CS152 – Computer Architecture and Engineering
Lecture 16 – Advanced Pipelining 2

2003-10-21

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Summary #1/2: Compiler techniques for parallelism

- Loop unrolling ⇒ Multiple iterations of loop in SW:
  - Amortizes loop overhead over several iterations
  - Gives more opportunity for scheduling around stalls
- Very Long Instruction Word machines (VLIW)
  ⇒ Multiple operations coded in single, long instruction
  - Requires sophisticated compiler to decide which operations can be done in parallel
  - Trace scheduling ⇒ find common path and schedule code as if branches didn't exist (+ add "fixup code")
- All of these require additional registers

Your Project Choice

- Superpipelined
- Superscalar
- Out-of-order execution

Reduce pipeline stalls for cache miss, hazards ?

- Key idea: Allow instructions behind stall to proceed:

```
DIVD    F0,F2,F4
ADDD    F10,F0,F8
SUBD    F12,F8,F14
```

- Or

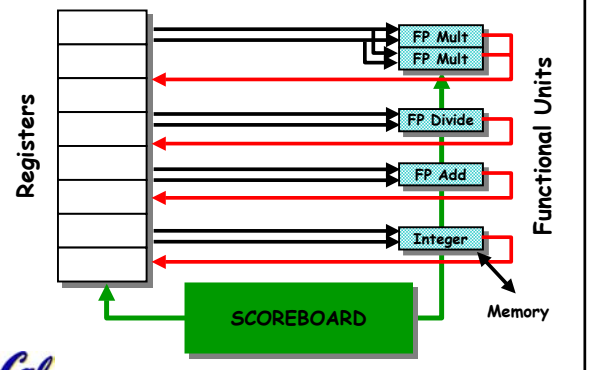
```
LW      F0,0(R1) # cache miss
ADDD    F10,F0,F8
SUBD    F12,F8,F14
```

- Out-of-order execution => out-of-order completion.
- Disadvantages?
  - Complexity
  - Precise interrupts harder!
- Why in HW at run time?
  - Works when can't know real dependence at compile time
  - Compiler simpler
  - Code for one machine runs well on another

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
- Instructions execute whenever not dependent on previous instructions and no hazards.
  - Scoreboards date to CDC 6600 in 1963
- 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)



Scoreboard Implications

- Out-of-order completion => WAR, WAW hazards?
- Solutions for WAR:
  - –Stall writeback until registers have been read
  - –Read registers only during Read Operands stage
- Solution for WAW:
  - –Detect hazard and stall issue of new instruction until other instruction completes
- Need to have multiple instructions in execution phase => multiple execution units or pipelined execution units
- Scoreboard keeps track of dependencies between instructions that have already issued.
- Scoreboard replaces ID, EX, WB with 4 stages

Unlike newer techniques, no register renaming!

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)

Example:

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

CDC 6600 scoreboard would stall SUBD until DIVD completes

Four Stages of Scoreboard Control

- 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.
  - Example:

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

CDC 6600 scoreboard would stall ADDD until DIVD completes

  - No forwarding of data in this model!
    - But it writes as soon as execution completes vs. delaying for extra stages

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,F4,F8
SUBD F8,F8,F14
```

CDC 6600 scoreboard would stall SUBD until ADDD reads operands

Administrivia

- Design full cache, but only simulation on Friday 10/24; demo board Friday 10/31
- Thur 11/6: Design Doc for Final Project due
  - Deep pipeline? Superscalar? Out-of-order?
  - Read section 4.2 from CA:AQA 2/e
- Fri 11/14: Demo Project modules
- Wed 11/19: 5:30 PM Midterm 2 in 1 LeConte
- Tues 11/22: Field trip to Xilinx
- CS 152 Project week: 12/1 to 12/5
  - Mon: TA Project demo, Tue: 30 min Presentation, Wed: Processor racing, Fri: Written report

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 functional unit is busy or not
  - Op: Operation to perform in the unit (e.g., + or –)
  - Fi: Destination register for a F.U.
  - Fj,Fk: Source-register numbers for a F.U.
  - Qj,Qk: Functional units producing source registers Fj, Fk
  - Rj,Rk: Flags indicating when registers Fj, Fk are ready for FU to ready them; if yes, others can't write
- Register result status—Indicates which functional unit will write each register, if one exists. Blank when no pending instructions will write that register

Detailed Scoreboard Pipeline Control

Instruction status	Wait until	Bookkeeping
Issue	Not busy (FU) and not result(D) *(No structural hazard and no WAW hazard)*	Busy(FU)← yes; Op(FU)← op; Fi(FU)← `D'; Fj(FU)← `S1'; Fk(FU)← `S2'; Result('D')← FU; Qj← Result('S1'); Qk← Result(`S2'); Rj← not Qj; Rk← not Qk;*
Read operands	Rj and Rk *(No RAW hazard)*	Rj← No; Rk← No; Qj← 0; Qk← 0; *(Registers available for others to write)*
Execution complete	Functional unit done	
Write result	∀f((Fj(f)≠Fi(FU) or Rj(f)=No) & (Fk(f) ≠Fi(FU) or Rk(f)=No)) *(No WAR hazard)*	∀f(if Qj(f)=FU then Rj(f)← Yes); ∀f(if Qk(f)=FU then Rj(f)← Yes); Result(Fi(FU))← 0; Busy(FU)← No *(For all other FUs, if waiting to for this FU to write register, mark source register ready. For this FU, reset destination, mark not busy)*

* (*Issue bookkeeping: Mark FU busy, Mark FU operation, Set FU register numbers, Set result register status to being written by this FU, Copy register write status of source registers into Qj,Qk fields, Mark FU source registers as ready if no other FU is writing them)*

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				

Notes: 5 FU.
Integer includes LD,SD
Latency: Add 2,
Multiply 10, Divide 40

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 Oper	Exec Comp	Write 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:

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
2	FU			Integer					

- **Issue 2nd LD?**

Scoreboard Example: Cycle 3

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
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:

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

Register result status:

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

- **Issue MULT?**

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								

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							

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							

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

Read multiply operands?

Scoreboard Example: Cycle 8a (First half of clock cycle)

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			

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

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			

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:

Time Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
Integer	No								
Note Remaining → 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 & SUB? Issue ADDD?

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

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			No	No
	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?

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

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

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

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

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

Why not write result of ADD???

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

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			No	No
	Divide	Yes	Div	F10	F0	F6			Yes	Yes

Register result status:

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

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			No	No
	Divide	Yes	Div	F10	F0	F6			Yes	Yes

Register result status:

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

WAR 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			No	No

Register result status:

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

Faster than light computation
(skip a couple of 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			No	No

Register result status:

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

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									

Review: 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 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
- Next time: out-of-order without limits of above

Scoreboard Example 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1				
MULTD	F4	F2	F0				
LD	F6	0	R2				
ADDD	F6	F4	F6				
SD		F6	R2				

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									

PRS: State Example 2

What is Instruction Status at end of Clock 5?

Instruction status:

Instruction		j	k	1)	2)	3)	4)	5)	6)
LD	F2	0	R1	Exec. Complete	Exec. Complete	Wrote Result	Wrote Result	Wrote Result	none
MULTD	F4	F2	F0	Read Operands	Read Operands	Read Operands	Read Operands	Read Operands	as
LD	F6	0	R2	Not Issued	Issued	Issued	Exec. Complete	Exec. Complete	above
ADDD	F6	F4	F6	Not Issued	Not Issued	Not Issued	Issued	Issued	
SD		F6	R2	Not Issued	Not Issued	Not Issued	Not Issued	Issued	

Scoreboard Example 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1	1			
MULTD	F4	F2	F0				
LD	F6	0	R2				
ADDD	F6	F4	F6				
SD		F6	R2				

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		R1				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 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1	1	2		
MULTD	F4	F2	F0	2			
LD	F6	0	R2				
ADDD	F6	F4	F6				
SD		F6	R2				

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		R1				Yes
	Mult1	Yes	Mult	F4	F2	F0	Integer		No	Yes
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1	1	2	3	
MULTD	F4	F2	F0	2			
LD	F6	0	R2				
ADDD	F6	F4	F6				
SD		F6	R2				

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		R1				No
	Mult1	Yes	Mult	F4	F2	F0	Integer		No	Yes
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1	1	2	3	4
MULTD	F4	F2	F0	2			
LD	F6	0	R2				
ADDD	F6	F4	F6				
SD		F6	R2				

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	F4	F2	F0			Yes	Yes
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5		
LD F6	0	R2	5			
ADDD F6	F4	F6				
SD	F6	R2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	FU Ok	Fj? Rj	Fk? Rk
	Integer	Yes	Load	F6		R2				Yes
10	Mult1	Yes	Mult	F4	F2	F0			No	No
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5		
LD F6	0	R2	5	6		
ADDD F6	F4	F6				
SD	F6	R2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	FU Ok	Fj? Rj	Fk? Rk
	Integer	Yes	Load	F6		R2				No
9	Mult1	Yes	Mult	F4	F2	F0			No	No
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5		
LD F6	0	R2	5	6	7	
ADDD F6	F4	F6				
SD	F6	R2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	FU Ok	Fj? Rj	Fk? Rk
	Integer	Yes	Load	F6		R2				No
8	Mult1	Yes	Mult	F4	F2	F0			No	No
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

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

- Issue ADDD?

PRS: State Example 2

What is Instruction Status at end of Clock 10?

Instruction status:

Instruction	j	k	1)	2)	3)	4)	5)
LD F2	0	R1	Wrote Result	Wrote Result	Wrote Result	Wrote Result	Wrote Result
MULTD F4	F2	F0	Read Operands	Read Operands	Read Operands	Read Operands	Read Operands
LD F6	0	R2	Exec. Complete	Wrote Result	Wrote Result	Wrote Result	Wrote Result
ADDD F6	F4	F6	Not Issued	Issued	Issued	Read Operands	Read Operands
SD	F6	R2	Not Issued	Not Issued	Issued	Issued	Read Operands

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5		
LD F6	0	R2	5	6	7	8
ADDD F6	F4	F6				
SD	F6	R2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	FU Ok	Fj? Rj	Fk? Rk
	Integer	No								
7	Mult1	Yes	Mult	F4	F2	F0			No	No
	Mult2	No								
	Add	No								
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5		
LD F6	0	R2	5	6	7	8
ADDD F6	F4	F6	9			
SD	F6	R2				

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	FU Ok	Fj? Rj	Fk? Rk
	Integer	No								
6	Mult1	Yes	Mult	F4	F2	F0			No	No
	Mult2	No								
	Add	Yes	Add	F6	F4	F6	Mult1		No	Yes
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1	1	2	3	4
MULTD	F4	F2	F0	2	5		
LD	F6	0	R2	5	6	7	8
ADDD	F6	F4	F6	9			
SD		F6	R2	10			

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	FU Ok	Fj? Rj	Fk? Rk
	Integer	Yes	SD		F6	R2	Add		No	Yes
5	Mult1	Yes	Mult	F4	F2	F0			No	No
	Mult2	No								
	Add	Yes	Add	F6	F4	F6	Mult1		No	Yes
	Divide	No								

Register result status:

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

PRS: State Example 2

What is Instruction Status at end of Clock 17?

Instruction status:

Instruction		j	k	1)	2)	3)	4)	5)
LD	F2	0	R1	Wrote Result	Wrote Result	Wrote Result	Wrote Result	Wrote Result
MULTD	F4	F2	F0	Exec. Complete	Wrote Result	Wrote Result	Wrote Result	Wrote Result
LD	F6	0	R2	Wrote Result	Wrote Result	Wrote Result	Wrote Result	Wrote Result
ADDD	F6	F4	F6	Issued	Issued	Read Operands	Exec. Complete	Wrote Result
SD		F6	R2	Issued	Issued	Issued	Issued	Read Operands

Faster than light computation
(skip a couple of cycles)

Scoreboard Example 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1	1	2	3	4
MULTD	F4	F2	F0	2	5		
LD	F6	0	R2	5	6	7	8
ADDD	F6	F4	F6	9			
SD		F6	R2	10			

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	FU Ok	Fj? Rj	Fk? Rk
	Integer	Yes	SD		F6	R2	Add		No	Yes
1	Mult1	Yes	Mult	F4	F2	F0			No	No
	Mult2	No								
	Add	Yes	Add	F6	F4	F6	Mult1		No	Yes
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1	1	2	3	4
MULTD	F4	F2	F0	2	5	15	
LD	F6	0	R2	5	6	7	8
ADDD	F6	F4	F6	9			
SD		F6	R2	10			

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	FU Ok	Fj? Rj	Fk? Rk
	Integer	Yes	SD		F6	R2	Add		No	Yes
0	Mult1	Yes	Mult	F4	F2	F0			No	No
	Mult2	No								
	Add	Yes	Add	F6	F4	F6	Mult1		No	Yes
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1	1	2	3	4
MULTD	F4	F2	F0	2	5	15	16
LD	F6	0	R2	5	6	7	8
ADDD	F6	F4	F6	9			
SD		F6	R2	10			

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	FU Ok	Fj? Rj	Fk? Rk
	Integer	Yes	SD		F6	R2	Add		No	Yes
0	Mult1	No								
	Mult2	No								
	Add	Yes	Add	F6	F4	F6			Yes	Yes
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5	15	16
LD F6	0	R2	5	6	7	8
ADDD F6	F4	F6	9	17		
SD	F6	R2	10			

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	Yes	SD		F6	R2	Add		No	Yes
	Mult1	No								
	Mult2	No								
2	Add	Yes	Add	F6	F4	F6			Yes	Yes
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5	15	16
LD F6	0	R2	5	6	7	8
ADDD F6	F4	F6	9	17		
SD	F6	R2	10			

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	Yes	SD		F6	R2	Add		No	Yes
	Mult1	No								
	Mult2	No								
1	Add	Yes	Add	F6	F4	F6			Yes	Yes
	Divide	No								

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5	15	16
LD F6	0	R2	5	6	7	8
ADDD F6	F4	F6	9	17	19	
SD	F6	R2	10			

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Qj	FU Qk	Fj? Rj	Fk? Rk
	Integer	Yes	SD		F6	R2	Add		No	Yes
	Mult1	No								
	Mult2	No								
0	Add	Yes	Add	F6	F4	F6			Yes	Yes
	Divide	No								

Register result status:

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
19	FU				Add					

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5	15	16
LD F6	0	R2	5	6	7	8
ADDD F6	F4	F6	9	17	19	20
SD	F6	R2	10			

Functional unit status:

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

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5	15	16
LD F6	0	R2	5	6	7	8
ADDD F6	F4	F6	9	17	19	20
SD	F6	R2	10	21		

Functional unit status:

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

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction	j	k	Issue	Read Oper	Exec Comp	Write Result
LD F2	0	R1	1	2	3	4
MULTD F4	F2	F0	2	5	15	16
LD F6	0	R2	5	6	7	8
ADDD F6	F4	F6	9	17	19	20
SD	F6	R2	10	21	22	

Functional unit status:

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

Register result status:

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

Scoreboard Example 2

Instruction status:

Instruction		j	k	Issue	Read Oper	Exec Comp	Write Result
LD	F2	0	R1	1	2	3	4
MULTD	F4	F2	F0	2	5	15	16
LD	F6	0	R2	5	6	7	8
ADDD	F6	F4	F6	9	17	19	20
SD		F6	R2	10	21	22	23

Functional unit status:

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU Oj	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
23	FU									

Peer: SP v. SS v. Scoreboard (SB)

- Which are true? (SP = superpipeline, SC= superscalar)

A. SB should have a better clock rate vs. just SP

B. SB should have a better CPI vs. just SS

C. SB works better with SP than with SS

1. ABC: FFF
2. ABC: FFT
3. ABC: FTF
4. ABC: FTT
5. ABC: TFF
6. ABC: TFT
7. ABC: TTF
8. ABC: TTT

Scoreboard Summary

- HW exploiting ILP (Instruction Level Parallelism)
  - Works when can't know dependence at compile time.
  - Code for one machine runs well on another
- Key idea of Scoreboard: Allow instructions behind stall to proceed (Decode => Issue instruction & read operands)
  - Enables out-of-order execution => out-of-order completion (but in order execution)
  - ID stage checked both for structural & data dependencies
  - Original version didn't handle forwarding.
  - No automatic register renaming = WAW, WAR stalls