OUT-OF-ORDER EXECUTION

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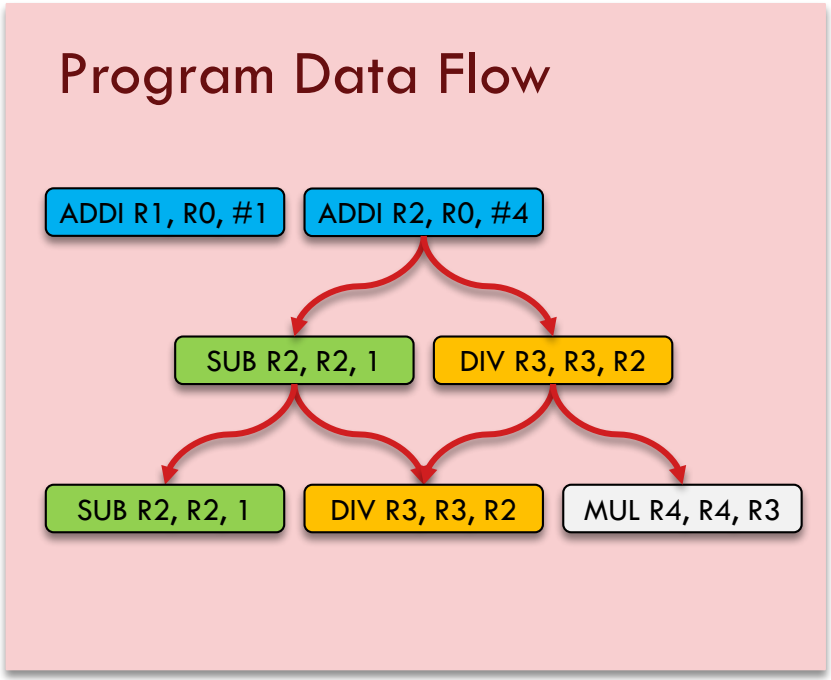
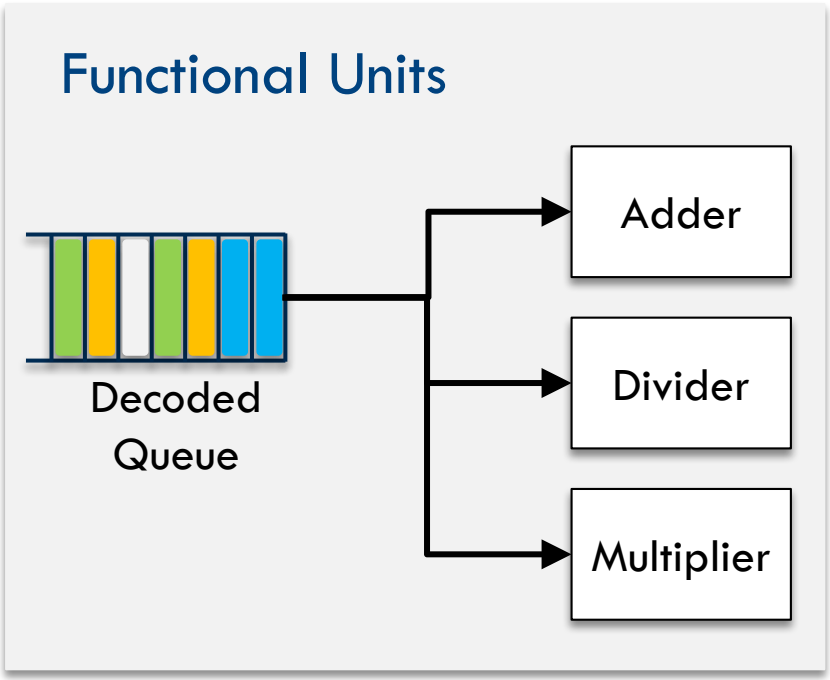
Overview

- Announcement
  - Homework 3 submission deadline: Feb. 25th
- This lecture
  - Tomasulo algorithm
    - Three-step OoO scheduling
    - Hardware implementation
    - Four-step algorithm
    - Reorder buffer

Recall: Dynamic Scheduling

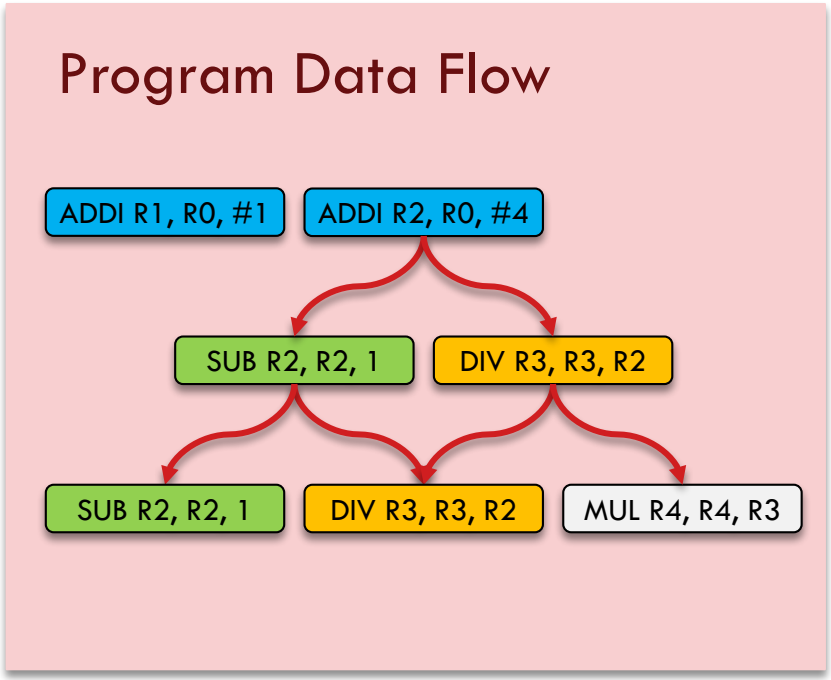
- The main idea is to issue dynamic instructions out of program order while maintaining data flow

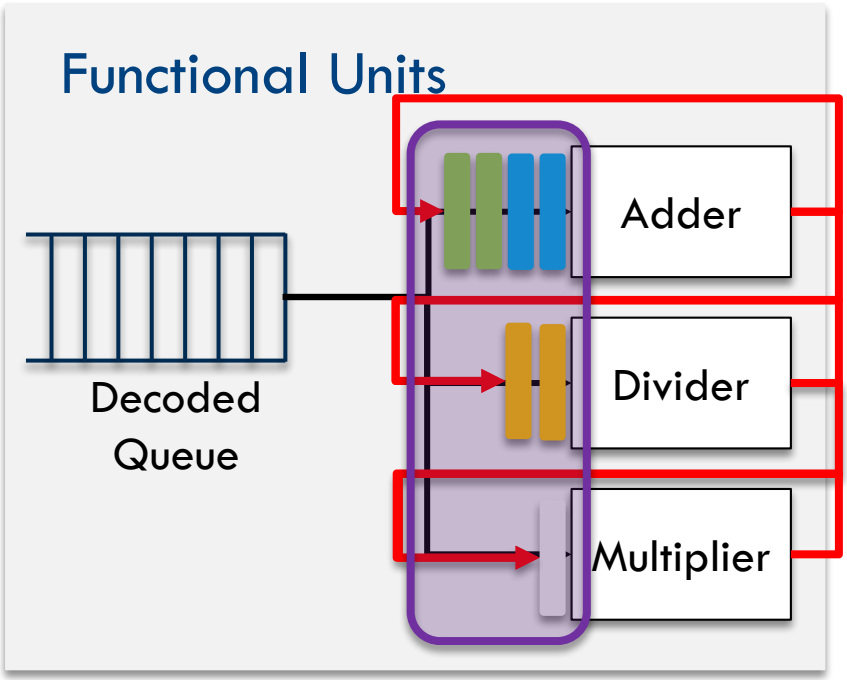




Recall: Dynamic Scheduling

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





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

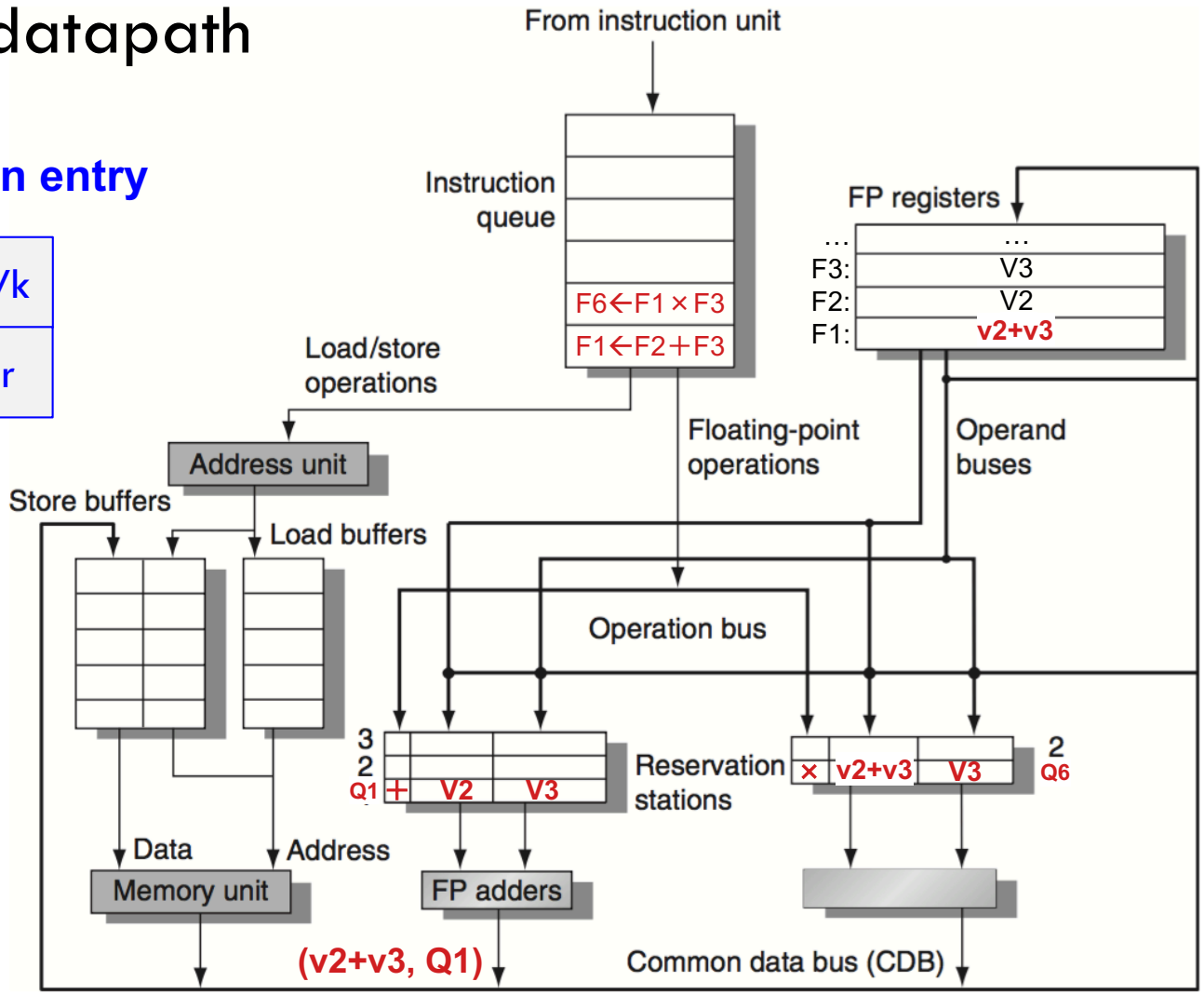
Reservation station entry

Busy	Op	Vj	Vk
Qj	Qk	Addr	

Code:

ADD F1, F2, F3

MUL F6, F1, F3



Example: Out-of-order Execution

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

	F0	F2	F4	F6	F8	F10	F12	…	F30
Clock 0 FU	value	value	value	value	value	value	value		

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1		
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	YES	43+R2	2
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

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

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1		
LD F2	45+	R3	2		
MUL F0	F2	F4			
SUB F8	F6	F2			
DIV F10	F0	F6			
ADD F6	F8	F2			

		Busy	Address	Time
2	load1	YES	43+R2	1
2	load2	YES	45+R3	2
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

	F0	F2	F4	F6	F8	F10	F12	…	F30
Clock 2 FU	value	load2	value	load1	value	value	value		

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1	3	
LD F2	45+	R3	2		
MUL F0	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	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 FU	mult1	load2	value	load1	value	value	value		

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1	3	4
LD F2	45+	R3	2	4	
MUL F0	F2	F4	3		
SUB F8	F6	F2	4		
DIV F10	F0	F6			
ADD F6	F8	F2			

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

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 FU	mult1	load2	value	value	add1	value	value		

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1	3	4
LD F2	45+	R3	2	4	5
MUL F0	F2	F4	3		
SUB F8	F6	F2	4		
DIV F10	F0	F6	5		
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	2	add1	YES	SUB	value	value		
2	0	add2	NO					
2	0	add3	NO					
10	10	mult1	YES	MULT	value	value		
40	0	mult2	YES	DIV		value	mult1	

Register Result Status

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

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1	3	4
LD F2	45+	R3	2	4	5
MUL F0	F2	F4	3		
SUB F8	F6	F2	4		
DIV F10	F0	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	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 FU	mult1	value	value	add2	add1	mult2	value		

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1	3	4
LD F2	45+	R3	2	4	5
MUL F0	F2	F4	3		
SUB F8	F6	F2	4	7	
DIV F10	F0	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	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 FU	mult1	value	value	add2	add1	mult2	value		

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1	3	4
LD F2	45+	R3	2	4	5
MUL F0	F2	F4	3		
SUB F8	F6	F2	4	7	8
DIV F10	F0	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	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 FU	mult1	value	value	add2	value	mult2	value		

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1	3	4
LD F2	45+	R3	2	4	5
MUL F0	F2	F4	3		
SUB F8	F6	F2	4	7	8
DIV F10	F0	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	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 FU	mult1	value	value	add2	value	mult2	value		

Example: Out-of-order Execution

Instruction Status

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

		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	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 FU	mult1	value	value	add2	value	mult2	value		

Example: Out-of-order Execution

Instruction Status

Instruction		j	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	F0	F2	F4	3		
SUB	F8	F6	F2	4	7	8
DIV	F10	F0	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	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

Clock 11

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

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1	3	4
LD F2	45+	R3	2	4	5
MUL F0	F2	F4	3	15	
SUB F8	F6	F2	4	7	8
DIV F10	F0	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	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 FU	mult1	value	value	value	value	mult2	value		

Example: Out-of-order Execution

Instruction Status

Instruction		j	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	F0	F2	F4	3	15	16
SUB	F8	F6	F2	4	7	8
DIV	F10	F0	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	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	16	FU	value	value	value	value	value	mult2	value	

Example: Out-of-order Execution

Instruction Status

Instruction		j	k	issue	complete	write
LD	F6	43+	R2	1	3	4
LD	F2	45+	R3	2	4	5
MUL	F0	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	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 **56** FU	value	value	value	value	value	mult2	value		

Example: Out-of-order Execution

Instruction Status

Instruction	j	k	issue	complete	write
LD F6	43+	R2	1	3	4
LD F2	45+	R3	2	4	5
MUL F0	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

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 *57* FU	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

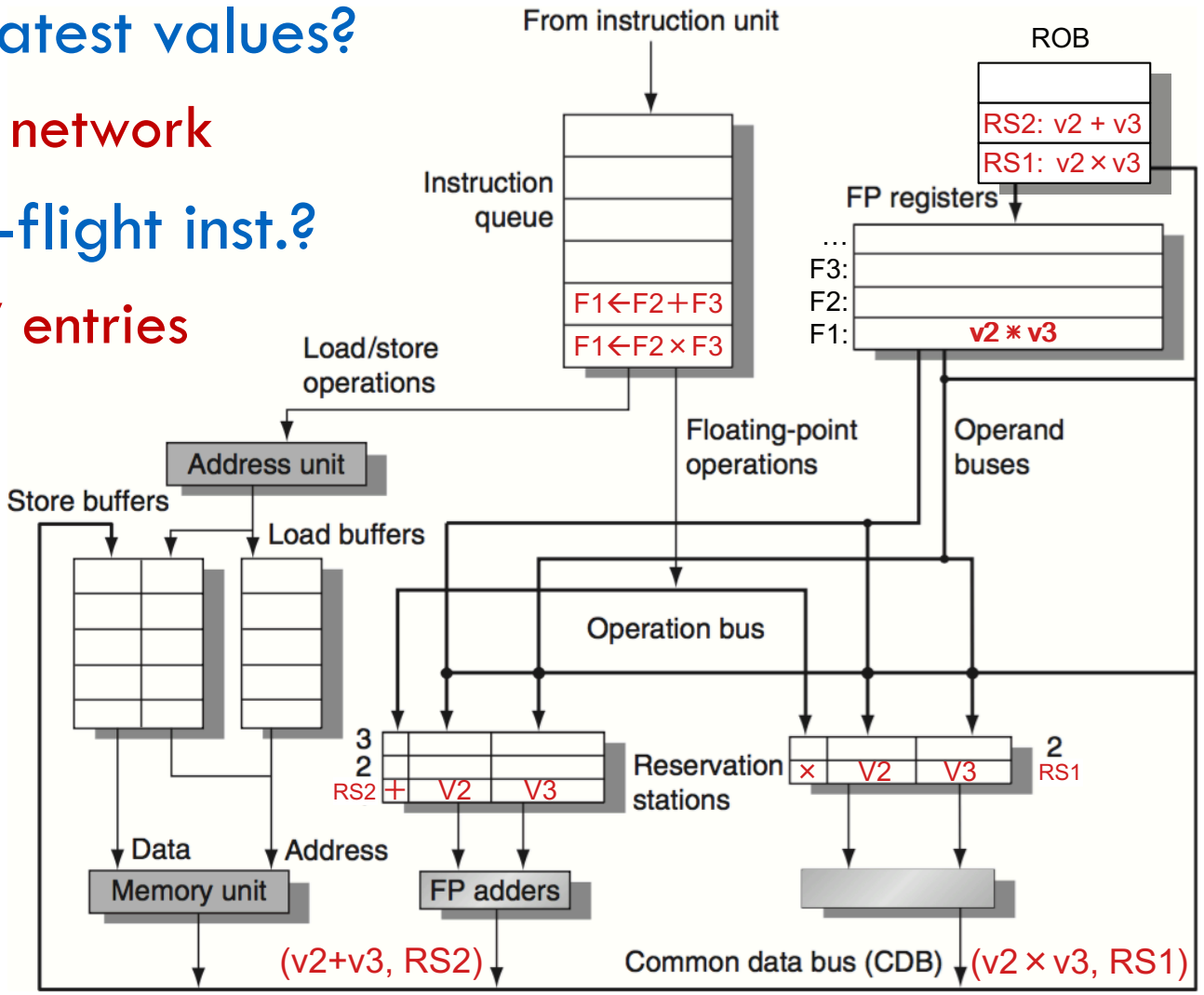
- How to find latest values?
  - Comparison network
- How many in-flight inst.?
  - Same as IW entries

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