

Initials:

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## 2. Register Renaming [40 points]

In this problem, we will give you the state of the Register Alias Table (RAT), Reservation Stations (RS), and Physical Register File (PRF) for a Tomasulo-like out-of-order execution engine.

The out-of-order machine in this problem has the following characteristics:

- The processor is fully pipelined with four stages: Fetch, decode, execute, and writeback.
- For all instructions, fetch takes 1 cycle, decode takes 1 cycle, and writeback takes 1 cycle.
- The processor implements ADD and MUL instructions only. Both the adder and multiplier are fully pipelined. ADD instructions take 3 cycles and MUL instructions take 4 cycles in the execute stage. Note that the adder and multiplier have separate common data buses (CDBs), which allow both the adder and multiplier to broadcast results in the same cycle.
- An instruction always allocates the first reservation station that is available (in top-to-bottom order) at the required functional unit.

Suppose the pipeline is initially empty and the machine fetches exactly 5 instructions. The diagram below shows the snapshot of the machine at a particular point in time.

**Register Alias Table**

ID	V	Tag
R0	1	P0
R1	1	P8
R2	0	P15
R3	1	P3
R4	0	P10
R5	1	P5
R6	1	P12
R7	1	P7

**Physical Register File**

ID	V	Data	ID	V	Data
P0	1	1	P8	1	87
P1	0	10	P9	1	90
P2	0	2	P10	1	11
P3	1	30	P11	0	110
P4	0	3	P12	1	37
P5	1	50	P13	0	130
P6	0	5	P14	1	17
P7	1	70	P15	1	159

**ADD Reservation Station**

ID	V	Tag	V	Tag	Dest. Tag
A	0	–	0	–	–
B	1	P15	1	P5	P14

**ADD CDB**

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**MUL Reservation Station**

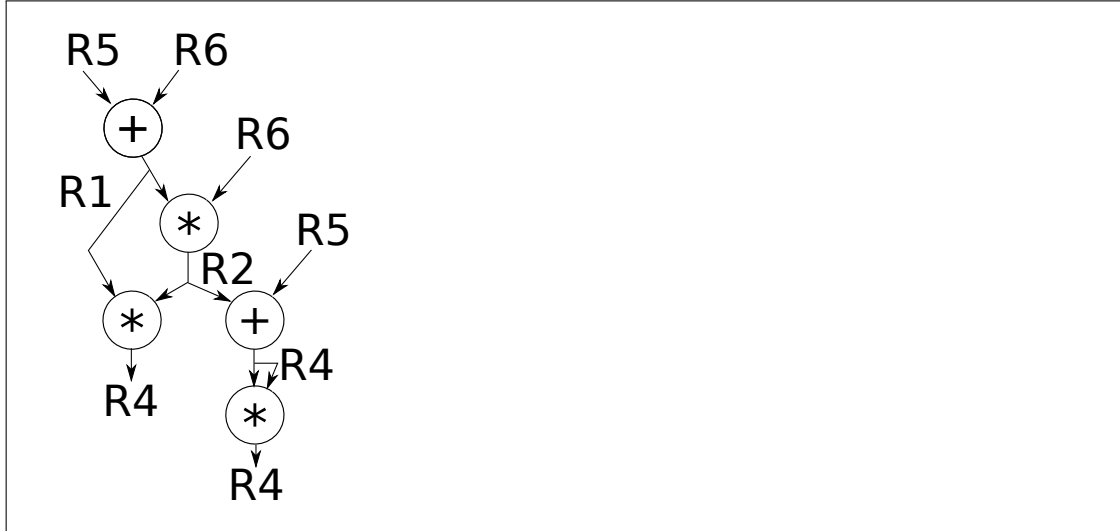
ID	V	Tag	V	Tag	Dest. Tag
X	1	P8	1	P12	P15
Y	1	P8	1	P15	P9
Z	0	P14	0	P14	P10

**MUL CDB**

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- (a) Your first task is to use only the supplied information to draw the data flow graph for the five instructions which have been fetched. Label nodes with the operation (+ or \*) being performed and edges with the architectural register alias numbers (e.g., R0).



- (b) Now, use the data flow graph to fill in the table below with the five instructions being executed on the processor in program order. The source registers for the first instruction can be specified in either order. Give instructions in the following format: “opcode, destination, source1, source2.”

OP	Dest	Src 1	Src 2
ADD	R1	R5	R6
MUL	R2	R1	R6
MUL	R4	R2	R1
ADD	R4	R5	R2
MUL	R4	R4	R4

- (c) Now show the full pipeline timing diagram below for the sequence of five instructions that you determined above, from the fetch of the first instruction to the writeback of the last instruction. Assume that the machine stops fetching instructions after the fifth instruction.

As we saw in class, use F for fetch, D for decode, En to signify the nth cycle of execution for an instruction, and W to signify writeback. You may or may not need all columns shown. Finally, identify the cycle after which the snapshot of the microarchitecture was taken. Shade the corresponding cycle in the last row of the table.

Cycle:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Instruction 1	F	D	E1	E2	E3	W													
Instruction 2		F	D			E1	E2	E3	E4	W									
Instruction 3			F	D						E1	E2	E3	E4	W					
Instruction 4				F	D					E1	E2	E3	W						
Instruction 5					F	D							E1	E2	E3	E4	W		
Snapshot cycle									X										