

# OUT-OF-ORDER EXECUTION

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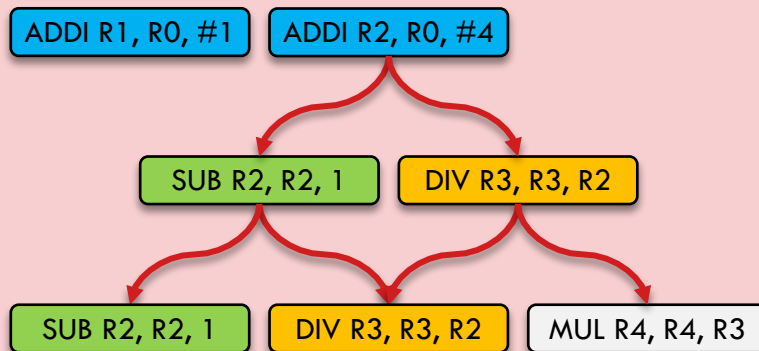
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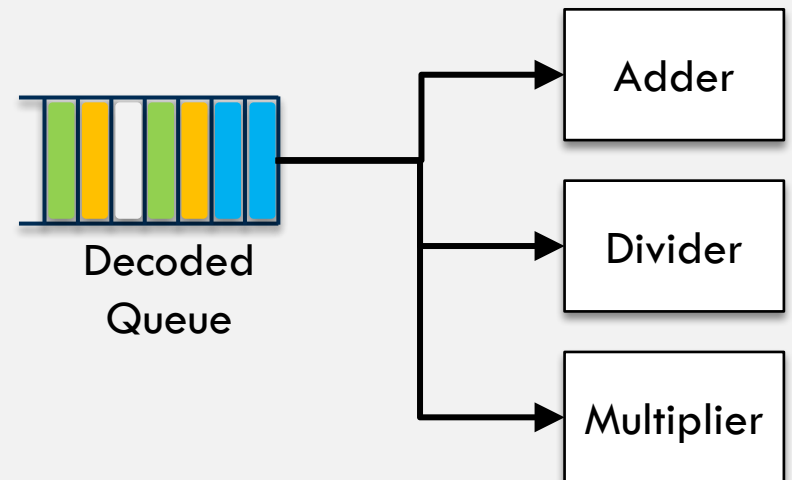
# Recall: Dynamic Scheduling

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

## Program Data Flow

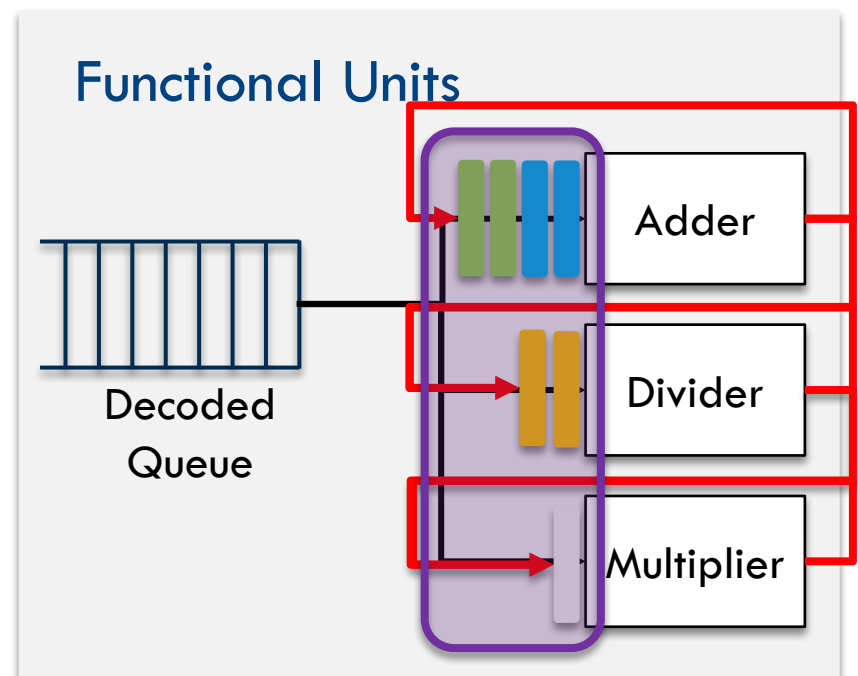
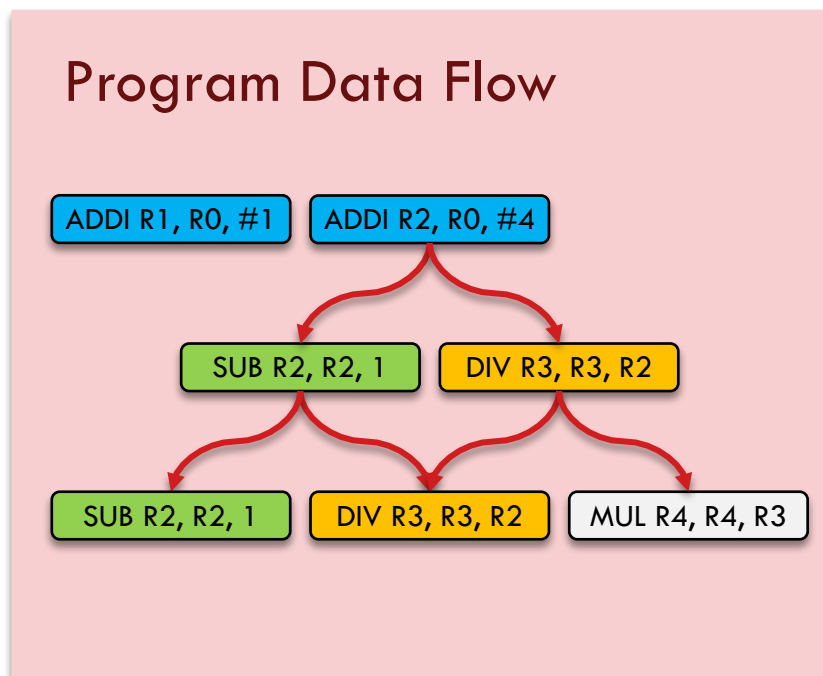


## Functional Units



# 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

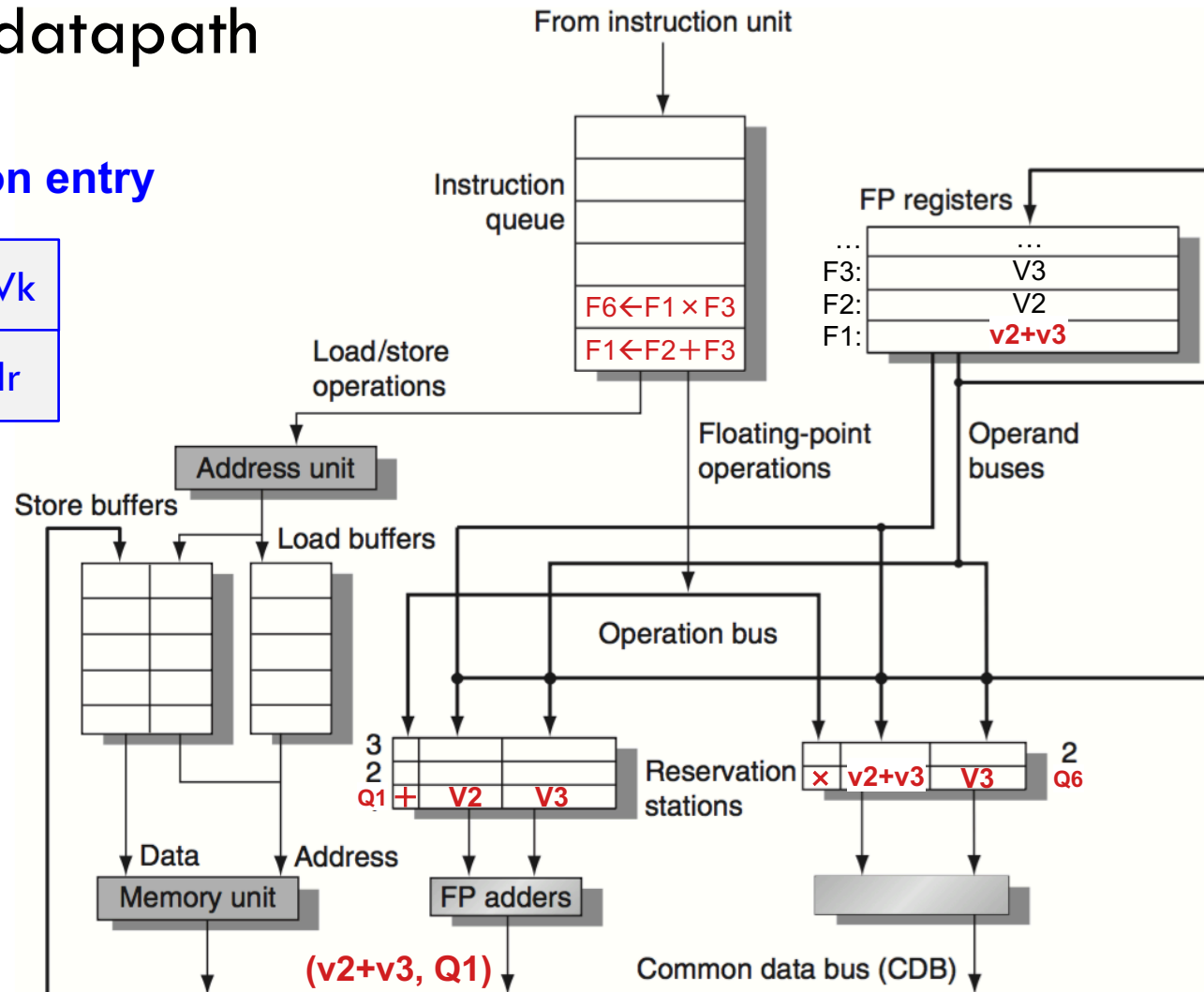
## □ Example FP datapath

### Reservation station entry

Busy	Op	Vj	Vk
Qj	Qk	Addr	

Code:

ADD F1, F2, F3  
 MUL F6, F1, F3



## Instruction Status

Instruction	j	k	issue	complete	write
LD	F6	43+ R2			
LD	F2	45+ R3			
MUL	F0	F2 F4			
SUB	F8	F6 F2			
DIV	F10	F0 F6			
ADD	F6	F8 F2			

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

## 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					

## Register Result Status

[illegible]

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1			2	load1	YES 43+R2	2
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					

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 1	value	value	value	load1	value	value	value		



# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1			2	load1	YES 43+R2	1
LD	F2	45+ R3	2			2	load2	YES 45+R3	2
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					

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock <b>2</b>	value	load2	value	load1	value	value	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3		2	load1	YES 43+R2	0
LD	F2	45+ R3	2			2	load2	YES 45+R3	1
MUL	F0	F2 F4	3			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	YES	MULT		value	load2	
40	0	mult2	NO					

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 3	mult1	load2	value	load1	value	value	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4		2	load2	YES 45+R3	0
MUL	F0	F2 F4	3			2	load3	NO	0
SUB	F8	F6 F2	4						
DIV	F10	F0 F6							
ADD	F6	F8 F2							

## Reservation Stations

	Time	Name	Busy	Op	Vj	Vk	Qj	Qk
2	0	add1	YES	SUB	value			load2
2	0	add2	NO					
2	0	add3	NO					
10	0	mult1	YES	MULT		value	load2	
40	0	mult2	NO					

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 4	mult1	load2	value	value	add1	value	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3			2	load3	NO	0
SUB	F8	F6 F2	4						
DIV	F10	F0 F6	5						
ADD	F6	F8 F2							

## Reservation Stations

Time	Name	Busy	Op	Vj	Vk	Qj	Qk
2	add1	YES	SUB	value	value		
2	add2	NO					
2	add3	NO					
10	mult1	YES	MULT	value	value		
40	mult2	YES	DIV		value	mult1	

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 5	mult1	value	value	value	add1	mult2	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3			2	load3	NO	0
SUB	F8	F6 F2	4						
DIV	F10	F0 F6	5						
ADD	F6	F8 F2	6						

## Reservation Stations

	Time	Name	Busy	Op	Vj	Vk	Qj	Qk
2	1	add1	YES	SUB	value	value		
2	0	add2	YES	ADD		value	add1	
2	0	add3	NO					
10	9	mult1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 6	mult1	value	value	add2	add1	mult2	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3			2	load3	NO	0
SUB	F8	F6 F2	4	7					
DIV	F10	F0 F6	5						
ADD	F6	F8 F2	6						

## Reservation Stations

	Time	Name	Busy	Op	Vj	Vk	Qj	Qk
2	0	add1	YES	SUB	value	value		
2	0	add2	YES	ADD		value	add1	
2	0	add3	NO					
10	8	mult1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 7	mult1	value	value	add2	add1	mult2	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3			2	load3	NO	0
SUB	F8	F6 F2	4	7	8				
DIV	F10	F0 F6	5						
ADD	F6	F8 F2	6						

## Reservation Stations

	Time	Name	Busy	Op	Vj	Vk	Qj	Qk
2	0	add1	NO					
2	2	add2	YES	ADD	value	value		
2	0	add3	NO					
10	7	mult1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 8	mult1	value	value	add2	value	mult2	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3			2	load3	NO	0
SUB	F8	F6 F2	4	7	8				
DIV	F10	F0 F6	5						
ADD	F6	F8 F2	6						

## Reservation Stations

Time	Name	Busy	Op	Vj	Vk	Qj	Qk
2 0	add1	NO					
2 1	add2	YES	ADD	value	value		
2 0	add3	NO					
10 6	mult1	YES	MULT	value	value		
40 0	mult2	YES	DIV		value	mult1	

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 9	mult1	value	value	add2	value	mult2	value		



# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3			2	load3	NO	0
SUB	F8	F6 F2	4	7	8				
DIV	F10	F0 F6	5						
ADD	F6	F8 F2	6	10					

## Reservation Stations

	Time	Name	Busy	Op	Vj	Vk	Qj	Qk
2	0	add1	NO					
2	0	add2	YES	ADD	value	value		
2	0	add3	NO					
10	5	mult1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 10	mult1	value	value	add2	value	mult2	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3			2	load3	NO	0
SUB	F8	F6 F2	4	7	8				
DIV	F10	F0 F6	5						
ADD	F6	F8 F2	6	10	11				

## Reservation Stations

	Time	Name	Busy	Op	Vj	Vk	Qj	Qk
2	0	add1	NO					
2	0	add2	NO					
2	0	add3	NO					
10	4	mult1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 11	mult1	value	value	value	value	mult2	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3	15		2	load3	NO	0
SUB	F8	F6 F2	4	7	8				
DIV	F10	F0 F6	5						
ADD	F6	F8 F2	6	10	11				

## 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	YES	MULT	value	value	
40	0	mult2	YES	DIV	value	mult1	

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock 15	mult1	value	value	value	value	mult2	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3	15	16	2	load3	NO	0
SUB	F8	F6 F2	4	7	8				
DIV	F10	F0 F6	5						
ADD	F6	F8 F2	6	10	11				

## 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	40	mult2	YES	DIV	value	value		

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock <b>16</b>	value	value	value	value	value	mult2	value		

# Example: Out-of-order Execution

## Instruction Status

Instruction	j	k	issue	complete	write		Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO	0
LD	F2	45+ R3	2	4	5	2	load2	NO	0
MUL	F0	F2 F4	3	15	16	2	load3	NO	0
SUB	F8	F6 F2	4	7	8				
DIV	F10	F0 F6	5	56					
ADD	F6	F8 F2	6	10	11				

## 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	YES	DIV	value	value	

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12	...	F30
Clock <b>56</b>	value	value	value	value	value	mult2	value		

## Instruction Status

Instruction	j	k	issue	complete	write			Busy	Address	Time
LD	F6	43+ R2	1	3	4	2	load1	NO		0
LD	F2	45+ R3	2	4	5	2	load2	NO		0
MUL	F0	F2 F4	3	15	16	2	load3	NO		0
SUB	F8	F6 F2	4	7	8					
DIV	F10	F0 F6	5	56	57					
ADD	F6	F8 F2	6	10	11					

## 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					

## Register Result Status

	F0	F2	F4	F6	F8	F10	F12 ... F30
Clock <b>57</b>	value	value	value	value	value	value	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

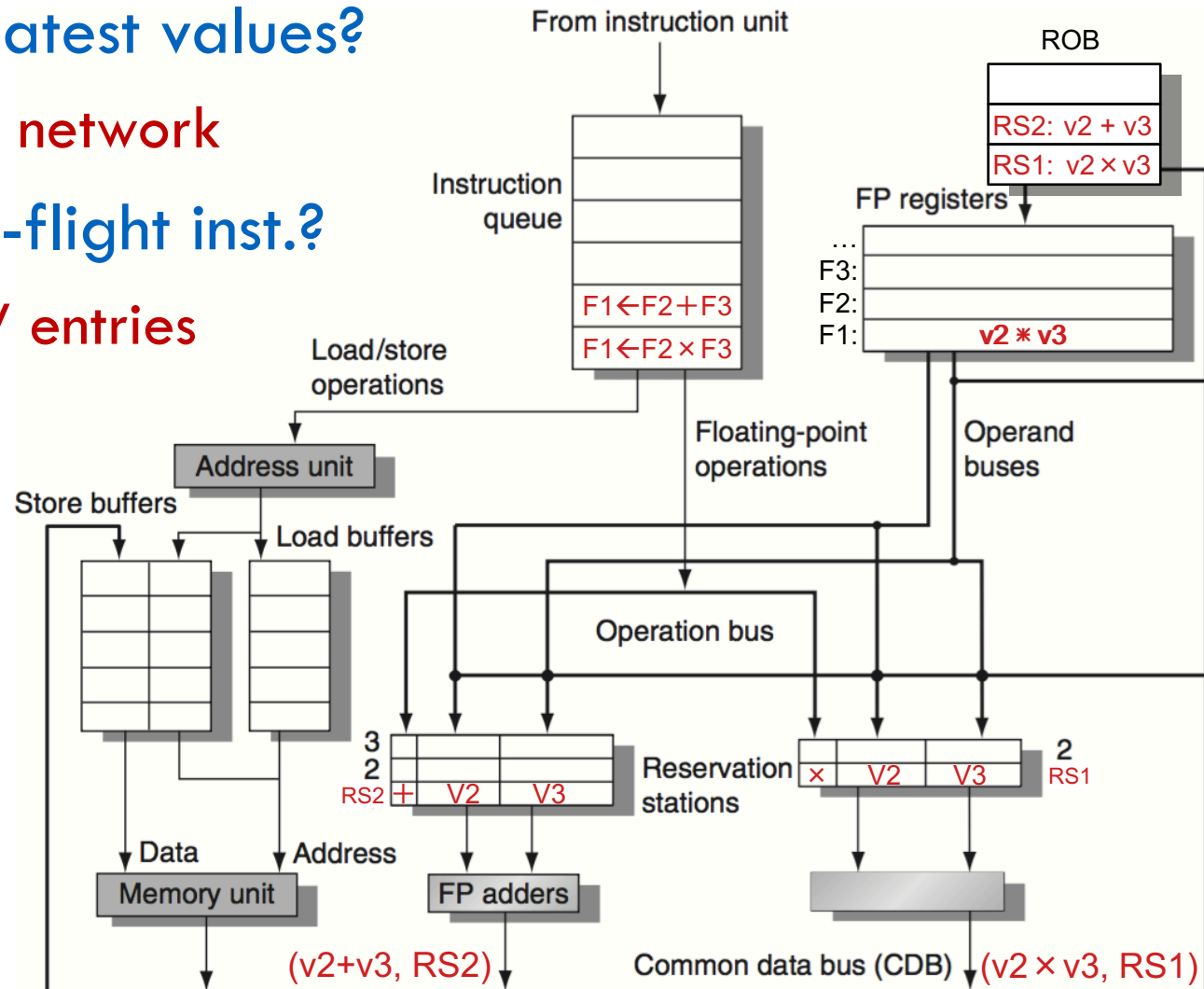
- How to find latest values?
  - ▣ Comparison network
- How many in-flight inst.?  
 ▣ Same as IW entries

ROB Entry

Valid	Result	Exception
Program Counter		

Code

MUL F1, F2, F3  
 ADD F1, F2, F3



# ROB Dependency Check

- Searching register values in AMD K-5

