

Lecture 5 Scoreboarding: Enforce Register Data Dependence

Scoreboard design, big example

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From MIPS pipeline to Scoreboard

- ◆ Out-of-order execution divides ID stage:
 1. Issue—decode instructions, check for structural hazards
 2. Read operands—wait until no data hazards, then read operands
- ◆ Scoreboards allow instruction to execute whenever 1 & 2 hold, not waiting for prior instructions
- ◆ CDC 6600: In order issue, out of order execution, out of order completion

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Scoreboard Implications

- ◆ Out-of-order completion => WAR, WAW hazards?
- ◆ Solutions for WAR
 - Queue both the operation and copies of its operands
 - Read registers only during Read Operands stage
- ◆ For WAW, must detect hazard: stall until other completes
- ◆ Need to have multiple instructions in execution phase => multiple execution units or pipelined execution units
- ◆ Scoreboard keeps track of dependencies, state or operations
- ◆ Scoreboard replaces ID, EX, WB with 4 stages

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Four Stages of Scoreboard Control

1. Issue—decode instructions & check for structural hazards
 - Wait conditions: (1) the required FU is free; (2) no other instruction writes to the same register destination (to avoid WAW)
 - Actions: (1) the instruction is assigned to the FU; (2) scoreboard updates its internal data structure

If an instruction is stalled at this stage, no other instructions can proceed
2. Read operands—wait until no data hazards, then read operands
 - Wait conditions: all source operands are available
 - Actions: the function unit reads register operands and start execution the next cycle

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Four Stages of Scoreboard Control

3. Execution—operate on operands (EX)
 - Actions: The functional unit begins execution upon receiving operands. When the result is ready, it notifies the scoreboard that it has completed execution.
4. Write result—finish execution (WB)
 - Wait condition: no other instruction/FU is going to read the register destination of the instruction
 - Actions: Write the register and update the scoreboard

WAR Example:

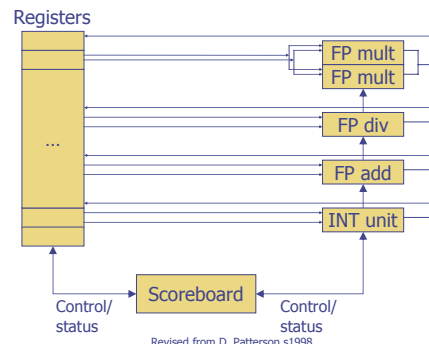
```
DIVD  F0,F2,F4
ADDD  F10,F0,F8
SUBD  F8,F8,F14
```

CDC 6600 scoreboard would stall SUBD until ADDD reads operands

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Scoreboard Connections



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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). 9 fields for each functional unit
 - 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
 - Qj, Qk—Functional units producing source registers Fj, Fk
 - Rj, Rk—Flags indicating when Fj, Fk are ready
3. **Register result status**—Indicates which functional unit will write each register, if one exists. Blank when no pending instructions will write that register

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Detailed Scoreboard Pipeline Control

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

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Scoreboard Example

Instruction status			Read operand				Execution complete				Write Result			
Instruction	j	k	Issue	operand	complete	Result	Issue	operand	complete	Result	Issue	operand	complete	Result
LD	F6	34+	R2											
LD	F2	45+	R3											
MULT	F0	F2	F4											
SUBD	F8	F6	F2											
DIVD	F10	F0	F6											
ADD	F6	F8	F2											

Functional unit status		Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
Time	Name									
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status		F0	F2	F4	F6	F8	F10	F12	...	F30
Clock	FU									

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Scoreboard Example Cycle 1

Instruction status			Read operand				Execution complete				Write Result			
Instruction	j	k	Issue	operand	complete	Result	Issue	operand	complete	Result	Issue	operand	complete	Result
LD	F6	34+	R2				1							
LD	F2	45+	R3											
MULT	F0	F2	F4											
SUBD	F8	F6	F2											
DIVD	F10	F0	F6											
ADD	F6	F8	F2											

Functional unit status		Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
Time	Name									
	Integer	Yes	Load	F6		R2				Yes
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status		F0	F2	F4	F6	F8	F10	F12	...	F30
Clock	FU									

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Scoreboard Example Cycle 2

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

Functional unit status		Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
Time	Name									
	Integer	Yes	Load	F6		R2				Yes
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status		F0	F2	F4	F6	F8	F10	F12	...	F30
Clock	FU									

- Issue 2nd LD?

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Scoreboard Example Cycle 3

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

Functional unit status		Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
Time	Name									
	Integer	Yes	Load	F6		R2				Yes
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status		F0	F2	F4	F6	F8	F10	F12	...	F30
Clock	FU									

- Issue MULT?

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Scoreboard Example Cycle 4

Instruction status			Read		Executic		Write	
Instruction	j	k	Issue	operand complete	Result			
LD	F6	34+	R2	1	2	3	4	
LD	F2	45+	R3					
MULT	F0	F2	F4					
SUBD	F8	F6	F2					
DIVD	F10	F0	F6					
ADD	F6	F8	F2					

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

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

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Scoreboard Example Cycle 5

Instruction status			Read		Executic		Write	
Instruction	j	k	Issue	operand complete	Result			
LD	F6	34+	R2	1	2	3	4	
LD	F2	45+	R3	5				
MULT	F0	F2	F4					
SUBD	F8	F6	F2					
DIVD	F10	F0	F6					
ADD	F6	F8	F2					

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

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

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Scoreboard Example Cycle 6

Instruction status			Read		Executic		Write	
Instruction	j	k	Issue	operand complete	Result			
LD	F6	34+	R2	1	2	3	4	
LD	F2	45+	R3	5	6			
MULT	F0	F2	F4	6				
SUBD	F8	F6	F2					
DIVD	F10	F0	F6					
ADD	F6	F8	F2					

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

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

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Scoreboard Example Cycle 7

Instruction status			Read		Executic		Write	
Instruction	j	k	Issue	operand complete	Result			
LD	F6	34+	R2	1	2	3	4	
LD	F2	45+	R3	5	6	7		
MULT	F0	F2	F4	6				
SUBD	F8	F6	F2	7				
DIVD	F10	F0	F6					
ADD	F6	F8	F2					

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

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

- Read multiply operands?

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Scoreboard Example Cycle 8a

Instruction status			Read		Executic		Write	
Instruction	j	k	Issue	operand complete	Result			
LD	F6	34+	R2	1	2	3	4	
LD	F2	45+	R3	5	6	7		
MULT	F0	F2	F4	6				
SUBD	F8	F6	F2	7				
DIVD	F10	F0	F6	8				
ADD	F6	F8	F2					

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

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

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Scoreboard Example Cycle 8b

Instruction status			Read		Executic		Write	
Instruction	j	k	Issue	operand complete	Result			
LD	F6	34+	R2	1	2	3	4	
LD	F2	45+	R3	5	6	7	8	
MULT	F0	F2	F4	6				
SUBD	F8	F6	F2	7				
DIVD	F10	F0	F6	8				
ADD	F6	F8	F2					

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

Register result status												
Clock	FU	F0	F2	F4	F6	F8	F10	F12	...	F30		
8												Mult1 Add Divide

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Scoreboard Example Cycle 9

Instruction status				Read		Executiv		Write	
Instruction	j	k		Issue	operand	complete	Result		
LD	F6	34+	R2	1	2	3	4		
LD	F2	45+	R3	5	6	7	8		
MULT	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	S1	S2	FU for j	FU for k	Fj?	Fk?
	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 MULT & SUBD? Issue ADDD?

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Scoreboard Example Cycle 11

Instruction status				Read		Executiv		Write	
Instruction	j	k		Issue	operand	complete	Result		
LD	F6	34+	R2	1	2	3	4		
LD	F2	45+	R3	5	6	7	8		
MULT	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	S1	S2	FU for j	FU for k	Fj?	Fk?
	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			

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Scoreboard Example Cycle 12

Instruction status				Read		Executiv		Write	
Instruction	j	k		Issue	operand	complete	Result		
LD	F6	34+	R2	1	2	3	4		
LD	F2	45+	R3	5	6	7	8		
MULT	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	S1	S2	FU for j	FU for k	Fj?	Fk?
	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			

- Read operands for DIVD?

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Scoreboard Example Cycle 13

Instruction status				Read		Executiv		Write	
Instruction	j	k		Issue	operand	complete	Result		
LD	F6	34+	R2	1	2	3	4		
LD	F2	45+	R3	5	6	7	8		
MULT	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	S1	S2	FU for j	FU for k	Fj?	Fk?
	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			

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Scoreboard Example Cycle 14

Instruction status				Read		Executiv		Write	
Instruction	j	k		Issue	operand	complete	Result		
LD	F6	34+	R2	1	2	3	4		
LD	F2	45+	R3	5	6	7	8		
MULT	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	S1	S2	FU for j	FU for k	Fj?	Fk?
	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			

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Scoreboard Example Cycle 15

Instruction status				Read		Executiv		Write	
Instruction	j	k		Issue	operand	complete	Result		
LD	F6	34+	R2	1	2	3	4		
LD	F2	45+	R3	5	6	7	8		
MULT	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	S1	S2	FU for j	FU for k	Fj?	Fk?
	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			

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Scoreboard Example Cycle 16

Instruction status				Read				Executic Write			
Instruction	j	k		Issue	operand complete	Result					
LD F6 34+ R2				1	2	3	4				
LD F2 45+ R3				5	6	7	8				
MULT F0 F2 F4				6	9						
SUBD F8 F6 F2				7	9	11	12				
DIVD F10 F0 F6				8							
ADD F6 F8 F2				13	14	16					

Functional unit status									
Time Name	Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
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			

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Scoreboard Example Cycle 17

Instruction status				Read				Executic Write			
Instruction	j	k		Issue	operand complete	Result					
LD F6 34+ R2				1	2	3	4				
LD F2 45+ R3				5	6	7	8				
MULT F0 F2 F4				6	9						
SUBD F8 F6 F2				7	9	11	12				
DIVD F10 F0 F6				8							
ADD F6 F8 F2				13	14	16					

Functional unit status									
Time Name	Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
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			

• Write result of ADD?

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Scoreboard Example Cycle 18

Instruction status				Read				Executic Write			
Instruction	j	k		Issue	operand complete	Result					
LD F6 34+ R2				1	2	3	4				
LD F2 45+ R3				5	6	7	8				
MULT F0 F2 F4				6	9						
SUBD F8 F6 F2				7	9	11	12				
DIVD F10 F0 F6				8							
ADD F6 F8 F2				13	14	16					

Functional unit status									
Time Name	Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
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			

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Scoreboard Example Cycle 19

Instruction status				Read				Executic Write			
Instruction	j	k		Issue	operand complete	Result					
LD F6 34+ R2				1	2	3	4				
LD F2 45+ R3				5	6	7	8				
MULT F0 F2 F4				6	9	19					
SUBD F8 F6 F2				7	9	11	12				
DIVD F10 F0 F6				8							
ADD F6 F8 F2				13	14	16					

Functional unit status									
Time Name	Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
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			

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Scoreboard Example Cycle 20

Instruction status				Read				Executic Write			
Instruction	j	k		Issue	operand complete	Result					
LD F6 34+ R2				1	2	3	4				
LD F2 45+ R3				5	6	7	8				
MULT F0 F2 F4				6	9	19	20				
SUBD F8 F6 F2				7	9	11	12				
DIVD F10 F0 F6				8							
ADD F6 F8 F2				13	14	16					

Functional unit status									
Time Name	Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
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			

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Scoreboard Example Cycle 21

Instruction status				Read				Executic Write			
Instruction	j	k		Issue	operand complete	Result					
LD F6 34+ R2				1	2	3	4				
LD F2 45+ R3				5	6	7	8				
MULT F0 F2 F4				6	9	19	20				
SUBD F8 F6 F2				7	9	11	12				
DIVD F10 F0 F6				8							
ADD F6 F8 F2				13	14	16					

Functional unit status									
Time Name	Busy	Op	dest	S1	S2	FU for j	FU for k	Fj?	Fk?
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
21	FU			Add		Divide			

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Scoreboard Example Cycle 22

Instruction status				Read				Executiv				Write			
Instruction	j	k		Issue	operand	complete	Result								
LD	F6	34+	R2	1	2	3	4								
LD	F2	45+	R3	5	6	7	8								
MULT	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		dest				S1	S2	FU for j	FU for k	Fj?	Fk?
Time	Name	Busy	Op	Fi	Fj	Fk	Qj	Qk	Rj	Rk	
	Integer	No									
	Mult1	No									
	Mult2	No									
	Add	No									
40	Divide	Yes	Div	F10	F0	F6				Yes	Yes

Register result status		dest															
Register	Result	F0	F2	F4	F6	F8	F10	F12	...	F30							
Clock	22	FU												Divide			

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Scoreboard Example Cycle 61

Instruction status				Read				Executiv				Write			
Instruction	j	k		Issue	operand	complete	Result								
LD	F6	34+	R2	1	2	3	4								
LD	F2	45+	R3	5	6	7	8								
MULT	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		dest				S1	S2	FU for j	FU for k	Fj?	Fk?
Time	Name	Busy	Op	Fi	Fj	Fk	Qj	Qk	Rj	Rk	
	Integer	No									
	Mult1	No									
	Mult2	No									
	Add	No									
0	Divide	Yes	Div	F10	F0	F6				Yes	Yes

Register result status		dest															
Register	Result	F0	F2	F4	F6	F8	F10	F12	...	F30							
Clock	61	FU												Divide			

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Scoreboard Example Cycle 62

Instruction status				Read				Executiv				Write			
Instruction	j	k		Issue	operand	complete	Result								
LD	F6	34+	R2	1	2	3	4								
LD	F2	45+	R3	5	6	7	8								
MULT	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		dest				S1	S2	FU for j	FU for k	Fj?	Fk?
Time	Name	Busy	Op	Fi	Fj	Fk	Qj	Qk	Rj	Rk	
	Integer	No									
	Mult1	No									
	Mult2	No									
	Add	No									
0	Divide	No									

Register result status		dest															
Register	Result	F0	F2	F4	F6	F8	F10	F12	...	F30							
Clock	62	FU															

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Scoreboard Scheduling

Inst	Issue	Read operands	Execution complete	Write Result
LD	1	2	3	4
LD	5	6	7	8
MULT	6	9	19	20
SUBD	7	9	11	12
DIVD	8	21	61	62
ADDD	13	14	16	22

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Machine Correctness

$$E(D,P) = E(S,P) \text{ if}$$

- $E(D,P)$ and $E(S,P)$ execute the same set of instructions
- For any inst i , i receives the outputs in $E(D,P)$ of its parents in $E(S,P)$
- In $E(D,P)$ any register or memory word receives the output of inst j , where j is the last instruction writes to the register or memory word in $E(S,P)$

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CDC 6600 Scoreboard

- ◆ Speedup 1.7 from compiler; 2.5 by hand BUT slow memory (no cache) limits benefit
- ◆ Limitations of 6600 scoreboard:
 - No forwarding hardware
 - Limited to instructions in basic block (small window)
 - Small number of functional units (structural hazards), especially integer/load store units
 - Do not issue on structural hazards
 - Wait for WAR hazards
 - Prevent WAW hazards

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