Course on: “Advanced Computer Architectures”

Scoreboard Dynamic Scheduling Algorithm

Prof. Cristina Silvano
Politecnico di Milano
email: cristina.silvano@polimi.it

Recap on Dynamic Scheduling

- **Simple scalar pipeline:** Hazards due to true data dependences that cannot be solved by forwarding cause the stall of the pipeline: no new instructions can be fetched nor issued even if there are not data dependences!

- **Solution: Allow data independent instructions behind a stall to proceed**
  - HW rearranges dynamically the instruction execution to reduce stalls

=> This enables out-of-order execution and out-of-order commit.

- First implemented in CDC 6600 (1963).

Example of Dynamic Scheduling

```
DIVD  F0,F2,F4     # takes many cycles
ADDD  F10,F0,F8    # RAW F0
SUBD  F12,F8,F14
```

- RAW hazard: **ADDD** stalls for RAW hazards on **F0** (stall many cycles for **DIVD** commit).
- **SUBD** would stall even if not data dependent on anything in the pipeline.

- **BASIC IDEA: to enable SUBD to proceed**
  => this generates *out-of-order execution*

Scoreboard Basic Assumptions

- We consider a ***single-issue*** processor.
- Instruction Fetch stage fetches and issues instructions in program order ***(in-order issue)***.
- Instruction execution begins ***as soon as operands are ready*** whenever not dependent on previous instructions *(no **RAW** hazards)*.
- There are ***multiple*** pipelined Functional Units with ***variable latencies.***
- Execution stage might require ***multiple cycles,*** depending on the operation type and latency.
- Memory stage might require ***multiple cycles*** access time due to data cache misses.

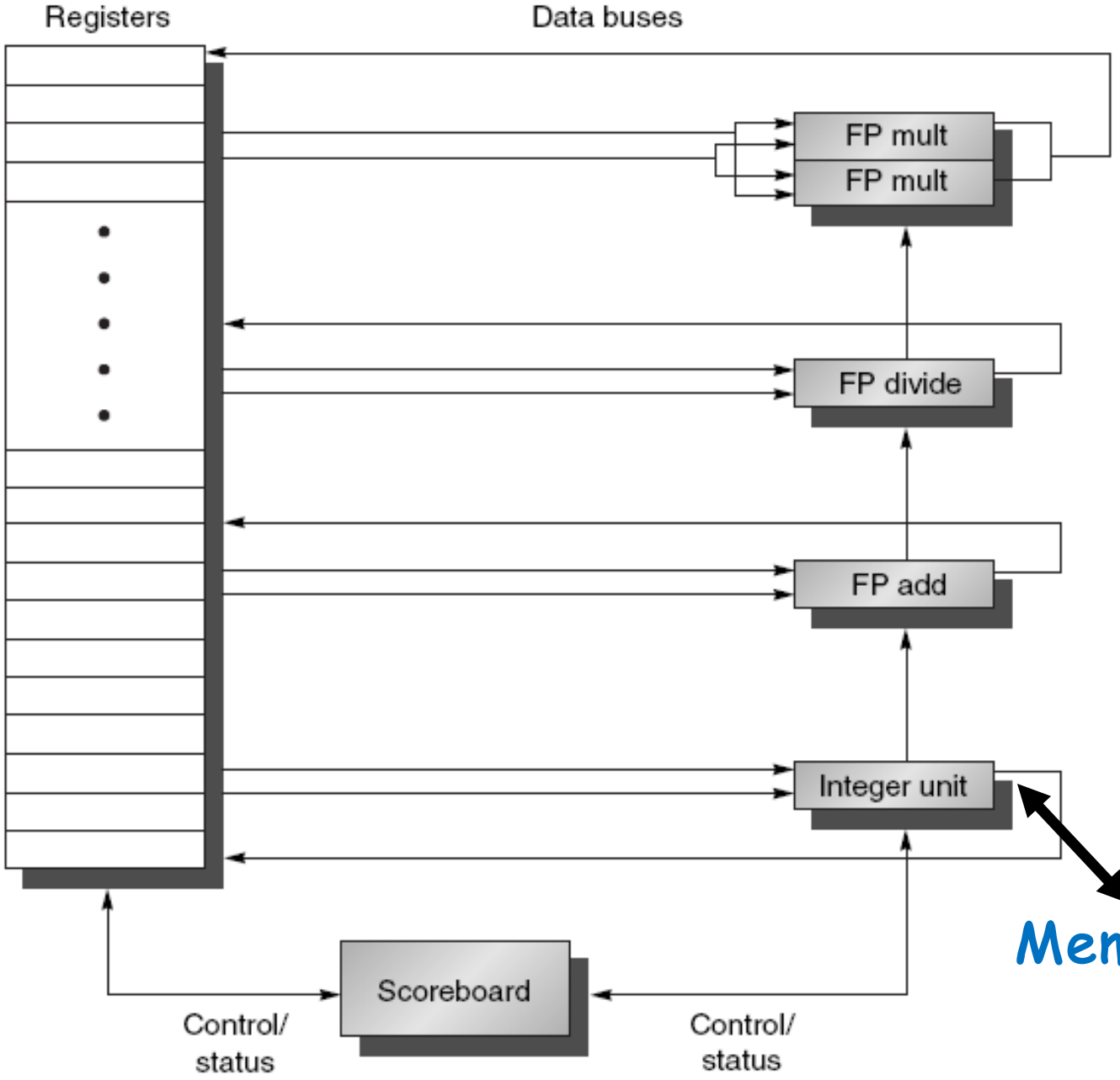
⇒ ***Out-of-order execution & out-of-order commit***

*(this introduces the possibility of **WAR** & **WAW** hazards)*.

Scoreboard basic scheme

- Scoreboard allows ***data independent instructions behind a stall to proceed,*** not waiting for prior instructions.
- We distinguish when an instruction begins execution and it completes execution: between the two times, the instruction is ***in execution.***
- Scoreboard pipeline allows ***multiple instructions in execution at the same time*** $\Rightarrow$ that requires multiple pipelined functional units.
- ***In-order issue, out-of-order execution, out-of-order completion (commit)***
  - ***No forwarding!***
  - ***Imprecise interrupt/exception model for now!***

Scoreboard basic architecture



Functional Units

Memory Unit

Scoreboard Pipeline Stages

- Scoreboard divides the **ID** stage in **two stages:**
  1. **Issue**—Decode instructions and check for structural hazards
  2. **Read operands (RR)**—Wait until not dependent on previous instructions and no data hazards, then read operands

Scoreboard Pipeline Stages

- Scoreboard divides the ID stage in two stages:
  1. Issue—Decode instructions and check for structural hazards
  2. Read operands (RR)—Wait until not dependent on previous instructions and no data hazards, then read operands

- Scoreboard allows instructions to execute whenever 1 & 2 hold, not waiting for prior instructions to complete.
- Scoreboard keeps track of **dependencies** and state of **parallel ongoing operations.**
- Instructions pass through the issue stage ***in-order,*** but they can be stalled or bypass each other in the read operand stage ***(out-of-order read operands).***
- Then instructions enter execution ***out-of-order*** and have different latencies, which implies ***out-of-order completion (commit).***
- **Summary: In-order *issue* but out-of-order *read-operands* ⇒ *out-of-order execution & commit.***

Scoreboard Implications

- There are multiple instructions in execution phase
  ➔ Multiple execution units or pipelined execution units
- No register renaming (compile time technique).
- Out-of-order commit ⇒ **WAR and WAW hazards can occur**

- **Solutions for WAR:**
  - Read registers only during Read Operands stage.
  - Stall write back until previous registers have been read.

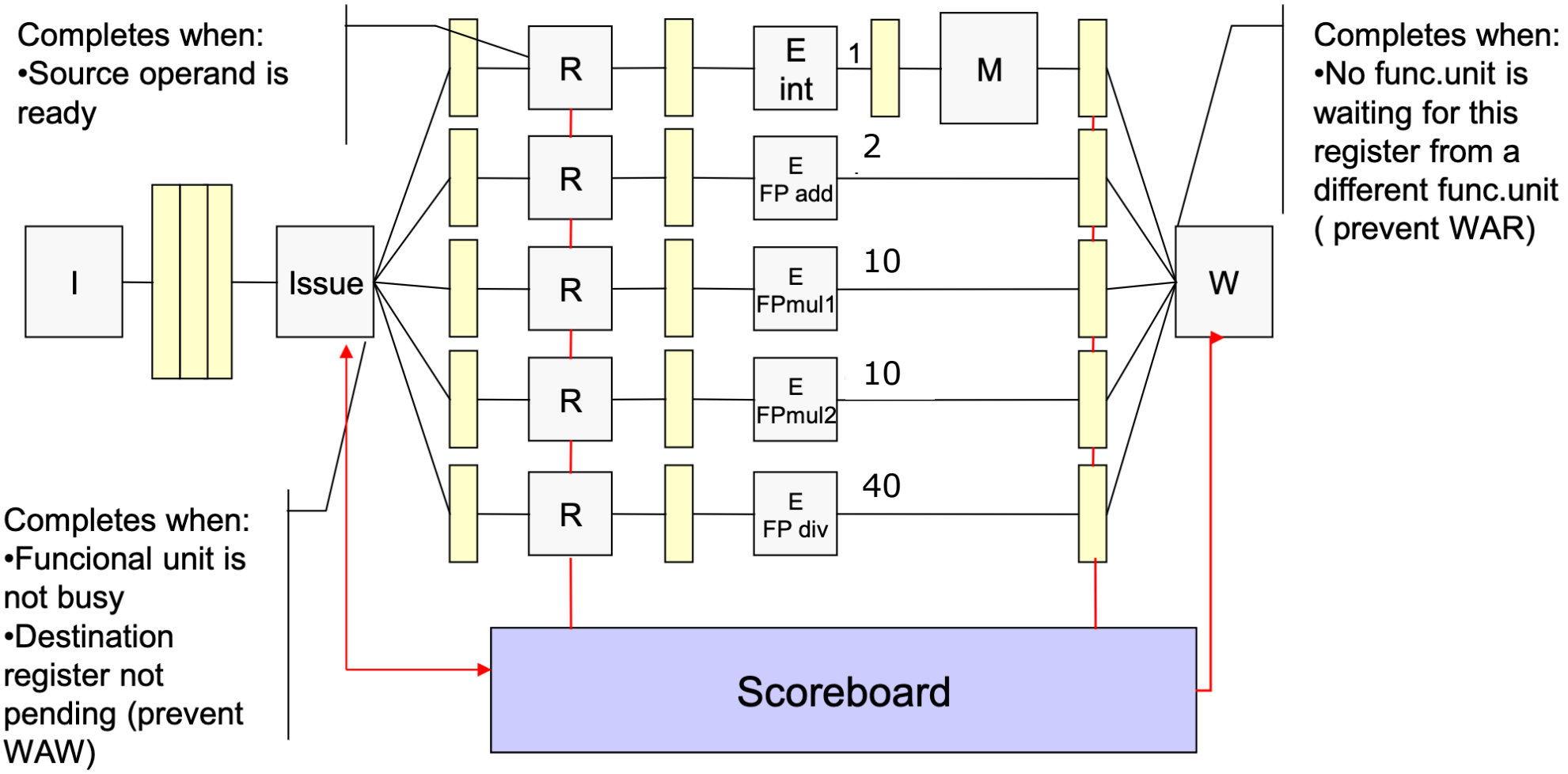
- **Solution for WAW:**
  - Detect WAW hazard and stall issue of new instruction until previous instruction causing WAW completes.

Scoreboard Scheme

- **Any hazard detection and resolution is centralized in the Scoreboard:**
  - Every instruction goes through the Scoreboard, where a record of data dependences is constructed
  - The Scoreboard then determines **when** the instruction can read its operand and begin execution **(check for RAW)**
  - If the Scoreboard decides the instruction cannot execute immediately, it monitors every change and decides **when** the instruction can execute.
  - The scoreboard controls **when** the instruction can write its result into destination register **(check for WAR & WAW)**

Scoreboard Architecture

- The idea of a scoreboard is to keep track of the status of instructions, functional units and registers



Four Stages of Scoreboard Control

1. **Issue**
   Decode instruction and check for structural hazards & WAW hazards

   Instructions issued in program order (for hazard checking)

   - If a functional unit for the instruction is available **(no structural hazard)** and no other active instruction has the same destination register **(no WAW hazard)** => the Scoreboard issues the instruction to the FU and updates its data structure.

   - If either a **structural hazard** or a **WAW hazard** exists => the instruction issue stalls, and no further instructions will issue until these hazards are solved.

Four Stages of Scoreboard Control

2. **Read Operands**

Wait until no RAW hazards => then read operands.
Check for structural hazards in reading ports of RF.

- A source operand is available if:
  - No earlier issued active instruction will write it or
  - A functional unit is writing its value in a register
- When the source operands are available, the Scoreboard tells the FU to proceed to read the operands from the RF and begin execution.
- RAW hazards are solved dynamically in this step
  => **out-of-order** reading of operands
  => instructions are sent into execution **out-of-order.**
- **No data forwarding**

Four Stages of Scoreboard Control

3. **Execution**

   The FU begins execution upon receiving operands.
   When the result is ready, it notifies the Scoreboard that execution has been completed.

- FUs are characterized by **variable latency** to complete execution.
- **Load/Store latency depends on data cache HIT/MISS times.**

=> Out-of-order execution

Four Stages of Scoreboard Control

4. **Write result**

Check for WAR hazards on destination.

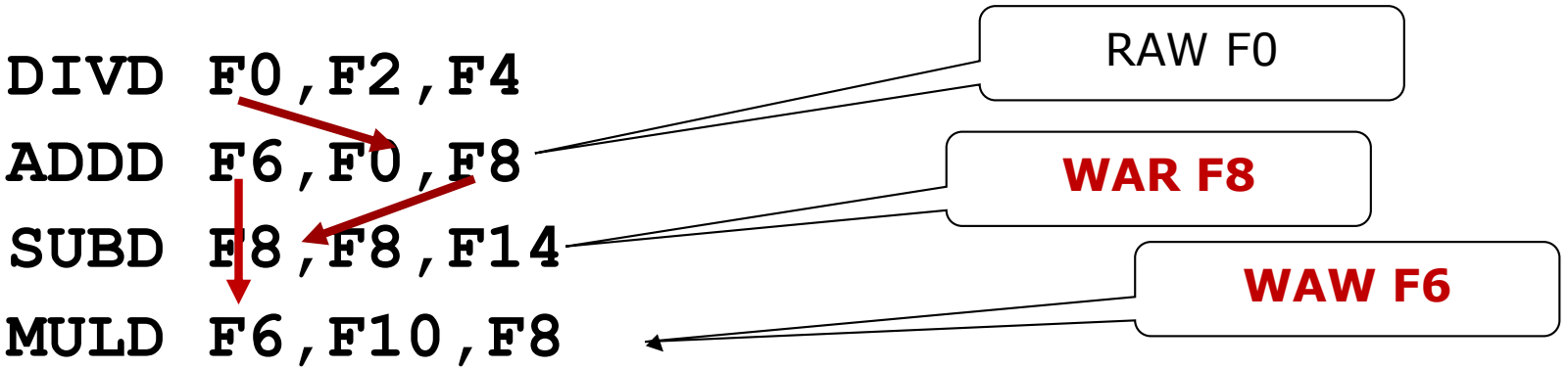
Check for structural hazards in writing RF and finish execution.

Once the Scoreboard is aware that the FU has completed execution, **the Scoreboard checks for WAR hazards.**

- If none, it writes results.
- If there is a **WAR** => the Scoreboard stalls the completing instruction.

=> Out-of-order commit

RAW/WAR/WAW Example



- To avoid the **WAR** hazard on F8, the Scoreboard would:
  - Stall **SUBD** in the WB stage, waiting for **ADDD** reads F0 and F8;
- To avoid the **WAW** hazard on F6, the Scoreboard would:
  - Stall **MULD** in the ISSUE stage until **ADDD** writes F6.

- Note: Any WAR/WAW hazard could have been solved through register renaming at compile time.

Recap: SCOREBOARD BASIC SCHEME

- IN-ORDER ISSUE
- OUT-OF-ORDER READ OPERANDS
- OUT-OF-ORDER EXECUTION
- OUT-OF-ORDER COMPLETION
- NO FORWARDING
- Control is centralized into the Scoreboard

Recap: SCOREBOARD STAGES

- **ISSUE (IN-ORDER):**
  - Check for structural hazards
  - Check for WAW hazards on destination operand **(*)**
- **READ OPERANDS (OUT-OF-ORDER)**
  - Check for RAW hazards
  - Check for structural hazards in reading RF
- **EXECUTION (OUT-OF-ORDER)**
  - Execution completion depends on latency of FUs
  - Execution completion of LD/ST depends on cache hit/miss latencies
- **WRITE RESULTS (OUT-OF-ORDER)**
  - Check for WAR hazards on destionation operand
  - Check for structural hazards in writing RF

Recap: SCOREBOARD optimizations

(*) Optimizations:

1. Check for **WAW** **postponed** from **ISSUE** stage to **WRITE** stage
2. Data forwarding

Scoreboard Structure

1. **Instruction status**
2. **Functional Unit status**

   Indicates the state of the functional unit (FU):

Busy	Indicates whether the unit is busy or not
Op	The operation to perform in the unit (+,-, etc.)
Fi	Destination register
Fj, Fk	Source register numbers
Qj, Qk	Functional units producing source registers Fj, Fk
Rj, Rk	Flags indicating when Fj, Fk are ready. Flags are set to NO after operands are read.

3. **Register result status**

   Indicates which functional unit will write each register. Blank if no pending instructions will write that register.

Scoreboard Example: Analysis of dependences and hazards

```
LD   F6, 34(R2)
LD   F2, 45(R3)
MULTD F0, F2, F4    # RAW F2
SUBD  F8, F6, F2    # RAW F2, RAW F6
DIVD  F10, F0, F6   # RAW F0, RAW F6
ADDD  F6, F8, F2    # WAW F6, WAR F6,
                    # RAW F8, RAW F2
```

Scoreboard Example

Instruction status:

Instruction		*j*	*k*	*Issue*	*Read Oper*	*Exec Comp*	*Write Result*
LD	F6	34+	R2				
LD	F2	45+	R3				
MULTD	F0	F2	F4				
SUBD	F8	F6	F2				
DIVD	**F10**	**F0**	**F6**				
ADDD	F6	F8	F2				

Functional unit status:

Time	*Name*	*Busy*	*Op*	*dest Fi*	*S1 Fj*	*S2 Fk*	*FU Qj*	*FU Qk*	*Fj? Rj*	*Fk? Rk*
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

Clock	*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
FU									

Scoreboard Example: Cycle 1

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1			
LD	F2	45+	R3				
MULTD	F0	F2	F4				
SUBD	F8	F6	F2				
DIVD	**F10**	**F0**	**F6**				
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	Yes	Load	F6		R2				Yes
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
1	*FU*				Integer					

Scoreboard Example Cycle 2

Instruction status

Instruction		j	k	Issue	Read operand	Executi comple	Write Result
LD	F6	34+	R2	1	2		
LD	F2	45+	R3				
MULTI	F0	F2	F4				
SUBD	F8	F6	F2				
DIVD	F10	F0	F6				
ADDD	F6	F8	F2				

Functional unit status

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

Register result status

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
2	FU				Integer					

Issue 2nd load? **No: Integer Unit busy – Cannot issue 2nd Load due to structural hazard on Integer Unit =>** ***Issue stalls***

Issue multiply?

Scoreboard Example Cycle 3

Instruction status

Instruction		j	k	Issue	Read operand	Execution complete	Write Result
LD	F6	34+	R2	1	2	3	
LD	F2	45+	R3				
MULTI	F0	F2	F4				
SUBD	F8	F6	F2				
DIVD	F10	F0	F6				
ADDD	F6	F8	F2				

Functional unit status

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

Register result status

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
3	FU				Integer					

- ***Issue stalls***
- **Load execution complete in one clock cycle (ideal data cache hit)**

Scoreboard Example: Cycle 4

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3				
MULTD	F0	F2	F4				
SUBD	F8	F6	F2				
DIVD	F10	F0	F6				
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
4	FU				Integer					

- ***Issue stalls***
- **Write F6 & Integer Unit no more busy**

Scoreboard Example: Cycle 5

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5			
MULTD	F0	F2	F4				
SUBD	F8	F6	F2				
DIVD	F10	F0	F6				
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	Yes	Load	F2		R3				Yes
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
5	FU		Integer							

- **The second load is issued**

Scoreboard Example: Cycle 6

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6		
MULTD	F0	F2	F4	6			
SUBD	F8	F6	F2				
DIVD	F10	F0	F6				
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	Yes	Load	F2		R3				Yes
	Mult1	Yes	Mult	F0	F2	F4	Integer		No	Yes
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
6	FU	Mult1	Integer							

- **MULT is issued, but it has to wait for F2 from 2nd LOAD (RAW Hazard on F2)**

Scoreboard Example: Cycle 7

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	
MULTD	F0	F2	F4	6			
SUBD	F8	F6	F2	7			
DIVD	F10	F0	F6				
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	Yes	Load	F2		R3				Yes
	Mult1	Yes	Mult	F0	F2	F4	Integer		No	Yes
	Mult2	No								
	Add	Yes	Sub	F8	F6	F2		Integer	Yes	No
	Divide	No								

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
7	FU	Mult1	Integer			Add				

- **Load execution completed in one clock cycle (data cache hit)**
- **Read multiply operands? *Not yet***
- **SUBD can be issued to ADD Functional Unit (then SUBD has to wait for RAW F2 from load)**

Scoreboard Example: Cycle 8

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	
MULTD	F0	F2	F4	6			
SUBD	F8	F6	F2	7			
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	Yes	Load	F2		R3				No
	Mult1	Yes	Mult	F0	F2	F4	Integer		No	Yes
	Mult2	No								
	Add	Yes	Sub	F8	F6	F2		Integer	Yes	No
	Divide	Yes	**Div**	**F10**	**F0**	**F6**	Mult1		**No**	**Yes**

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
8	*FU*	Mult1	Integer			Add	**Divide**			

- **DIVD is issued but there is another RAW hazard (F0) from MULTD**
  -> DIVD has to wait for reading F0

Scoreboard Example: Cycle 8 cont'd

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6			
SUBD	F8	F6	F2	7			
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
	Mult1	Yes	Mult	F0	F2	F4			Yes	Yes
	Mult2	No								
	Add	Yes	Sub	F8	F6	F2			Yes	Yes
	Divide	Yes	**Div**	**F10**	**F0**	**F6**	Mult1		**No**	**Yes**

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
8	*FU*	Mult1				Add	**Divide**			

- **Load completes (Writes F2), and F2 operands for MULT and SUBD are ready**

Scoreboard Example: Cycle 9

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9		
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2				

Functional unit status:

Note Remaining

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
10	Mult1	Yes	Mult	F0	F2	F4			Yes	Yes
	Mult2	No								
2	Add	Yes	Sub	F8	F6	F2			Yes	Yes
	Divide	Yes	**Div**	**F10**	**F0**	**F6**	Mult1		**No**	**Yes**

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
9	*FU*	Mult1				Add	**Divide**			

- **Read operands for MULTD & SUBD by multiple-port Register File (4 read ports)**
- **Issue ADDD? WAW F6 is gone but there is a structural hazard on ADD Functional Unit**
- **MULTD & SUBD are sent in execution in parallel with latency 10 cycles for MULTD & 2 cycles for SUBD**

Scoreboard Example: Cycle 10

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9		
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
9	Mult1	Yes	Mult	F0	F2	F4			Yes	Yes
	Mult2	No								
1	Add	Yes	Sub	F8	F6	F2			Yes	Yes
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
10	*FU*	Mult1				Add	Divide			

Scoreboard Example: Cycle 11

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9	11	
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
8	Mult1	Yes	Mult	F0	F2	F4			Yes	Yes
	Mult2	No								
0	Add	Yes	Sub	F8	F6	F2			Yes	Yes
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
11	*FU*	Mult1				Add	Divide			

- **SUBD ends execution**

Scoreboard Example: Cycle 12

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
7	Mult1	Yes	Mult	F0	F2	F4			Yes	Yes
	Mult2	No								
	Add	No								
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
12	*FU*	Mult1					Divide			

- **SUBD writes result in F8**

Scoreboard Example: Cycle 13

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2	13			

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
6	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	Yes

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	…	F30
13	*FU*	Mult1			Add		Divide			

- **ADDD can be issued (WAW F6 was gone and ADD unit is available)**
- **DIVD still waits for operand F0 from MULTD**

Scoreboard Example: Cycle 14

Instruction status:

Instruction		j	k	*Issue*	*Read Oper*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2	13	14		

Functional unit status:

Time	*Name*	*Busy*	*Op*	*dest Fi*	*S1 Fj*	*S2 Fk*	*FU Qj*	*FU Qk*	*Fj? Rj*	*Fk? Rk*
	Integer	No								
5	Mult1	Yes	Mult	F0	F2	F4			Yes	Yes
	Mult2	No								
2	Add	Yes	Add	F6	F8	F2			Yes	Yes
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
14	*FU*	Mult1			Add		Divide			

- **ADDD reads operands (out-of-order read operands: ADDD reads operands before DIVD)**

Scoreboard Example: Cycle 15

Instruction status:

Instruction		*j*	*k*	*Issue*	*Read Oper*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2	13	14		

Functional unit status:

Time	*Name*	*Busy*	*Op*	*dest Fi*	*S1 Fj*	*S2 Fk*	*FU Qj*	*FU Qk*	*Fj? Rj*	*Fk? Rk*
	Integer	No								
4	Mult1	Yes	Mult	F0	F2	F4			Yes	Yes
	Mult2	No								
1	Add	Yes	Add	F6	F8	F2			Yes	Yes
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
15	*FU*	Mult1			Add		Divide			

- **ADDD starts execution**

Scoreboard Example: Cycle 16

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2	13	14	16	

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
3	Mult1	Yes	Mult	F0	F2	F4			Yes	Yes
	Mult2	No								
0	Add	Yes	Add	F6	F8	F2			Yes	Yes
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
16	*FU*	Mult1			Add		Divide			

- **ADDD ends execution, but WAR F6 must be detected before writing the result in RF**

Scoreboard Example: Cycle 17

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2	13	14	16	

WAR F6 Hazard!

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	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**	**Yes**

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
17	*FU*	Mult1			Add		**Divide**			

- ***Why not write result of ADDD???*** **WAR F6 must be detected before writing for result of ADDD in F6**
- **DIVD must first read F6 (before ADDD write F6), but DIVD cannot read operands until MULTD writes F0 (RAW on F0)**

Scoreboard Example: Cycle 18

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9		
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2	13	14	16	

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
1	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	Yes

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
18	*FU*	Mult1			Add		Divide			

Scoreboard Example: Cycle 19

Instruction status:

Instruction		*j*	*k*	*Issue*	*Read Oper*	*Exec Comp*	*Write Result*
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9	19	
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2	13	14	16	

Functional unit status:

Time	*Name*	*Busy*	*Op*	*dest Fi*	*S1 Fj*	*S2 Fk*	*FU Qj*	*FU Qk*	*Fj? Rj*	*Fk? Rk*
	Integer	No								
0	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	Yes

Register result status:

Clock		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	*…*	*F30*
19	*FU*	Mult1			Add		Divide			

- **MULTD ends execution**

Scoreboard Example: Cycle 20

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9	19	20
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8			
ADDD	F6	F8	F2	13	14	16	

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	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		F0	F2	F4	F6	F8	F10	F12	...	F30
20	*FU*				Add		**Divide**			

- **MULTD writes in F0**

Scoreboard Example: Cycle 21

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9	19	20
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8	21		
ADDD	F6	F8	F2	13	14	16	

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	Yes	Add	F6	F8	F2			Yes	Yes
40	Divide	Yes	**Div**	**F10**	**F0**	**F6**			**Yes**	**Yes**

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
21	*FU*				Add		**Divide**			

- **DIVD can read operands**
- **WAR F6 hazard is now gone...**

Scoreboard Example: Cycle 22

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9	19	20
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8	21		
ADDD	F6	F8	F2	13	14	16	22

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	No								
39	Divide	Yes	**Div**	**F10**	**F0**	**F6**			**Yes**	**Yes**

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
22	*FU*						**Divide**			

- **DIVD has read its operands in previous cycle, so WAR F6 is gone**
- **ADDD can now write the result in F6**

skipping some cycles…

Scoreboard Example: Cycle 61

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9	19	20
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8	21	61	
ADDD	F6	F8	F2	13	14	16	22

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	No								
0	Divide	Yes	**Div**	**F10**	**F0**	**F6**			**Yes**	**Yes**

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
61	*FU*						**Divide**			

- **DIVD ends execution**

Scoreboard Example: Cycle 62

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9	19	20
SUBD	F8	F6	F2	7	9	11	12
DIVD	F10	F0	F6	8	21	61	62
ADDD	F6	F8	F2	13	14	16	22

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
62	*FU*									

- **DIVD writes in F10**

Recap: Scoreboard Example: Cycle 62

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F6	34+	R2	1	2	3	4
LD	F2	45+	R3	5	6	7	8
MULTD	F0	F2	F4	6	9	19	20
SUBD	F8	F6	F2	7	9	11	12
DIVD	**F10**	**F0**	**F6**	8	21	61	62
ADDD	F6	F8	F2	13	14	16	22

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
62	*FU*									

- *In-order issue*
- ***Out-of-order reading operands & execute & commit***

Reference

Appendix A of the text book: J. Hennessey, D. Patterson,
"Computer Architecture: a quantitative approach"
4th Edition, Morgan-Kaufmann Publishers.