

Page replacement algorithms

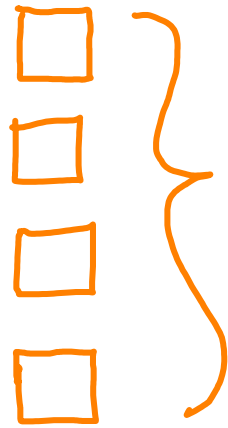
loic.guegan@uit.no

Optimal

Optimal

VP:

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



4 page frames



5 \neq 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>	<div>1</div>	<div>2</div>	<div>3</div>	<div>4</div>	1	2	5	1	2	3	4	5
	1	1	1	1								
		2	2	2								
			3	3								
				4								

Optimal

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

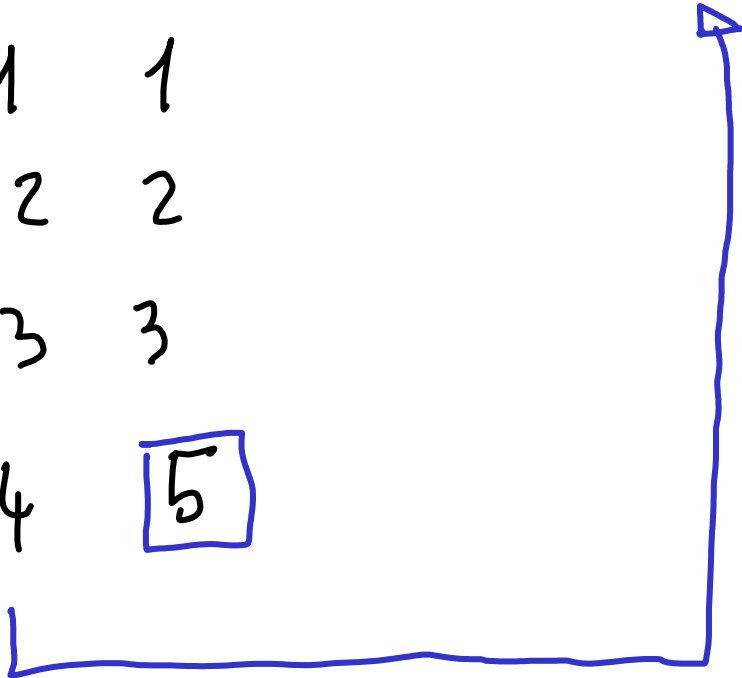
Optimal

<u>VP %</u>	1	2	3	4	1	<div>↓ 2</div>	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

↓

<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	3					
				4	4	4	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				
		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	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	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	5	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 % \downarrow 1 2 3 4 1 2 5 1 2 3 4 5
 1^0

Not Recently Used

VP: 1 2 3 4 1 2 5 1 2 3 4 5

↓

1° 1° 2°

Not Recently Used

VP %

1	2	3
1°	1°	1°
	2°	2°
		3°

Not Recently Used

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

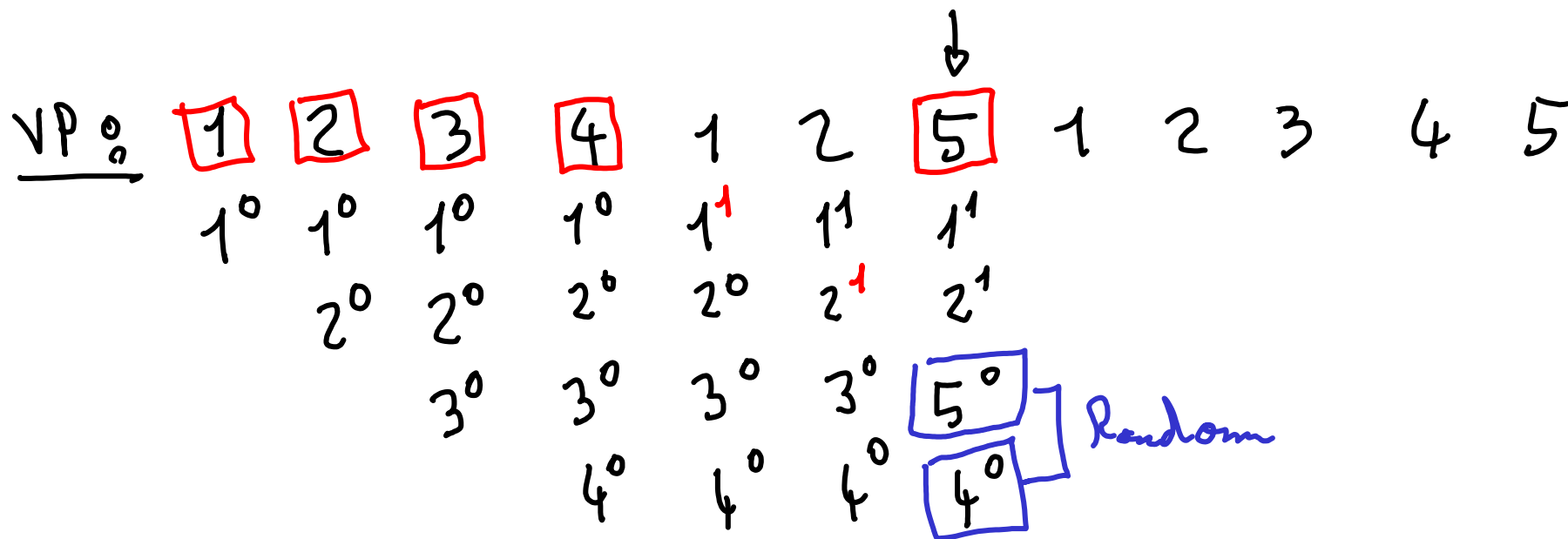
Not Recently Used

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

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

[illegible]

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		
		2 ⁰	2 ⁰	2 ⁰	2 ⁰	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹		
			3 ⁰	3 ⁰	3 ⁰	3 ⁰	5 ⁰	5 ⁰	5 ⁰	5⁰		
				4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3⁰		

} Random

Not Recently Used

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1°	1°	1°	1°	1 ¹	11	1 ¹	1 ¹	11	1 ¹	1 ¹	
		2°	2°	2°	2°	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹	
			3°	3°	3°	3°	5°	5°	5°	5°	4°	
				4°	4°	4°	4°	4°	4°	3°	3°	

Random

Not Recently Used

<u>VP %</u>	1	2	3	4	1	2	5	1	2	3	4	5
	1°	1°	1°	1°	1 ¹	11	1 ¹	1 ¹	11	1 ¹	1 ¹	1 ¹
		2°	2°	2°	2°	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹	2 ¹
			3°	3°	3°	3°	5°	5°	5°	5°	4°	5°
				4°	4°	4°	4°	4°	4°	3°	3°	3°

↓

Random

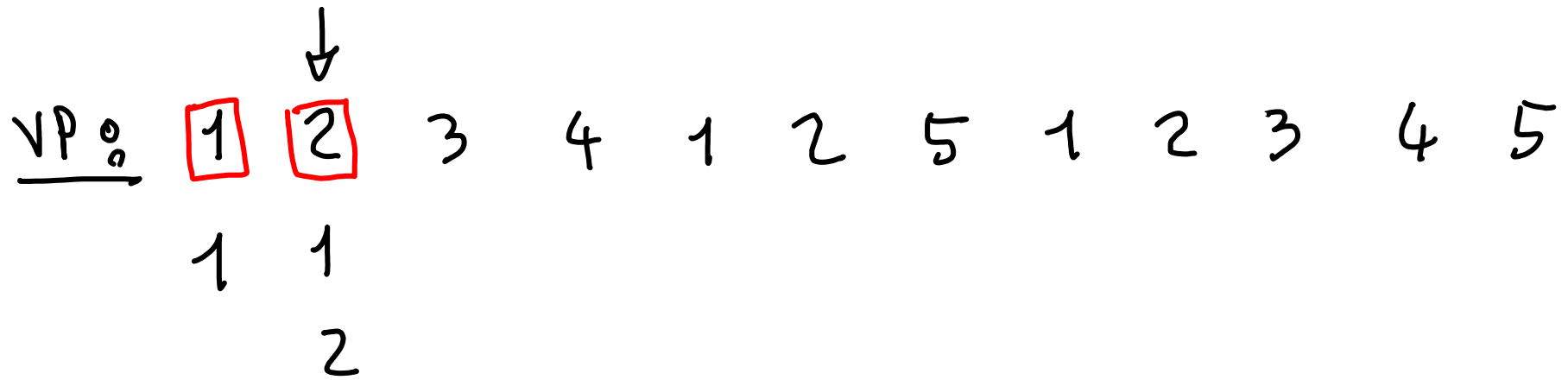
FIFO

FIFO

↓
VP : 1 2 3 4 1 2 5 1 2 3 4 5
1

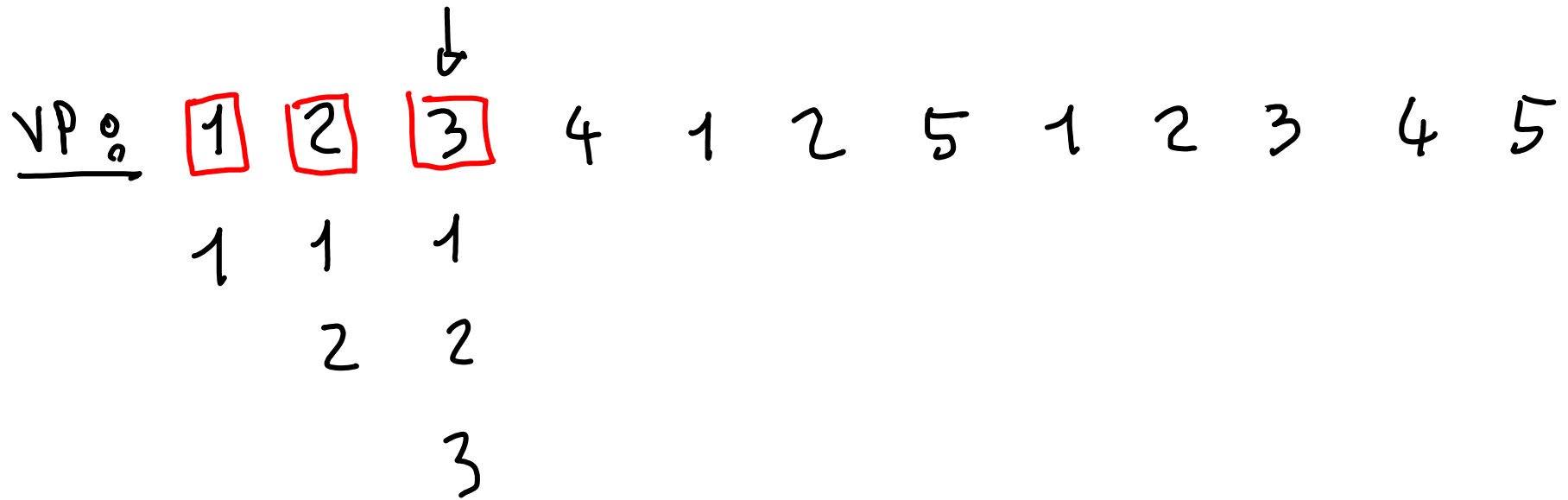
FIFO : 1

FIFO



FIFO : 1, 2

FIFO



FIFO : 1, 2, 3

FIFO



<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

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

↓

<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						

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					
		2	2	2	2	2	2					
			3	3	3	3	3					
				4	4	4	4					

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	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>	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 : 2, 3, 4, 5

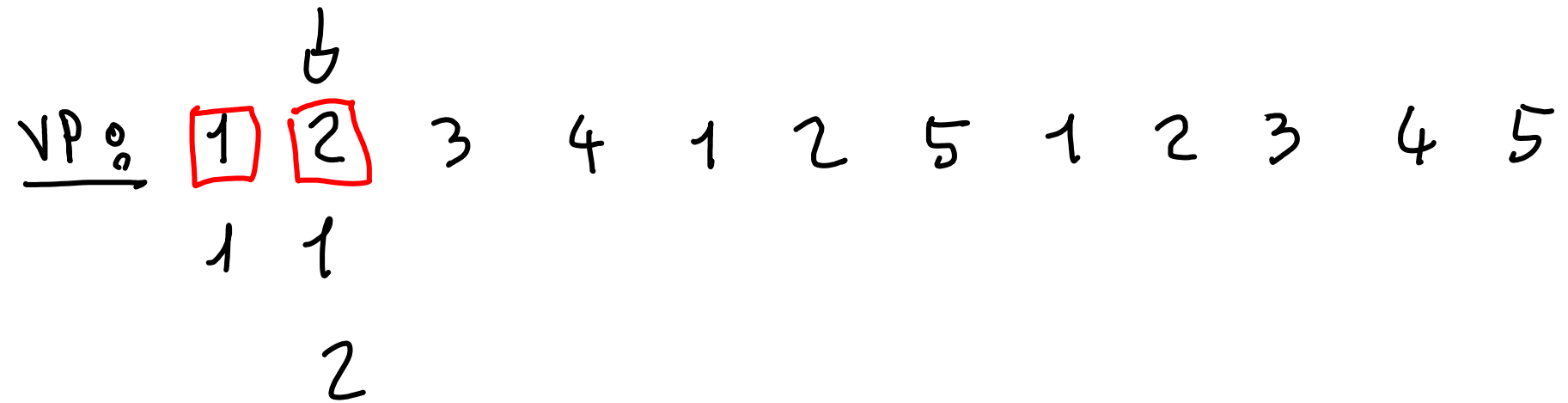
FIFO 2nd Chance

FIFO 2nd Chance

VP: ↓
 1
1 2 3 4 1 2 5 1 2 3 4 5
 1

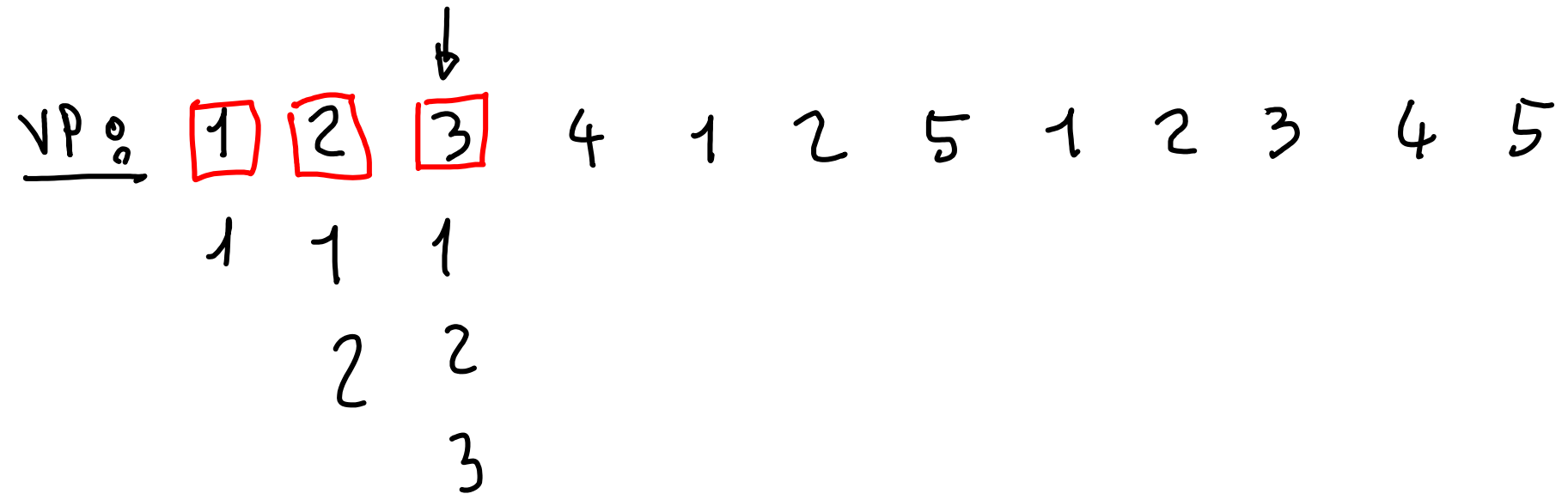
FIFO: 1

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

↓

<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 ⁰							
			3	3	3 ⁰							
				4	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						
		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>	<div>↓</div> <div>1</div>	<div>↓</div> <div>2</div>	<div>↓</div> <div>3</div>	<div>↓</div> <div>4</div>	1	2	<div>↓</div> <div>5</div>	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 → 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>	<div>↓</div> <div>1</div>	<div>↓</div> <div>2</div>	<div>↓</div> <div>3</div>	<div>↓</div> <div>4</div>	1	2	<div>↓</div> <div>5</div>	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>	<div>↓</div> <div>1</div>	<div>2</div>	<div>3</div>	<div>4</div>	1	2	<div>5</div>	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	<div>5⁰</div>					
				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

									↓		
<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	3 ⁰	

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 → 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 → 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	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	3 ⁰	3 ⁰	

FIFO: 3, 1, 2, 4

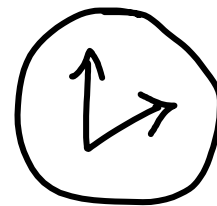
FIFO 2nd Chance

↓

<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~~, 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

VP% 1 2 3 4 \downarrow 1 2 5 1 2 3 4 5

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

clock%

4 1
 \uparrow
 2

3

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%

4 1 2
↑
3

clock



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

1 1 1 1 1¹ 1¹ 1⁰
 2 2 2 2⁰ 2¹
 3 3 3⁰ 3⁰
 4 4⁰ 4⁰

1

clock%

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						
				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	5 ⁰					
				4	4 ⁰	4 ⁰	4 ⁰					

clock %

1

4 2

↓

~~3~~

clock



VP: 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					

1

clock:

4



2

5

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				
		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 %

1

4 ← 2

5

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 %

1

4 ← 2

5

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		
										3 ⁰		

clock %

1

~~1~~ ← 2

5

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	3 ⁰	

clock %

3 1 2

↑

5

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		
			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	3^0		

clock%

1

3 → 2

5

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		
				4	4^0	4^0	4^0	4^0	4^0	3^0		

clock%

1

3 2

↓

5

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%

1

3

2

↓

~~5~~


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	4 ⁰	
				4	4 ⁰	4 ⁰	4 ⁰	4 ⁰	4 ⁰	3 ⁰	3 ⁰	

clock %

1

3  2

4

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

1

clock %

~~3~~

→

2

4

LRU

LRU

VP % 1 2 3 4 1 2 5 1 2 3 4 5
 ↓
 1

LRU list % 1

LRU

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

MRU
↓
LRU list % 2, 1

↙ 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							
		2	2	2	2							
			3	3	3							
				4	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								
		2	2	2	2								
			3	3	3								
				4	4								

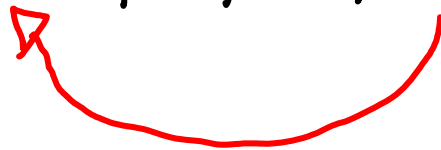
LRU List % 1, 4, 3, 2

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



L R U

↓

<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~~ → 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				
		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>	<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	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	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	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	
			3	3	3	3	5	5	5	5	4	
				4	4	4	4	4	4	3	3	

LRU List : 3, 2, 1, ~~5~~ \rightarrow 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

Aging: NFU

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

\downarrow
VP % 1 2 3 4 1 2 5 1 2 3 4 5
 1

Counters %

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

[
3 bits
]

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

Counters % aging
 PF - 1 → 1 0 0
 PF - 2 → 0 0 0
 PF - 3 → 0 0 0
 PF - 4 → 0 0 0

3 bits

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

Counters %

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

3 bits

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

Counters %

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

3 bits

↓

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

1 1

2

Counters %

aging →

PF - 1 →	○	1	○
PF - 2 →	1	○	○
PF - 3 →	○	○	○
PF - 4 →	○	○	○

3 bits

↓

VP % 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

↓

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

1 1 1

2 2

3

Counters %

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

3 bits

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

Counters % aging

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

3 bits

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

Counters %

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

3 bits

<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	1
PF - 3 →	0	1	0
PF - 4 →	1	0	0

3 bits

VP % 1 2 3 4 \downarrow
 1 1 1 1 1 2 5 1 2 3 4 5
 1 1 1 1
 2 2 2
 3 3
 4

Counters %

PF - 1 \longrightarrow 0 0 0
 PF - 2 \longrightarrow 0 0 1
 PF - 3 \longrightarrow 0 1 0
 PF - 4 \longrightarrow 1 0 0

3 bits

VP % 1 2 3 4 \downarrow
 1 1 1 1 1 2 5 1 2 3 4 5
 1 1 1 1
 2 2 2
 3 3
 4

Counters % align \rightarrow
 PF - 1 \rightarrow 0 0 0
 PF - 2 \rightarrow 0 0 1
 PF - 3 \rightarrow 0 1 0
 PF - 4 \rightarrow 1 0 0

 3 bits

VP % 1 2 3 4 \downarrow 1 2 5 1 2 3 4 5

1	1	1	1
	2	2	2
		3	3
			4

Counters %

PF - 1 \longrightarrow 0 0 0

PF - 2 \longrightarrow 0 0 0

PF - 3 \longrightarrow 0 0 1

PF - 4 \longrightarrow 0 1 0

3 bits

<u>VP %</u>	1	2	3	4	\downarrow	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 \longrightarrow 1 0 0

PF - 2 \longrightarrow 0 0 0

PF - 3 \longrightarrow 0 0 1

PF - 4 \longrightarrow 0 1 0

3 bits

<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

[0 1 0]

3 bits

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

<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

<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

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

3 bits

<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		

<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						

<u>Counters %</u>				<u>aging</u> →
PF - 1 →	0	0	1	
PF - 2 →	0	1	0	
PF - 3 →	1	0	0	
PF - 4 →	0	0	0	
	3 bits			

<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

<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

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
	3 bits		

<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

[0 0 0]

3 bits

smallest!



<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		

Counters %

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

3 bits

<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		

Counters %

PF - 1 →

0 1 0

PF - 2 →

1 0 0

PF - 3 →

0 0 1

PF - 4 →

0 0 0

[

3 bits

<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

<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

↓

<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 →

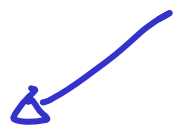
PF - 2 →

PF - 3 →

PF - 4 →

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

smaller + !



3 bits

↓

<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

↓

<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 →

PF - 2 →

PF - 3 →

PF - 4 →

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

3 bits

↓

<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

0 1 0

3 bits

↓

<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

← smallest!

↓

<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 →

aging

0 0 0

0 0 1

1 0 0

0 1 0

0 1 0

3 bits

<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	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