Lecture 4: Tomasulo Algorithm and Dynamic Branch Prediction

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Computer Science 252

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Review: Summary

- Instruction Level Parallelism (ILP) in SW or HW
- Loop level parallelism is easiest to see
- SW parallelism dependencies defined for program, hazards if HW cannot resolve
- SW dependencies/compiler sophistication determine if compiler can unroll loops
  - Memory dependencies hardest to determine
- HW exploiting ILP
  - Works when can't know dependence at run time
  - Code for one machine runs well on another
- Key idea of Scoreboard: Allow instructions behind stall to proceed (Decode => Issue instr & read operands)
  - Enables out-of-order execution => out-of-order completion
  - ID stage checked both for structural & data dependencies

Review: 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**

Review: 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				
MULT	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 Qj	FU for 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 MULT? No, stall on structural hazard**

Review: Scoreboard Example Cycle 9

Instruction status

Instruction	j	k	Issue	Read operanc	Executi comple	Write 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		
DIVD F10	F0	F6	8			
ADDD F6	F8	F2				

Functional unit status

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU for Qj	FU for k 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 MULT & SUBD? Issue ADDD?**

Review: Scoreboard Example Cycle 17

Instruction status

Instruction		j	k	Issue	Read operanc	Executi comple	Write 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	16	

Functional unit status

Time	Name	Busy	Op	dest Fi	S1 Fj	S2 Fk	FU for Qj	FU for k 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			

- **Write result of ADDD? No, WAR hazard**

Review: Scoreboard Example Cycle 62

Instruction status

Instruction		j	k	Issue	Read operand	Execution complete	Write 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

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

Register result status

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

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

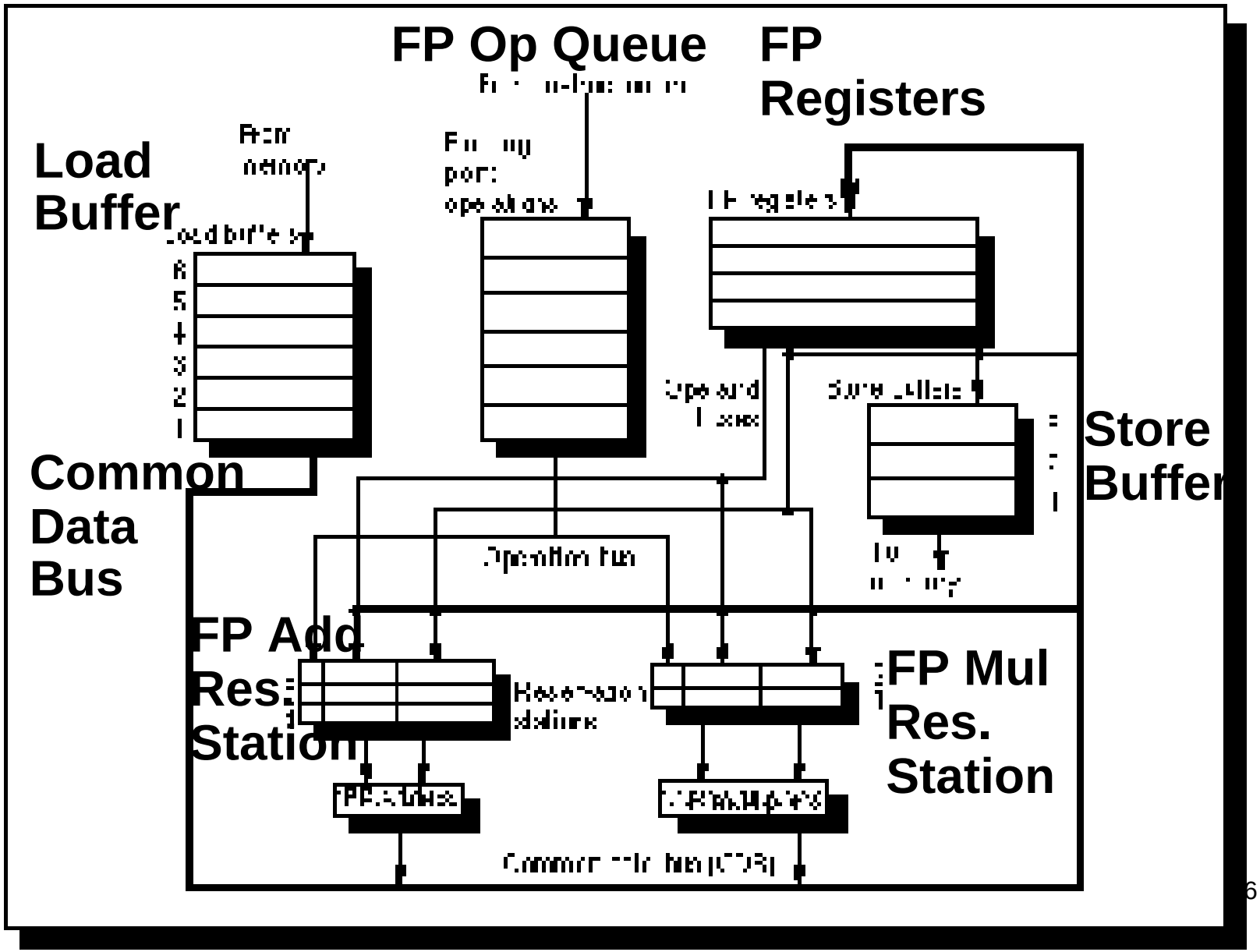
Review: Scoreboard Summary

- **Speedup 1.7 from compiler; 2.5 by hand**
  BUT slow memory (no cache)
- **Limitations of 6600 scoreboard**
  - **No forwarding (First write regsiter then read it)**
  - **Limited to instructions in basic block (small *window*)**
  - **Number of functional units(structural hazards)**
  - **Wait for WAR hazards**
  - **Prevent WAW hazards**

Another Dynamic Algorithm: Tomasulo Algorithm

- For IBM 360/91 about 3 years after CDC 6600 (1966)
- Goal: High Performance without special compilers
- Differences between IBM 360 & CDC 6600 ISA
  - IBM has only 2 register specifiers/instr vs. 3 in CDC 6600
  - IBM has 4 FP registers vs. 8 in CDC 6600
- Differences between Tomasulo Algorithm & Scoreboard
  - Control & buffers *distributed* with Function Units vs. centralized in scoreboard; called "reservation stations"
  - Registers in instructions replaced by pointers to reservation station buffer
  - HW *renaming* of registers to avoid WAR, WAW hazards
  - Common Data Bus broadcasts results to all FUs
  - Load and Stores treated as FUs as well
- Why Study? It lead to Pentium Pro, PowerPC 604, …

Tomasulo Organization



Reservation Station Components

Op—Operation to perform in the unit (e.g., + or –)

Qj, Qk—Reservation stations producing source registers (value to be written)

Vj, Vk—Value of Source operands

Rj, Rk—Flags indicating when Vj, Vk are ready

Busy—Indicates reservation station and FU is busy

Register result status—Indicates which functional unit will write each register, if one exists. Blank when no pending instructions that will write that register.

Three Stages of Tomasulo Algorithm

1. **Issue—get instruction from FP Op Queue**

   If reservation station free (no structural hazard), the scoreboard issues instr & sends operands (renames registers).

2. **Execution—operate on operands (EX)**

   When both operands ready then execute;
   if not ready, watch CDB for result

3. **Write result—finish execution (WB)**

   Write on Common Data Bus to all awaiting units;
   mark reservation station available

- **Normal bus: data + destination**
  Common Data Bus: data + *source*:
  Normal = "Go To" bus; CDB = "Come From" bus

Tomasulo Example Cycle 0

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2					Load1	No			
LD	F2	45+	R3					Load2	No			
MULT	F0	F2	F4					Load3	No			
SUBD	F8	F6	F2									
DIVD	F10	F0	F6									
ADDD	F6	F8	F2									

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for j Qj*	*RS for k Qk*				
	0	Add1	No									
	0	Add2	No									
	0	Add3	No									
	0	Mult1	No									
	0	Mult2	No									

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

CS 252 Administrivia

- **Reading Assignments for Lectures 3 to 6**
  - **Computer Architecture: A Quantitative Approach, Second Edition (1996)**
  - **Chapter 4, Appendix B**
- **Exercises for Lectures 3 to 6**
  - **4.14, all parts (a - k)**
  - **4.25, table of pros and cons + short essay**
  - **B.3, all parts (a - g)**
  - **B.15, table of pros and cons + short essay**
  - **Due Monday September 16 at 5PM homework box in 283 Soda (building is locked at 6:45 PM)**
  - **Done in pairs, but both need to understand whole assignment**
  - **Study groups encouraged, but pairs do own work**

Tomasulo Example Cycle 1

Instruction status

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

	Busy	Address
Load1	Yes	34+R2
Load2	No	
Load3	No	

Reservation Stations

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

Register result status

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
1	FU				Load1					

Tomasulo Example Cycle 2

Instruction status

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

	Busy	Address
Load1	Yes	34+R2
Load2	Yes	45+R3
Load3	No	

Reservation Stations

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

Register result status

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
2	FU		Load2		Load1					

Tomasulo Example Cycle 3

Instruction status

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

	Busy	Address
Load1	Yes	34+R2
Load2	Yes	45+R3
Load3	No	

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for j Qj	RS for k Qk
0	Add1	No					
0	Add2	No					
	Add3	No					
0	Mult1	Yes	MULTD		R(F4)	Load2	
0	Mult2	No					

Register result status

Clock		F0	F2	F4	F6	F8	F10	F12	...	F30
3	FU	Mult1	Load2		Load1					

- **Issue MULT now vs in scoreboard?**

Tomasulo Example Cycle 4

Instruction status					Execution	Write					
Instruction		j	k	Issue	complete	Result			Busy	Address	
LD	F6	34+	R2	1	3	4		Load1	No		
LD	F2	45+	R3	2	4			Load2	Yes	45+R3	
MULT	F0	F2	F4	3				Load3	No		
SUBD	F8	F6	F2	4							
DIVD	F10	F0	F6								
ADDD	F6	F8	F2								

Reservation Stations					S1	S2	RS for j	RS for k				
	Time	Name	Busy	Op	Vj	Vk	Qj	Qk				
	0	Add1	Yes	SUBD	M(34+R2)			Load2				
	0	Add2	No									
		Add3	No									
	0	Mult1	Yes	MULTD		R(F4)	Load2					
	0	Mult2	No									

Register result status											
Clock			F0	F2	F4	F6	F8	F10	F12	...	F30
4		FU	Mult1	Load2		M(34+R2)	Add1				

Tomasulo Example Cycle 5

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4								
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2									

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for j Qj*	*RS for k Qk*				
	2	Add1	Yes	SUBD	M(34+R2)	M(45+R3)						
	0	Add2	No									
		Add3	No									
	10	Mult1	Yes	MULTD	M(45+R3)	R(F4)						
	0	Mult2	Yes	DIVD		M(34+R2)	Mult1					

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
5			*FU*	Mult1	M(45+R3)		M(34+R2)	Add1	Mult2			

Tomasulo Example Cycle 6

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4								
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6								

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

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

- **Issue MULT vs. scoreboard?**

Tomasulo Example Cycle 7

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4	7							
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6								

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

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

Tomasulo Example Cycle 8

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6								

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

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	*...*	*F30*
8			*FU*	Mult1	M(45+R3)		Add2	M()-M()	Mult2			

Tomasulo Example Cycle 9

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6								

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for j Qj*	*RS for k Qk*				
	0	Add1	No									
	1	Add2	Yes	ADDD	M()–M()	M(45+R3)						
	0	Add3	No									
	6	Mult1	Yes	MULTD	M(45+R3)	R(F4)						
	0	Mult2	Yes	DIVD		M(34+R2)	Mult1					

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	*...*	*F30*
9			*FU*	Mult1	M(45+R3)		Add2	M()–M()	Mult2			

Tomasulo Example Cycle 10

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6	10							

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for j Qj*	*RS for k Qk*				
	0	Add1	No									
	0	Add2	Yes	ADDD	M()–M()	M(45+R3)						
	0	Add3	No									
	5	Mult1	Yes	MULTD	M(45+R3)	R(F4)						
	0	Mult2	Yes	DIVD		M(34+R2)	Mult1					

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	*...*	*F30*
10			*FU*	Mult1	M(45+R3)		Add2	M()–M()	Mult2			

Tomasulo Example Cycle 11

Instruction status

Instruction		j	k	Issue	Execution complete	Write Result			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6	10	11						

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for j Qj	RS for k Qk				
	0	Add1	No									
	1	Add2	No									
	0	Add3	No									
	4	Mult1	Yes	MULTD	M(45+R3)	R(F4)						
	0	Mult2	Yes	DIVD		M(34+R2)	Mult1					

Register result status

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

- **Write result of ADDD vs. scoreboard?**

Tomasulo Example Cycle 12

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4	6	7						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6	10	11						

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for j Qj*	*RS for k Qk*				
	0	Add1	No									
	0	Add2	No									
	0	Add3	No									
	3	Mult1	Yes	MULTD	M(45+R3)	R(F4)						
	0	Mult2	Yes	DIVD		M(34+R2)	Mult1					

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
12			*FU*	Mult1	M(45+R3)		(M-M)+M()	M()–M()	Mult2			

Tomasulo Example Cycle 13

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6	10	11						

Reservation Stations					*S1*	*S2*	*RS for j*	*RS for k*				
	Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*				
	0	Add1	No									
	0	Add2	No									
		Add3	No									
	2	Mult1	Yes	MULTD	M(45+R3)	R(F4)						
	0	Mult2	Yes	DIVD		M(34+R2)	Mult1					

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	*...*	*F30*
13			*FU*	Mult1	M(45+R3)		(M–M)+M()	M()–M()	Mult2			

Tomasulo Example Cycle 14

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3				Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6	10	11						

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for j Qj*	*RS for k Qk*				
	0	Add1	No									
	0	Add2	No									
	0	Add3	No									
	1	Mult1	Yes	MULTD	M(45+R3)	R(F4)						
	0	Mult2	Yes	DIVD		M(34+R2)	Mult1					

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
14			*FU*	Mult1	M(45+R3)		(M–M)+M()	M()–M()	Mult2			

Tomasulo Example Cycle 15

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3	15			Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6	10	11						

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

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	*...*	*F30*
15			*FU*	Mult1	M(45+R3)		(M–M)+M()	M()–M()	Mult2			

Tomasulo Example Cycle 16

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3	15	16		Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6	10	11						

Reservation Stations					*S1*	*S2*	*RS for j*	*RS for k*				
	Time	*Name*	*Busy*	*Op*	*Vj*	*Vk*	*Qj*	*Qk*				
	0	Add1	No									
	0	Add2	No									
		Add3	No									
	0	Mult1	No									
	40	Mult2	Yes	DIVD	M*F4	M(34+R2)						

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	*...*	*F30*
16			*FU*	M*F4	M(45+R3)		(M–M)+M()	M()–M()	Mult2			

Tomasulo Example Cycle 55

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3	15	16		Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5								
ADDD	F6	F8	F2	6	10	11						

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for j Qj*	*RS for k Qk*				
	0	Add1	No									
	0	Add2	No									
		Add3	No									
	0	Mult1	No									
	1	Mult2	Yes	DIVD	M*F4	M(34+R2)						

Register result status												
Clock			*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*	
55			*FU*	M*F4	M(45+R3)		(M–M)+M()	M()–M()	Mult2			

Tomasulo Example Cycle 56

Instruction status												
Instruction		*j*	*k*	*Issue*	*Execution complete*	*Write Result*			Busy	Address		
LD	F6	34+	R2	1	3	4		Load1	No			
LD	F2	45+	R3	2	4	5		Load2	No			
MULT	F0	F2	F4	3	15	16		Load3	No			
SUBD	F8	F6	F2	4	7	8						
DIVD	F10	F0	F6	5	56							
ADDD	F6	F8	F2	6	10	11						

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for j Qj*	*RS for k Qk*				
	0	Add1	No									
	0	Add2	No									
		Add3	No									
	0	Mult1	No									
	0	Mult2	Yes	DIVD	M*F4	M(34+R2)						

Register result status												
Clock				*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
56			*FU*	M*F4	M(45+R3)		(M–M)+M()	M()–M()	Mult2			

Tomasulo Example Cycle 57

Instruction status					Execution	Write					
Instruction		j	k	Issue	complete	Result			Busy	Address	
LD	F6	34+	R2	1	3	4		Load1	No		
LD	F2	45+	R3	2	4	5		Load2	No		
MULT	F0	F2	F4	3	15	16		Load3	No		
SUBD	F8	F6	F2	4	7	8					
DIVD	F10	F0	F6	5	56	57					
ADDD	F6	F8	F2	6	10	11					

Reservation Stations					S1	S2	RS for j	RS for k				
	Time	Name	Busy	Op	Vj	Vk	Qj	Qk				
	0	Add1	No									
	0	Add2	No									
		Add3	No									
	0	Mult1	No									
	0	Mult2	No									

Register result status												
Clock				F0	F2	F4	F6	F8	F10	F12	...	F30
57			FU	M*F4	M(45+R3)		(M–M)+M()	M()–M()	M*F4/M			

Compare to Scoreboard Cycle 62

Instruction status

Instruction		j	k	Issue	Read operand	Execution complete	Write 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

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

Register result status

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

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

Tomasulo Loop Example

```
Loop: LD      F0    0     R1
      MULTD   F4    F0    F2
      SD      F4    0     R1
      SUBI    R1    R1    #8
      BNEZ    R1    Loop
```

- Multiply takes 4 clocks
- Assume loads talke 8 clocks (cache miss)

Loop Example Cycle 0

Instruction status

Instruction	j	k	iteration	Issue	Execution complete	Write Result
LD F0	0	R1	1			
MULT F4	F0	F2	1			
SD F4	0	R1	1			
LD F0	0	R1	2			
MULT F4	F0	F2	2			
SD F4	0	R1	2			

	Busy	Address	Qi
Load1	No		
Load2	No		
Load3	No		
Store1	No		
Store2	No		
Store3	No		

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
0	Mult1	No					
0	Mult2	No					

Code:

```
LD    F0   0  R1
MULT  F4   F0 F2
SD    F4   0  R1
SUBI  R1   R1 #8
BNEZ  R1   Loop
```

Register result status

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

5 minute Class Break

- **Lecture Format:**
  - **≈ 1 minute: review last time & motivate this lecture**
  - **≈ 20 minute lecture**
  - **≈ 3 minutes: discuss class manangement**
  - **≈ 25 minutes: lecture**
  - **5 minutes: break**
  - **≈25 minutes: lecture**
  - **≈1 minute: summary of today's important topics**

Loop Example Cycle 1

Instruction status

Instruction	j	k	iteration	Issue	Execution complete	Write Result
LD F0	0	R1	1	1		
MULT F4	F0	F2	1			
SD F4	0	R1	1			
LD F0	0	R1	2			
MULT F4	F0	F2	2			
SD F4	0	R1	2			

	Busy	Address	Qi
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	No		
Store2	No		
Store3	No		

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
0	Mult1	No					
0	Mult2	No					

Code:

```
LD   F0   0  R1
MULT F4   F0 F2
SD   F4   0  R1
SUBI R1   R1 #8
BNEZ R1   Loop
```

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12 ...	F30
1	80	Qi	Load1							

Loop Example Cycle 2

Instruction status

Instruction	j	k	iteration	Issue	Execution complete	Write Result
LD F0	0	R1	1	1		
MULT F4	F0	F2	1	2		
SD F4	0	R1	1			
LD F0	0	R1	2			
MULT F4	F0	F2	2			
SD F4	0	R1	2			

	Busy	Address	Qi
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	No		
Store2	No		
Store3	No		

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
0	Mult1	Yes	MULTD		R(F2)	Load1	
0	Mult2	No					

Code:

```
LD    F0   0  R1
MULT  F4   F0 F2
SD    F4   0  R1
SUBI  R1   R1 #8
BNEZ  R1   Loop
```

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12 ...	F30
2	80	Qi	Load1		Mult1					

Loop Example Cycle 3

Instruction status

Instruction	j	k	iteration	Issue	Execution complete	Write Result
LD F0	0	R1	1	1		
MULT F4	F0	F2	1	2		
SD F4	0	R1	1	3		
LD F0	0	R1	2			
MULT F4	F0	F2	2			
SD F4	0	R1	2			

	Busy	Address	Qi
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
0	Mult1	Yes	MULTD		R(F2)	Load1	
0	Mult2	No					

Code:

```
LD   F0   0  R1
MULT F4   F0 F2
SD   F4   0  R1
SUBI R1   R1 #8
BNEZ R1   Loop
```

Register result status

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

Loop Example Cycle 4

Instruction status

Instruction	j	k	iteration	Issue	Execution complete	Write Result
LD F0	0	R1	1	1		
MULT F4	F0	F2	1	2		
SD F4	0	R1	1	3		
LD F0	0	R1	2			
MULT F4	F0	F2	2			
SD F4	0	R1	2			

	Busy	Address	Qi
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
0	Mult1	Yes	MULTD		R(F2)	Load1	
0	Mult2	No					

Code:

```
LD   F0   0  R1
MULT F4   F0 F2
SD   F4   0  R1
SUBI R1   R1 #8
BNEZ R1   Loop
```

Register result status

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

Loop Example Cycle 5

Instruction status

Instruction	j	k	iteration	Issue	Execution complete	Write Result
LD F0	0	R1	1	1		
MULT F4	F0	F2	1	2		
SD F4	0	R1	1	3		
LD F0	0	R1	2			
MULT F4	F0	F2	2			
SD F4	0	R1	2			

	Busy	Address	Qi
Load1	Yes	80	
Load2	No		
Load3	No		
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
0	Mult1	Yes	MULTD		R(F2)	Load1	
0	Mult2	No					

Code:

```
LD   F0   0  R1
MULT F4   F0 F2
SD   F4   0  R1
SUBI R1   R1 #8
BNEZ R1   Loop
```

Register result status

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

Loop Example Cycle 6

Instruction status

Instruction		j	k	iteration	Issue	Execution complete	Write Result
LD	F0	0	R1	1	1		
MULT	F4	F0	F2	1	2		
SD	F4	0	R1	1	3		
LD	F0	0	R1	2	6		
MULT	F4	F0	F2	2			
SD	F4	0	R1	2			

Load1	Yes	80	
Load2	Yes	72	
Load3	No		Qi
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for k Qk
	0	Add1	No					
	0	Add2	No					
	0	Add3	No					
	0	Mult1	Yes	MULTD		R(F2)	Load1	
	0	Mult2	No					

Code:

LD	F0	0	R1
MULT	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
6	72	Qi	Load2		Mult1						

Loop Example Cycle 7

Instruction status

Instruction		j	k	iteration	Issue	Execution complete	Write Result
LD	F0	0	R1	1	1		
MULT	F4	F0	F2	1	2		
SD	F4	0	R1	1	3		
LD	F0	0	R1	2	6		
MULT	F4	F0	F2	2	7		
SD	F4	0	R1	2			

	Busy	Address	Qi
Load1	Yes	80	
Load2	Yes	72	
Load3	No		
Store1	Yes	80	Mult1
Store2	No		
Store3	No		

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for k Qk
	0	Add1	No					
	0	Add2	No					
	0	Add3	No					
	0	Mult1	Yes	MULTD		R(F2)	Load1	
	0	Mult2	Yes	MULTD		R(F2)	Load2	

Code:			
LD	F0	0	R1
MULT	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
7	72	Qi	Load2		Mult2						

Loop Example Cycle 8

Instruction status

Instruction	j	k	iteration	Issue	Execution complete	Write Result
LD F0	0	R1	1	1		
MULT F4	F0	F2	1	2		
SD F4	0	R1	1	3		
LD F0	0	R1	2	6		
MULT F4	F0	F2	2	7		
SD F4	0	R1	2	8		

	Busy	Address	Qi
Load1	Yes	80	
Load2	Yes	72	
Load3	No		
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
0	Mult1	Yes	MULTD		R(F2)	Load1	
0	Mult2	Yes	MULTD		R(F2)	Load2	

Code:

```
LD   F0   0  R1
MULT F4   F0 F2
SD   F4   0  R1
SUBI R1   R1 #8
BNEZ R1   Loop
```

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12 ...	F30
8	72	Qi	Load2		Mult2					

Loop Example Cycle 9

Instruction status

Instruction	j	k	iteration	Issue	Execution complete	Write Result
LD F0	0	R1	1	1	9	
MULT F4	F0	F2	1	2		
SD F4	0	R1	1	3		
LD F0	0	R1	2	6		
MULT F4	F0	F2	2	7		
SD F4	0	R1	2	8		

	Busy	Address	Qi
Load1	Yes	80	
Load2	Yes	72	
Load3	No		
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
0	Mult1	Yes	MULTD		R(F2)	Load1	
0	Mult2	Yes	MULTD		R(F2)	Load2	

Code:

```
LD   F0   0  R1
MULT F4   F0 F2
SD   F4   0  R1
SUBI R1   R1 #8
BNEZ R1   Loop
```

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12 ...	F30
9	64	Qi	Load2		Mult2					

Loop Example Cycle 10

Instruction status

Instruction	j	k	iteration	Issue	Execution complete	Write Result
LD F0	0	R1	1	1	9	10
MULT F4	F0	F2	1	2		
SD F4	0	R1	1	3		
LD F0	0	R1	2	6	10	
MULT F4	F0	F2	2	7		
SD F4	0	R1	2	8		

	Busy	Address	Qi
Load1	No		
Load2	Yes	72	
Load3	No		
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations

Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for Qk
0	Add1	No					
0	Add2	No					
0	Add3	No					
4	Mult1	Yes	MULTD	M(80)	R(F2)		
0	Mult2	Yes	MULTD		R(F2)	Load2	

Code:

```
LD    F0   0  R1
MULT  F4   F0 F2
SD    F4   0  R1
SUBI  R1   R1 #8
BNEZ  R1   Loop
```

Register result status

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

Loop Example Cycle 11

Instruction status

Instruction		j	k	iteration	Issue	Execution complete	Write Result
LD	F0	0	R1	1	1	9	10
MULT	F4	F0	F2	1	2		
SD	F4	0	R1	1	3		
LD	F0	0	R1	2	6	10	11
MULT	F4	F0	F2	2	7		
SD	F4	0	R1	2	8		

Load1	No		
Load2	No		
Load3	Yes	64	Qi
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for k Qk
	0	Add1	No					
	0	Add2	No					
	0	Add3	No					
	3	Mult1	Yes	MULTD	M(80)	R(F2)		
	4	Mult2	Yes	MULTD	M(72)	R(F2)		

Code:			
LD	F0	0	R1
MULT	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12 ...	F30
11	64	Qi	Load3		Mult2					

Loop Example Cycle 12

Instruction status

Instruction		j	k	iteration	Issue	Execution complete	Write Result
LD	F0	0	R1	1	1	9	10
MULT	F4	F0	F2	1	2		
SD	F4	0	R1	1	3		
LD	F0	0	R1	2	6	10	11
MULT	F4	F0	F2	2	7		
SD	F4	0	R1	2	8		

Load1	No		
Load2	No		
Load3	Yes	64	Qi
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for k Qk
	0	Add1	No					
	0	Add2	No					
	0	Add3	No					
	2	Mult1	Yes	MULTD	M(80)	R(F2)		
	3	Mult2	Yes	MULTD	M(72)	R(F2)		

Code:			
LD	F0	0	R1
MULT	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
12	64	Qi	Load3		Mult2						

Loop Example Cycle 13

Instruction status												
Instruction		*j*	*k*	*iteration*	*Issue*	*Execution complete*	*Write Result*		Busy	Address		
LD	F0	0	R1	1	1	9	10	Load1	No			
MULT	F4	F0	F2	1	2			Load2	No			
SD	F4	0	R1	1	3			Load3	Yes	64	Qi	
LD	F0	0	R1	2	6	10	11	Store1	Yes	80	Mult1	
MULT	F4	F0	F2	2	7			Store2	Yes	72	Mult2	
SD	F4	0	R1	2	8			Store3	No			

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for Qj*	*RS for k Qk*	*Code:*			
	0	Add1	No						LD	F0	0	R1
	0	Add2	No						MULT	F4	F0	F2
	0	Add3	No						SD	F4	0	R1
	1	Mult1	Yes	MULTD	M(80)	R(F2)			SUBI	R1	R1	#8
	2	Mult2	Yes	MULTD	M(72)	R(F2)			BNEZ	R1	Loop	

Register result status												
Clock		**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	*...*	*F30*
13		**64**	*Qi*	Load3		Mult2						

Loop Example Cycle 14

Instruction status

Instruction		j	k	iteration	Issue	Execution complete	Write Result
LD	F0	0	R1	1	1	9	10
MULT	F4	F0	F2	1	2	14	
SD	F4	0	R1	1	3		
LD	F0	0	R1	2	6	10	11
MULT	F4	F0	F2	2	7		
SD	F4	0	R1	2	8		

	Busy	Address	Qi
Load1	No		
Load2	No		
Load3	Yes	64	Qi
Store1	Yes	80	Mult1
Store2	Yes	72	Mult2
Store3	No		

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for k Qk
	0	Add1	No					
	0	Add2	No					
	0	Add3	No					
	0	Mult1	Yes	MULTD	M(80)	R(F2)		
	1	Mult2	Yes	MULTD	M(72)	R(F2)		

Code:			
LD	F0	0	R1
MULT	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

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

Loop Example Cycle 15

Instruction status												
Instruction		*j*	*k*	*iteration*	*Issue*	*Execution complete*	*Write Result*		Busy	Address		
LD	F0	0	R1	1	1	9	10	Load1	No			
MULT	F4	F0	F2	1	2	14	15	Load2	No			
SD	F4	0	R1	1	3			Load3	Yes	64	Qi	
LD	F0	0	R1	2	6	10	11	Store1	Yes	80	M(80)*R(	
MULT	F4	F0	F2	2	7	15		Store2	Yes	72	Mult2	
SD	F4	0	R1	2	8			Store3	No			

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for Qj*	*RS for k Qk*	*Code:*			
	0	Add1	No						LD	F0	0	R1
	0	Add2	No						MULT	F4	F0	F2
	0	Add3	No						SD	F4	0	R1
	0	Mult1	No						SUBI	R1	R1	#8
	0	Mult2	Yes	MULTD	M(72)	R(F2)			BNEZ	R1	Loop	

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

- **Update to regsiter F0?**

Loop Example Cycle 16

Instruction status

Instruction		j	k	iteration	Issue	Execution complete	Write Result
LD	F0	0	R1	1	1	9	10
MULT	F4	F0	F2	1	2	14	15
SD	F4	0	R1	1	3		
LD	F0	0	R1	2	6	10	11
MULT	F4	F0	F2	2	7	15	16
SD	F4	0	R1	2	8		

	Busy	Address	
Load1	No		
Load2	No		
Load3	Yes	64	Qi
Store1	Yes	80	M(80)*R(
Store2	Yes	72	M(72)*R(
Store3	No		

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for k Qk
	0	Add1	No					
	0	Add2	No					
	0	Add3	No					
	0	Mult1	Yes	MULTD		R(F2)	Load3	
	0	Mult2	No					

Code:			
LD	F0	0	R1
MULT	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

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

Loop Example Cycle 17

Instruction status

Instruction		j	k	iteration	Issue	Execution complete	Write Result
LD	F0	0	R1	1	1	9	10
MULT	F4	F0	F2	1	2	14	15
SD	F4	0	R1	1	3		
LD	F0	0	R1	2	6	10	11
MULT	F4	F0	F2	2	7	15	16
SD	F4	0	R1	2	8		

	Busy	Address	Qi
Load1	No		
Load2	No		
Load3	Yes	64	Qi
Store1	Yes	80	M(80)*R(
Store2	Yes	72	M(72)*R(
Store3	Yes	64	Mult1

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for k Qk
	0	Add1	No					
	0	Add2	No					
	0	Add3	No					
	0	Mult1	Yes	MULTD		R(F2)	Load3	
	0	Mult2	No					

Code:			
LD	F0	0	R1
MULT	F4	F0	F2
SD	F4	0	R1
SUBI	R1	R1	#8
BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12	...	F30
17	64	Qi	Load3		Mult1						

Loop Example Cycle 18

Instruction status												
Instruction		*j*	*k*	*iteration*	*Issue*	*Execution complete*	*Write Result*		Busy	Address		
LD	F0	0	R1	1	1	9	10	Load1	No			
MULT	F4	F0	F2	1	2	14	15	Load2	No			
SD	F4	0	R1	1	3	18		Load3	Yes	64	Qi	
LD	F0	0	R1	2	6	10	11	Store1	Yes	80	M(80)*R(	
MULT	F4	F0	F2	2	7	15	16	Store2	Yes	72	M(72)*R(	
SD	F4	0	R1	2	8			Store3	Yes	64	Mult1	

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for Qj*	*RS for k Qk*	*Code:*			
	0	Add1	No						LD	F0	0	R1
	0	Add2	No						MULT	F4	F0	F2
	0	Add3	No						SD	F4	0	R1
	0	Mult1	Yes	MULTD		R(F2)	Load3		SUBI	R1	R1	#8
	0	Mult2	No						BNEZ	R1	Loop	

Register result status											
Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
18	**56**	*Qi*	Load3		Mult1						

Loop Example Cycle 19

Instruction status

Instruction		j	k	iteration	Issue	Execution complete	Write Result		Busy	Address	
LD	F0	0	R1	1	1	9	10	Load1	No		
MULT	F4	F0	F2	1	2	14	15	Load2	No		
SD	F4	0	R1	1	3	18	19	Load3	Yes	64	Qi
LD	F0	0	R1	2	6	10	11	Store1	No		
MULT	F4	F0	F2	2	7	15	16	Store2	Yes	72	M(72)*R(
SD	F4	0	R1	2	8			Store3	Yes	64	Mult1

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for k Qk	Code:			
	0	Add1	No						LD	F0	0	R1
	0	Add2	No						MULT	F4	F0	F2
	0	Add3	No						SD	F4	0	R1
	0	Mult1	Yes	MULTD		R(F2)	Load3		SUBI	R1	R1	#8
	0	Mult2	No						BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12 ...	F30
19	56	Qi	Load3		Mult1					

Loop Example Cycle 20

Instruction status

Instruction		j	k	iteration	Issue	Execution complete	Write Result		Busy	Address	
LD	F0	0	R1	1	1	9	10	Load1	No		
MULT	F4	F0	F2	1	2	14	15	Load2	No		
SD	F4	0	R1	1	3	18	19	Load3	Yes	64	Qi
LD	F0	0	R1	2	6	10	11	Store1	No		
MULT	F4	F0	F2	2	7	15	16	Store2	Yes	72	M(72)*R(
SD	F4	0	R1	2	8	20		Store3	Yes	64	Mult1

Reservation Stations

	Time	Name	Busy	Op	S1 Vj	S2 Vk	RS for Qj	RS for k Qk	Code:			
	0	Add1	No						LD	F0	0	R1
	0	Add2	No						MULT	F4	F0	F2
	0	Add3	No						SD	F4	0	R1
	0	Mult1	Yes	MULTD		R(F2)	Load3		SUBI	R1	R1	#8
	0	Mult2	No						BNEZ	R1	Loop	

Register result status

Clock	R1		F0	F2	F4	F6	F8	F10	F12 ...	F30
20	56	Qi	Load3		Mult1					

Loop Example Cycle 21

Instruction status												
Instruction		*j*	*k*	*iteration*	*Issue*	*Execution complete*	*Write Result*		Busy	Address		
LD	F0	0	R1	1	1	9	10	Load1	No			
MULT	F4	F0	F2	1	2	14	15	Load2	No			
SD	F4	0	R1	1	3	18	19	Load3	Yes	64	Qi	
LD	F0	0	R1	2	6	10	11	Store1	No			
MULT	F4	F0	F2	2	7	15	16	Store2	No			
SD	F4	0	R1	2	8	20	21	Store3	Yes	64	Mult1	

Reservation Stations												
	Time	*Name*	*Busy*	*Op*	*S1 Vj*	*S2 Vk*	*RS for Qj*	*RS for k Qk*	*Code:*			
	0	Add1	No						LD	F0	0	R1
	0	Add2	No						MULT	F4	F0	F2
	0	Add3	No						SD	F4	0	R1
	0	Mult1	Yes	MULTD		R(F2)	Load3		SUBI	R1	R1	#8
	0	Mult2	No						BNEZ	R1	Loop	

Register result status											
Clock	**R1**		*F0*	*F2*	*F4*	*F6*	*F8*	*F10*	*F12*	...	*F30*
21	**56**	*Qi*	Load3		Mult1						

Tomasulo Summary

- Prevents Register as bottleneck
- Avoids WAR, WAW hazards of Scoreboard
- Allows loop unrolling in HW
- Not limited to basic blocks (provided branch prediction)
- Lasting Contributions
  - Dynamic scheduling
  - Register renaming
  - Load/store disambiguation
- 360/91 descendants are PowerPC 604, 620; MIPS R10000; HP-PA 8000; Intel Pentium Pro