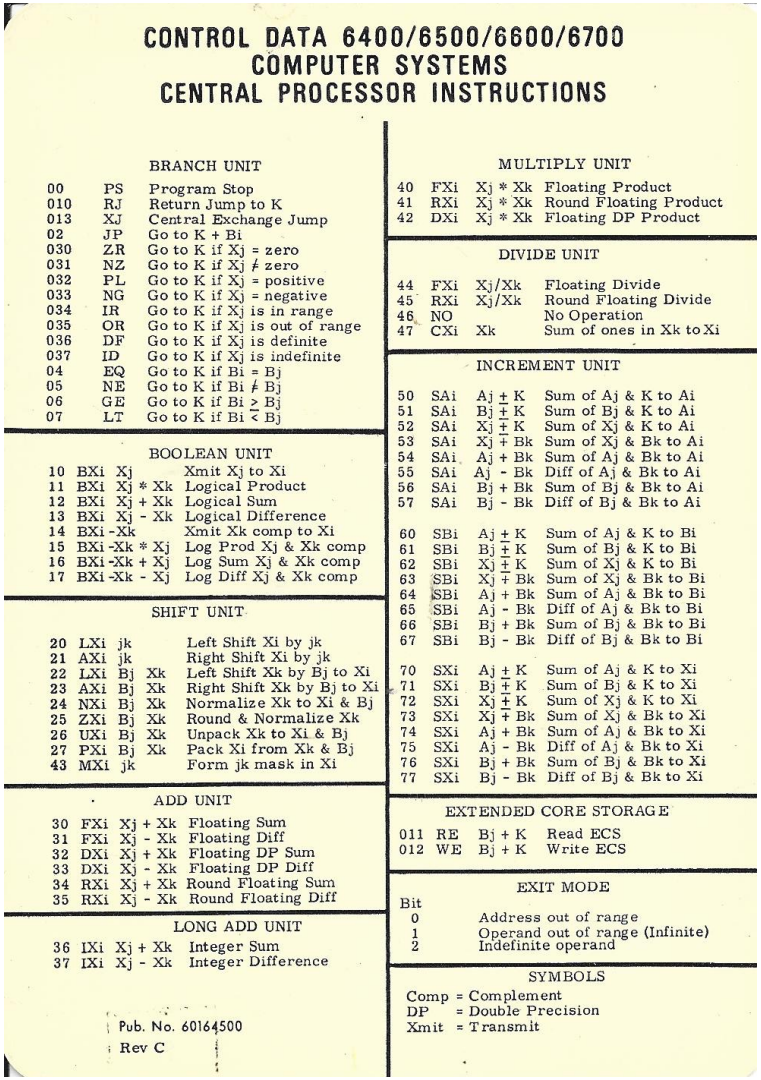
CDC Programing Card



CONTROL DATA 6400/6500/6600/6700
COMPUTER SYSTEMS
CENTRAL PROCESSOR INSTRUCTIONS

BRANCH UNIT

00	PS	Program Stop
010	RJ	Return Jump to K
013	XJ	Central Exchange Jump
02	JP	Go to K + Bi
030	ZR	Go to K if Xj = zero
031	NZ	Go to K if Xj ≠ zero
032	PL	Go to K if Xj = positive
033	NG	Go to K if Xj = negative
034	IR	Go to K if Xj is in range
035	OR	Go to K if Xj is out of range
036	DF	Go to K if Xj is definite
037	ID	Go to K if Xj is indefinite
04	EQ	Go to K if Bi = Bj
05	NE	Go to K if Bi ≠ Bj
06	GE	Go to K if Bi ≥ Bj
07	LT	Go to K if Bi < Bj

BOOLEAN UNIT

10	BXi	Xj	Xmit Xj to Xi
11	BXi	Xj * Xk	Logical Product
12	BXi	Xj + Xk	Logical Sum
13	BXi	Xj - Xk	Logical Difference
14	BXi	-Xk	Xmit Xk comp to Xi
15	BXi	-Xk * Xj	Log Prod Xj & Xk comp
16	BXi	-Xk + Xj	Log Sum Xj & Xk comp
17	BXi	-Xk - Xj	Log Diff Xj & Xk comp

SHIFT UNIT

20	LXi	jk		Left Shift Xi by jk
21	AXi	jk		Right Shift Xi by jk
22	LXi	Bj	Xk	Left Shift Xk by Bj to Xi
23	AXi	Bj	Xk	Right Shift Xk by Bj to Xi
24	NXi	Bj	Xk	Normalize Xk to Xi & Bj
25	ZXi	Bj	Xk	Round & Normalize Xk
26	UXi	Bj	Xk	Unpack Xk to Xi & Bj
27	PXi	Bj	Xk	Pack Xi from Xk & Bj
43	MXi	jk		Form jk mask in Xi

ADD UNIT

30	FXi	Xj + Xk	Floating Sum
31	FXi	Xj - Xk	Floating Diff
32	DXi	Xj + Xk	Floating DP Sum
33	DXi	Xj - Xk	Floating DP Diff
34	RXi	Xj + Xk	Round Floating Sum
35	RXi	Xj - Xk	Round Floating Diff

LONG ADD UNIT

36	IXi	Xj + Xk	Integer Sum
37	IXi	Xj - Xk	Integer Difference

Pub. No. 60164500
Rev C

MULTIPLY UNIT

40	FXi	Xj * Xk	Floating Product
41	RXi	Xj * Xk	Round Floating Product
42	DXi	Xj * Xk	Floating DP Product

DIVIDE UNIT

44	FXi	Xj/Xk	Floating Divide
45	RXi	Xj/Xk	Round Floating Divide
46	NO		No Operation
47	CXi	Xk	Sum of ones in Xk to Xi

INCREMENT UNIT

50	SAi	Aj ± K	Sum of Aj & K to Ai
51	SAi	Bj ± K	Sum of Bj & K to Ai
52	SAi	Xj ± K	Sum of Xj & K to Ai
53	SAi	Xj ± Bk	Sum of Xj & Bk to Ai
54	SAi	Aj + Bk	Sum of Aj & Bk to Ai
55	SAi	Aj - Bk	Diff of Aj & Bk to Ai
56	SAi	Bj + Bk	Sum of Bj & Bk to Ai
57	SAi	Bj - Bk	Diff of Bj & Bk to Ai
60	SBi	Aj ± K	Sum of Aj & K to Bi
61	SBi	Bj ± K	Sum of Bj & K to Bi
62	SBi	Xj ± K	Sum of Xj & K to Bi
63	SBi	Xj ± Bk	Sum of Xj & Bk to Bi
64	SBi	Aj + Bk	Sum of Aj & Bk to Bi
65	SBi	Aj - Bk	Diff of Aj & Bk to Bi
66	SBi	Bj + Bk	Sum of Bj & Bk to Bi
67	SBi	Bj - Bk	Diff of Bj & Bk to Bi
70	SXi	Aj ± K	Sum of Aj & K to Xi
71	SXi	Bj ± K	Sum of Bj & K to Xi
72	SXi	Xj ± K	Sum of Xj & K to Xi
73	SXi	Xj ± Bk	Sum of Xj & Bk to Xi
74	SXi	Aj + Bk	Sum of Aj & Bk to Xi
75	SXi	Aj - Bk	Diff of Aj & Bk to Xi
76	SXi	Bj + Bk	Sum of Bj & Bk to Xi
77	SXi	Bj - Bk	Diff of Bj & Bk to Xi

EXTENDED CORE STORAGE

011	RE	Bj + K	Read ECS
012	WE	Bj + K	Write ECS

EXIT MODE

Bit	
0	Address out of range
1	Operand out of range (Infinite)
2	Indefinite operand

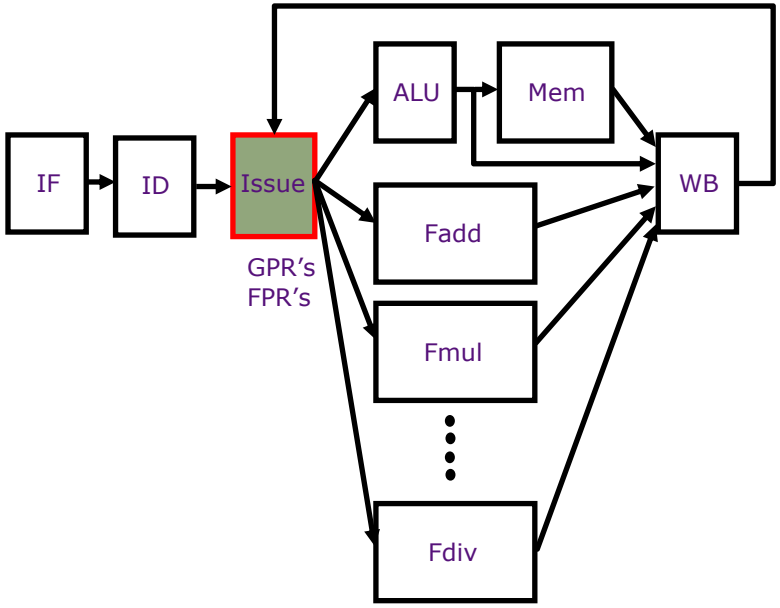
SYMBOLS

Comp = Complement
DP = Double Precision
Xmit = Transmit

Complex Pipelining: Out-of-Order Execution, Register Renaming, and Exceptions

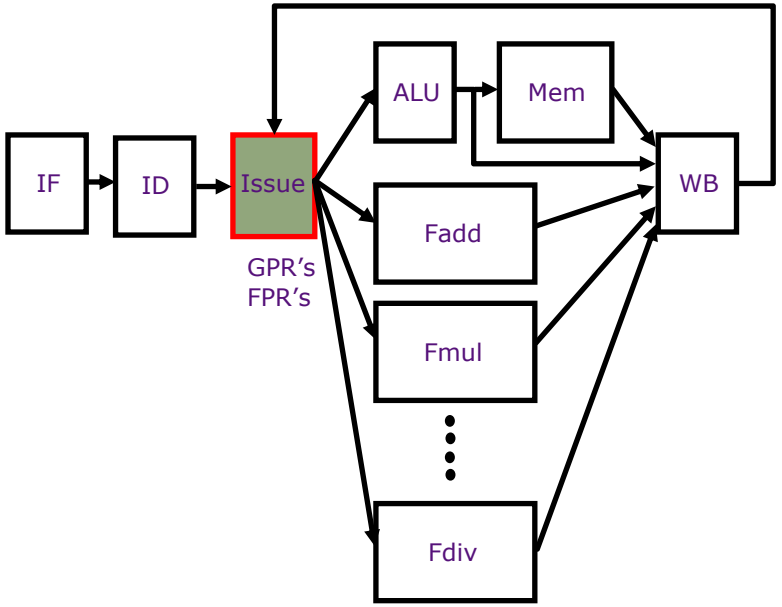
Joel Emer
Computer Science and Artificial Intelligence Laboratory
M.I.T.

CDC 6600-style Scoreboard



CDC 6600-style Scoreboard

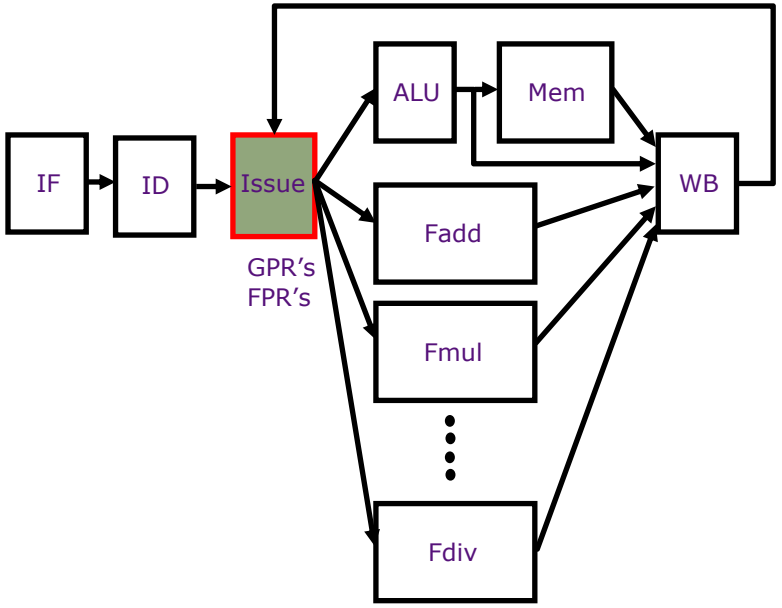
Instructions are issued in order.



CDC 6600-style Scoreboard

Instructions are issued in order.

An instruction is issued only if

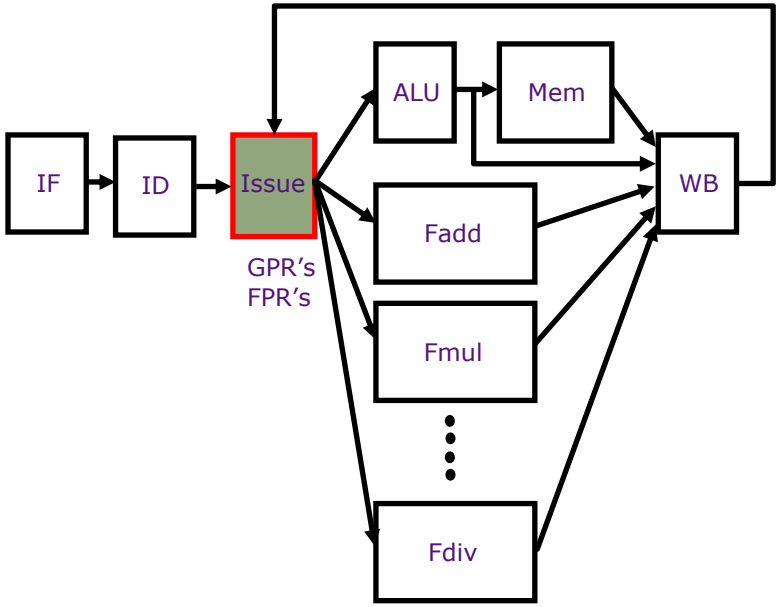


CDC 6600-style Scoreboard

Instructions are issued in order.

An instruction is issued only if

- It cannot cause a RAW hazard

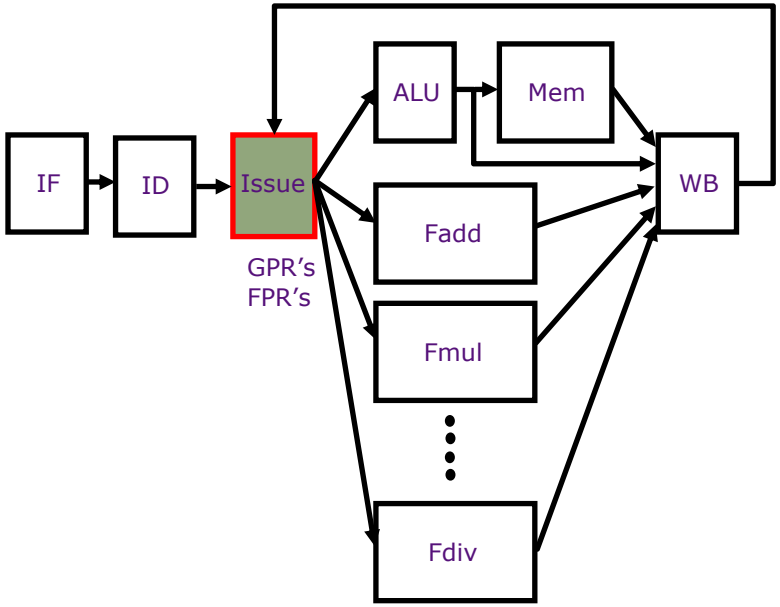


CDC 6600-style Scoreboard

Instructions are issued in order.

An instruction is issued only if

- It cannot cause a RAW hazard
- It cannot cause a WAW hazard



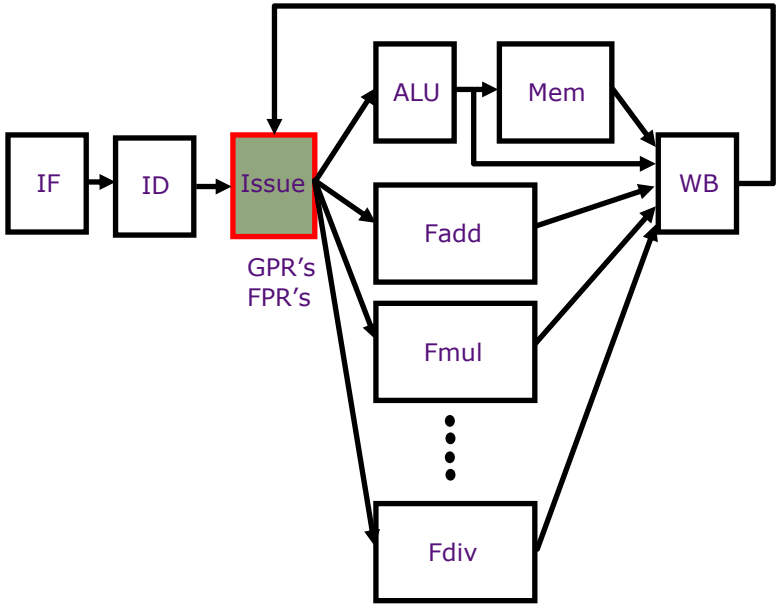
CDC 6600-style Scoreboard

Instructions are issued in order.

An instruction is issued only if

- It cannot cause a RAW hazard
- It cannot cause a WAW hazard

⇒*There can be at most instruction in the execute phase that can write in a particular register*



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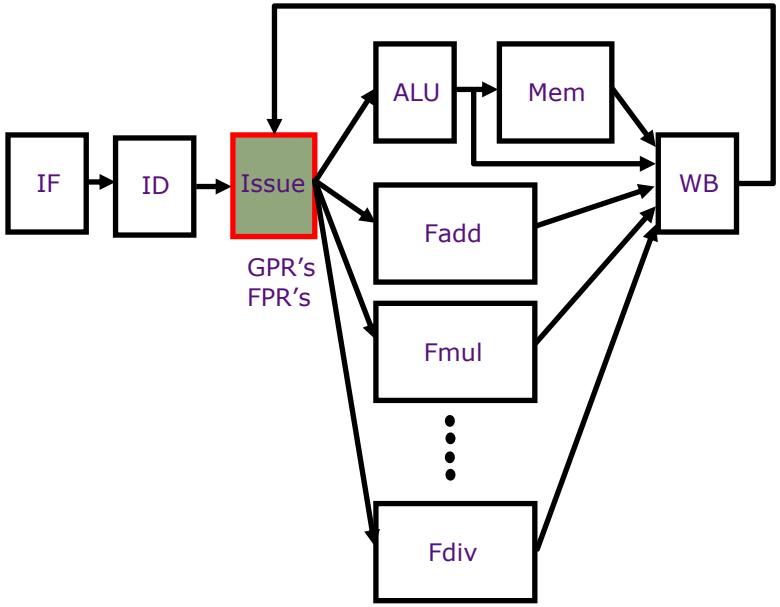
  ⇒*There can be at most instruction in the execute phase that can write in a particular register*

WAR hazards are not possible

- Due to in-order issue + operands read immediately



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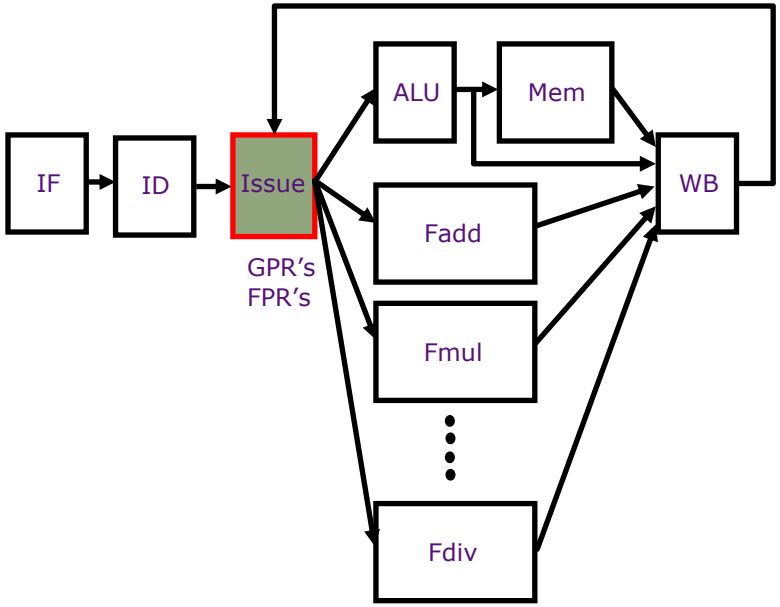

Scoreboard:
Two bit-vectors

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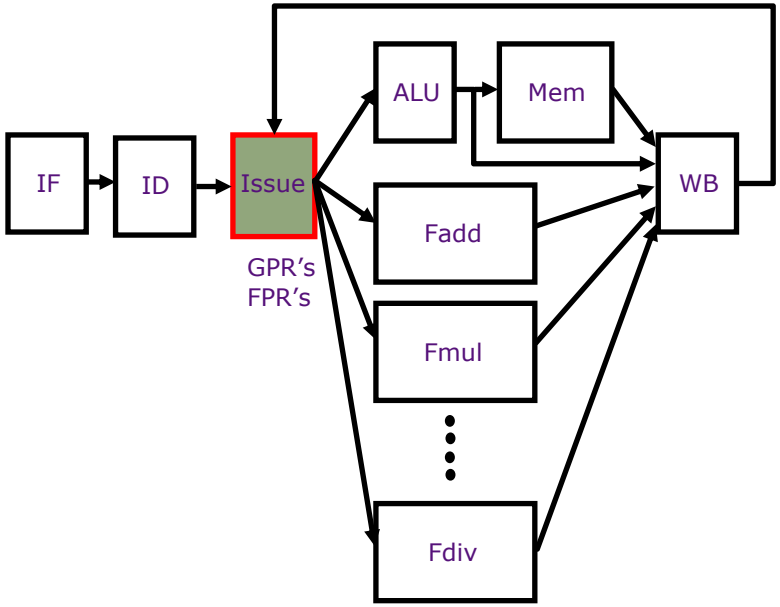

Scoreboard:
Two bit-vectors

Busy[FU#]: Indicates FU's availability
These bits are hardwired to FU's.

CDC 6600-style Scoreboard

Instructions are issued in order.

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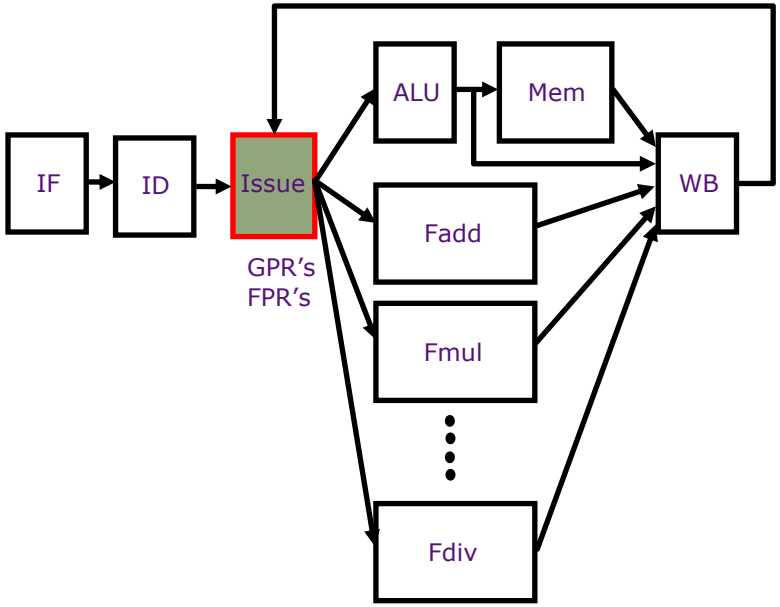
- It cannot cause a RAW hazard
- It cannot cause a WAW hazard

  ⇒*There can be at most instruction in the execute phase that can write in a particular register*

WAR hazards are not possible

- Due to in-order issue + operands read immediately



Scoreboard:
Two bit-vectors

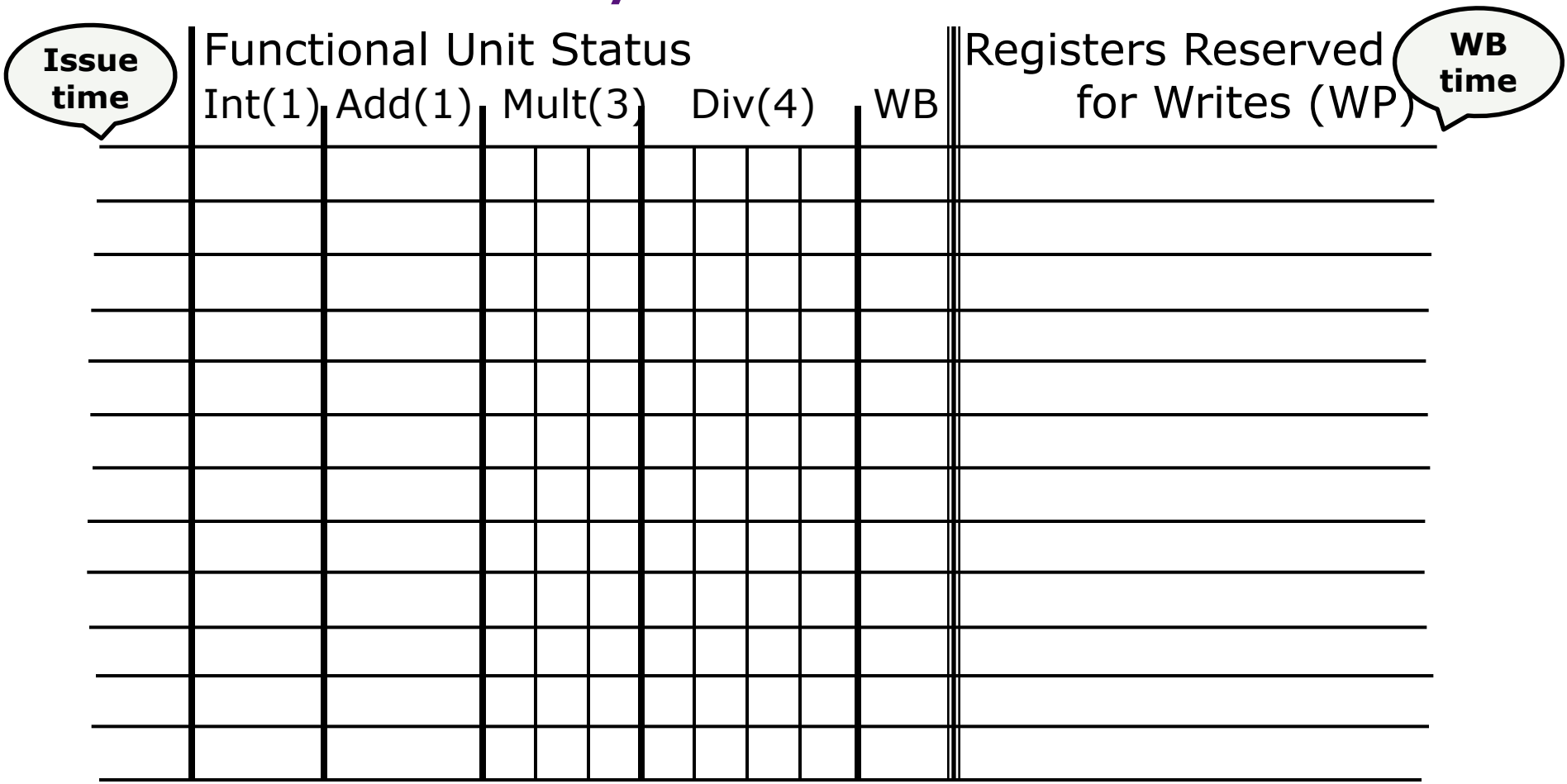
Busy[FU#]: Indicates FU's availability

These bits are hardwired to FU's.

WP[reg#]: Records if a write is pending for a register

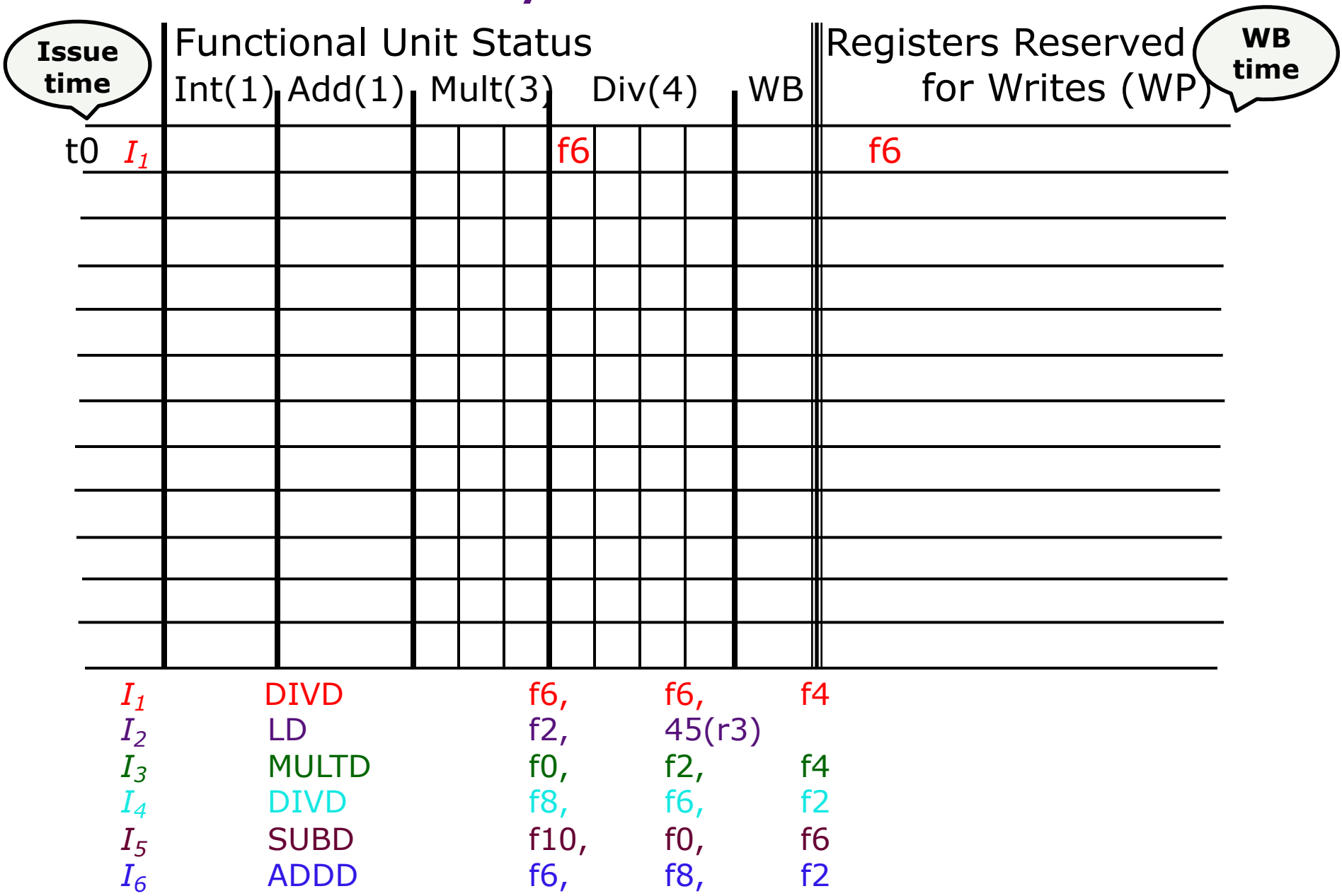
Set to true by the Issue stage and set to false by the WB stage

Scoreboard Dynamics

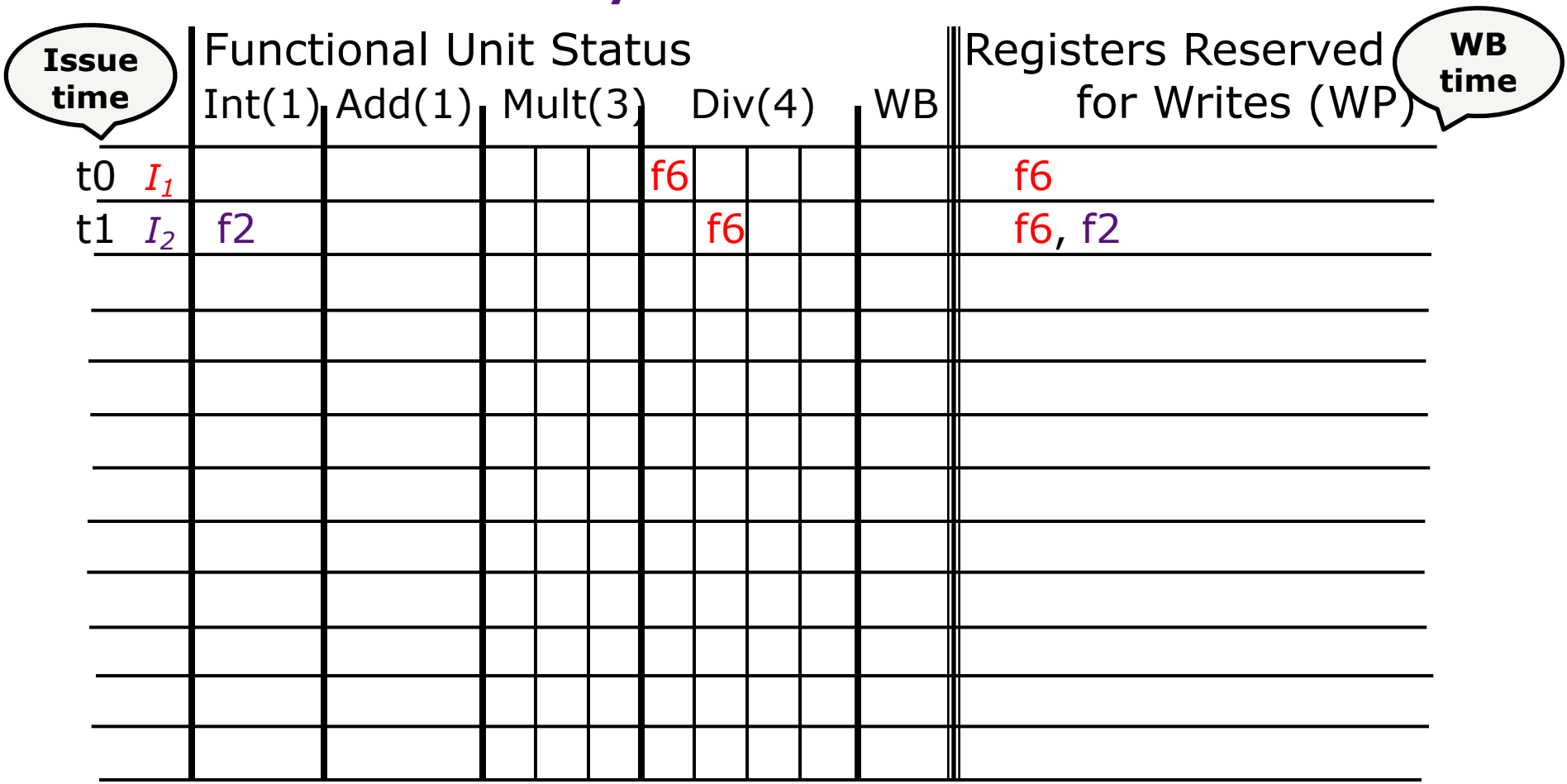


I_1	DIVD	f6,	f6,	f4
I_2	LD	f2,	45(r3)	
I_3	MULTD	f0,	f2,	f4
I_4	DIVD	f8,	f6,	f2
I_5	SUBD	f10,	f0,	f6
I_6	ADDD	f6,	f8,	f2

Scoreboard Dynamics

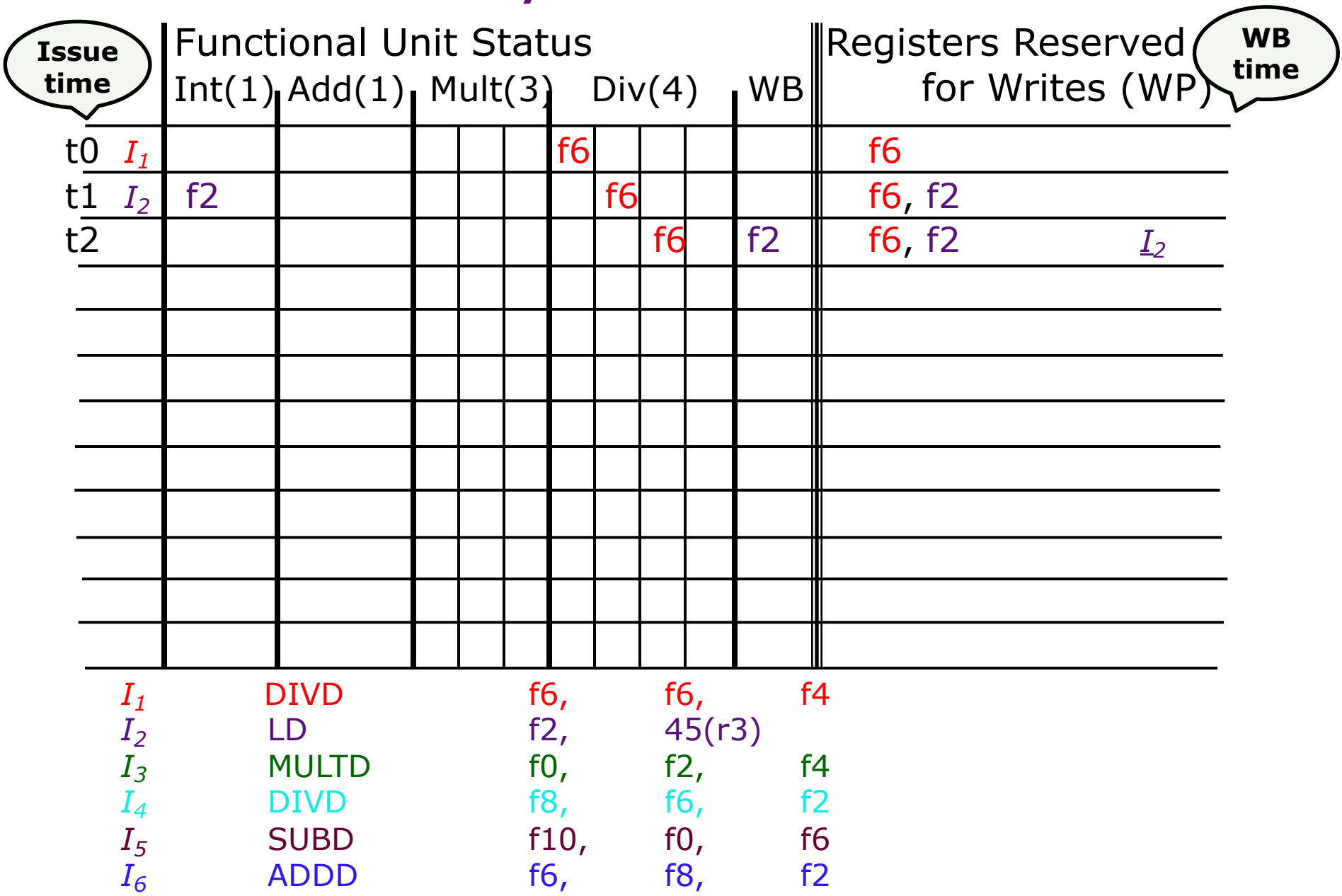


Scoreboard Dynamics

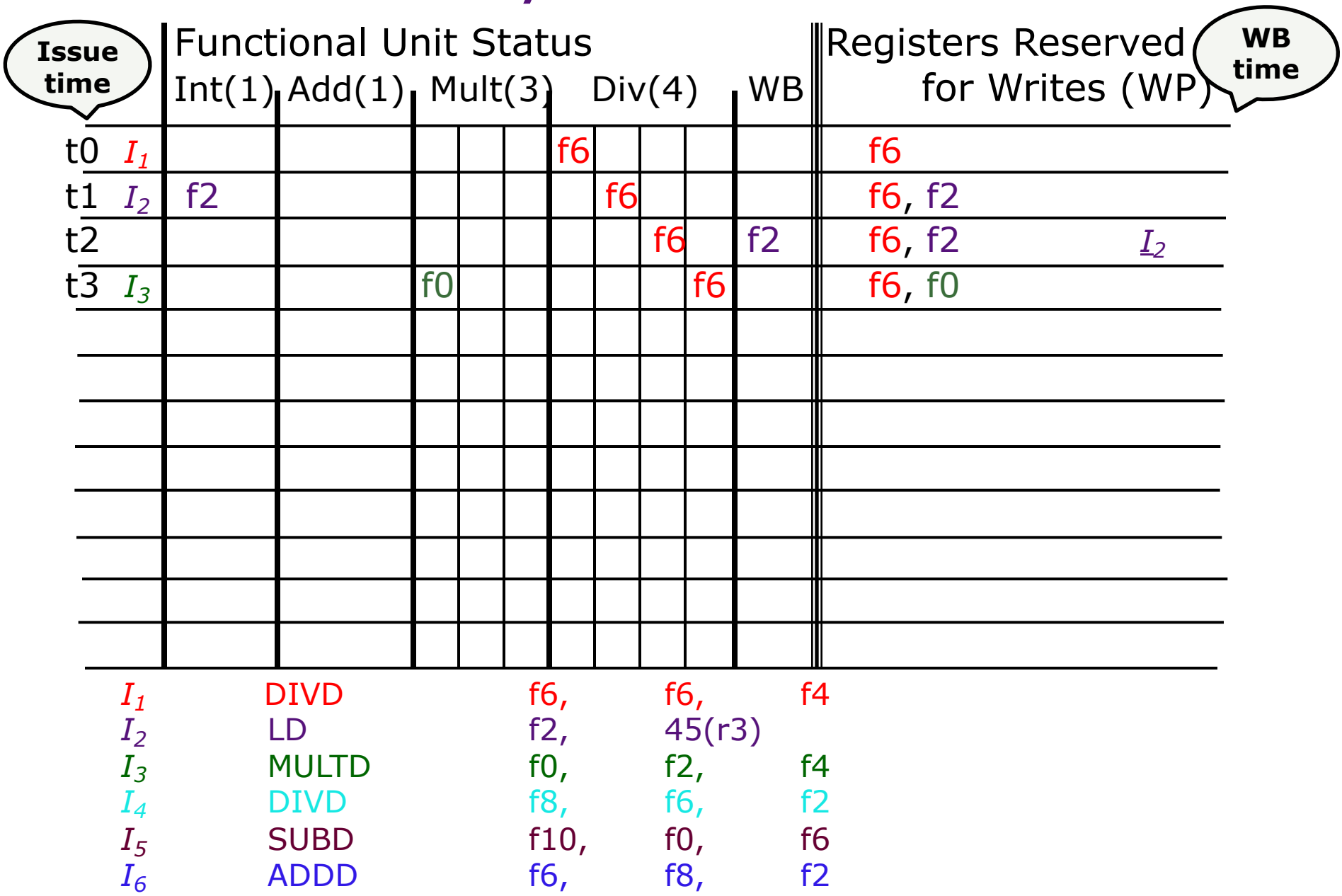


I_1	DIVD	f6,	f6,	f4
I_2	LD	f2,	45(r3)	
I_3	MULTD	f0,	f2,	f4
I_4	DIVD	f8,	f6,	f2
I_5	SUBD	f10,	f0,	f6
I_6	ADDD	f6,	f8,	f2

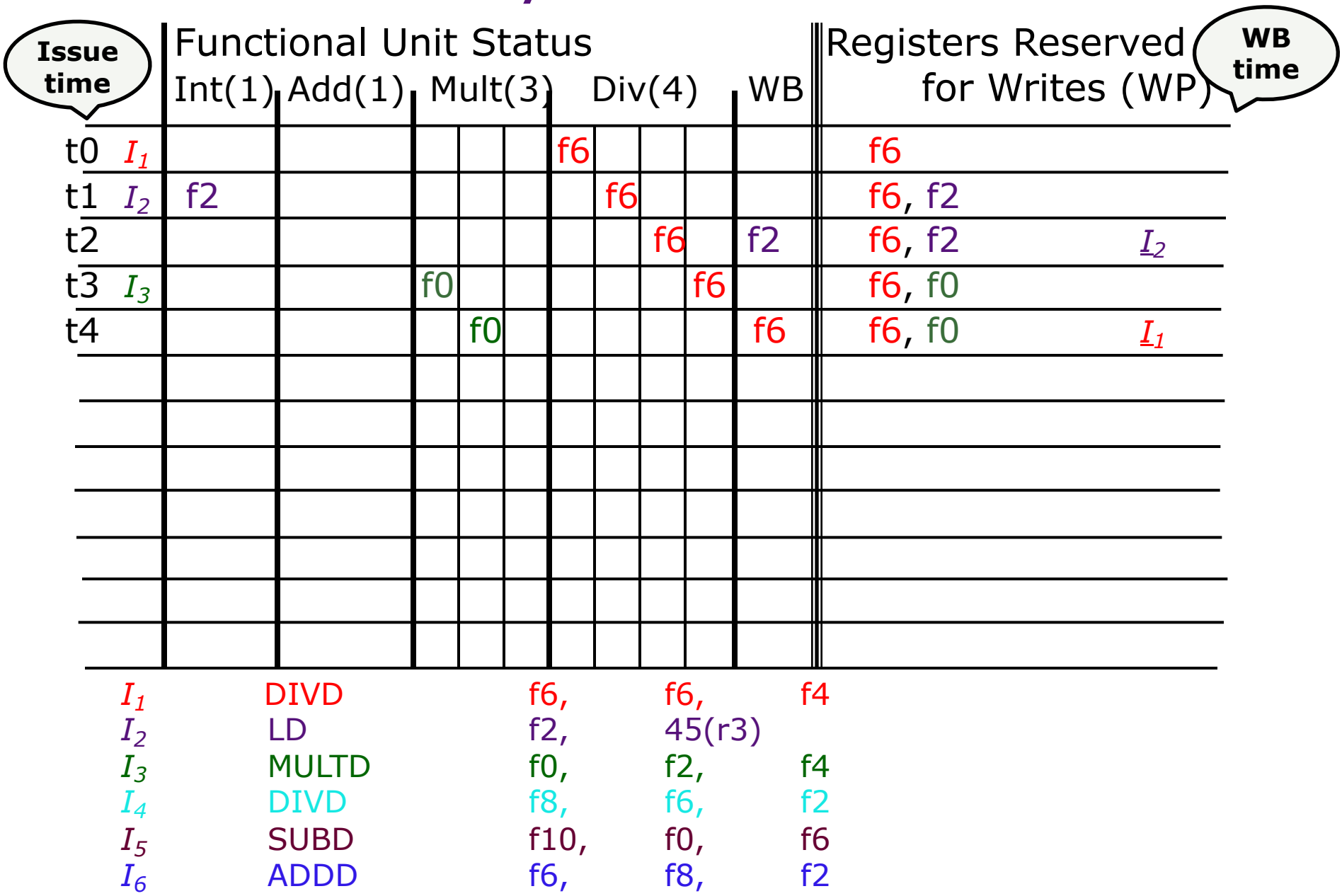
Scoreboard Dynamics



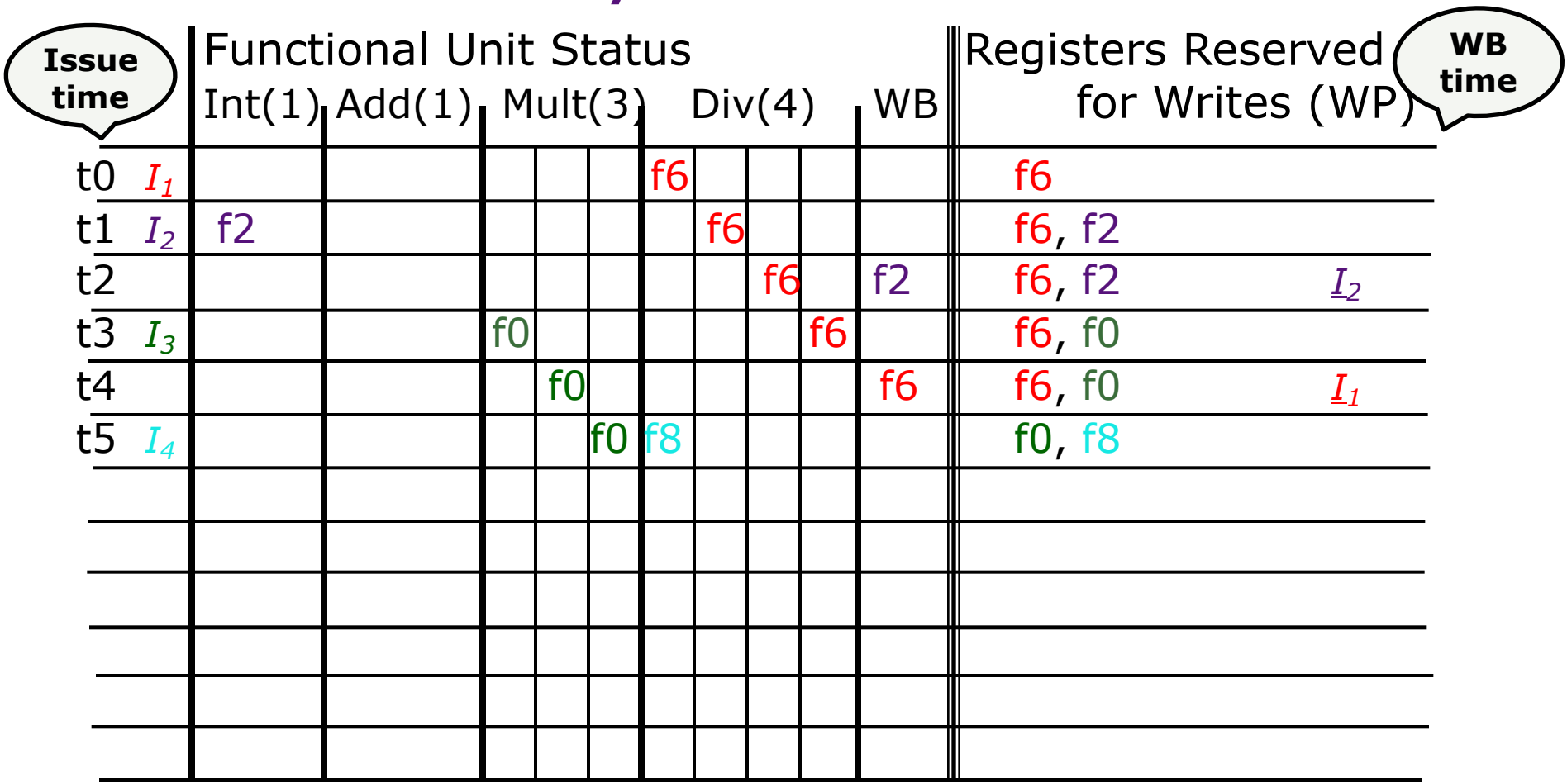
Scoreboard Dynamics



Scoreboard Dynamics

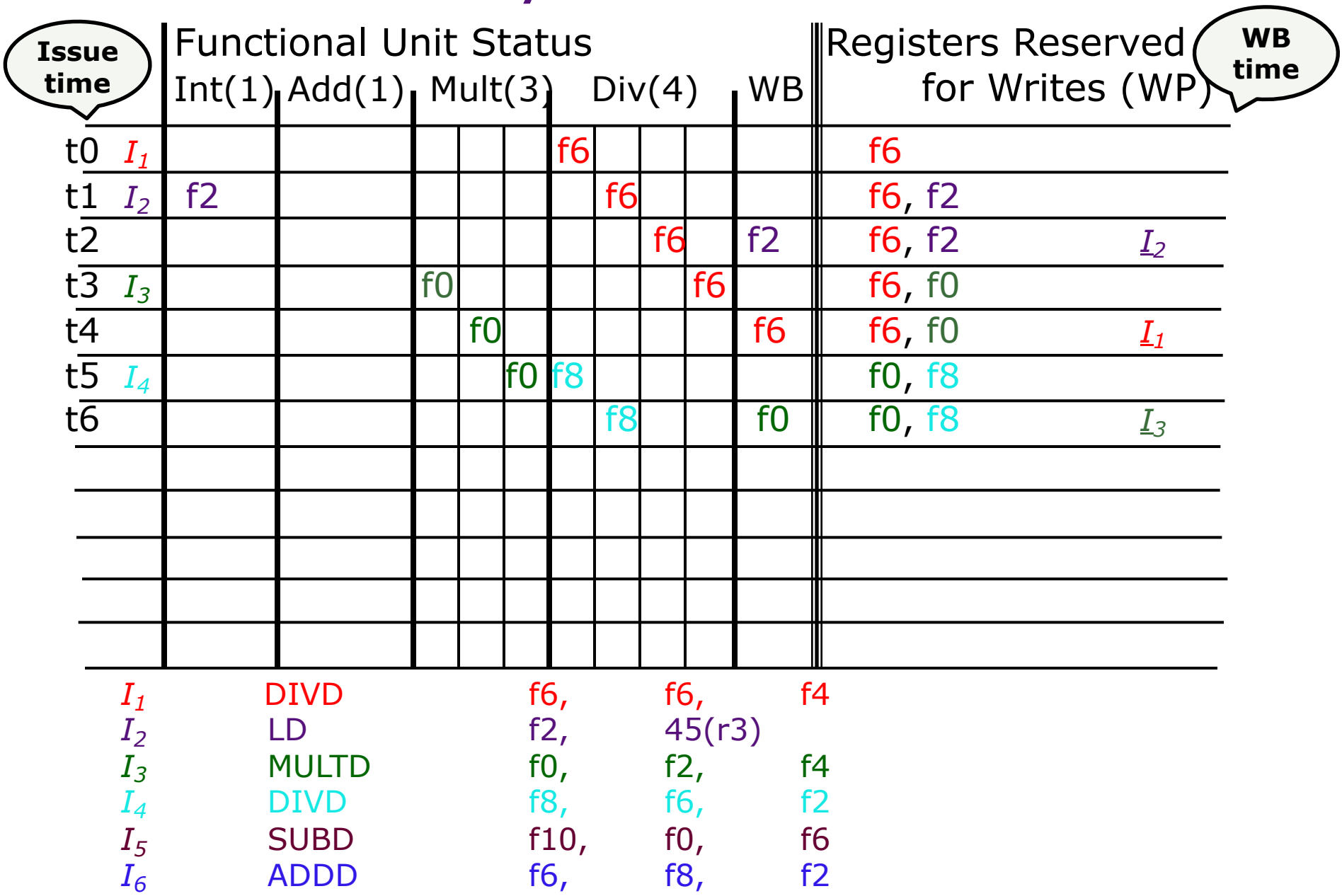


Scoreboard Dynamics

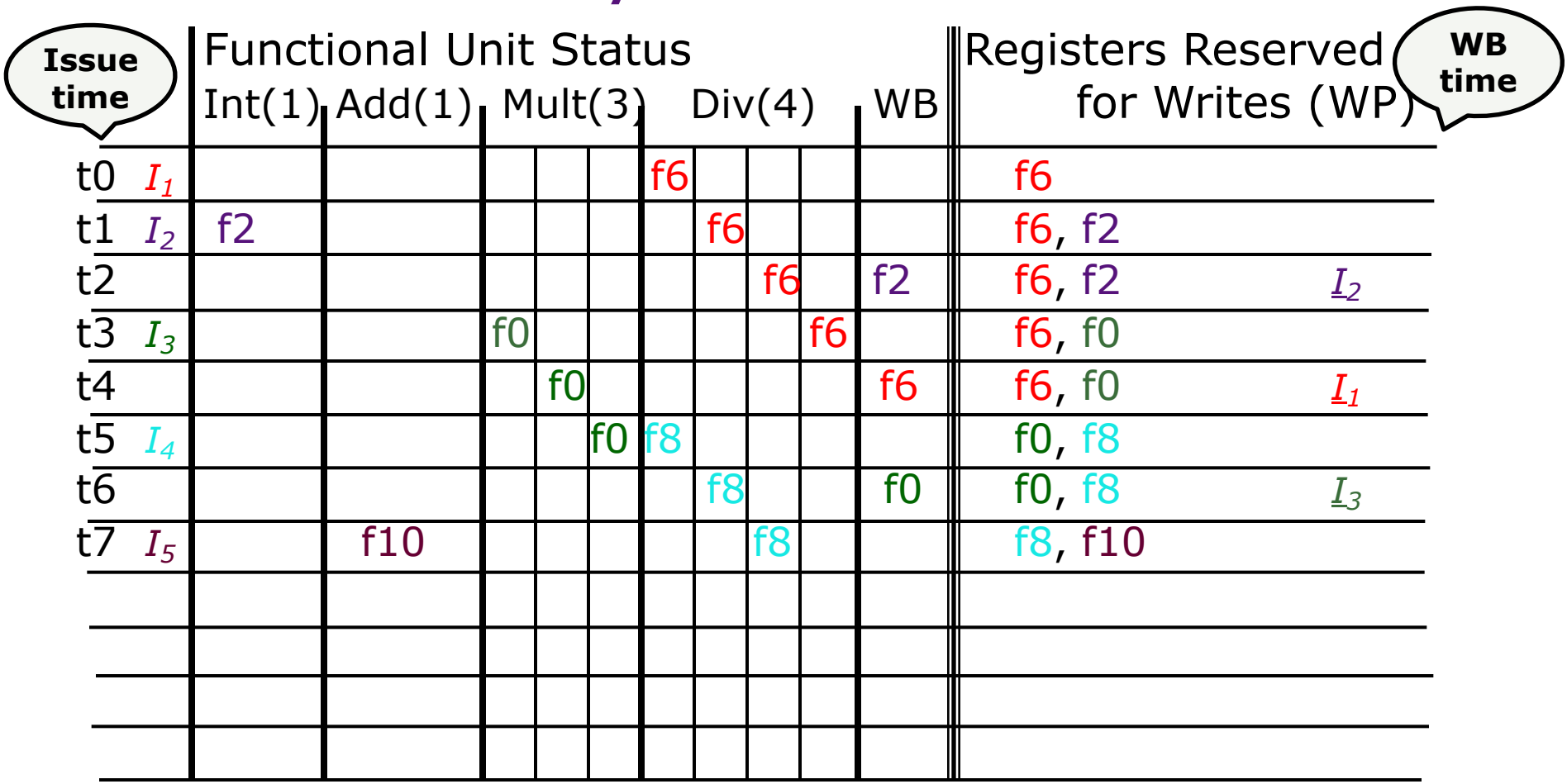


I_1	DIVD	f6,	f6,	f4
I_2	LD	f2,	45(r3)	
I_3	MULTD	f0,	f2,	f4
I_4	DIVD	f8,	f6,	f2
I_5	SUBD	f10,	f0,	f6
I_6	ADDD	f6,	f8,	f2

Scoreboard Dynamics



Scoreboard Dynamics



I_1	DIVD	f6,	f6,	f4
I_2	LD	f2,	45(r3)	
I_3	MULTD	f0,	f2,	f4
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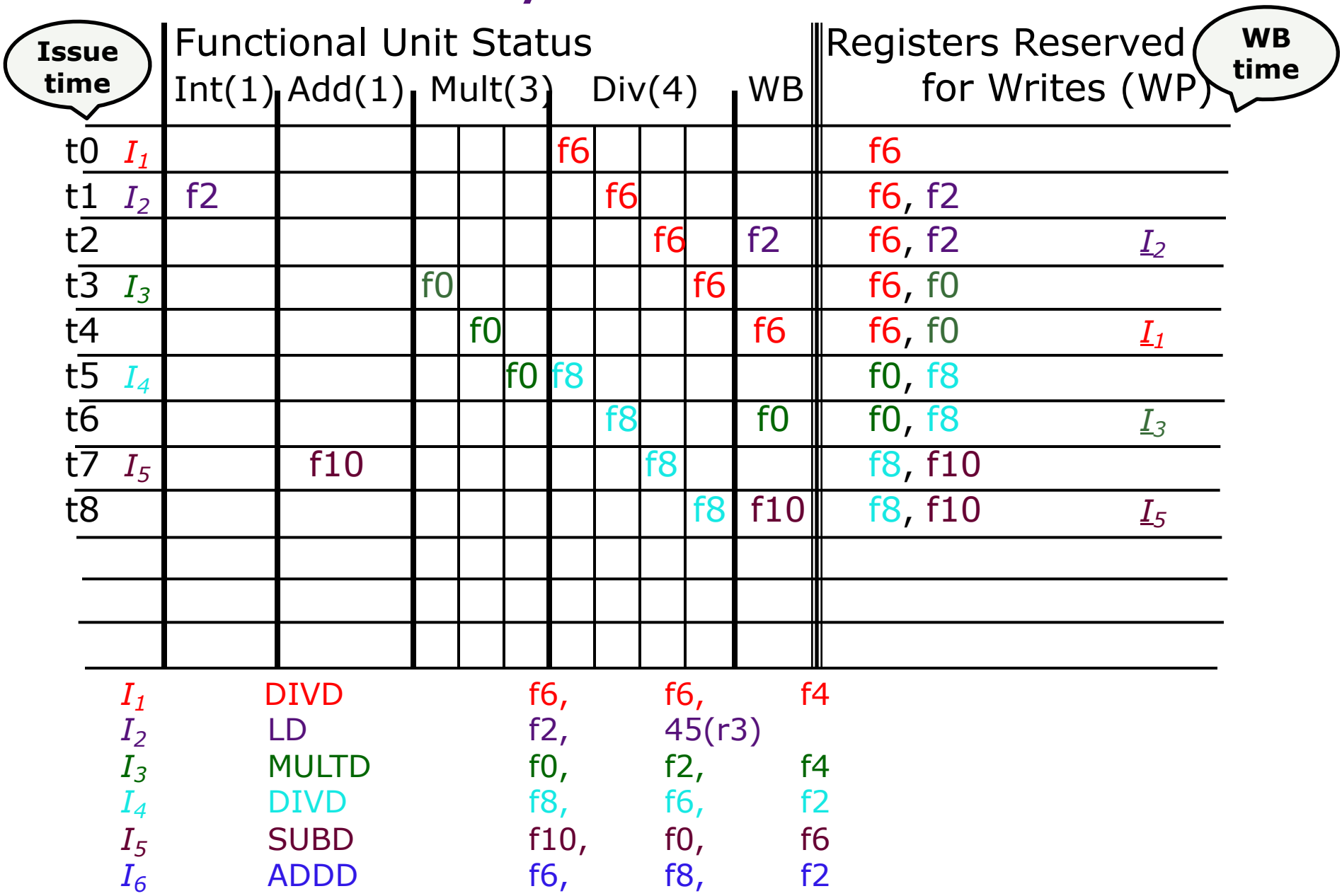
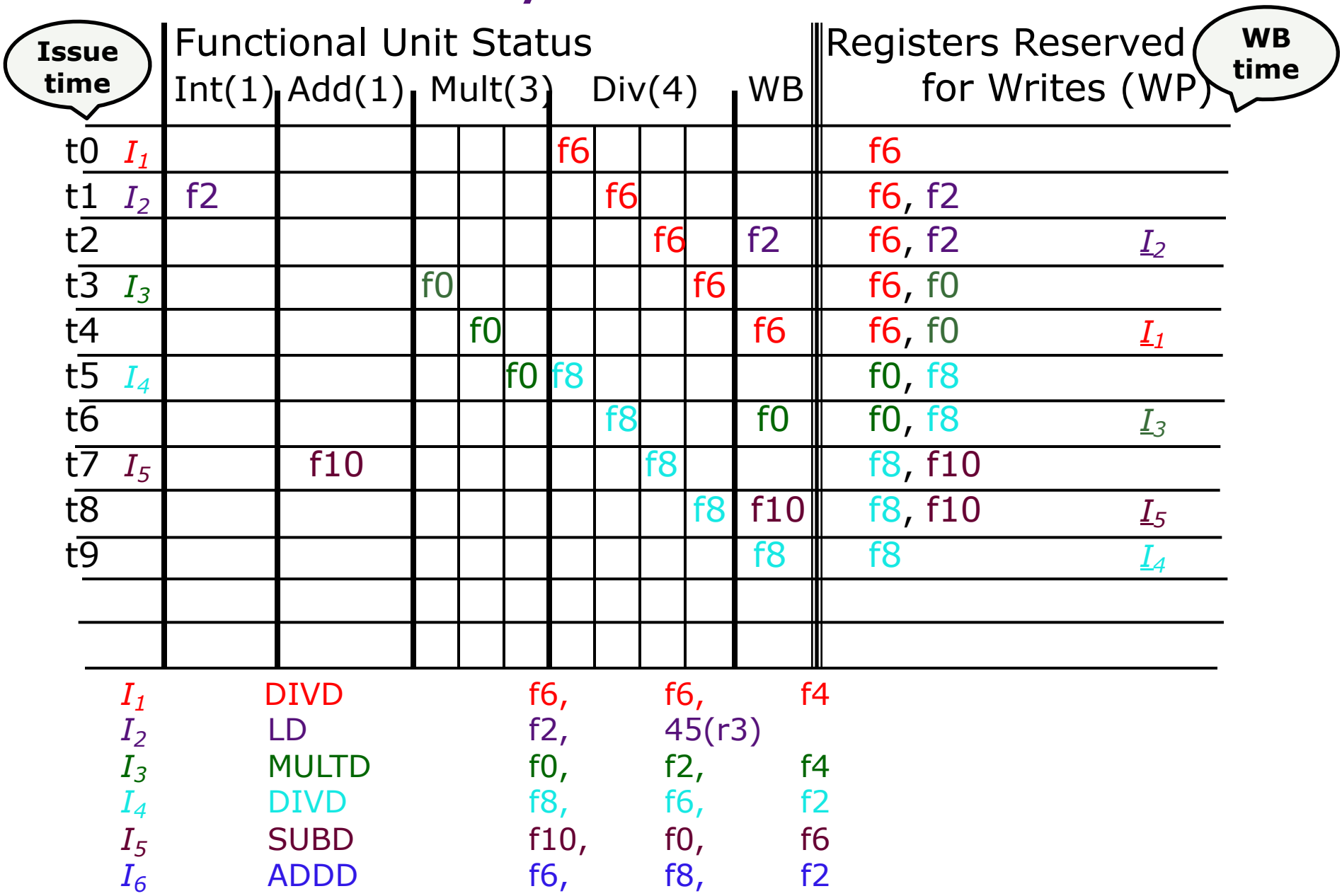
I_5	SUBD	f10,	f0,	f6
I_6	ADDD	f6,	f8,	f2

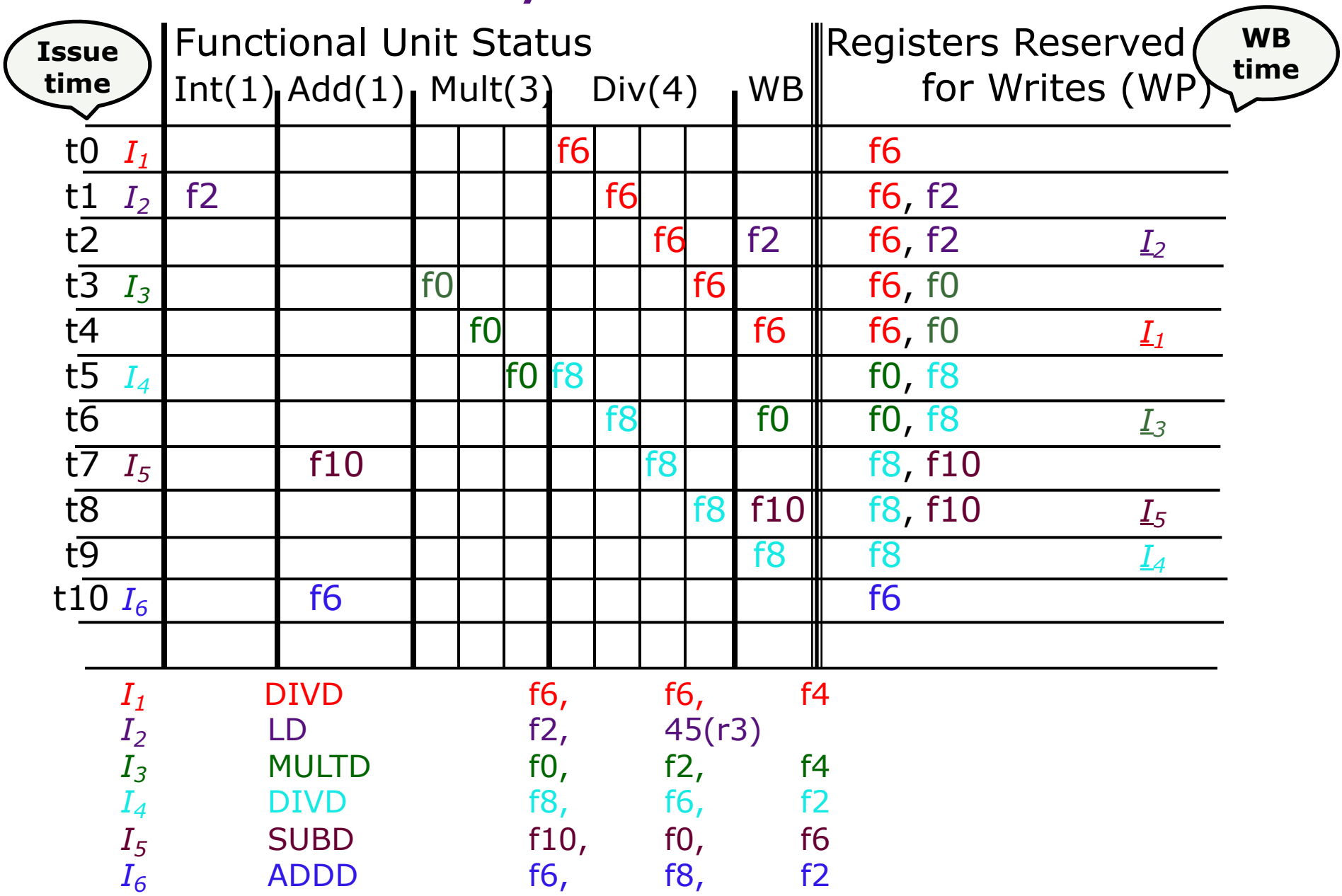
Scoreboard Dynamics



Scoreboard Dynamics



Scoreboard Dynamics



Scoreboard Dynamics

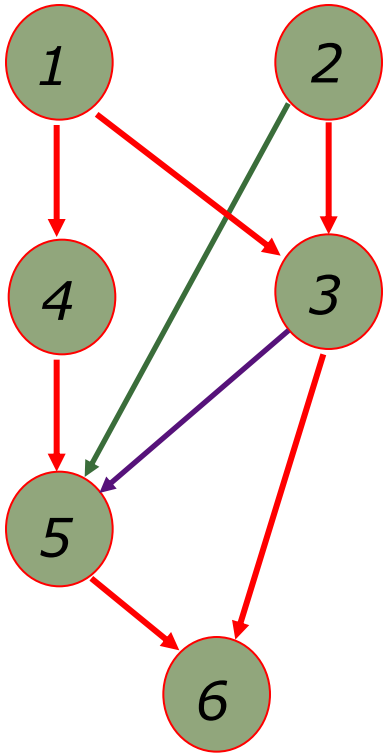
Issue time	Functional Unit Status: Int(1)	Add(1)	Mult(3)			Div(4)				WB	Registers Reserved for Writes (WP)	WB time
t0 I_1						f6					f6	
t1 I_2	f2						f6				f6, f2	
t2								f6		f2	f6, f2	I_2
t3 I_3			f0						f6		f6, f0	
t4				f0						f6	f6, f0	I_1
t5 I_4					f0	f8					f0, f8	
t6							f8			f0	f0, f8	I_3
t7 I_5		f10						f8			f8, f10	
t8									f8	f10	f8, f10	I_5
t9										f8	f8	I_4
t10 I_6		f6									f6	
t11										f6	f6	I_6

I_1	DIVD	f6,	f6,	f4
I_2	LD	f2,	45(r3)	
I_3	MULTD	f0,	f2,	f4
I_4	DIVD	f8,	f6,	f2
I_5	SUBD	f10,	f0,	f6
I_6	ADDD	f6,	f8,	f2

In-Order Issue Limitations

An example

					latency
1	LD	F2,	34(R2)		*1*
2	LD	F4,	45(R3)		*long*
3	MULTD	F6,	F4,	F2	*3*
4	SUBD	F8,	F2,	F2	*1*
5	DIVD	F4,	F2,	F8	*4*
6	ADDD	F10,	F6,	F4	*1*

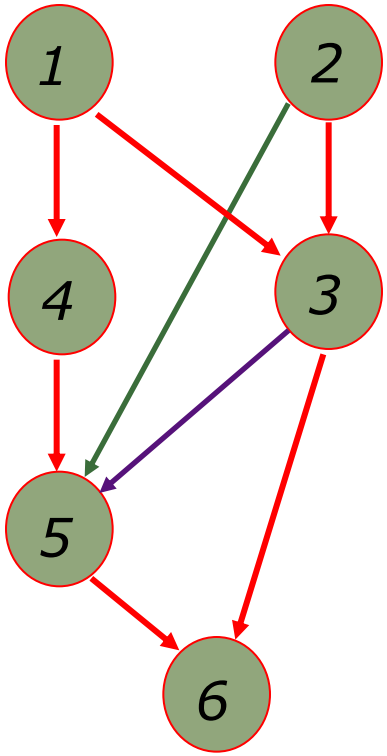


In-order: 1 (2,1) . . . . . 2 3 4 4 3 5 . . . 5 6 6

In-Order Issue Limitations

An example

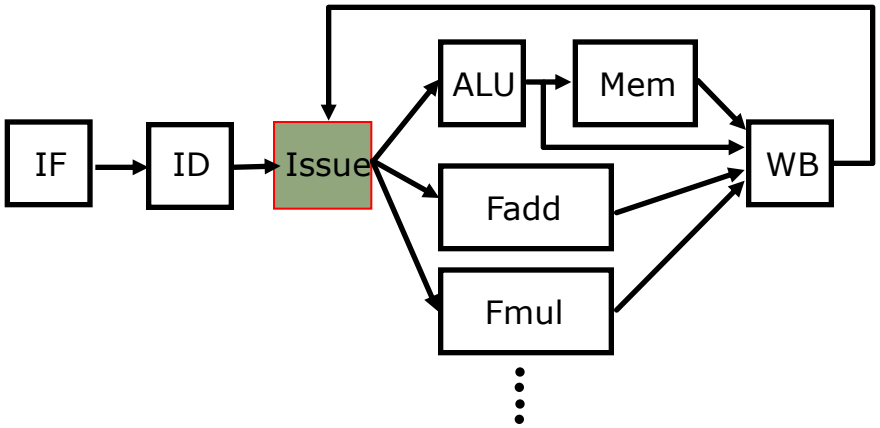
					latency
1	LD	F2,	34(R2)		*1*
2	LD	F4,	45(R3)		*long*
3	MULTD	F6,	F4,	F2	*3*
4	SUBD	F8,	F2,	F2	*1*
5	DIVD	F4,	F2,	F8	*4*
6	ADDD	F10,	F6,	F4	*1*



In-order: 1 (2,1) . . . . . 2 3 4 4 3 5 . . . 5 6 6

In-order restriction prevents instruction 4 from being dispatched

How can we address the delay caused by a RAW dependence associated with the next in-order instruction?



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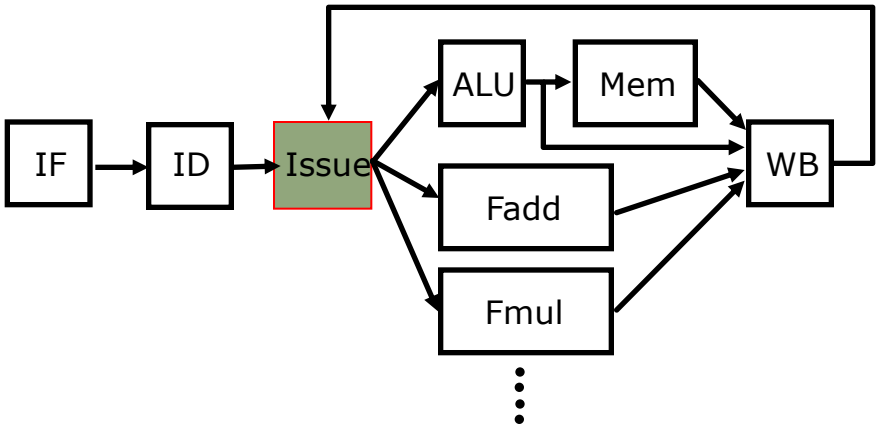
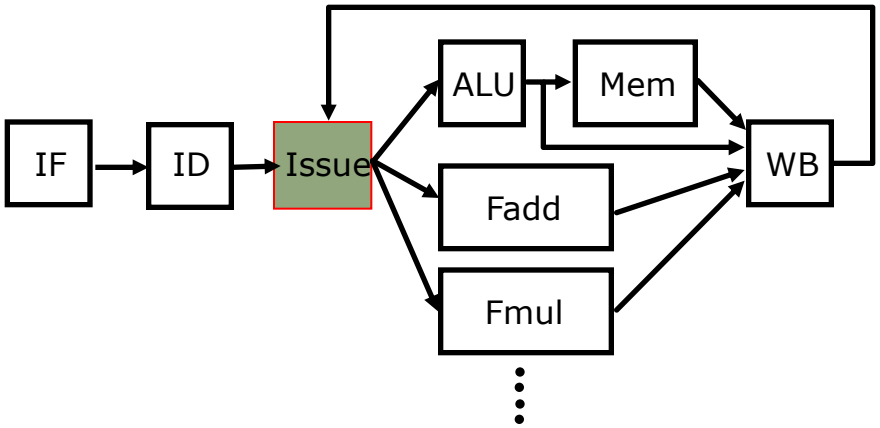


Find something else to do!

Out-of-Order Issue

How can we address the delay caused by a RAW dependence associated with the next in-order instruction?



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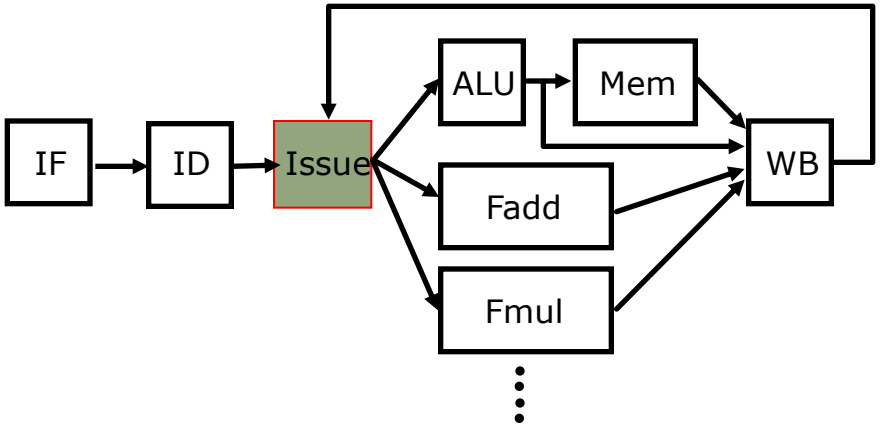
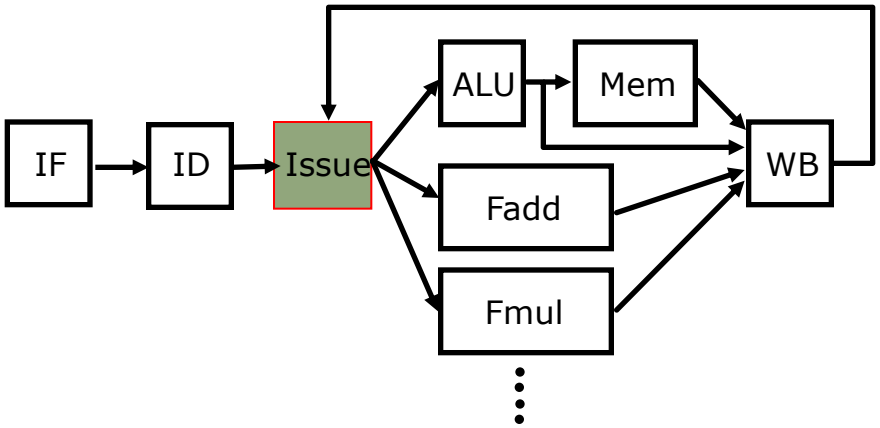


Find something else to do!

- Issue stage buffer holds multiple instructions waiting to issue.

Out-of-Order Issue

How can we address the delay caused by a RAW dependence associated with the next in-order instruction?

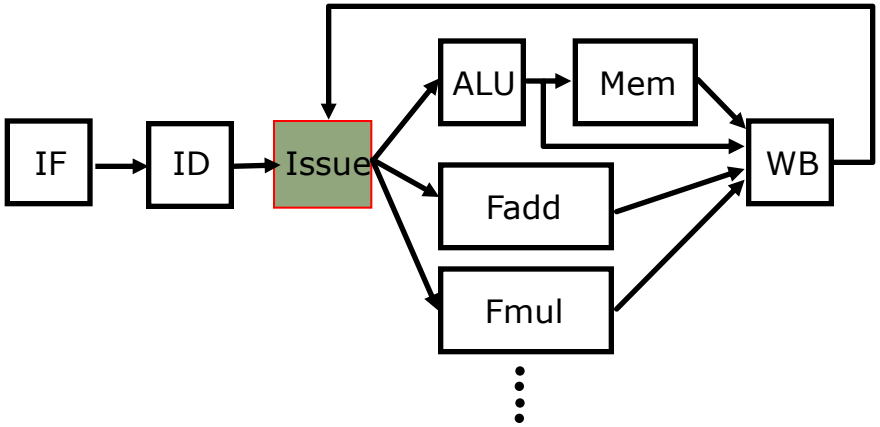


Find something else to do!

- Issue stage buffer holds multiple instructions waiting to issue.
- Decode adds next instruction to buffer if there is space and the instruction does not cause a WAR or WAW hazard.

Out-of-Order Issue

How can we address the delay caused by a RAW dependence associated with the next in-order instruction?



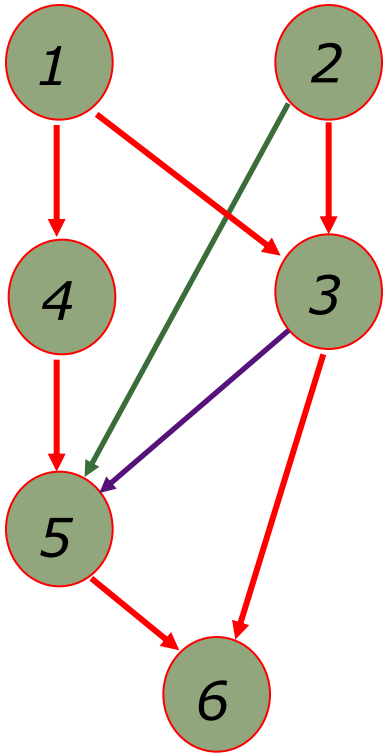
Find something else to do!

- Issue stage buffer holds multiple instructions waiting to issue.
- Decode adds next instruction to buffer if there is space and the instruction does not cause a WAR or WAW hazard.
- Can issue any instruction in buffer whose RAW hazards are satisfied *(for now at most one dispatch per cycle).*
  Note: A writeback (WB) may enable more instructions.

In-Order Issue Limitations

An example

					latency
1	LD	F2,	34(R2)		*1*
2	LD	F4,	45(R3)		*long*
3	MULTD	F6,	F4,	F2	*3*
4	SUBD	F8,	F2,	F2	*1*
5	DIVD	F4,	F2,	F8	*4*
6	ADDD	F10,	F6,	F4	*1*

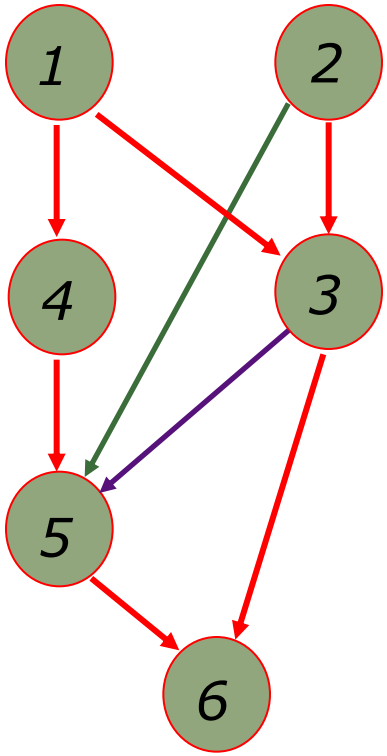


In-order: 1 (2,1) . . . . . 2 3 4 4 3 5 . . . 5 6 6

In-Order Issue Limitations

An example

					latency
1	LD	F2,	34(R2)		*1*
2	LD	F4,	45(R3)		*long*
3	MULTD	F6,	F4,	F2	*3*
4	SUBD	F8,	F2,	F2	*1*
5	DIVD	F4,	F2,	F8	*4*
6	ADDD	F10,	F6,	F4	*1*



In-order: 1 (2,1) . . . . . 2 3 4 4 3 5 . . . 5 6 6

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In-Order Issue Limitations

An example

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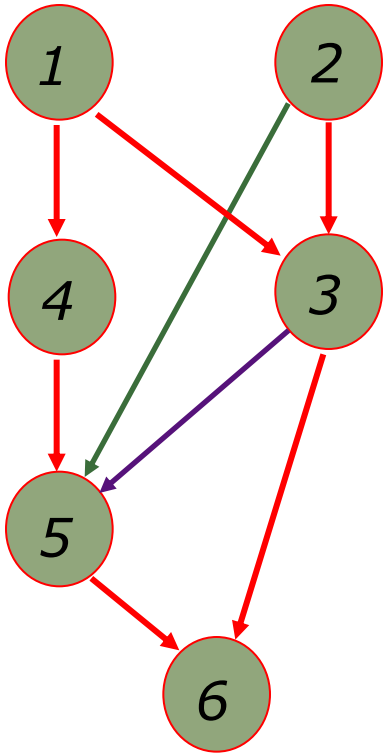

In-order: 1 (2,1) . . . . . 2 3 4 4 3 5 . . . 5 6 6

Out-of-order: 1 (2,1) 4 4 . . . . 2 3 5 . 3 . 5 6 6

Out-of-order execution did not produce a significant improvement!

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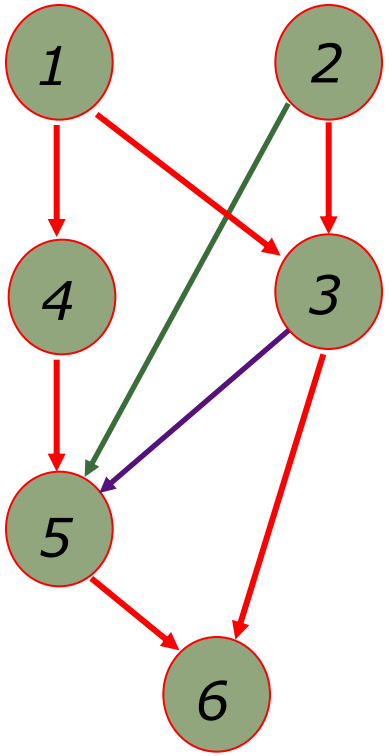

In-order: 1 (2,1) . . . . . 2 3 4 4 3 5 . . . 5 6 6

Out-of-order: 1 (2,1) 4 4 . . . . 2 3 5 . 3 . 5 6 6

WAR/WAW hazards prevent instruction 5 from being dispatched

Out-of-order execution did not produce a significant improvement!

How many Instructions can be in the pipeline

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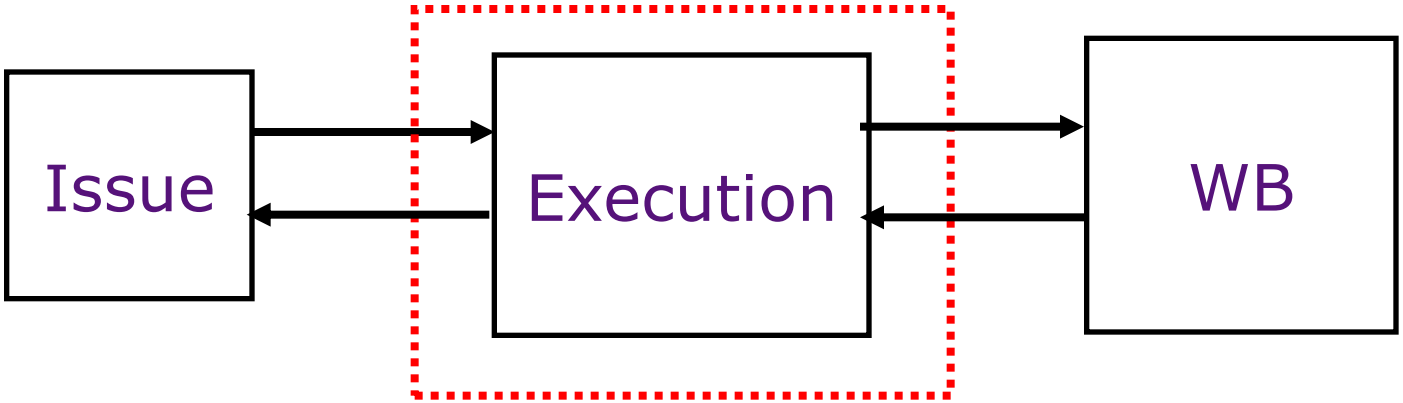
How can we better understand the impact of number of registers on throughput?

Little's Law

Throughput ($\overline{T}$) = Number in Flight ($\overline{N}$) / Latency ($\overline{L}$)



Example:

4 floating point registers
8 cycles per floating point operation

$\Rightarrow$

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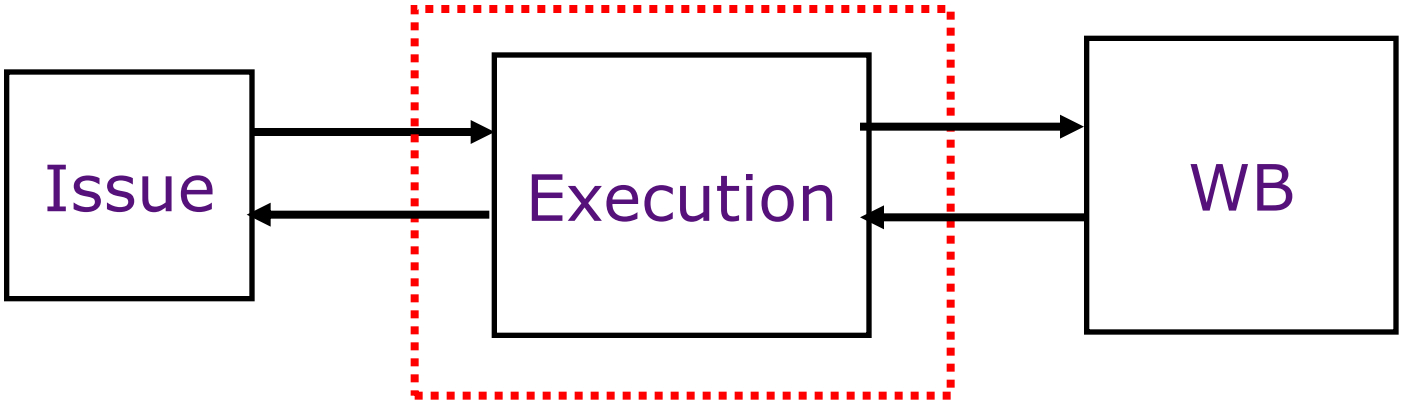

Example:

4 floating point registers
8 cycles per floating point operation

⇒ *½ issues per cycle!*

Overcoming the Lack of Register Names

Floating Point pipelines often cannot be kept filled with small number of registers.

IBM 360 had only 4 Floating Point Registers

Can a microarchitecture use more registers than specified by the ISA without loss of ISA compatibility ?

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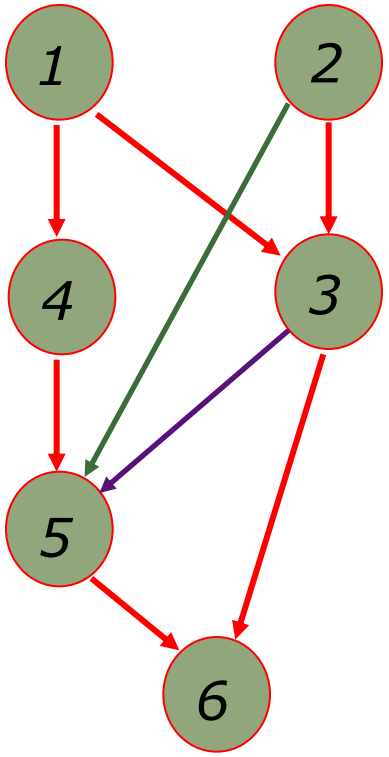
Can a microarchitecture use more registers than specified by the ISA without loss of ISA compatibility ?

Yes, Robert Tomasulo of IBM suggested an ingenious solution in 1967 based on on-the-fly *register renaming*

Instruction-level Parallelism via *Renaming*

					latency
1	LD	F2,	34(R2)		*1*
2	LD	F4,	45(R3)		*long*
3	MULTD	F6,	F4,	F2	*3*
4	SUBD	F8,	F2,	F2	*1*
5	DIVD	F4,	F2,	F8	*4*
6	ADDD	F10,	F6,	F4	*1*



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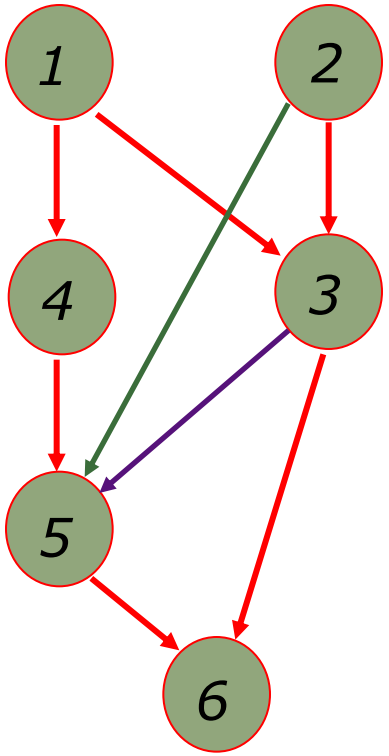

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Renaming eliminates WAR and WAW hazards

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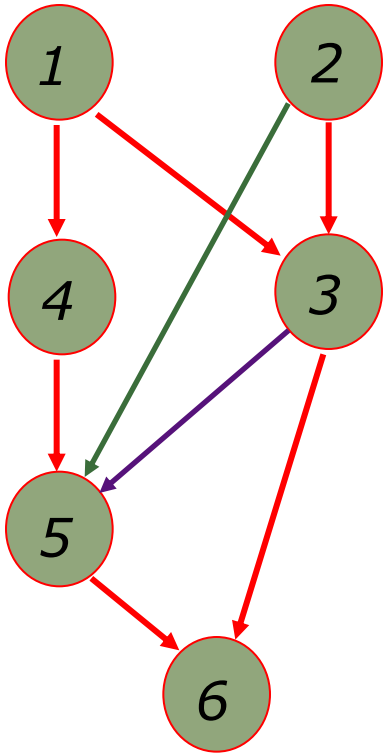

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(renaming ⇒ additional storage)

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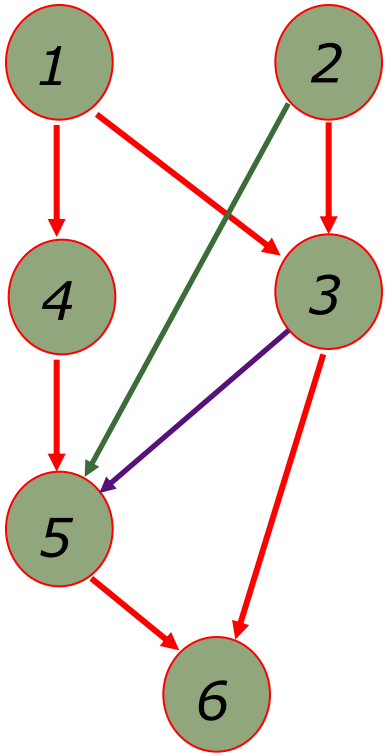

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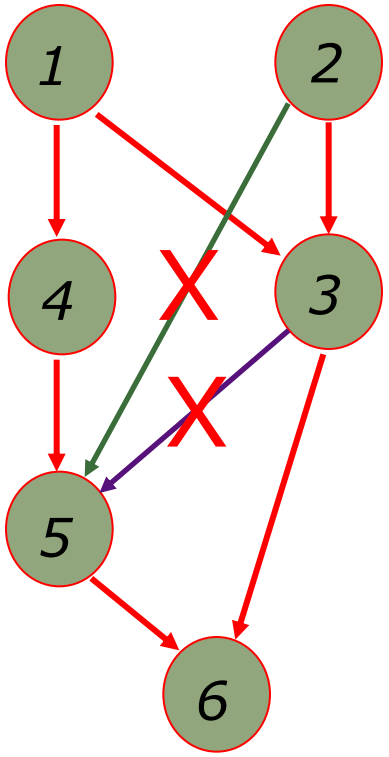

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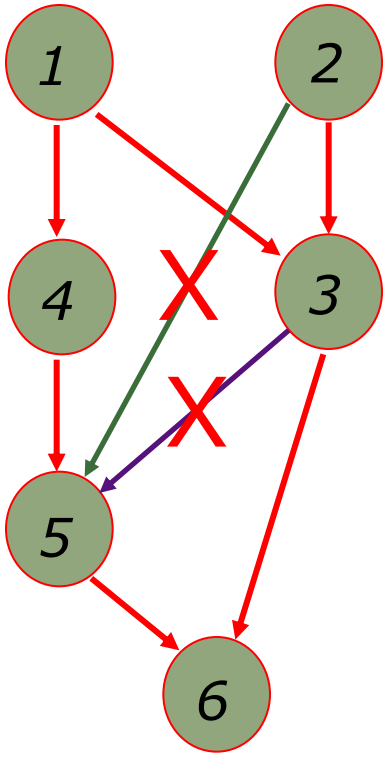

In-order: 1 (2,1) . . . . . 2 3 4 4 3 5 . . . 5 6 6
Out-of-order: 1 (2,1) 4 4 5 . . . (2,5) 3 . . 3 6 6

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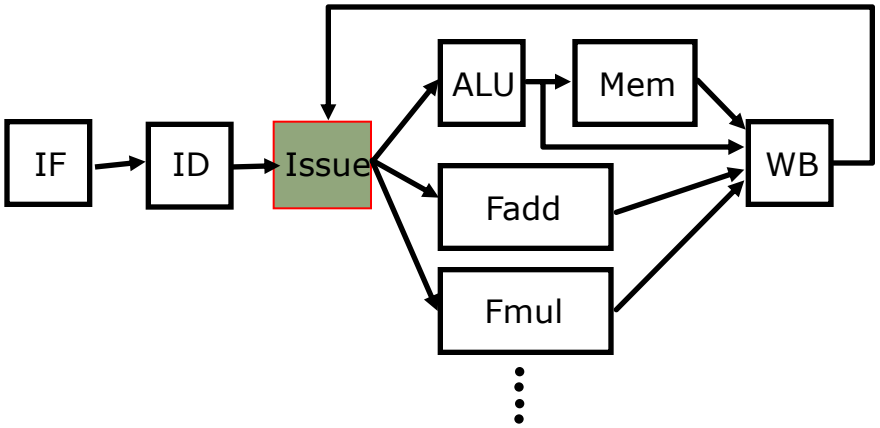
Handling register dependencies



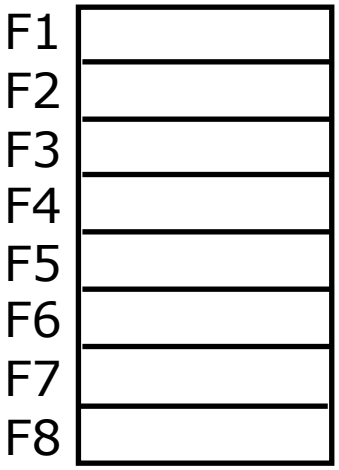
- Decode does register renaming, providing a new spot for each register write
  - Renaming eliminates WAR and WAW hazards by allowing use of more storage space

- Renamed instructions added to an issue stage structure, called the reorder buffer (ROB). Any instruction in the ROB whose RAW hazards have been satisfied can be dispatched
  - Out-of-order or dataflow execution handles RAW hazards

Reorder Buffer

Smith and Pleszkun, 1985

Register File



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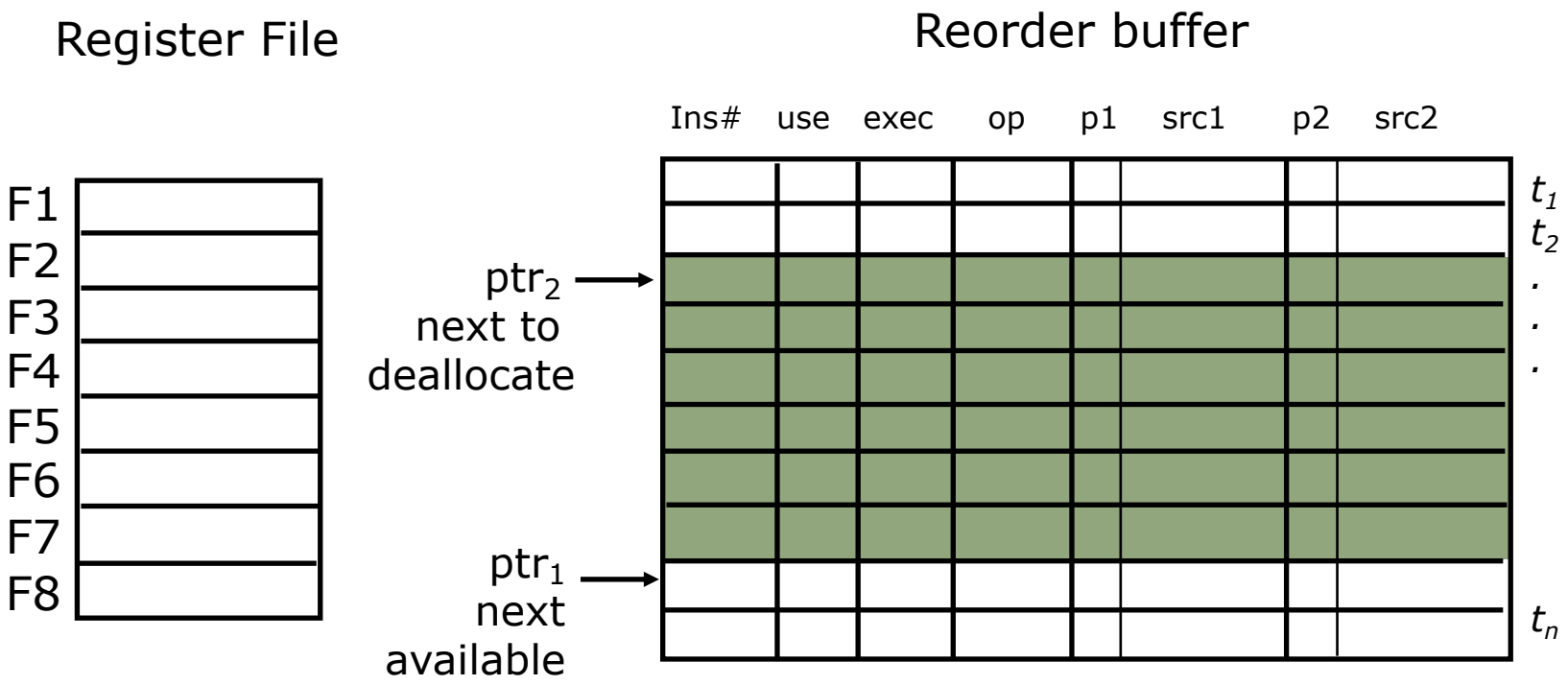

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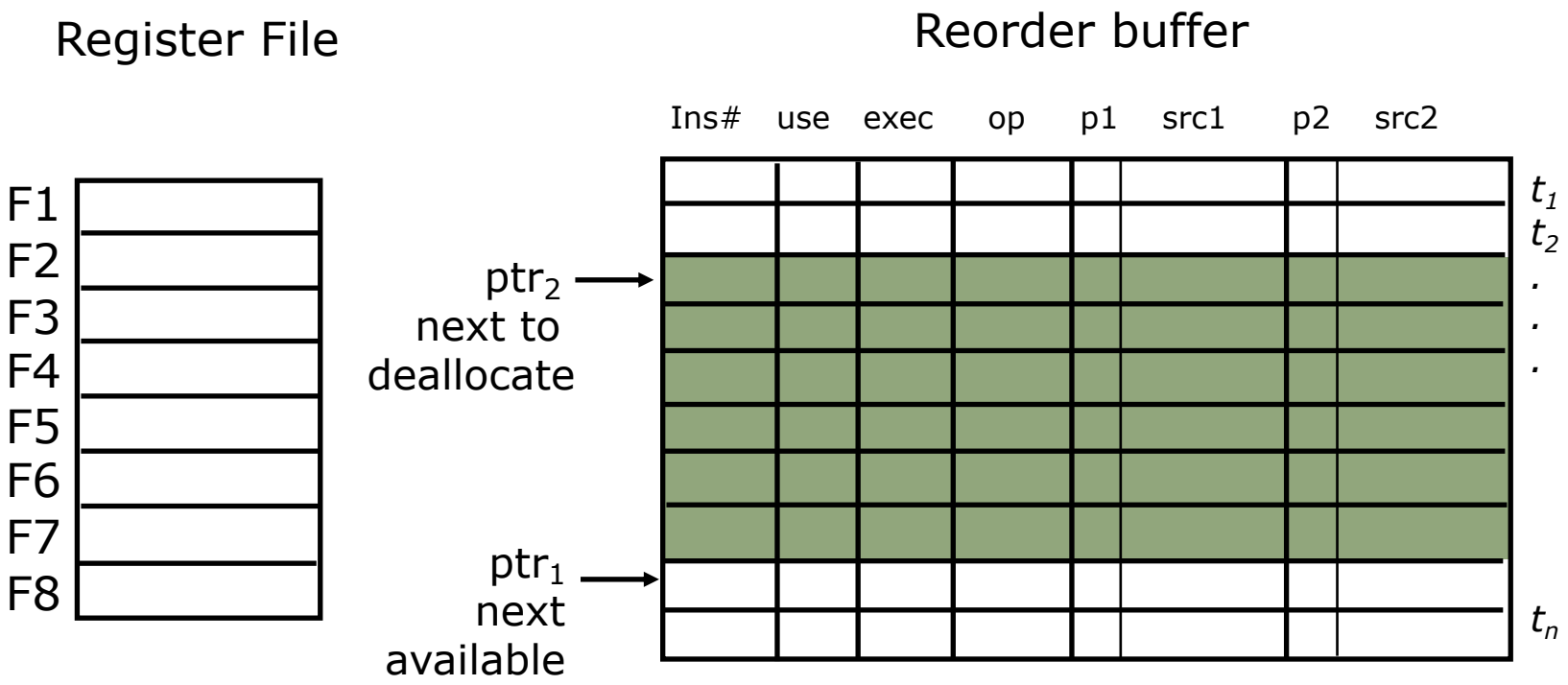

Instruction slot is candidate for execution when:

- It holds a valid instruction ("use" bit is set)
- It has not already started execution ("exec" bit is clear)
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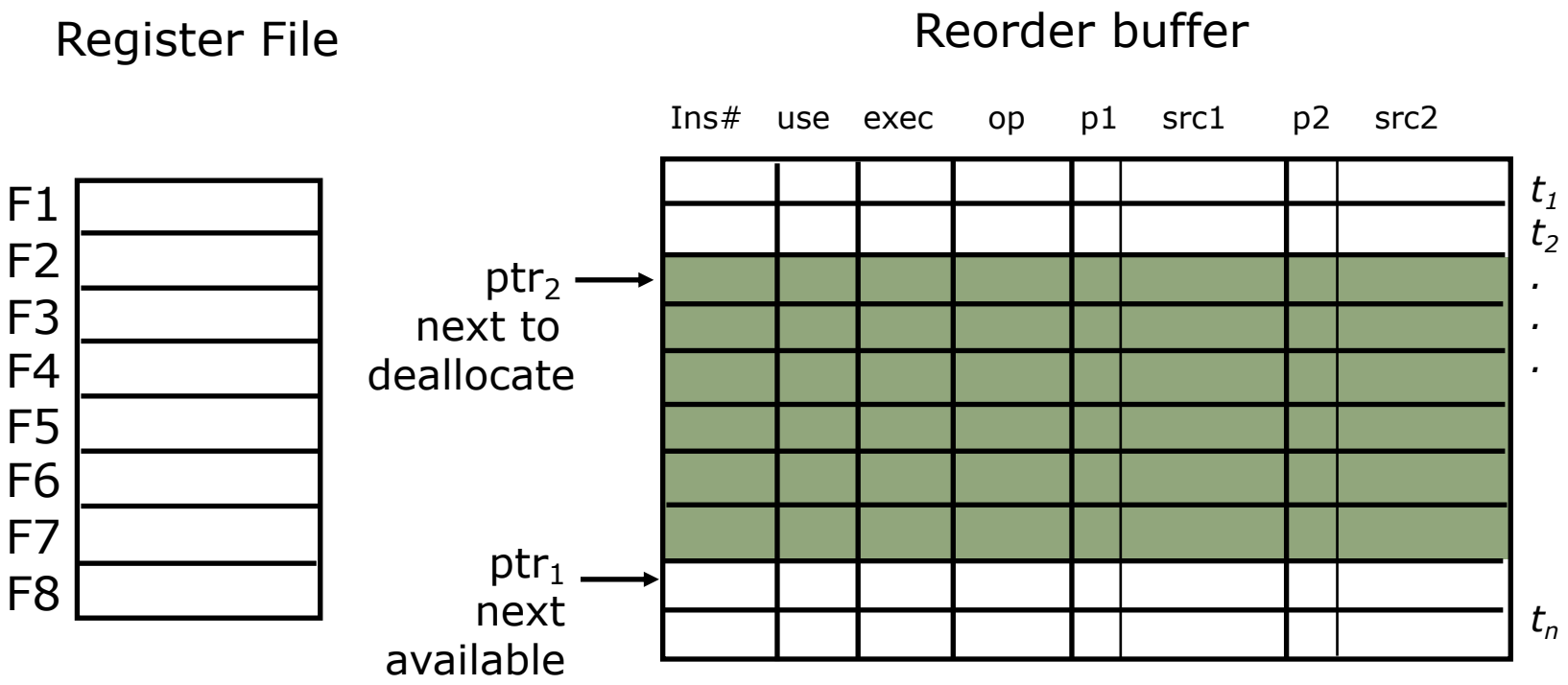

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Is it obvious where an architectural register value is?

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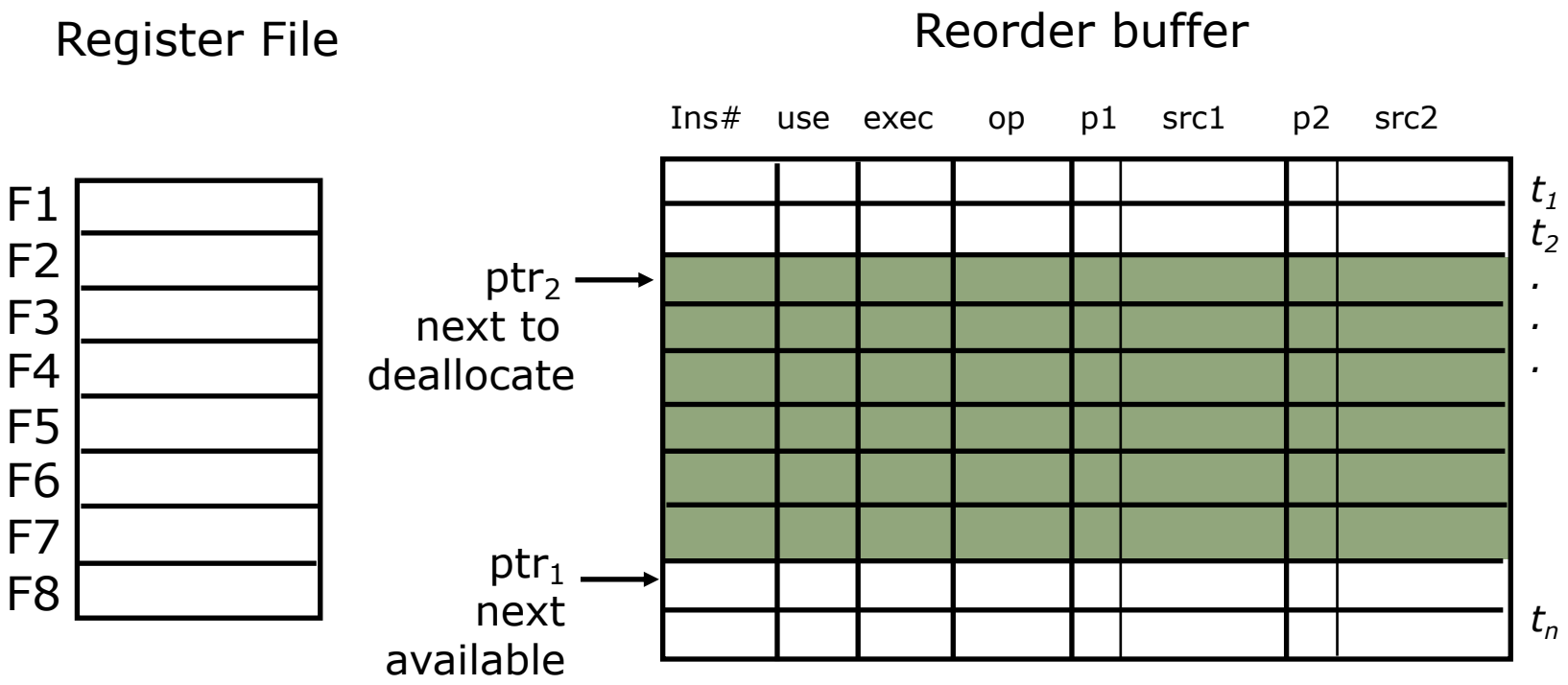

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Is it obvious where an architectural register value is? *No*

Renaming & Out-of-order Issue

Renaming table & reg file

	p	data
F1		
F2		
F3		
F4		
F5		
F6		
F7		
F8		

Reorder buffer

Ins#	use	exec	op	p1	src1	p2	src2	
								t_1
								t_2
								t_3
								t_4
								t_5
								.
								.

Holds data (v_i)
or tag(t_i)

Renaming & Out-of-order Issue

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								t_1
								t_2
								t_3
								t_4
								t_5
								.
								.

- *When are names in sources replaced by data?*
- *When can a name be reused?*

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F2		
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Holds data (v_i) or tag(t_i)

Reorder buffer

Ins#	use	exec	op	p1	src1	p2	src2	
								t_1
								t_2
								t_3
								t_4
								t_5
								.
								.

- *When are names in sources replaced by data?*
  Whenever an FU produces data
- *When can a name be reused?*

Renaming & Out-of-order Issue

Renaming table & reg file

	p	data
F1		
F2		
F3		
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F6		
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F8		

Holds data (v_i) or tag(t_i)

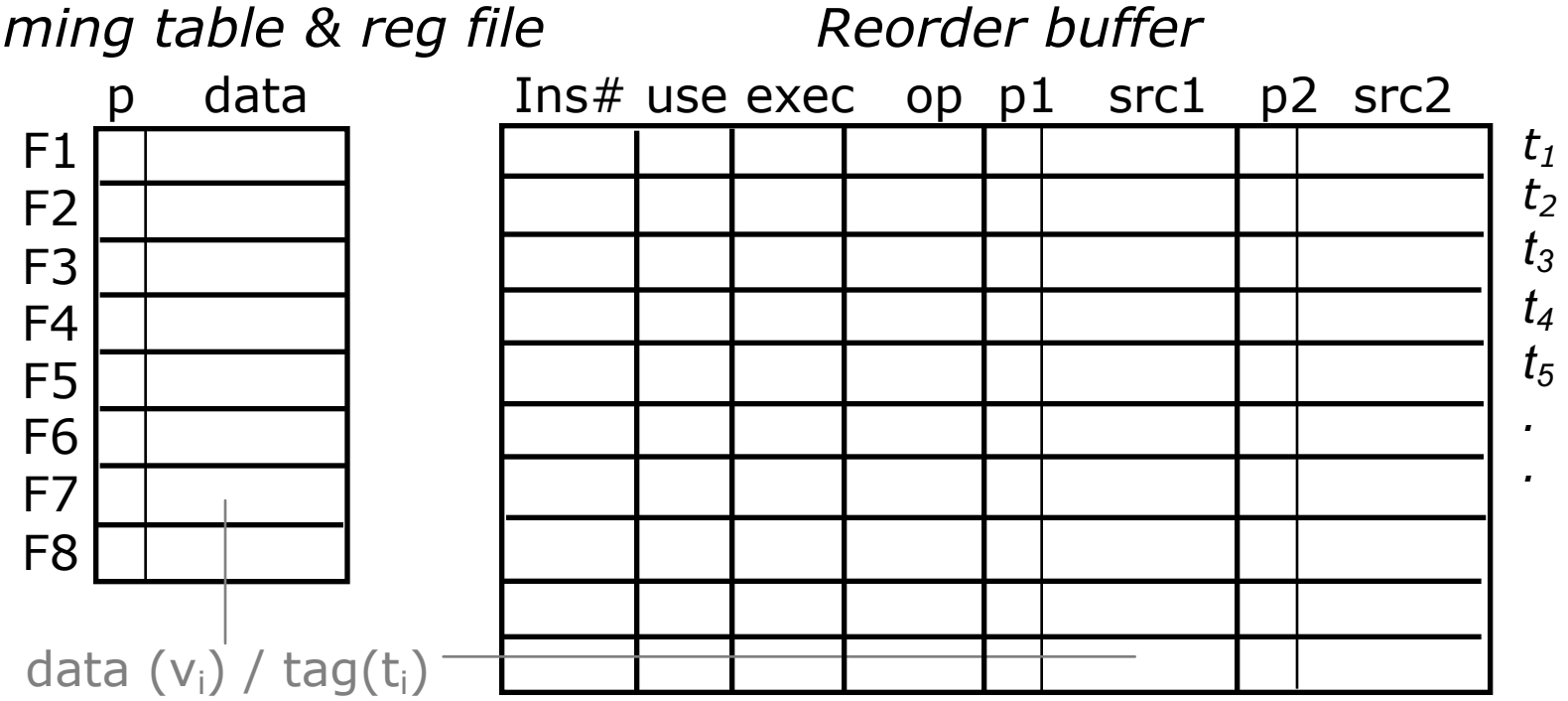
Reorder buffer

Ins#	use	exec	op	p1	src1	p2	src2	
								t_1
								t_2
								t_3
								t_4
								t_5
								.
								.

- *When are names in sources replaced by data?*
  Whenever an FU produces data
- *When can a name be reused?*
  Whenever an instruction completes

Renaming & Out-of-order Issue

An example



- *Insert instruction in ROB*
- *Issue instruction from ROB*
- *Complete instruction*
- *Empty ROB entry*

1	LD	F2,	34(R2)	
2	LD	F4,	45(R3)	
3	MULTD	F6,	F4,	F2
4	SUBD	F8,	F2,	F2
5	DIVD	F4,	F2,	F8
6	ADDD	F10,	F6,	F4

Renaming & Out-of-order Issue

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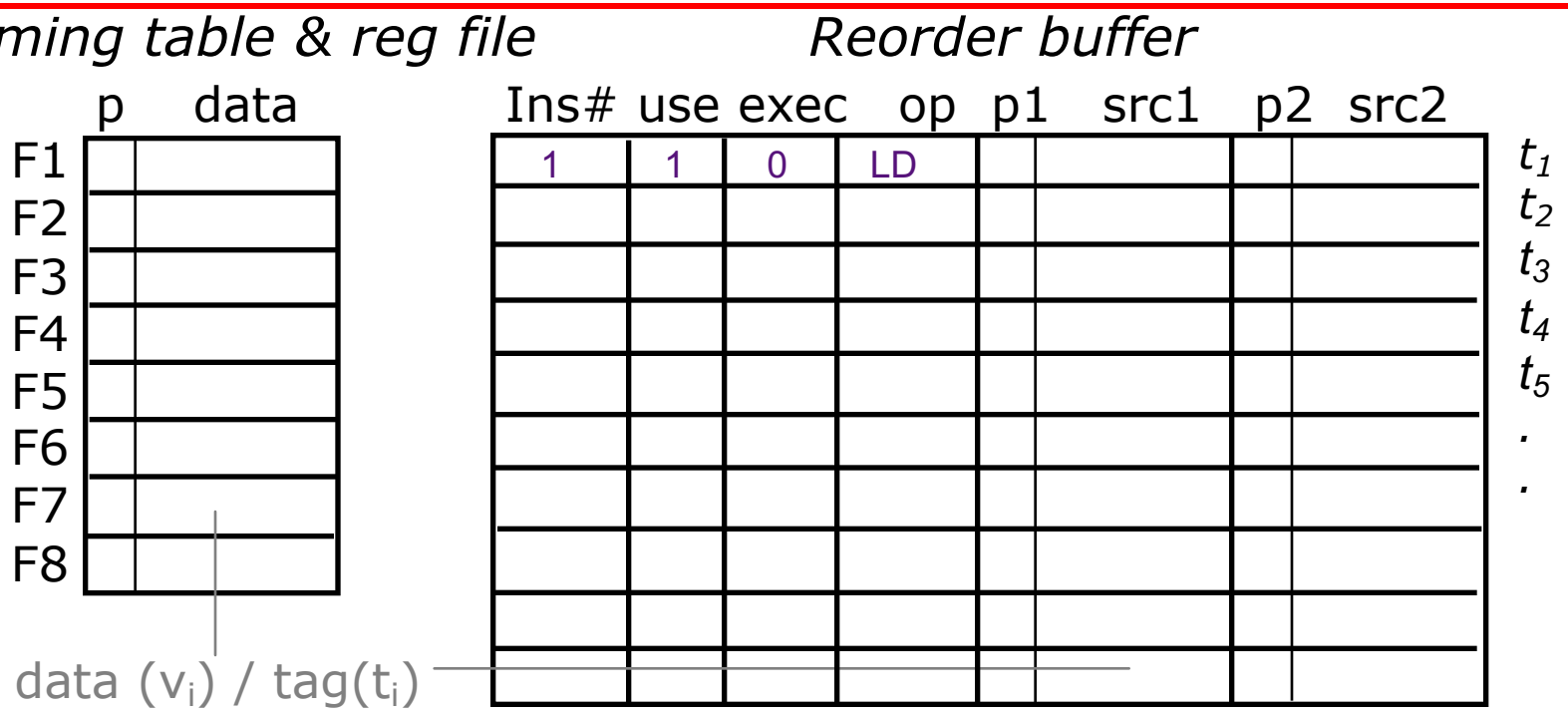

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Renaming & Out-of-order Issue

An example

Renaming table & reg file

	p	data
F1		
F2	0	t1
F3		
F4		
F5		
F6		
F7		
F8		

data (v_i) / tag(t_i)

Reorder buffer

	Ins#	use	exec	op	p1	src1	p2	src2
t_1	1	1	0	LD				
t_2								
t_3								
t_4								
t_5								
.								
.								

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F5		
F6		
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data (v_i) / tag(t_i)

Reorder buffer

Ins#	use	exec	op	p1	src1	p2	src2	
1	1	1	LD					t_1
								t_2
								t_3
								t_4
								t_5
								.
								.

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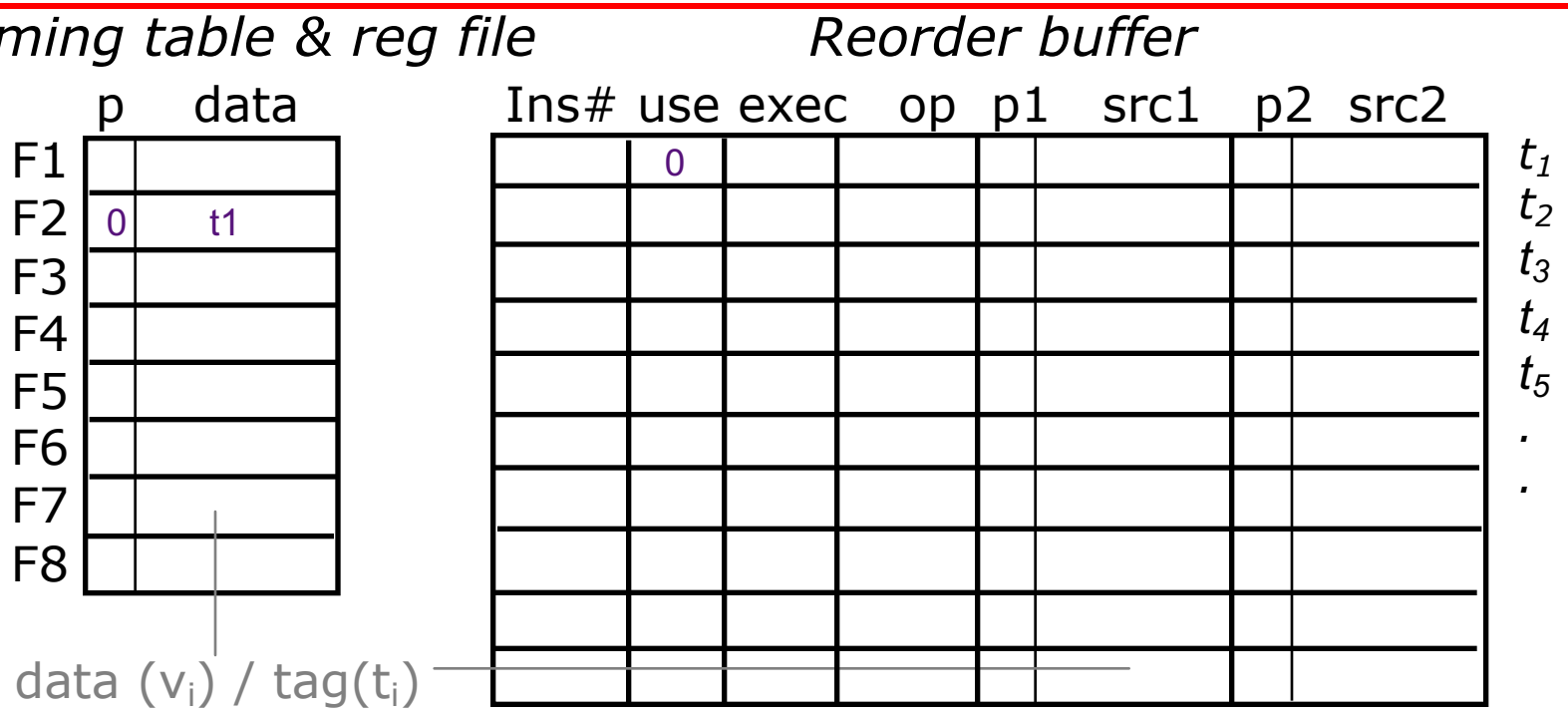

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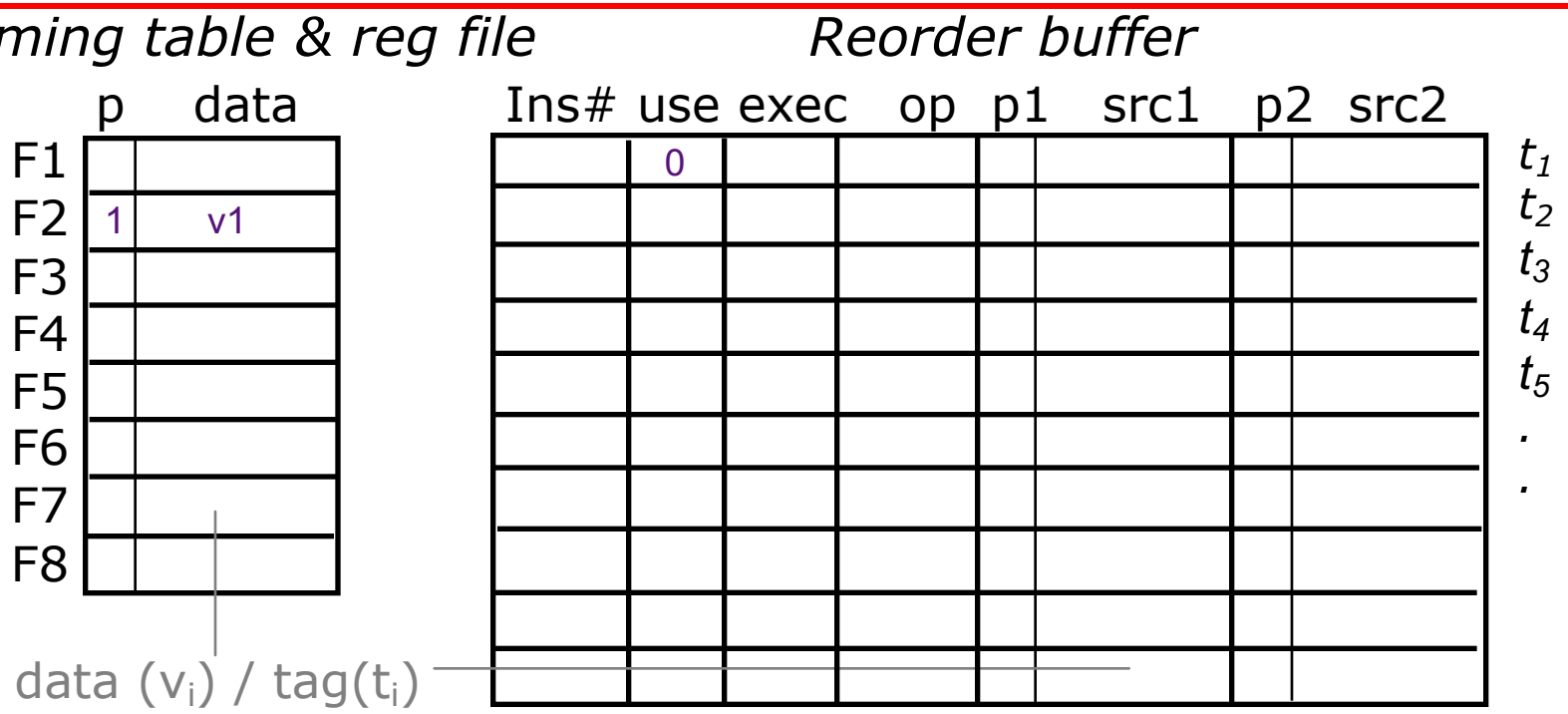

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Renaming & Out-of-order Issue

An example

Renaming table & reg file

	p	data
F1		
F2	1	v1
F3		
F4	0	t2
F5		
F6		
F7		
F8		

data (v_i) / tag(t_i)

Reorder buffer

	Ins#	use	exec	op	p1	src1	p2	src2
t_1		0						
t_2	2	1	0	LD				
t_3								
t_4								
t_5								
.								
.								

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Reorder buffer

	Ins#	use	exec	op	p1	src1	p2	src2
t_1		0						
t_2	2	1	1	LD				
t_3								
t_4								
t_5								
.								
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data (v_i) / tag(t_i)

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	Ins#	use	exec	op	p1	src1	p2	src2
t_1		0						
t_2	2	1	1	LD				
t_3	3	1	0	MUL	0	t2	1	v1
t_4								
t_5								
.								
.								

- *Insert instruction in ROB*
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1   LD    F2,  34(R2)
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5   DIVD  F4,  F2,  F8
6   ADDD  F10, F6,  F4
```

Renaming & Out-of-order Issue

An example

Renaming table & reg file

	p	data
F1		
F2	1	v1
F3		
F4	0	t2
F5		
F6	0	t3
F7		
F8	0	t4

data (v_i) / tag(t_i)

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2	1	1	LD					t_2
3	1	0	MUL	0	t2	1	v1	t_3
4	1	0	SUB	1	v1	1	v1	t_4
								t_5
								.
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```
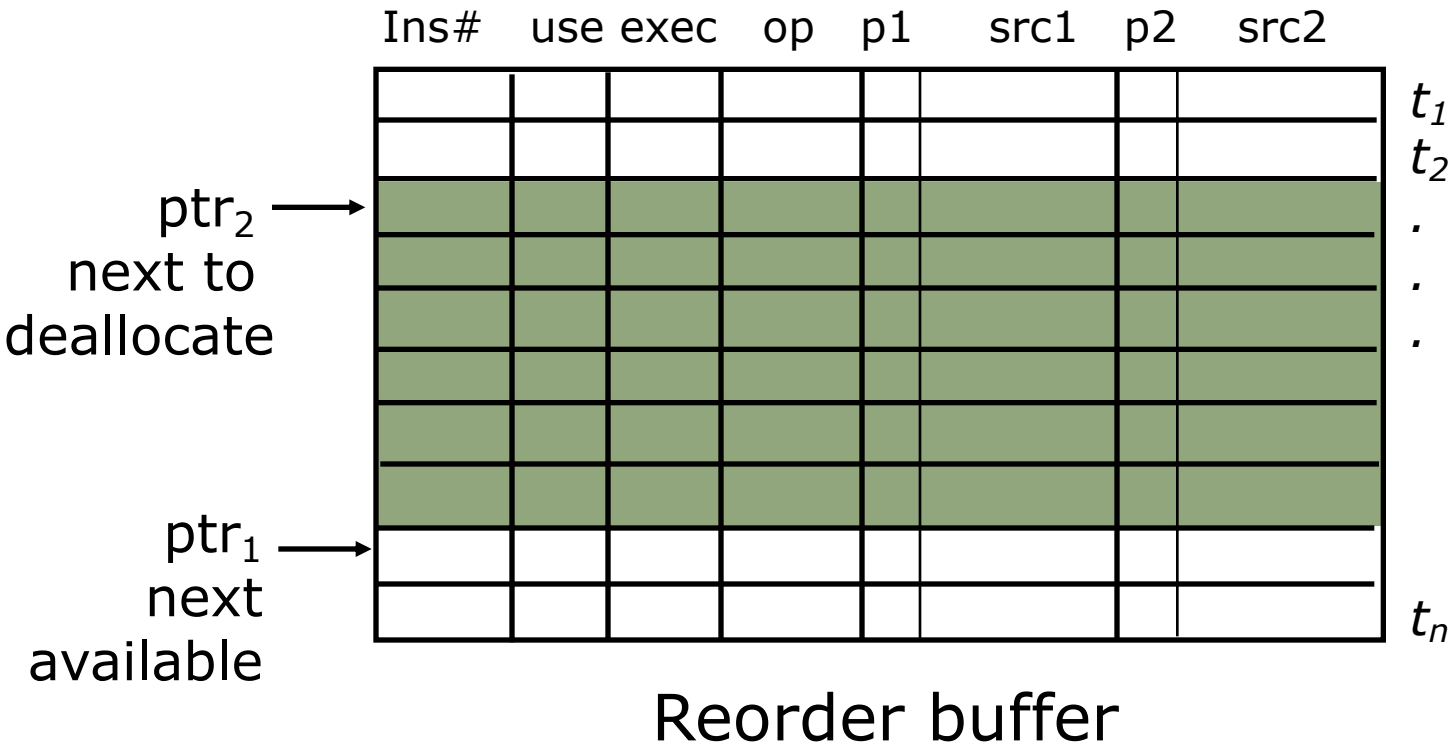
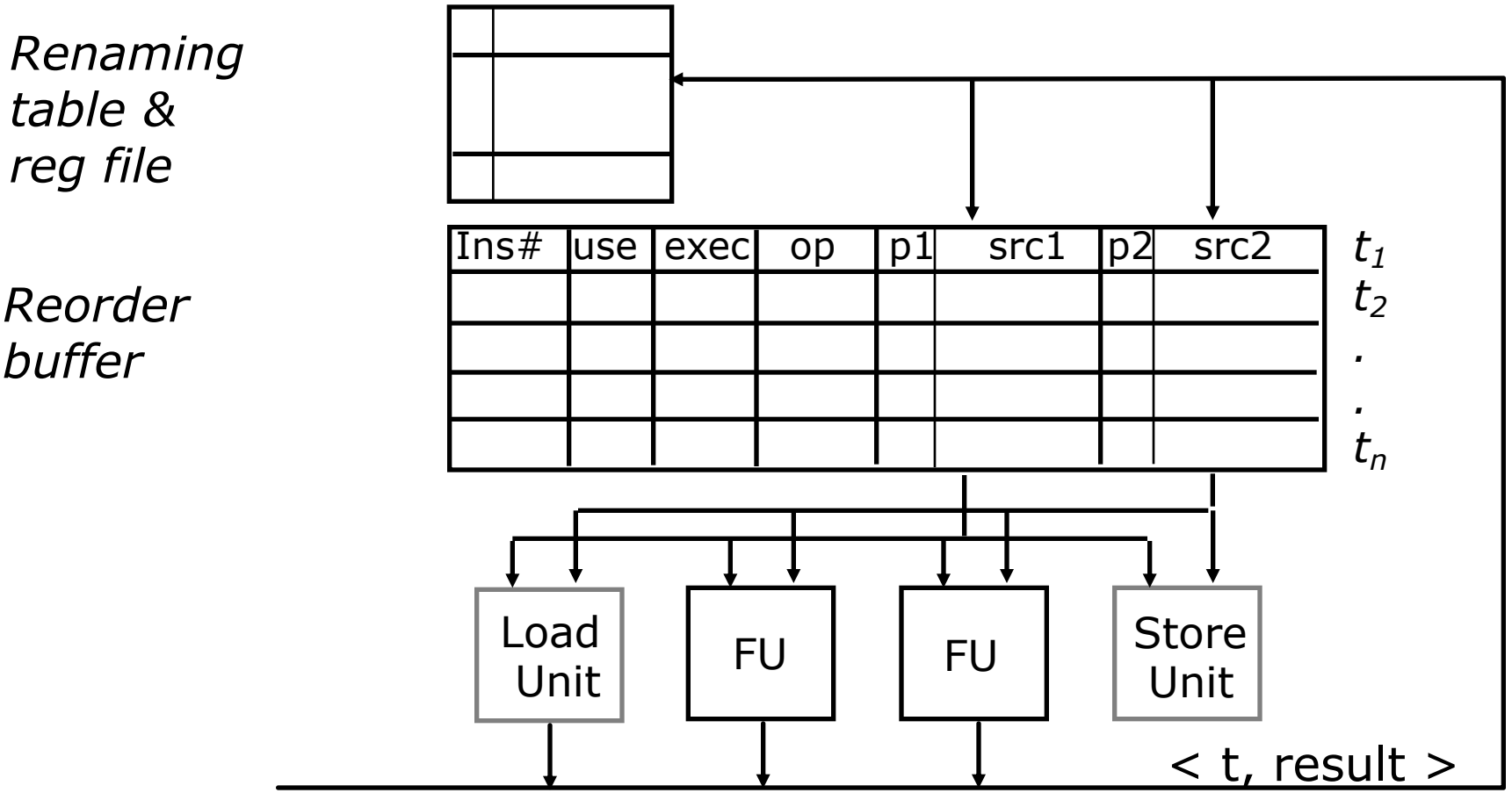

Simplifying Allocation/Deallocation



Instruction buffer is managed circularly

- Set "exec" bit when instruction begins execution
- When an instruction completes its "use" bit is marked free
- Increment ptr_2 only if the "use" bit is marked free

Data-Driven Execution



- Instruction template (i.e., tag t) is allocated by the Decode stage, which also stores the tag in the reg file
- When an instruction completes, its tag is deallocated

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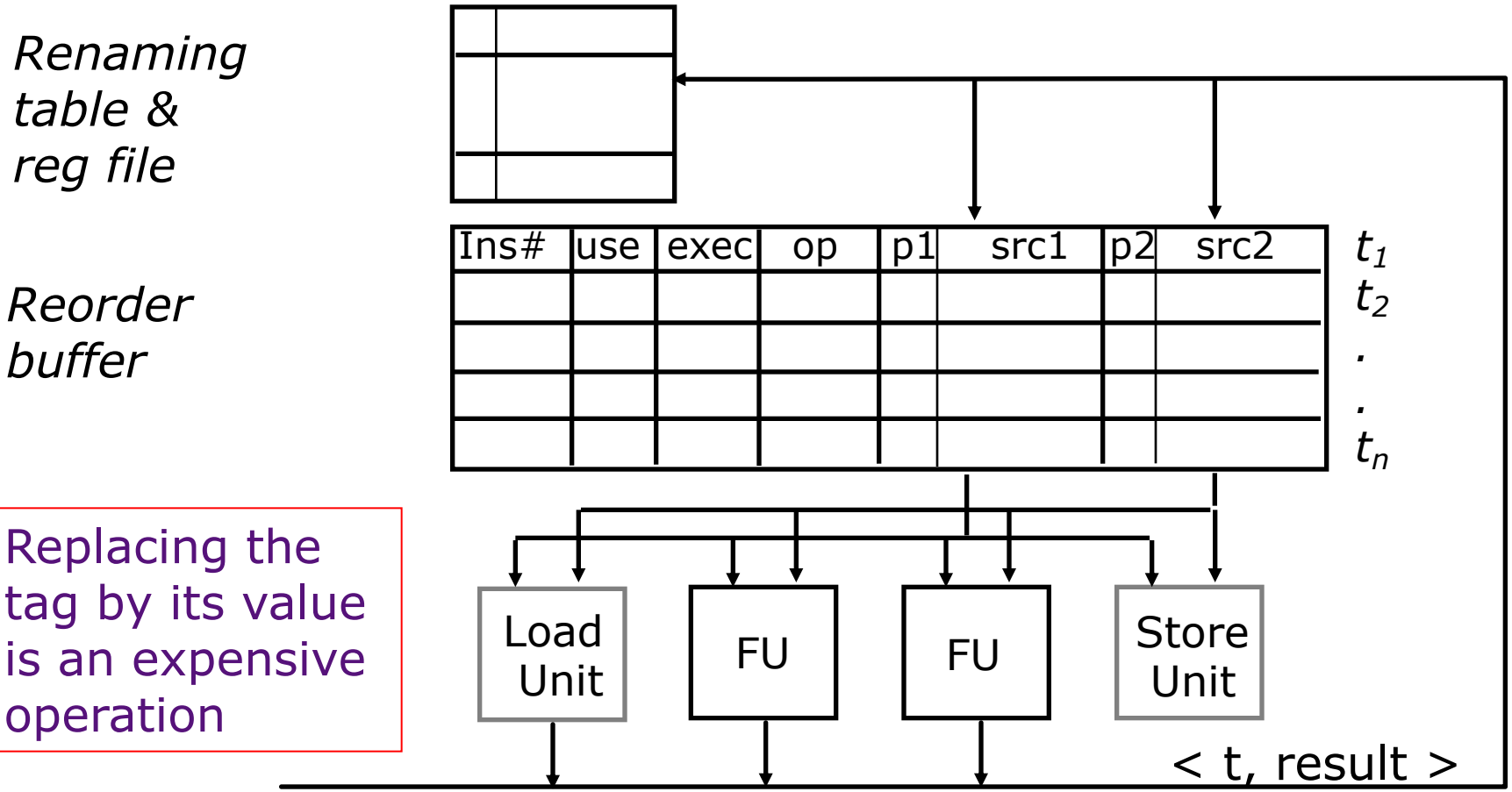

Replacing the tag by its value is an expensive operation

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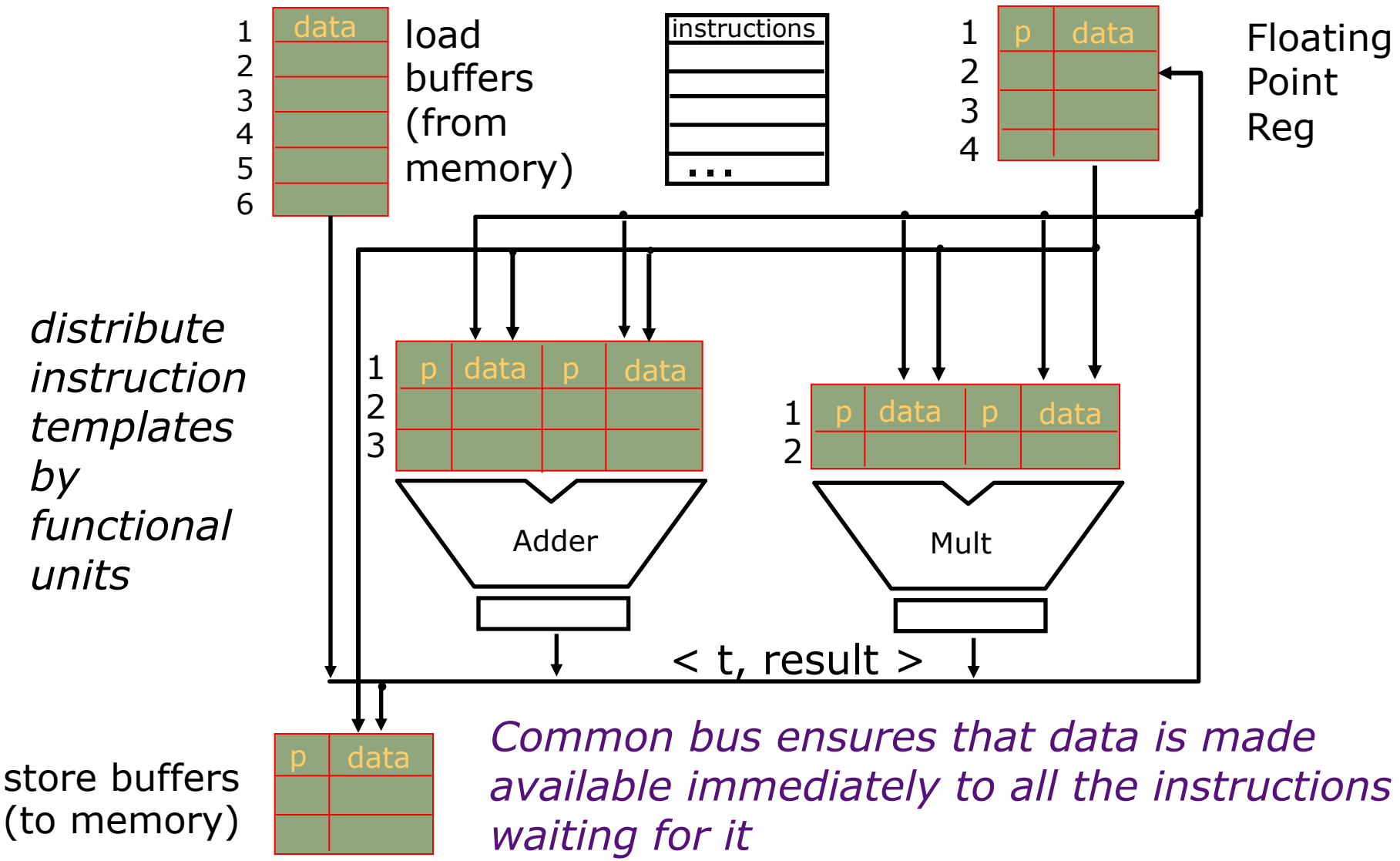
- When an instruction completes, its tag is deallocated

IBM 360/91 Floating Point Unit

R. M. Tomasulo, 1967



Common bus ensures that data is made available immediately to all the instructions waiting for it

Effectiveness?

Renaming and Out-of-order execution was first implemented in 1969 in IBM 360/91 but was effective only on a very small class of problems and thus did not show up in the subsequent models until mid-nineties. *Why?*

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Branch/jump penalties

More on this in the next lecture

Reminder: Precise Exceptions

Exceptions are relatively unlikely events that need special processing, but where adding explicit control flow instructions is not desired, e.g., divide by 0, page fault

Exceptions can be viewed as an implicit conditional subroutine call that is inserted between two instructions.

Therefore, it must appear as if the exception is taken between two instructions (say I_i and I_{i+1})

- the effect of all instructions up to and including I_i is complete
- no effect of any instruction after I_i has taken place

The handler either aborts the program or restarts it at I_{i+1} .

Effect on Exceptions
Out-of-order Completion

I_1	DIVD	f6,	f6,	f4
I_2	LD	f2,	45(r3)	
I_3	MULTD	f0,	f2,	f4
I_4	DIVD	f8,	f6,	f2
I_5	SUBD	f10,	f0,	f6
I_6	ADDD	f6,	f8,	f2

out-of-order comp 1 2 2 3 1 4 3 5 5 4 6 6

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Consider exceptions
on "DIVD"s

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out-of-order comp 1 2 2 3 1 4 3 5 5 4 6 6

restore f2

Consider exceptions
on "DIVD"s

Effect on Exceptions
Out-of-order Completion

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restore f2 *restore f10*

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Out-of-order Completion

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out-of-order comp 1 2 2 3 1 4 3 5 5 4 6 6

restore f2 *restore f10*

Consider exceptions *on "DIVD"s*

Precise exceptions are difficult to implement at high speed
- want to start execution of later instructions before exception checks finished on earlier instructions

Exceptions

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- How can we handle rollback on mis-speculation?

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  Delay state update until commit on speculated instructions

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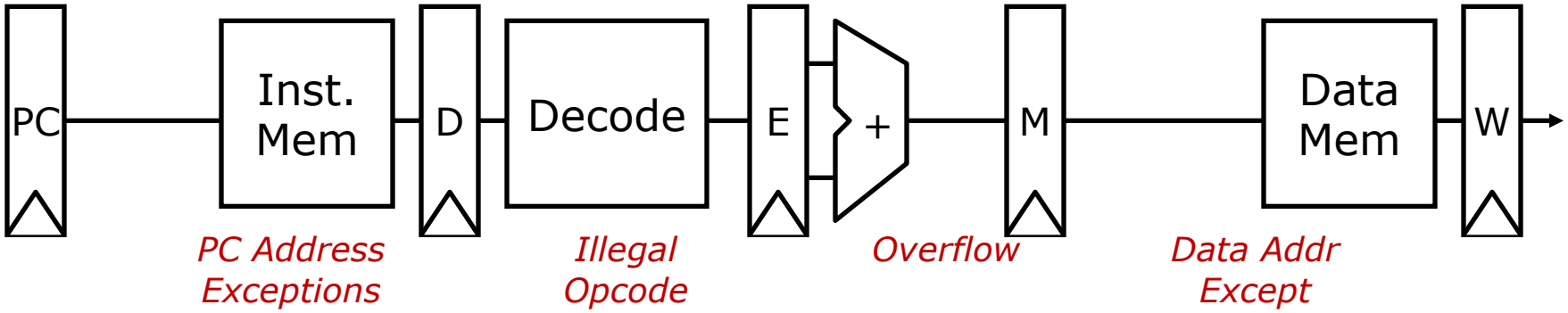
- Note: earlier exceptions must override later ones

Reminder: Exception Handling
(In-Order Five-Stage Pipeline)



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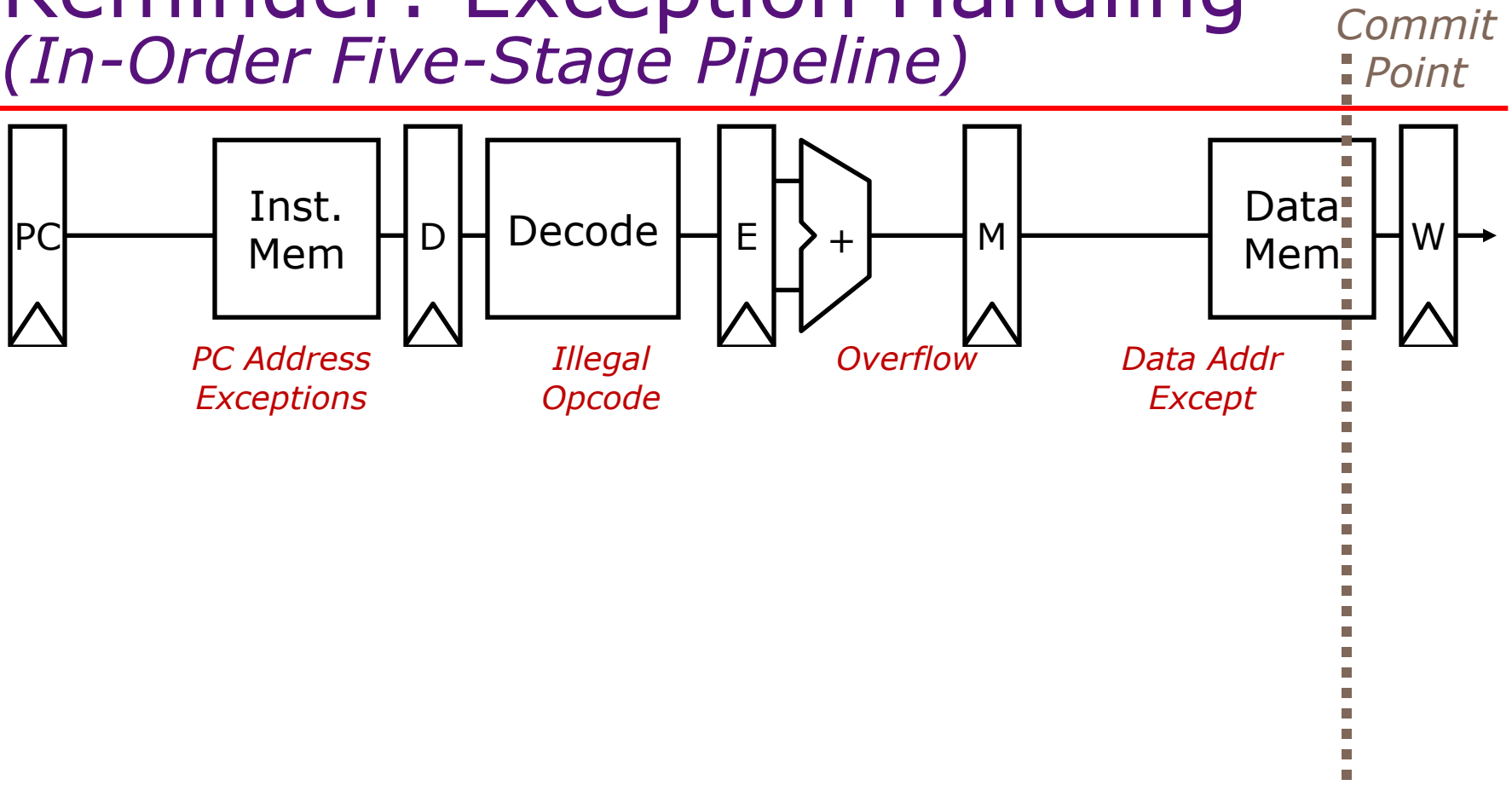

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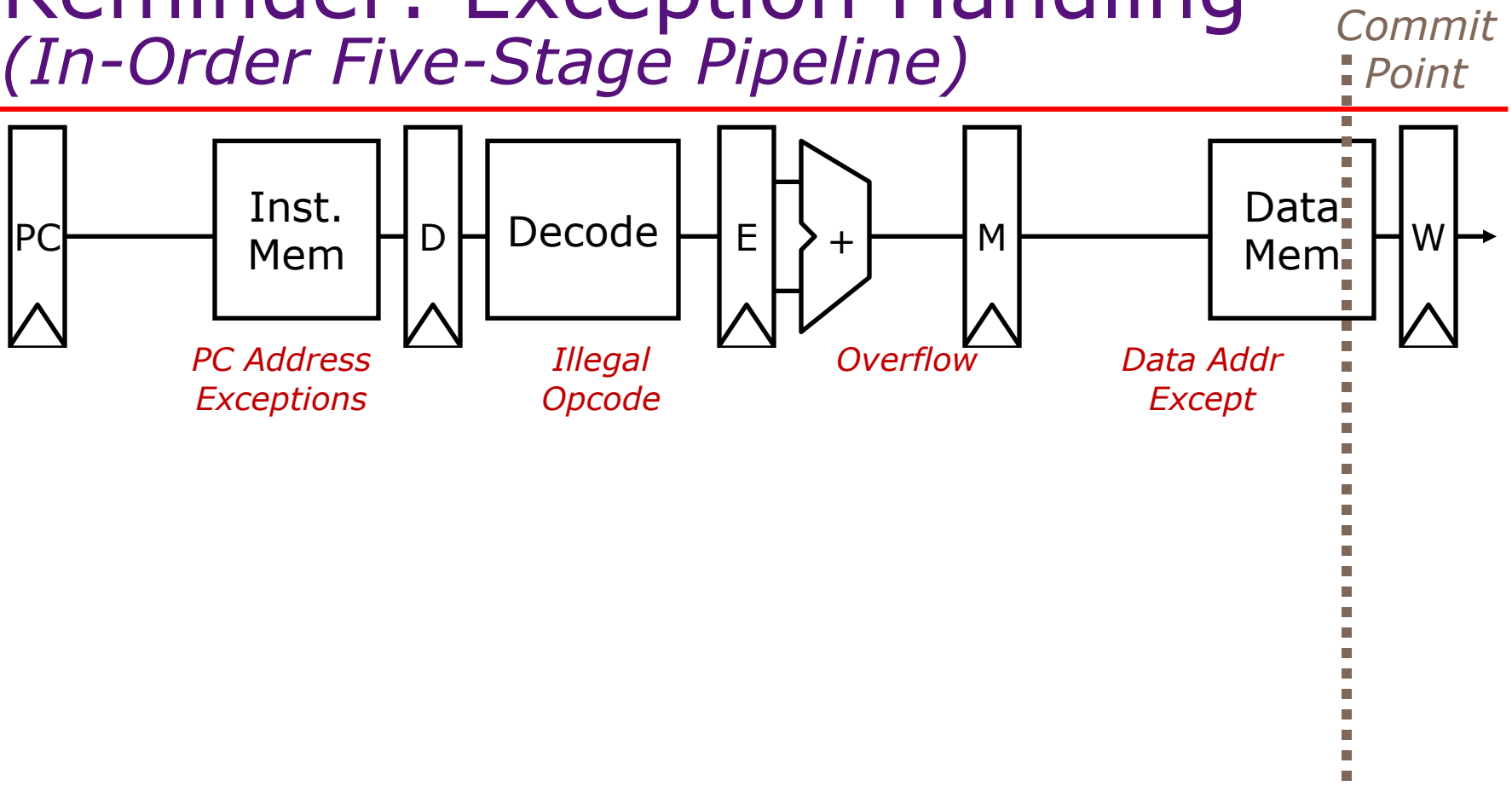
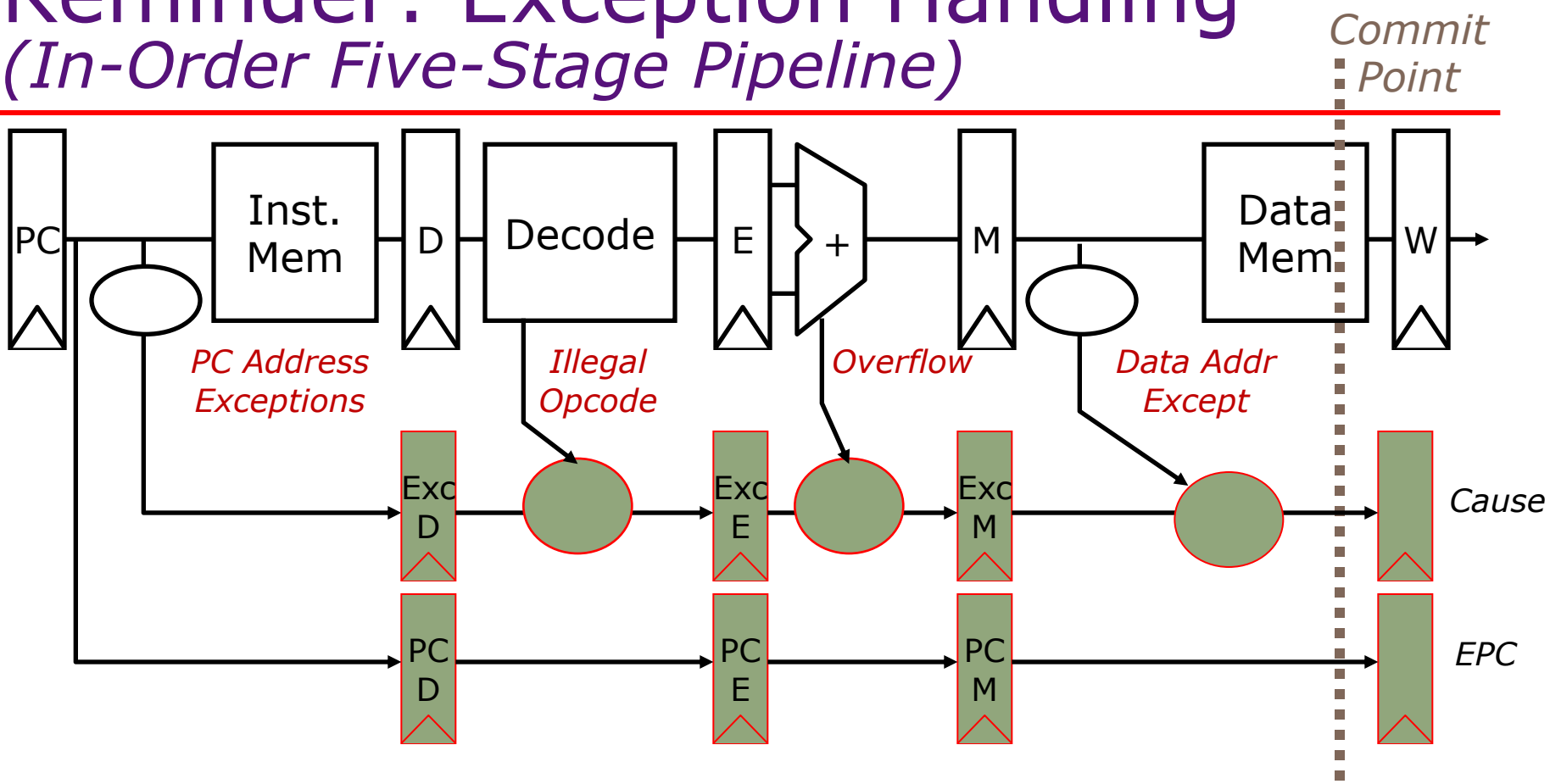


Hold exception flags in pipeline until commit point (M stage)

Reminder: Exception Handling
(In-Order Five-Stage Pipeline)



Hold exception flags in pipeline until commit point (M stage)

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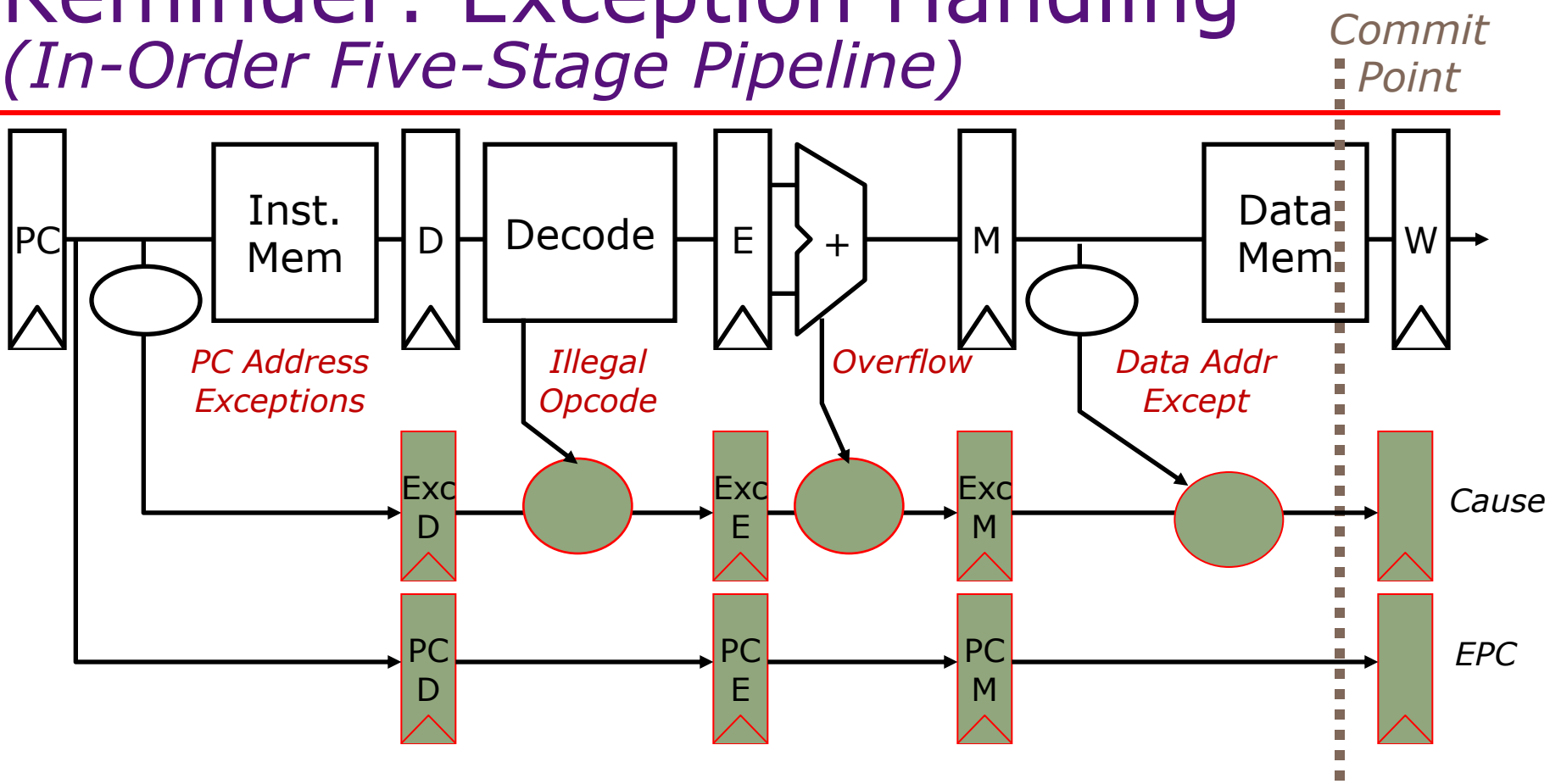

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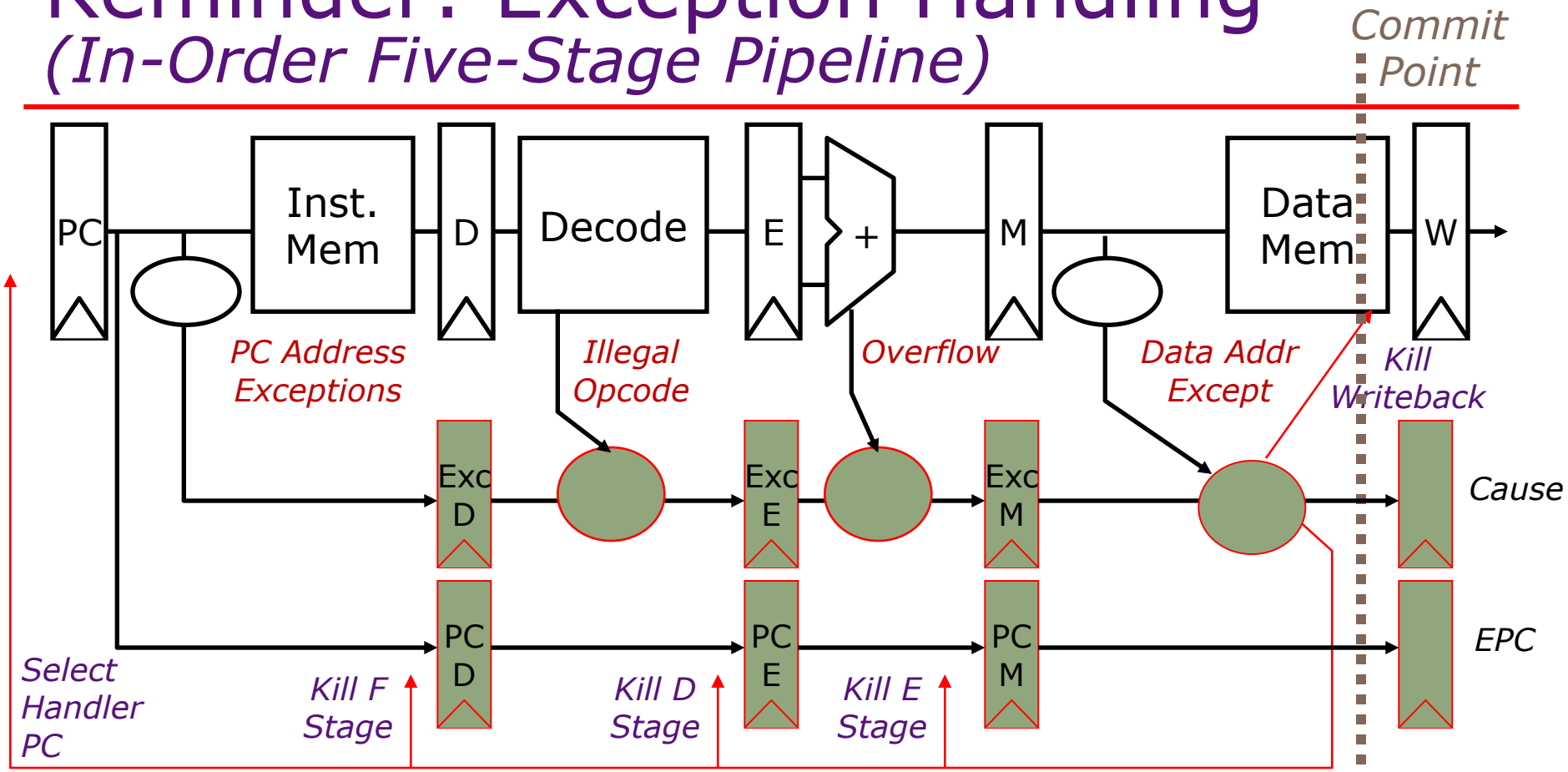

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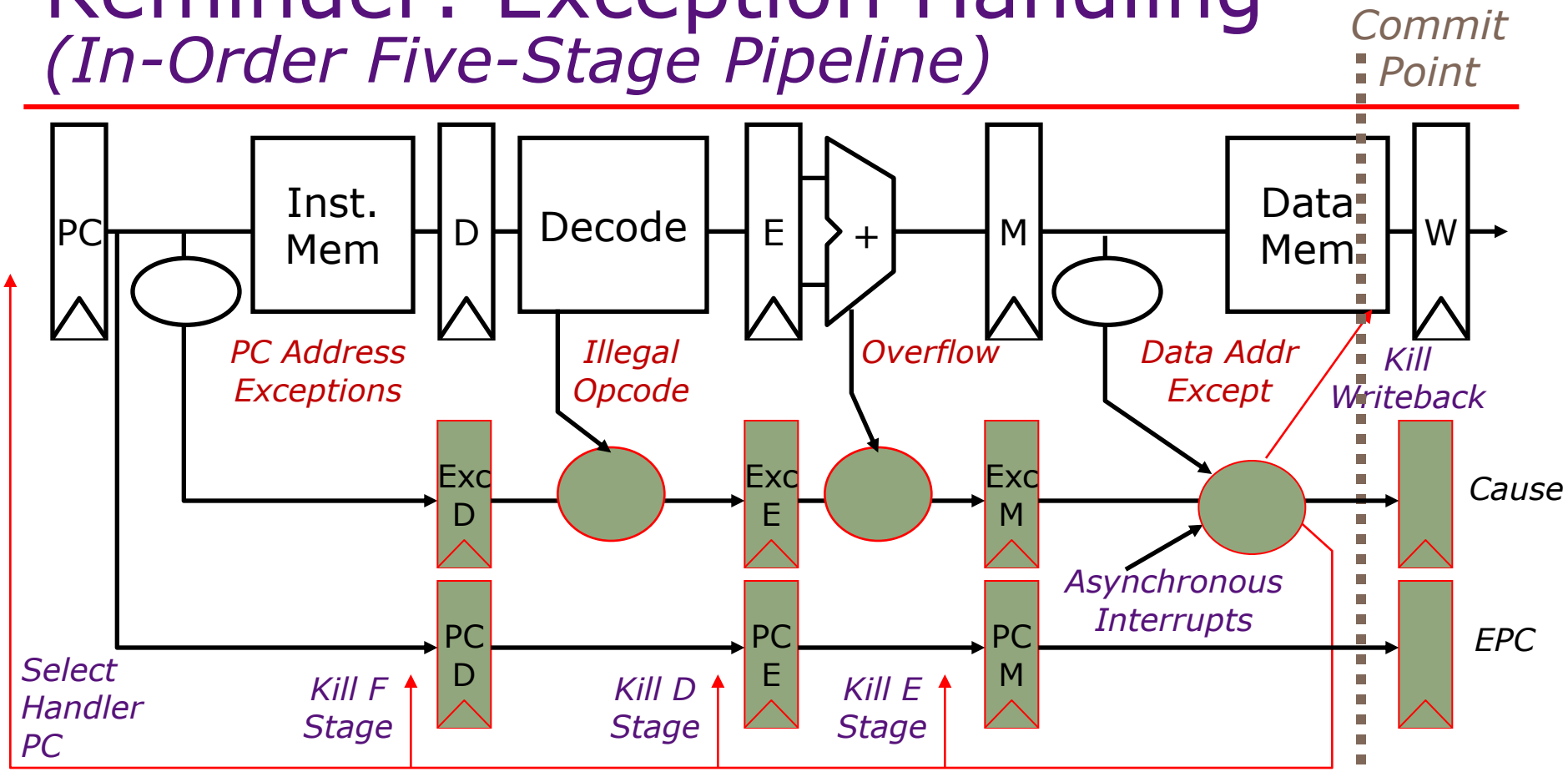

Hold exception flags in pipeline until commit point (M stage)

- If exception at commit:
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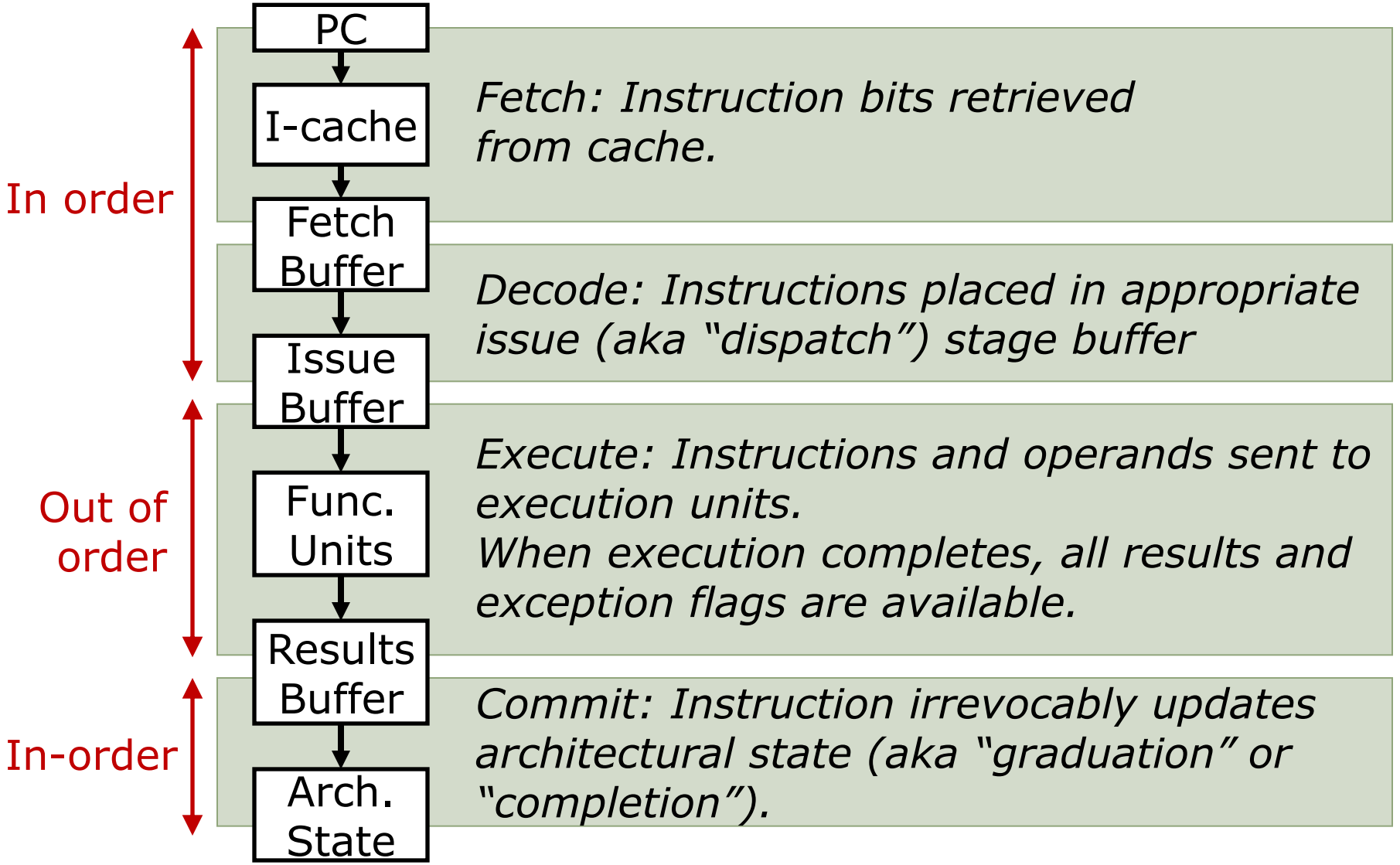
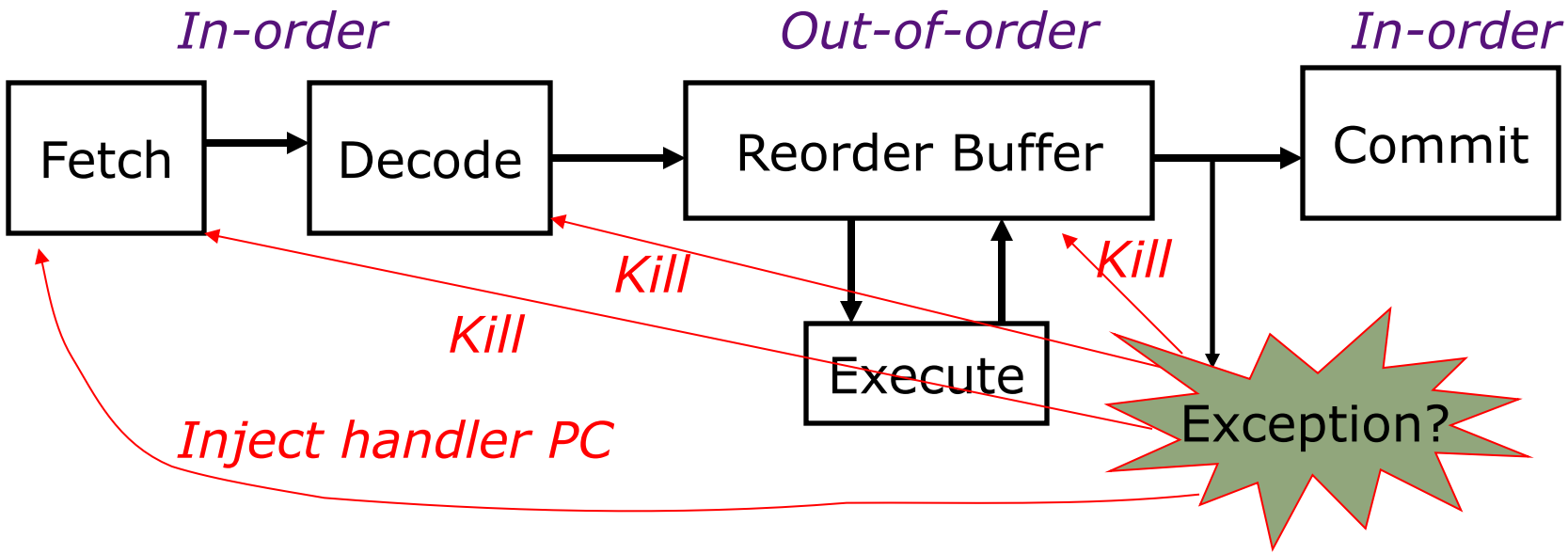
Inject external interrupts at commit point

Phases of Instruction Execution



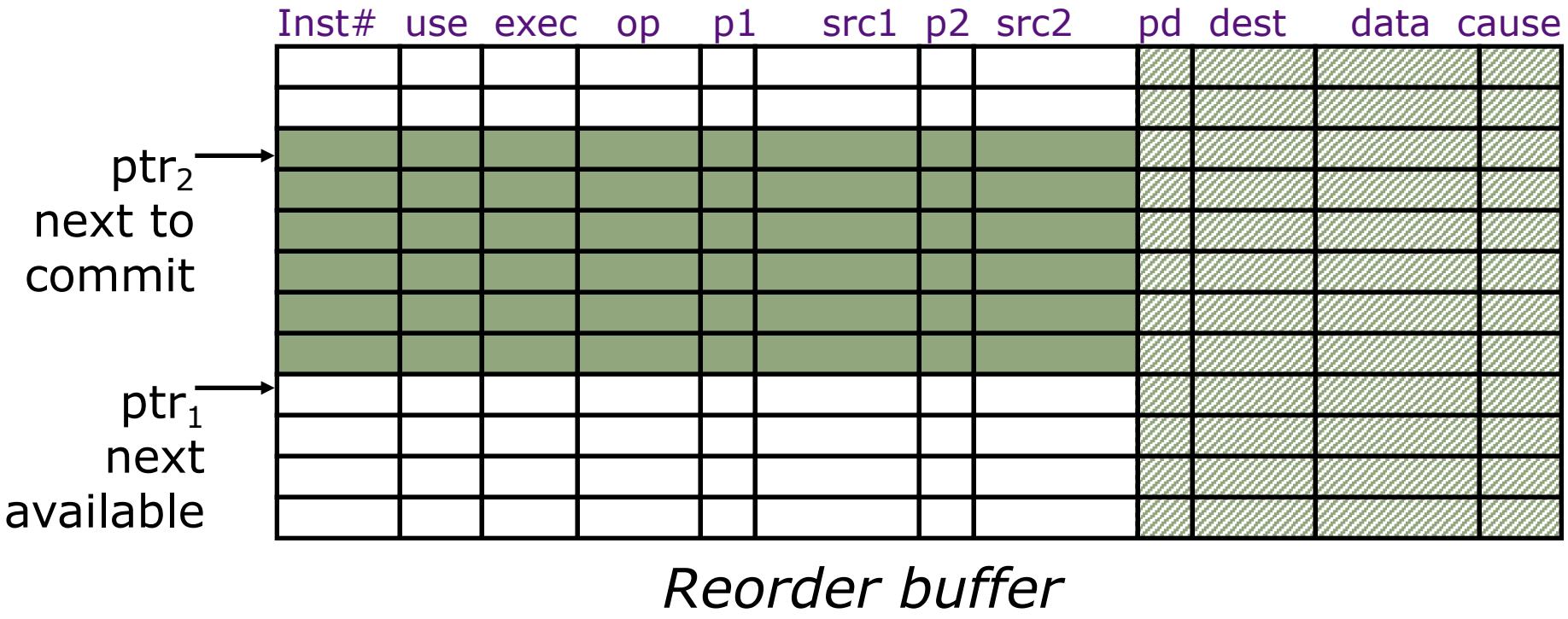
In-Order Commit for Precise Exceptions



- Instructions fetched and decoded into instruction reorder buffer in-order
- Execution is out-of-order (⇒ out-of-order completion)
- *Commit* (write-back to architectural state, i.e., regfile & memory) is in-order

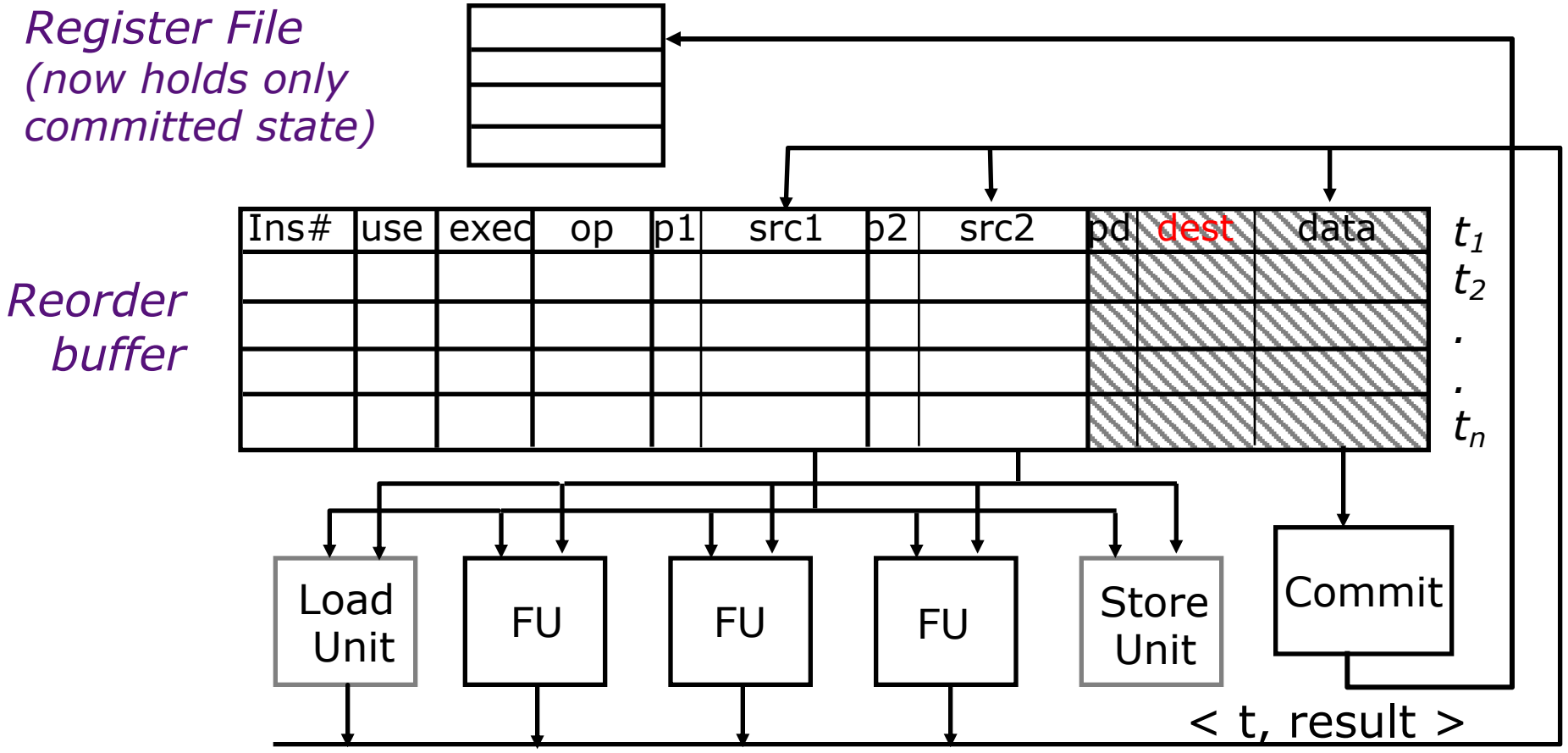
Temporary storage needed to hold results before commit (shadow registers and store buffers)

Extensions for Precise Exceptions



- add <pd, dest, data, cause> fields in the instruction template
- commit instructions to reg file and memory in program order ⇒ buffers can be maintained circularly
- on exception, clear reorder buffer by resetting $ptr_1 = ptr_2$
  (stores must wait for commit before updating memory)

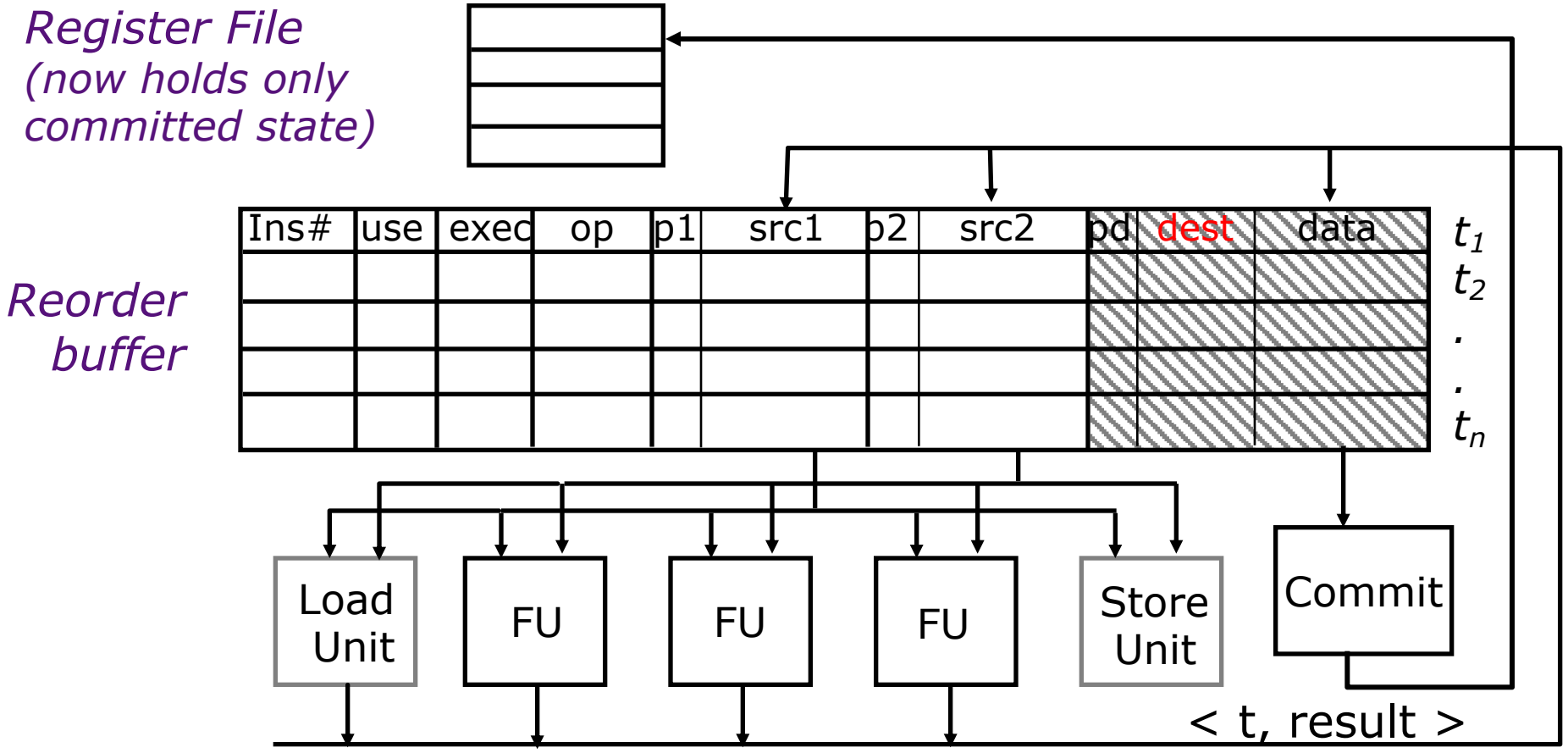
Rollback and Renaming



Register file does not contain renaming tags any more.

How does the decode stage find the tag of a source register?

Rollback and Renaming

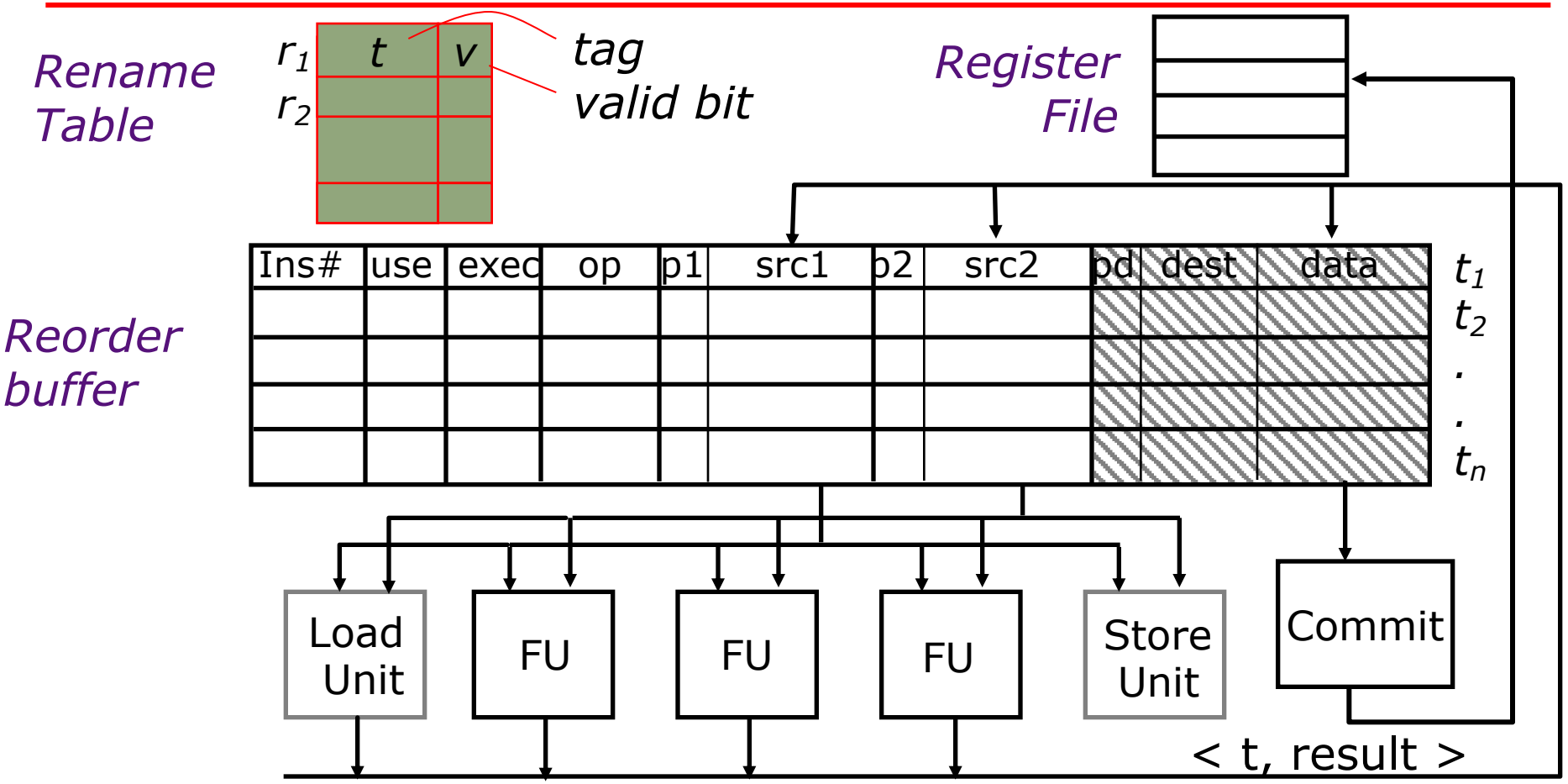


Register file does not contain renaming tags any more.

How does the decode stage find the tag of a source register?

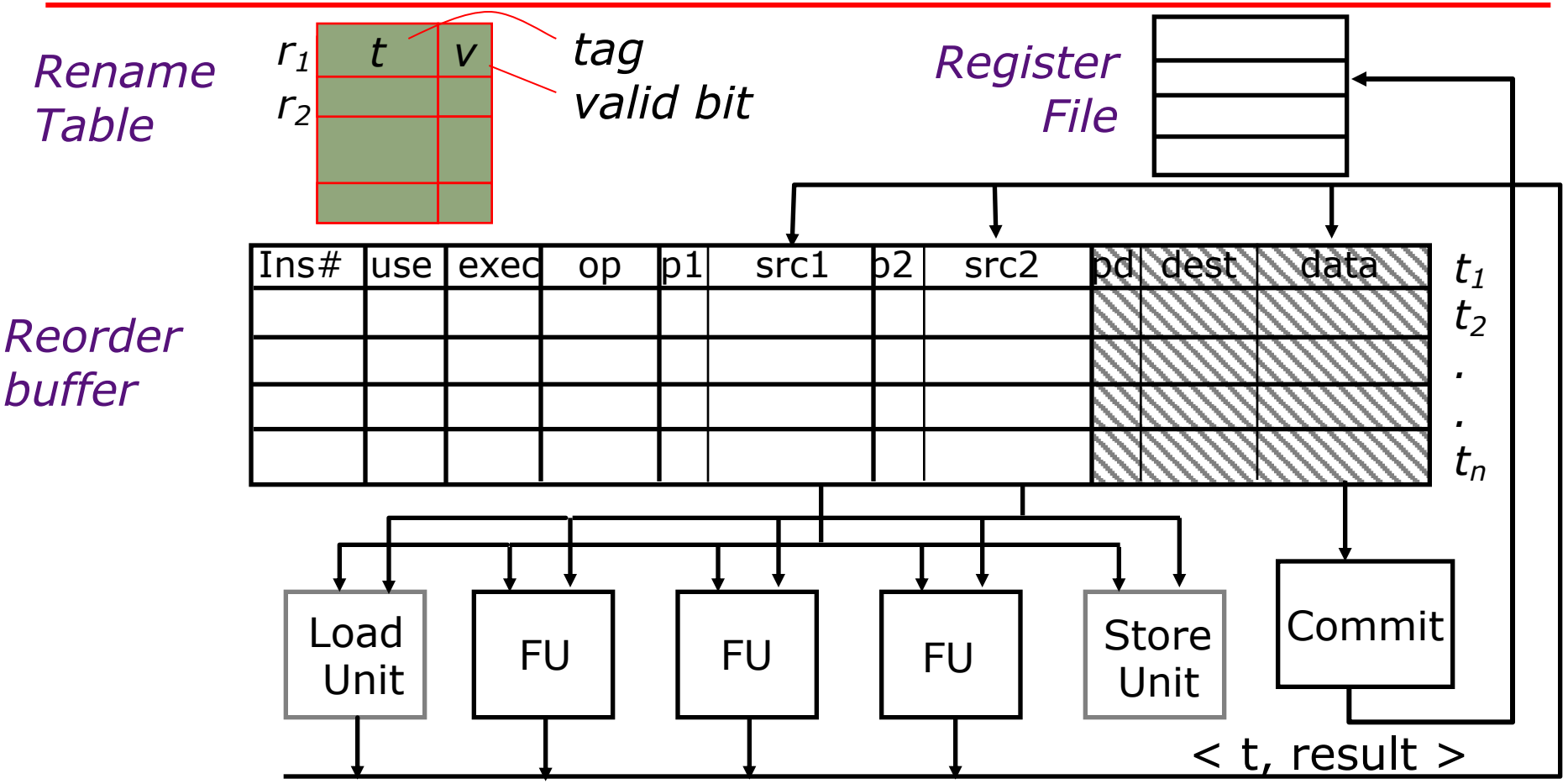
Search the "dest" field in the reorder buffer

Renaming Table



Renaming table is a cache to speed up register name lookup.
It needs to be cleared after each exception taken.
When else are valid bits cleared?

Renaming Table



Renaming table is a cache to speed up register name lookup.
It needs to be cleared after each exception taken.
When else are valid bits cleared? *Control transfers*

Physical Register Files

- Reorder buffers are space inefficient – a data value may be stored in multiple places in the reorder buffer
- Idea: Keep all data values in a physical register file
  - Tag represents the name of the data value and name of the physical register that holds it
  - Reorder buffer contains only tags

Thus, 64-bit data values may be replaced by 8-bit tags for a 256-element physical register file

More on this in later lectures …

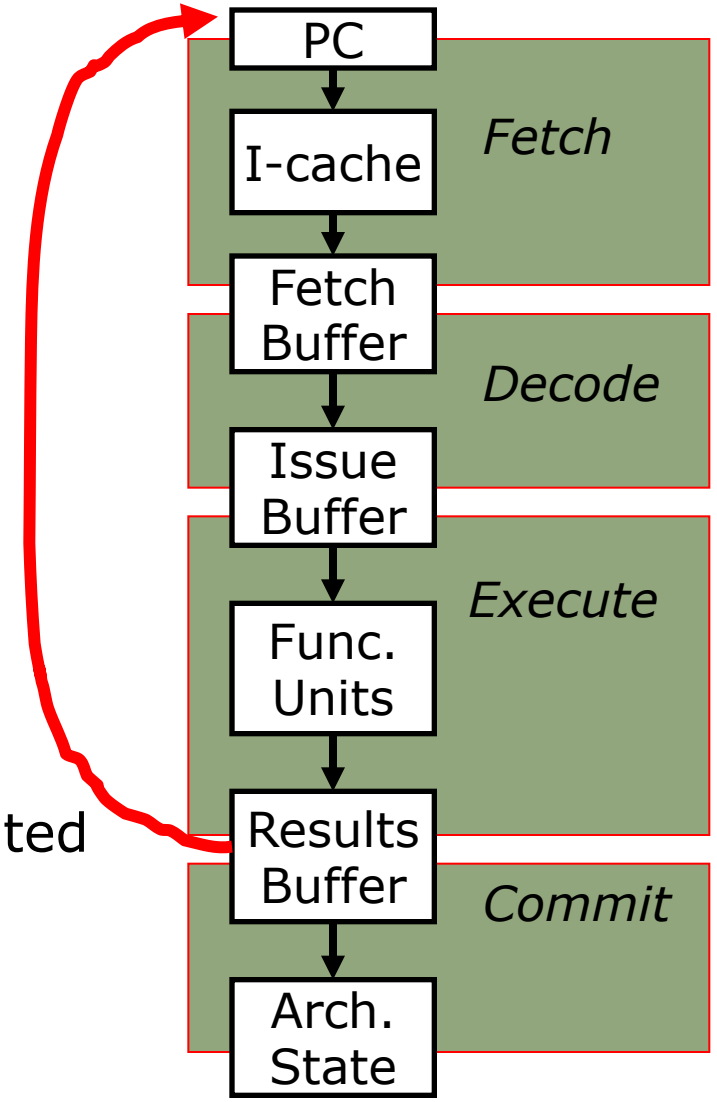
Branch Penalty

Next fetch started

How many instructions need to be killed on a misprediction?

Modern processors may have > 10 pipeline stages between nextPC calculation and branch resolution !

Branch executed



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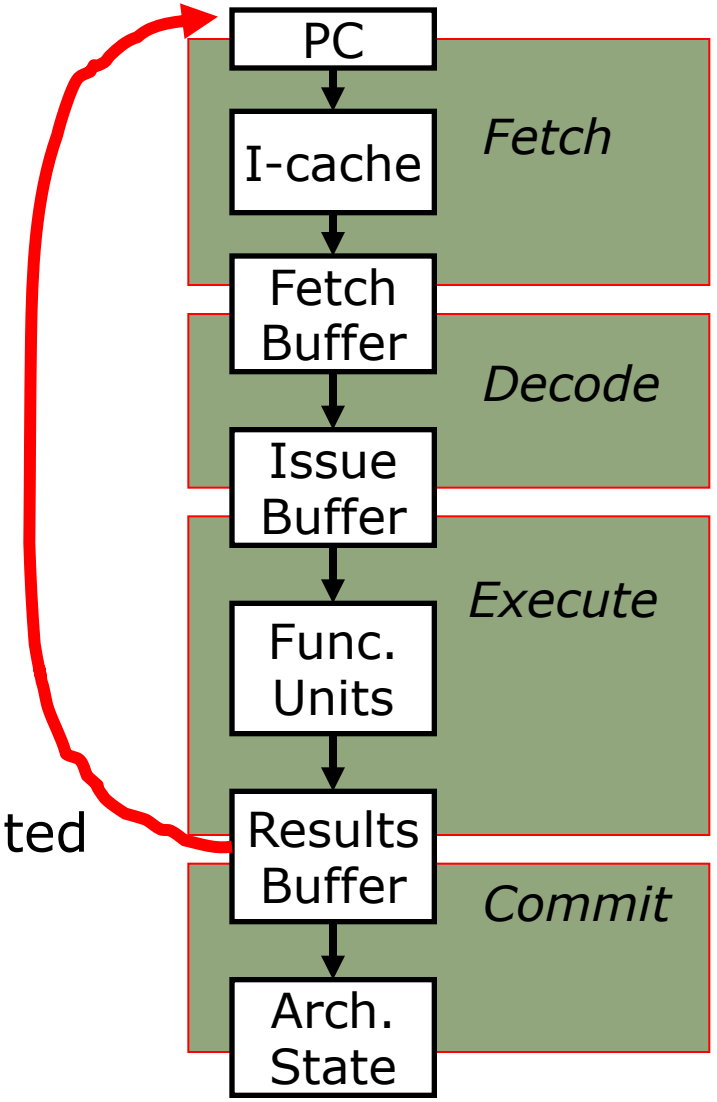

Next lecture:
Branch prediction &
Speculative execution