

U. Wisconsin CS/ECE 752

Advanced Computer Architecture I

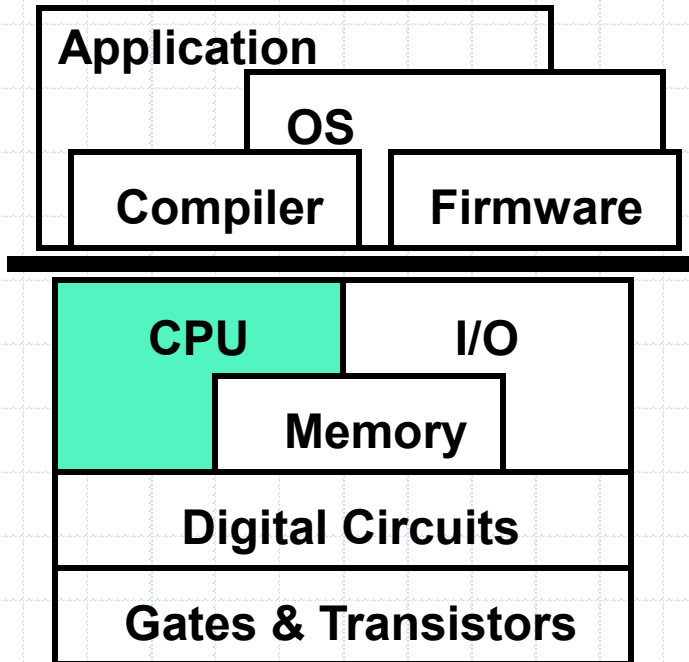
Prof. Guri Sohi

Unit 6: Dynamic Scheduling II

Slides developed by Amir Roth of University of Pennsylvania with sources that included University of Wisconsin slides by Mark Hill, Guri Sohi, Jim Smith, and David Wood.

Slides enhanced by Milo Martin, Mark Hill, and David Wood with sources that included Profs. Asanovic, Falsafi, Hoe, Lipasti, Shen, Smith, Sohi, Vijaykumar, and Wood

This Unit: Dynamic Scheduling II



- Previously: dynamic scheduling
 - Insn buffer + scheduling algorithms
 - Scoreboard: no register renaming
 - Tomasulo: register renaming
- Now: add speculation, precise state
 - Re-order buffer
 - PentiumPro vs. MIPS R10000
- Also: dynamic load scheduling
 - Out-of-order memory operations

Superscalar + Out-of-Order + Speculation

- Three great tastes that taste great together
 - $\text{CPI} \geq 1$?
 - Go superscalar
 - Superscalar increases RAW hazards?
 - Go out-of-order (OoO)
 - RAW hazards still a problem?
 - Build a larger window
 - Branches a problem for filling large window?
 - Add control speculation

Speculation and Precise Interrupts

- Why are we discussing these together?
 - Sequential (vN) semantics for interrupts
 - All insns before interrupt should be complete
 - All insns after interrupt should look as if never started (abort)
 - **Basically want same thing for mis-predicted branch**
 - What makes precise interrupts difficult?
 - OoO completion → must undo post-interrupt writebacks
 - Same thing for branches
 - In-order → branches complete before younger insns writeback
 - OoO → not necessarily
- Precise interrupts, mis-speculation recovery: same problem
- **Same problem → same solution**

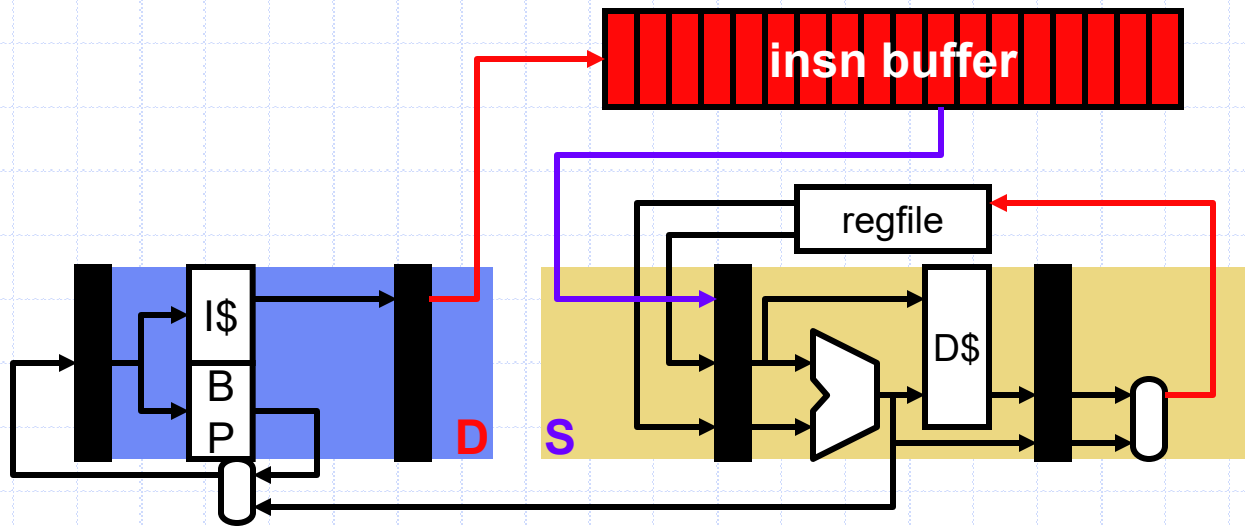
Precise State

- Speculative execution requires
 - (Ability to) abort & restart at every branch
 - Abort & restart at every load useful for load speculation (later)
 - And for shared memory multiprocessing (much later)
- Precise synchronous (program-internal) interrupts require
 - Abort & restart at every load, store, ??
- Precise asynchronous (external) interrupts require
 - Abort & restart at every ??
- Bite the bullet
 - Implement abort & restart at every insn
 - Called **"precise state"**

Precise State Options

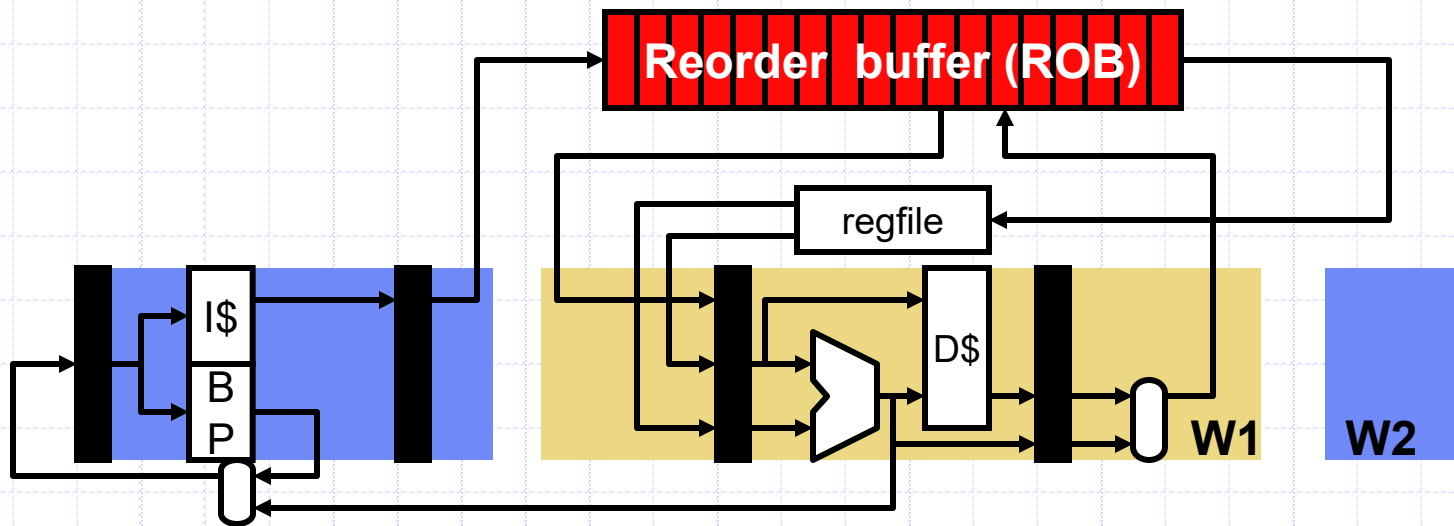
- Imprecise state: ignore the problem!
 - Makes page faults (any restartable exceptions) difficult
 - Makes speculative execution almost impossible
 - IEEE standard strongly suggests precise state
 - Compromise: Alpha implemented precise state only for integer ops
- Force in-order completion (W): stall pipe if necessary
 - Slow
- Precise state in software: trap to recovery routine
 - Implementation dependent
 - Trap on every mis-predicted branch (you must be joking)
- Precise state in hardware
 - + Everything is better in hardware (except policy)

The Problem with Precise State



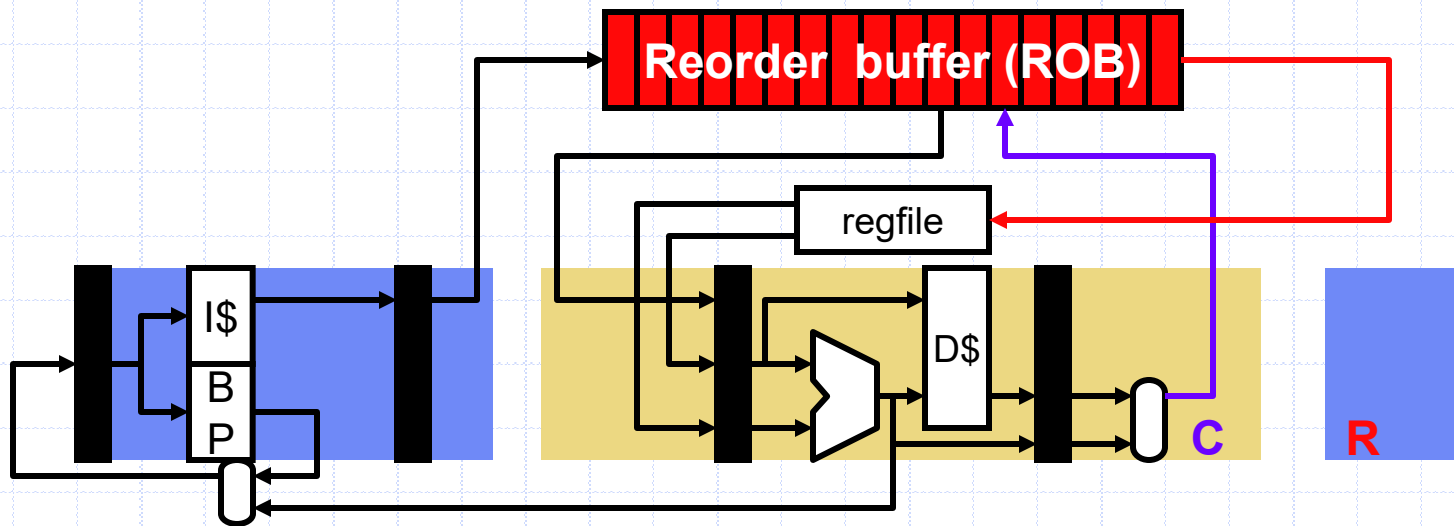
- Problem: **writeback** combines two separate functions
 - Forwards values to younger insns: OK for this to be out-of-order
 - Write values to registers: would like this to be in-order
- Similar problem (decode) for OoO execution: solution?
 - Split decode (D) → **in-order dispatch (D)** + **out-of-order issue (S)**
 - Separate using insn buffer: scoreboard or reservation station

Re-Order Buffer (ROB)



- **Insn buffer → re-order buffer (ROB)**
 - Buffers completed results en route to register file
 - May be combined with RS or separate
 - Combined in picture: register-update unit RUU (Sohi's method)
 - Separate (more common today): P6-style
- Split writeback (W) into two stages
 - Why is there no latch between W1 and W2?

Complete and Retire

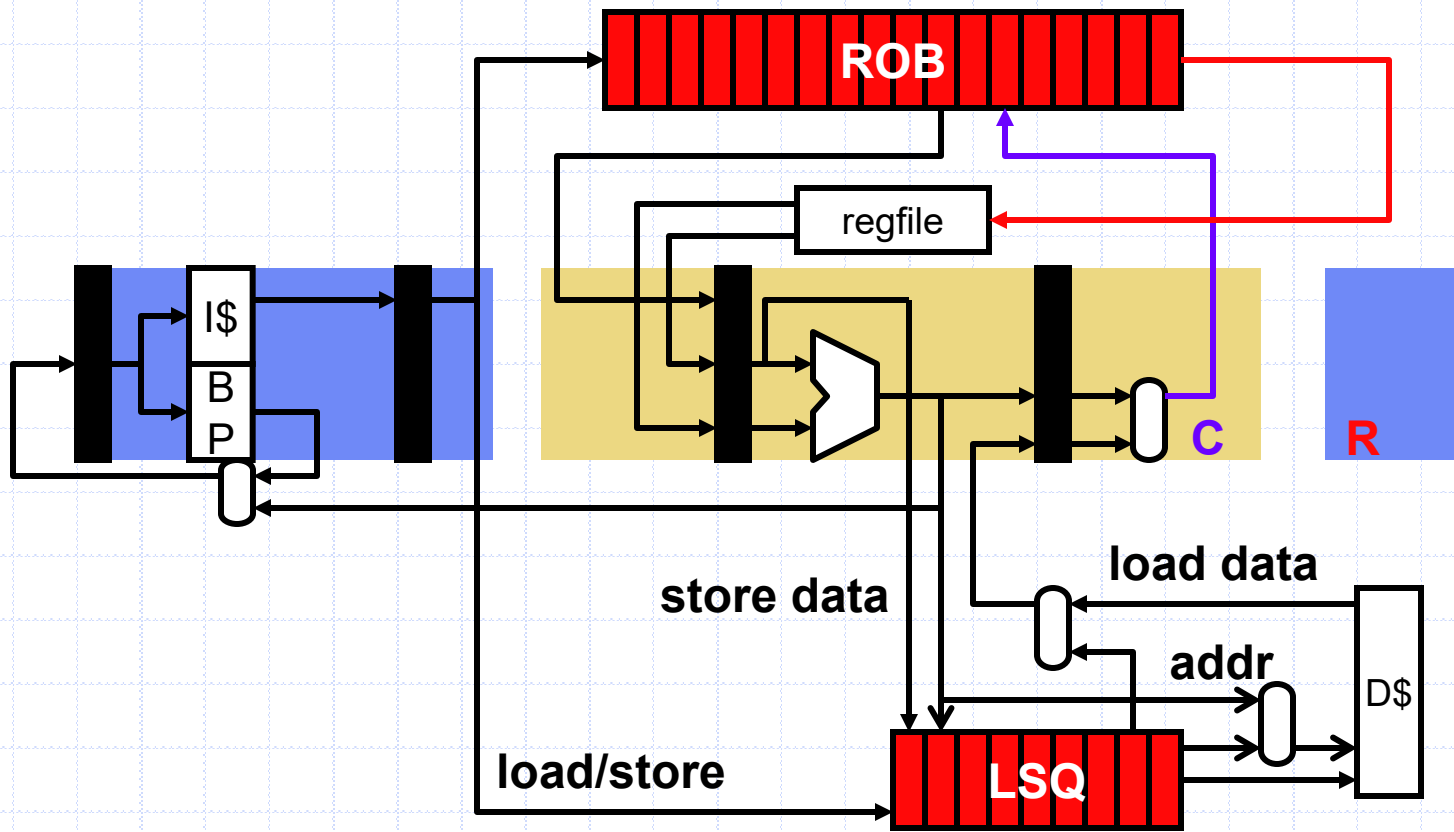


- **Complete (C)**: first part of writeback (W)
 - Completed insns write results into ROB
 - + Out-of-order: **wait** doesn't back-propagate to younger insns
- **Retire (R)**: aka commit, graduate
 - ROB writes results to register file
 - In order: **stall** back-propagates to younger insns

Load/Store Queue (LSQ)

- ROB makes register writes in-order, but what about stores?
- **Load/store queue (LSQ)**
 - Completed stores write to LSQ
 - When store retires, head of LSQ written to D\$
 - When loads execute, access LSQ and D\$ in parallel
 - Forward from LSQ if older store with matching address
 - More modern design: loads and stores in separate queues
 - More on this later

ROB + LSQ



- Modulo gross simplifications, this picture is almost realistic!

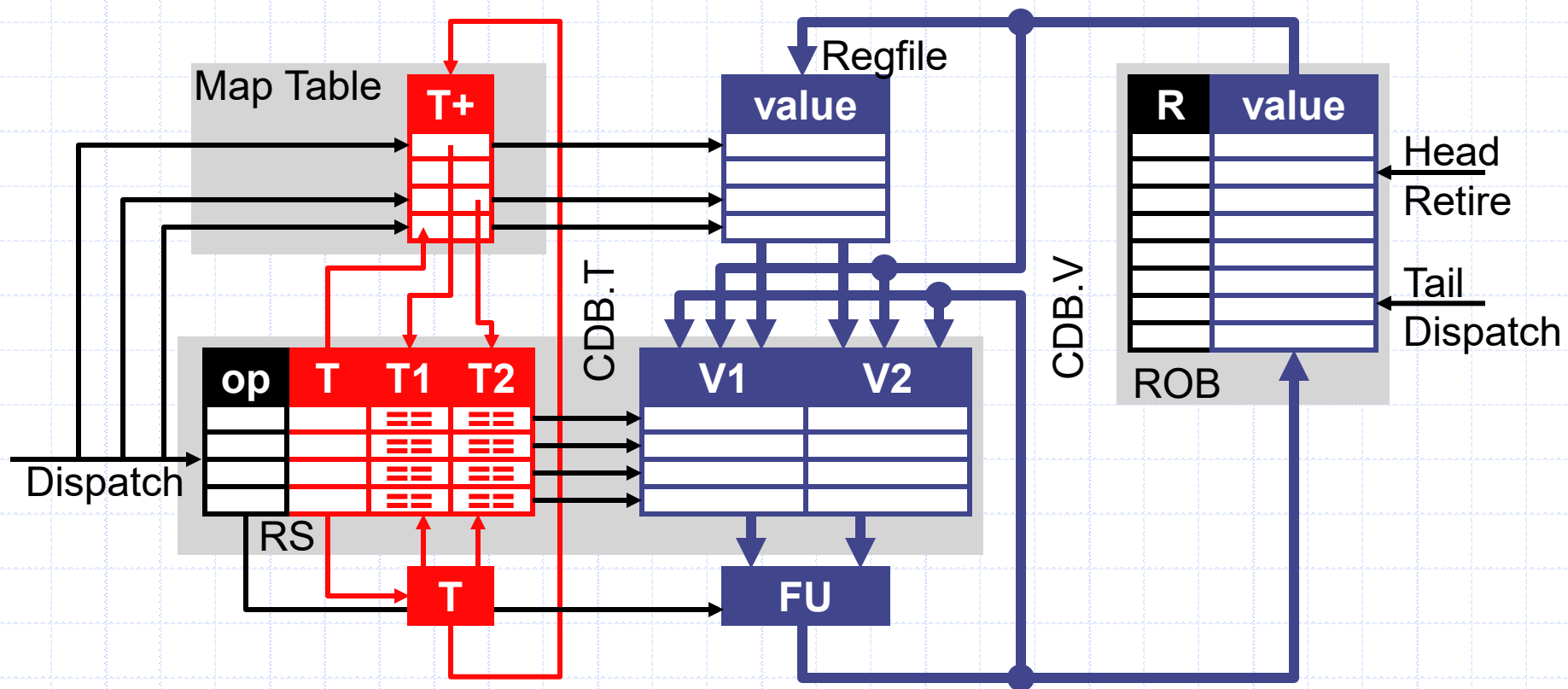
P6

- P6: Start with Tomasulo's algorithm... add ROB
 - Separate ROB and RS
- Simple-P6
 - Our old RS organization: 1 ALU, 1 load, 1 store, 2 3-cycle FP

P6 Data Structures

- Reservation Stations are same as before
- ROB
 - **head, tail**: pointers maintain sequential order
 - **R**: insn output register, **V**: insn output value
- Tags are different
 - Tomasulo: RS# $\rightarrow$ P6: ROB#
- Map Table is different
 - **T+**: tag + “ready-in-ROB” bit
 - $T=0 \rightarrow$ Value is ready in regfile
 - $T \neq 0 \rightarrow$ Value is not ready
 - $T \neq 0+ \rightarrow$ Value is ready in the ROB

P6 Data Structures



- Insn fields and status bits
- **Tags**
- **Values**

P6 Data Structures

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1),f1					
	2	mulf f0,f1,f2					
	3	stf f2,Z(r1)					
	4	addi r1,4,r1					
	5	ldf X(r1),f1					
	6	mulf f0,f1,f2					
	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	
f1	
f2	
r1	

CDB	
T	V

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	no						
3	ST	no						
4	FP1	no						
5	FP2	no						

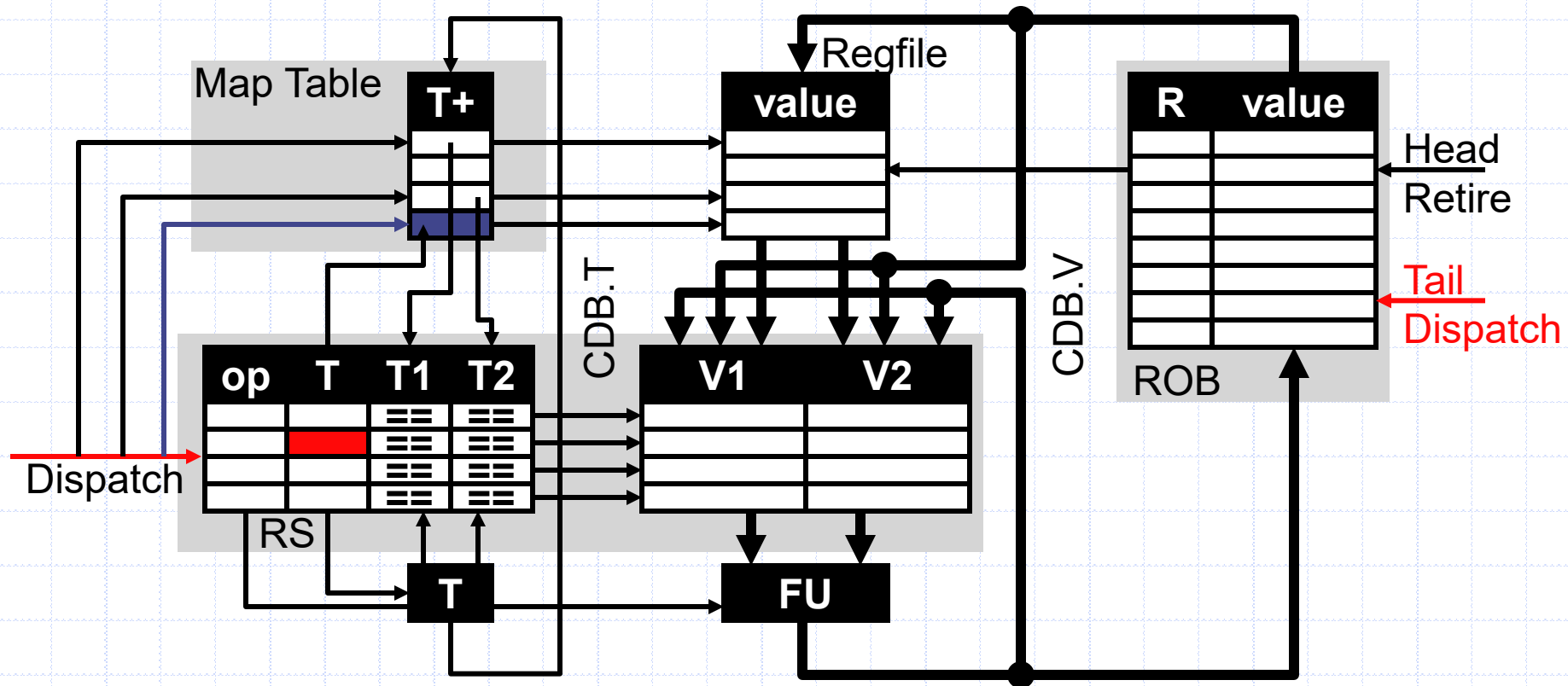
P6 Pipeline

- New pipeline structure: F, **D**, S, **X**, **C**, **R**
 - **D (dispatch)**
 - Structural hazard (ROB/LSQ/RS) ? **Stall**
 - Allocate ROB/LSQ/RS
 - Set RS tag to ROB#
 - Set Map Table entry to ROB# and clear “ready-in-ROB” bit
 - Read ready registers into RS (from either ROB or Regfile)
 - **X (execute)**
 - Free RS entry
 - Use to be at W, can be earlier because RS# are not tags

P6 Pipeline

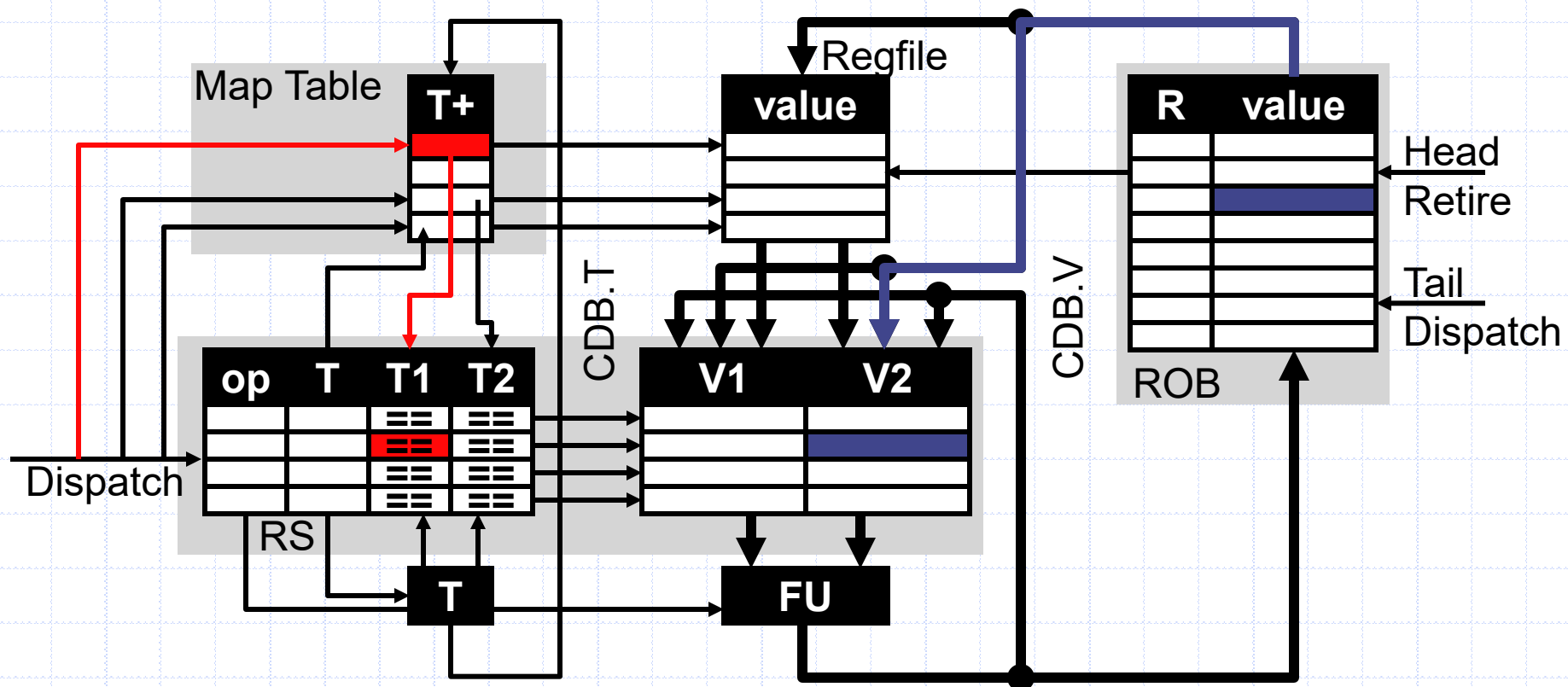
- **C (complete)**
 - Structural hazard (CDB)? **wait**
 - Write value into ROB entry indicated by RS tag
 - Mark ROB entry as complete
 - If not overwritten, mark Map Table entry “ready-in-ROB” bit (+)
- **R (retire)**
 - Insn at ROB head not completed? **stall**
 - Handle any exceptions
 - Write ROB head value to register file
 - If store, write LSQ head to D\$
 - Free ROB/LSQ entries

P6 Dispatch (D): Part I



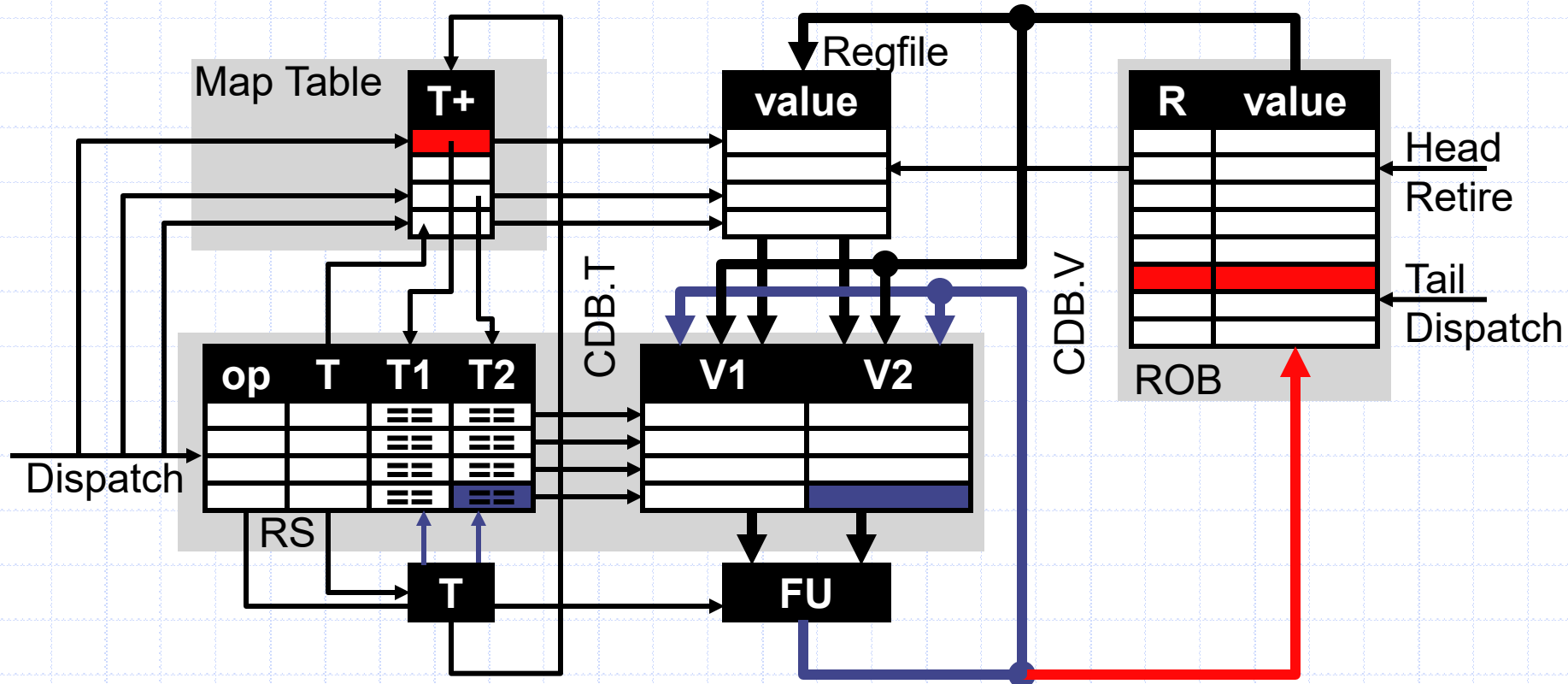
- RS/ROB full ? stall
- **Allocate RS/ROB entries, assign ROB# to RS output tag**
- **Set output register Map Table entry to ROB#, clear "ready-in-ROB"**

P6 Dispatch (D): Part II



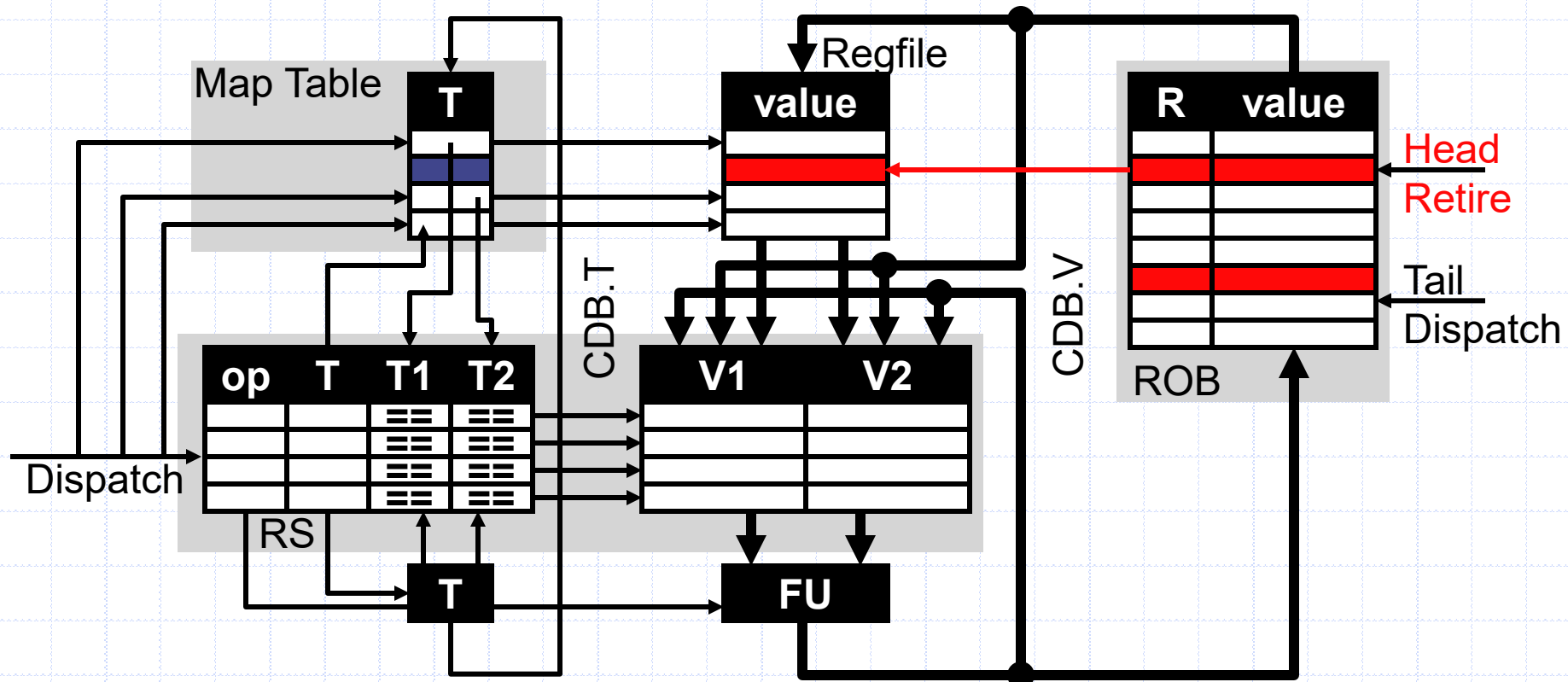
- Read tags for register inputs from Map Table
 - Tag==0 → copy value from Regfile (not shown)
 - Tag!=0 → copy Map Table tag to RS
 - Tag!=0+ → copy value from ROB

P6 Complete (C)



- Structural hazard (CDB) ? Stall : broadcast <value,tag> on CDB
- Write result into ROB, if still valid set MapTable "ready-in-ROB" bit
- Match tags, write CDB.V into RS slots of dependent insns

P6 Retire (R)



- ROB head not complete ? stall : free ROB entry
- Write ROB head result to Regfile
- If still valid, clear Map Table entry

P6: Cycle 1

ROB							
ht	#	Insn	R	V	S	X	C
ht	1	ldf X(r1), f1	f1				
	2	mulf f0, f1, f2					
	3	stf f2, Z(r1)					
	4	addi r1, 4, r1					
	5	ldf X(r1), f1					
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#1
f2	
r1	

CDB	
T	V

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	yes	ldf	ROB#1				[r1]
3	ST	no						
4	FP1	no						
5	FP2	no						

set ROB# tag

allocate

P6: Cycle 2

ROB							
ht	#	Insn	R	V	S	X	C
h	1	ldf X(r1), f1	f1		c2		
t	2	mulf f0, f1, f2	f2				
	3	stf f2, Z(r1)					
	4	addi r1, 4, r1					
	5	ldf X(r1), f1					
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#1
f2	ROB#2
r1	

CDB	
T	V

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	yes	ldf	ROB#1				[r1]
3	ST	no						
4	FP1	yes	mulf	ROB#2		ROB#1	[f0]	
5	FP2	no						

set ROB# tag

allocate

P6: Cycle 3

ROB							
ht	#	Insn	R	V	S	X	C
h	1	ldf X(r1), f1	f1		c2	c3	
	2	mulf f0, f1, f2	f2				
t	3	stf f2, Z(r1)					
	4	addi r1, 4, r1					
	5	ldf X(r1), f1					
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#1
f2	ROB#2
r1	

CDB	
T	V

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	no						
3	ST	yes	stf	ROB#3	ROB#2			[r1]
4	FP1	yes	mulf	ROB#2		ROB#1	[f0]	
5	FP2	no						

free
allocate

P6: Cycle 4

ROB							
ht	#	Insn	R	V	S	X	C
h	1	ldf X(r1), f1	f1	[f1]	c2	c3	c4
	2	mulf f0, f1, f2	f2		c4		
	3	stf f2, Z(r1)					
t	4	addi r1, 4, r1	r1				
	5	ldf X(r1), f1					
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#1+
f2	ROB#2
r1	ROB#4

CDB	
T	V
ROB#1	[f1]

ldf finished

1. set "ready-in-ROB" bit
2. write result to ROB
3. CDB broadcast

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	yes	add	ROB#4			[r1]	
2	LD	no						
3	ST	yes	stf	ROB#3	ROB#2			[r1]
4	FP1	yes	mulf	ROB#2		ROB#1	[f0]	CDB.V
5	FP2	no						

allocate

ROB#1 ready
grab CDB.V

P6: Cycle 5

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1), f1	f1	[f1]	c2	c3	c4
h	2	mulf f0, f1, f2	f2		c4	c5	
	3	stf f2, Z(r1)					
	4	addi r1, 4, r1	r1		c5		
t	5	ldf X(r1), f1	f1				
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#5
f2	ROB#2
r1	ROB#4

CDB	
T	V

ldf retires
1. write ROB result to regfile

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	yes	add	ROB#4			[r1]	
2	LD	yes	ldf	ROB#5		ROB#4		
3	ST	yes	stf	ROB#3	ROB#2			[r1]
4	FP1	no						
5	FP2	no						

allocate

free

P6: Cycle 6

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1), f1	f1	[f1]	c2	c3	c4
h	2	mulf f0, f1, f2	f2		c4	c5+	
	3	stf f2, Z(r1)					
	4	addi r1, 4, r1	r1		c5	c6	
	5	ldf X(r1), f1	f1				
t	6	mulf f0, f1, f2	f2				
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#5
f2	ROB#6
r1	ROB#4

CDB	
T	V

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	yes	ldf	ROB#5		ROB#4		
3	ST	yes	stf	ROB#3	ROB#2			[r1]
4	FP1	yes	mulf	ROB#6		ROB#5	[f0]	
5	FP2	no						

free

allocate

P6: Cycle 7

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1), f1	f1	[f1]	c2	c3	c4
h	2	mulf f0, f1, f2	f2		c4	c5+	
	3	stf f2, Z(r1)					
	4	addi r1, 4, r1	r1	[r1]	c5	c6	c7
	5	ldf X(r1), f1	f1		c7		
t	6	mulf f0, f1, f2	f2				
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#5
f2	ROB#6
r1	ROB#4+

CDB	
T	V
ROB#4	[r1]

stall D (no free ST RS)

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	yes	ldf	ROB#5		ROB#4		CDB.V
3	ST	yes	stf	ROB#3	ROB#2			[r1]
4	FP1	yes	mulf	ROB#6		ROB#5	[f0]	
5	FP2	no						

ROB#4 ready
grab CDB.V

P6: Cycle 8

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1), f1	f1	[f1]	c2	c3	c4
h	2	mulf f0, f1, f2	f2	[f2]	c4	c5+	c8
	3	stf f2, Z(r1)			c8		
	4	addi r1, 4, r1	r1	[r1]	c5	c6	c7
	5	ldf X(r1), f1	f1		c7	c8	
t	6	mulf f0, f1, f2	f2				
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#5
f2	ROB#6
r1	ROB#4+

CDB	
T	V
ROB#2	[f2]

stall R for addi (in-order)

ROB#2 invalid in MapTable
don't set "ready-in-ROB"

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	no						
3	ST	yes	stf	ROB#3	ROB#2		[f2]	[r1]
4	FP1	yes	mulf	ROB#6		ROB#5	[f0]	
5	FP2	no						

ROB#2 ready
grab CDB.V

P6: Cycle 9

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1), f1	f1	[f1]	c2	c3	c4
	2	mulf f0, f1, f2	f2	[f2]	c4	c5+	c8
h	3	stf f2, Z(r1)			c8	c9	
	4	addi r1, 4, r1	r1	[r1]	c5	c6	c7
	5	ldf X(r1), f1	f1	[f1]	c7	c8	c9
	6	mulf f0, f1, f2	f2		c9		
t	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#5+
f2	ROB#6
r1	ROB#4+

CDB	
T	V
ROB#5	[f1]

retire mulf

all pipe stages active at once!

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	no						
3	ST	yes	stf	ROB#7	ROB#6			ROB#4.V
4	FP1	yes	mulf	ROB#6		ROB#5	[f0]	CDB.V
5	FP2	no						

free, re-allocate
ROB#5 ready
grab CDB.V

P6: Cycle 10

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1),f1	f1	[f1]	c2	c3	c4
	2	mulf f0,f1,f2	f2	[f2]	c4	c5+	c8
h	3	stf f2,Z(r1)			c8	c9	c10
	4	addi r1,4,r1	r1	[r1]	c5	c6	c7
	5	ldf X(r1),f1	f1	[f1]	c7	c8	c9
	6	mulf f0,f1,f2	f2		c9	c10	
t	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#5+
f2	ROB#6
r1	ROB#4+

CDB	
T	V

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	no						
3	ST	yes	stf	ROB#7	ROB#6			ROB#4.V
4	FP1	no						
5	FP2	no						

free

P6: Cycle 11

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1),f1	f1	[f1]	c2	c3	c4
	2	mulf f0,f1,f2	f2	[f2]	c4	c5	c8
	3	stf f2,Z(r1)			c8	c9	c10
h	4	addi r1,4,r1	r1	[r1]	c5	c6	c7
	5	ldf X(r1),f1	f1	[f1]	c7	c8	c9
	6	mulf f0,f1,f2	f2		c9	c10	
t	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#5+
f2	ROB#6
r1	ROB#4+

retire stf

CDB	
T	V

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	no						
3	ST	yes	stf	ROB#7	ROB#6			ROB#4.V
4	FP1	no						
5	FP2	no						

Precise State in P6

- Point of ROB is maintaining **precise state**
 - How does that work?
 - Easy as 1,2,3
 1. Wait until last good insn retires, first bad insn at ROB head
 2. Clear contents of ROB, RS, and Map Table
 3. Start over
 - Works because zero (0) means the right thing...
 - 0 in ROB/RS → entry is empty
 - Tag == 0 in Map Table → register is in regfile
 - ...and because regfile and D\$ writes take place at R
 - Example: page fault in first `stf`

P6: Cycle 9 (with precise state)

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1), f1	f1	[f1]	c2	c3	c4
	2	mulf f0, f1, f2	f2	[f2]	c4	c5+	c8
h	3	stf f2, Z(r1)			c8	c9	
	4	addi r1, 4, r1	r1	[r1]	c5	c6	c7
	5	ldf X(r1), f1	f1	[f1]	c7	c8	c9
	6	mulf f0, f1, f2	f2		c9		
t	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	
f1	ROB#5+
f2	ROB#6
r1	ROB#4+

CDB	
T	V
ROB#5	[f1]

PAGE FAULT

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	no						
3	ST	yes	stf	ROB#7	ROB#6			ROB#4.V
4	FP1	yes	mulf	ROB#6		ROB#5	[f0]	CDB.V
5	FP2	no						

P6: Cycle 10 (with precise state)

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1),f1	f1	[f1]	c2	c3	c4
	2	mulf f0,f1,f2	f2	[f2]	c4	c5+	c8
	3	stf f2,Z(r1)					
	4	addi r1,4,r1					
	5	ldf X(r1),f1					
	6	mulf f0,f1,f2					
	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	
f1	
f2	
r1	

CDB	
T	V

faulting insn at ROB head?
CLEAR EVERYTHING

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	no						
3	ST	no						
4	FP1	no						
5	FP2	no						

P6: Cycle 11 (with precise state)

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1),f1	f1	[f1]	c2	c3	c4
	2	mulf f0,f1,f2	f2	[f2]	c4	c5+	c8
ht	3	stf f2,Z(r1)					
	4	addi r1,4,r1					
	5	ldf X(r1),f1					
	6	mulf f0,f1,f2					
	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	
f1	
f2	
r1	

CDB	
T	V

START OVER
(after OS fixes page fault)

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	no						
2	LD	no						
3	ST	yes	stf	ROB#3			[f2]	[r1]
4	FP1	no						
5	FP2	no						

P6: Cycle 12 (with precise state)

ROB							
ht	#	Insn	R	V	S	X	C
	1	ldf X(r1),f1	f1	[f1]	c2	c3	c4
	2	mulf f0,f1,f2	f2	[f2]	c4	c5+	c8
h	3	stf f2,Z(r1)			c12		
t	4	addi r1,4,r1	r1				
	5	ldf X(r1),f1					
	6	mulf f0,f1,f2					
	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	
f1	
f2	
r1	ROB#4

CDB	
T	V

Reservation Stations								
#	FU	busy	op	T	T1	T2	V1	V2
1	ALU	yes	addi	ROB#4			[r1]	
2	LD	no						
3	ST	yes	stf	ROB#3			[f2]	[r1]
4	FP1	no						
5	FP2	no						

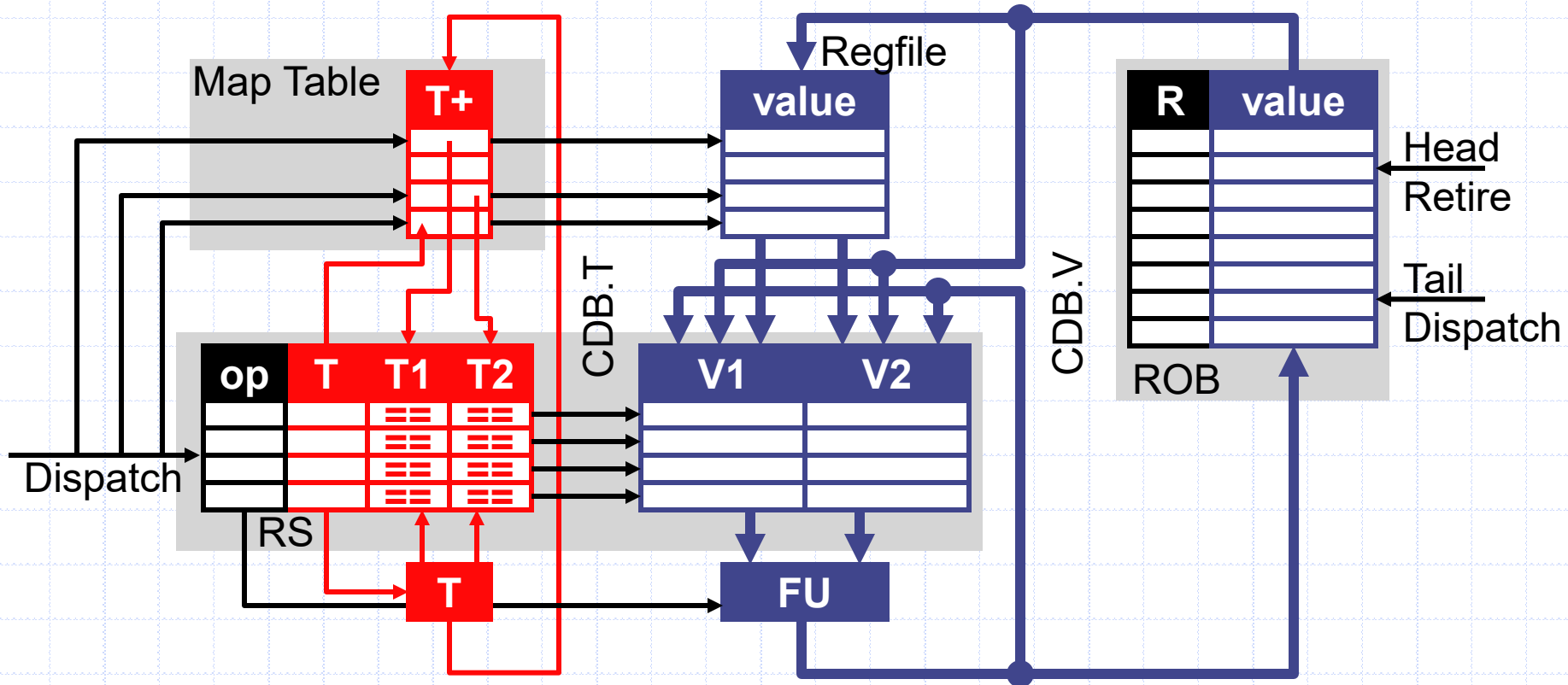
P6 Performance

- In other words: what is the cost of precise state?
 - + In general: same performance as “plain” Tomasulo
 - ROB is not a performance device
 - Maybe a little better (RS freed earlier → fewer struct hazards)
 - Unless ROB is too small
 - In which case ROB struct hazards become a problem
- Rules of thumb for ROB size
 - At least N (width) * number of pipe stages between D and R
 - At least $N * t_{\text{hit-L2}}$
 - Can add a factor of 2 to both if you want
 - What is the rationale behind these?

P6 (Tomasulo+ROB) Redux

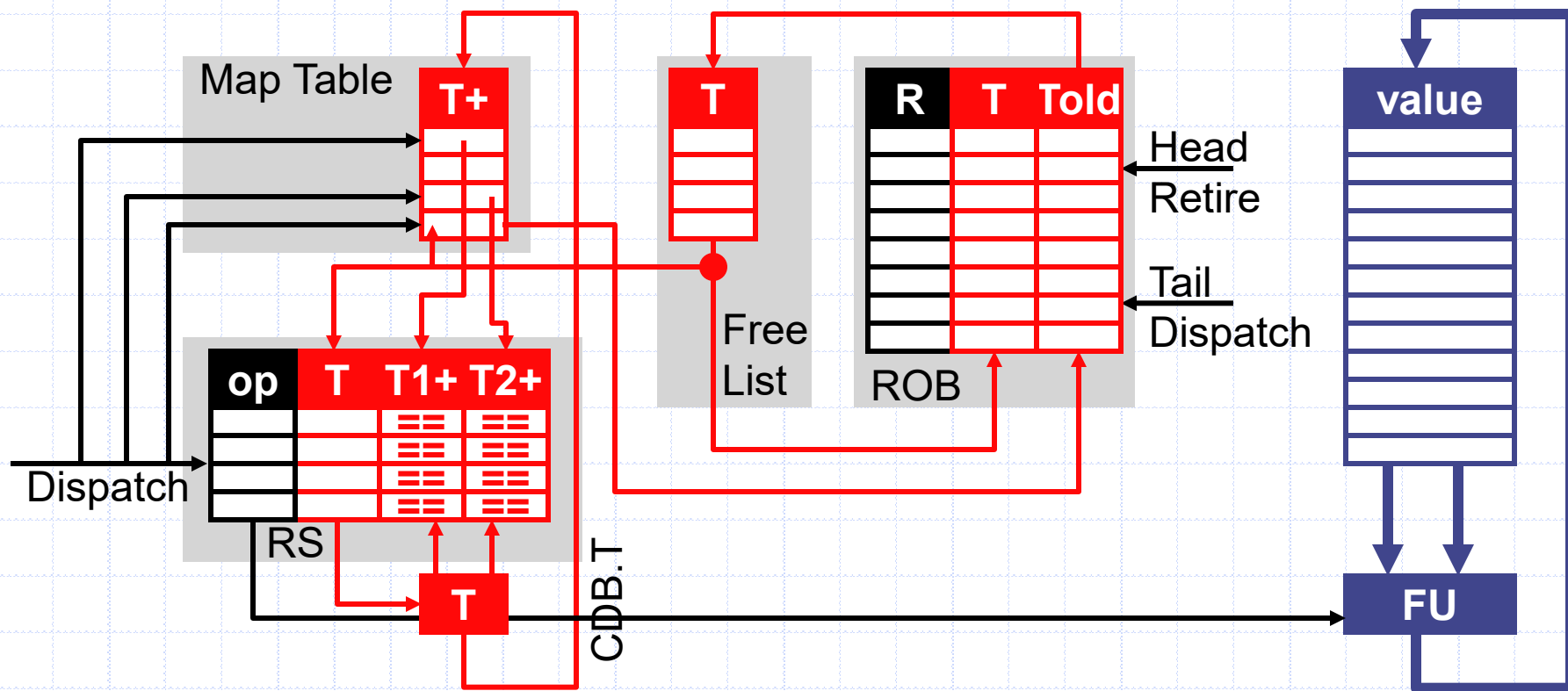
- Popular design for a while
 - (Relatively) easy to implement correctly
 - Anything goes wrong (mispredicted branch, fault, interrupt)?
 - Just clear everything and start again
 - Examples: Intel PentiumPro, IBM/Motorola PowerPC, AMD K6
- Actually making a comeback...
 - Examples: Intel PentiumM
- But went away for a while, why?

The Problem with P6



- Problem for high performance implementations
 - Too much **value movement** (regfile/ROB→RS→ROB→regfile)
 - Multi-input muxes, long buses complicate routing and slow clock

MIPS R10K: Alternative Implementation



- One big **physical register file** holds all data no copies
 - + Register file close to FUs → small fast data path
 - ROB and RS “on the side” used only for control and tags

Register Renaming in R10K

- Architectural register file? Gone
- **Physical register file** holds all values
 - $\text{\#physical registers} = \text{\#architectural registers} + \text{\#ROB entries}$
 - Map architectural registers to physical registers
 - Removes WAW, WAR hazards (physical registers replace RS copies)
- Fundamental change to **map table**
 - Mappings cannot be 0 (there is no architectural register file)
- **Free list** keeps track of unallocated physical registers
 - ROB is responsible for returning physical registers to free list
- Conceptually, this is “true register renaming”
 - Have already seen an example

Register Renaming Example

- Parameters

- Names: `r1, r2, r3`
- Locations: `11, 12, 13, 14, 15, 16, 17`
- Original mapping: `r1→11, r2→12, r3→13`, 14–17 are “free”

MapTable			FreeList	Raw insns	Renamed insns
r1	r2	r3			
11	12	13	14 , 15, 16, 17	add r2, r3, r1	add 12, 13, 14
14	12	13	15, 16, 17	sub r2, r1, r3	sub 12, 14, 15
14	12	15	16, 17	mul r2, r3, r1	mul 12, 15, 16
16	12	15	17	div r1, r3, r2	div 14, 15, 17

- Question: how is the insn after div renamed?
 - We are out of free locations (physical registers)
 - Real question: how/when are physical registers freed?

Freeing Registers in P6 and R10K

- P6
 - No need to free storage for speculative (“in-flight”) values explicitly
 - Temporary storage comes with ROB entry
 - R: copy speculative value from ROB to register file, free ROB entry
- R10K
 - Can’t free physical register when insn retires
 - No architectural register to copy value to
 - But...
 - Can free physical register previously mapped to same logical register
 - Why? All insns that will ever read its value have retired

Freeing Registers in R10K

MapTable

r1	r2	r3
11	12	13
14	12	13
14	12	15
16	12	15

FreeList

14, 15, 16, 17
15, 16, 17
16, 17
17

Raw insns

```
add r2,r3,r1
sub r2,r1,r3
mul r2,r3,r1
div r1,r3,r2
```

Renamed insns

```
add 12,13,14
sub 12,14,15
mul 12,15,16
div 14,15,17
```

- When **add** retires, free l1
- When **sub** retires, free l3
- When **mul** retires, free ?
- When **div** retires, free ?
- See the pattern?

R10K Data Structures

- New tags (again)
 - P6: ROB# $\rightarrow$ R10K: PR#
- ROB
 - **T**: physical register corresponding to insn's logical output
 - **Told**: physical register previously mapped to insn's logical output
- RS
 - **T**, **T1**, **T2**: output, input physical registers
- Map Table
 - **T+**: PR# (never empty) + "ready" bit
- Free List
 - **T**: PR#
- No values in ROB, RS, or on CDB

R10K Data Structures

ROB							
ht	#	Insn	T	Told	S	X	C
	1	ldf X(r1),f1					
	2	mulf f0,f1,f2					
	3	stf f2,Z(r1)					
	4	addi r1,4,r1					
	5	ldf X(r1),f1					
	6	mulf f0,f1,f2					
	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#2+
f2	PR#3+
r1	PR#4+

CDB
T

Free List
PR#5, PR#6, PR#7, PR#8

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	no				
2	LD	no				
3	ST	no				
4	FP1	no				
5	FP2	no				

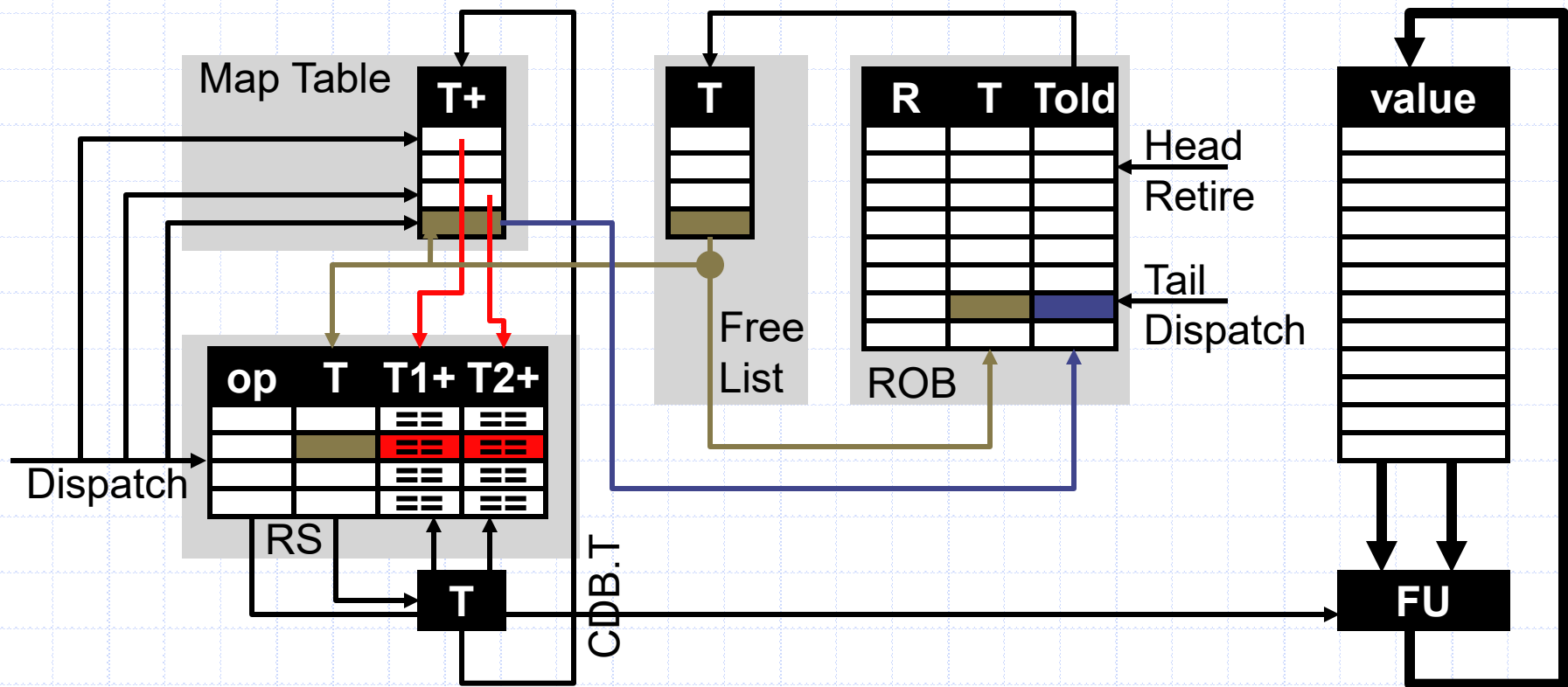
Notice I: no values anywhere

Notice II: MapTable is never empty

R10K Pipeline

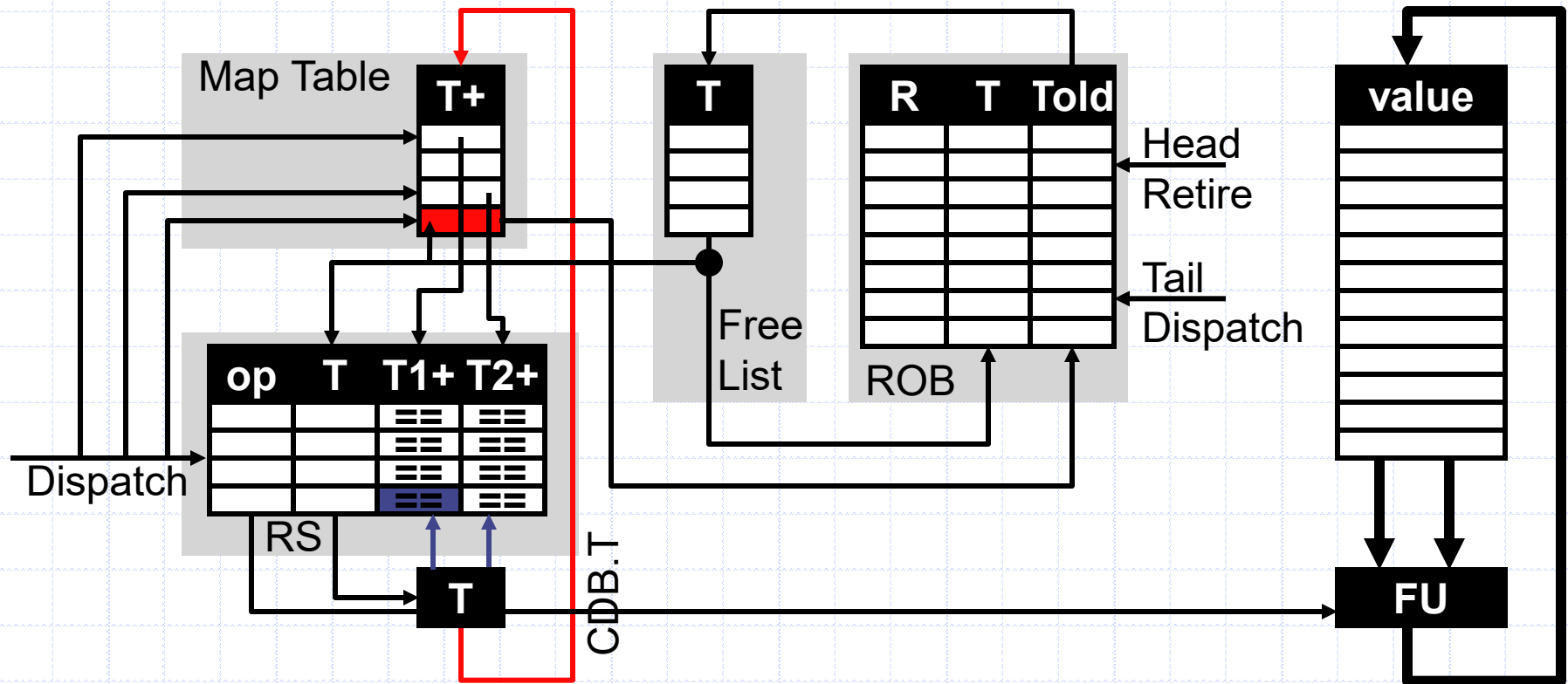
- R10K pipeline structure: F, **D**, S, X, **C**, **R**
 - **D (dispatch)**
 - Structural hazard (RS, ROB, LSQ, **physical registers**) ? stall
 - Allocate RS, ROB, LSQ entries and new physical register (T)
 - **Record previously mapped physical register (Told)**
 - **C (complete)**
 - Write destination physical register
 - **R (retire)**
 - ROB head not complete ? Stall
 - Handle any exceptions
 - Store write LSQ head to D\$
 - Free ROB, LSQ entries
 - **Free previous physical register (Told)**

R10K Dispatch (D)



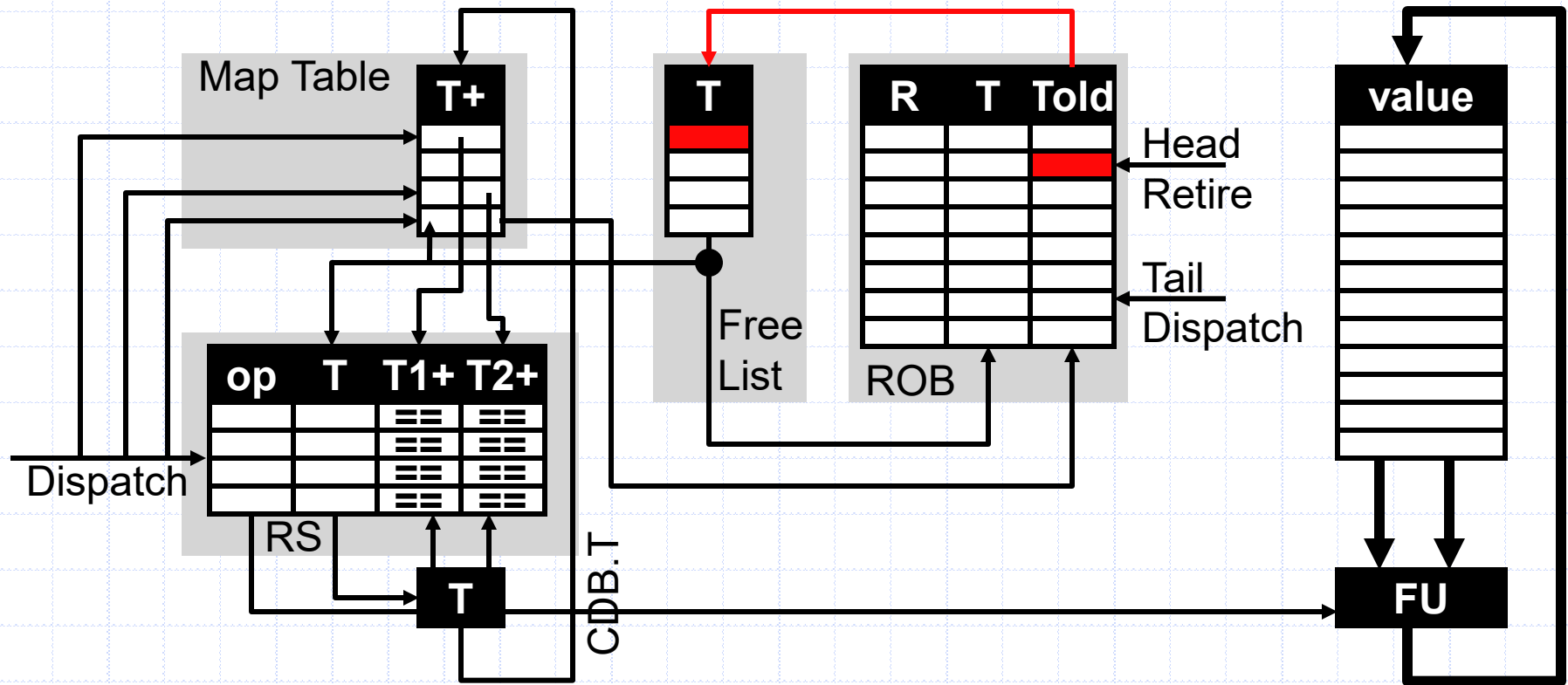
- Read preg (physical register) tags for input registers, store in RS
- Read preg tag for output register, store in ROB (Told)
- Allocate new preg (free list) for output register, store in RS, ROB, Map Table

R10K Complete (C)



- Set insn's output register ready bit in map table
- Set ready bits for matching input tags in RS

R10K Retire (R)



- Return Told of ROB head to free list

R10K: Cycle 1

ROB							
ht	#	Insn	T	Told	S	X	C
ht	1	ldf X(r1), f1	PR#5	PR#2			
	2	mulf f0, f1, f2					
	3	stf f2, Z(r1)					
	4	addi r1, 4, r1					
	5	ldf X(r1), f1					
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#5
f2	PR#3+
r1	PR#4+

CDB
T

Free List	
PR#5 , PR#6,	
PR#7, PR#8	

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	no				
2	LD	yes	ldf	PR#5		PR#4+
3	ST	no				
4	FP1	no				
5	FP2	no				

Allocate new preg (PR#5) to f1

Remember old preg mapped to f1 (PR#2) in ROB

R10K: Cycle 2

ROB							
ht	#	Insn	T	Told	S	X	C
h	1	ldf X(r1), f1	PR#5	PR#2	c2		
t	2	mulf f0, f1, f2	PR#6	PR#3			
	3	stf f2, Z(r1)					
	4	addi r1, 4, r1					
	5	ldf X(r1), f1					
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#5
f2	PR#6
r1	PR#4+

CDB
T

Free List	
PR#6, PR#7, PR#8	

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	no				
2	LD	yes	ldf	PR#5		PR#4+
3	ST	no				
4	FP1	yes	mulf	PR#6	PR#1+	PR#5
5	FP2	no				

Allocate new preg (PR#6) to f2

Remember old preg mapped to f2 (PR#3) in ROB

R10K: Cycle 3

ROB							
ht	#	Insn	T	Told	S	X	C
h	1	ldf X(r1),f1	PR#5	PR#2	c2	c3	
	2	mulf f0,f1,f2	PR#6	PR#3			
t	3	stf f2,Z(r1)					
	4	addi r1,4,r1					
	5	ldf X(r1),f1					
	6	mulf f0,f1,f2					
	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#5
f2	PR#6
r1	PR#4+

CDB
T

Free List
PR#7, PR#8

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	no				
2	LD	no				
3	ST	yes	stf		PR#6	PR#4+
4	FP1	yes	mulf	PR#6	PR#1+	PR#5
5	FP2	no				

Stores are not allocated pregs

Free

R10K: Cycle 4

ROB							
ht	#	Insn	T	Told	S	X	C
h	1	ldf X(r1), f1	PR#5	PR#2	c2	c3	c4
	2	mulf f0, f1, f2	PR#6	PR#3	c4		
	3	stf f2, Z(r1)					
t	4	addi r1, 4, r1	PR#7	PR#4			
	5	ldf X(r1), f1					
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#5+
f2	PR#6
r1	PR#7

CDB
T
PR#5

Free List
PR#7, PR#8

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	yes	addi	PR#7	PR#4+	
2	LD	no				
3	ST	yes	stf		PR#6	PR#4+
4	FP1	yes	mulf	PR#6	PR#1+	PR#5+
5	FP2	no				

ldf completes
set MapTable ready bit

Match PR#5 tag from CDB & issue

R10K: Cycle 5

ROB							
ht	#	Insn	T	Told	S	X	C
	1	ldf X(r1), f1	PR#5	PR#2	c2	c3	c4
h	2	mulf f0, f1, f2	PR#6	PR#3	c4	c5	
	3	stf f2, Z(r1)					
	4	addi r1, 4, r1	PR#7	PR#4	c5		
t	5	ldf X(r1), f1	PR#8	PR#5			
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#8
f2	PR#6
r1	PR#7

CDB
T

Free List
PR#8, PR#2

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	yes	addi	PR#7	PR#4+	
2	LD	yes	ldf	PR#8		PR#7
3	ST	yes	stf		PR#6	PR#4+
4	FP1	no				
5	FP2	no				

ldf retires
Return PR#2 to free list

Free

Precise State in R10K

- Problem with R10K design? Precise state is more difficult
 - Physical registers are written out-of-order (at C)
 - That's OK, there is no architectural register file
 - We can "free" written registers and "restore" old ones
 - Do this by manipulating the Map Table and Free List, not regfile
- Two ways of restoring Map Table and Free List
 - Option I: serial rollback using T , T_{old} ROB fields
 - ± Slow, but simple
 - Option II: single-cycle restoration from some checkpoint
 - ± Fast, but checkpoints are expensive
 - Modern processor compromise: **make common case fast**
 - Checkpoint only (low-confidence) branches (frequent rollbacks)
 - Serial recovery for page-faults and interrupts (rare rollbacks)

R10K: Cycle 5 (with precise state)

ROB							
ht	#	Insn	T	Told	S	X	C
	1	ldf X(r1), f1	PR#5	PR#2	c2	c3	c4
h	2	mulf f0, f1, f2	PR#6	PR#3	c4	c5	
	3	stf f2, Z(r1)					
	4	addi r1, 4, r1	PR#7	PR#4	c5		
t	5	ldf X(r1), f1	PR#8	PR#5			
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#8
f2	PR#6
r1	PR#7

CDB
T

Free List
PR#8, PR#2

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	yes	addi	PR#7	PR#4+	
2	LD	yes	ldf	PR#8		PR#7
3	ST	yes	stf		PR#6	PR#4+
4	FP1	no				
5	FP2	no				

undo insns 3-5
(doesn't matter why)
use serial rollback

R10K: Cycle 6 (with precise state)

ROB							
ht	#	Insn	T	Told	S	X	C
	1	ldf X(r1), f1	PR#5	PR#2	c2	c3	c4
h	2	mulf f0, f1, f2	PR#6	PR#3	c4	c5	
	3	stf f2, Z(r1)					
t	4	addi r1, 4, r1	PR#7	PR#4	c5		
	5	ldf X(r1), f1	PR#8	PR#5			
	6	mulf f0, f1, f2					
	7	stf f2, Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#5+
f2	PR#6
r1	PR#7

CDB
T

Free List
PR#2, PR#8

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	yes	addi	PR#7	PR#4+	
2	LD	no				
3	ST	yes	stf		PR#6	PR#4+
4	FP1	no				
5	FP2	no				

undo ldf (ROB#5)

1. free RS
2. free T (PR#8), return to FreeList
3. restore MT[f1] to Told (PR#5)
4. free ROB#5

insns may execute during rollback
(not shown)

R10K: Cycle 7 (with precise state)

ROB							
ht	#	Insn	T	Told	S	X	C
	1	ldf X(r1),f1	PR#5	PR#2	c2	c3	c4
h	2	mulf f0,f1,f2	PR#6	PR#3	c4	c5	
t	3	stf f2,Z(r1)					
	4	addi r1,4,r1	PR#7	PR#4	c5		
	5	ldf X(r1),f1					
	6	mulf f0,f1,f2					
	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#5+
f2	PR#6
r1	PR#4+

CDB
T

Free List
PR#2, PR#8, PR#7

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	no				
2	LD	no				
3	ST	yes	stf		PR#6	PR#4+
4	FP1	no				
5	FP2	no				

undo addi (ROB#4)

1. free RS
2. free T (PR#7), return to FreeList
3. restore MT[r1] to Told (PR#4)
4. free ROB#4

R10K: Cycle 8 (with precise state)

ROB							
ht	#	Insn	T	Told	S	X	C
	1	ldf X(r1),f1	PR#5	PR#2	c2	c3	c4
ht	2	mulf f0,f1,f2	PR#6	PR#3	c4	c5	
	3	stf f2,Z(r1)					
	4	addi r1,4,r1					
	5	ldf X(r1),f1					
	6	mulf f0,f1,f2					
	7	stf f2,Z(r1)					

Map Table	
Reg	T+
f0	PR#1+
f1	PR#5+
f2	PR#6
r1	PR#4+

CDB
T

Free List
PR#2, PR#8, PR#7

Reservation Stations						
#	FU	busy	op	T	T1	T2
1	ALU	no				
2	LD	no				
3	ST	no				
4	FP1	no				
5	FP2	no				

undo stf (ROB#3)

1. free RS

2. free ROB#3

3. no registers to restore/free

4. how is D\$ write undone?

P6 vs. R10K (Renaming)

Feature	P6	R10K
Value storage	ARF,ROB,RS	PRF
Register read	@D: ARF/ROB → RS	@S: PRF → FU
Register write	@R: ROB → ARF	@C: FU → PRF
Speculative value free	@R: automatic (ROB)	@R: overwriting insn
Data paths	ARF/ROB → RS RS → FU FU → ROB ROB → ARF	PRF → FU FU → PRF
Precise state	Simple: clear everything	Complex: serial/checkpoint

- R10K-style became popular in late 90's, early 00's
 - E.g., MIPS R10K (duh), DEC Alpha 21264, Intel Pentium4
- P6-style is perhaps making a comeback
 - Why? Frequency (power) is on the retreat, simplicity is important

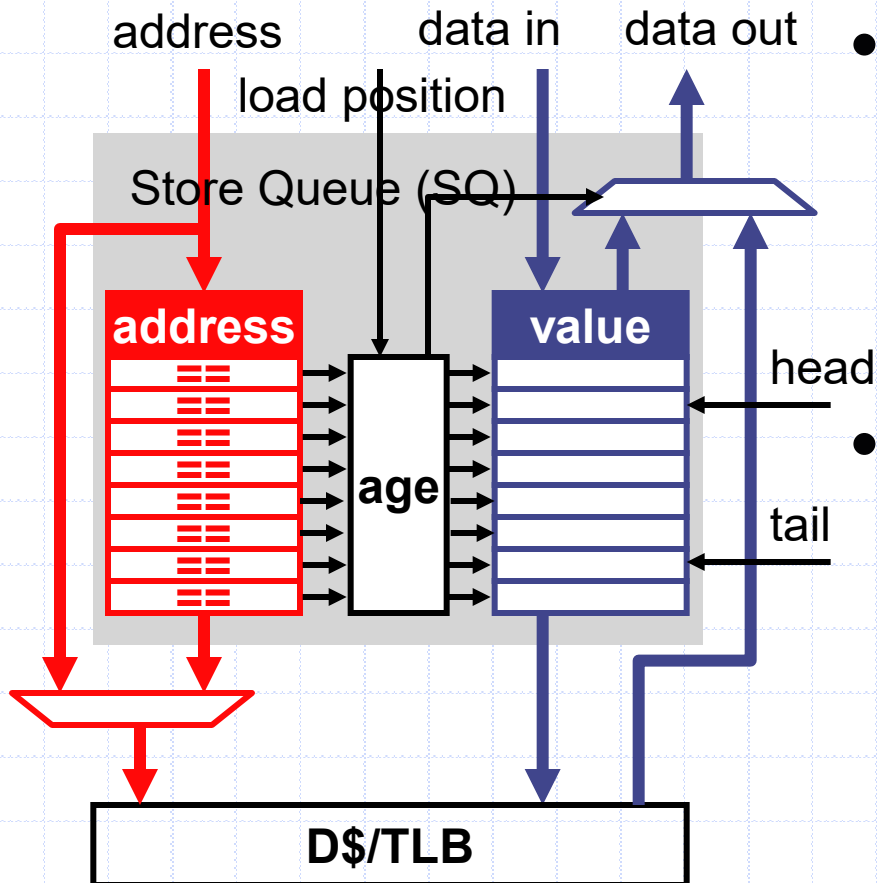
Out of Order Memory Operations

- All insns are easy in out-of-order...
 - Register inputs only
 - Register renaming captures all dependences
 - Tags tell you exactly when you can execute
- ... except loads
 - Register and memory inputs (older stores)
 - Register renaming does not tell you all dependences
 - Memory renaming (a little later)
 - How do loads find older in-flight stores to same address (if any)?

Data Memory Functional Unit

- D\$/TLB + structures to handle in-flight loads/stores
 - Performs four functions
 - **In-order store retirement**
 - Writes stores to D\$ in order
 - Basic, implemented by store queue (SQ)
 - **Store-load forwarding**
 - Allows loads to read values from older un-retired stores
 - Also basic, also implemented by store queue (SQ)
 - **Memory ordering violation detection**
 - Checks load speculation (more later)
 - Advanced, implemented by load queue (LQ)
 - **Memory ordering violation avoidance**
 - Advanced, implemented by dependence predictors

Simple Data Memory FU: D\$/TLB + SQ

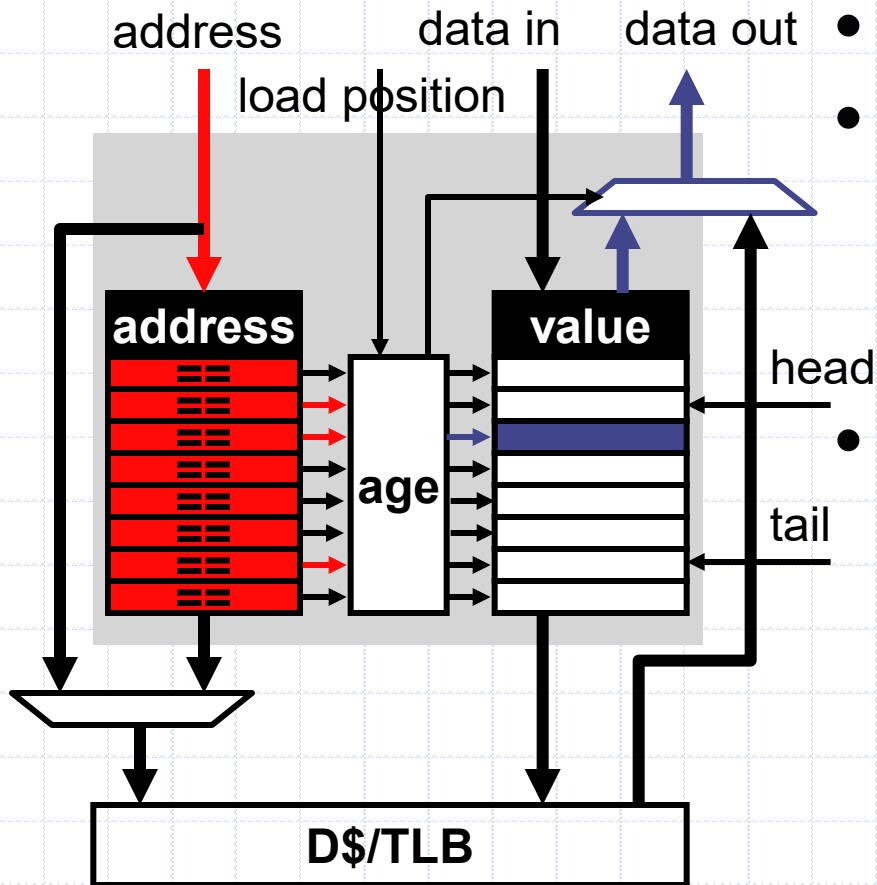


- Just like any other FU
 - 2 register inputs (addr, data in)
 - 1 register output (data out)
 - 1 non-register input (load pos)?
- **Store queue (SQ)**
 - In-flight store address/value
 - In program order (like ROB)
 - Addresses associatively searchable
 - Size heuristic: 15-20% of ROB
- But what does it do?

Data Memory FU “Pipeline”

- Stores
 - **Dispatch (D)**
 - Allocate entry at SQ tail
 - **Execute (X)**
 - Write address and data into corresponding SQ slot
 - **Retire (R)**
 - Write address/data from SQ head to D\$, free SQ head
- Loads
 - **Dispatch (D)**
 - Record current SQ tail as “load position”
 - **Execute (X)**
 - Where the good stuff happens

“Out-of-Order” Load Execution



- In parallel with D\$ access
- **Send address to SQ**
 - Compare with all store addresses
 - CAM: like FA\$, or RS tag match
 - Select all matching addresses
- **Age logic selects youngest store that is older than load**
 - Uses load position input
 - Any? load **“forwards”** value from SQ
 - None? Load gets value from D\$

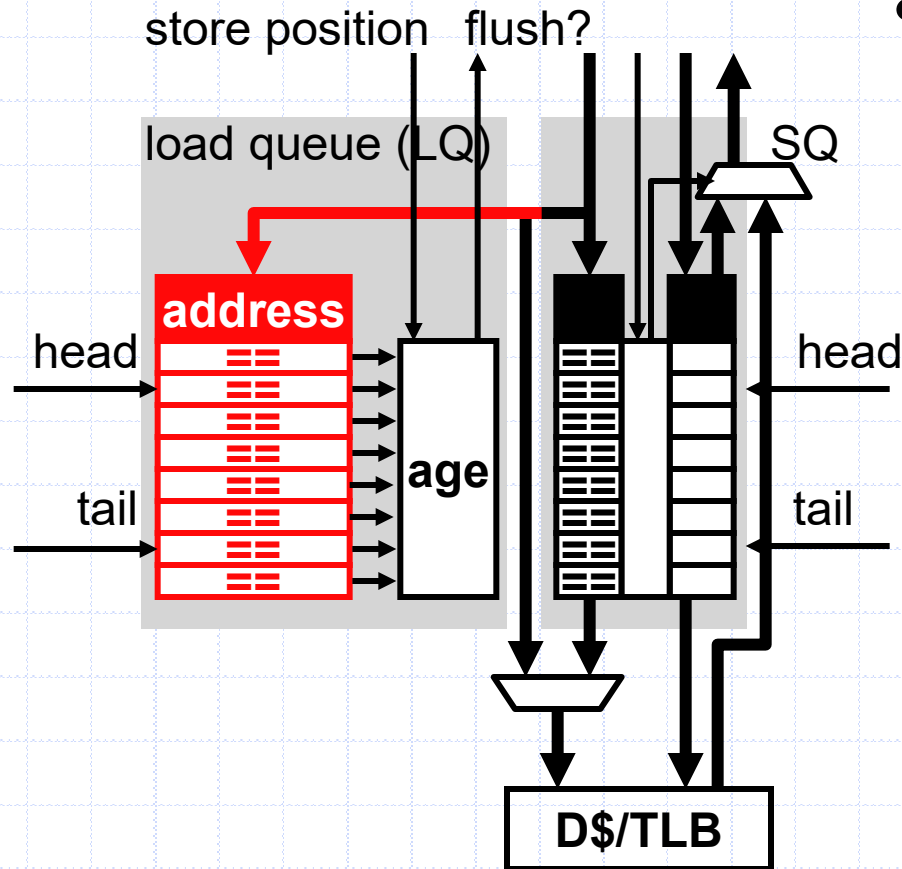
Conservative Load Scheduling

- Why "" in "out-of-order"?
 - + Load can execute out-of-order with respect to (wrt) other loads
 - + Stores can execute out-of-order wrt other stores
 - **Loads must execute in-order wrt older stores**
 - Load execution requires knowledge of all older store addresses
 - + Simple
 - Restricts performance
- Used in P6

Opportunistic Memory Scheduling

- Observe: on average, $< 10\%$ of loads forward from SQ
 - Even if older store address is unknown, chances are it won't match
 - Let loads execute in presence of older **"ambiguous stores"**
 - + Increases performance
 - But what if ambiguous store *does* match?
- **Memory ordering violation**: load executed too early
 - Must detect...
 - And fix (e.g., by flushing/refetching insns starting at load)

D\$/TLB + SQ + LQ

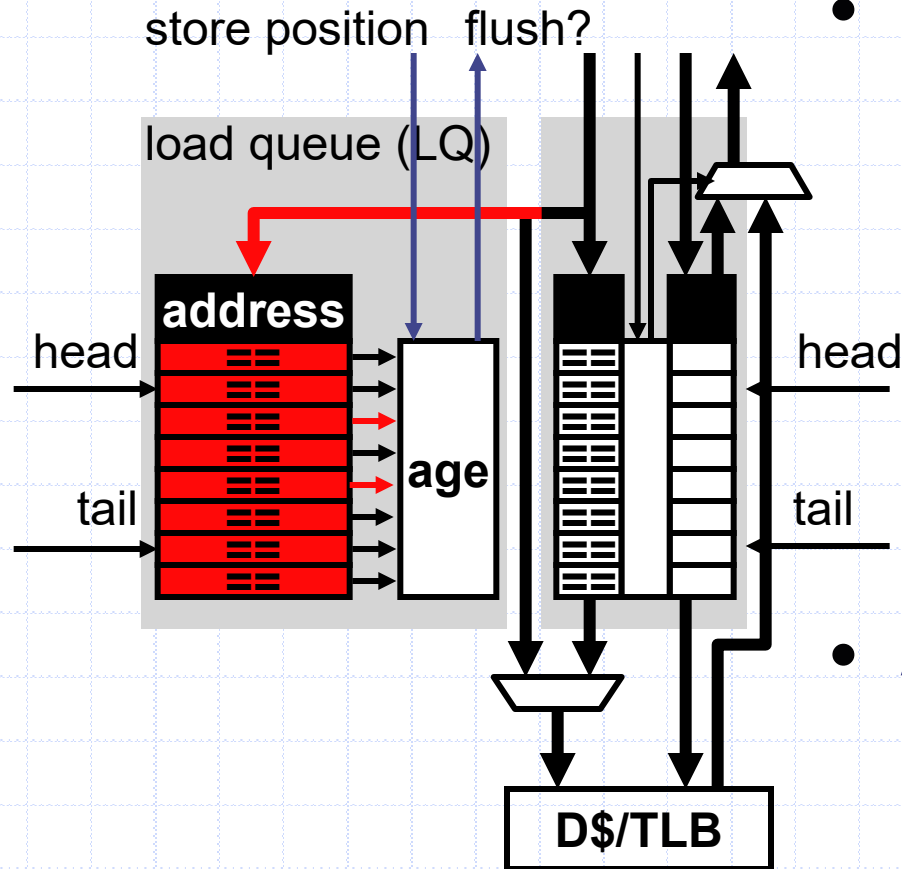


- **Load queue (LQ)**
 - In-flight load addresses
 - In program-order (like ROB, SQ)
 - Associatively searchable
 - Size heuristic: 20-30% of ROB

Advanced Memory “Pipeline” (LQ Only)

- Loads
 - **Dispatch (D)**
 - Allocate entry at LQ tail
 - **Execute (X)**
 - Write address into corresponding LQ slot
- Stores
 - **Dispatch (D)**
 - Record current LQ tail as “store position”
 - **Execute (X)**
 - Where the good stuff happens

Detecting Memory Ordering Violations



- **Store sends address to LQ**
 - Compare with all load addresses
 - Selecting matching addresses
 - Matching address?
 - Load executed before store
 - Violation
 - Fix!
- **Age logic selects oldest load that is younger than store**
 - Use store position
 - Processor flushes and restarts

Intelligent Load Scheduling

- Opportunistic scheduling better than conservative...
 - + Avoids many unnecessary delays
- ...but not significantly
 - Introduces a few flushes, but each is much costlier than a delay
- Observe: loads/stores that cause violations are “stable”
 - Dependences are mostly program based, program doesn’t change
 - Scheduler is deterministic
- Exploit: **intelligent load scheduling**
 - Hybridize conservative and opportunistic
 - Predict which loads, or load/store pairs will cause violations
 - Use conservative scheduling for those, opportunistic for the rest

Memory Dependence Prediction

- Store-blind prediction
 - Predict load only, wait for all older stores to execute
 - ± Simple, but a little too heavy handed
 - Example: Alpha 21264
- Store-load pair prediction
 - Predict load/store pair, wait only for one store to execute
 - ± More complex, but minimizes delay

Limits of Insn-Level Parallelism (ILP)

- Before we build a big superscalar... how much ILP is there?
 - **ILP: instruction-level parallelism** [Fisher`81]
 - Sustainable rate of useful instruction execution
- ILP limit study
 - Assume perfect/infinite hardware, successively add realism
 - Examples: [Wall'88][Wilson+Lam'92]
 - Some surprising results
 - + Perfect/infinite "theoretical" ILP: int > 50, FP > 150
 - Sometimes called the **"dataflow limit"**
 - Real machine "actual" ILP: int ~2, FP ~ 3
 - Fundamental culprits: branch prediction, memory latency
 - Engineering culprits: "window" (RS/SQ/regfile) size, issue width
 - Read on your own: P+H: 3.8+3.9

Clock Rate vs. IPC

- Does frequency vs. width tradeoff actually work?
 - Yes in some places, no in others
 - + **Yes**: fetch, decode, rename, retire (all the in-order stages)
 - **No**: issue, execute, complete (all the out-of-order stages)
 - What's the difference?
 - Out-of-order: parallelism doesn't help if insns themselves serial
 - 2 dependent insns execute in 2 cycles, regardless of width
 - In-order: inter-insn parallelism doesn't matter
- Intel Pentium4: **multiple clock domains**
 - In-order stages run at 3.4 GHz, out-of-order stages at 6.8 GHz!
 - Frequency $\propto$ Power_{dynamic} $\rightarrow$ high frequency only where necessary

Dynamic Scheduling Redux

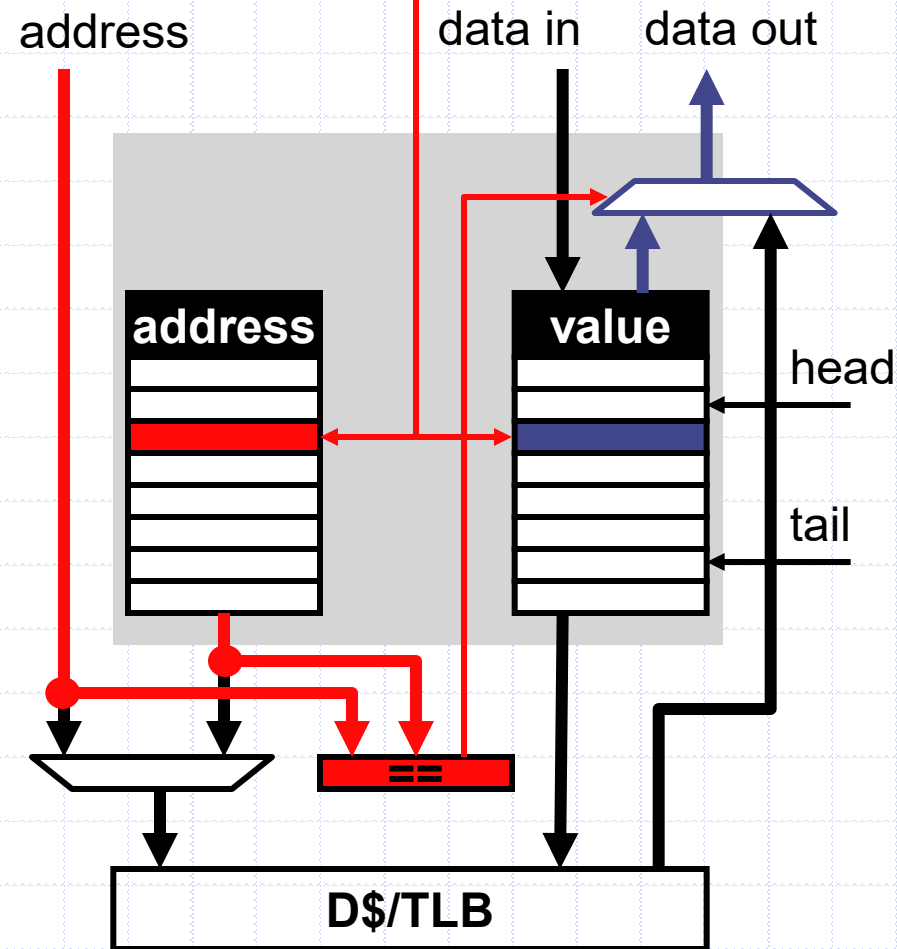
- Dynamic scheduling is a performance technique
- But what about...
 - **"Scalability"**: how big can we profitably make it?
 - Power/energy?
 - Reliability?

“Scalability”

- **Scalability**: how big/wide should we make a window?
 - Bigger/wider structures (can) improve IPC, but degrade clock
 - Where is the cross-over?
 - Caveat: scalability is conjunctive (the “Anna Karenina” principle)
 - For a design to be scalable, all components must be scalable
- Non-scalable (and scalable) structures
 - Mostly in execution core (see clock rate vs. IPC)
 - N^2 networks (e.g., bypassing network)
 - Large SRAMs with many read/write ports (e.g., physical regfile)
 - Large multi-ported CAMs (e.g., scheduler or reservation stations)
 - Large age-ordered CAMs (e.g., load and store queues)
 - A lot of current research on scalable versions of these structures
 - + ROB is not a problem: few ports, none in “execution core” really

Research: Speculative Indexed SQ

Predicted SQ entry (from Store-Sets)



- **Observe:** if load forwards, can guess store's SQ position with high accuracy
 - Store-Sets works this way
- **Exploit:** no need to match all stores, use Store-Sets to guess one and match on it
 - CAM+age → RAM+comparator
 - How to verify speculation?
 - LQ? DIVA? Load-only DIVA?
 - Indexed SQ [Sha,Martin,Roth'05]

Pentium III vs. Pentium4 (Processors)

Feature	Pentium III	Pentium 4
Peak clock	800 MHz	3.4 GHz (6.8 internal)
Pipeline stages	15	22
Branch prediction	512 local + 512 BTB	2K hybrid + 2K BTB
Primary caches	16KB 4-way	8KB 4-way + 64KB T\$
L2	512KB-2MB	256KB-2MB
Fetch width	16 bytes	3 μ ops (16 bytes on miss)
Rename/retire width	3 μ ops	3 μ ops
Execute width	5 μ ops	7 μ ops (X2)
Register renaming	P6	R10K
ROB/RS size	40/20	128/60
Load scheduling	Conservative	Intelligent
Anything else?	No	Hyperthreading

Dynamic Scheduling and Power/Energy

- Is dynamic scheduling low-power?
 - Probably not
 - New SRAMs consume a lot of power
 - Re-order buffer, reservation stations, **physical register file**
 - New CAMs consume even more (relatively)
 - Reservation stations, **load/store queue**
- Is dynamic scheduling low-energy?
 - ± Could be
 - Does performance improvement offset power increase?
 - Are there “deep sleep” modes?

Dynamic Scheduling and Reliability

- How does dynamic scheduling affect reliability?
 - What is the fault model?
 - ± Transient faults (α -particles)? No effect, I guess
 - ± Gradual faults (electro-migration)? Same
 - Permanent faults (design errors)? Worse, ooo is complicated
- A holistic view of electrical reliability
 - Vulnerability to electrical faults is function of transistor size
 - Mitigate (even eliminate) with larger transistors
 - But larger transistors are slower
 - Overcome clock frequency reductions with increased bandwidth
 - Performance = clock-frequency * IPC
 - Clock-frequency / 2 $\rightarrow$ IPC * 2 $\rightarrow$ superscalar width * 3?

Unit Summary

- Modern dynamic scheduling must support precise state
 - A software sanity issue, not a performance issue
- Strategy: Writeback → Complete (OoO) + Retire (iO)
- Two basic designs
 - P6: Tomasulo + re-order buffer, copy based register renaming
 - ± Precise state is simple, but fast implementations are difficult
 - R10K: implements true register renaming
 - ± Easier fast implementations, but precise state is more complex
- Out-of-order memory operations
 - Store queue: conservative load scheduling (iO wrt older stores)
 - Load queue: opportunistic load scheduling (OoO wrt older stores)
 - Intelligent memory scheduling: hybrid

Dynamic Scheduling Summary

- Out-of-order execution: a performance technique
 - Easier/more effective in hardware than software (isn't everything?)
 - Idea: make scheduling transparent to software
- Feature I: Dynamic scheduling (iO $\rightarrow$ OoO)
 - "Performance" piece: re-arrange insns into high-performance order
 - Decode (iO) $\rightarrow$ dispatch (iO) + issue (OoO)
 - Two algorithms: Scoreboard, Tomasulo
- Feature II: Precise state (OoO $\rightarrow$ iO)
 - "Correctness" piece: put insns back into program order
 - Writeback (OoO) $\rightarrow$ complete (OoO) + retire (iO)
 - Two designs: P6, R10K
- Don't forget about memory scheduling