



EECS 252 Graduate Computer Architecture

Lec 6 - Scoreboard

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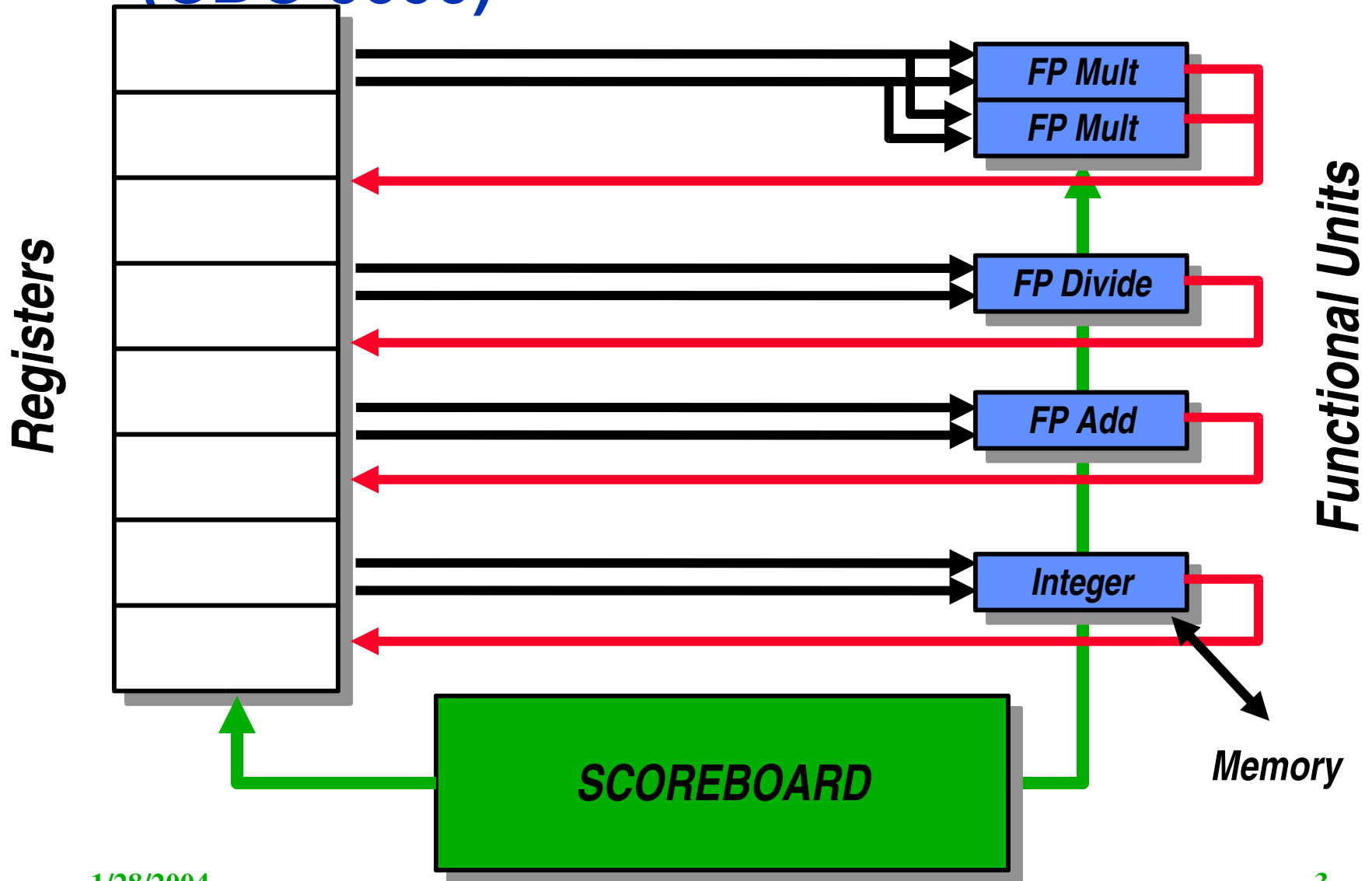


Scoreboard: a bookkeeping technique

- **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 date to CDC6600 in 1963**
- **Instructions execute whenever not dependent on previous instructions and no hazards.**
- **CDC 6600: In order issue, out-of-order execution, out-of-order commit (or completion)**
 - No forwarding!
 - Imprecise interrupt/exception model for now



Scoreboard Architecture (CDC 6600)





Four Stages of Scoreboard Control

- **Issue**—decode instructions & check for structural hazards (ID1)
 - Instructions issued in program order (for hazard checking)
 - Don't issue if **structural hazard**
 - Don't issue if instruction is **output dependent** on any previously issued but uncompleted instruction (no WAW hazards)
- **Read operands**—wait until no data hazards, then read operands (ID2)
 - All real dependencies (RAW hazards) resolved in this stage, since we wait for instructions to write back data.
 - **No forwarding of data** in this model!



Four Stages of Scoreboard Control

- **Execution**—operate on operands (EX)
 - The functional unit begins execution upon receiving operands. When the result is ready, it notifies the scoreboard that it has completed execution.
- **Write result**—finish execution (WB)
 - Stall until no WAR hazards with previous instructions:

Example:

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

CDC 6600 scoreboard would stall SUBD until ADDD reads operands



Three Parts of the Scoreboard

- **Instruction status:**
Which of 4 steps the instruction is in
- **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
- **Register result status**—Indicates which functional unit will write each register, if one exists. Blank when no pending instructions will write that register



Scoreboard Example

Instruction status: *Read Exec Write*

Instruction	<i>j</i>	<i>k</i>	<i>Issue Oper CompResult</i>
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:

<i>al unit status:</i>		<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU</i>	<i>FU</i>	<i>Fj?</i>	<i>Fk?</i>	
<i>TimeName</i>	<i>Busy</i>	<i>Op</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	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>...</i>	<i>F30</i>
<i>FU</i>									



Detailed Scoreboard Pipeline

Control

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



Scoreboard Example: Cycle 1

Instruction status:

			Read	Exec	Write
Instruction	<i>j</i>	<i>k</i>	Issue	Oper	CompResult
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:

<i>al unit status:</i>			<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU</i>	<i>FU</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>	<i>Rj</i>	<i>Rk</i>
	Integer	Yes	Load	F6		R2				Yes
	Mult1	No								
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

Clock
1

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



Scoreboard Example: Cycle 2

Instruction status:

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

Functional unit status:

<i>al unit status:</i>			<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU</i>	<i>FU</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>	<i>Rj</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>
2	FU Integer								

- Issue 2nd LD?



Scoreboard Example: Cycle 3

Instruction status:

			Read	Exec	Write
Instruction	<i>j</i>	<i>k</i>	Issue	Oper	CompResult
LD	F6	34+ R2	1	2	3
LD	F2	45+ R3			
MULTD	F0	F2 F4			
SUBD	F8	F6 F2			
DIVD	F10	F0 F6			
ADDD	F6	F8 F2			

Functional unit status:

<i>al unit status:</i>			<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU</i>	<i>FU</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>	<i>Rj</i>	<i>Rk</i>
	Integer	Yes	Load	F6		R2				No
	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 MULT?



Scoreboard Example: Cycle 4

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
	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>
4	FU Integer								



Scoreboard Example: Cycle 5

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</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	FU Integer								



Scoreboard Example: Cycle 6

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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:

<i>al unit status:</i>			<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU</i>	<i>FU</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>	<i>Rj</i>	<i>Rk</i>
	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	<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
6	<i>FU</i>	Mult1	Integer						



Scoreboard Example: Cycle 7

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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:

<i>al unit status:</i>			<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU</i>	<i>FU</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>	<i>Rj</i>	<i>Rk</i>
	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	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>
7	<i>FU</i>	Mult1	Integer			Add				

- Read multiply operands?

Scoreboard Example: Cycle 8a

(First half of clock cycle)



Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	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		<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
8	<i>FU</i>	<div><div>Mult1 Integer Add Divide</div></div>								



Scoreboard Example: Cycle 8b

(Second half of clock cycle)

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	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	<i>F0</i>	<i>F2</i>	<i>F4</i>	<i>F6</i>	<i>F8</i>	<i>F10</i>	<i>F12</i>	...	<i>F30</i>
8	<div> <div>FU</div> <div>Mult1</div> <div>Add</div> <div>Divide</div> </div>								



Scoreboard Example: Cycle 9

Instruction status:

Read Exec Write

Instruction	j	k	Issue	Oper	Comp	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								
Note	→	10 Mult1	Yes	Mult	F0	F2	F4			Yes	Yes
Remaining		Mult2	No								
		2 Add	Yes	Sub	F8	F6	F2			Yes	Yes
		Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
9	<i>FU</i>	Mult1AddDivide								

- Read operands for MULT & SUB? Issue ADDD?



Scoreboard Example: Cycle 10

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
9	Mult1	Yes	Mult	F0	F2	F4			No	No
	Mult2	No								
1	Add	Yes	Sub	F8	F6	F2			No	No
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
10	<i>FU</i> Mult1				Add	Divide			



Scoreboard Example: Cycle 11

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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:

<i>al unit status:</i>			<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU</i>	<i>FU</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>	<i>Rj</i>	<i>Rk</i>
	Integer	No								
8	Mult1	Yes	Mult	F0	F2	F4			No	No
	Mult2	No								
0	Add	Yes	Sub	F8	F6	F2			No	No
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
11	<i>FU</i>	Mult1				Add	Divide			



Scoreboard Example: Cycle 12

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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:

<i>al unit status:</i>			<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU</i>	<i>FU</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>	<i>Rj</i>	<i>Rk</i>
	Integer	No								
7	Mult1	Yes	Mult	F0	F2	F4			No	No
	Mult2	No								
	Add	No								
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
12	<i>FU</i> Mult1					Divide			

- Read operands for DIVD?



Scoreboard Example: Cycle 13

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
6	Mult1	Yes	Mult	F0	F2	F4			No	No
	Mult2	No								
	Add	Yes	Add	F6	F8	F2			Yes	Yes
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
13	FU Mult1			Add		Divide			



Scoreboard Example: Cycle 14

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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:

<i>al unit status:</i>			<i>dest</i>	<i>S1</i>	<i>S2</i>	<i>FU</i>	<i>FU</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>	<i>Rj</i>	<i>Rk</i>
	Integer	No								
5	Mult1	Yes	Mult	F0	F2	F4			No	No
	Mult2	No								
2	Add	Yes	Add	F6	F8	F2			Yes	Yes
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
14	FU	Mult1			Add		Divide			



Scoreboard Example: Cycle 15

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
4	Mult1	Yes	Mult	F0	F2	F4			No	No
	Mult2	No								
1	Add	Yes	Add	F6	F8	F2			No	No
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
15	<i>FU</i>	Mult1			Add		Divide			



Scoreboard Example: Cycle 16

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
3	Mult1	Yes	Mult	F0	F2	F4			No	No
	Mult2	No								
0	Add	Yes	Add	F6	F8	F2			No	No
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
16	<i>FU</i>	Mult1			Add		Divide			



Scoreboard Example: Cycle 17

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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 Hazard!

Functional unit status:

al 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			No	No
	Mult2	No								
	Add	Yes	Add	F6	F8	F2			No	No
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
17	<i>FU</i>	Mult1			Add		Divide			

- **Why not write result of ADD???**



Scoreboard Example: Cycle 18

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
1	Mult1	Yes	Mult	F0	F2	F4			No	No
	Mult2	No								
	Add	Yes	Add	F6	F8	F2			No	No
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
18	<i>FU</i> Mult1			Add		Divide			



Scoreboard Example: Cycle 19

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
0	Mult1	Yes	Mult	F0	F2	F4			No	No
	Mult2	No								
	Add	Yes	Add	F6	F8	F2			No	No
	Divide	Yes	Div	F10	F0	F6	Mult1		No	Yes

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>
19	<i>FU</i>	Mult1			Add		Divide			



Scoreboard Example: Cycle 20

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	Yes	Add	F6	F8	F2			No	No
	Divide	Yes	Div	F10	F0	F6			Yes	Yes

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>
20	<i>FU</i>	Add				Divide				



Scoreboard Example: Cycle 21

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	Yes	Add	F6	F8	F2			No	No
	Divide	Yes	Div	F10	F0	F6			Yes	Yes

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>
21	<i>FU</i>				Add		Divide			

- **WAR Hazard is now gone...**



Scoreboard Example: Cycle 22

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</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			No	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>
22	FU Divide								



**Faster than light computation
(skip a couple of cycles)**



Scoreboard Example: Cycle 61

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
	Mult1	No								
	Mult2	No								
	Add	No								
	0Divide	Yes	Div	F10	F0	F6			No	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>
61	<i>FU</i>								

Divide



Scoreboard Example: Cycle 62

Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	<i>Issue</i>	<i>Oper</i>	<i>Comp</i>	<i>Result</i>
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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
	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>
62	<i>FU</i>								

Review: Scoreboard Example: Cycle 62



Instruction status:

Read Exec Write

Instruction	<i>j</i>	<i>k</i>	Issue	Oper	Comp	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:

<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</i> <i>Qj</i>	<i>FU</i> <i>Qk</i>	<i>Fj?</i> <i>Rj</i>	<i>Fk?</i> <i>Rk</i>
	Integer	No								
	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>
62	FU								

- In-order issue; out-of-order execute & commit



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