

CMPE 110: Computer Architecture

Out-of-Order Execution

Jishen Zhao (<http://users.soe.ucsc.edu/~jzhao/>)

[Adapted in part from Jose Renau, Mary Jane Irwin, Joe Devietti, Onur Mutlu, and others]

Tomasulo's Algorithm

- If reservation station available before renaming
 - Instruction + renamed operands (registers) inserted into the reservation station
 - Only rename if reservation station is available
- Else stall
- While in reservation station, each instruction:
 - Watches common data bus (CDB) for tag of its sources
 - When tag seen, grab value for the source and keep it in the reservation station
 - When both operands available, instruction ready to be dispatched
- Dispatch instruction to the Functional Unit when instruction is ready

Tomasulo's Algorithm Con't

- After instruction finishes in the Functional Unit
 - Arbitrate for CDB
 - Put tagged value onto CDB (tag broadcast)
 - Register file is connected to the CDB
 - Register contains a tag indicating the latest writer to the register
 - If the tag in the register file matches the broadcast tag, write broadcast value into register (and set valid bit)
 - Reclaim rename tag
 - no valid copy of tag in system!

Put it all together: An Exercise

MUL R3 \leftarrow R1, R2

ADD R5 \leftarrow R3, R4

ADD R7 \leftarrow R2, R6

ADD R10 \leftarrow R8, R9

MUL R11 \leftarrow R7, R10

ADD R5 \leftarrow R5, R11



- F, D, X, W, i.e., 4-stage pipeline
 - Assume ADD (4 cycle pipelined execute, i.e., X takes 4 cycles), MUL (6 cycle pipelined execute, i.e., X takes 6 cycles)
 - Assume one adder and one multiplier
-

- How many cycles
 - In a pipelined machine without bypassing (forwarding) →stall on data hazards (Answer: 28 cycles, Quiz 1 question 2)
 - In a pipelined machine with bypassing (Answer: 25 cycles)
 - **In an out-of-order dispatch pipelined with forwarding**

Cycle: 1

tag value valid?

R1

1

1

R2

2

1

R3

3

1

R4

4

1

R5

5

1

R6

6

1

R7

7

1

R8

8

1

R9

9

1

R10

10

1

R11

11

1

SRC1

V

tag

value

SRC2

V

tag

value

A

B

C

D

ADD

SRC1

V

tag

value

SRC2

V

tag

value

X

Y

Z

T

MUL

Cycle: 2

tag value valid?

R1		1	1
R2		2	1
R3	X	3	0
R4		4	1
R5		5	1
R6		6	1
R7		7	1
R8		8	1
R9		9	1
R10		10	1
R11		11	1

SRC1

V tag value

SRC2

V tag value

A

B

C

D

ADD

SRC1

V tag value

SRC2

V tag value

X

Y

Z

T

1	-	1	1	-	2

MUL

Cycle: 3

tag value valid?

R1

1

1

R2

2

1

R3

X

3

0

R4

4

1

R5

A

5

0

R6

6

1

R7

7

1

R8

8

1

R9

9

1

R10

10

1

R11

11

1

SRC1

V tag value

0

X

-

SRC2

V tag value

1

-

4

A

B

C

D

ADD

SRC1

V tag value

1

-

1

SRC2

V tag value

1

-

2

X

Y

Z

T

MUL

Cycle: 4

tag value valid?

R1

1

1

R2

2

1

R3

X

3

0

R4

4

1

R5

A

5

0

R6

6

1

R7

B

7

0

R8

8

1

R9

9

1

R10

10

1

R11

11

1

SRC1

V tag value

0 X -

1 - 2

SRC2

V tag value

1 - 4

1 - 6

ADD

SRC1

V tag value

1 - 1

SRC2

V tag value

1 - 2

MUL

Cycle: 5

tag value valid?

R1

R2

R3

R4

R5

R6

R7

R8

R9

R10

R11

X

A

B

C

1

2

3

4

5

6

7

8

9

10

11

1

1

0

1

0

1

0

1

1

0

1

SRC1

V tag value

A

B

C

D

0

X

-

V

tag

value

1

-

4

1

-

2

1

-

6

1

-

8

1

-

9

ADD

SRC1

V tag value

X

Y

Z

T

1

-

1

V

tag

value

1

-

2

MUL

Cycle: 6

	tag	value	valid?
R1		1	1
R2		2	1
R3	X	3	0
R4		4	1
R5	A	5	0
R6		6	1
R7	B	7	0
R8		8	1
R9		9	1
R10	C	10	0
R11	Y	11	0

	SRC1			SRC2		
	V	tag	value	V	tag	value
A	0	X	-	1	-	4
B	1	-	2	1	-	6
C	1	-	8	1	-	9
D						



	SRC1			SRC2		
	V	tag	value	V	tag	value
X	1	-	1	1	-	2
Y	0	B	-	0	C	-
Z						
T						



Cycle: 7

	tag	value	valid?
R1		1	1
R2		2	1
R3	X	3	0
R4		4	1
R5	D	5	0
R6		6	1
R7	B	7	0
R8		8	1
R9		9	1
R10	C	10	0
R11	Y	11	0

	SRC1			SRC2		
	V	tag	value	V	tag	value
A	0	X	-	1	-	4
B	1	-	2	1	-	6
C	1	-	8	1	-	9
D	0	A	-	0	Y	-

ADD

	SRC1			SRC2		
	V	tag	value	V	tag	value
X	1	-	1	1	-	2
Y	0	B	-	0	C	-
Z						
T						

MUL

Cycle: 8

	tag	value	valid?
R1		1	1
R2		2	1
R3	X	2	1
R4		4	1
R5	D	5	0
R6		6	1
R7	B	8	1
R8		8	1
R9		9	1
R10	C	10	0
R11	Y	11	0

	SRC1			SRC2		
	V	tag	value	V	tag	value
A	1	X	2	1	-	4
B	1	-	2	1	-	6
C	1	-	8	1	-	9
D	0	A	-	0	Y	-

ADD

	SRC1			SRC2		
	V	tag	value	V	tag	value
X	1	-	1	1	-	2
Y	1	B	8	0	C	-
Z						
T						

MUL

Cycle: 9

	tag	value	valid?
R1		1	1
R2		2	1
R3	X	2	1
R4		4	1
R5	D	5	0
R6		6	1
R7	B	8	1
R8		8	1
R9		9	1
R10	C	17	1
R11	Y	11	0

	SRC1			SRC2		
	V	tag	value	V	tag	value
A	1	X	2	1	-	4
B						
C	1	-	8	1	-	9
D	0	A	-	0	Y	-



	SRC1			SRC2		
	V	tag	value	V	tag	value
X						
Y	1	B	8	1	C	17
Z						
T						



Cycle: 10

	tag	value	valid?
R1		1	1
R2		2	1
R3	X	2	1
R4		4	1
R5	D	5	0
R6		6	1
R7	B	8	1
R8		8	1
R9		9	1
R10	C	17	1
R11	Y	11	0

	SRC1			SRC2		
	V	tag	value	V	tag	value
A	1	X	2	1	-	4
B						
C						
D	0	A	-	0	Y	-

ADD

	SRC1			SRC2		
	V	tag	value	V	tag	value
X						
Y	1	B	8	1	C	17
Z						
T						

MUL

Cycle: 12

tag value valid?

R1		1	1
R2		2	1
R3	X	2	1
R4		4	1
R5	D	5	0
R6		6	1
R7	B	8	1
R8		8	1
R9		9	1
R10	C	17	1
R11	Y	11	0

SRC1

V tag value

A
B
C
D

1	X	2	1	-	4
1	A	6	0	Y	-

ADD

SRC1

V tag value

X
Y
Z
T

1	B	8	1	C	17

MUL

SRC2

V tag value

Cycle: 13

	tag	value	valid?
R1		1	1
R2		2	1
R3	X	2	1
R4		4	1
R5	D	5	0
R6		6	1
R7	B	8	1
R8		8	1
R9		9	1
R10	C	17	1
R11	Y	11	0

	SRC1			SRC2		
	V	tag	value	V	tag	value
A						
B						
C						
D	1	A	6	0	Y	-



	SRC1			SRC2		
	V	tag	value	V	tag	value
X						
Y	1	B	8	1	C	17
Z						
T						



Cycle: 15

	tag	value	valid?
R1		1	1
R2		2	1
R3	X	2	1
R4		4	1
R5	D	5	0
R6		6	1
R7	B	8	1
R8		8	1
R9		9	1
R10	C	17	1
R11	Y	136	1

	SRC1			SRC2		
	V	tag	value	V	tag	value
A						
B						
C						
D	1	A	6	1	Y	136



	SRC1			SRC2		
	V	tag	value	V	tag	value
X						
Y	1	B	8	1	C	17
Z						
T						



Cycle: 16

	tag	value	valid?
R1		1	1
R2		2	1
R3	X	2	1
R4		4	1
R5	D	5	0
R6		6	1
R7	B	8	1
R8		8	1
R9		9	1
R10	C	17	1
R11	Y	136	1

	SRC1			SRC2		
	V	tag	value	V	tag	value
A						
B						
C						
D	1	A	6	1	Y	136



	SRC1			SRC2		
	V	tag	value	V	tag	value
X						
Y						
Z						
T						



Cycle: 20

tag value valid?

R1		1	1
R2		2	1
R3	X	2	1
R4		4	1
R5	D	142	1
R6		6	1
R7	B	8	1
R8		8	1
R9		9	1
R10	C	17	1
R11	Y	136	1

SRC1

V tag value

SRC2

V tag value

A

B

C

D

ADD

SRC1

V tag value

SRC2

V tag value

X

Y

Z

T

MUL

Instruction	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
MUL R3 ← R1, R2	F	D	X1	X2	x3	X4	X5	X6	W											
ADD R5 ← R3, R4		F	D	-	-	-	-	-	X1	X2	X3	X4	W							
ADD R7 ← R2, R6			F	D	X1	X2	X3	X4	W											
ADD R10 ← R8, R9				F	D	X1	X2	X3	X4	W										
MUL R11 ← R7, R10					F	D	-	-	-	X1	X2	X3	X4	X5	X6	W				
ADD R5 ← R5, R11						F	D	-	-	-	-	-	-	-	-	X1	X2	X3	X4	W