Homework 3

CS-GY 6133

Bo Yao, by677
Tianyu Gu, tg1553

Q1. Out-of-Order Execution Using Tomasulo's Algorithm

(a) Data-flow graph

In our graph, **f**a(n) means that register a contains value n. After the code executes, the result should be:

R[f0]=0, R[f1]=1, R[f2]=0, R[f3]=3, R[f4]=4, R[f5]=5.

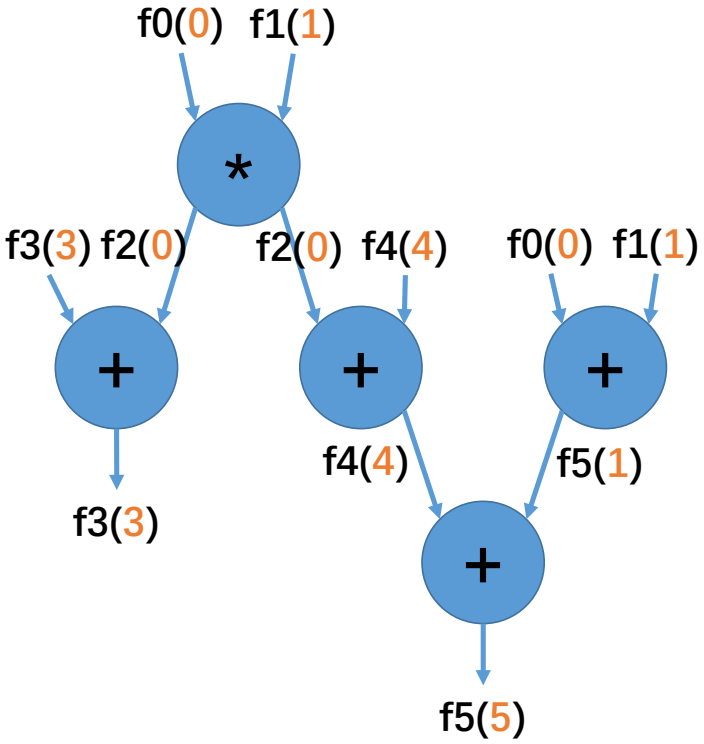
T0: **muld** *f0, f1, f2*

T1: **addd** *f0, f1, f5*

T2: **addd** *f2, f3, f3*

T3: **addd** *f2, f4, f4*

T4: **addd** *f4, f5, f5*



(b) Simulate cycle-by-cycle

In the table below, **'wE'** means waiting to execute (RAW dependency, waiting in reservation stations); **'wD'** means waiting to decode/dispatch (reservation stations is full, instruction stalling).

Cycle 0

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		2	1
f3		3	1
f4		4	1
f5		5	1

Instruction	Stage
muld *f0, f1, f2*	
addd *f0, f1, f5*	
addd *f2, f3, f3*	
addd *f2, f4, f4*	
addd *f4, f5, f5*	

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP ADD (1 cycle)

	Tag	Value	Valid	Tag	Value	Valid
a						
b						

Cycle 1

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		2	1
f3		3	1
f4		4	1
f5		5	1

Instruction	Stage
muld *f0, f1, f2*	F
addd *f0, f1, f5*	
addd *f2, f3, f3*	
addd *f2, f4, f4*	
addd *f4, f5, f5*	

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP ADD (1 cycle)

	Tag	Value	Valid	Tag	Value	Valid
a						
b						

Cycle 2

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3		3	1
f4		4	1
f5		5	1

Instruction	Stage
muld *f0, f1, f2*	D
addd *f0, f1, f5*	F
addd *f2, f3, f3*	
addd *f2, f4, f4*	
addd *f4, f5, f5*	

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP ADD (1 cycle)

	Tag	Value	Valid	Tag	Value	Valid
a						
b						

Cycle 3

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3		3	1
f4		4	1
f5	a	5	0

Instruction	Stage
muld *f0, f1, f2*	E1
addd *f0, f1, f5*	D
addd *f2, f3, f3*	F
addd *f2, f4, f4*	
addd *f4, f5, f5*	

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP ADD (1 cycle)

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	1	1
b						

Cycle 4

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3	b	3	0
f4		4	1
f5	a	5	0

Instruction	Stage
muld *f0, f1, f2*	E2
addd *f0, f1, f5*	E1
addd *f2, f3, f3*	D
addd *f2, f4, f4*	F
addd *f4, f5, f5*	

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP ADD (1 cycle)

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	1	1
b	x	~	0	~	3	1

Cycle 5

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3	b	3	0
f4		4	1
f5		1	1

Instruction	Stage
muld *f0, f1, f2*	E3
addd *f0, f1, f5*	WB
addd *f2, f3, f3*	wE
addd *f2, f4, f4*	wD
addd *f4, f5, f5*	

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP ADD (1 cycle)

	Tag	Value	Valid	Tag	Value	Valid
a	~	~~0~~	~~1~~	~	~~1~~	~~1~~
b	x	~	0	~	3	1

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3	b	3	0
f4	a	4	0
f5		1	1

Instruction	Stage
muld *f0, f1, f2*	E4
addd *f0, f1, f5*	~
addd *f2, f3, f3*	wE
addd *f2, f4, f4*	D
addd *f4, f5, f5*	F

Cycle 6

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	x	~	0	~	4	1
b	x	~	0	~	3	1

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3	b	3	0
f4	a	4	0
f5		1	1

Instruction	Stage
muld *f0, f1, f2*	WB
addd *f0, f1, f5*	~
addd *f2, f3, f3*	wE
addd *f2, f4, f4*	wE
addd *f4, f5, f5*	wD

Cycle 7

	Tag	Value	Valid	Tag	Value	Valid
x	~~~~~~					
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	4	1
b	~	0	1	~	3	1

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3	b	3	0
f4	a	4	0
f5		1	1

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	E1
addd *f2, f4, f4*	wE
addd *f4, f5, f5*	wD

Cycle 8

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	4	1
b	~	0	1	~	3	1

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4	a	4	0
f5		1	1

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	WB
addd *f2, f4, f4*	E1
addd *f4, f5, f5*	wD

Cycle 9

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	4	1
b	~~~~~~					

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5	b	1	0

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	WB
addd *f4, f5, f5*	D

Cycle 10

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~~~~~~					
b	~	4	1	~	1	1

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5	b	1	0

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	~
addd *f4, f5, f5*	E1

Cycle 11

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a						
b	~	4	1	~	1	1

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5		5	1

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	~
addd *f4, f5, f5*	WB

Cycle 12

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a						
b	~~~~~~					

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5		5	1

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	~
addd *f4, f5, f5*	~

Cycle 13

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a						
b						

FP ADD (1 cycle)

(c) Simulate cycle-by-cycle without stalling

At (b) - cycle 7 we found that FP ADD reservation station was full. The instruction had to wait until a free station was released. So we have to add one more station to FP ADD. We can also observe that FP MULT only need one reservation station at least.

Cycle 0

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		2	1
f3		3	1
f4		4	1
f5		5	1

	Tag	Value	Valid	Tag	Value	Valid
x						

FP MULT (4 cycles)

Instruction	Stage
muld f0, f1, f2	
addd f0, f1, f5	
addd f2, f3, f3	
addd f2, f4, f4	
addd f4, f5, f5	

	Tag	Value	Valid	Tag	Value	Valid
a						
b						
c						

FP ADD (1 cycle)

Cycle 1

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		2	1
f3		3	1
f4		4	1
f5		5	1

	Tag	Value	Valid	Tag	Value	Valid
x						

FP MULT (4 cycles)

Instruction	Stage
muld f0, f1, f2	F
addd f0, f1, f5	
addd f2, f3, f3	
addd f2, f4, f4	
addd f4, f5, f5	

	Tag	Value	Valid	Tag	Value	Valid
a						
b						
c						

FP ADD (1 cycle)

Cycle 2

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3		3	1
f4		4	1
f5		5	1

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1

FP MULT (4 cycles)

Instruction	Stage
muld f0, f1, f2	D
addd f0, f1, f5	F
addd f2, f3, f3	
addd f2, f4, f4	
addd f4, f5, f5	

	Tag	Value	Valid	Tag	Value	Valid
a						
b						
c						

FP ADD (1 cycle)

Cycle 3

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3		3	1
f4		4	1
f5	a	5	0

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1

FP MULT (4 cycles)

Instruction	Stage
muld f0, f1, f2	E1
addd f0, f1, f5	D
addd f2, f3, f3	F
addd f2, f4, f4	
addd f4, f5, f5	

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	1	1
b						
c						

FP ADD (1 cycle)

Cycle 4

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3	b	3	0
f4		4	1
f5	a	5	0

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1

FP MULT (4 cycles)

Instruction	Stage
muld f0, f1, f2	E2
addd f0, f1, f5	E1
addd f2, f3, f3	D
addd f2, f4, f4	F
addd f4, f5, f5	

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	1	1
b	x	~	0	~	3	1
c						

FP ADD (1 cycle)

Cycle 5

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3	b	3	0
f4	c	4	0
f5		1	1

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1

FP MULT (4 cycles)

Instruction	Stage
muld f0, f1, f2	E3
addd f0, f1, f5	WB
addd f2, f3, f3	wE
addd f2, f4, f4	D
addd f4, f5, f5	F

	Tag	Value	Valid	Tag	Value	Valid
a	~~~~	~~0~~	~~1~~	~~~~	~~1~~	~~1~~
b	x	~	0	~	3	1
c	x	~	0	~	4	1

FP ADD (1 cycle)

Cycle 6

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3	b	3	0
f4	c	4	0
f5	a	1	0

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1

FP MULT (4 cycles)

Instruction	Stage
muld *f0, f1, f2*	E4
addd *f0, f1, f5*	~
addd *f2, f3, f3*	wE
addd *f2, f4, f4*	wE
addd *f4, f5, f5*	D

	Tag	Value	Valid	Tag	Value	Valid
a	c	~	0	~	1	1
b	x	~	0	~	3	1
c	x	~	0	~	4	1

FP ADD (1 cycle)

Cycle 7

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3	b	3	0
f4	c	4	0
f5	a	1	0

	Tag	Value	Valid	Tag	Value	Valid
x	~	~~0~~	~~1~~	~	~~1~~	~~1~~

FP MULT (4 cycles)

Instruction	Stage
muld *f0, f1, f2*	WB
addd *f0, f1, f5*	~
addd *f2, f3, f3*	wE
addd *f2, f4, f4*	wE
addd *f4, f5, f5*	wE

	Tag	Value	Valid	Tag	Value	Valid
a	c	~	0	~	1	1
b	~	0	1	~	3	1
c	~	0	1	~	4	1

FP ADD (1 cycle)

Cycle 8

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3	b	3	0
f4	c	4	0
f5	a	1	0

	Tag	Value	Valid	Tag	Value	Valid
x						

FP MULT (4 cycles)

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	E1
addd *f2, f4, f4*	wE
addd *f4, f5, f5*	wE

	Tag	Value	Valid	Tag	Value	Valid
a	c	~	0	~	1	1
b	~	0	1	~	3	1
c	~	0	1	~	4	1

FP ADD (1 cycle)

Cycle 9

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4	c	4	0
f5	a	1	0

	Tag	Value	Valid	Tag	Value	Valid
x						

FP MULT (4 cycles)

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	WB
addd *f2, f4, f4*	E1
addd *f4, f5, f5*	wE

	Tag	Value	Valid	Tag	Value	Valid
a	c	~	0	~	1	1
b	~	~~0~~	~~1~~	~	~~3~~	~~1~~
c	~	0	1	~	4	1

FP ADD (1 cycle)

Cycle 10

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5	a	1	0

	Tag	Value	Valid	Tag	Value	Valid
x						

FP MULT (4 cycles)

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	WB
addd *f4, f5, f5*	wE

	Tag	Value	Valid	Tag	Value	Valid
a	~	4	1	~	1	1
b						
c	~	~~0~~	~~1~~	~	~~4~~	~~1~~

FP ADD (1 cycle)

Cycle 11

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5	a	1	0

	Tag	Value	Valid	Tag	Value	Valid
x						

FP MULT (4 cycles)

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	~
addd *f4, f5, f5*	E1

	Tag	Value	Valid	Tag	Value	Valid
a	~	4	1	~	1	1
b						
c						

FP ADD (1 cycle)

Cycle 12

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5		5	1

	Tag	Value	Valid	Tag	Value	Valid
x						

FP MULT (4 cycles)

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	~
addd *f4, f5, f5*	WB

	Tag	Value	Valid	Tag	Value	Valid
a	~	~~4~~	~~1~~	~	~~1~~	~~1~~
b						
c						

FP ADD (1 cycle)

Cycle 13

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5		5	1

	Tag	Value	Valid	Tag	Value	Valid
x						

FP MULT (4 cycles)

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	~
addd *f4, f5, f5*	~

	Tag	Value	Valid	Tag	Value	Valid
a						
b						
c						

FP ADD (1 cycle)

(d) Simulate cycle-by-cycle with parallel FP adders

After simulation, we found that parallel process was needed at cycle 8. Two instructions could be dispatched at the same time. Thus, M = 2.

Cycle 0

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		2	1
f3		3	1
f4		4	1
f5		5	1

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a						
b						
c						

FP ADD (1 cycle)

Instruction	Stage
muld f0, f1, f2	
addd f0, f1, f5	
addd f2, f3, f3	
addd f2, f4, f4	
addd f4, f5, f5	

Cycle 1

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		2	1
f3		3	1
f4		4	1
f5		5	1

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a						
b						
c						

FP ADD (1 cycle)

Instruction	Stage
muld f0, f1, f2	F
addd f0, f1, f5	
addd f2, f3, f3	
addd f2, f4, f4	
addd f4, f5, f5	

Cycle 2

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3		3	1
f4		4	1
f5		5	1

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a						
b						
c						

FP ADD (1 cycle)

Instruction	Stage
muld f0, f1, f2	D
addd f0, f1, f5	F
addd f2, f3, f3	
addd f2, f4, f4	
addd f4, f5, f5	

Cycle 3

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3		3	1
f4		4	1
f5	a	5	0

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	1	1
b						
c						

FP ADD (1 cycle)

Instruction	Stage
muld f0, f1, f2	E1
addd f0, f1, f5	D
addd f2, f3, f3	F
addd f2, f4, f4	
addd f4, f5, f5	

Cycle 4

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3	b	3	0
f4		4	1
f5	a	5	0

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	1	1
b	x	~	0	~	3	1
c						

FP ADD (1 cycle)

Instruction	Stage
muld f0, f1, f2	E2
addd f0, f1, f5	E1
addd f2, f3, f3	D
addd f2, f4, f4	F
addd f4, f5, f5	

Cycle 5

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3	b	3	0
f4	c	4	0
f5		1	1

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~	0	1	~	1	1
b	x	~	0	~	3	1
c	x	~	0	~	4	1

FP ADD (1 cycle)

Instruction	Stage
muld f0, f1, f2	E3
addd f0, f1, f5	WB
addd f2, f3, f3	wE
addd f2, f4, f4	D
addd f4, f5, f5	F

Cycle 6

	Tag	Value	Valid
f0		0	1
f1		1	1
f2	x	2	0
f3	b	3	0
f4	c	4	0
f5	a	1	0

	Tag	Value	Valid	Tag	Value	Valid
x	~	0	1	~	1	1
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	c	~	0	~	1	1
b	x	~	0	~	3	1
c	x	~	0	~	4	1

FP ADD (1 cycle)

Instruction	Stage
muld f0, f1, f2	E4
addd f0, f1, f5	~
addd f2, f3, f3	wE
addd f2, f4, f4	wE
addd f4, f5, f5	D

Cycle 7

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3	b	3	0
f4	c	4	0
f5	a	1	0

	Tag	Value	Valid	Tag	Value	Valid
x	~~~~	~~0~~	~~1~~	~~~~	~~1~~	~~1~~
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	c	~	0	~	1	1
b	~	0	1	~	3	1
c	~	0	1	~	4	1

FP ADD (1 cycle)

Instruction	Stage
muld f0, f1, f2	WB
addd f0, f1, f5	~
addd f2, f3, f3	wE
addd f2, f4, f4	wE
addd f4, f5, f5	wE

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3	b	3	0
f4	c	4	0
f5	a	1	0

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	E1
addd *f2, f4, f4*	E1
addd *f4, f5, f5*	wE

Cycle 8

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	c	~	0	~	1	1
b	~	0	1	~	3	1
c	~	0	1	~	4	1

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5	a	1	0

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	WB
addd *f2, f4, f4*	WB
addd *f4, f5, f5*	wE

Cycle 9

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~	4	1	~	1	1
b	~~	~~0~~	~~1~~	~~~~	~~3~~	~~1~~
c	~~	~~0~~	~~1~~	~~~~	~~4~~	~~1~~

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5		5	1

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	~
addd *f4, f5, f5*	E1

Cycle 10

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~	4	1	~	1	1
b						
c						

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5		5	1

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	~
addd *f4, f5, f5*	WB

Cycle 11

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a	~~	~~4~~	~~1~~	~~~~	~~1~~	~~1~~
b						
c						

FP ADD (1 cycle)

	Tag	Value	Valid
f0		0	1
f1		1	1
f2		0	1
f3		3	1
f4		4	1
f5		5	1

Instruction	Stage
muld *f0, f1, f2*	~
addd *f0, f1, f5*	~
addd *f2, f3, f3*	~
addd *f2, f4, f4*	~
addd *f4, f5, f5*	~

Cycle 12

	Tag	Value	Valid	Tag	Value	Valid
x						
y						

FP MULT (4 cycles)

	Tag	Value	Valid	Tag	Value	Valid
a						
b						
c						

FP ADD (1 cycle)

Q3. Branch Prediction

(a) last-value prediction

The first 16 loops is shown below. We wrote a simple program to generate this table and calculate the mis-prediction rate. **The mis-prediction rate for branch B1 is always 0%. B2 converges to 50%. B3 converges to 100%.**
What's more from the table we could also observe that after i=3, the prediction and the actual behavior became periodic with period of 4. So we could easy get that mis-prediction rate B1 = 50%, B2 = 100%.

i	B1	B2	B3	Pre	N/T	Mis Rate
0	SN			N	N	0.00%
0		SN		N	N	0.00%
0			SN	N	N	0.00%
1	SN			N	N	0.00%
1		SN		N	T	0.00%
1			SN	N	T	0.00%
2	SN			N	N	0.00%
2		ST		T	T	50.00%
2			ST	T	N	50.00%
3	SN			N	N	0.00%
3		ST		T	T	33.33%
3			SN	N	T	66.67%
4	SN			N	N	0.00%
4		ST		T	N	25.00%
4			ST	T	N	75.00%
5	SN			N	N	0.00%
5		SN		N	T	40.00%
5			SN	N	T	80.00%
6	SN			N	N	0.00%
6		ST		T	T	50.00%
6			ST	T	N	83.33%
7	SN			N	N	0.00%
7		ST		T	T	42.86%
7			SN	N	T	85.71%
8	SN			N	N	0.00%
8		ST		T	N	37.50%
8			ST	T	N	87.50%
9	SN			N	N	0.00%
9		SN		N	T	44.44%
9			SN	N	T	88.89%
10	SN			N	N	0.00%
10		ST		T	T	50.00%
10			ST	T	N	90.00%
11	SN			N	N	0.00%
11		ST		T	T	45.45%
11			SN	N	T	90.91%
12	SN			N	N	0.00%
12		ST		T	N	41.67%
12			ST	T	N	91.67%
13	SN			N	N	0.00%
13		SN		N	T	46.15%
13			SN	N	T	92.31%
14	SN			N	N	0.00%
14		ST		T	T	50.00%
14			ST	T	N	92.86%
15	SN			N	N	0.00%
15		ST		T	T	46.67%
15			SN	N	T	93.33%

i	B1	B2	B3	Pre	N/T	Mis Rate
0	SN			N	N	0.00%
1	SN			N	N	0.00%
2	SN			N	N	0.00%
3	SN			N	N	0.00%
4	SN			N	N	0.00%
5	SN			N	N	0.00%
6	SN			N	N	0.00%
7	SN			N	N	0.00%
8	SN			N	N	0.00%
9	SN			N	N	0.00%
10	SN			N	N	0.00%
11	SN			N	N	0.00%
12	SN			N	N	0.00%
13	SN			N	N	0.00%
14	SN			N	N	0.00%
15	SN			N	N	0.00%

i	B1	B2	B3	Pre	N/T	Mis Rate
0		SN		N	N	0.00%
1		SN		N	T	0.00%
2		ST		T	T	50.00%
3		ST		T	T	33.33%
4		ST		T	N	25.00%
5		SN		N	T	40.00%
6		ST		T	T	50.00%
7		ST		T	T	42.86%
8		ST		T	N	37.50%
9		SN		N	T	44.44%
10		ST		T	T	50.00%
11		ST		T	T	45.45%
12		ST		T	N	41.67%
13		SN		N	T	46.15%
14		ST		T	T	50.00%
15		ST		T	T	46.67%

i	B1	B2	B3	Pre	N/T	Mis Rate
0			SN	N	N	0.00%
1			SN	N	T	0.00%
2			ST	T	N	50.00%
3			SN	N	T	66.67%
4			ST	T	N	75.00%
5			SN	N	T	80.00%
6			ST	T	N	83.33%
7			SN	N	T	85.71%
8			ST	T	N	87.50%
9			SN	N	T	88.89%
10			ST	T	N	90.00%
11			SN	N	T	90.91%
12			ST	T	N	91.67%
13			SN	N	T	92.31%
14			ST	T	N	92.86%
15			SN	N	T	93.33%

(b) separate 2-bit saturating counter prediction

The first 16 loops is shown below. We wrote a simple program to generate this table and calculate the mis-prediction rate. **The mis-prediction rate for branch B1 is always 0%. B2 converges to 25%. B3 converges to 50%.**
What's more from the table we could also observe that after i=3, the prediction and the actual behavior became periodic with period of 4. So we could easy get that mis-prediction rate B1 = 25%, B2 = 50%.

i	B1	B2	B3	Pre	N/T	Mis Rate
0	SN			N	N	0.00%
0		SN		N	N	0.00%
0			SN	N	N	0.00%
1	SN			N	N	0.00%
1		SN		N	T	0.00%
1			SN	N	T	0.00%
2	SN			N	N	0.00%
2		WN		N	T	50.00%
2			WN	N	N	50.00%
3	SN			N	N	0.00%
3		ST		T	T	66.67%
3			SN	N	T	33.33%
4	SN			N	N	0.00%
4		ST		T	N	50.00%
4			WN	N	N	50.00%
5	SN			N	N	0.00%
5		WT		T	T	60.00%
5			SN	N	T	40.00%
6	SN			N	N	0.00%
6		ST		T	T	50.00%
6			WN	N	N	50.00%
7	SN			N	N	0.00%
7		ST		T	T	42.86%
7			SN	N	T	42.86%
8	SN			N	N	0.00%
8		ST		T	N	37.50%
8			WN	N	N	50.00%
9	SN			N	N	0.00%
9		WT		T	T	44.44%
9			SN	N	T	44.44%
10	SN			N	N	0.00%
10		ST		T	T	40.00%
10			WN	N	N	50.00%
11	SN			N	N	0.00%
11		ST		T	T	36.36%
11			SN	N	T	45.45%
12	SN			N	N	0.00%
12		ST		T	N	33.33%
12			WN	N	N	50.00%
13	SN			N	N	0.00%
13		WT		T	T	38.46%
13			SN	N	T	46.15%
14	SN			N	N	0.00%
14		ST		T	T	35.71%
14			WN	N	N	50.00%
15	SN			N	N	0.00%
15		ST		T	T	33.33%
15			SN	N	T	46.67%

i	B1	B2	B3	Pre	N/T	Mis Rate
0	SN			N	N	0.00%
1	SN			N	N	0.00%
2	SN			N	N	0.00%
3	SN			N	N	0.00%
4	SN			N	N	0.00%
5	SN			N	N	0.00%
6	SN			N	N	0.00%
7	SN			N	N	0.00%
8	SN			N	N	0.00%
9	SN			N	N	0.00%
10	SN			N	N	0.00%
11	SN			N	N	0.00%
12	SN			N	N	0.00%
13	SN			N	N	0.00%
14	SN			N	N	0.00%
15	SN			N	N	0.00%

i	B1	B2	B3	Pre	N/T	Mis Rate
0		SN		N	N	0.00%
1		SN		N	T	0.00%
2		WN		N	T	50.00%
3		ST		T	T	66.67%
4		ST		T	N	50.00%
5		WT		T	T	60.00%
6		ST		T	T	50.00%
7		ST		T	T	42.86%
8		ST		T	N	37.50%
9		WT		T	T	44.44%
10		ST		T	T	40.00%
11		ST		T	T	36.36%
12		ST		T	N	33.33%
13		WT		T	T	38.46%
14		ST		T	T	35.71%
15		ST		T	T	33.33%

i	B1	B2	B3	Pre	N/T	Mis Rate
0			SN	N	N	0.00%
1			SN	N	T	0.00%
2			WN	N	N	50.00%
3			SN	N	T	33.33%
4			WN	N	N	50.00%
5			SN	N	T	40.00%
6			WN	N	N	50.00%
7			SN	N	T	42.86%
8			WN	N	N	50.00%
9			SN	N	T	44.44%
10			WN	N	N	50.00%
11			SN	N	T	45.45%
12			WN	N	N	50.00%
13			SN	N	T	46.15%
14			WN	N	N	50.00%
15			SN	N	T	46.67%

(c) 2-level correlating prediction

The first 16 loops is shown below. We wrote a simple program to generate this table and calculate the mis-prediction rate. **The mis-prediction rate for branch B1 is always 0%. B2 converges to 25%. B3 converges to 25%.**
What's more from the table we could also observe that after i=7, the prediction and the actual behavior became periodic with period of 4. So we could easy get that mis-prediction rate B1 = B2 = 25%.

		B1				B2				B3				Pre	N/T	Miss Rate
i	History	N,N	N,T	T,N	T,T	N,N	N,T	T,N	T,T	N,N	N,T	T,N	T,T	~	~	~
0	N,N	SN	SN	SN	SN									N	N	0.00%
0	N,N					SN	SN	SN	SN					N	N	0.00%
0	N,N									SN	SN	SN	SN	N	N	0.00%
1	N,N	SN	SN	SN	SN									N	N	0.00%
1	N,N					SN	SN	SN	SN					N	T	0.00%
1	N,T									SN	SN	SN	SN	N	T	0.00%
2	T,T	SN	SN	SN	SN									N	N	0.00%
2	T,N					WN	SN	SN	SN					N	T	50.00%
2	N,T									SN	WN	SN	SN	N	N	50.00%
3	T,N	SN	SN	SN	SN									N	N	0.00%
3	N,N					WN	SN	WN	SN					N	T	66.67%
3	N,T									SN	SN	SN	SN	N	T	33.33%
4	T,T	SN	SN	SN	SN									N	N	0.00%
4	T,N					ST	SN	WN	SN					N	N	75.00%
4	N,N									SN	WN	SN	SN	N	N	50.00%
5	N,N	SN	SN	SN	SN									N	N	0.00%
5	N,N					ST	SN	SN	SN					T	T	60.00%
5	N,T									SN	WN	SN	SN	N	T	40.00%
6	T,T	SN	SN	SN	SN									N	N	0.00%
6	T,N					ST	SN	SN	SN					N	T	50.00%
6	N,T									SN	ST	SN	SN	T	N	50.00%
7	T,N	SN	SN	SN	SN									N	N	0.00%
7	N,N					ST	SN	WN	SN					T	T	57.14%
7	N,T									SN	WT	SN	SN	T	T	57.14%
8	T,T	SN	SN	SN	SN									N	N	0.00%
8	T,N					ST	SN	WN	SN					N	N	50.00%
8	N,N									SN	ST	SN	SN	N	N	50.00%
9	N,N	SN	SN	SN	SN									N	N	0.00%
9	N,N					ST	SN	SN	SN					T	T	44.44%
9	N,T									SN	ST	SN	SN	T	T	44.44%
10	T,T	SN	SN	SN	SN									N	N	0.00%
10	T,N					ST	SN	SN	SN					N	T	40.00%
10	N,T									SN	ST	SN	SN	T	N	40.00%
11	T,N	SN	SN	SN	SN									N	N	0.00%
11	N,N					ST	SN	WN	SN					T	T	45.45%
11	N,T									SN	WT	SN	SN	T	T	45.45%
12	T,T	SN	SN	SN	SN									N	N	0.00%
12	T,N					ST	SN	WN	SN					N	N	41.67%
12	N,N									SN	ST	SN	SN	N	N	41.67%
13	N,N	SN	SN	SN	SN									N	N	0.00%
13	N,N					ST	SN	SN	SN					T	T	38.46%
13	N,T									SN	ST	SN	SN	T	T	38.46%
14	T,T	SN	SN	SN	SN									N	N	0.00%
14	T,N					ST	SN	SN	SN					N	T	35.71%
14	N,T									SN	ST	SN	SN	T	N	35.71%
15	T,N	SN	SN	SN	SN									N	N	0.00%
15	N,N					ST	SN	WN	SN					T	T	40.00%
15	N,T									SN	WT	SN	SN	T	T	40.00%

		B1				B2				B3				Pre	N/T	Miss Rate
i	History	N,N	N,T	T,N	T,T	N,N	N,T	T,N	T,T	N,N	N,T	T,N	T,T	~	~	~
0	N,N	SN	SN	SN	SN									N	N	0.00%
1	N,N	SN	SN	SN	SN									N	N	0.00%
2	T,T	SN	SN	SN	SN									N	N	0.00%
3	T,N	SN	SN	SN	SN									N	N	0.00%
4	T,T	SN	SN	SN	SN									N	N	0.00%
5	N,N	SN	SN	SN	SN									N	N	0.00%
6	T,T	SN	SN	SN	SN									N	N	0.00%
7	T,N	SN	SN	SN	SN									N	N	0.00%
8	T,T	SN	SN	SN	SN									N	N	0.00%
9	N,N	SN	SN	SN	SN									N	N	0.00%
10	T,T	SN	SN	SN	SN									N	N	0.00%
11	T,N	SN	SN	SN	SN									N	N	0.00%
12	T,T	SN	SN	SN	SN									N	N	0.00%
13	N,N	SN	SN	SN	SN									N	N	0.00%
14	T,T	SN	SN	SN	SN									N	N	0.00%
15	T,N	SN	SN	SN	SN									N	N	0.00%

		B1				B2				B3				Pre	N/T	Miss Rate
i	History	N,N	N,T	T,N	T,T	N,N	N,T	T,N	T,T	N,N	N,T	T,N	T,T	~	~	~
0	N,N					SN	SN	SN	SN					N	N	0.00%
1	N,N					SN	SN	SN	SN					N	T	0.00%
2	T,N					WN	SN	SN	SN					N	T	50.00%
3	N,N					WN	SN	WN	SN					N	T	66.67%
4	T,N					ST	SN	WN	SN					N	N	75.00%
5	N,N					ST	SN	SN	SN					T	T	60.00%
6	T,N					ST	SN	SN	SN					N	T	50.00%
7	N,N					ST	SN	WN	SN					T	T	57.14%
8	T,N					ST	SN	WN	SN					N	N	50.00%
9	N,N					ST	SN	SN	SN					T	T	44.44%
10	T,N					ST	SN	SN	SN					N	T	40.00%
11	N,N					ST	SN	WN	SN					T	T	45.45%
12	T,N					ST	SN	WN	SN					N	N	41.67%
13	N,N					ST	SN	SN	SN					T	T	38.46%
14	T,N					ST	SN	SN	SN					N	T	35.71%
15	N,N					ST	SN	WN	SN					T	T	40.00%

		B1				B2				B3				Pre	N/T	Miss Rate
i	History	N,N	N,T	T,N	T,T	N,N	N,T	T,N	T,T	N,N	N,T	T,N	T,T	~	~	~
0	N,N									SN	SN	SN	SN	N	N	0.00%
1	N,T									SN	SN	SN	SN	N	T	0.00%
2	N,T									SN	WN	SN	SN	N	N	50.00%
3	N,T									SN	SN	SN	SN	N	T	33.33%
4	N,N									SN	WN	SN	SN	N	N	50.00%
5	N,T									SN	WN	SN	SN	N	T	40.00%
6	N,T									SN	ST	SN	SN	T	N	50.00%
7	N,T									SN	WT	SN	SN	T	T	57.14%
8	N,N									SN	ST	SN	SN	N	N	50.00%
9	N,T									SN	ST	SN	SN	T	T	44.44%
10	N,T									SN	ST	SN	SN	T	N	40.00%
11	N,T									SN	WT	SN	SN	T	T	45.45%
12	N,N									SN	ST	SN	SN	N	N	41.67%
13	N,T									SN	ST	SN	SN	T	T	38.46%
14	N,T									SN	ST	SN	SN	T	N	35.71%
15	N,T									SN	WT	SN	SN	T	T	40.00%