### **OUT-OF-ORDER EXECUTION**

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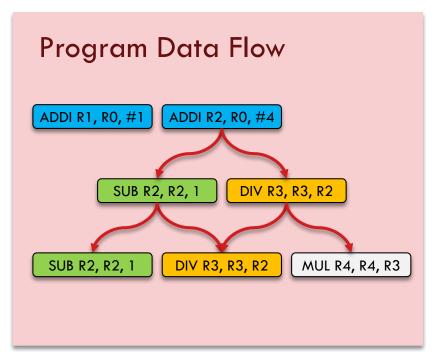
### Overview

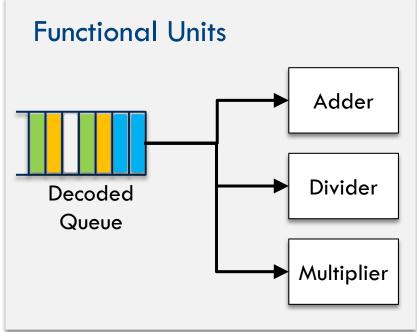
- Announcement
  - Homework 3 submission deadline: Feb. 25<sup>th</sup>

- □ This lecture
  - Tomasulo algorithm
    - Three-step OoO scheduling
    - Hardware implementation
    - Four-step algorithm
    - Reorder buffer

### Recall: Dynamic Scheduling

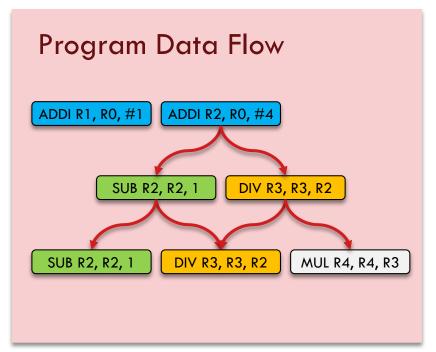
 The main idea is to issue dynamic instructions out of program order while maintaining data flow

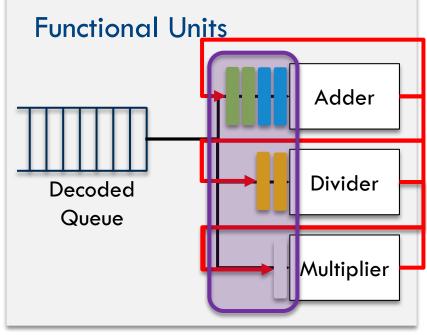




### Recall: Dynamic Scheduling

 The main idea is to issue dynamic instructions out of program order while maintaining data flow





Reservation Stations

### Tomasulo Algorithm

- Dispatch instructions to functional units
  - Use reservation stations (RS)

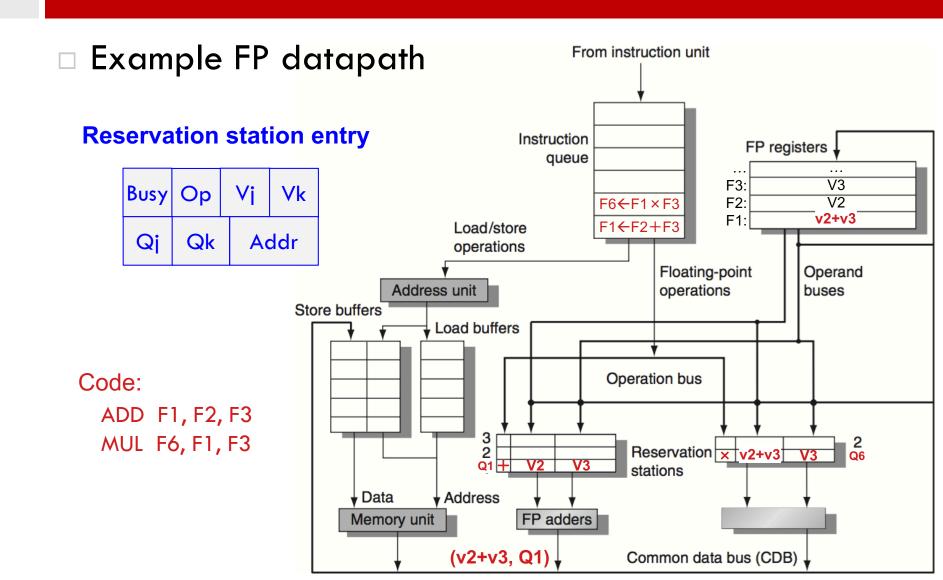
- Execute an instruction as soon as all of its operands are ready
  - Watch the common data bus (CDB)

- Remove false (anti- and output-) data dependence
  - Rename destination register to RS name

### Three-Step Tomasulo Algorithm

- □ Issue: take an instruction from the instruction queue
  - If there are free reservation stations without structural hazards, rename and read/send operands or RS names
- □ Execute: operate on operand(s) when ready
  - If all of the operands are ready, execute; if not watch the common data bus
- Write result: update the register values
  - Write the result through CDB to all waiting reservation stations and the register file; release the RS entry

### Hardware Implementation



Instruction Status							
Instruction j k	issue complete	e write	_	_	Busy	Address	_Time
LD F6 43+ R2			2	load1	NO		0
LD F2 45+ R3			2	load2	NO		0
MUL F0 F2 F4			2	load3	NO		0
SUB F8 F6 F2				-			_
DIV F10 F0 F6							
ADD F6 F8 F2							
Reservation Stations							
Time Name Busy	Op Vj	Vk	Qj	Qk			
2 0 add1 NO							
2 0 add2 NO							
2 0 add3 NO							
10 0 mult1 NO							
40 0 mult2 NO							

F4

value

F6

value

F8

value

F10

value value

F12 ... F30

F2

value

F0

value

FU

Clock 0

#### **Instruction Status** Address Time Instruction k issue complete write Busy YES LD F6 43+ R2 43+R2 2 load 1 ID F2 45 + R3load2 NO 0 F0 F2 F4 MUI load3 NO 0 F8 F6 SUB F2 DIV F10 F0 F6 F6 F8 F2 ADD **Reservation Stations** Vk Time Name Busy Op Qi Qk add 1 NO add2 NO add3 NO 10 0 mult1 NO 40 mult2 | NO **Register Result Status**

F4

value

**F6** 

load 1

F8

value

F10

value

F12

value

... F30

F2

value

F0

value

FU

Clock 1

#### **Instruction Status** Address Time Instruction k issue complete write Busy LD F6 43+ R2 YES 43+R2 load 1 2 2 ID F2 45 + R3load2 YES 45 + R3F0 F2 F4 MUI load3 0 NO F8 F6 SUB F2 DIV F10 F0 F6 F6 F8 F2 ADD **Reservation Stations** Vk Time Name Busy Op Qi Qk add 1 NO add2 NO add3 NO 10 0 mult1 NO 40 mult2 | NO

F4

value

**F6** 

load 1

F8

value

F10

value

F12

value

... F30

F2

load2

F0

value

FU

**Register Result Status** 

Clock 2

### **Instruction Status**

Instruct	tion	i	k	issue	complete	write
LD	F6	43+	R2	1	3	
LD	F2	45+	R3	2		
MUL	FO	F2	F4	3		
SUB	F8	F6	F2			
DIV	F10	F0	F6			
ADD	F6	F8	F2			

		Busy	Address	Time
2	load1	YES	43+R2	0
2	load2	YES	45+R3	1
2	load3	NO		0

#### **Reservation Stations**

-	Time Name Busy			Ор	۷j	Vk	Qj	Qk
2	0	add1	NO					
2	0	add2	NO					
2	0	add3	NO					
10	0	mult 1	YES	MULT		value	load2	
40	0	mult2	NO					

### **Register Result Status**

F2 F4 F<sub>0</sub> F6 F8 F10 F12 ... F30 Clock 3 FU load2 value mult 1 value load 1 value value

#### **Instruction Status**

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	
MUL	FO	F2	F4	3		
SUB	F8	F6	F2	4		
DIV	F1C	) FO	F6			
ADD	F6	F8	F2			

		Busy	Address	Time
2	load 1	NO		0
2	load2	YES	45+R3	0
2	load3	NO		0

#### **Reservation Stations**

		Name			۷j	Vk	Qj	Qk
2	0	add1	YES	SUB	value			load2
2	0	add2	NO					
		add3						
10	0	mult 1	YES	MULT		value	load2	
40	0	mult2	NO					

### **Register Result Status**

F2 F10 F12 ... F30 F<sub>0</sub> F4 F6 F8 Clock 4 FU load2 mult 1 value add1 value value value

#### **Instruction Status**

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3		
SUB	F8	F6	F2	4		
DIV	F10	FO	F6	5		
ADD	F6	F8	F2			

		Busy	Address	Time
2	load 1	NO		0
2	load2	NO		0
2	load3	NO		0

#### **Reservation Stations**

-	Time	Name	Busy	Ор	٧j	Vk	Qj	Qk
				SUB	value	value		
2	0	add2	NO					
		add3						
10	10	mult 1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult 1	

		FO	F2	F4	F6	F8	FIO	FI2	F30
Clock 5	FU	mult1	value	value	value	add1	mult2	value	

#### **Instruction Status**

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3		
SUB	F8	F6	F2	4		
DIV	F10	) FO	F6	5		
ADD	F6	F8	F2	6		

		Busy	Address	Time
2	load1	NO		0
2	load2	NO		0
2	load3	NO		0

#### **Reservation Stations**

,	Time	Name	Busy	Ор	٧j	Vk	Qj	Qk
					value	value		
		add2		ADD		value	add1	
2	0	add3	NO					
10	9	mult 1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

### **Register Result Status**

F2 F<sub>0</sub> F4 F6 F8 F10 F12 ... F30 Clock 6 FU add2 mult2 mult 1 value value add1 value

#### **Instruction Status**

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3		
SUB	F8	F6	F2	4	7	
DIV	F10	) FO	F6	5		
ADD	F6	F8	F2	6		

		Busy	Address	Time
2	load 1	NO		0
2	load2	NO		0
2	load3	NO		0

#### **Reservation Stations**

1	Гіте	Name	Busy	Ор	٧i	Vk	Qj	Qk
2	0	add1	YES	SUB	value	value		
2	0	add2	YES	ADD		value	add1	
2	0	add3	NO					
10	8	mult 1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult 1	

F2

### **Register Result Status**

Clock 7

FU

10	1 4
mult 1	valu

FΩ

F4 value F6

add2

F8

add1

F10

mult2

F12 ... F30

value

#### **Instruction Status**

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3		
SUB	F8	F6	F2	4	7	8
DIV	F10	FO	F6	5		
ADD	F6	F8	F2	6		

		Busy	Address	Time
2	load 1	NO		0
2	load2	NO		0
2	load3	NO		0

#### **Reservation Stations**

Time Name Busy			Ор	۷j	Vk	Qj	Qk	
2	0	add1	20					
2	2	add2	YES	ADD	value	value		
2	0	add3	NO					
10	7	mult 1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

### **Register Result Status**

F2 F4 F10 F<sub>0</sub> F6 F8 F12 ... F30 Clock 8 FU add2 mult2 mult 1 value value value value

#### **Instruction Status**

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3		
SUB	F8	F6	F2	4	7	8
DIV	F10	) FO	F6	5		
ADD	F6	F8	F2	6		

		Busy	Address	Time
2	load 1	NO		0
2	load2	NO		0
2	load3	NO		0

#### **Reservation Stations**

Time Name Busy			Ор	۷į	Vk	Qj	Qk	
2	0	add1	<b>N</b> O					
2	1	add2	YES	ADD	value	value		
2	0	add3	NO					
10	6	mult 1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

### **Register Result Status**

F2 F4 F<sub>0</sub> F6 F8 F10 F12 ... F30 Clock 9 FU add2 mult2 mult 1 value value value value

#### **Instruction Status**

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3		
SUB	F8	F6	F2	4	7	8
DIV	F1C	) FO	F6	5		
ADD	F6	F8	F2	6	10	

		Busy	Address	Time
2	load 1	NO		0
2	load2	NO		0
2	load3	NO		0

#### **Reservation Stations**

•	Time Name Busy			Ор	۷į	Vk	Qj	Qk
2	0	add1	20					
2	0	add2	YES	ADD	value	value		
2	0	add3	NO					
10	5	mult 1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

		FO	F2	F4	F6	F8	FIO	FI2	F30
Clock 10	FU	mult1	value	value	add2	value	mult2	value	

### Instruction Status

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3		
SUB	F8	F6	F2	4	7	8
DIV	F10	) FO	F6	5		
ADD	F6	F8	F2	6	10	11

		Busy	Address	Time
2	load1	NO		0
2	load2	NO		0
2	load3	NO		0

### **Reservation Stations**

7	Time Name Busy			Ор	۷j	Vk	Qj	Qk
2	0	add1	<b>N</b>					
2	0	add2	NO					
2	0	add3	NO					
10	4	mult 1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

		FO	F2	F4	F6	F8	FIO	FI2	F30
Clock 11	FU	mult1	value	value	value	value	mult2	value	

#### **Instruction Status**

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3	15	
SUB	F8	F6	F2	4	7	8
DIV	F10	FO	F6	5		
ADD	F6	F8	F2	6	10	11

		Busy	Address	Time
2	load1	NO		0
2	load2	NO		0
2	load3	NO		0

#### **Reservation Stations**

	Time	Name	Busy	Ор	٧j	Vk	Qį	Qk
2	0	add1	NO					
2	0	add2	NO					
2	0	add3	NO					
10	0	mult 1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult 1	

		<u> FO</u>	F2	F4	F6	F8	FIO	F12	F30
Clock 15	FU	mult1	value	value	value	value	mult2	value	

Time

0

Instruc	ction Statu	IS	_						
Instruc	tion j	k	issue	complete	write			Busy	Address
LD	F6 43	+ R2	1	3	4	2	load1	NO	
LD	F2 45	+ R3	2	4	5	2	load2	NO	
MUL	F0 F2	F4	3	15	16	2	load3	NO	
SUB	F8 F6	F2	4	7	8				
DIV	F10 F0	F6	5						
ADD	F6 F8	F2	6	10	11				
Ресек	ration Stat	<b>!!</b>							

#### **Reservation Stations**

•	Time	Name	Busy	Ор	۷j	Vk	Qj	Qk
2	0	add1	NO					
2	0	add2	NO					
2	0	add3	NO					
10	0	mult 1	NO					
40	40	mult2	YES	DIV	value	value		

### **Register Result Status**

F2 F4 F<sub>0</sub> **F6** F8 F10 F12 ... F30 Clock 16 FU mult2 value value value value value value

Instru	iction	<b>Status</b>
1113616	10ti0ii	Otatus

Instruction		i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3	15	16
SUB	F8	F6	F2	4	7	8
DIV	F10	F0	F6	5	56	
ADD	F6	F8	F2	6	10	11

		Busy	Address	Time
2	load1	NO		0
2	load2	NO		0
2	load3	NO		0

#### **Reservation Stations**

	Time	Name	Busy	Ор	۷j	Vk	Qj	Qk
2	0	add1	NO					
		add2						
2	0	add3	NO					
10	0	mult 1	NO					
40	0	mult2	YES	DIV	value	value		

		FO	F2	F4	F6	F8	FIO	FI2	F30
Clock 56	FU	value	value	value	value	value	mult2	value	

#### **Instruction Status**

Instruct	ion	i	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	FO	F2	F4	3	15	16
SUB	F8	F6	F2	4	7	8
DIV	F10	F0	F6	5	56	57
ADD	F6	F8	F2	6	10	11

		Busy	Address	Time
2	load1	NO		0
2	load2	NO		0
2	load3	NO		0

#### **Reservation Stations**

-	Гime	Name	Busy	Ор	۷j	Vk	Qj	Qk
2	0	add1	NO					
		add2						
2	0	add3	NO					
10	0	mult 1	NO					
40	0	mult2	NO					

	_	FU	F2	F4	FO	F8	FIU	FIZ	F30
Clock 57	FU	value							

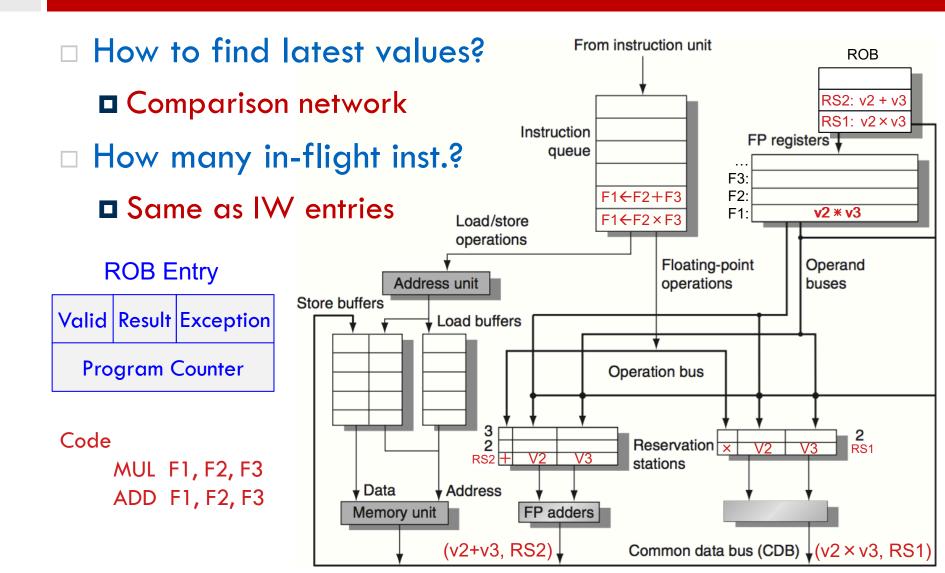
### Summary of Tomasulo Algorithm

- Data hazards
  - RAW is handled by forwarding over CDB
  - WAR and WAW are removed by RS-based renaming
- Structural hazards
  - Multiple FUs may be accessing CDB simultaneously
    - Solution: delay conflicting instructions at issue and RS
- Precise exception handling
  - Not possible because of OoO writeback to register file
    - Solution: maintain the destination value in ROB (IW)

### Four-Step Tomasulo Algorithm

- Issue (dispatch)
  - If RS and ROB slots are free; read/rename operands
- Execution
  - Execute operation as soon as the operand values are ready
- Write result
  - Send result to ROB and reservation stations via CDB
- □ Commit (retire)
  - Update register file for the head of ROB

### Four-Step Tomasulo Algorithm



### ROB Dependency Check

□ Searching register values in AMD K-5

