

Page replacement algorithms

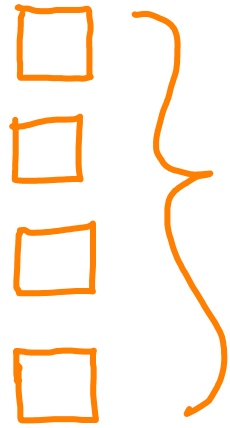
loic.guegan@uit.no

Optimal

Optimal

VP:

1 2 3 4 1 2 5 1 2 3 4 5



4 page frames



5 ≠ Virtual Pages

Optimal

VP% ↓ 1 2 3 4 1 2 5 1 2 3 4 5
1

Optimal

VP % 1 2 3 4 1 2 5 1 2 3 4 5

 ↓

 1 1

 2

Optimal

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1								
		2	2	2								
			3	3								
				4								

Optimal

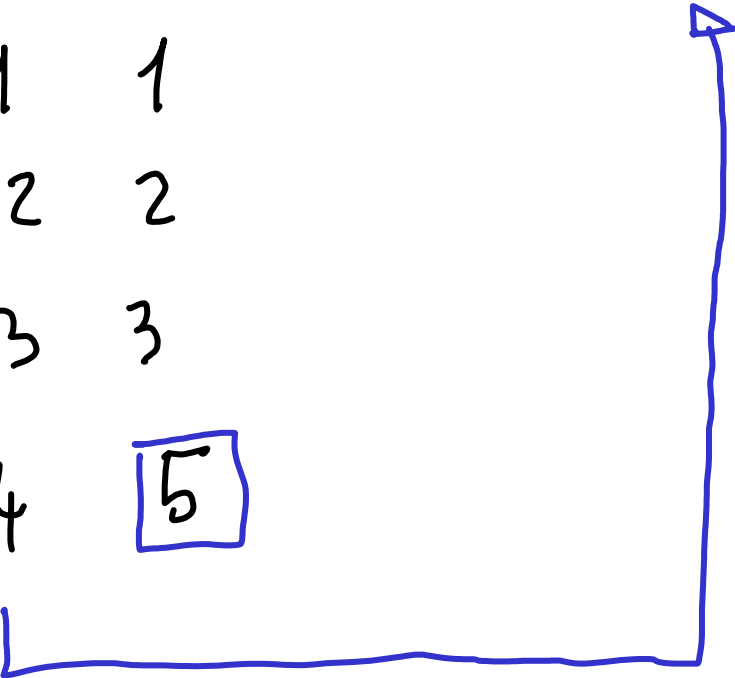
<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1						
		2	2	2	2	2						
			3	3	3	3						
				4	4	4						

Optimal

VP %

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	1	2	<u>5</u>	1	2	3	4	5
1	1	1	1	1	1	1					
	2	2	2	2	2	2					
		3	3	3	3	3					
			4	4	4	<u>5</u>					

↙



Optimal

<u>VP %</u>	1	2	3	4	1	2	5	↓	1	2	3	4	5
	1	1	1	1	1	1	1	1					
		2	2	2	2	2	2	2					
			3	3	3	3	3	3					
				4	4	4	5	5					

Optimal

<u>VP %</u>	1	2	3	4	1	2	5	1	↓ 2	3	4	5
	1	1	1	1	1	1	1	1	1			
		2	2	2	2	2	2	2	2			
			3	3	3	3	3	3	3			
				4	4	4	5	5	5			

Optimal

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1		
		2	2	2	2	2	2	2	2	2		
			3	3	3	3	3	3	3	3		
				4	4	4	5	5	5	5		

Optimal

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	4	
		2	2	2	2	2	2	2	2	2	2	
			3	3	3	3	3	3	3	3	3	
				4	4	4	5	5	5	6	5	

Optimal

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	↓
	1	1	1	1	1	1	1	1	1	1	4	4
		2	2	2	2	2	2	2	2	2	2	2
			3	3	3	3	3	3	3	3	3	3
				4	4	4	5	5	5	6	5	5

N R U



Not Recently Used

VP% 1 2 3 4 1 2 5 1 2 3 4 5

- Only reference bit \Rightarrow 2 categories
- Reference bit not reset

Not Recently Used

VP % ↓
1 2 3 4 1 2 5 1 2 3 4 5
1⁰

Not Recently Used

VP % 1 2 3 ↓
 1° 1° 1°
 2° 2°
 3°

4 1 2 5 1 2 3 4 5

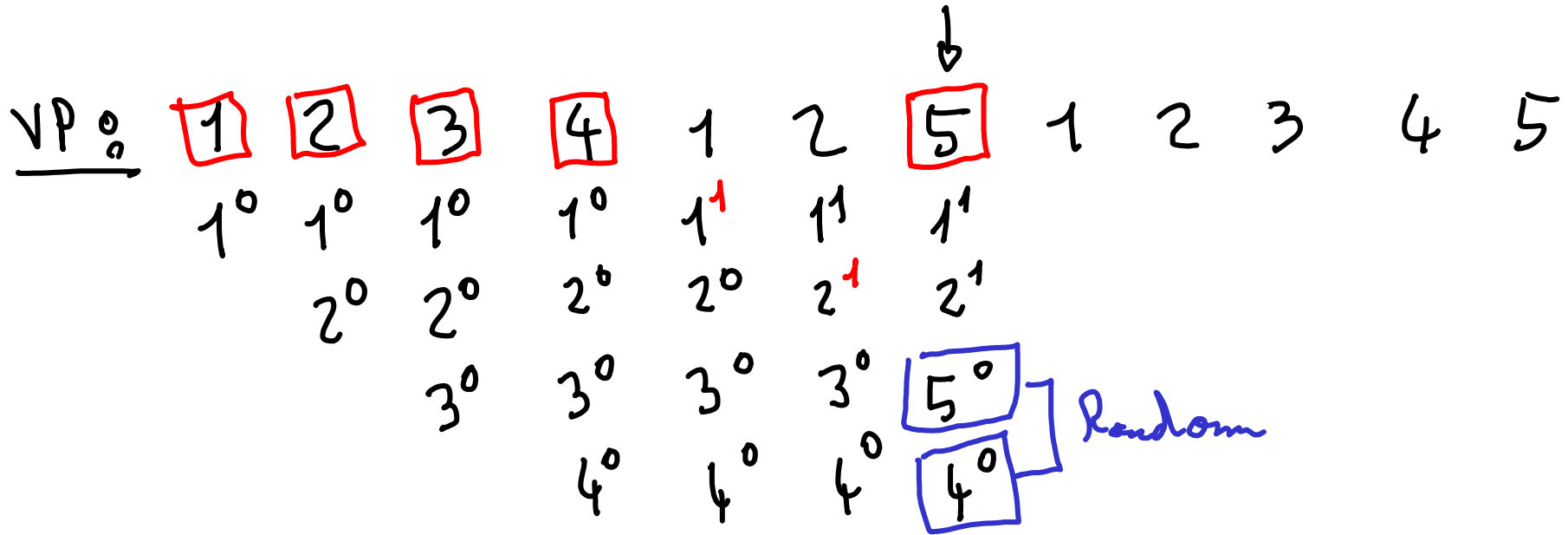
Not Recently Used

<u>VP %</u>	1	2	3	4	↓	1	2	5	1	2	3	4	5
	1°	1°	1°	1°	1 ¹								
		2°	2°	2°	2°								
			3°	3°	3°								
				4°	4°								

Not Recently Used

<u>VP %</u>	1	2	3	4	1	↓ 2	5	1	2	3	4	5
	1 ⁰	1 ⁰	1 ⁰	1 ⁰	1 ¹	1 ¹						
		2 ⁰	2 ⁰	2 ⁰	2 ⁰	2 ¹						
			3 ⁰	3 ⁰	3 ⁰	3 ⁰						
				4 ⁰	4 ⁰	4 ⁰						

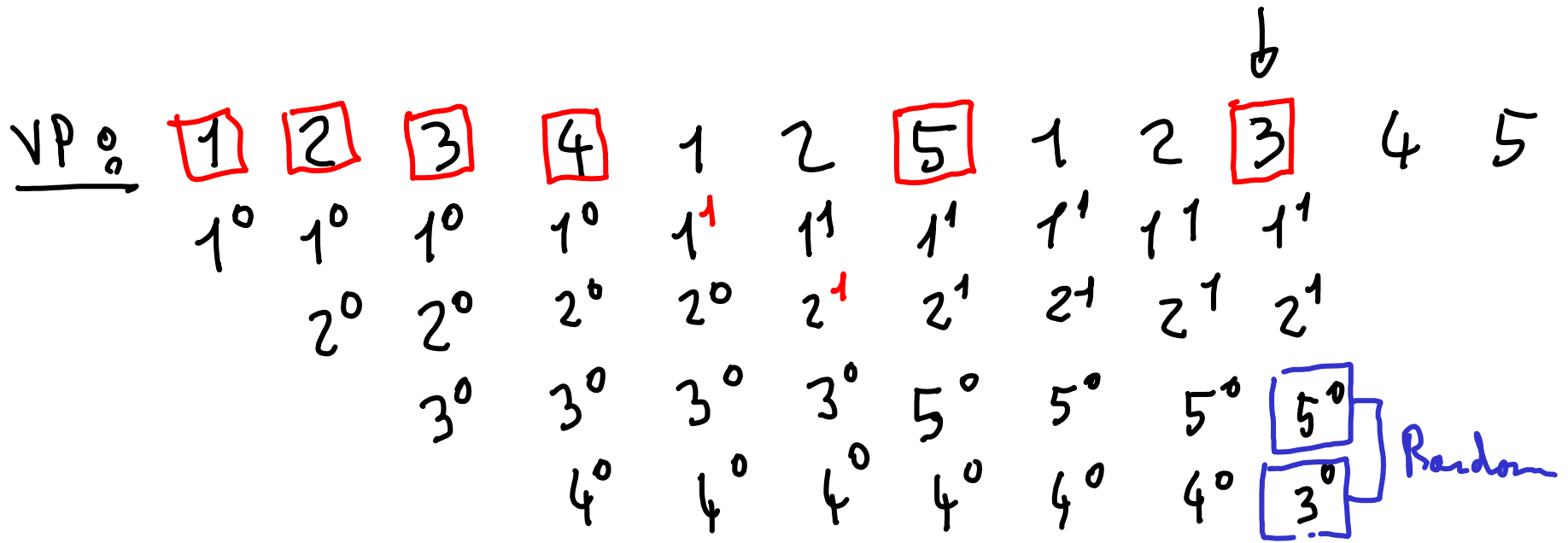
Not Recently Used



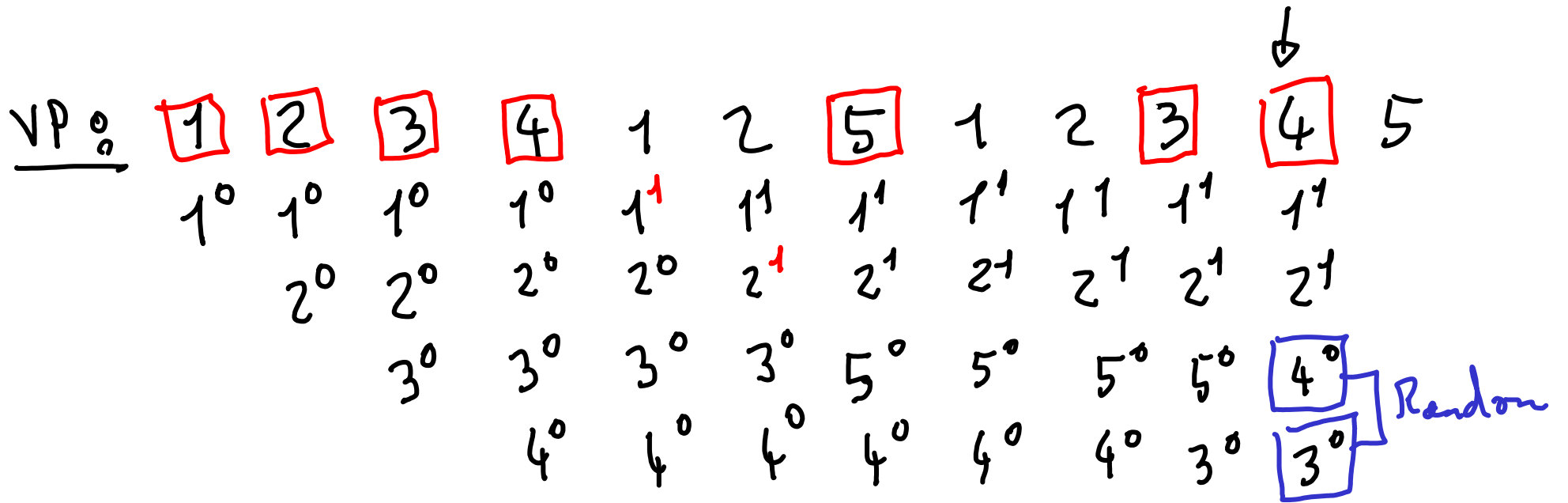
Not Recently Used

<u>VP %</u>	1	2	3	4	1	2	5	↓	1	2	3	4	5
	1 ⁰	1 ⁰	1 ⁰	1 ⁰	1 ¹	1 ¹	1 ¹	1 ¹					
		2 ⁰	2 ⁰	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ¹					
			3 ⁰	3 ⁰	3 ⁰	3 ⁰	5 ⁰	5 ⁰					
				4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰					

Not Recently Used



Not Recently Used



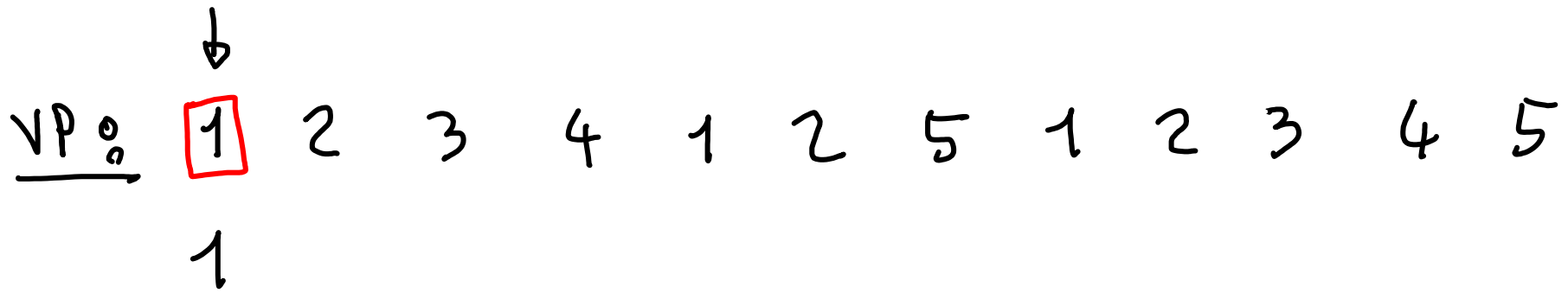
Not Recently Used

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5	↓
	1 ⁰	1 ⁰	1 ⁰	1 ⁰	1 ¹	1 ¹	1 ¹	1 ¹	1 ¹	1 ¹	1 ¹	1 ¹	1 ¹
		2 ⁰	2 ⁰	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹
			3 ⁰	3 ⁰	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	4 ⁰	4 ⁰	5 ⁰
				4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	3 ⁰	3 ⁰

Random

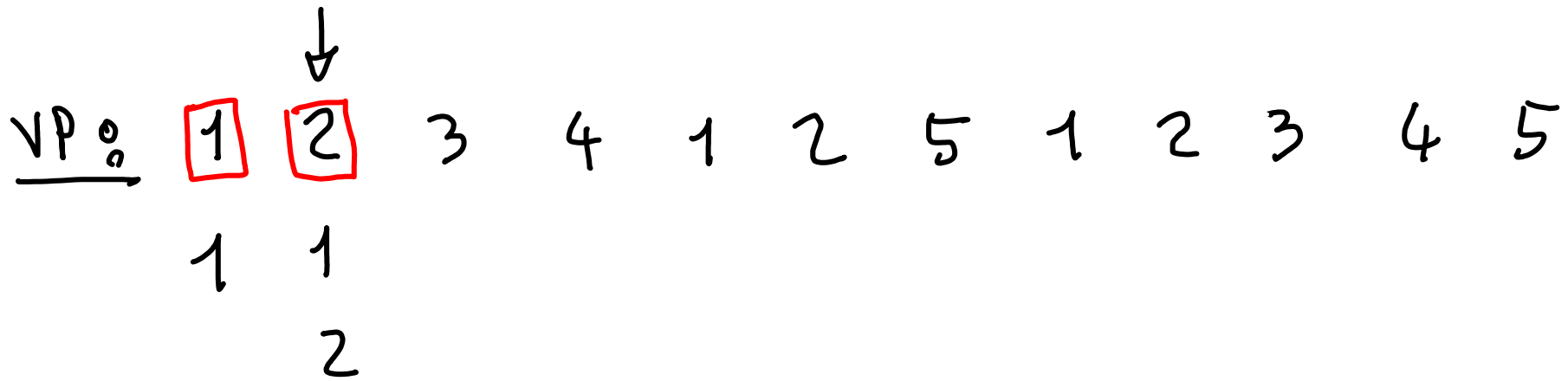
FIFO

FIFO



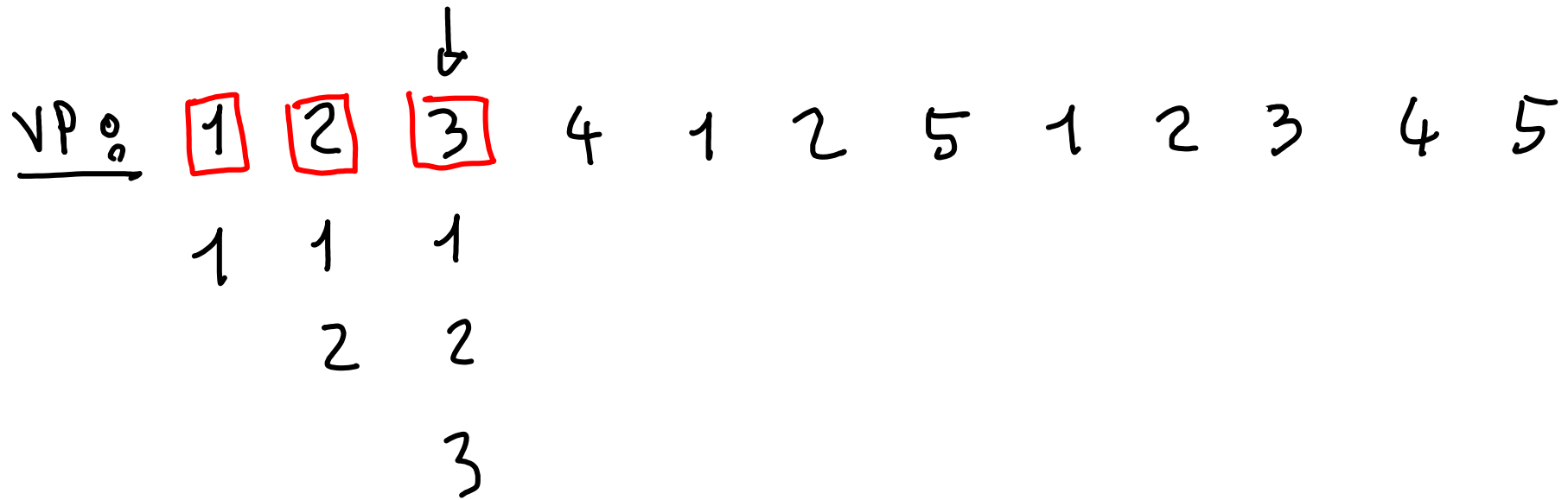
FIFO: 1

FIFO



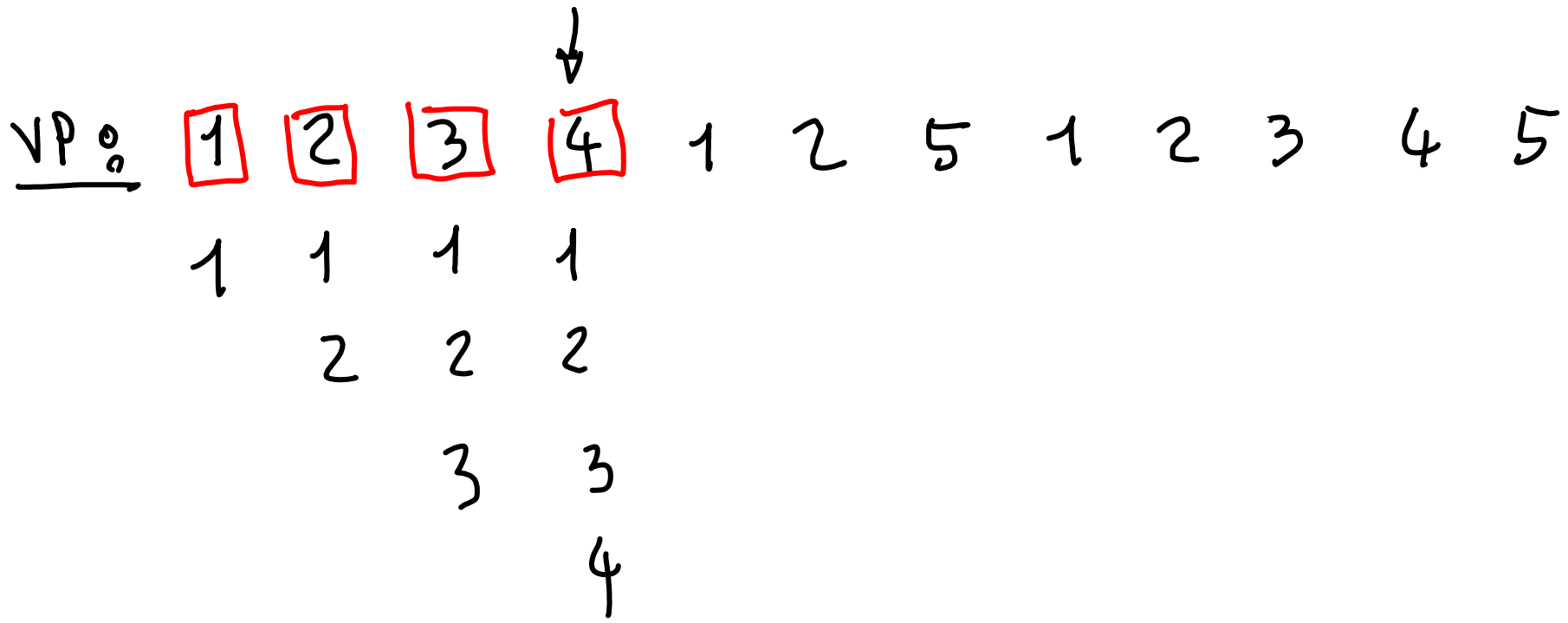
FIFO: 1, 2

FIFO



FIFO: 1, 2, 3

FIFO



FIFO: 1, 2, 3, 4

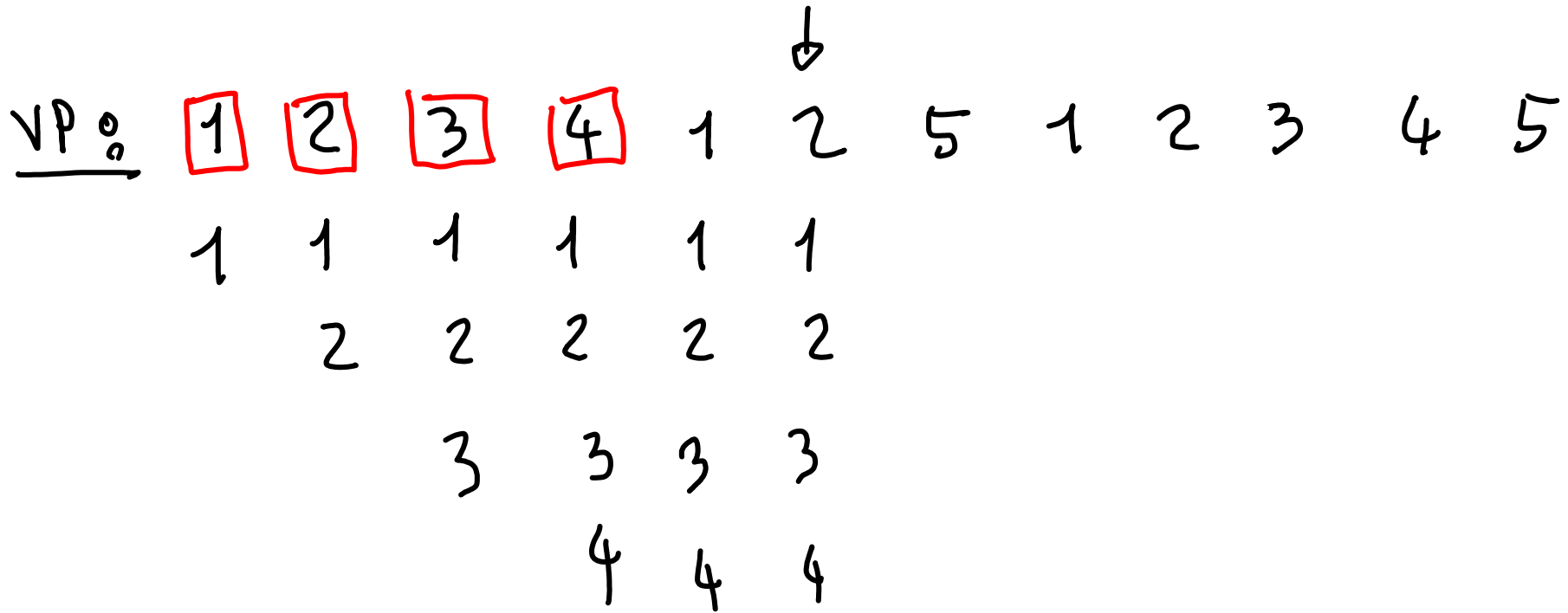
F I F O

↓

<u>VP :</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1							
		2	2	2	2							
			3	3	3							
				4	4							

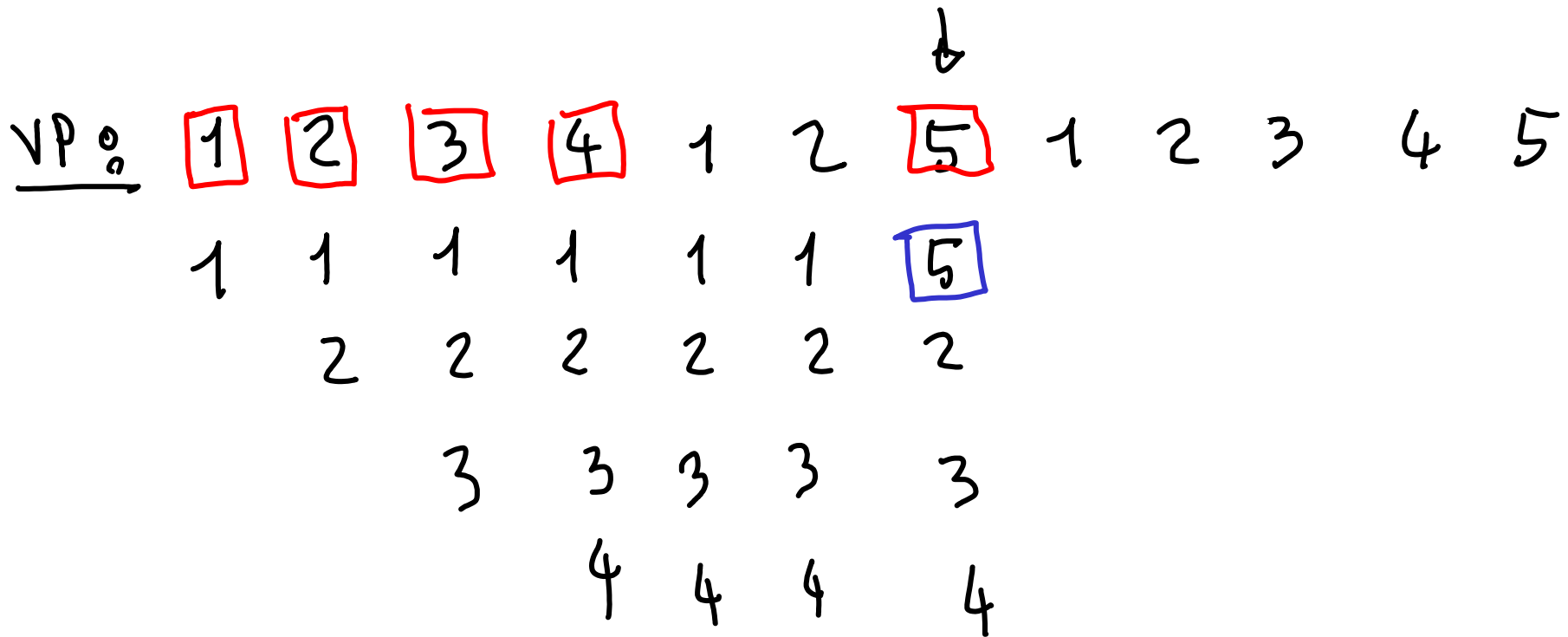
F I F O : 1, 2, 3, 4

FIFO



FIFO: 1, 2, 3, 4

FIFO



FIFO: ~~1~~, 2, 3, 4, 5

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	5					
		2	2	2	2	2	2					
			3	3	3	3	3					
				4	4	4	4					

FIFO: 2, 3, 4, 5

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	↓	1	2	3	4	5
	1	1	1	1	1	1	5		5				
		2	2	2	2	2	2		1				
			3	3	3	3	3		3				
				4	4	4	4		4				

FIFO: ~~2~~, 3, 4, 5, 1

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	5	5				
		2	2	2	2	2	2	1				
			3	3	3	3	3	3				
				4	4	4	4	4				

FIFO: 3, 4, 5, 1

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	5	5	5			
		2	2	2	2	2	2	1	1			
			3	3	3	3	3	3	2			
				4	4	4	4	4	4			

FIFO: ~~3~~, 4, 5, 1, 2

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	5	5	5			
		2	2	2	2	2	2	1	1			
			3	3	3	3	3	3	2			
				4	4	4	4	4	4			

FIFO: 4, 5, 1, 2

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	5	5	5	5		
		2	2	2	2	2	2	1	1	1		
			3	3	3	3	3	3	2	2		
				4	4	4	4	4	4	4	3	

FIFO: ~~4~~, 5, 1, 2, 3

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	5	5	5	5		
		2	2	2	2	2	2	1	1	1		
			3	3	3	3	3	3	2	2		
				4	4	4	4	4	4	3		

FIFO: 5, 1, 2, 3

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	5	5	5	5	4	
		2	2	2	2	2	2	1	1	1	1	
			3	3	3	3	3	3	2	2	2	
				4	4	4	4	4	4	3	3	

FIFO: ~~5~~, 1, 2, 3, 4

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	5	5	5	5	4	
		2	2	2	2	2	2	1	1	1	1	
			3	3	3	3	3	3	2	2	2	
				4	4	4	4	4	4	3	3	

FIFO: 1, 2, 3, 4

FIFO

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	5	5	5	5	4	4
		2	2	2	2	2	2	1	1	1	1	5
			3	3	3	3	3	3	2	2	2	2
				4	4	4	4	4	4	3	3	3

FIFO: ~~1~~, 2, 3, 4, 5

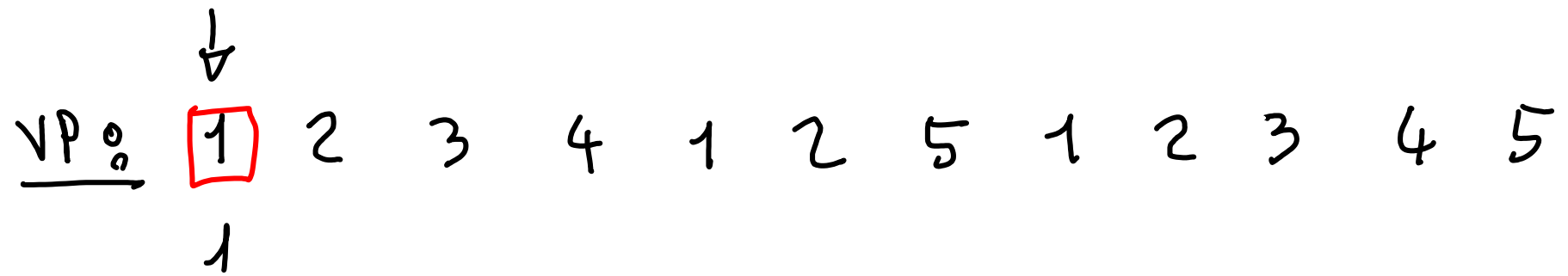
FIFO

<u>VP:</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	1	2	<u>5</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
	1	1	1	1	1	1	5	5	5	5	4	4
		2	2	2	2	2	2	1	1	1	1	5
			3	3	3	3	3	3	2	2	2	2
				4	4	4	4	4	4	3	3	3

FIFO: 2, 3, 4, 5

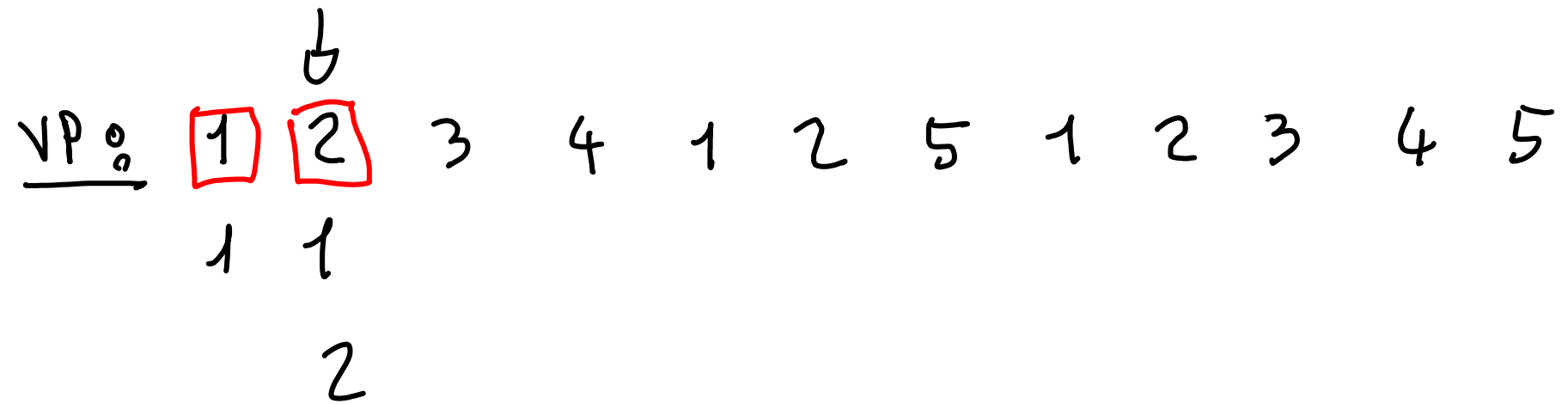
FIFO 2nd Chance

FIFO 2nd Chance



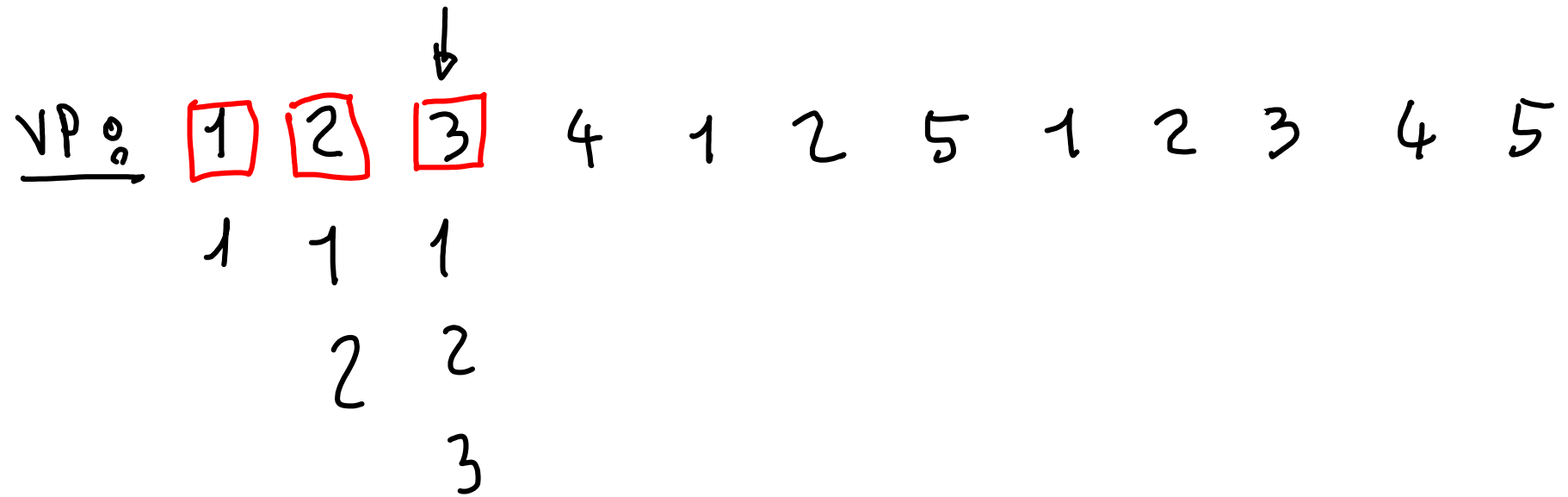
FIFO: 1

FIFO 2nd Chance



FIFO: 1, 2

FIFO 2nd Chance



FIFO: 1, 2, 3

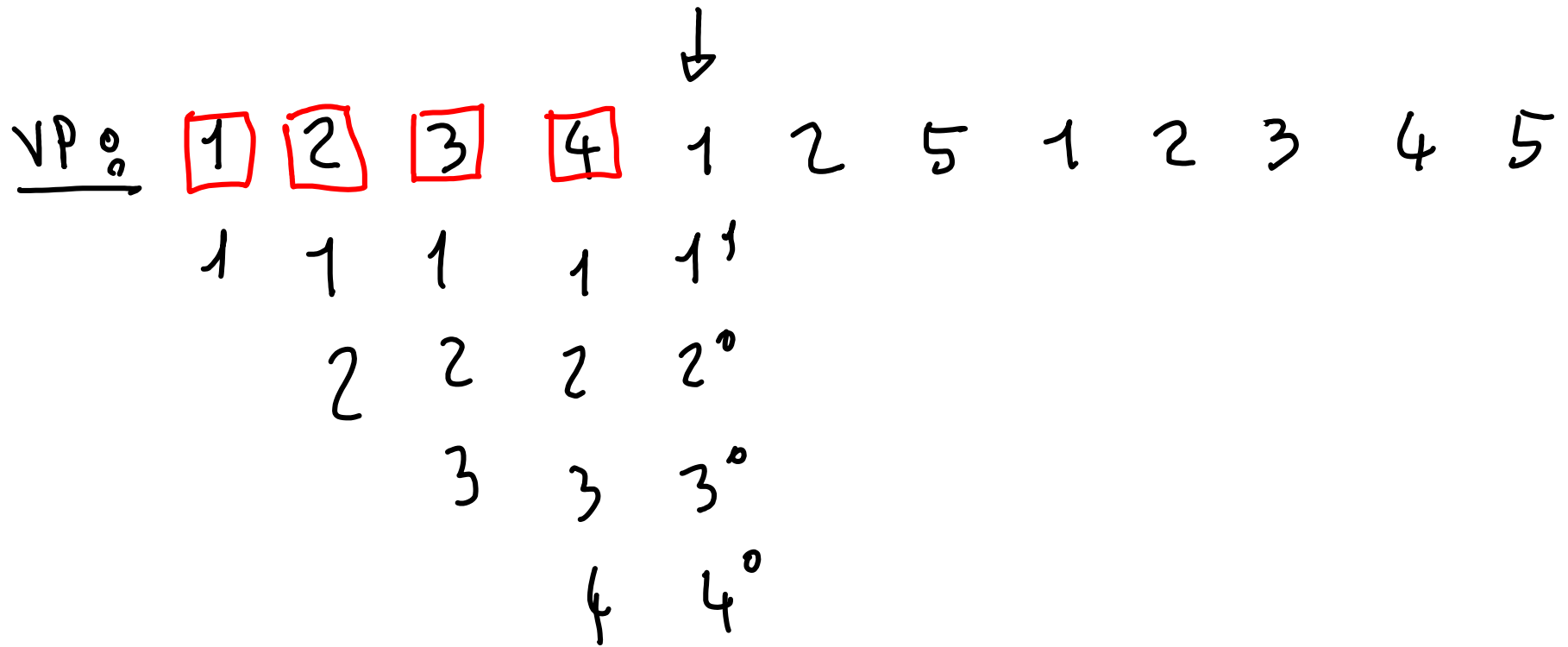
FIFO 2nd Chance

↓

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1								
		2	2	2								
			3	3								
				4								

FIFO: 1, 2, 3, 4

FIFO 2nd Chance



FIFO: 1, 2, 3, 4

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹						
		2	2	2	2 ⁰	2 ¹						
			3	3	3 ⁰	3 ⁰						
				4	4 ⁰	4 ⁰						

FIFO: 1, 2, 3, 4

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰					
		2	2	2	2 ⁰	2 ¹						
			3	3	3 ⁰	3 ⁰						
				4	4 ⁰	4 ⁰						

FIFO: 1, 2, 3, 4 \rightarrow 2, 3, 4, 1

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰					
		2	2	2	2 ⁰	2 ¹						
			3	3	3 ⁰	3 ⁰						
				4	4 ⁰	4 ⁰						

FIFO: 2, 3, 4, 1

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰					
		2	2	2	2 ⁰	2 ¹	2 ⁰					
			3	3	3 ⁰	3 ⁰						
				4	4 ⁰	4 ⁰						

FIFO: 2, 3, 4, 1 \rightarrow 3, 4, 1, 2

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰					
		2	2	2	2 ⁰	2 ¹	2 ⁰					
			3	3	3 ⁰	3 ⁰						
				4	4 ⁰	4 ⁰						

FIFO: 3, 4, 1, 2

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰					
		2	2	2	2 ⁰	2 ¹	2 ⁰					
			3	3	3 ⁰	3 ⁰	5⁰					
				4	4 ⁰	4 ⁰	4 ⁰					

FIFO: ~~3~~, 4, 1, 2, 5

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	↓	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹					
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰					
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰					
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰					

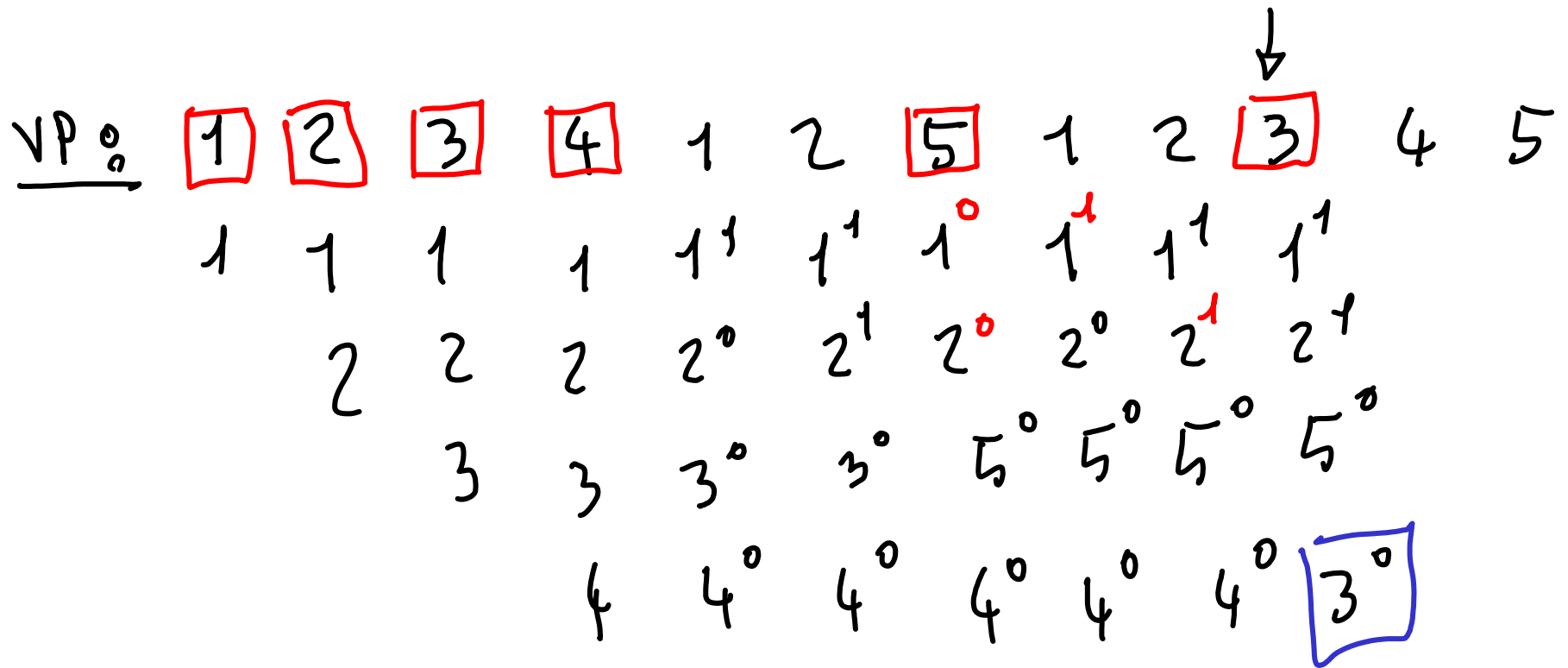
FIFO: 4, 1, 2, 5

FIFO 2nd Chance

								↓				
<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹			
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹			
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰			
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰			

FIFO: 4, 1, 2, 5

FIFO 2nd Chance



FIFO: ~~4~~, 1, 2, 5, 3

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹		
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹		
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰		
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	

FIFO: 1, 2, 5, 3

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ⁰	
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹		
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰		
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	

FIFO: 1, 2, 5, 3 \rightarrow 2, 5, 3, 1

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ⁰	
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹		
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰		
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	

FIFO: 2, 5, 3, 1

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ⁰	
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ⁰	
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰		
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	

FIFO: 2, 5, 3, 1 \rightarrow 5, 3, 1, 2

FIFO 2nd Chance

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ⁰	
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ⁰	
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰		
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	

FIFO: 5, 3, 1, 2

FIFO 2nd Chance

											↓	
<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ⁰	
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ⁰	
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	4⁰	
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	3 ⁰

FIFO: ~~1~~, 3, 1, 2, 4

FIFO 2nd Chance

↓

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ⁰	
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ⁰	
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	4 ⁰	
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	3 ⁰

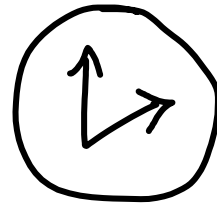
FIFO: 3, 1, 2, 4

FIFO 2nd Chance

												↓
<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ⁰	1 ⁰
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ⁰	2 ⁰
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	4 ⁰	4 ⁰
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	3 ⁰	5⁰

FIFO: ~~1~~, 2, 4, 5

clock



2nd chance

clock 2nd chance



VP:

1

2

3

4

1

2

5

1

2

3

4

5

1



clock:

1



clock

VP% 1 2 3 4 1 2 5 1 2 3 4 5

 ↓

 1 1

 2

clock%

1

↑

2

clock



VP%

1

2

3

4

1

2

5

1

2

3

4

5

1

1

1

2

2

3



clock%

1



2

3

clock



VP%

1 2 3 4 1 2 5 1 2 3 4 5

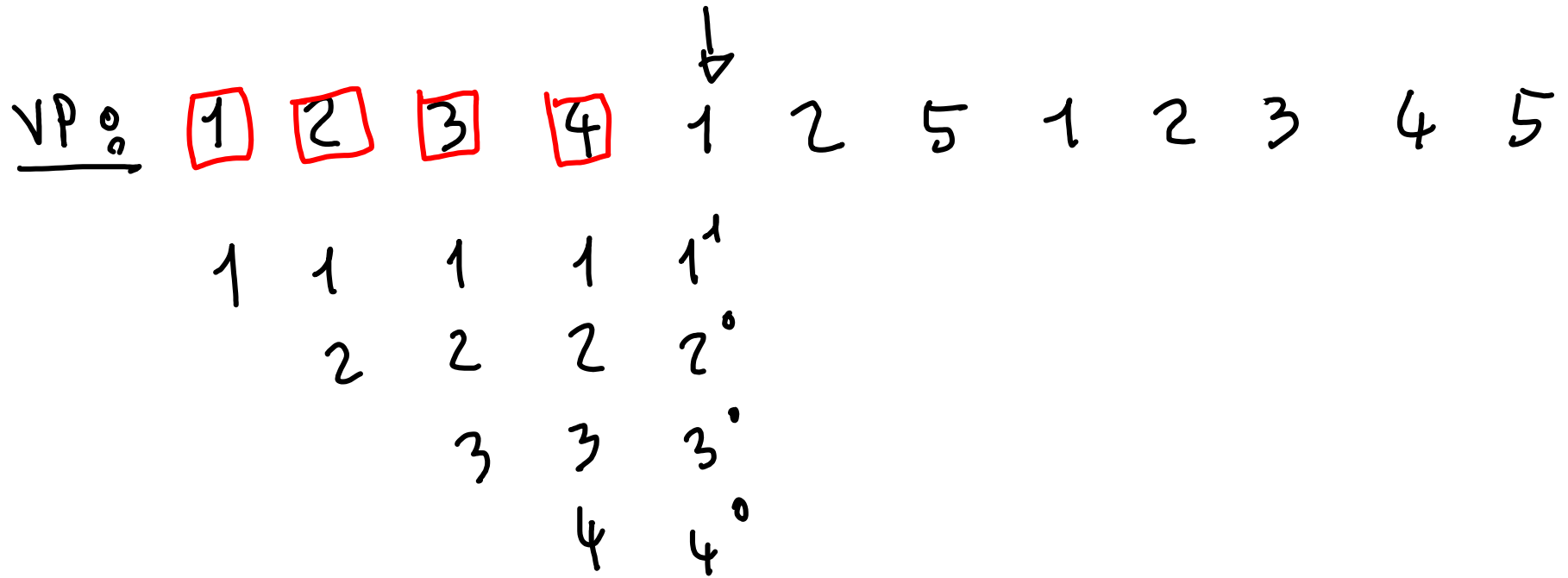
1 1 1 1
2 2 2
3 3
4



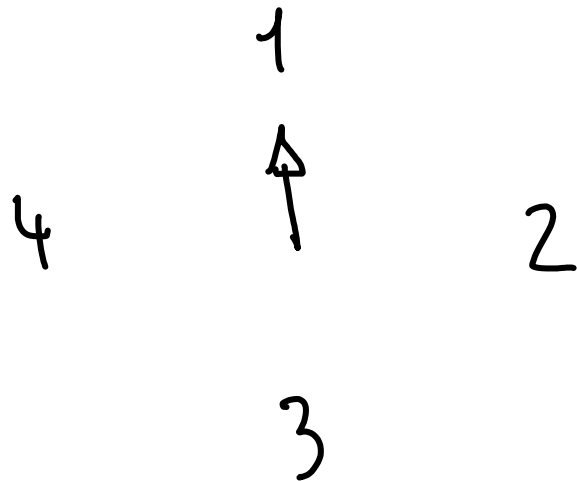
clock%

1
4 ↑ 2
3

clock



clock%



clock



VP% 1 2 3 4 1 2 5 1 2 3 4 5

1	1	1	1	1 ¹	1 ¹							
	2	2	2	2 ⁰	2 ¹							
		3	3	3 ⁰	3 ⁰							
			4	4 ⁰	4 ⁰							

clock%

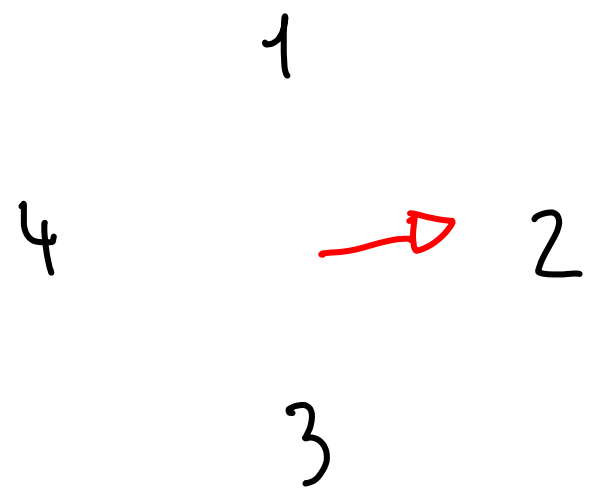
		1			
		↑		2	
4					
		3			

clock

↓

<u>VP%</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰					
		2	2	2	2 ⁰	2 ¹						
			3	3	3 ⁰	3 ⁰						
				4	4 ⁰	4 ⁰						

clock%



clock

↓

<u>VP%</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰					
		2	2	2	2 ⁰	2 ¹	2 ⁰					
			3	3	3 ⁰	3 ⁰						
				4	4 ⁰	4 ⁰						

clock%

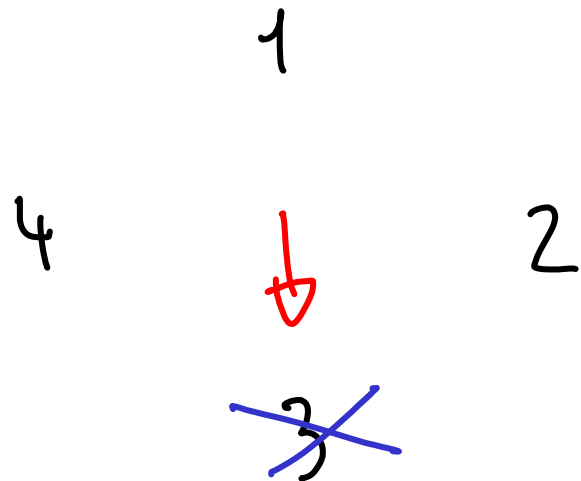
		1		
	4	↓	2	
		3		

clock

↓

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰					
		2	2	2	2 ⁰	2 ¹	2 ⁰					
			3	3	3 ⁰	3 ⁰	5⁰					
				4	4 ⁰	4 ⁰	4 ⁰					

clock:

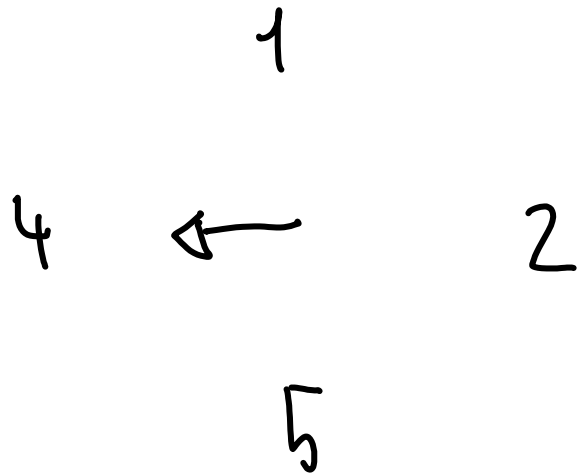


clock

↓

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰					
		2	2	2	2 ⁰	2 ¹	2 ⁰					
			3	3	3 ⁰	3 ⁰	5 ⁰					
				4	4 ⁰	4 ⁰	4 ⁰					

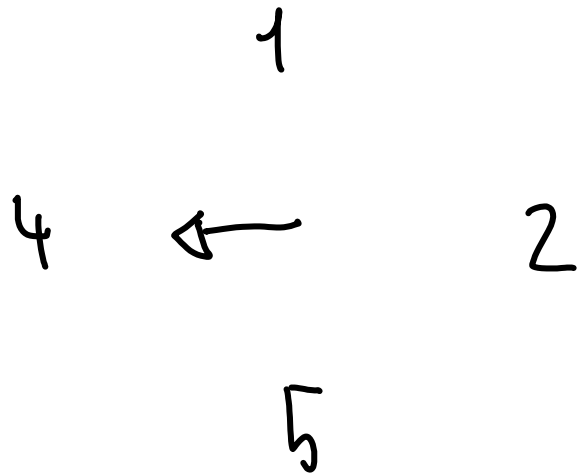
clock:



clock

<u>VP:</u>	1	2	3	4	1	2	5	6	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹					
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰					
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰					
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰					

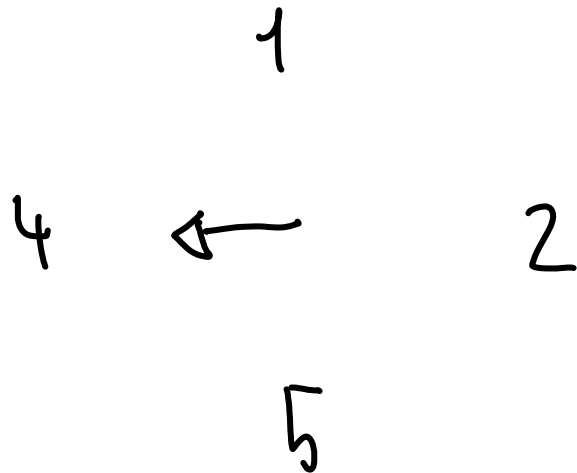
clock:



clock

								↓					
<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5	
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹				
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹				
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰				
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰				

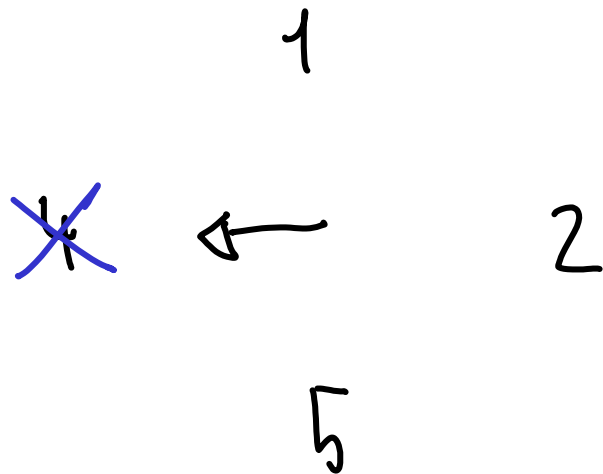
clock:



clock

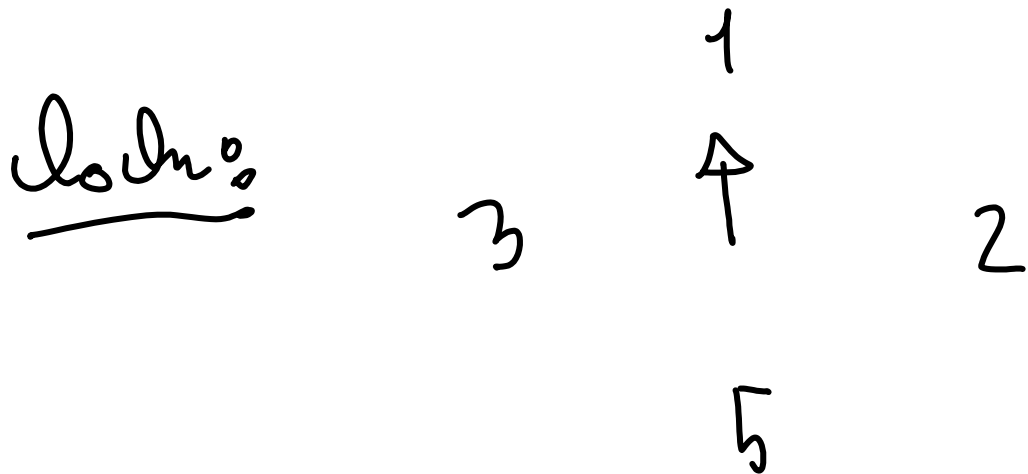
<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹		
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹		
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰		
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3⁰	

clock:



clock

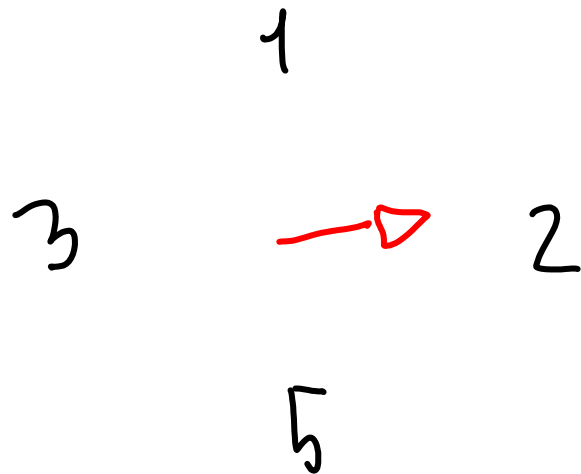
<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹		
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹		
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰		
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3⁰	



clock

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ¹	1 ⁰
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ¹	
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	

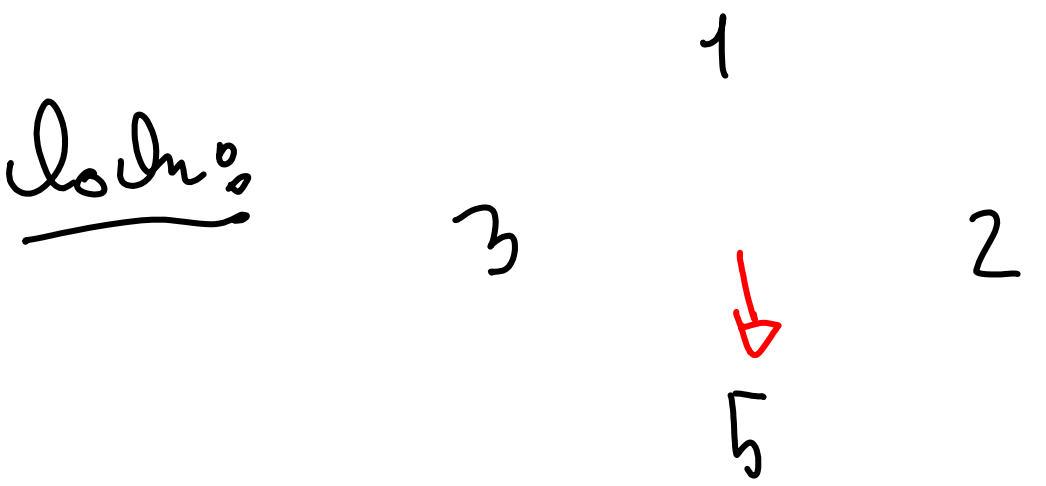
clock:



clock

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ¹	1 ⁰
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ¹	2 ⁰
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	

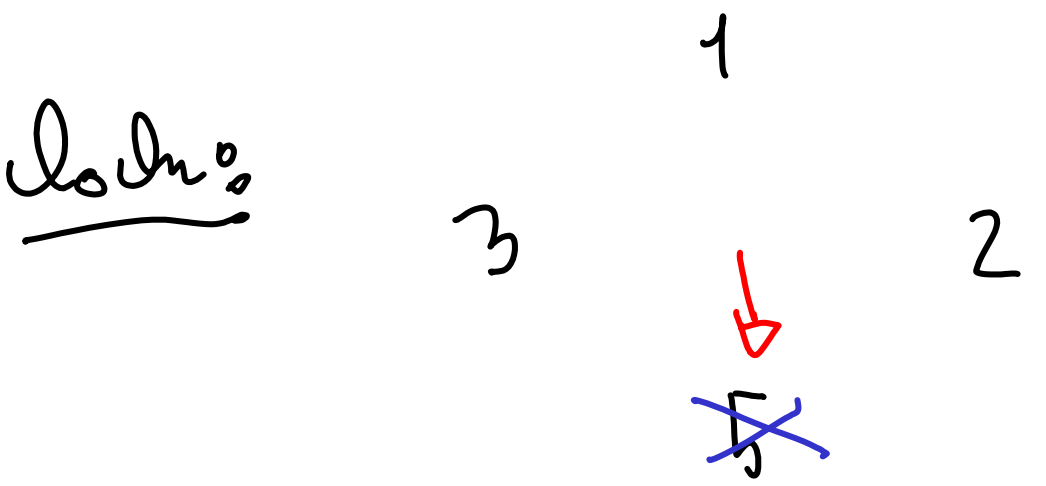
↓



clock

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ⁰	
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ⁰	
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	4⁰	
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	3 ⁰	

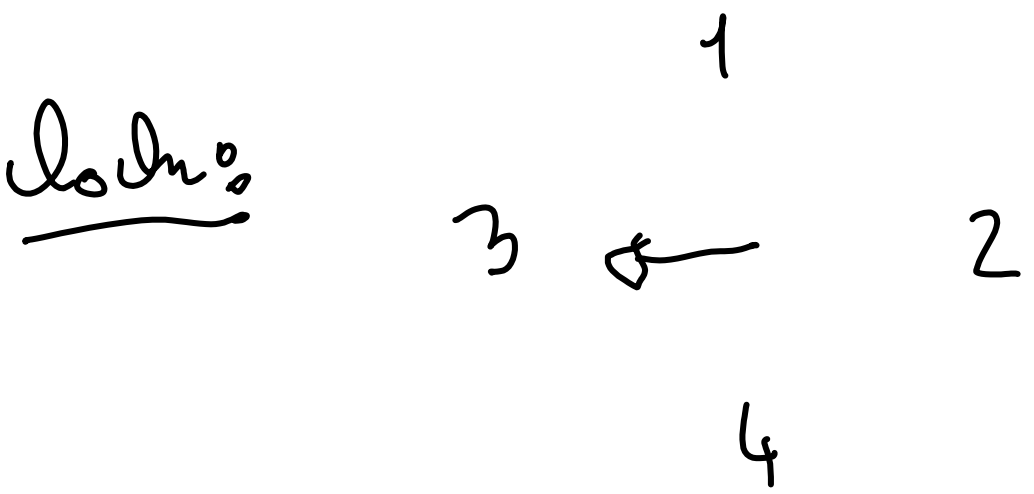
↓



clock

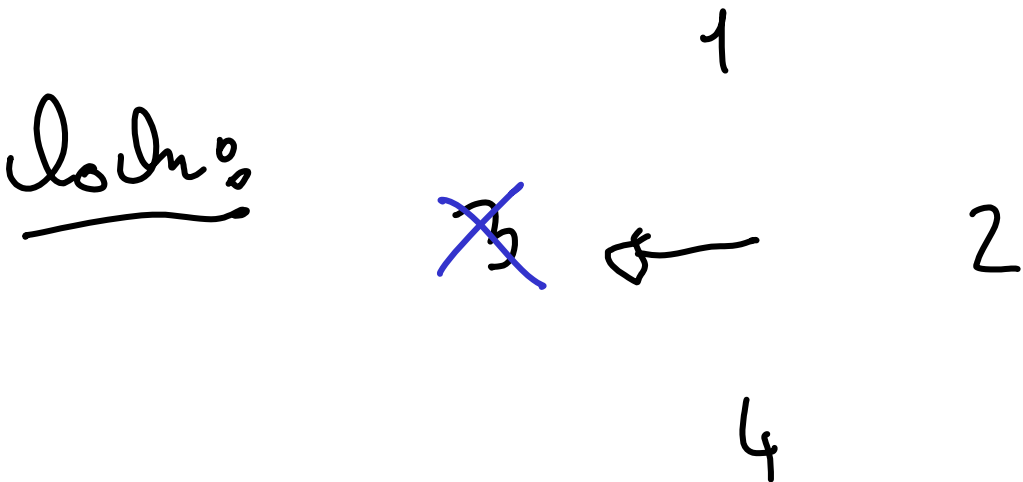
<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ¹	1 ⁰
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ¹	2 ⁰
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	4 ⁰
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	3 ⁰

↓



clock

<u>VP:</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1 ¹	1 ¹	1 ⁰	1 ¹	1 ¹	1 ¹	1 ⁰	1 ⁰
		2	2	2	2 ⁰	2 ¹	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ⁰	2 ⁰
			3	3	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5 ⁰	4 ⁰	4 ⁰
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	3 ⁰	5⁰



LRU

LRU

VP % 0
 ↓
 1
 1 2 3 4 1 2 5 1 2 3 4 5
 1

LRU list % 1

LRU

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1										
		2										

LRU list % 2, 1

MRU
↓
LRU

LRU

↓

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1									
		2	2									
			3									

LRU list : 3, 2, 1

LRU


<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1								
		2	2	2								
			3	3								
				4								

LRU list : 4, 3, 2, 1

LRU

<u>VP %</u>	1	2	3	4	↓	1	2	5	1	2	3	4	5
	1	1	1	1	1	1							
		2	2	2	2	2							
			3	3	3	3							
				4	4	4							

LRU list : 4, 3, 2, 1



LRU

<u>VP %</u>	1	2	3	4	↓							
	1	1	1	1	1	2	5	1	2	3	4	5
		2	2	2	2							
			3	3	3							
				4	4							

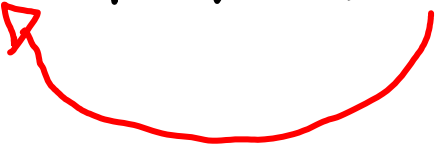
LRU list : 1, 4, 3, 2

LRU



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1							
		2	2	2	2							
			3	3	3							
				4	4							

LRU list : 1, 4, 3, 2



LRU

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1						
		2	2	2	2	2						
			3	3	3	3						
				4	4	4						

LRU list : 2, 1, 4, 3

LRU

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1					
		2	2	2	2	2	2					
			3	3	3	3	5					
				4	4	4	4					

LRU list % 2, 1, 4, ~~3~~ \rightarrow 5, 2, 1, 4

LRU


<u>VP %</u>	1	2	3	4	1	2	↓ 5	1	2	3	4	5
	1	1	1	1	1	1	1					
		2	2	2	2	2	2					
			3	3	3	3	5					
				4	4	4	4					

LRU list : 5, 2, 1, 4

LRU

<u>VP %</u>	1	2	3	4	1	2	5	↓	1	2	3	4	5
	1	1	1	1	1	1	1						
		2	2	2	2	2	2						
			3	3	3	3	5						
				4	4	4	4						

LRU list : 5, 2, 1, 4



LRU


<u>VP %</u>	1	2	3	4	1	2	5	↓	1	2	3	4	5
	1	1	1	1	1	1	1	1	1				
		2	2	2	2	2	2	2	2				
			3	3	3	3	5	5	5				
				4	4	4	4	4	4				

LRU list : 1, 5, 2, 4

LRU

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1				
		2	2	2	2	2	2	2				
			3	3	3	3	5	5				
				4	4	4	4	4				

LRU list : 1, 5, 2, 4



LRU

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1			
		2	2	2	2	2	2	2	2			
			3	3	3	3	5	5	5			
				4	4	4	4	4	4			

LRU list : 2, 1, 5, 4

LRU

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1		
		2	2	2	2	2	2	2	2	2		
			3	3	3	3	5	5	5	5		
				4	4	4	4	4	4	4	3	

LRU list % 2, 1, 5, ~~4~~ → 3, 2, 1, 5

LRU

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1		
		2	2	2	2	2	2	2	2	2		
			3	3	3	3	5	5	5	5		
				4	4	4	4	4	4	3		

LRU list : 3, 2, 1, 5

LRU



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	1	
		2	2	2	2	2	2	2	2	2	2	
			3	3	3	3	5	5	5	5	4	
				4	4	4	4	4	4	3	3	

LRU list % 3, 2, 1, ~~5~~ → 4, 3, 2, 1

LRU



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	1	
		2	2	2	2	2	2	2	2	2	2	
			3	3	3	3	5	5	5	5	4	
				4	4	4	4	4	4	3	3	

LRU list % 4, 3, 2, 1

LRU

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	1	5
		2	2	2	2	2	2	2	2	2	2	2
			3	3	3	3	5	5	5	5	4	4
				4	4	4	4	4	4	3	3	3

LRU list % 4, 3, 2, ~~1~~ → 5, 4, 3, 2

LRU + Aging

LRU + Aging

VP % 1 2 3 4 1 2 5 1 2 3 4 5

Counters %

PF - 1 → 0 0 0

PF - 2 → 0 0 0

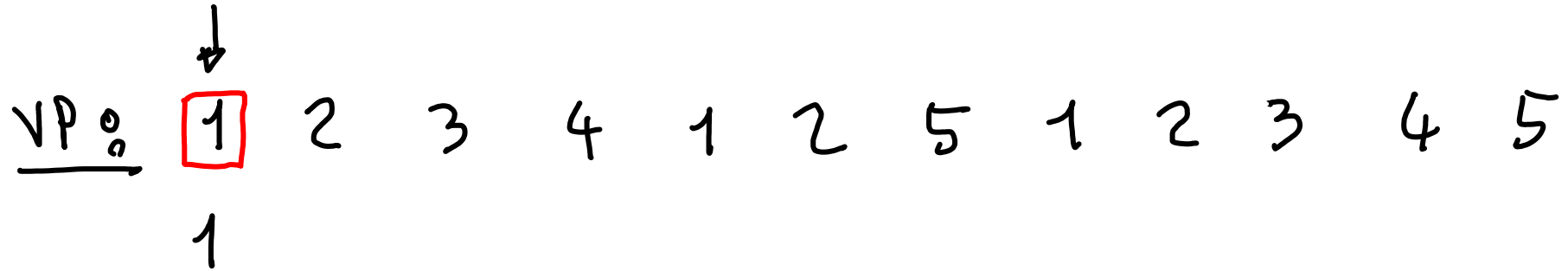
PF - 3 → 0 0 0

PF - 4 → 0 0 0

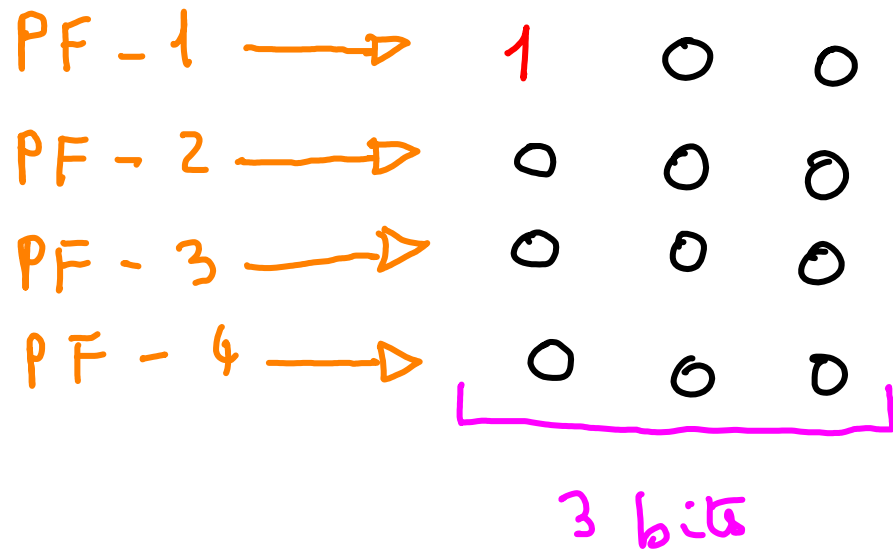


3 bits

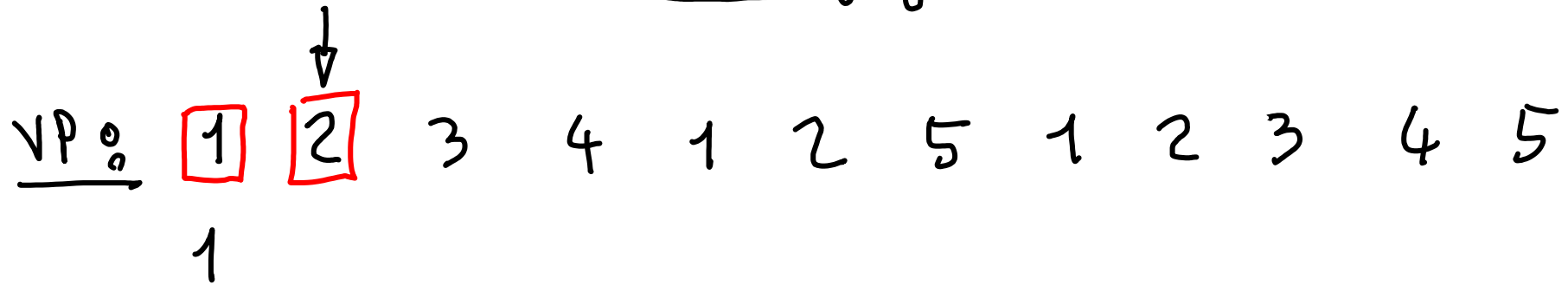
LRU + Aging



Counters %



LRU + Aging



Counters %

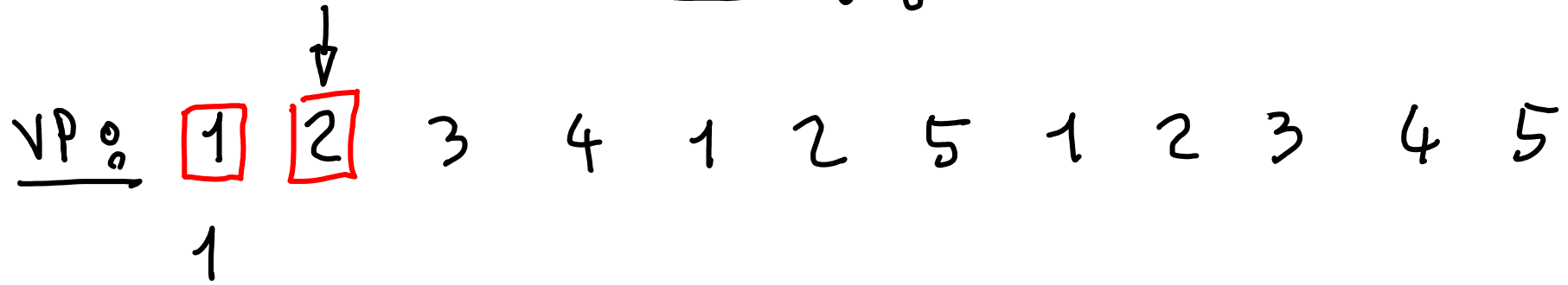
PF - 1 →	1	0	0
PF - 2 →	0	0	0
PF - 3 →	0	0	0
PF - 4 →	0	0	0

aging
→



3 bits

LRU + Aging

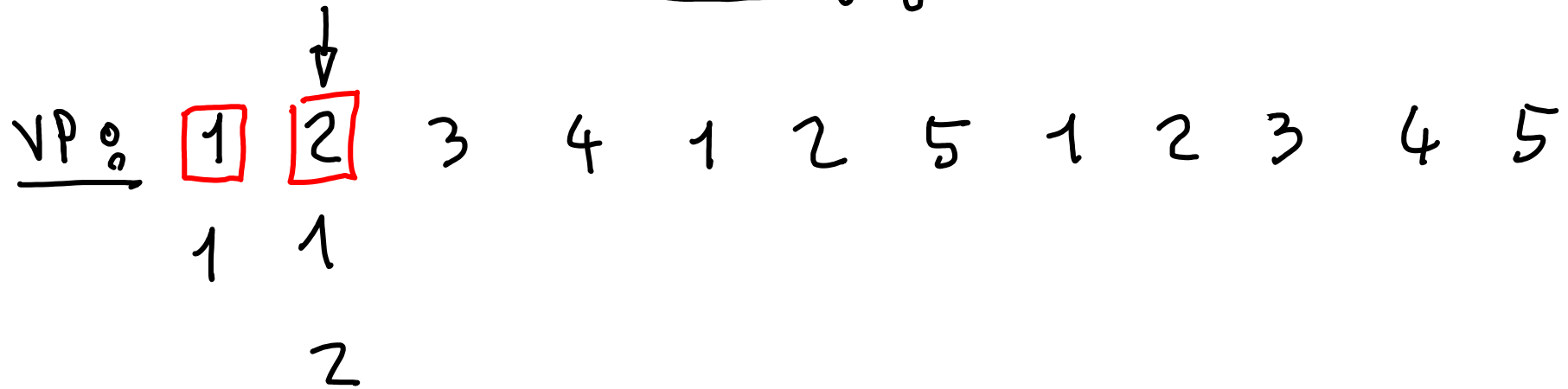


Counters %

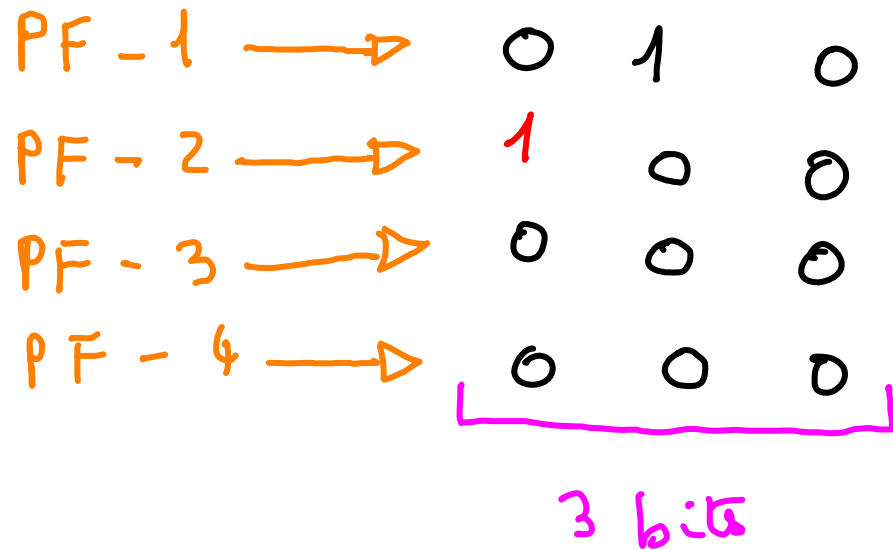
PF - 1 →	0	1	0
PF - 2 →	0	0	0
PF - 3 →	0	0	0
PF - 4 →	0	0	0

3 bits

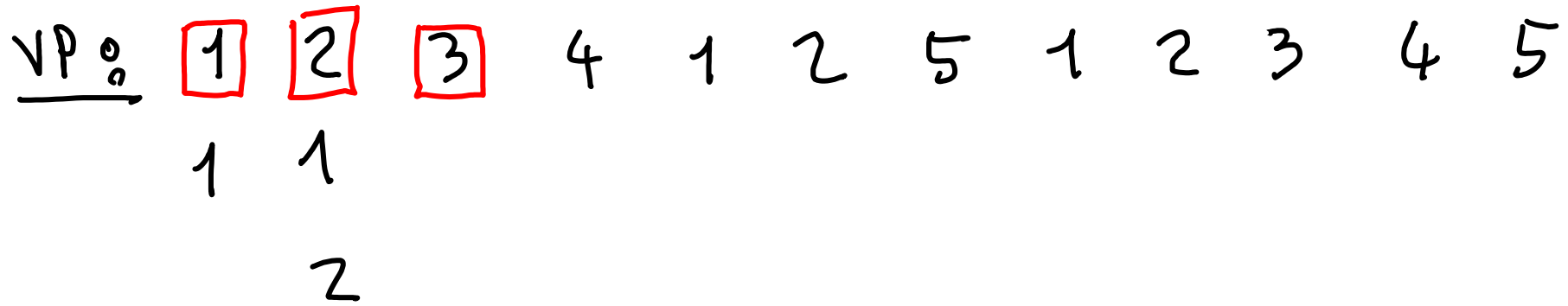
LRU + Aging



Counters %



LRU + Aging



aging



Counters %

PF - 1 → 0 1 0

PF - 2 → 1 0 0

PF - 3 → 0 0 0

PF - 4 → 0 0 0



3 bits

LRU + Aging



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1										
		2										

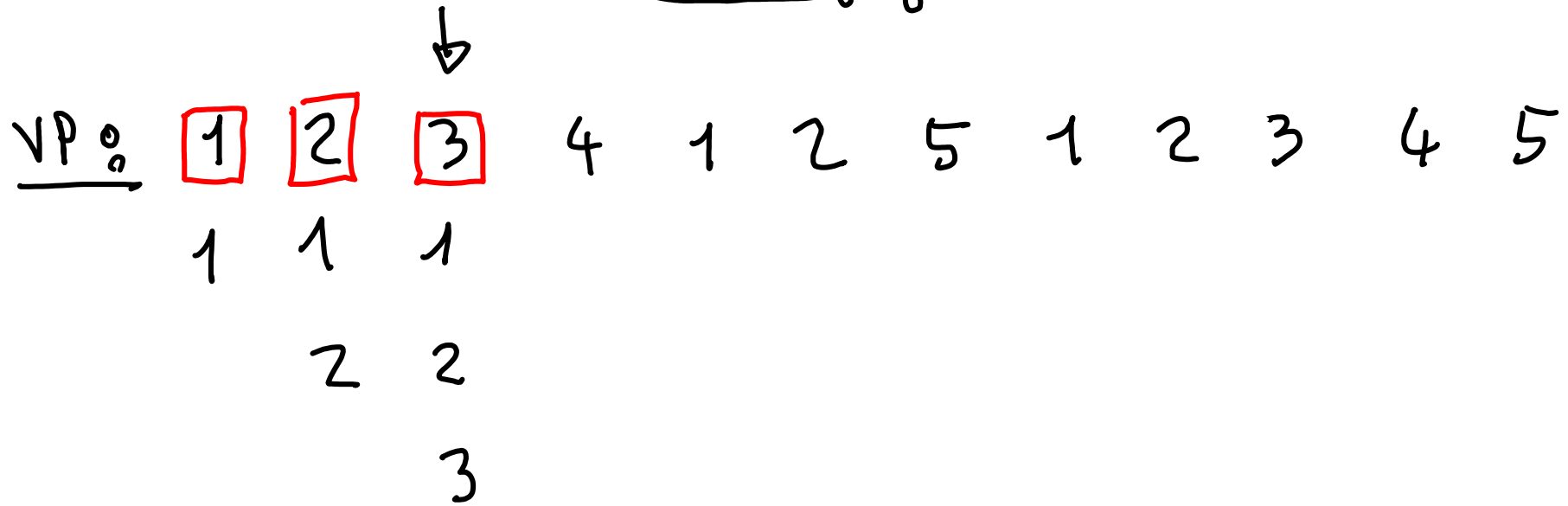
Counters %

PF - 1 →	0	0	1
PF - 2 →	0	1	0
PF - 3 →	0	0	0
PF - 4 →	0	0	0

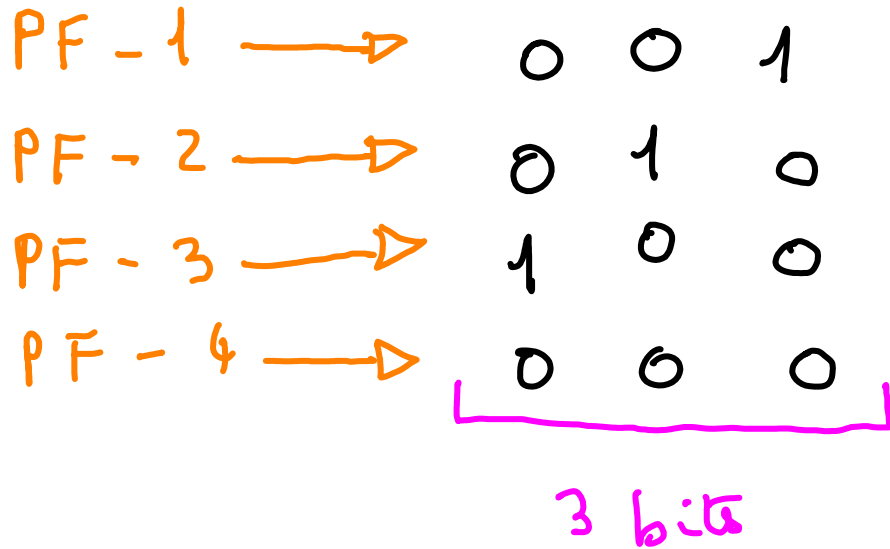


3 bits

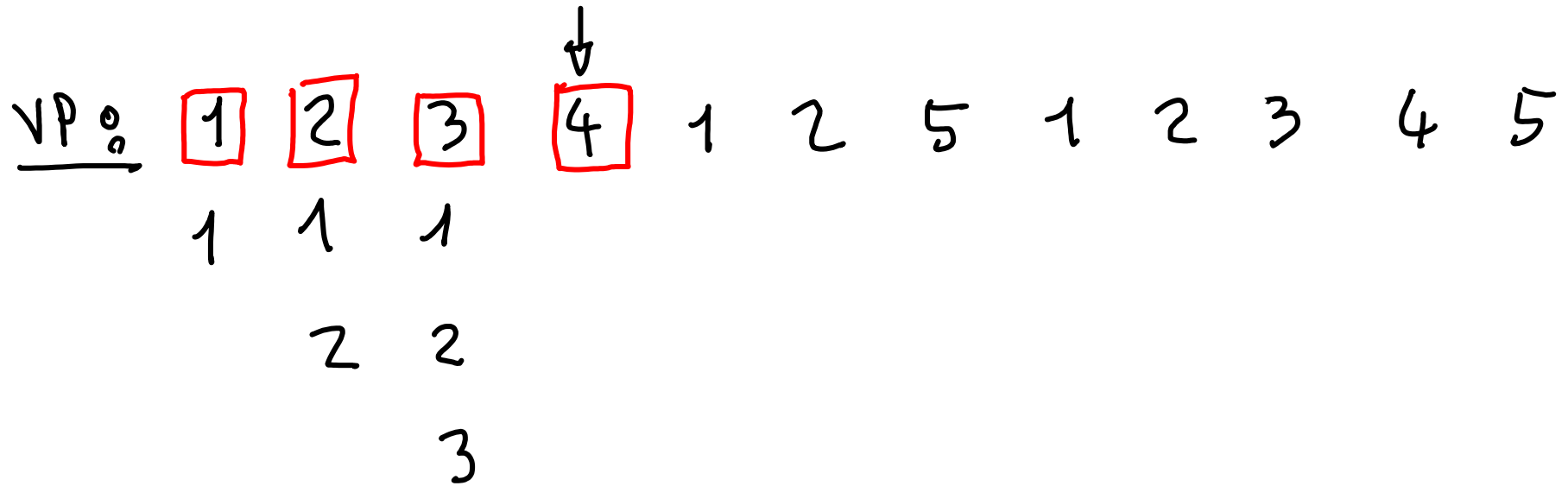
LRU + Aging



Counters %



LRU + Aging



Counters %

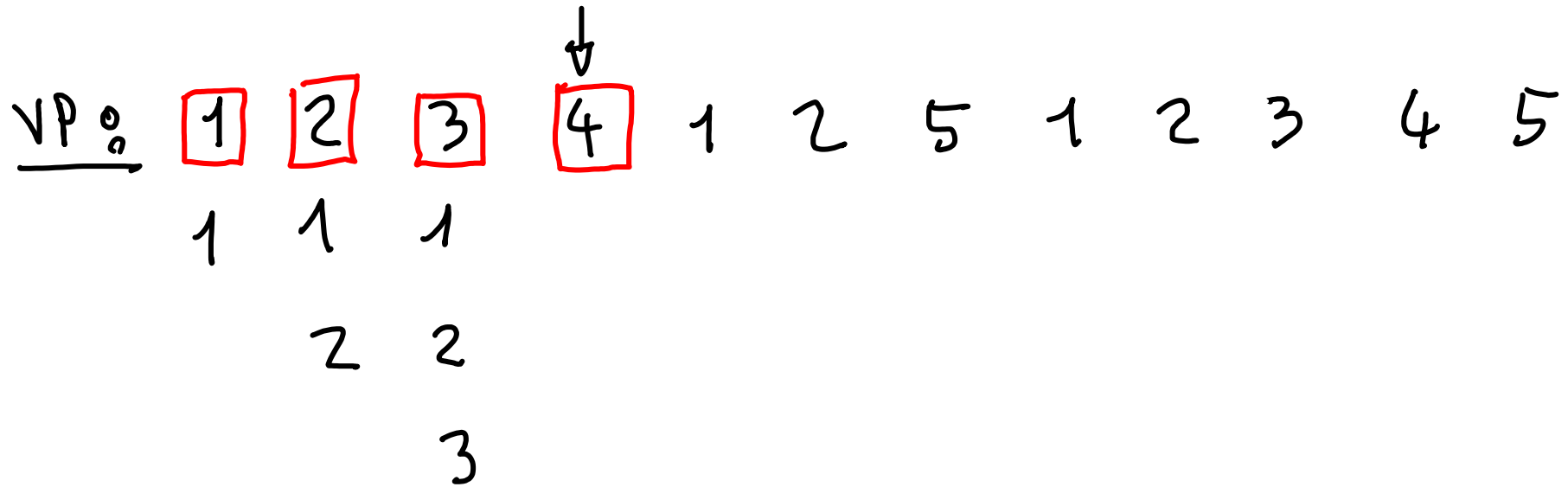
aging →

PF - 1 →	0	0	1
PF - 2 →	0	1	0
PF - 3 →	1	0	0
PF - 4 →	0	0	0

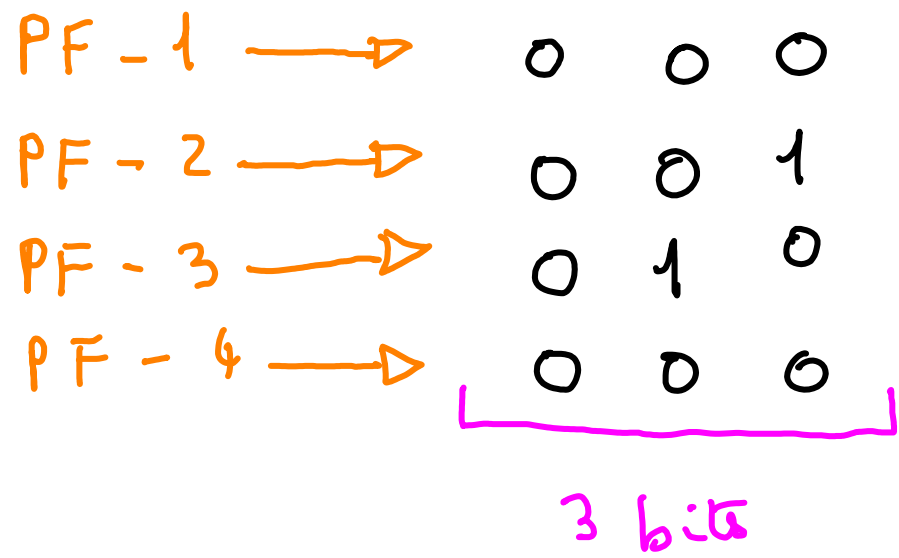


3 bits

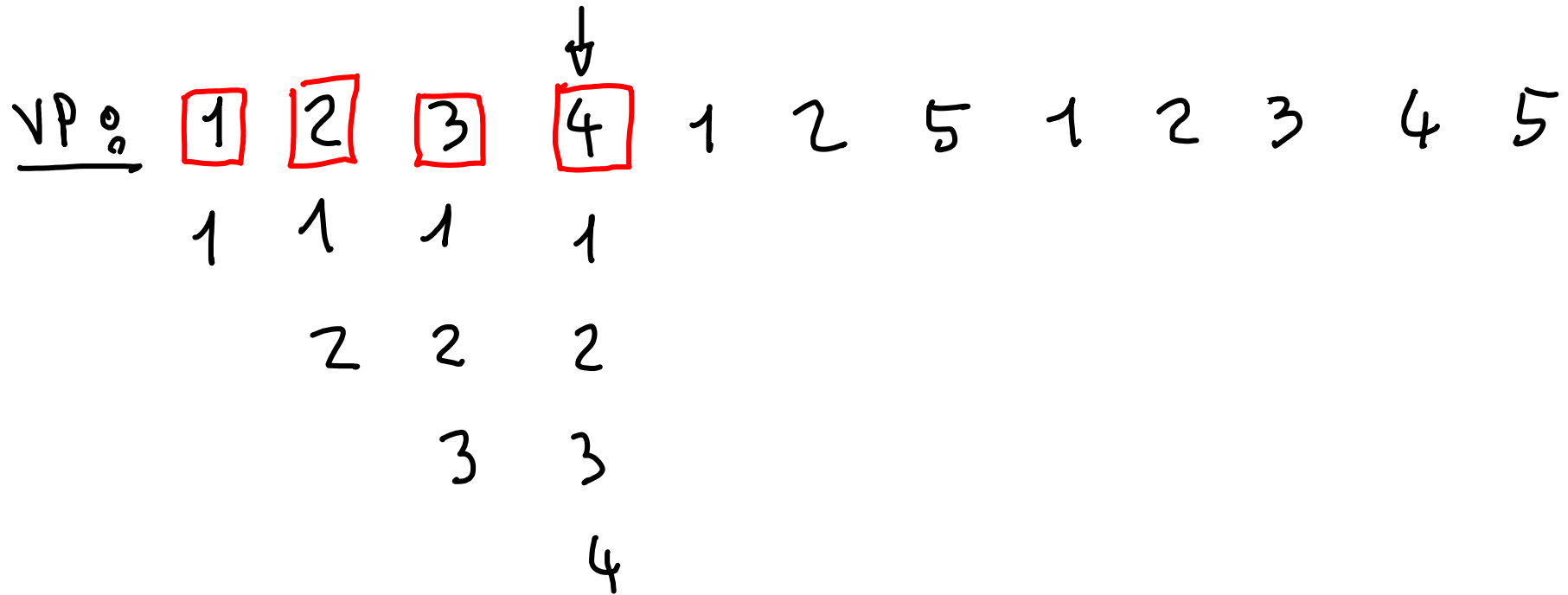
LRU + Aging



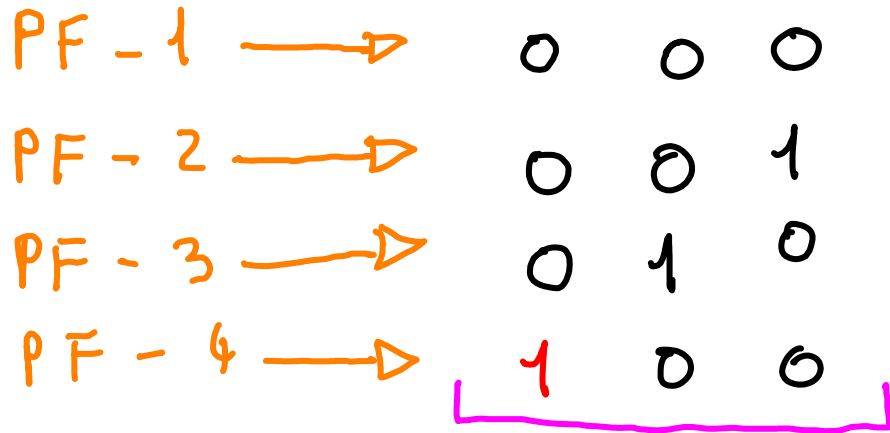
Counters %



LRU + Aging

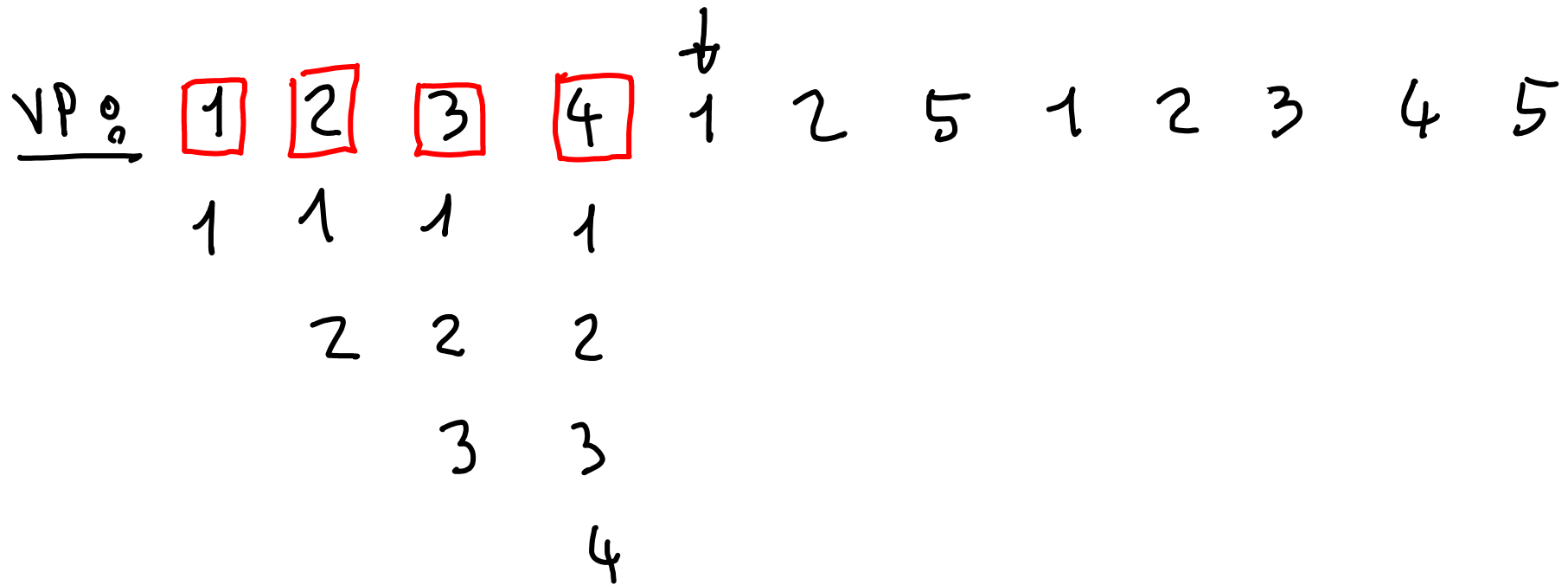


Counters %



3 bits

LRU + Aging

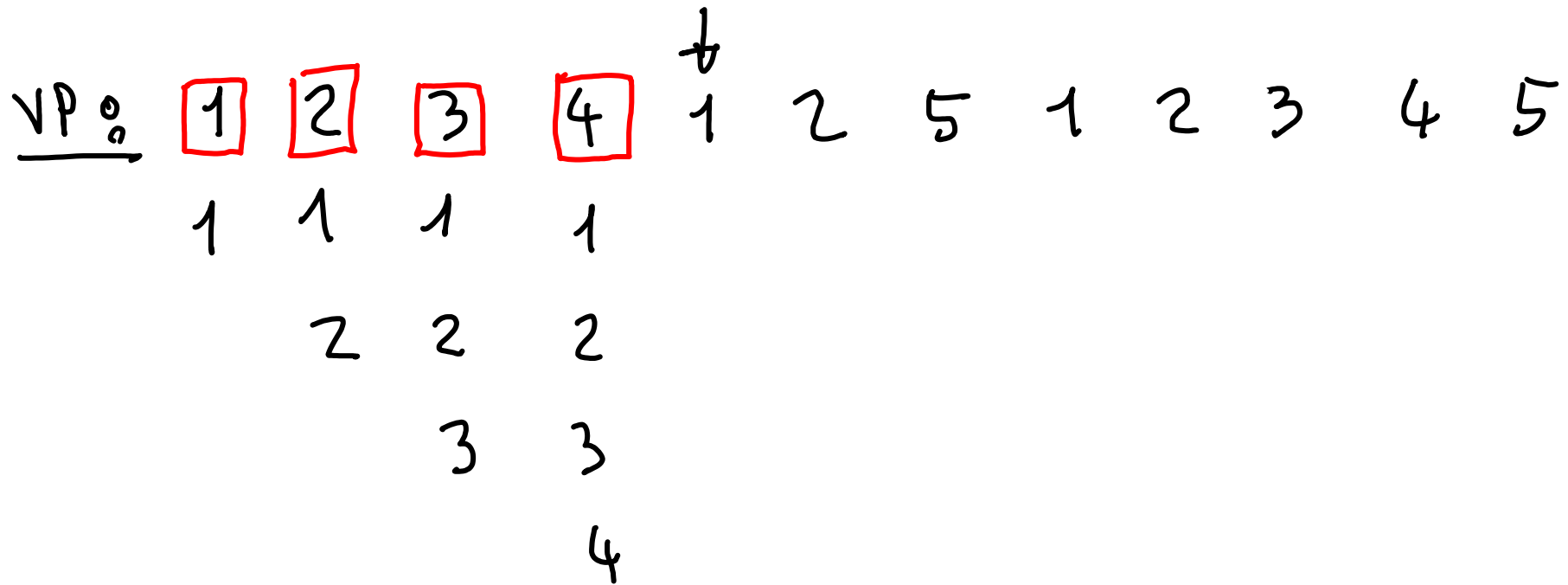


Counters %

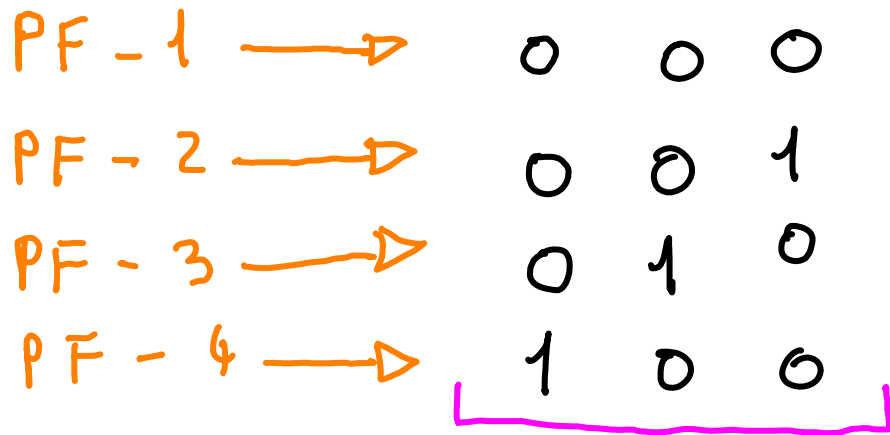
PF - 1 →	0	0	0
PF - 2 →	0	0	1
PF - 3 →	0	1	0
PF - 4 →	1	0	0

3 bits

LRU + Aging



Counters %



3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	↓	1	2	5	1	2	3	4	5
	1	1	1	1									
		2	2	2									
			3	3									
				4									

Counters %

PF - 1 → 0 0 0

PF - 2 → 0 0 0

PF - 3 → 0 0 1

PF - 4 → 0 1 0



3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	↓	1	2	5	1	2	3	4	5
	1	1	1	1	1								
		2	2	2	2								
			3	3	3								
				4	4								

Counters %

PF - 1 → 1 0 0

PF - 2 → 0 0 0

PF - 3 → 0 0 1

PF - 4 → 0 1 0



3 bits

LRU + Aging



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1							
		2	2	2	2							
			3	3	3							
				4	4							

Counters %

aging ↓

PF - 1 → 1 0 0

PF - 2 → 0 0 0

PF - 3 → 0 0 1

PF - 4 → 0 1 0



3 bits

LRU + Aging



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1							
		2	2	2	2							
			3	3	3							
				4	4							

Counters %

PF - 1 →	0	1	0
PF - 2 →	0	0	0
PF - 3 →	0	0	0
PF - 4 →	0	0	1



3 bits

LRU + Aging



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1						
		2	2	2	2	2						
			3	3	3	3						
				4	4	4						

Counters %

PF - 1 →	0	1	0
PF - 2 →	1	0	0
PF - 3 →	0	0	0
PF - 4 →	0	0	1

3 bits

LRU + Aging



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1						
		2	2	2	2	2						
			3	3	3	3						
				4	4	4						

Counters %

PF - 1 → 0 1 0

PF - 2 → 1 0 0

PF - 3 → 0 0 0

PF - 4 → 0 0 1

smallest !!



3 bits

LRU + Aging



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1					
		2	2	2	2	2	2					
			3	3	3	3	5					
				4	4	4	4					

Counters %

aging →

PF - 1 →	0	1	0
PF - 2 →	1	0	0
PF - 3 →	0	0	0
PF - 4 →	0	0	1



3 bits

LRU + Aging

↓

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1					
		2	2	2	2	2	2					
			3	3	3	3	5					
				4	4	4	4					

Counters %

PF - 1 →	0	0	1
PF - 2 →	0	1	0
PF - 3 →	1	0	0
PF - 4 →	0	0	0

3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	↓	1	2	3	4	5
	1	1	1	1	1	1	1						
		2	2	2	2	2	2						
			3	3	3	3	5						
				4	4	4	4						

Counters %

PF - 1 →	0	0	1
PF - 2 →	0	1	0
PF - 3 →	1	0	0
PF - 4 →	0	0	0

3 bits

aging →

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	↓	1	2	3	4	5
	1	1	1	1	1	1	1	1	1				
		2	2	2	2	2	2	2	2				
			3	3	3	3	5	5					
				4	4	4	4	4					

Counters %

PF - 1 →	1	0	0
PF - 2 →	0	0	1
PF - 3 →	0	1	0
PF - 4 →	0	0	0

└──────────┘
3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	1	↓	2	3	4	5
	1	1	1	1	1	1	1	1					
		2	2	2	2	2	2	2					
			3	3	3	3	5	5					
				4	4	4	4	4					

Counters %

PF - 1 →	1	0	0
PF - 2 →	0	0	1
PF - 3 →	0	1	0
PF - 4 →	0	0	0

3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	1	↓	2	3	4	5
	1	1	1	1	1	1	1	1	1	1			
		2	2	2	2	2	2	2	2	2			
			3	3	3	3	5	5	5				
				4	4	4	4	4	4	4			

Counters %

PF - 1 →	0	1	0
PF - 2 →	1	0	0
PF - 3 →	0	0	1
PF - 4 →	0	0	0

└──────────┘
3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1			
		2	2	2	2	2	2	2	2			
			3	3	3	3	5	5	5			
				4	4	4	4	4	4			

Counters %

PF - 1 →	0	1	0
PF - 2 →	1	0	0
PF - 3 →	0	0	1
PF - 4 →	0	0	0

smallest!



3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1		
		2	2	2	2	2	2	2	2	2		
			3	3	3	3	5	5	5	5		
				4	4	4	4	4	4	4	3	

Counters %

PF - 1 →	0	1	0
PF - 2 →	1	0	0
PF - 3 →	0	0	1
PF - 4 →	0	0	0

└──────────┘
3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1		
		2	2	2	2	2	2	2	2	2		
			3	3	3	3	5	5	5	5		
				4	4	4	4	4	4	4		
										3		

Counters %

		<u>aging</u> →		
PF - 1 →	0	1	0	
PF - 2 →	1	0	0	
PF - 3 →	0	0	1	
PF - 4 →	0	0	0	
	└──────────┘			
	3 bits			

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1		
		2	2	2	2	2	2	2	2	2		
			3	3	3	3	5	5	5	5		
				4	4	4	4	4	4	4	3	

Counters %

PF - 1 →	0	0	1
PF - 2 →	0	1	0
PF - 3 →	0	0	0
PF - 4 →	1	0	0

3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1		
		2	2	2	2	2	2	2	2	2		
			3	3	3	3	5	5	5	5		
				4	4	4	4	4	4	4	3	

Counters %

PF - 1 →	0	0	1
PF - 2 →	0	1	0
PF - 3 →	0	0	0
PF - 4 →	1	0	0

3 bits

LRU + Aging



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1		
		2	2	2	2	2	2	2	2	2		
			3	3	3	3	5	5	5	5		
				4	4	4	4	4	4	4	3	

Counters %

PF - 1 →

0 0 1

PF - 2 →

0 1 0

PF - 3 →

0 0 0

PF - 4 →

1 0 0

smaller +!



3 bits

LRU + Aging

↓

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	1	
		2	2	2	2	2	2	2	2	2	2	
			3	3	3	3	5	5	5	5	4	
				4	4	4	4	4	4	3	3	

Counters %

PF - 1 →	0	0	1
PF - 2 →	0	1	0
PF - 3 →	0	0	0
PF - 4 →	1	0	0

3 bits

LRU + Aging

↓

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	1	
		2	2	2	2	2	2	2	2	2	2	
			3	3	3	3	5	5	5	5	4	
				4	4	4	4	4	4	3	3	

Counters %

aging →

PF - 1 →

0 0 1

PF - 2 →

0 1 0

PF - 3 →

0 0 0

PF - 4 →

1 0 0

3 bits

LRU + Aging



<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	1	
		2	2	2	2	2	2	2	2	2	2	
			3	3	3	3	5	5	5	5	4	
				4	4	4	4	4	4	3	3	

Counters %

PF - 1 →

0 0 0

PF - 2 →

0 0 1

PF - 3 →

1 0 0

PF - 4 →

0 1 0

3 bits

LRU + Aging

↓

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	1	
		2	2	2	2	2	2	2	2	2	2	
			3	3	3	3	5	5	5	5	4	
				4	4	4	4	4	4	3	3	

Counters %

PF - 1 →

0 0 0

PF - 2 →

0 0 1

PF - 3 →

1 0 0

PF - 4 →

0 1 0

← smallest!

3 bits

LRU + Aging

↓

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	1	5
		2	2	2	2	2	2	2	2	2	2	2
			3	3	3	3	5	5	5	5	4	4
				4	4	4	4	4	4	3	3	3

Counters %

aging

PF - 1 →

0 0 0

PF - 2 →

0 0 1

PF - 3 →

1 0 0

PF - 4 →

0 1 0

3 bits

LRU + Aging

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1	1	1	1	1	1	1	1	1	1	1	5
		2	2	2	2	2	2	2	2	2	2	2
			3	3	3	3	5	5	5	5	4	4
				4	4	4	4	4	4	3	3	3

Counters %

PF - 1 →

PF - 2 →

PF - 3 →

PF - 4 →

1	0	0
0	0	0
0	1	0
0	0	1

3 bits