

Instruction	<i>j</i>	<i>k</i>	Issue	Read operands	Execution complete	Write Result
L.D F6	34+	R2	1	2	3	4
L.D F2	45+	R3				
MUL.D F0	F2	F4				
SUB.D F8	F6	F2				
DIV.D F10	F0	F6				
ADD.D F6	F8	F2				

Issue ? →

Functional unit status

Time Name

Actually free end
of this cycle 4
(available for
instruction issue
next cycle)

Integer
Mult1
Mult2
Add
Divide

Busy	Op	dest <i>F_i</i>	<i>S1</i> <i>F_j</i>	<i>S2</i> <i>F_k</i>	<i>FU for j</i> <i>Q_j</i>	<i>FU for k</i> <i>Q_k</i>	<i>F_j?</i> <i>R_j</i>	<i>F_k?</i> <i>R_k</i>
No								
No								
No								
No								
No								

Register result status

Clock

4

FU

<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>

Issue second L.D?

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Scoreboard Example: Cycle 5

Issue →

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands</i>	<i>complete</i>	<i>Result</i>
L.D	F6	34+	R2	1	2	3
L.D	F2	45+	R3	5		
MUL.D	F0	F2	F4			
SUB.D	F8	F6	F2			
DIV.D	F10	F0	F6			
ADD.D	F6	F8	F2			

<u>Functional unit status</u>		<i>Busy</i>	<i>Op</i>	<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU for j</i>	<i>FU for k</i>	<i>Fj?</i>	<i>Fk?</i>
<i>Time</i>	<i>Name</i>	<i>Fi</i>	<i>Fj</i>	<i>Fk</i>	<i>Qj</i>	<i>Qk</i>	<i>Rj</i>	<i>Rk</i>		
→	Integer	Yes	Load	F2		R3				Yes
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status

Clock	<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
5		Integer							

Issue second L.D

Scoreboard Example: Cycle 6

Issue →

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>	
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands</i>	<i>complete</i>	<i>Result</i>	
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6		
MUL.D	F0	F2	F4	6			
SUB.D	F8	F6	F2				
DIV.D	F10	F0	F6				
ADD.D	F6	F8	F2				

Producer of Result Needed Ready Flags

Functional unit status

Time Name
 → Integer
 → Mult1
 Mult2
 Add
 Divide

<i>Busy</i>	<i>Op</i>	<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU for j</i>	<i>FU for k</i>	<i>Fj?</i>	<i>Fk?</i>
		<i>Fi</i>	<i>Fj</i>	<i>Fk</i>	<i>Qj</i>	<i>Qk</i>	<i>Rj</i>	<i>Rk</i>
Yes	Load	F2		R3				Yes
Yes	Mult	F0	F2	F4	Integer	No	Yes	
No								
No								
No								

Register result status

Clock

6

FU

<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
Mult1	Integer							

Issue MUL.D

Scoreboard Example: Cycle 7

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>	
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands</i>	<i>complete</i>	<i>Result</i>	
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	
MUL.D	F0	F2	F4	6	?		
SUB.D	F8	F6	F2	7			
DIV.D	F10	F0	F6				
ADD.D	F6	F8	F2				

Issue →

<u>Functional unit status</u>		<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU for j</i>	<i>FU for k</i>	<i>Fj?</i>	<i>Fk?</i>
<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>Fi</i>	<i>Fj</i>	<i>Fk</i>	<i>Qj</i>	<i>Qk</i>
	Integer	Yes	Load	F2		R3		
	Mult1	Yes	Mult	F0	F2	F4	Integer	No
	Mult2	No						
→	Add	Yes	Sub	F8	F6	F2	Integer	Yes
	Divide	No						No

<u>Register result status</u>		<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
Clock										
7	<i>FU</i>	Mult1	Integer			Add				

- Issue SUB.D
- Read multiply operands?

Scoreboard Example: Cycle 8b (Second half of cycle 8)

End of Cycle 8

Instruction status				Read	Execution	Write	
Instruction	<i>j</i>	<i>k</i>	Issue	operands complete	Result		
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	8
MUL.D	F0	F2	F4	6			
SUB.D	F8	F6	F2	7			
DIV.D	F10	F0	F6	8			
ADD.D	F6	F8	F2				

Functional unit status

Time Name

Busy	Op	dest <i>Fi</i>	<i>S1</i> <i>Fj</i>	<i>S2</i> <i>Fk</i>	<i>FU for j</i> <i>Qj</i>	<i>FU for k</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
No								
Yes	Mult	F0	F2	F4		Yes	Yes	
No								
Yes	Sub	F8	F6	F2		Yes	Yes	
Yes	Div	F10	F0	F6	Mult1	No	Yes	

Register result status

Clock

8

FU

<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
Mult1				Add	Divide			

- Second L.D writes result to F2

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Scoreboard Example: Cycle 9

FP EX Cycles : Add = 2 cycles, Multiply = 10, Divide = 40

Instruction status				Read	Execution	Write	
Instruction	<i>j</i>	<i>k</i>	Issue	operands complete	complete	Result	
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	8
MUL.D	F0	F2	F4	6	9		
SUB.D	F8	F6	F2	7	9		
DIV.D	F10	F0	F6	8			
ADD.D	F6	F8	F2	?			

Issue ? →

Execution cycles Remaining (execution actually starts next cycle)

Functional unit status		<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU for j</i>	<i>FU for k</i>	<i>Fj?</i>	<i>Fk?</i>
<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>Fi</i>	<i>Fj</i>	<i>Fk</i>	<i>Qj</i>	<i>Qk</i>
	Integer	No						
10	Mult1	Yes	Mult	F0	F2	F4		Yes
	Mult2	No						Yes
2	Add	Yes	Sub	F8	F6	F2		Yes
	Divide	Yes	Div	F10	F0	F6	Mult1	No

Register result status		<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
Clock	9									
	<i>FU</i>	Mult1				Add	Divide			

- Read operands for MUL.D & SUB.D
- Issue ADD.D?

Ex starts next cycle for both instructions

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Scoreboard Example: Cycle 11

Instruction status

Instruction	<i>j</i>	<i>k</i>
L.D F6 34+ R2		
L.D F2 45+ R3		
MUL.D F0 F2 F4		
SUB.D F8 F6 F2		
DIV.D F10 F0 F6		
ADD.D F6 F8 F2		

Read ExecutionWrite

Issue	operands	complete	Result
1	2	3	4
5	6	7	8
6	9		
7	9	11	
8			
?			

Issue ?

Functional unit status

Time Name

Execution cycles Remaining

Done executing

8	Mult1
	Mult2
0	Add
	Divide

Busy Op dest S1 S2 FU for j FU for k Fj? Fk?

Busy	Op	Fi	Fj	Fk	Qj	Qk	Rj	Rk
No								
Yes	Mult	F0	F2	F4			Yes	Yes
No								
Yes	Sub	F8	F6	F2			Yes	Yes
Yes	Div	F10	F0	F6	Mult1		No	Yes

Register result status

Clock

11

FU

F0	F2	F4	F6	F8	F10	F12	...	F30
			Mult1		Add	Divide		

? • Issue ADD.D?

Scoreboard Example: Cycle 12

Instruction status				Read	Execution	Write	
Instruction	<i>j</i>	<i>k</i>	Issue	operands complete	Result		
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	8
MUL.D	F0	F2	F4	6	9		
SUB.D	F8	F6	F2	7	9	11	12
DIV.D	F10	F0	F6	8	?		
ADD.D	F6	F8	F2	?			

Issue ?

Functional unit status

Execution cycles Remaining

Actually free end of this cycle 12

Time	Name
	Integer
7	Mult1
	Mult2
	Add
	Divide

Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
		<i>Fi</i>	<i>Fj</i>	<i>Fk</i>	<i>Qj</i>	<i>Qk</i>	<i>Rj</i>	<i>Rk</i>
No								
Yes	Mult	F0	F2	F4			Yes	Yes
No								
No								
Yes	Div	F10	F0	F6	Mult1		No	Yes

Register result status

Clock

12

FU

F0	F2	F4	F6	F8	F10	F12	...	F30
Mult1					Divide			

- ? • Read operands for DIV.D?
- ? • Issue ADD.D?

Scoreboard Example: Cycle 17

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>	
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands</i>	<i>complete</i>	<i>Result</i>	
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	8
MUL.D	F0	F2	F4	6	9		
SUB.D	F8	F6	F2	7	9	11	12
DIV.D	F10	F0	F6	8			
ADD.D	F6	F8	F2	13	14	16	<input type="checkbox"/>

Write result of ADD.D?
No WAR hazard

<u>Functional unit status</u>		<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU for j</i>	<i>FU for k</i>	<i>Fj?</i>	<i>Fk?</i>
<i>Time</i>	<i>Name</i>	<i>Fi</i>	<i>Fj</i>	<i>Fk</i>	<i>Qj</i>	<i>Qk</i>	<i>Rj</i>	<i>Rk</i>
	Integer	No						
2	Mult1	Yes	Mult	F0	F2	F4	Yes	Yes
	Mult2	No						
	Add	Yes	Add	F6	F8	F2	Yes	Yes
	Divide	Yes	Div	F10	F0	F6	Mult1	No

<u>Register result status</u>		<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	<i>...</i>	<i>F30</i>
Clock	17									
	<i>FU</i>	Mult1			Add		Divide			

- Write result of ADD.D? No, WAR hazard (DIV.D did not read any operands including F6)

Scoreboard Example: Cycle 20

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>	
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands</i>	<i>complete</i>	<i>Result</i>	
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	8
MUL.D	F0	F2	F4	6	9	19	20
SUB.D	F8	F6	F2	7	9	11	12
DIV.D	F10	F0	F6	8	?		
ADD.D	F6	F8	F2	13	14	16	?

Functional unit status

<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU for j</i>	<i>FU for k</i>	<i>Fj?</i>	<i>Fk?</i>
				<i>Fi</i>	<i>Fj</i>	<i>Fk</i>	<i>Qj</i>	<i>Qk</i>	<i>Rj</i>	<i>Rk</i>
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	Yes	Add	F6	F8	F2			Yes	Yes
	Divide	Yes	Div	F10	F0	F6			Yes	Yes

Register result status

Clock	<i>FU</i>	<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
20					Add		Divide			

- ? • Read operands for DIV.D?
- ? • Write result of ADD.D?

Scoreboard Example: Cycle 21

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>	
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands complete</i>	<i>Result</i>		
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	8
MUL.D	F0	F2	F4	6	9	19	20
SUB.D	F8	F6	F2	7	9	11	12
DIV.D	F10	F0	F6	8	21		
ADD.D	F6	F8	F2	13	14	16	?

Functional unit status

Execution cycles Remaining (execution actually starts next cycle)

Time Name
Integer
Mult1
Mult2
Add
40 Divide

<i>Busy</i>	<i>Op</i>	<i>dest</i> <i>Fi</i>	<i>S1</i> <i>Fj</i>	<i>S2</i> <i>Fk</i>	<i>FU for j</i> <i>Qj</i>	<i>FU for k</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
No								
No								
No								
Yes	Add	F6	F8	F2			Yes	Yes
Yes	Div	F10	F0	F6			Yes	Yes

Register result status

Clock
21

<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
			Add		Divide			

- DIV.D reads operands, starts execution next cycle
- ? • Write result of ADD.D?

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Scoreboard Example: Cycle 22

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>	
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands</i>	<i>complete</i>	<i>Result</i>	
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	8
MUL.D	F0	F2	F4	6	9	19	20
SUB.D	F8	F6	F2	7	9	11	12
DIV.D	F10	F0	F6	8	21		
ADD.D	F6	F8	F2	13	14	16	22

Functional unit status

<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>dest</i> <i>Fi</i>	<i>S1</i> <i>Fj</i>	<i>S2</i> <i>Fk</i>	<i>FU for j</i> <i>Qj</i>	<i>FU for k</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	No								
39	Divide	Yes	Div	F10	F0	F6			Yes	Yes

Register result status

Clock

22

FU

<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
					Divide			

First cycle DIV.D execution (39 more ex cycles)

ADD.D writes result in F6 (No WAR, DIV.D read operands in cycle 21)

(Possible)

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Scoreboard Example: Cycle 61

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>	
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands complete</i>	<i>Result</i>		
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	8
MUL.D	F0	F2	F4	6	9	19	20
SUB.D	F8	F6	F2	7	9	11	12
DIV.D	F10	F0	F6	8	21	61	
ADD.D	F6	F8	F2	13	14	16	22

Functional unit status

Time Name

<i>Busy</i>	<i>Op</i>	<i>dest</i> <i>Fi</i>	<i>S1</i> <i>Fj</i>	<i>S2</i> <i>Fk</i>	<i>FU for j</i> <i>Qj</i>	<i>FU for k</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
No								
No								
No								
No								
Yes	Div	F10	F0	F6			Yes	Yes

Done executing

0 Divide

Register result status

Clock

61

FU

<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
					Divide			

- DIV.D done executing

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Scoreboard Example: Cycle 62

<u>Instruction status</u>				<i>Read</i>	<i>Execution</i>	<i>Write</i>	
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>operands</i>	<i>complete</i>	<i>Result</i>	
L.D	F6	34+	R2	1	2	3	4
L.D	F2	45+	R3	5	6	7	8
MUL.D	F0	F2	F4	6	9	19	20
SUB.D	F8	F6	F2	7	9	11	12
DIV.D	F10	F0	F6	8	21	61	62
ADD.D	F6	F8	F2	13	14	16	22

**Instruction
Block done**

Functional unit status

<i>Time</i>	<i>Name</i>
	Integer
	Mult1
	Mult2
	Add
	Divide

<i>Busy</i>	<i>Op</i>	<i>dest</i> <i>Fi</i>	<i>S1</i> <i>Fj</i>	<i>S2</i> <i>Fk</i>	<i>FU for j</i> <i>Qj</i>	<i>FU for k</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
No								
No								
No								
No								
No								

Register result status

Clock

62

FU

<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>

- **We have:**
 - **In-order issue,**
 - **Out-of-order read operands, execution, completion**

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Dynamic Scheduling: The Tomasulo Algorithm

- Developed at IBM and first implemented in IBM's 360/91 mainframe in 1966, about 3 years after the debut of the scoreboard in the CDC 6600.
- Dynamically schedule the pipeline in hardware to reduce stalls.
- Differences between IBM 360 & CDC 6600 ISA.
 - IBM has only 2 register specifiers/instr vs. 3 in CDC 6600.
 - IBM has 4 FP registers vs. 8 in CDC 6600 (part of ISA).
- Current CPU architectures that can be considered descendants of the IBM 360/91 which implement and utilize a variation of the Tomasulo Algorithm include:

RISC CPUs: Alpha 21264, HP 8600, MIPS R12000, PowerPC G4 ..

RISC-core x86 CPUs: AMD Athlon, Intel Pentium III, 4, Xeon,

In Fourth Edition: Chapter 2.4 (In Third Edition: Chapter 3.2)

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Tomasulo Algorithm Vs. Scoreboard

- Control & buffers *distributed* with Functional Units (FUs) Vs. centralized in Scoreboard:
 - FU buffers are called “^{RS}reservation stations” which have pending instructions and operands and other instruction status info (including data dependencies).
 - Reservations stations are sometimes referred to as “physical registers” or “renaming registers” as opposed to architecture ISA registers specified by the ISA. i.e. Operands
- ISA Registers in instructions are replaced by either values (if available) or pointers (renamed) to reservation stations (RS) that will supply the value later:
 - This process is called register renaming. Done in issue stage (in-order)
 - Register renaming eliminates WAR, WAW hazards (name dependence).
 - Allows for a *hardware-based* version of loop unrolling.
 - More reservation stations than ISA registers are possible, leading to optimizations that compilers can't achieve and prevents the number of ISA registers from becoming a bottleneck.
- Instruction results go (forwarded) from RSs to RSs , *not through registers*, over a broadcast bus, *Common Data Bus (CDB)* that broadcasts results to all waiting RSs (dependant instructions).
- Loads and Stores are treated as FUs with RSs as well.

1

Register Renaming

2

Data Forwarding

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Control Data Corp.

IBM 360/91 Vs. CDC 6600

Tomasulo-based (1966)

Scoreboard-based (1963)

Pipelined Functional Units

Multiple Functional Units

(Not pipelined)

(6 load, 3 store, 3 +, 2 x/÷)

(1 load/store, 1 +, 2 x, 1 ÷)

window size: ≤ 14 instructions

≤ 5 instructions

No issue on structural hazard

same

WAW: renaming avoids it

Eliminated
By register
renaming

stall issue ID1

WAR: renaming avoids it

stall completion WB

Broadcast results from FU Over CDB

Write/read registers

(Implements forwarding)

(Forwarding *not* supported)

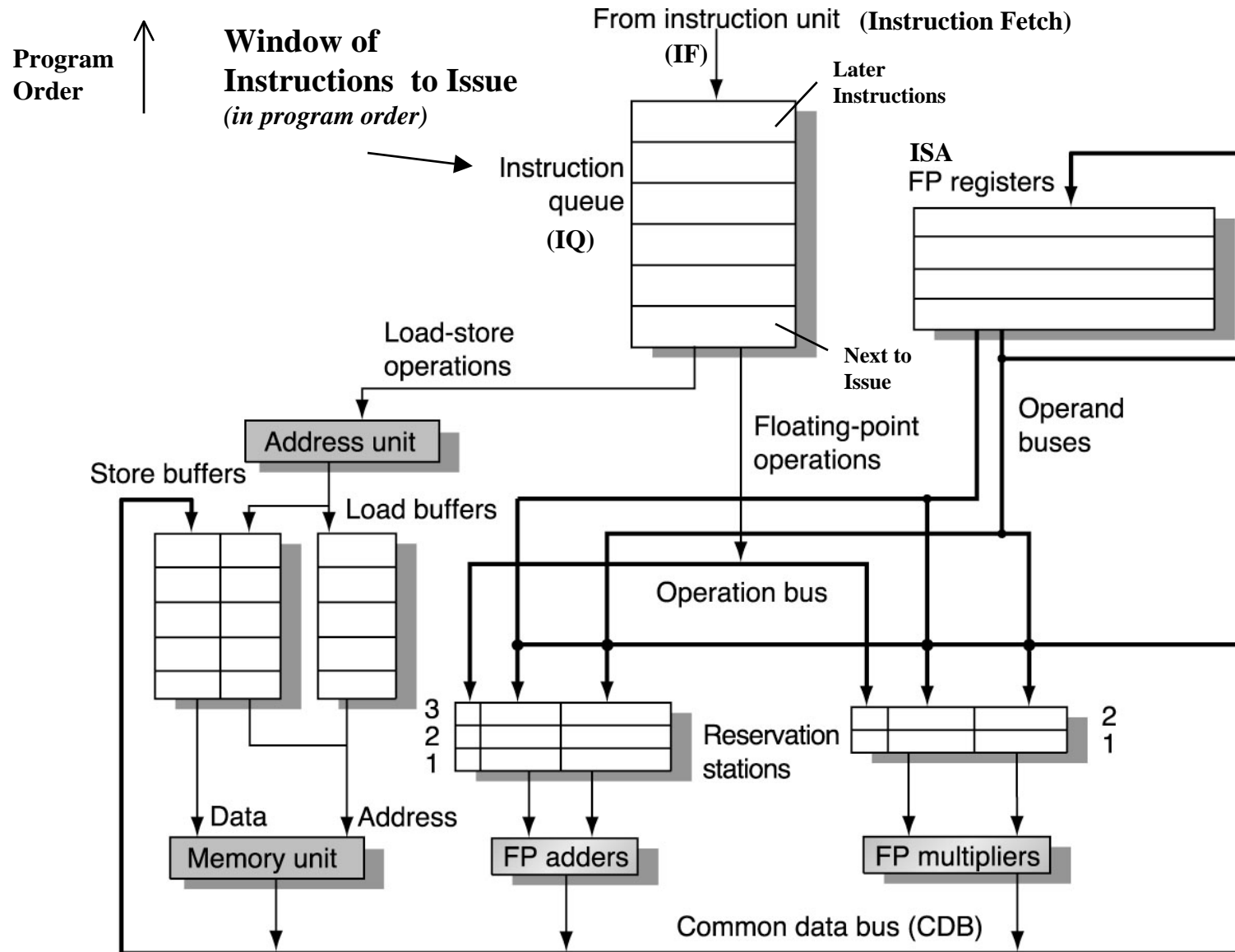
**Control: reservation stations
distributed**

central scoreboard

In Fourth Edition: Chapter 2.4 (In Third Edition: Chapter 3.2)

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Dynamic Scheduling: The Tomasulo Approach



The basic structure of a MIPS floating-point unit using Tomasulo's algorithm

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(In Third Edition: Chapter 3.2)

Pipelined FP units are used here

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Reservation Station (RS) Fields

- **Op** Operation to perform in the unit (e.g., + or –)
- **Vj, Vk** **Value** of Source operands S1 and S2 When available
 - Store buffers have a single **V** field indicating result to be stored.

Used/Needed
To Track Data
Dependencies

- **Qj, Qk** Reservation stations producing source registers. RS's (i.e. operand values needed by instruction) (value to be written).
 - No ready flags as in Scoreboard; $Qj, Qk=0 \Rightarrow$ ready.
 - Store buffers only have **Qi** for RS producing result. to be stored
- **A:** Address information for loads or stores. Initially immediate field of instruction then effective address when calculated.
- **Busy:** Indicates reservation station is busy.
- **Register result status:** **Qi** Indicates which Reservation Station will write each register, if one exists.
 - Blank (or 0) when no pending instruction (i.e. RS) exist that will write to that register.

In Fourth Edition: Chapter 2.4
(In Third Edition: Chapter 3.2)

Register bank behaves like a reservation station
(listen to CDB for data)

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#34 lec # 4 Spring 2018 2-7-2018

Three Stages of Tomasulo Algorithm

1 Issue: Get instruction from pending Instruction Queue (IQ).

1

Always done in program order

- Instruction issued to ²a free reservation station(RS) (no structural hazard).
- Selected RS is marked busy.
- Control sends available instruction operands values (from ISA registers) to assigned RS.
- Operands not available yet are renamed to RSs that will produce the operand (register renaming). (Dynamic construction of data dependency graph)

Stage 0 Instruction Fetch (IF): No changes, in-order

2 Execution (EX): Operate on operands.

Also includes waiting for operands + MEM

- When both operands are ready then start executing on assigned FU.
- If all operands are not ready, watch Common Data Bus (CDB) for needed result (forwarding done via CDB). (i.e. wait on any remaining operands, no RAW)

3 Write result (WB): Finish execution.

Data dependencies observed

And also to destination register

- Write result on Common Data Bus (CDB) to all awaiting units (RSs)
- Mark reservation station as available.

i.e broadcast result on CDB (forwarding)

- Normal data bus: data + destination (“go to” bus).

Note: No WB for stores or branches

Common Data Bus (CDB): data + source (“come from” bus):

- 64 bits for data + 4 bits for Functional Unit source address.
- Write data to waiting RS if source matches expected RS (that produces result).
- Does the result forwarding via broadcast to waiting RSs.

Can be done out of program order

In Fourth Edition: Chapter 2.4
(In Third Edition: Chapter 3.2)

Including destination register

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Steps in The Tomsulo Approach and The Requirements of Each Step

Instruction status	Wait until	Action or bookkeeping
Issue	Station or buffer empty	<pre> if (Register['S1'].Qi ≠ 0) {RS[r].Qj ← Register['S1'].Qi} else {RS[r].Vj ← S1; RS[r].Qj ← 0}; if (Register[S2].Qi ≠ 0) {RS[r].Qk ← Register[S2].Qi}; else {RS[r].Vk ← S2; RS[r].Qk ← 0} RS[r].Busy ← yes; Register['D'].Qi = r; </pre>
Execute	(RS[r].Qj=0) and (RS[r].Qk=0)	None—operands are in Vj and Vk
Write result	Execution completed at r and CDB available	<pre> ∀x(if (Register[x].Qi=r) {Fx ← result; Register[x].Qi ← 0}); ∀x(if (RS[x].Qj=r) {RS[x].Vj ← result; RS[x].Qj ← 0}); ∀x(if (RS[x].Qk=r) {RS[x].Vk ← result; RS[x].Qk ← 0}); ∀x(if (Store[x].Qi=r) {Store[x].V ← result; Store[x].Qi ← 0}); RS[r].Busy ← No </pre>

Drawbacks of The Tomasulo Approach

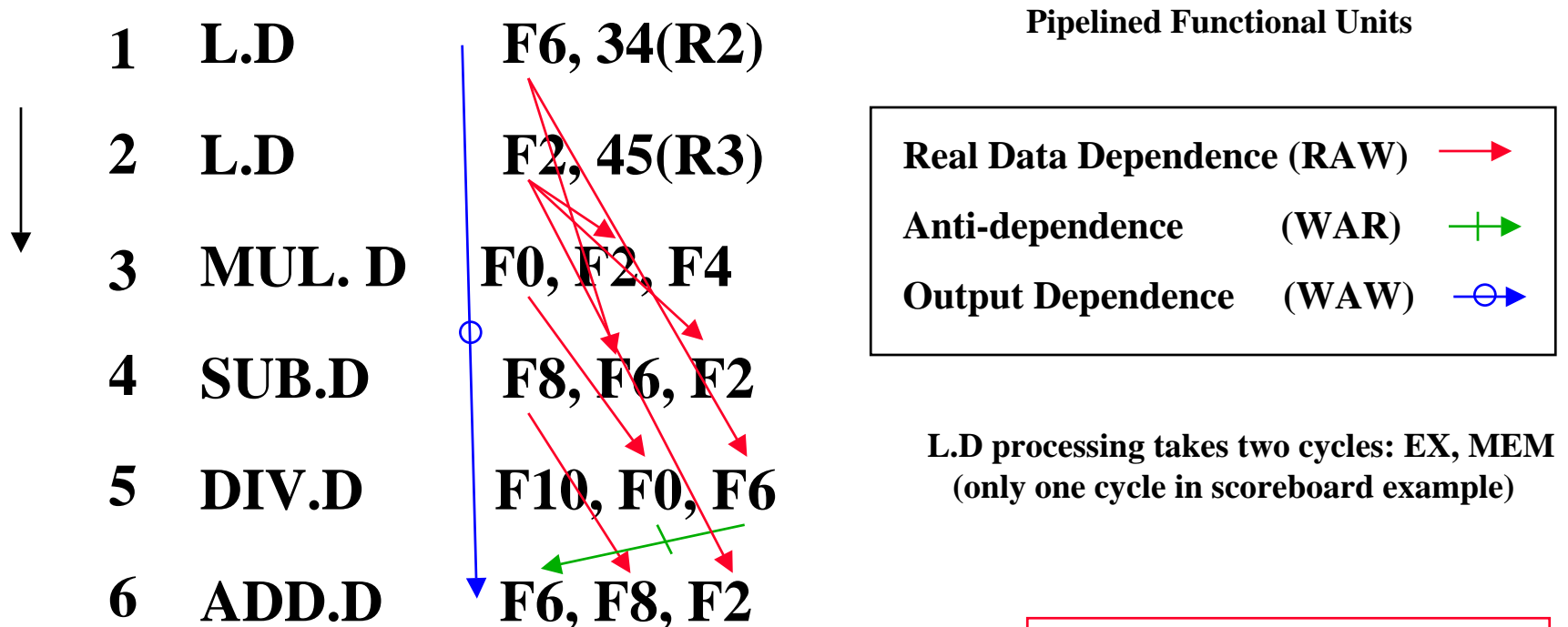
- **Implementation Complexity:**
 - **Example:** The implementation of the Tomasulo algorithm may have caused delays in the introduction of 360/91, MIPS 10000, IBM 620 among other CPUs.
- **Many high-speed associative result stores using (CDB) are required.**
- **Performance limited by one Common Data Bus**
 - **Possible solution:**
Multiple CDBs → more Functional Unit and RS logic needed for parallel associative stores. (Even more complexity)

Tomasulo Approach Example

Using the same code used in the scoreboard example to be run on the Tomasulo configuration given earlier:

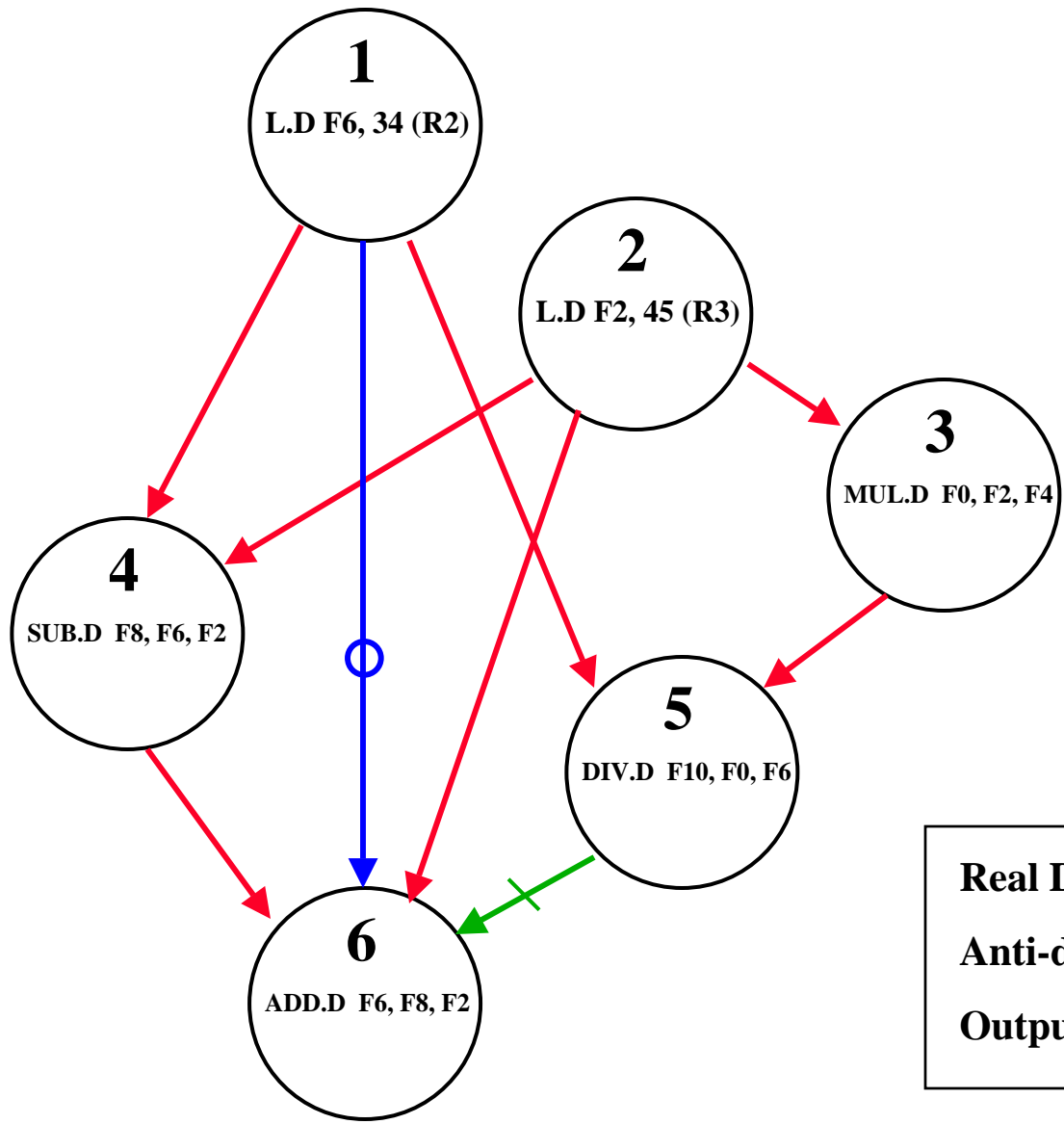
RS = Reservation Stations

	# of RSs	EX Cycles
Integer	3	1
Floating Point Multiply/divide	2	10/40
Floating Point add/sub	3	2



Dependency Graph For Example Code

∅ →



Example Code

1	L.D	F6, 34(R2)
2	L.D	F2, 45(R3)
3	MUL.D	F0, F2, F4
4	SUB.D	F8, F6, F2
5	DIV.D	F10, F0, F6
6	ADD.D	F6, F8, F2

Date Dependence:

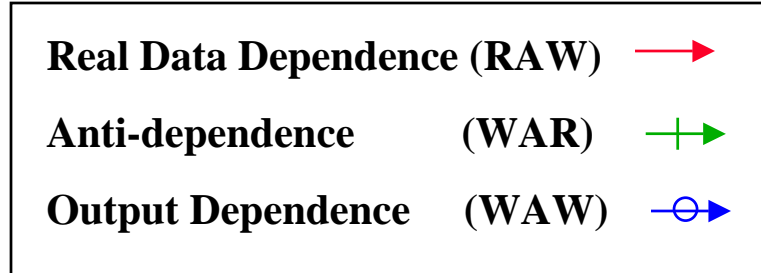
(1, 4) (1, 5) (2, 3) (2, 4)
(2, 6) (3, 5) (4, 6)

Output Dependence:

(1, 6)

Anti-dependence:

(5, 6)



The same code used is the scoreboard example

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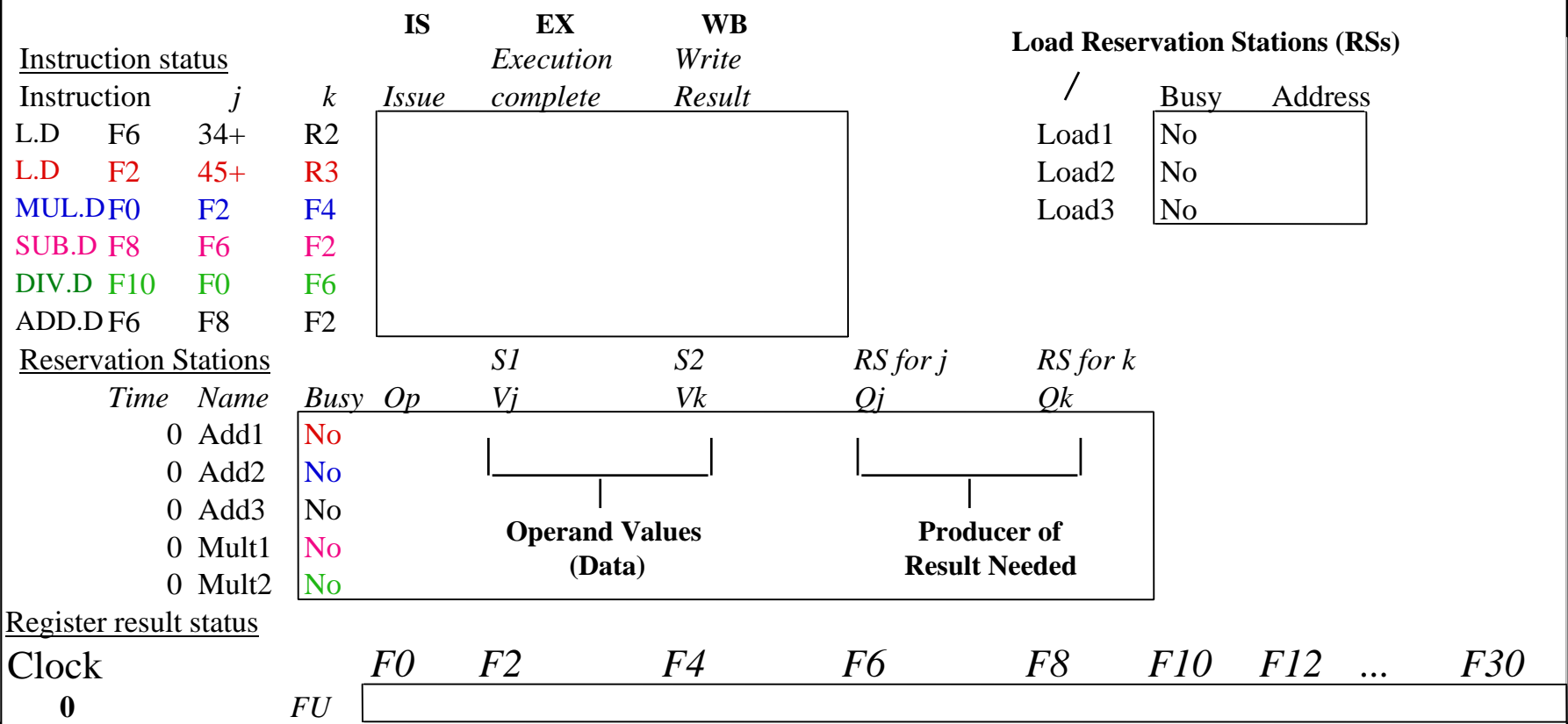
Tomasulo Example: Cycle 0

(i.e at end of cycle 0)

FP EX Cycles : Add = 2 cycles, Multiply = 10, Divide = 40

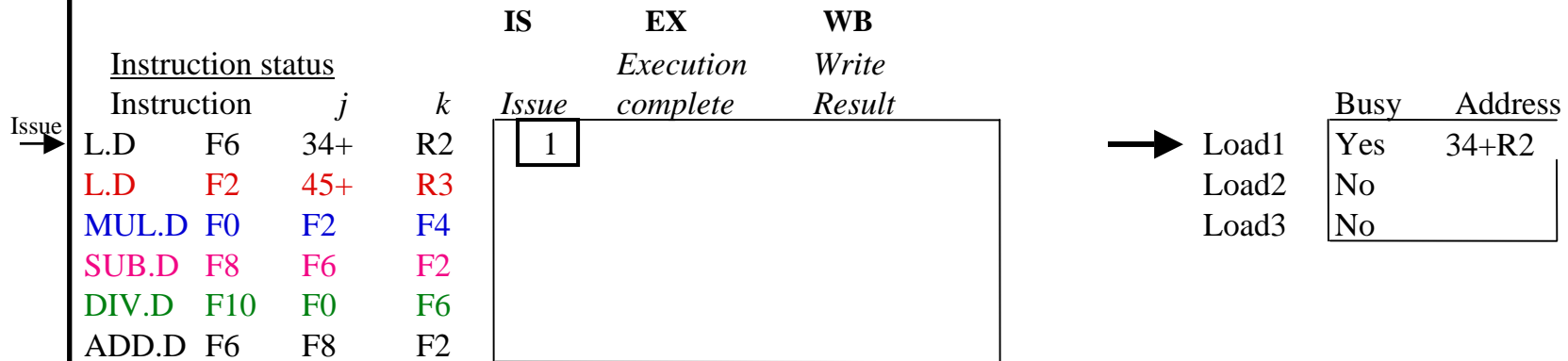


RSs



Tomasulo Example Cycle 1

FP EX Cycles : Add = 2 cycles, Multiply = 10, Divide = 40



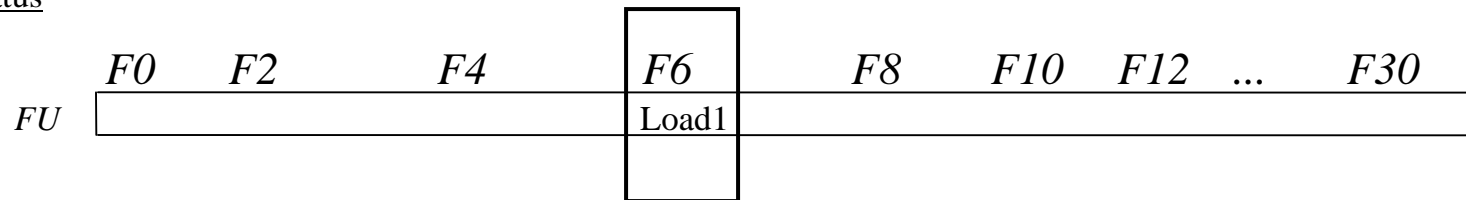
Reservation Stations

Time	Name	Busy	Op	S1 <i>Vj</i>	S2 <i>Vk</i>	RS for <i>j</i> <i>Qj</i>	RS for <i>k</i> <i>Qk</i>
0	Add1	No					
0	Add2	No					
	Add3	No					
0	Mult1	No					
0	Mult2	No					

Register result status

Clock

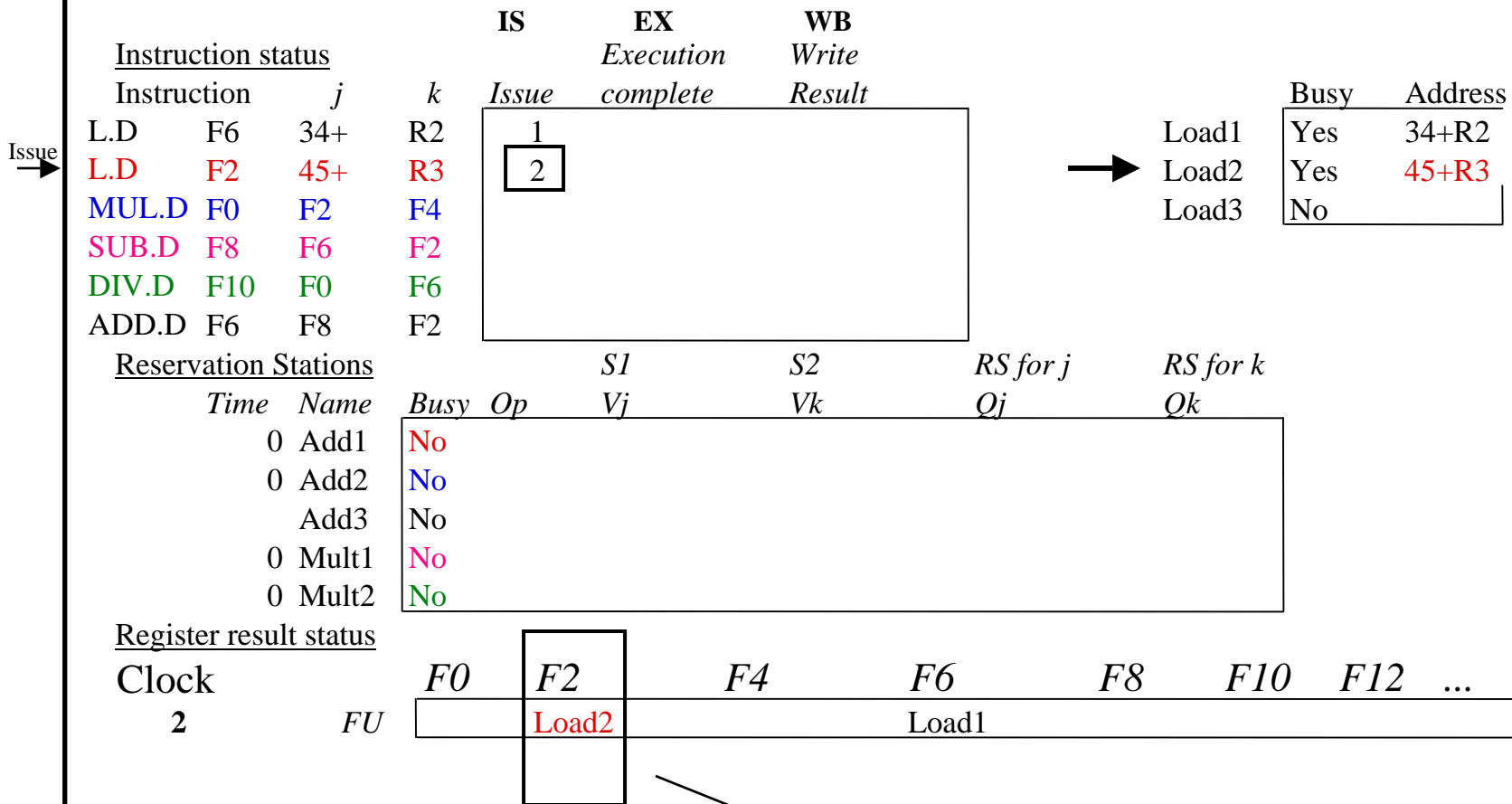
1



- Issue first load to load1 reservation station

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Tomasulo Example: Cycle 2



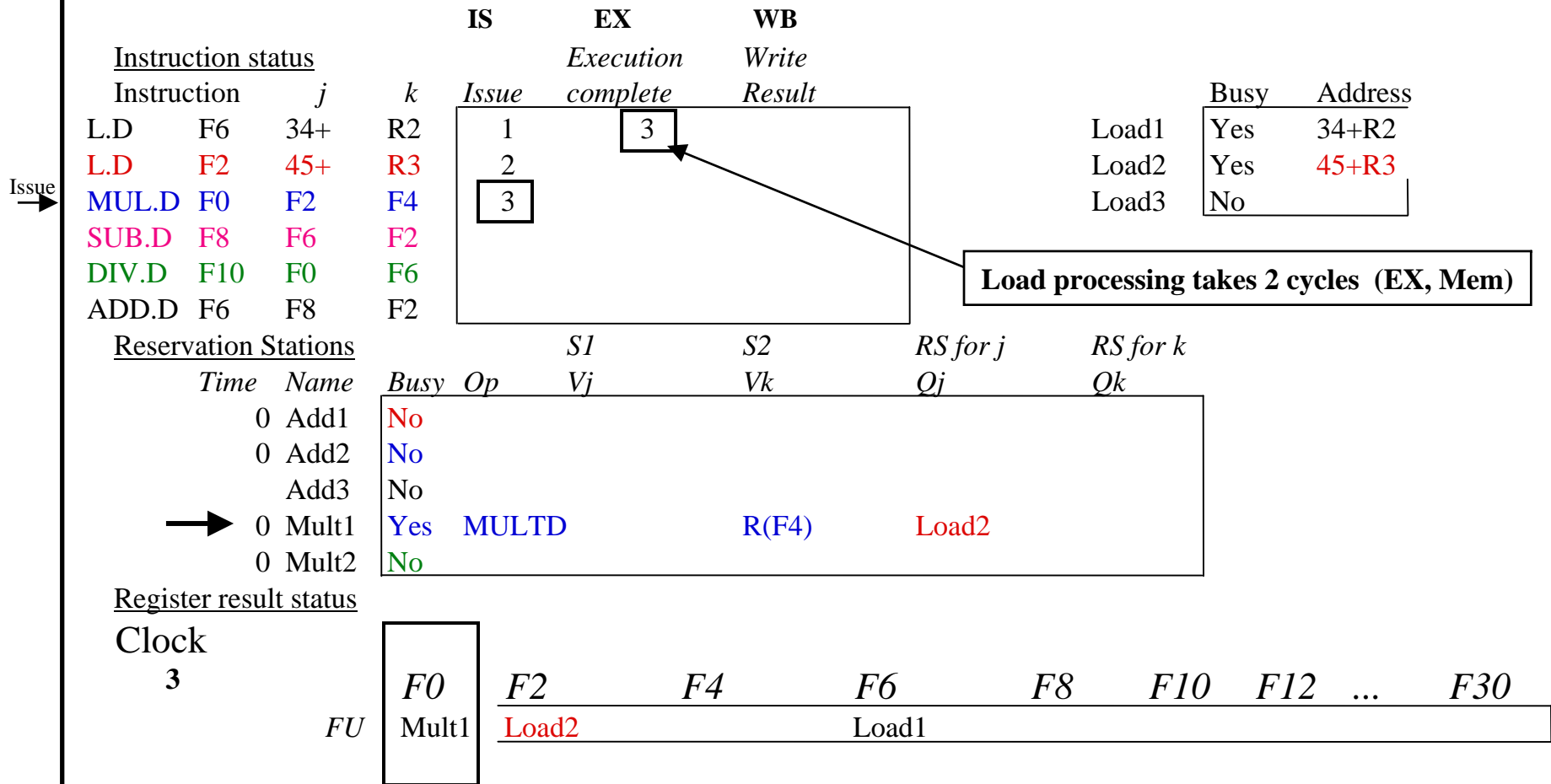
- Issue second load to load2 reservation station

Note: Unlike 6600, can have multiple loads outstanding

(CDC6600 only has one integer FU)

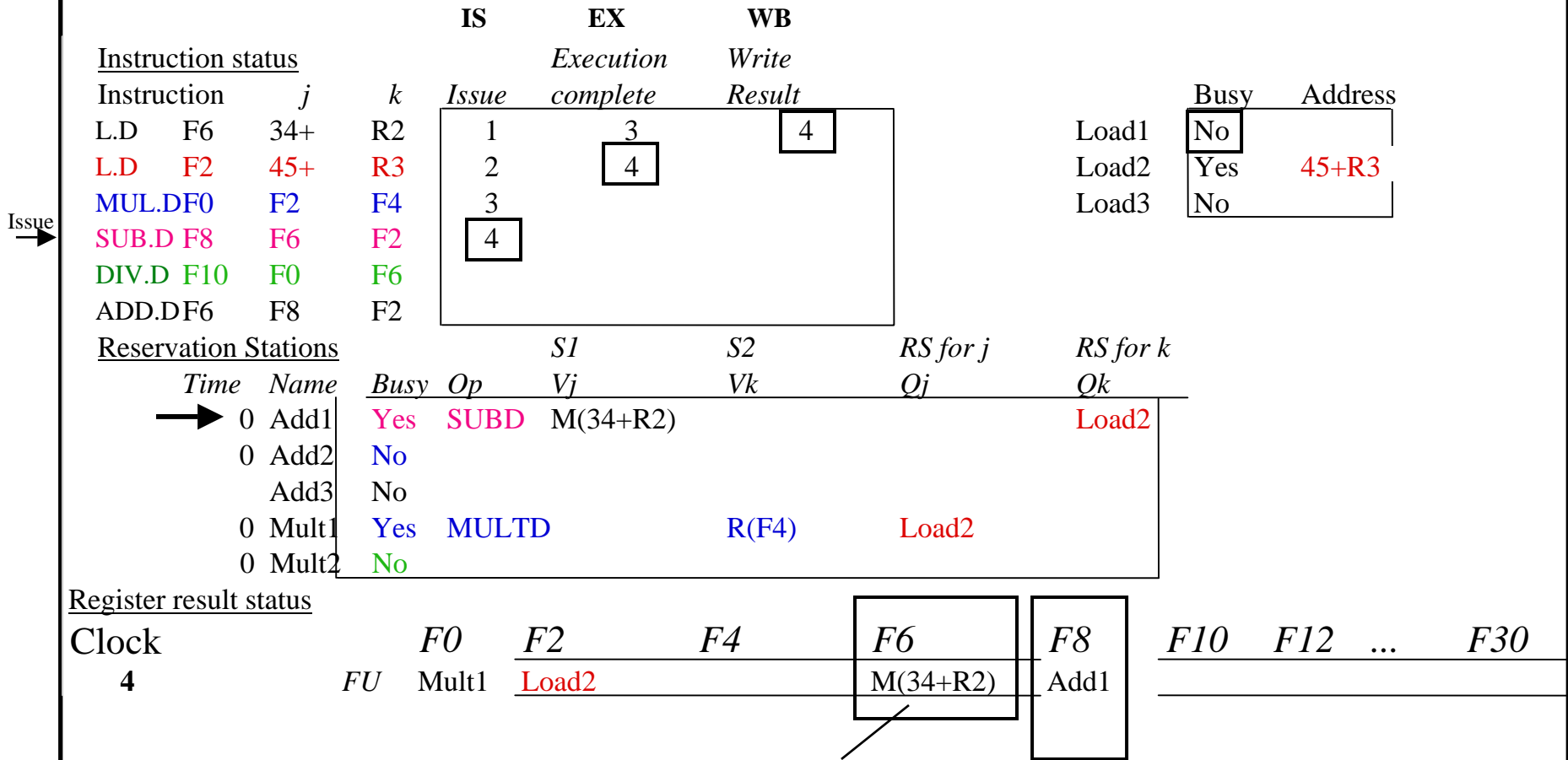
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Tomasulo Example: Cycle 3



• Issue MUL.D to reservation station Mult1

Tomasulo Example: Cycle 4



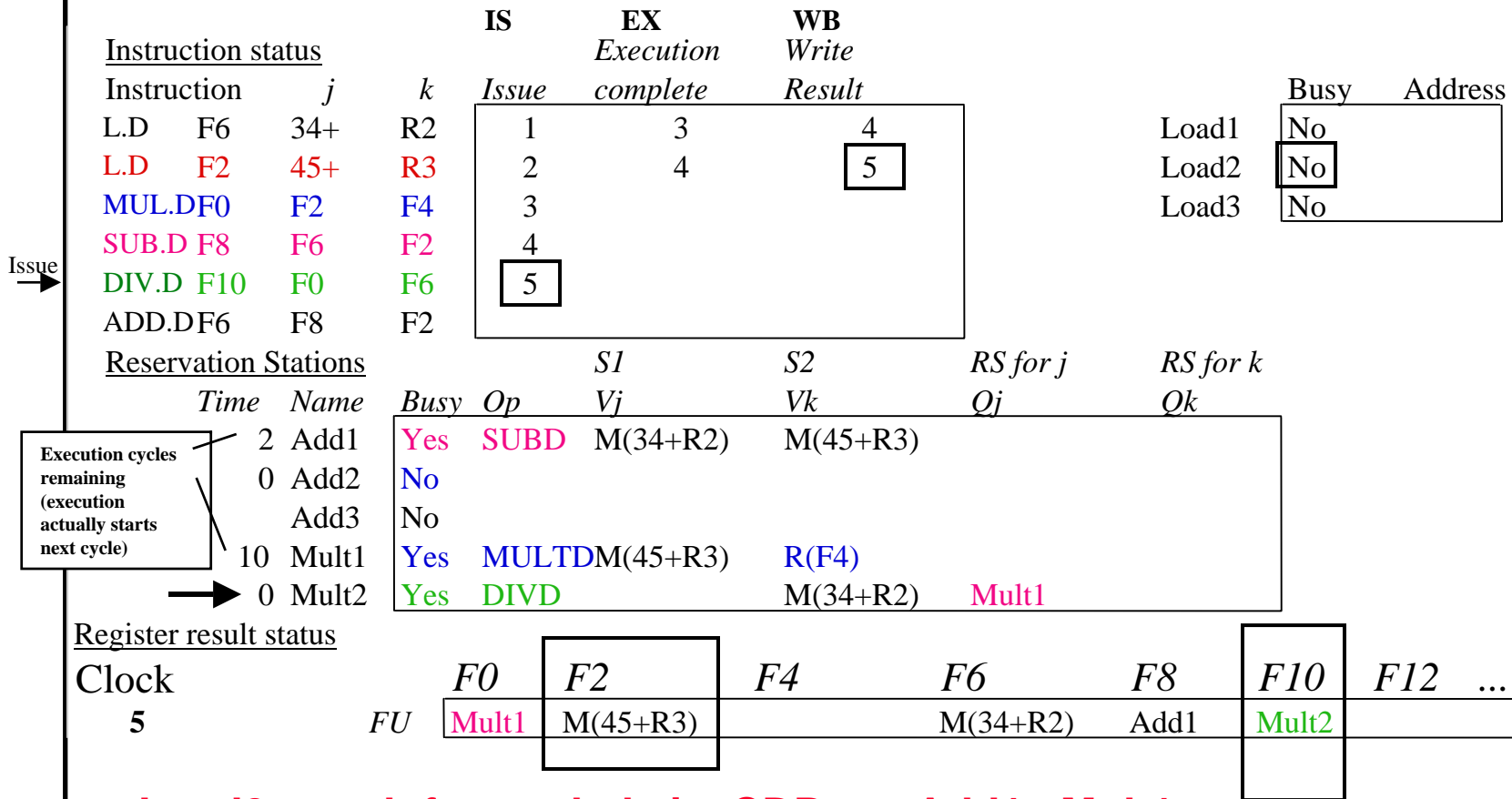
• Issue SUB.D

i.e. register F6 has the loaded value from memory

• Load2 completing; what is waiting for it?

Tomasulo Example: Cycle 5

FP EX Cycles : Add = 2 cycles, Multiply = 10, Divide = 40



- Load2 result forwarded via CDB to Add1, Mult1 (SUB.D, MUL.D execution will start execution next cycle 6)
- Issue DIV.D to Mult2 reservation station

Tomasulo Example Cycle 6

FP EX Cycles : Add = 2 cycles, Multiply = 10, Divide = 40

Instruction status			IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>	Issue	Execution complete	Write Result	Busy	Address
L.D F6	34+	R2	1	3	4	Load1	No
L.D F2	45+	R3	2	4	5	Load2	No
MUL.D F0	F2	F4	3			Load3	No
SUB.D F8	F6	F2	4				
DIV.D F10	F0	F6	5				
ADD.D F6	F8	F2	6				

Reservation Stations		<i>S1</i>	<i>S2</i>	<i>RS for j</i>	<i>RS for k</i>
Time	Name	Busy	Op	<i>Vj</i>	<i>Vk</i>
1	Add1	Yes	SUBD	M(34+R2)	M(45+R3)
0	Add2	Yes	ADDD		M(45+R3) Add1
	Add3	No			
9	Mult1	Yes	MULTD	M(45+R3)	R(F4)
0	Mult2	Yes	DIVD		M(34+R2) Mult1

Register result status		<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
Clock										
6	FU	Mult1	M(45+R3)		Add2	Add1	Mult2			

- ADD.D is issued here vs. scoreboard (in cycle 16)

Tomasulo Example: Cycle 7

FP EX Cycles : Add = 2 cycles, Multiply = 10, Divide = 40

Instruction status				IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>		Issue	Execution complete	Write Result	Busy	Address
L.D F6	34+	R2		1	3	4	Load1	No
L.D F2	45+	R3		2	4	5	Load2	No
MUL.DF0	F2	F4		3			Load3	No
SUB.D F8	F6	F2		4	7			
DIV.D F10	F0	F6		5				
ADD.DF6	F8	F2		6				

Reservation Stations		Busy	Op	S1 Vj	S2 Vk	RS for j Qj	RS for k Qk
Done executing	0 Add1	Yes	SUBD	M(34+R2)	M(45+R3)		
	0 Add2	Yes	ADDD		M(45+R3)	Add1	
	Add3	No					
	8 Mult1	Yes	MULTD	M(45+R3)	R(F4)		
	0 Mult2	Yes	DIVD		M(34+R2)	Mult1	

Register result status

Clock	F0	F2	F4	F6	F8	F10	F12	...	F30
7	FU	Mult1	M(45+R3)		Add2	Add1	Mult2		

- RS Add1 completing; what is waiting for it?

Tomasulo Example: Cycle 10

Instruction status				IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>		<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Load1	Address
L.D	F6	34+	R2	1	3	4	No	
L.D	F2	45+	R3	2	4	5	No	
MUL.D	F0	F2	F4	3			No	
SUB.D	F8	F6	F2	4	7	8		
DIV.D	F10	F0	F6	5				
ADD.D	F6	F8	F2	6	10			

Reservation Stations		<i>S1</i>	<i>S2</i>	<i>RS for j</i>	<i>RS for k</i>
Time	Name	Busy	Op	<i>Vj</i>	<i>Vk</i>
0	Add1	No			
0	Add2	Yes	ADD	M()-M()	M(45+R3)
0	Add3	No			
5	Mult1	Yes	MULT	M(45+R3)	R(F4)
0	Mult2	Yes	DIV		M(34+R2) Mult1

Done executing

Register result status

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
10	FU	Mult1	M(45+R3)		Add2	M()-M()	Mult2			

- RS Add2 (i.e. ADD.D) completed execution

Tomasulo Example: Cycle 11

<u>Instruction status</u>				IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>		<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Busy	Address
L.D	F6	34+	R2	1	3	4	Load1	No
L.D	F2	45+	R3	2	4	5	Load2	No
MUL.D	F0	F2	F4	3			Load3	No
SUB.D	F8	F6	F2	4	7	8		
DIV.D	F10	F0	F6	5				
ADD.D	F6	F8	F2	6	10	11		

<u>Reservation Stations</u>			S1	S2	RS for <i>j</i>	RS for <i>k</i>
Time	Name	Busy Op	<i>V_j</i>	<i>V_k</i>	<i>Q_j</i>	<i>Q_k</i>
0	Add1	No				
0	Add2	No				
0	Add3	No				
4	Mult1	Yes MULTD	M(45+R3)	R(F4)		
0	Mult2	Yes DIVD		M(34+R2)	Mult1	

<u>Register result status</u>		F0	F2	F4	F6	F8	F10	F12	...	F30
Clock										
11	FU	Mult1	M(45+R3)		(M-M)+M()	M()-M()	Mult2			

- Write back result of ADD.D in this cycle
(What about anti-dependence over F6 with DIV.D ?)

Tomasulo Example: Cycle 15

<u>Instruction status</u>			IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Busy	Address
L.D F6	34+	R2	1	3	4	Load1	No
L.D F2	45+	R3	2	4	5	Load2	No
MUL.D F0	F2	F4	3	15		Load3	No
SUB.D F8	F6	F2	4	7	8		
DIV.D F10	F0	F6	5				
ADD.D F6	F8	F2	6	10	11		

<u>Reservation Stations</u>		<i>Busy</i>	<i>Op</i>	<i>S1</i> <i>Vj</i>	<i>S2</i> <i>Vk</i>	<i>RS for j</i> <i>Qj</i>	<i>RS for k</i> <i>Qk</i>
Time	Name						
0	Add1	No					
0	Add2	No					
	Add3	No					
Done executing	0 Mult1	Yes	MULTDM(45+R3)		R(F4)		
	0 Mult2	Yes	DIVD		M(34+R2)	Mult1	

Register result status

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
15	FU	Mult1	M(45+R3)		(M-M)+M()	M()-M()	Mult2			

- Mult1 completed execution; what is waiting for it?

Tomasulo Example: Cycle 16

FP EX Cycles : Add = 2 cycles, Multiply = 10, Divide = 40

Instruction status			IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>	Issue	Execution complete	Write Result	Busy	Address
L.D F6	34+	R2	1	3	4	Load1	No
L.D F2	45+	R3	2	4	5	Load2	No
MUL.D F0	F2	F4	3	15	16	Load3	No
SUB.D F8	F6	F2	4	7	8		
DIV.D F10	F0	F6	5				
ADD.D F6	F8	F2	6	10	11		

Reservation Stations		Busy	Op	<i>S1</i> V _j	<i>S2</i> V _k	<i>RS for j</i> Q _j	<i>RS for k</i> Q _k
Time	Name						
0	Add1	No					
0	Add2	No					
	Add3	No					
0	Mult1	No					
40	Mult2	Yes	DIVD	M*F4	M(34+R2)		

Execution cycles remaining (execution actually starts next cycle)

Register result status

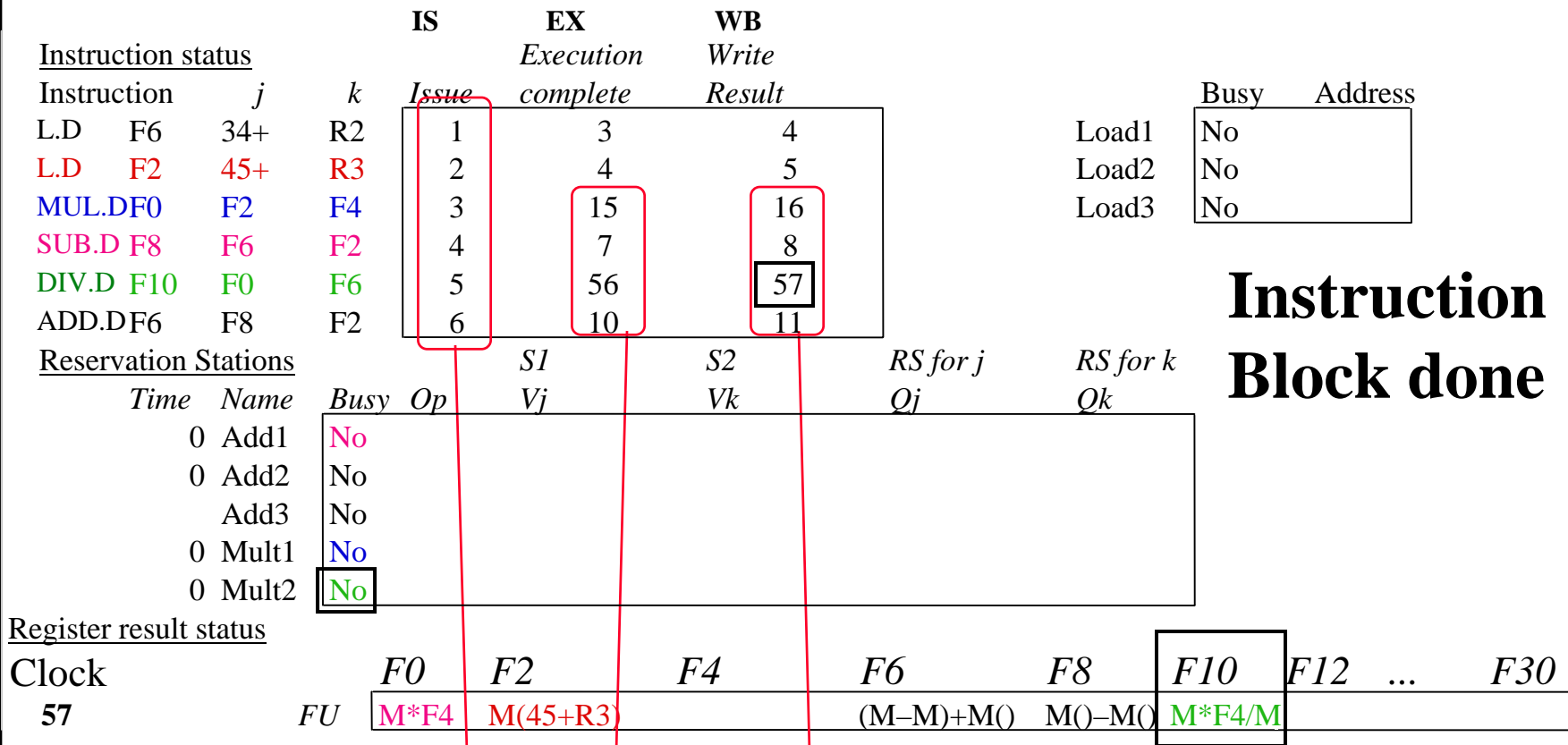
Clock	F0	F2	F4	F6	F8	F10	F12	...	F30
16	M*F4	M(45+R3)		(M-M)+M()	M()-M()	Mult2			

Only Divide instruction remains
DIV.D execution will start next cycle (17)

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Tomasulo Example: Cycle 57

(vs 62 cycles for scoreboard)



Instruction Block done

- Again we have:
 - In-order issue,
 - Out-of-order execution, completion

Tomasulo Loop Example

(Hardware-Based Version of Loop-Unrolling)

Loop: L.D	F0, 0(R1)
	↓
MUL.D	F4, F0, F2
	↓
S.D	F4, 0(R1)
DADDUI	R1, R1, # -8
BNE	R1, R2, Loop ; branch if R1 ≠ R2

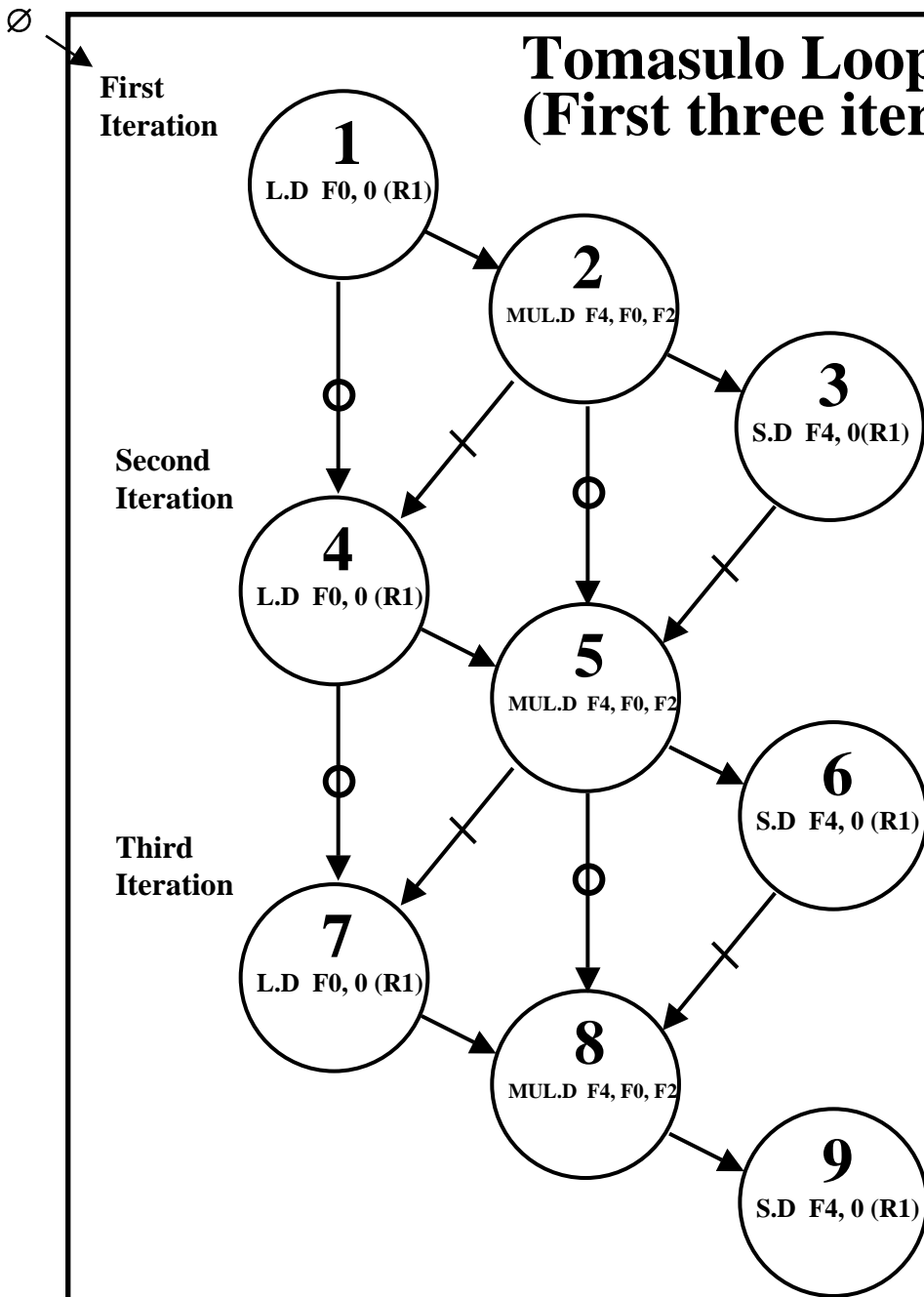
Note independent loop iterations
(the same loop used in loop unrolling example)

- Assume FP Multiply takes 4 execution clock cycles.
- Assume first load takes 8 cycles (possibly due to a cache miss), second load takes 4 cycles (cache hit). 3rd
- Assume R1 = 80 initially.
- Assume DADDUI only takes one cycle (issue) i.e. Perfect branch prediction. How?
- Assume branch resolved in issue stage (no EX or CDB write) Target?
- Assume branch is predicted taken and no branch misprediction. What if prediction Is wrong?
- No branch delay slot is used in this example.
- Stores take 4 cycles (ex, mem) and do not write on CDB
- We'll go over the execution to complete first two loop iterations.

Expanded from loop example in Chapter 2.5 (Third Edition Chapter 3.3)

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Tomasulo Loop Example Dependency Graph (First three iterations shown)



Example Code

First Iteration	{	1	L.D	F0, 0 (R1)
		2	MUL.D	F4, F0, F2
		3	S.D	F4, 0(R1)
Second Iteration	{	4	L.D	F0, 0(R1)
		5	MUL.D	F4, F0, F2
		6	S.D	F4, 0(R1)
Third Iteration	{	7	L.D	F0, 0(R1)
		8	MUL.D	F4, F0, F2
		9	S.D	F4, 0(R1)

Loop maintenance (DADDUI)
and branches (BNE) not shown

Name dependencies between iteration 3 instructions
and iteration 1 instructions are not shown in graph

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Loop Example Cycle 0

(i.e at end of cycle 0)

<u>Instruction status</u>				IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>complete</i>	<i>Result</i>	Busy	Address
L.D F0	0	R1	1				No	
MUL.D F4	F0	F2	1				No	
S.D F4	0	R1	1				No	Qi
L.D F0	0	R1	2				No	
MUL.D F4	F0	F2	2				No	
S.D F4	0	R1	2				No	

Reservation Stations

Time	Name	Busy	Op	<i>S1</i> <i>Vj</i>	<i>S2</i> <i>Vk</i>	<i>RS for j</i> <i>Qj</i>	<i>RS for k</i> <i>Qk</i>	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4,F0,F2
0	Add3	No						S.D F4, 0(R1)
0	Mult1	No						DADDUI R1, R1, #-8
0	Mult2	No						BNE R1,R2,loop

Operand Values
(Data)

Producer of
Result Needed

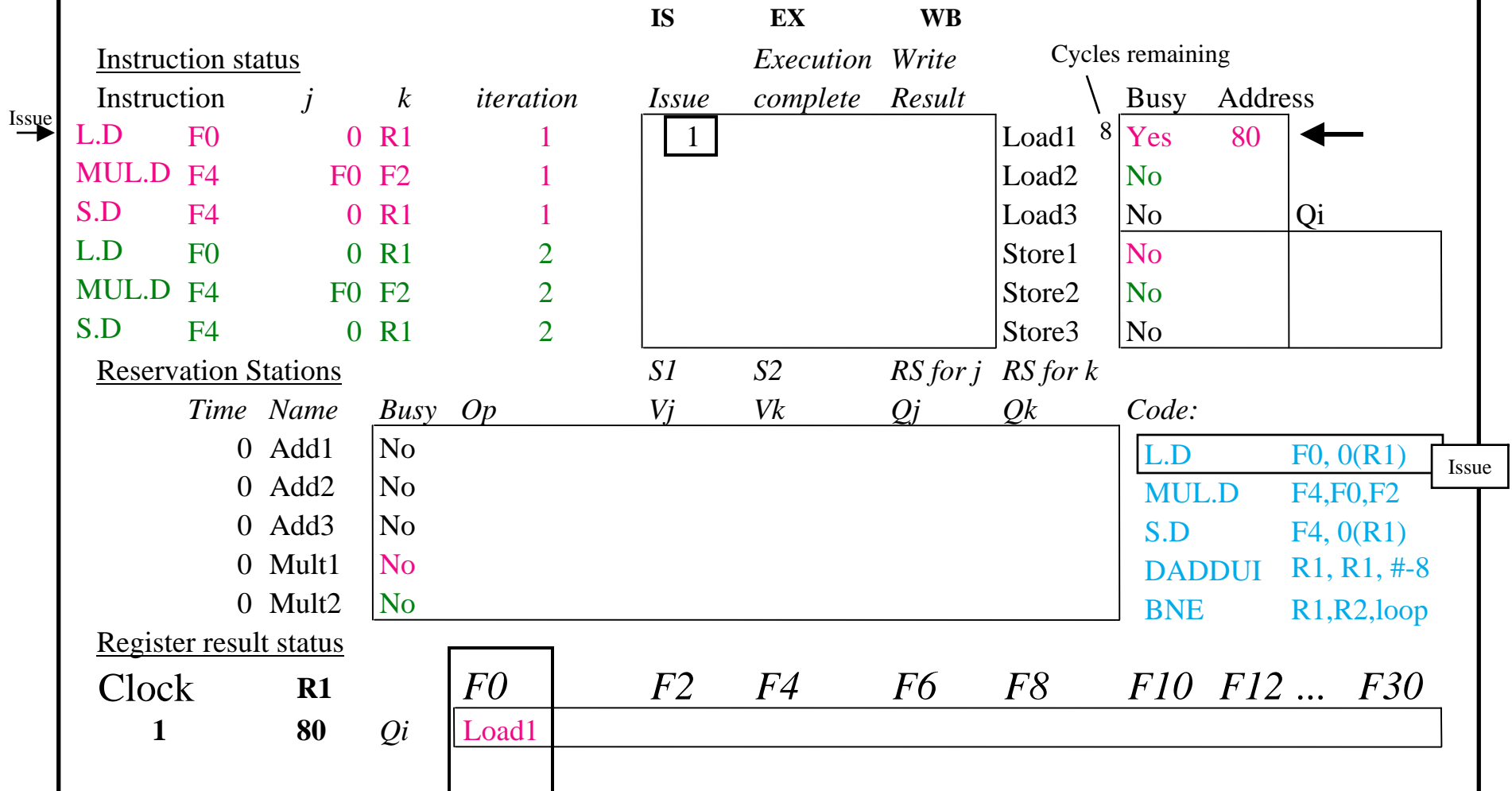
Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
0	80	Qi								



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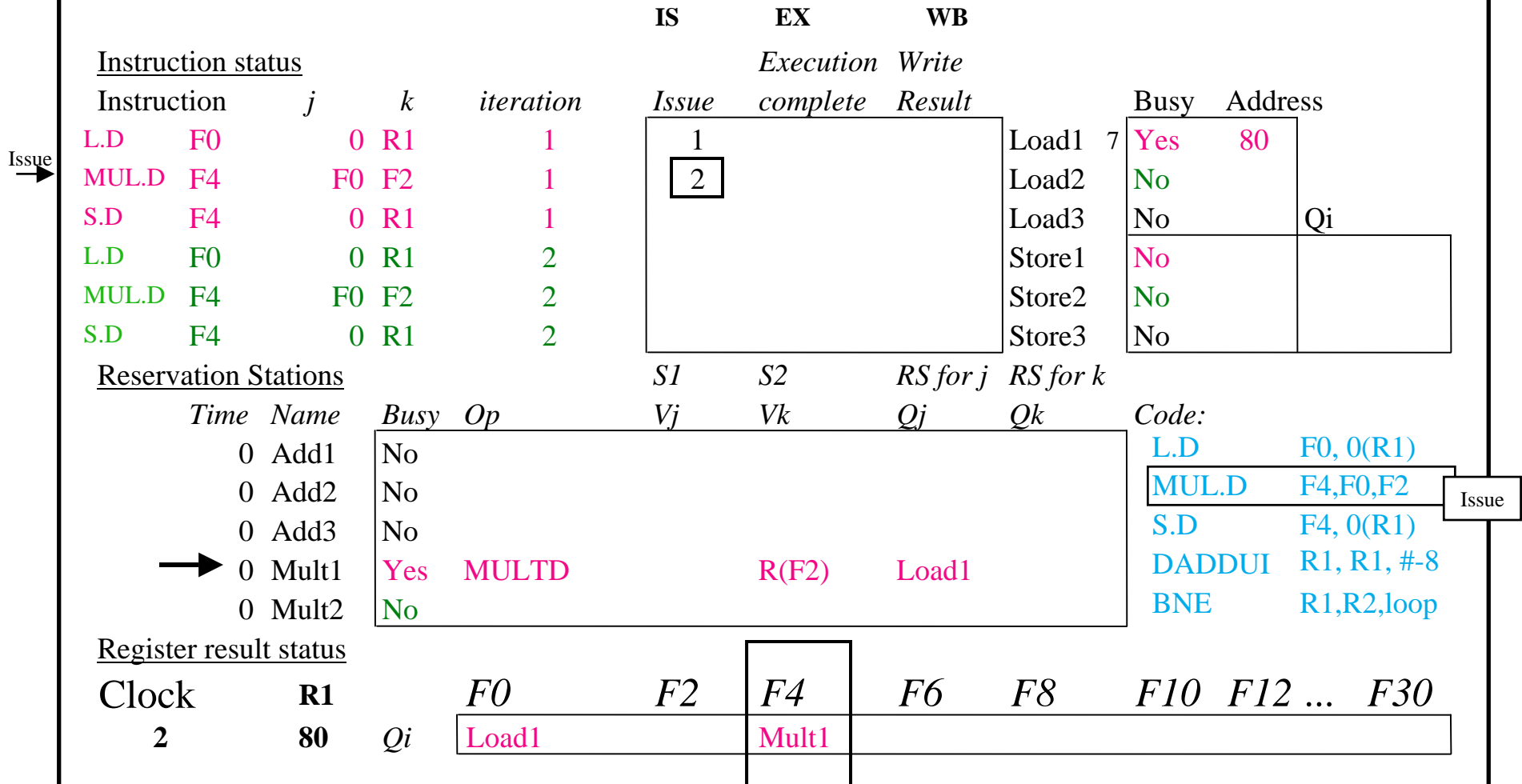
Loop Example Cycle 1



First L.D issues, takes 8 cycles to complete execution (including mem access)

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Loop Example Cycle 2



First MUL.D issues, wait on first L.D (Load1) to write on CDB

Loop Example Cycle 3

<u>Instruction status</u>				IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Busy	Address
L.D F0	0	R1	1	1		Load1	6 Yes	80
MUL.D F4	F0	F2	1	2		Load2	No	
S.D F4	0	R1	1	3		Load3	No	Qi
L.D F0	0	R1	2			Store1	Yes	80
MUL.D F4	F0	F2	2			Store2	No	
S.D F4	0	R1	2			Store3	No	

Issue →

←

Reservation Stations

Time	Name	Busy	Op	<i>S1</i> <i>Vj</i>	<i>S2</i> <i>Vk</i>	<i>RS for j</i> <i>Qj</i>	<i>RS for k</i> <i>Qk</i>	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
0	Mult1	Yes	MULTD		R(F2)	Load1		DADDUI R1, R1, #-8
0	Mult2	No						BNE R1, R2, loop

Issue

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
3	80	Qi	Load1	Mult1						

First S.D issues, wait on first MUL.D (Mult1) to write on CDB

Loop Example Cycle 4

<u>Instruction status</u>				IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Busy	Address
L.D F0	0	R1	1	1		Load1	Yes	80
MUL.D F4	F0	F2	1	2		Load2	No	
S.D F4	0	R1	1	3		Load3	No	Qi
L.D F0	0	R1	2			Store1	Yes	80
MUL.D F4	F0	F2	2			Store2	No	
S.D F4	0	R1	2			Store3	No	

Reservation Stations

Time	Name	Busy	Op	<i>S1</i> <i>Vj</i>	<i>S2</i> <i>Vk</i>	<i>RS for j</i> <i>Qj</i>	<i>RS for k</i> <i>Qk</i>	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
0	Mult1	Yes	MULTD		R(F2)	Load1		DADDUI R1, R1, #-8
0	Mult2	No						BNE R1, R2, loop

Issue

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
4	72	Qi	Load1			Mult1				

First DADDUI issues (not shown)

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Loop Example Cycle 5

<u>Instruction status</u>				IS	EX	WB			
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Busy	Address	
L.D F0	0	R1	1	1			Yes	80	
MUL.D F4	F0	F2	1	2			No		
S.D F4	0	R1	1	3			No		Qi
L.D F0	0	R1	2				Yes	80	Mult1
MUL.D F4	F0	F2	2				No		
S.D F4	0	R1	2				No		

Reservation Stations

Time	Name	Busy	Op	S1 <i>Vj</i>	S2 <i>Vk</i>	RS for <i>j</i> <i>Qj</i>	RS for <i>k</i> <i>Qk</i>	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
0	Mult1	Yes	MULTD		R(F2)	Load1		DADDUI R1, R1, #-8
0	Mult2	No						BNE R1, R2, loop

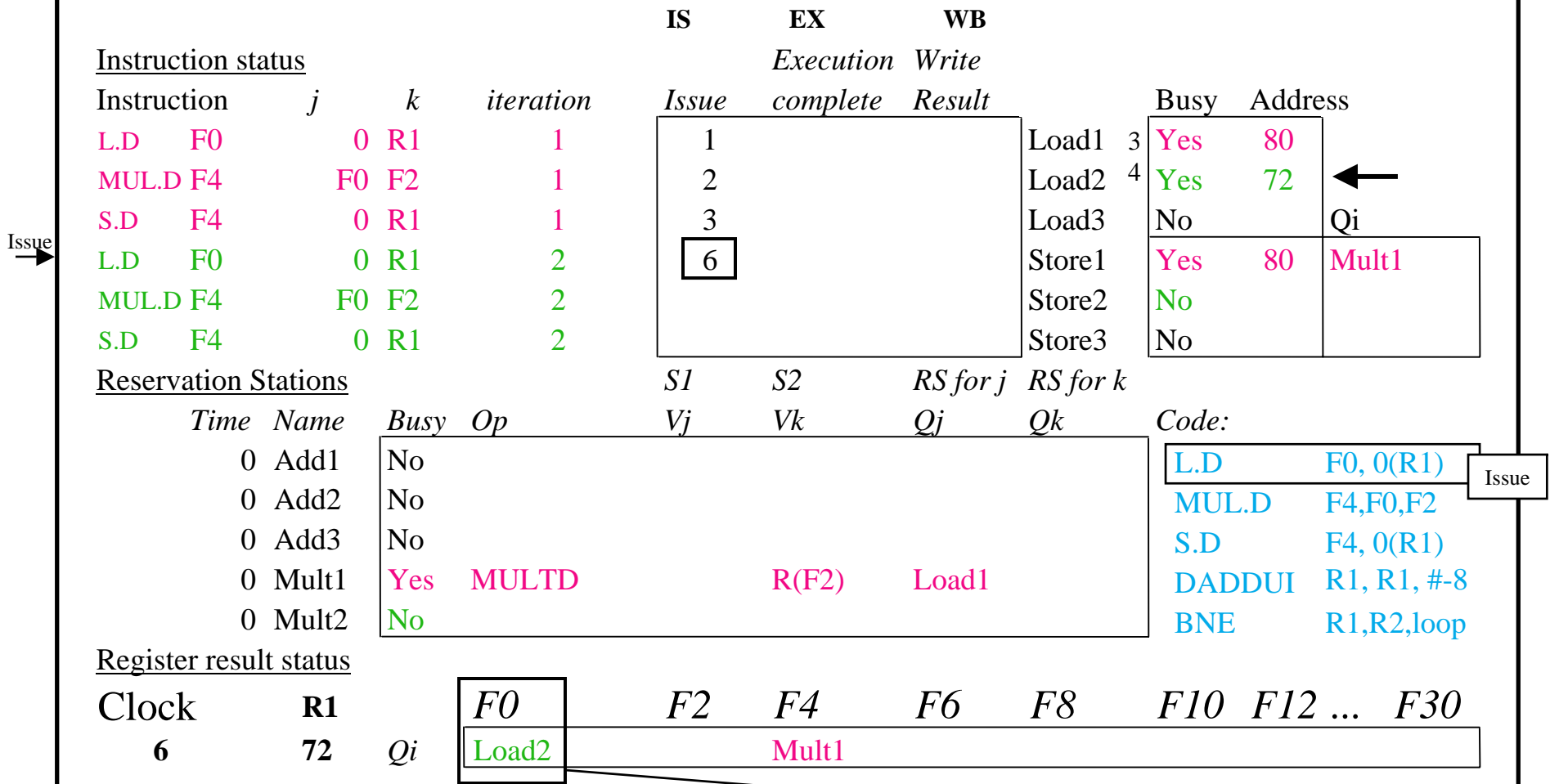
Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
5	72	Qi	Load1							
				Mult1						

First BNE issues (not shown), assumed predicted taken

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Loop Example Cycle 6



- Second L.D. issues (will take four ex cycles) Note: F0 never sees Load1 result
- WAW between first and second L.D on F0 eliminated by register renaming

Loop Example Cycle 7

<u>Instruction status</u>				IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Busy	Address
L.D F0	0	R1	1	1		Load1	2 Yes	80
MUL.D F4	F0	F2	1	2		Load2	3 Yes	72
S.D F4	0	R1	1	3		Load3	No	Qi
L.D F0	0	R1	2	6		Store1	Yes	80
MUL.D F4	F0	F2	2	7		Store2	No	Mult1
S.D F4	0	R1	2			Store3	No	

<u>Reservation Stations</u>				<i>S1</i>	<i>S2</i>	<i>RS for j</i>	<i>RS for k</i>	
<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>Vj</i>	<i>Vk</i>	<i>Qj</i>	<i>Qk</i>	<i>Code:</i>
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
0	Mult1	Yes	MULTD		R(F2)	Load1		DADDUI R1, R1, #-8
0	Mult2	Yes	MULTD		R(F2)	Load2		BNE R1, R2, loop

<u>Register result status</u>																														
Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30																				
7	72	Qi	Load2	Mult2																										

- Second MUL.D issues (to RS Mult2) Note: F4 never sees Mult1 result
- WAW between first and second MUL.D on F4 eliminated by register renaming

Loop Example Cycle 8

<u>Instruction status</u>				IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Busy	Address
L.D F0	0	R1	1	1		Load1	1 Yes	80
MUL.D F4	F0	F2	1	2		Load2	2 Yes	72
S.D F4	0	R1	1	3		Load3	No	Qi
L.D F0	0	R1	2	6		Store1	Yes	80
MUL.D F4	F0	F2	2	7		Store2	Yes	72
S.D F4	0	R1	2	8		Store3	No	

<u>Reservation Stations</u>				<i>S1</i>	<i>S2</i>	<i>RS for j</i>	<i>RS for k</i>		
<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>Vj</i>	<i>Vk</i>	<i>Qj</i>	<i>Qk</i>	<i>Code:</i>	
0	Add1	No						L.D	F0, 0(R1)
0	Add2	No						MUL.D	F4, F0, F2
0	Add3	No						S.D	F4, 0(R1)
0	Mult1	Yes	MULTD		R(F2)	Load1		DADDUI	R1, R1, #-8
0	Mult2	Yes	MULTD		R(F2)	Load2		BNE	R1, R2, loop

<u>Register result status</u>											
Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30	
8	72	Qi	Load2	Mult2							

- Second S.D issues (to RS Store2)

Loop Example Cycle 9

<u>Instruction status</u>				IS	EX	WB			
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>complete</i>	<i>Result</i>	Load1	Load2	Load3
L.D	F0	0 R1	1	1	9		0	1	
MUL.D	F4	F0 F2	1	2					
S.D	F4	0 R1	1	3					
L.D	F0	0 R1	2	6					
MUL.D	F4	F0 F2	2	7					
S.D	F4	0 R1	2	8					

<u>Reservation Stations</u>				<i>S1</i>	<i>S2</i>	<i>RS for j</i>	<i>RS for k</i>	<i>Code:</i>
<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>Vj</i>	<i>Vk</i>	<i>Qj</i>	<i>Qk</i>	
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4,F0,F2
0	Add3	No						S.D F4, 0(R1)
0	Mult1	Yes	MULTD		R(F2)	Load1		DADDUI R1, R1, #-8
0	Mult2	Yes	MULTD		R(F2)	Load2		BNE R1,R2,loop

<u>Register result status</u>		<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
Clock	R1									
9	64	Qi	Load2	Mult2						

- Issue second DADDUI (not shown)
- Load1 completing; what is waiting for it?

Loop Example Cycle 10

<u>Instruction status</u>				IS	EX	WB			
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>complete</i>	<i>Result</i>		Busy	Address
L.D F0	0	R1	1	1	9	10	Load1	No	
MUL.D F4	F0	F2	1	2			Load2	Yes	72
S.D F4	0	R1	1	3			Load3	No	Qi
L.D F0	0	R1	2	6	10		Store1	Yes	80
MUL.D F4	F0	F2	2	7			Store2	Yes	72
S.D F4	0	R1	2	8			Store3	No	

Second Load EX Done

Reservation Stations

Time Name Busy Op S1 S2 RS for j RS for k Code:

Execution cycles remaining (execution actually starts next cycle)

Time	Name	Busy	Op	Vj	Vk	Qj	Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
4	Mult1	Yes	MULTD	M(80)	R(F2)		
0	Mult2	Yes	MULTD		R(F2)	Load2	

L.D F0, 0(R1)
 MUL.D F4, F0, F2
 S.D F4, 0(R1)
 DADDUI R1, R1, #-8
 BNE R1, R2, loop

Issue

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
10	64	Qi	Load2	Mult2						

- Load1 result forwarded via CDB to Mult1, execution will start next cycle 11
- Issue second BNE (not shown)
- Load2 completing; what is waiting for it?

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Loop Example Cycle 11

<u>Instruction status</u>				IS	EX	WB			
				Issue	Execution complete	Write Result	Busy	Address	
Instruction	<i>j</i>	<i>k</i>	iteration						
L.D F0	0	R1	1	1	9	10	No		
MUL.D F4	F0	F2	1	2			No		
S.D F4	0	R1	1	3			Yes	64	Qi ←
L.D F0	0	R1	2	6	10	11	Yes	80	Mult1
MUL.D F4	F0	F2	2	7			Yes	72	Mult2
S.D F4	0	R1	2	8			No		

<u>Reservation Stations</u>				<i>S1</i>	<i>S2</i>	<i>RS for j</i>	<i>RS for k</i>		
Time	Name	Busy	Op	<i>Vj</i>	<i>Vk</i>	<i>Qj</i>	<i>Qk</i>	Code:	
0	Add1	No						L.D	F0, 0(R1)
0	Add2	No						MUL.D	F4, F0, F2
0	Add3	No						S.D	F4, 0(R1)
3	Mult1	Yes	MULTD	M(80)	R(F2)			DADDUI	R1, R1, #-8
4	Mult2	Yes	MULTD	M(72)	R(F2)			BNE	R1, R2, loop

Execution cycles remaining (execution actually starts next cycle)

<u>Register result status</u>			<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
Clock	R1										
11	64	Qi	Load3		Mult2						

Load2 result forwarded via CDB to Mult2, execution will start next cycle 12
Third iteration L.D. issues (to RS Load3)

Loop Example Cycle 12

<u>Instruction status</u>				IS	EX	WB			
				<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Busy	Address	
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>						
L.D F0	0	R1	1	1	9	10	Load1	No	
MUL.D F4	F0	F2	1	2			Load2	No	
S.D F4	0	R1	1	3			Load3	Yes	64 Qi
L.D F0	0	R1	2	6	10	11	Store1	Yes	80 Mult1
MUL.D F4	F0	F2	2	7			Store2	Yes	72 Mult2
S.D F4	0	R1	2	8			Store3	No	

<u>Reservation Stations</u>				<i>S1</i>	<i>S2</i>	<i>RS for j</i>	<i>RS for k</i>		
<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>Vj</i>	<i>Vk</i>	<i>Qj</i>	<i>Qk</i>	<i>Code:</i>	
0	Add1	No						L.D	F0, 0(R1)
0	Add2	No						MUL.D	F4, F0, F2 – Issue?
0	Add3	No						S.D	F4, 0(R1)
2	Mult1	Yes	MULTD	M(80)	R(F2)			DADDUI	R1, R1, #-8
3	Mult2	Yes	MULTD	M(72)	R(F2)			BNE	R1, R2, loop

<u>Register result status</u>											
Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30	
12	64 Qi	Load3		Mult2							

Issue third iteration MUL.D ?

Loop Example Cycle 13

<u>Instruction status</u>				IS	EX	WB			
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>	Load	Busy	Address
L.D F0	0	R1	1	1	9	10	Load1	No	
MUL.D F4	F0	F2	1	2			Load2	No	
S.D F4	0	R1	1	3			Load3	Yes	64 Qi
L.D F0	0	R1	2	6	10	11	Store1	Yes	80 Mult1
MUL.D F4	F0	F2	2	7			Store2	Yes	72 Mult2
S.D F4	0	R1	2	8			Store3	No	

<u>Reservation Stations</u>				<i>S1</i>	<i>S2</i>	<i>RS for j</i>	<i>RS for k</i>		
<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>Vj</i>	<i>Vk</i>	<i>Qj</i>	<i>Qk</i>	<i>Code:</i>	
0	Add1	No						L.D	F0, 0(R1)
0	Add2	No						MUL.D	F4, F0, F2
0	Add3	No						S.D	F4, 0(R1)
1	Mult1	Yes	MULTD	M(80)	R(F2)			DADDUI	R1, R1, #-8
2	Mult2	Yes	MULTD	M(72)	R(F2)			BNE	R1, R2, loop

<u>Register result status</u>											
Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30	
13	64 Qi	Load3		Mult2							

Issue third iteration MUL.D, S.D ?

Loop Example Cycle 14

<u>Instruction status</u>				IS	EX	WB		Busy	Address
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>			
L.D F0	0	R1	1	1	9	10	Load1	No	
MUL.D F4	F0	F2	1	2	14		Load2	No	
S.D F4	0	R1	1	3			Load3	Yes	64 Qi
L.D F0	0	R1	2	6	10	11	Store1	Yes	80 Mult1
MUL.D F4	F0	F2	2	7			Store2	Yes	72 Mult2
S.D F4	0	R1	2	8			Store3	No	

Reservation Stations

Time	Name	Busy	Op	S1 <i>Vj</i>	S2 <i>Vk</i>	RS for <i>j</i> <i>Qj</i>	RS for <i>k</i> <i>Qk</i>	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
0	Mult1	Yes	MULTD	M(80)	R(F2)			DADDUI R1, R1, #-8
1	Mult2	Yes	MULTD	M(72)	R(F2)			BNE R1, R2, loop

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
14	64 Qi	Load3		Mult2						

- Mult1 completing; what is waiting for it?

Loop Example Cycle 15

Instruction status				IS	EX	WB	Third Load EX Done		
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>complete</i>	<i>Result</i>	Load1	Busy	Address
L.D F0	0	R1	1	1	9	10	Load1	No	
MUL.D F4	F0	F2	1	2	14	15	Load2	No	
S.D F4	0	R1	1	3			Load3	Yes	64 Qi
L.D F0	0	R1	2	6	10	11	Store1	Yes	80 M(80)*R(F2)
MUL.D F4	F0	F2	2	7	15		Store2	Yes	72 Mult2
S.D F4	0	R1	2	8			Store3	No	

Reservation Stations

Time	Name	Busy	Op	<i>S1</i> <i>Vj</i>	<i>S2</i> <i>Vk</i>	<i>RS for j</i> <i>Qj</i>	<i>RS for k</i> <i>Qk</i>	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2- Issue?
0	Add3	No						S.D F4, 0(R1)
0	Mult1	No						DADDUI R1, R1, #-8
0	Mult2	Yes	MULTD	M(72)	R(F2)			BNE R1, R2, loop

Available by end of this cycle

EX Done

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
15	64 Qi	Load3		Mult2						

- Mult2 completing; what is waiting for it? Issue third multiply?
- Third iteration L.D done execution

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Loop Example Cycle 16

<u>Instruction status</u>				IS	EX	WB		Busy	Address
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>			
L.D F0	0	R1	1	1	9	10	Load1	No	
MUL.D F4	F0	F2	1	2	14	15	Load2	No	
S.D F4	0	R1	1	3			Load3	Yes	Qi
L.D F0	0	R1	2	6	10	11	Store1	3 Yes	80
MUL.D F4	F0	F2	2	7	15	16	Store2	4 Yes	72
S.D F4	0	R1	2	8			Store3	No	

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for j Qj	RS for k Qk	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
→ 0	Mult1	Yes	MULTD		R(F2)	Load3		DADDUI R1, R1, #-8
0	Mult2	No						BNE R1, R2, loop

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
16	64	Qi	Load3	Mult1						

Issue third iteration MUL.D (to RS Mult1)

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Loop Example Cycle 17

<u>Instruction status</u>				IS	EX	WB		Busy	Address
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>			
L.D F0	0	R1	1	1	9	10	Load1	No	
MUL.D F4	F0	F2	1	2	14	15	Load2	No	
S.D F4	0	R1	1	3			Load3	No	Qi
L.D F0	0	R1	2	6	10	11	Store1	2 Yes	80
MUL.D F4	F0	F2	2	7	15	16	Store2	3 Yes	72
S.D F4	0	R1	2	8			Store3	Yes	64
									M(80)*R(F2)
									M(72)*R(72)
									Mult1

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for j Qj	RS for k Qk	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
4	Mult1	Yes	MULTD	M(64)	R(F2)			DADDUI R1, R1, #-8
0	Mult2	No						BNE R1, R2, loop

Execution cycles remaining (execution actually starts next cycle) Delayed one cycle

```

L.D      F0, 0(R1)
MUL.D   F4, F0, F2
S.D     F4, 0(R1)
DADDUI  R1, R1, #-8
BNE     R1, R2, loop
    
```

Issue

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
17	64	Qi		Mult1						

**Third iteration L.D writes on CDB (delayed one cycle due to CDB conflict)
Issue third iteration S.D (to RS Store3)**

Loop Example Cycle 18

<u>Instruction status</u>				IS	EX	WB		Busy	Address
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>complete</i>	<i>Result</i>			
L.D F0	0	R1	1	1	9	10	Load1	No	
MUL.D F4	F0	F2	1	2	14	15	Load2	No	
S.D F4	0	R1	1	3			Load3	No	Qi
L.D F0	0	R1	2	6	10	11	Store1	1 Yes	80 M(80)*R(F2)
MUL.D F4	F0	F2	2	7	15	16	Store2	2 Yes	72 M(72)*R(72)
S.D F4	0	R1	2	8			Store3	Yes	64 Mult1

Reservation Stations

Time	Name	Busy	Op	<i>S1</i> <i>Vj</i>	<i>S2</i> <i>Vk</i>	<i>RS for j</i> <i>Qj</i>	<i>RS for k</i> <i>Qk</i>	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4,F0,F2
0	Add3	No						S.D F4, 0(R1)
3	Mult1	Yes	MULTD	M(64)	R(F2)			DADDUI R1, R1, #-8
0	Mult2	No						BNE R1,R2,loop

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
18	56	Qi	Mult1							

Issue third iteration DADDUI

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(First Loop Iteration Done)

Loop Example Cycle 19

<u>Instruction status</u>				IS	EX	WB		Busy	Address
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>Execution complete</i>	<i>Write Result</i>			
L.D F0	0	R1	1	1	9	10	Load1	No	
MUL.D F4	F0	F2	1	2	14	15	Load2	No	
S.D F4	0	R1	1	3	19		Load3	No	Qi
L.D F0	0	R1	2	6	10	11	Store1	0 No	
MUL.D F4	F0	F2	2	7	15	16	Store2	1 Yes	72 M(72)*R(72)
S.D F4	0	R1	2	8			Store3	Yes	64 Mult1

First Store Done

Reservation Stations

Time	Name	Busy	Op	S1 <i>Vj</i>	S2 <i>Vk</i>	RS for <i>j</i> <i>Qj</i>	RS for <i>k</i> <i>Qk</i>	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
2	Mult1	Yes	MULTD	M(64)	R(F2)			DADDUI R1, R1, #-8
0	Mult2	No						BNE R1, R2, loop

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
19	56	Qi								

First S.D done (No write on CDB for stores) First loop iteration done
Issue third iteration BNE

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(First Two Loop Iterations Done)

Loop Example Cycle 20

<u>Instruction status</u>				IS	EX	WB		
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>complete</i>	<i>Result</i>	Busy	Address
L.D F0	0	R1	1	1	9	10	Load1	4 Yes 54
MUL.D F4	F0	F2	1	2	14	15	Load2	No
S.D F4	0	R1	1	3	19		Load3	No Qi
L.D F0	0	R1	2	6	10	11	Store1	No
MUL.D F4	F0	F2	2	7	15	16	Store2	0 No
S.D F4	0	R1	2	8	20		Store3	Yes 64 Mult1

<u>Reservation Stations</u>				<i>S1</i>	<i>S2</i>	<i>RS for j</i>	<i>RS for k</i>	
<i>Time</i>	<i>Name</i>	<i>Busy</i>	<i>Op</i>	<i>Vj</i>	<i>Vk</i>	<i>Qj</i>	<i>Qk</i>	<i>Code:</i>
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
1	Mult1	Yes	MULTD	M(64)	R(F2)			DADDUI R1, R1, #-8
0	Mult2	No						BNE R1, R2, loop

<u>Register result status</u>														
Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30				
20	56	Qi	Load1	Mult1										

Second S.D done (No write on CDB for stores) Second loop iteration done
Issue fourth iteration L.D (to RS Load1)

Loop Example Cycle 21

<u>Instruction status</u>				IS	EX	WB			
				<i>Execution Write</i>					
Instruction	<i>j</i>	<i>k</i>	<i>iteration</i>	<i>Issue</i>	<i>complete</i>	<i>Result</i>	Busy	Address	
L.D F0	0	R1	1	1	9	10	Load1	3 Yes	54
MUL.D F4	F0	F2	1	2	14	15	Load2	No	
S.D F4	0	R1	1	3	19		Load3	No	Qi
L.D F0	0	R1	2	6	10	11	Store1	No	
MUL.D F4	F0	F2	2	7	15	16	Store2	No	
S.D F4	0	R1	2	8	20		Store3	Yes	64 Mult1

Reservation Stations

Time	Name	Busy	Op	<i>S1</i> <i>Vj</i>	<i>S2</i> <i>Vk</i>	<i>RS for j</i> <i>Qj</i>	<i>RS for k</i> <i>Qk</i>	Code:
0	Add1	No						L.D F0, 0(R1)
0	Add2	No						MUL.D F4, F0, F2
0	Add3	No						S.D F4, 0(R1)
0	Mult1	Yes	MULTD	M(64)	R(F2)			DADDUI R1, R1, #-8
0	Mult2	Yes	MULTD		R(F2)	Load1		BNE R1, R2, loop

Register result status

Clock	R1	F0	F2	F4	F6	F8	F10	F12	...	F30
21	56	Qi	Load3		Mult2					

Mult1 (third iteration MUL.D) completing; what is waiting for it?
Issue fourth iteration MUL.D (to RS Mult2)

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Tomasulo Loop Example Timing Diagram

Cycle

Iteration

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
1	L.D.	I	E	E	E	E	E	E	E	W												
	MUL.D		I								E	E	E	E	W							
	S.D.			I												E	E	E	E			
	DADDUI				I																	
	BNE					I																
2	L.D.					I	E	E	E	E	W											
	MUL.D						I					E	E	E	E	W						
	S.D.							I									E	E	E	E		
	DADDUI								I													
	BNE									I												
3	L.D.										I	E	E	E	E		W					
	MUL.D															I		E	E	E	E	
	S.D.																	I				
	DADDUI																		I			
	BNE																			I		
4	L.D.																				I	E
	MUL.D																					I
	S.D.																					
	DADDUI																					
	BNE																					

3rd L.D write delayed one cycle

3rd MUL.D issue delayed until mul RS is available

I = Issue E = Execute W = Write Result on CDB