Operating Systems

David Hay

SYNCHRONIZATION

Motivation: Two processes (or threads) want to print

- Both processors write their job to the *spooler* – the (**shared**) queue from which the printer extracts job to print.
  - NULL: No job to print
  - OUT: Next job to print
  - IN: End of queue, write new job here

- Code for each process (adding jobs):
  Spooler[IN] = job
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IN and Spooler[] are shared among all processes

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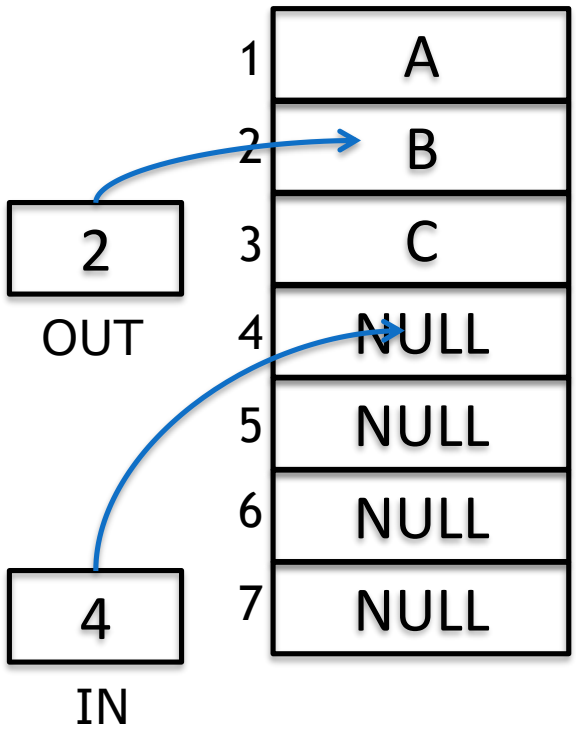
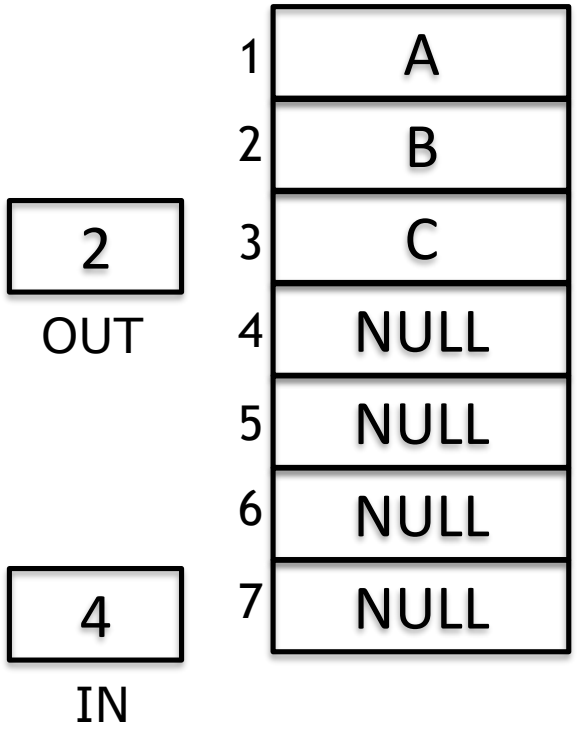
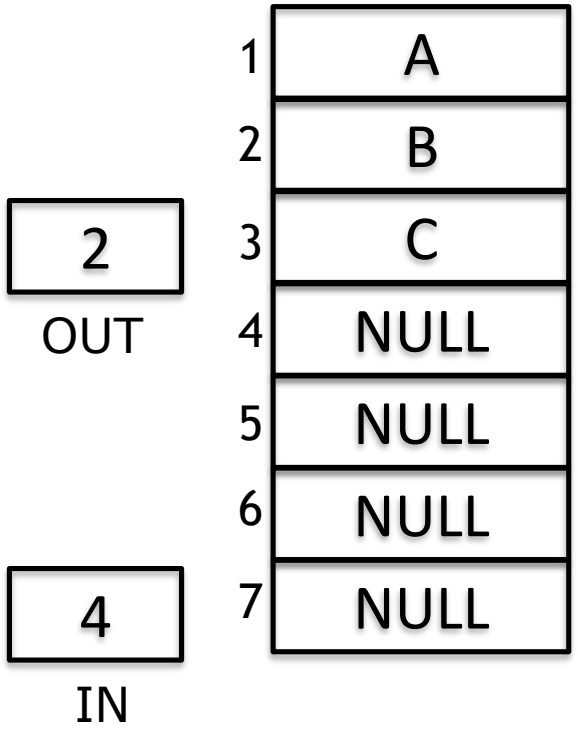


Possible Outcomes 1/2



Possible Outcomes 1/2

Process 1: Spooler[IN] = JOB1



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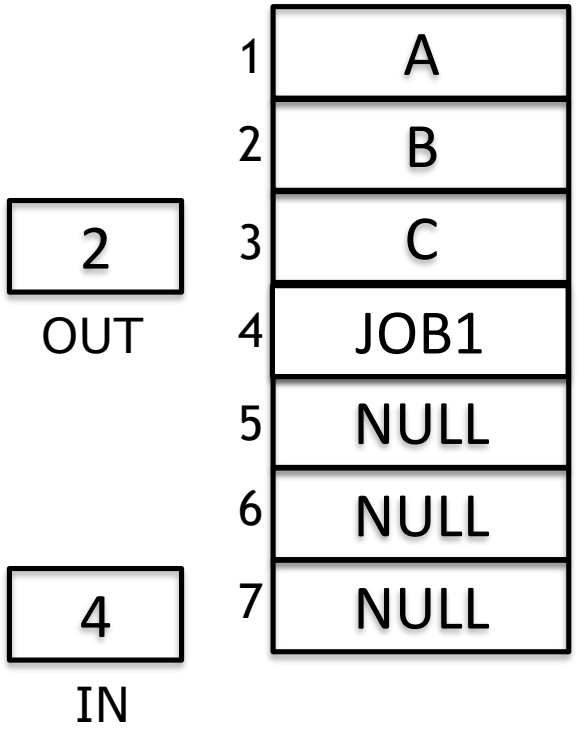
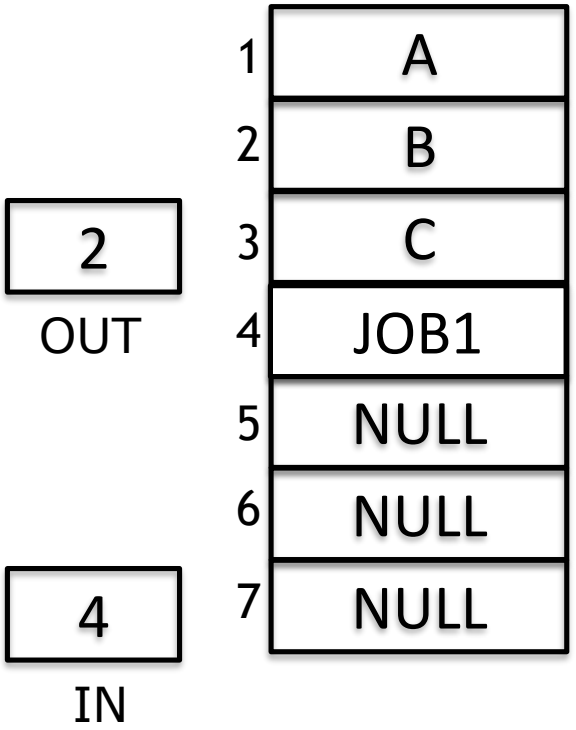


Possible Outcomes 1/2

Process 1: Spooler[IN] = JOB1

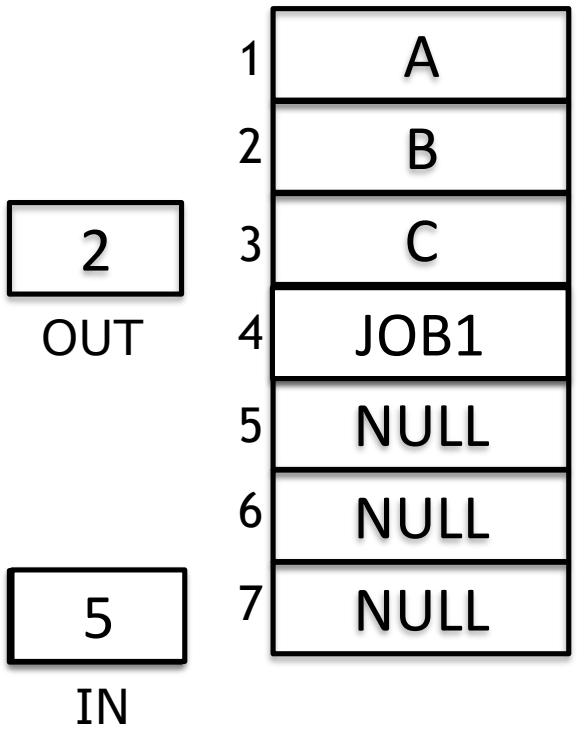
Process 1: IN++



Possible Outcomes 1/2

Process 1: Spooler[IN] = JOB1

Process 1: IN++

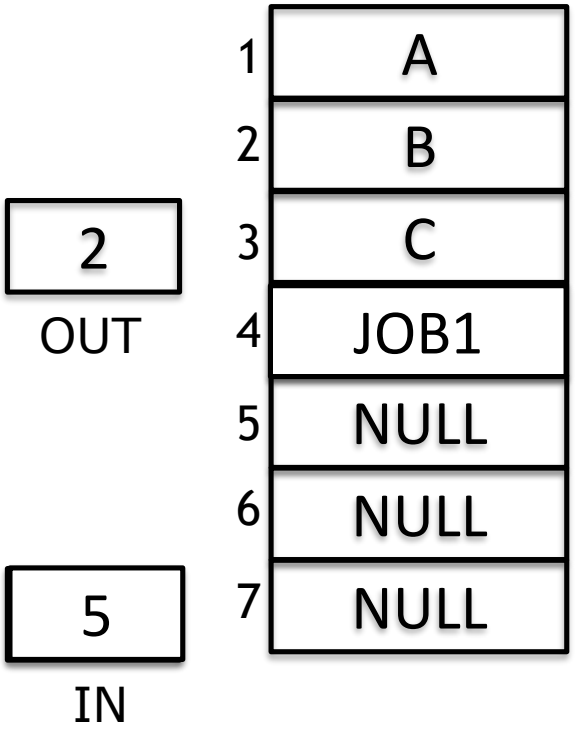


Possible Outcomes 1/2

Process 1: Spooler[IN] = JOB1

Process 1: IN++

<Context Switch by OS>



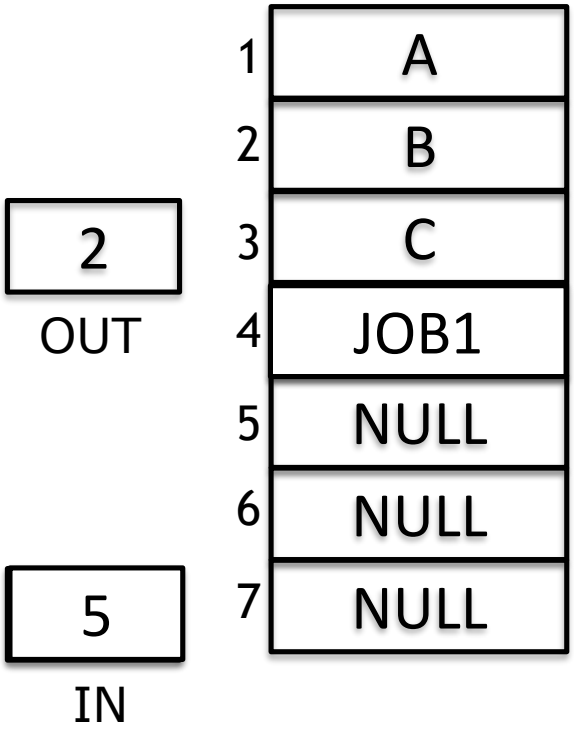
Possible Outcomes 1/2

Process 1: Spooler[IN] = JOB1

Process 1: IN++

<Context Switch by OS>

Process 2: Spooler[IN] = JOB2



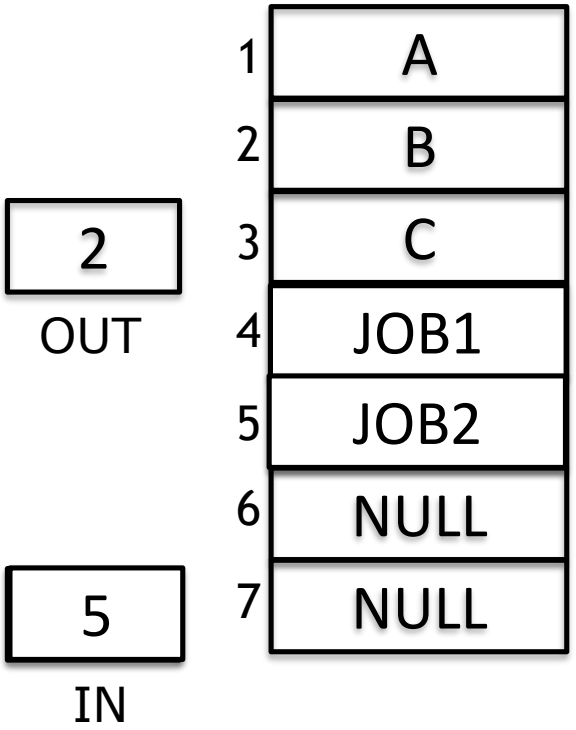
Possible Outcomes 1/2

Process 1: Spooler[IN] = JOB1

Process 1: IN++

<Context Switch by OS>

Process 2: Spooler[IN] = JOB2



Possible Outcomes 1/2

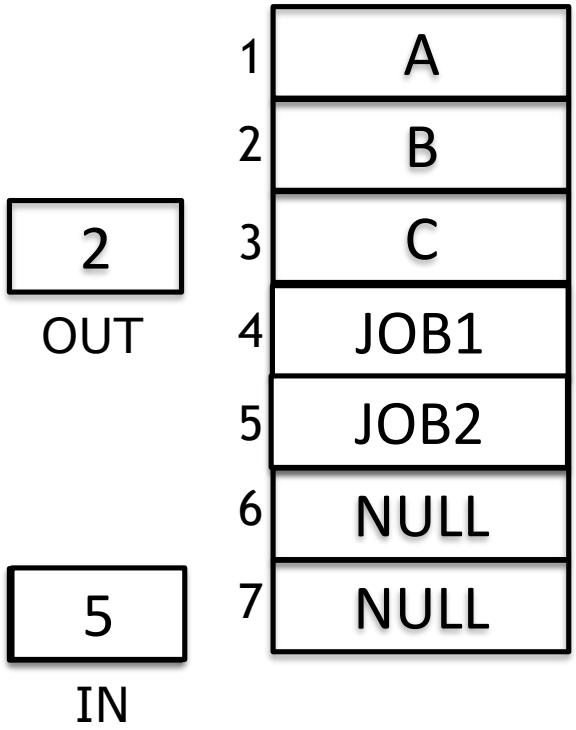
Process 1: Spooler[IN] = JOB1

Process 1: IN++

<Context Switch by OS>

Process 2: Spooler[IN] = JOB2

Process 2: IN++



Possible Outcomes 1/2

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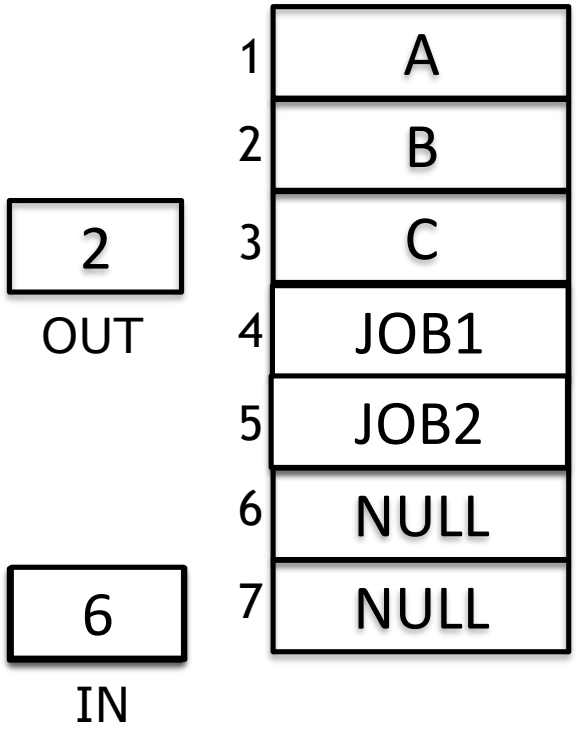
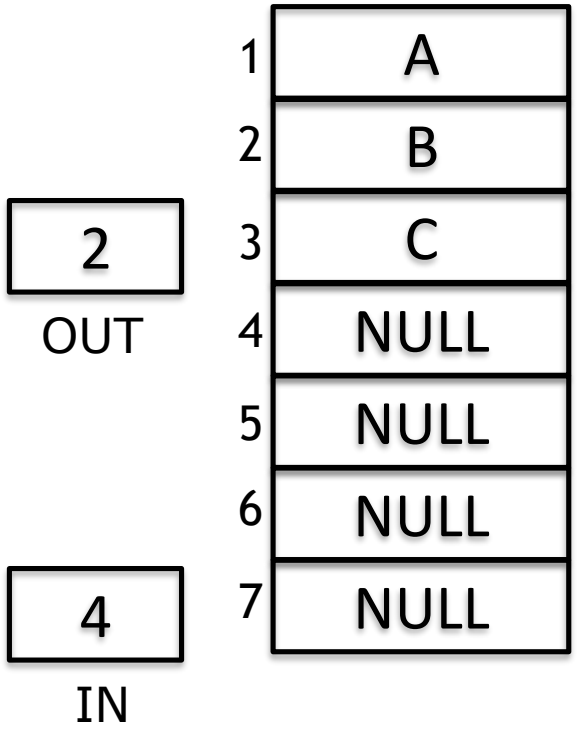
Process 2: Spooler[IN] = JOB2

Process 2: IN++



Possible Outcomes 2/2



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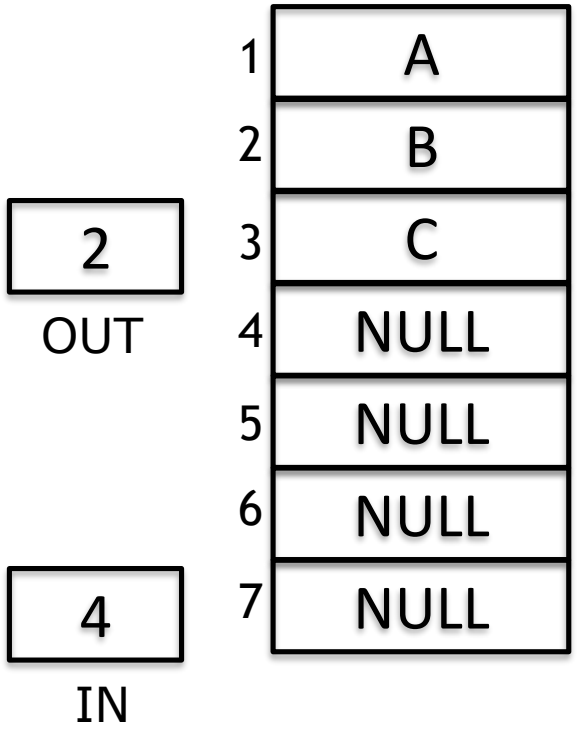

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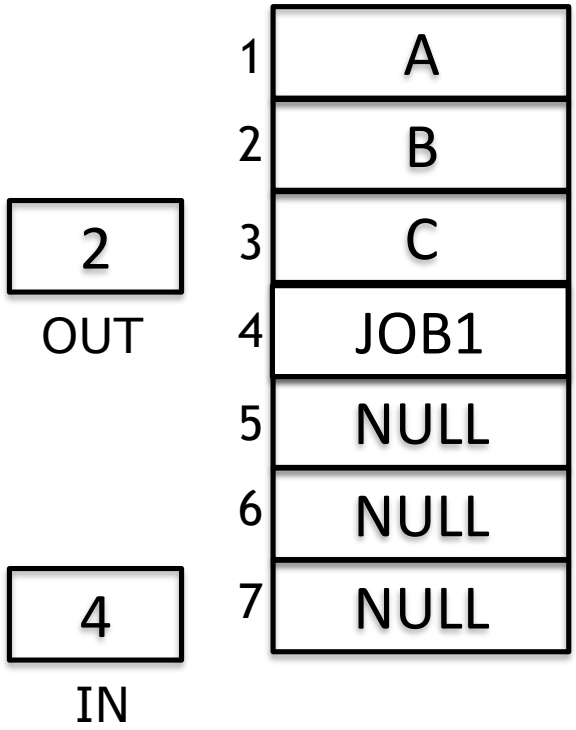

Possible Outcomes 2/2

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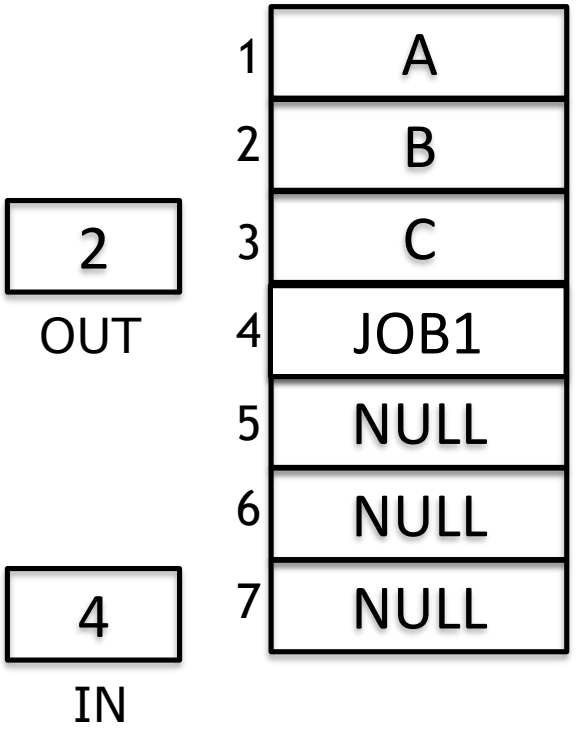
<Context Switch by OS>



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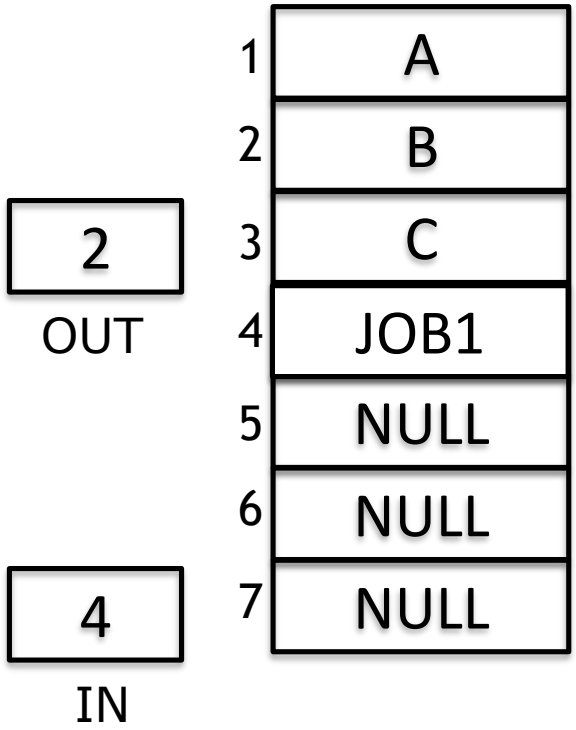

Possible Outcomes 2/2

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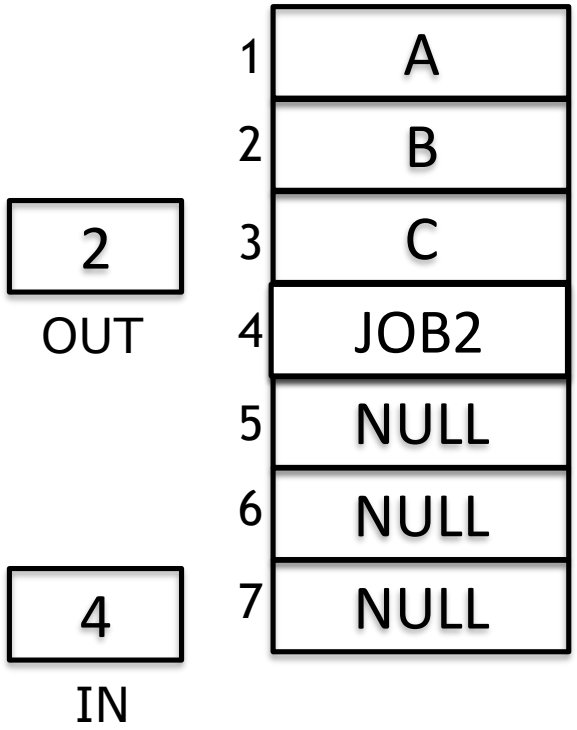

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Process 2: Spooler[IN] = JOB2

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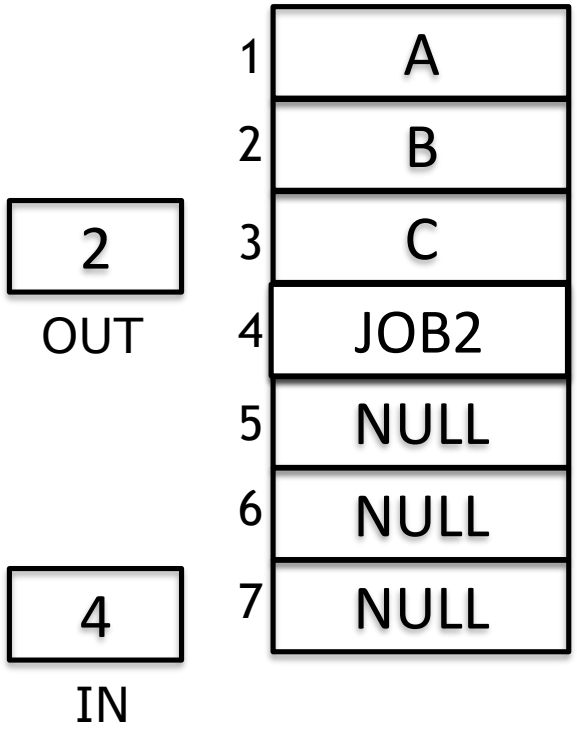

Possible Outcomes 2/2

Process 1: Spooler[IN] = JOB1

<Context Switch by OS>

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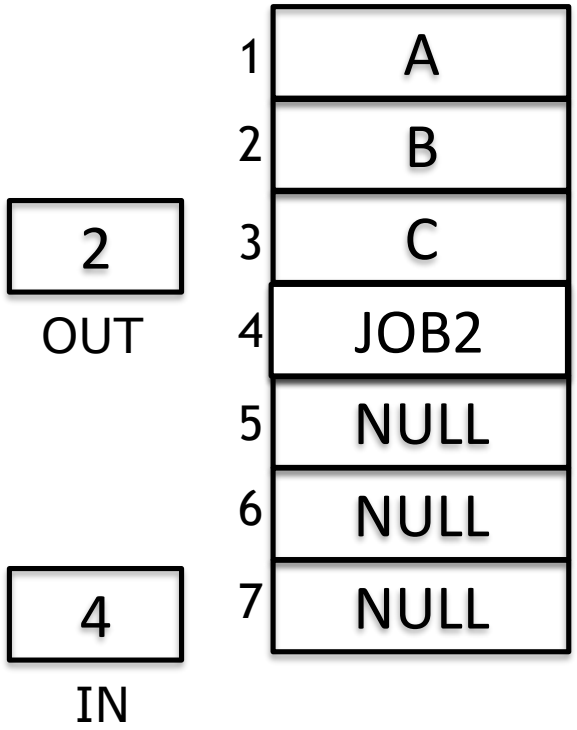
Process 1: IN++



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Process 1: Spooler[IN] = JOB1

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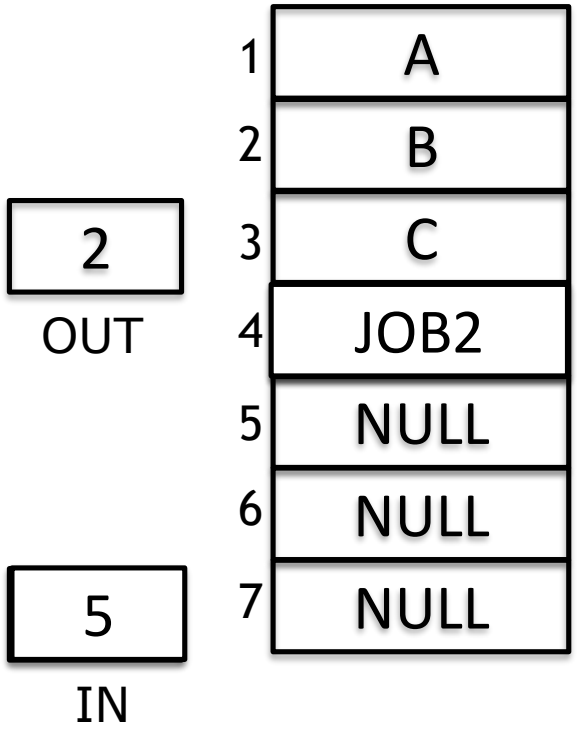
Process 1: IN++



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Process 1: Spooler[IN] = JOB1

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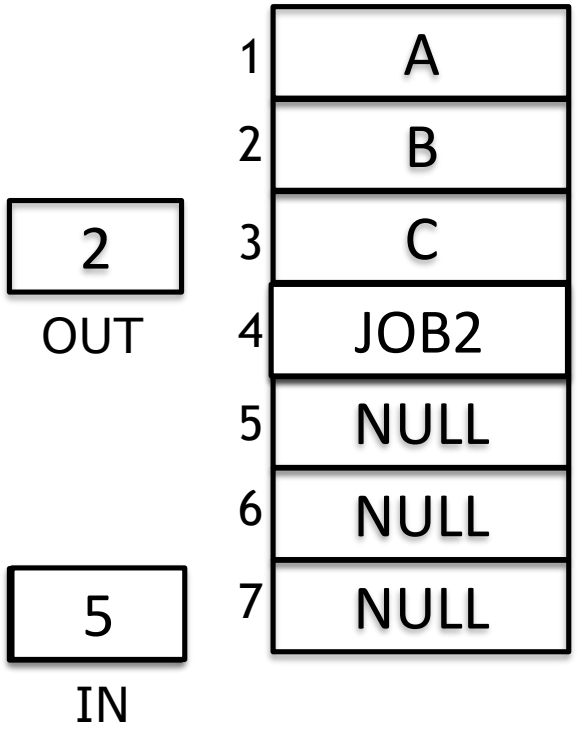
Process 1: IN++

<Context Switch by OS>



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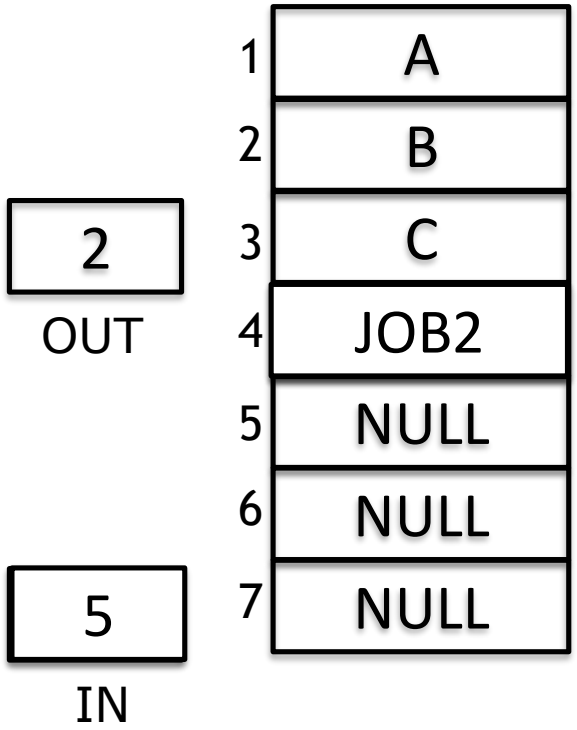
Process 2: IN++



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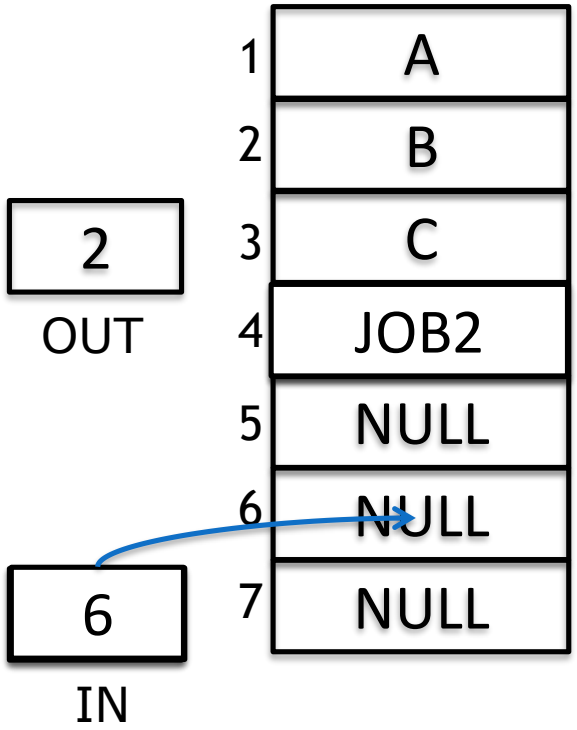
Process 2: IN++



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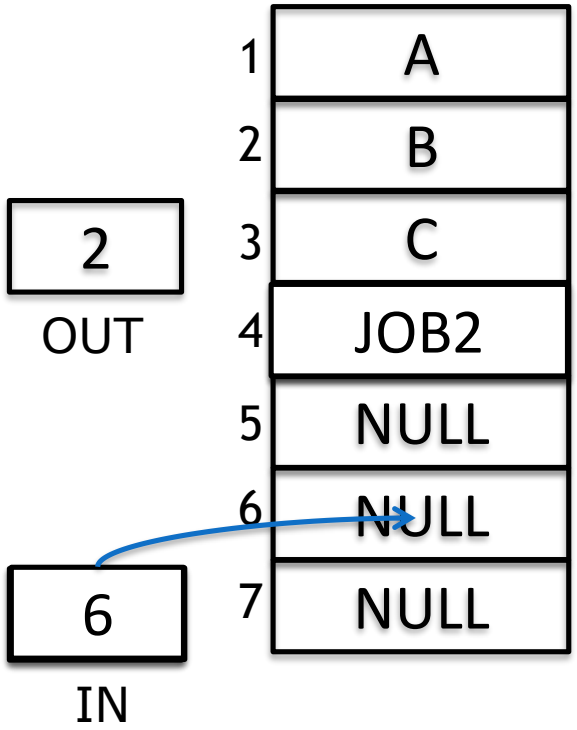
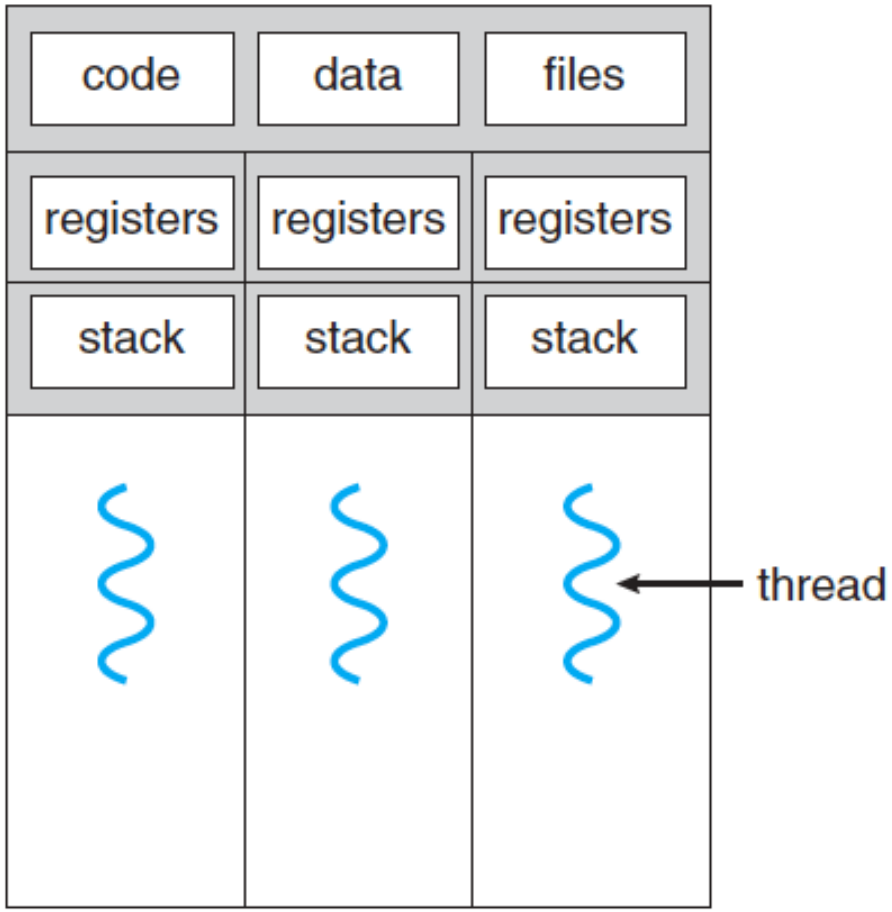


→ JOB1 is lost; all jobs after JOB2 may not be printed as well, because of the gap

Further Motivation



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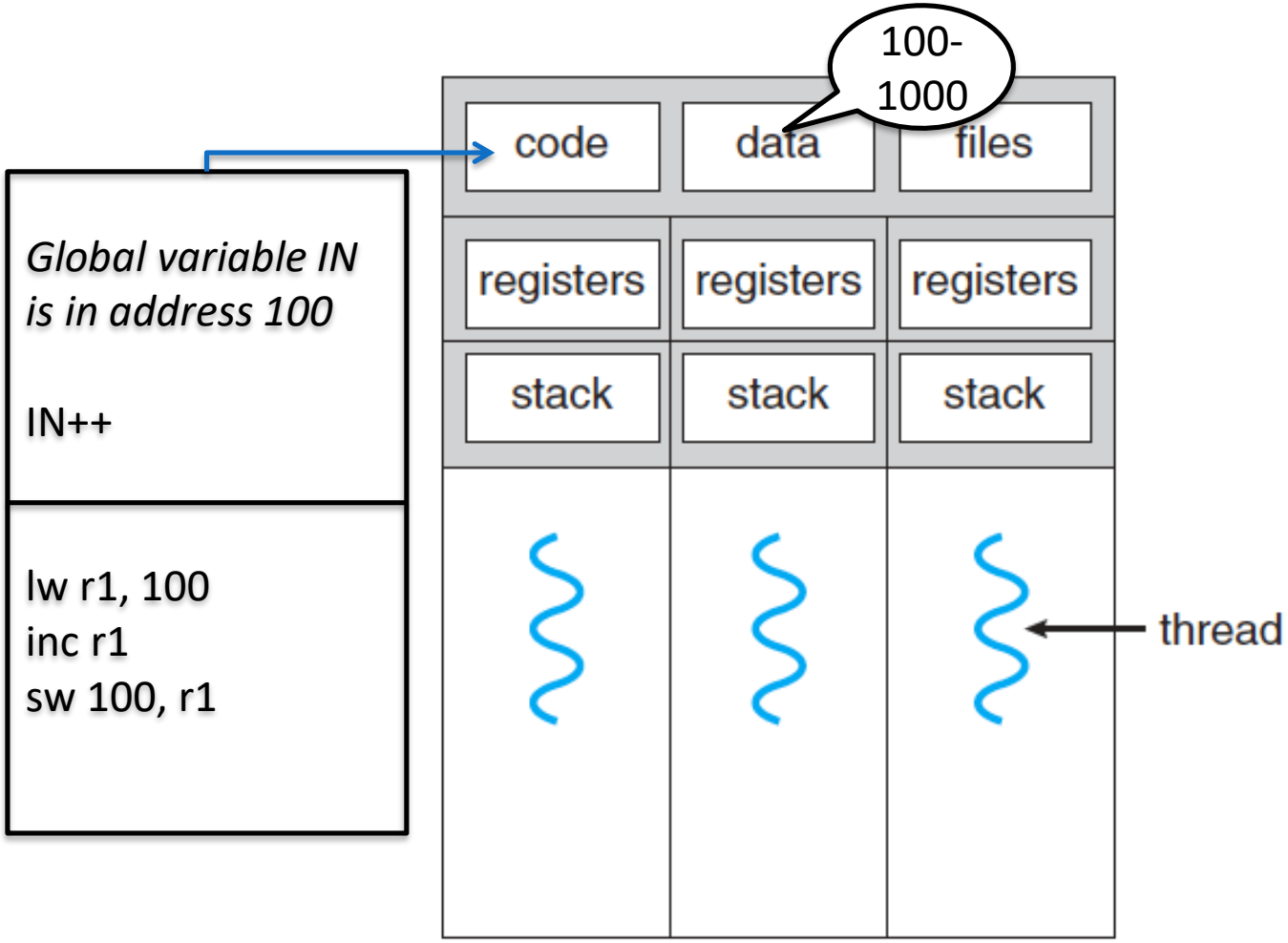
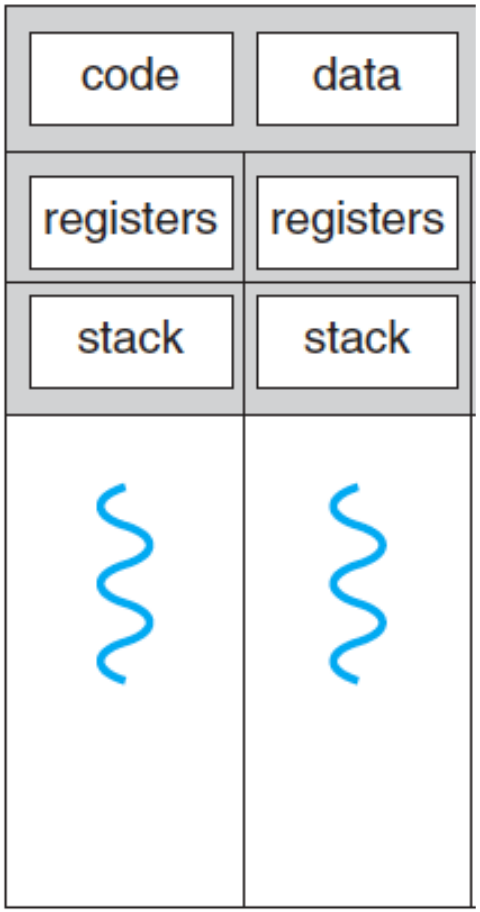


Further Motivation

```
lw r1, 100
inc r1
sw 100, r1
```



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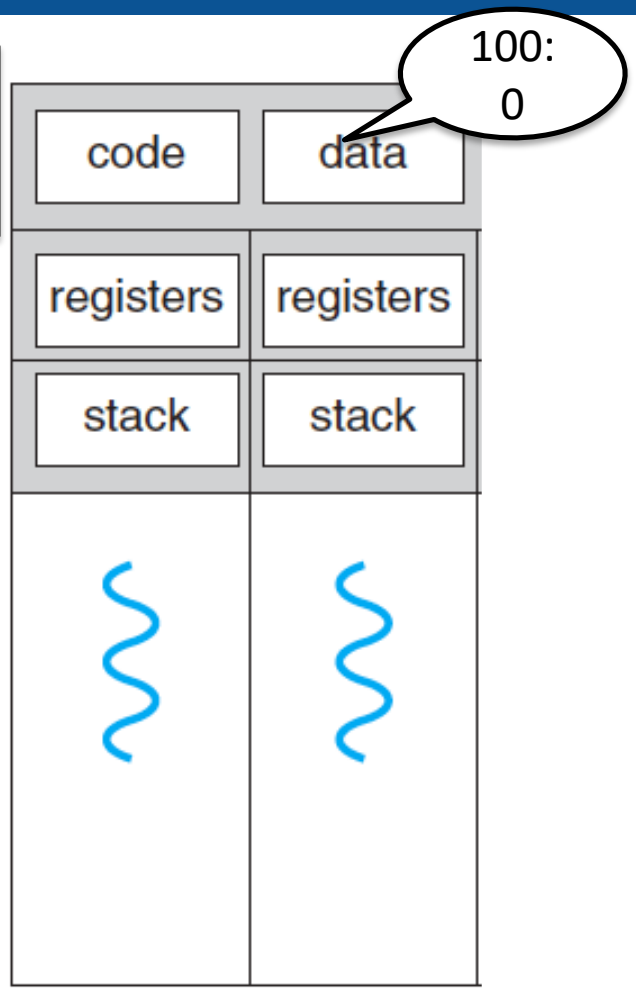

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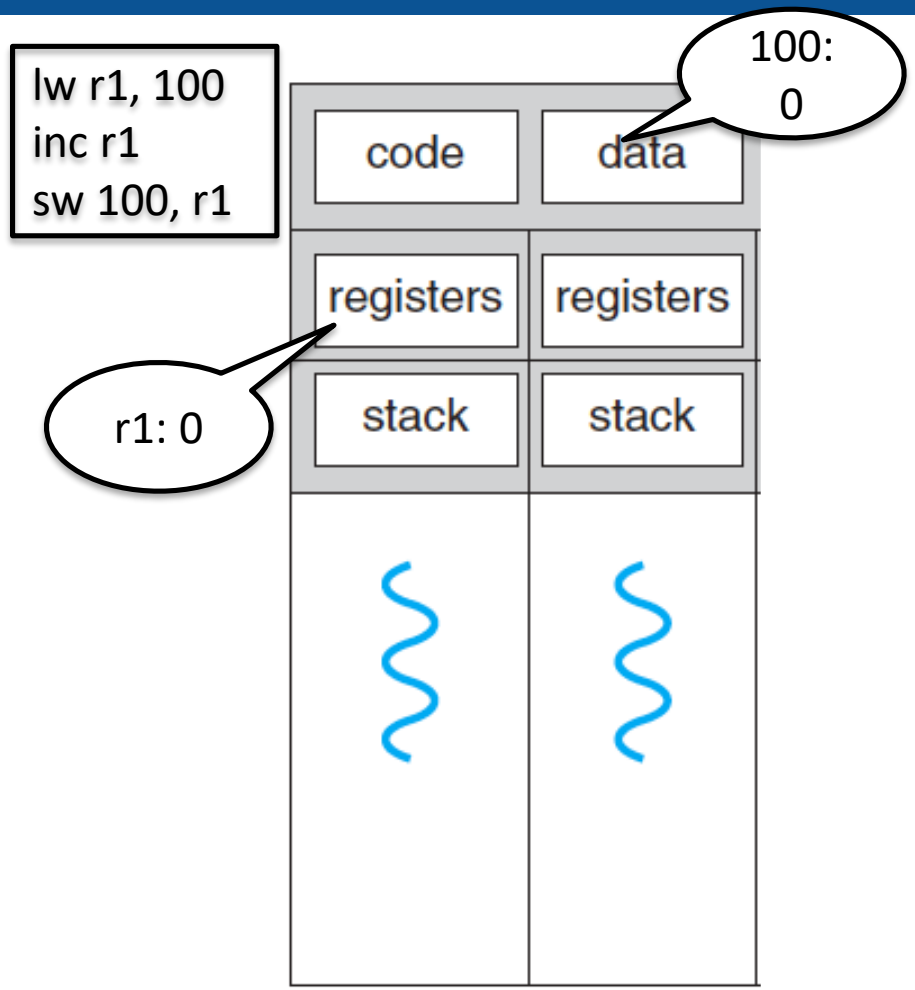
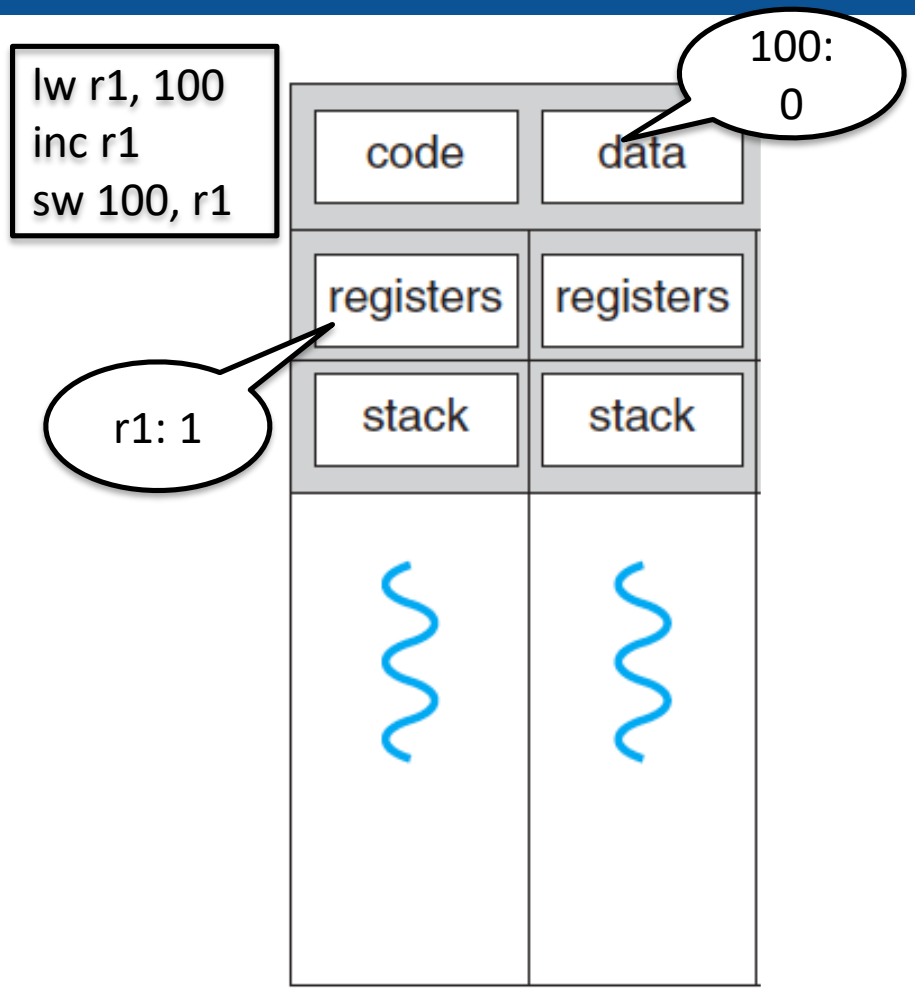


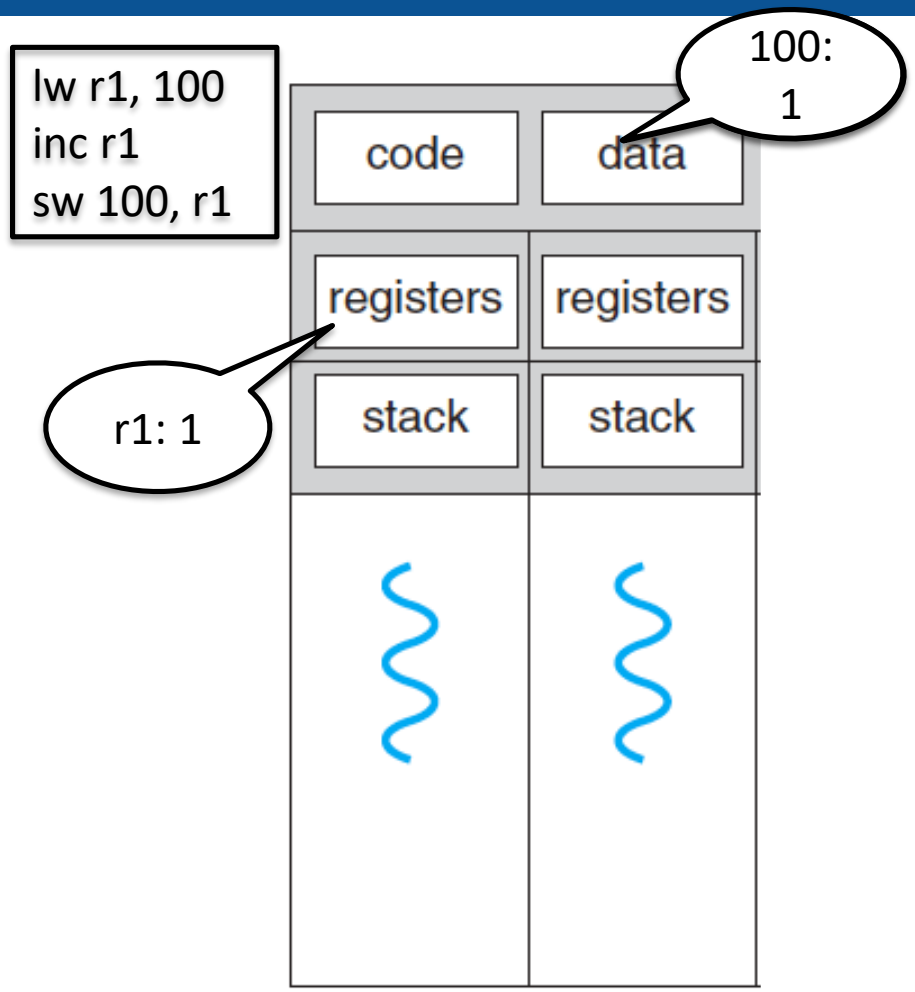
- Thread 1: lw r1,100

Further Motivation



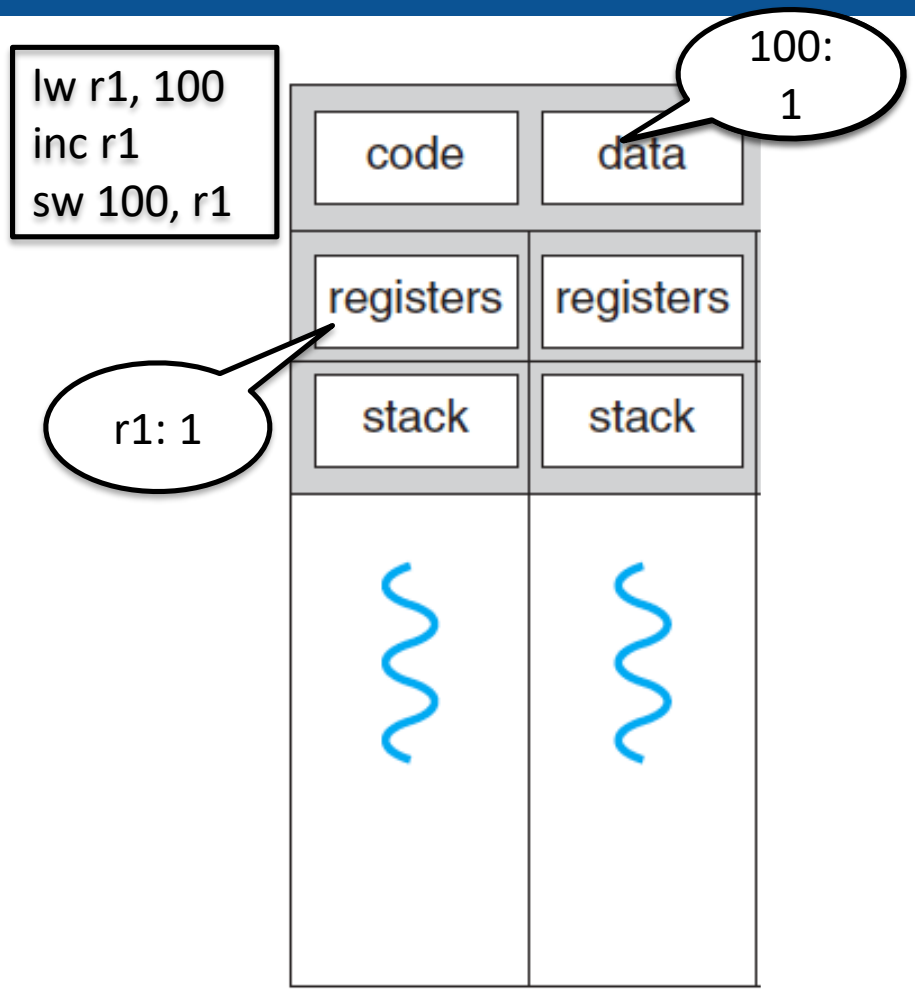
- Thread 1: lw r1,100
- Thread 1: inc r1

Further Motivation



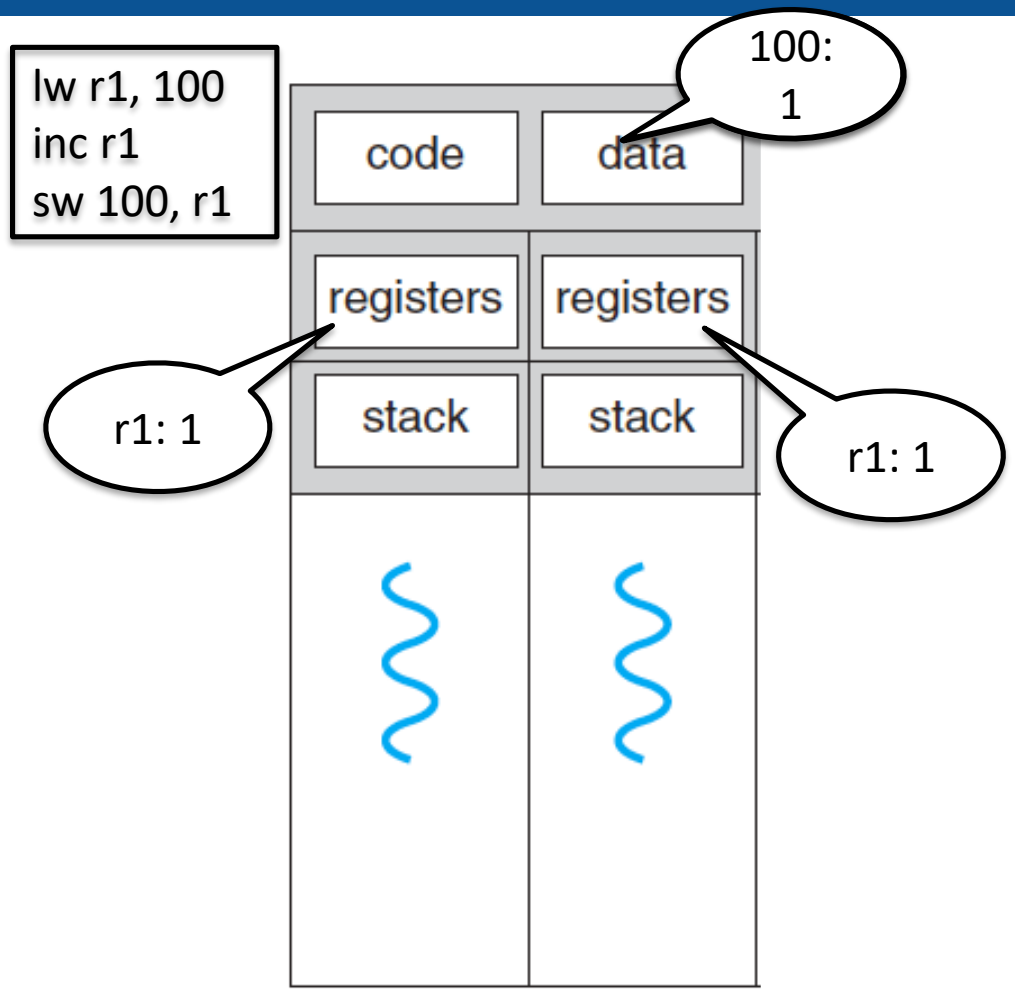
- Thread 1: lw r1,100
- Thread 1: inc r1
- Thread 1: sw 100,r1

Further Motivation



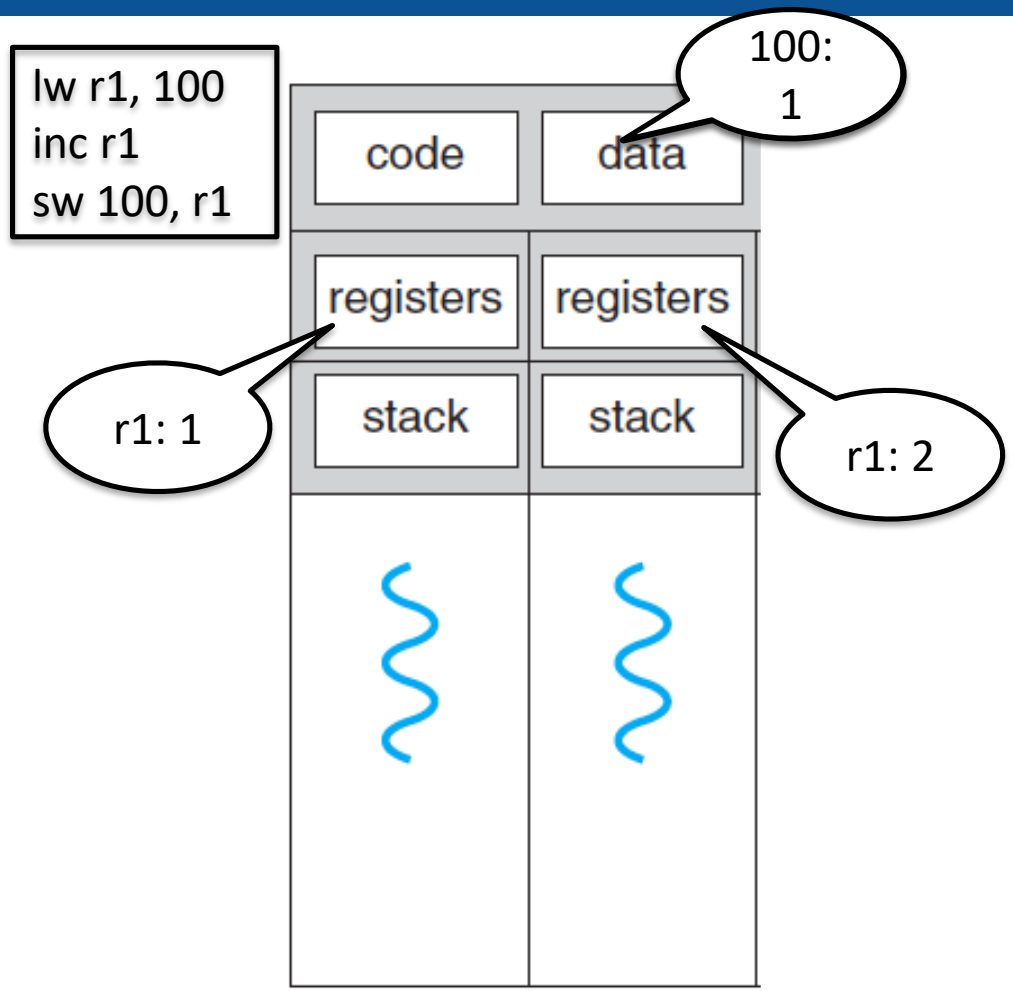
- Thread 1: lw r1,100
- Thread 1: inc r1
- Thread 1: sw 100,r1
- <Context Switch>

Further Motivation



- Thread 1: lw r1,100
- Thread 1: inc r1
- Thread 1: sw 100,r1
- <Context Switch>
- Thread 2: lw r1, 100

Further Motivation



- Thread 1: lw r1,100
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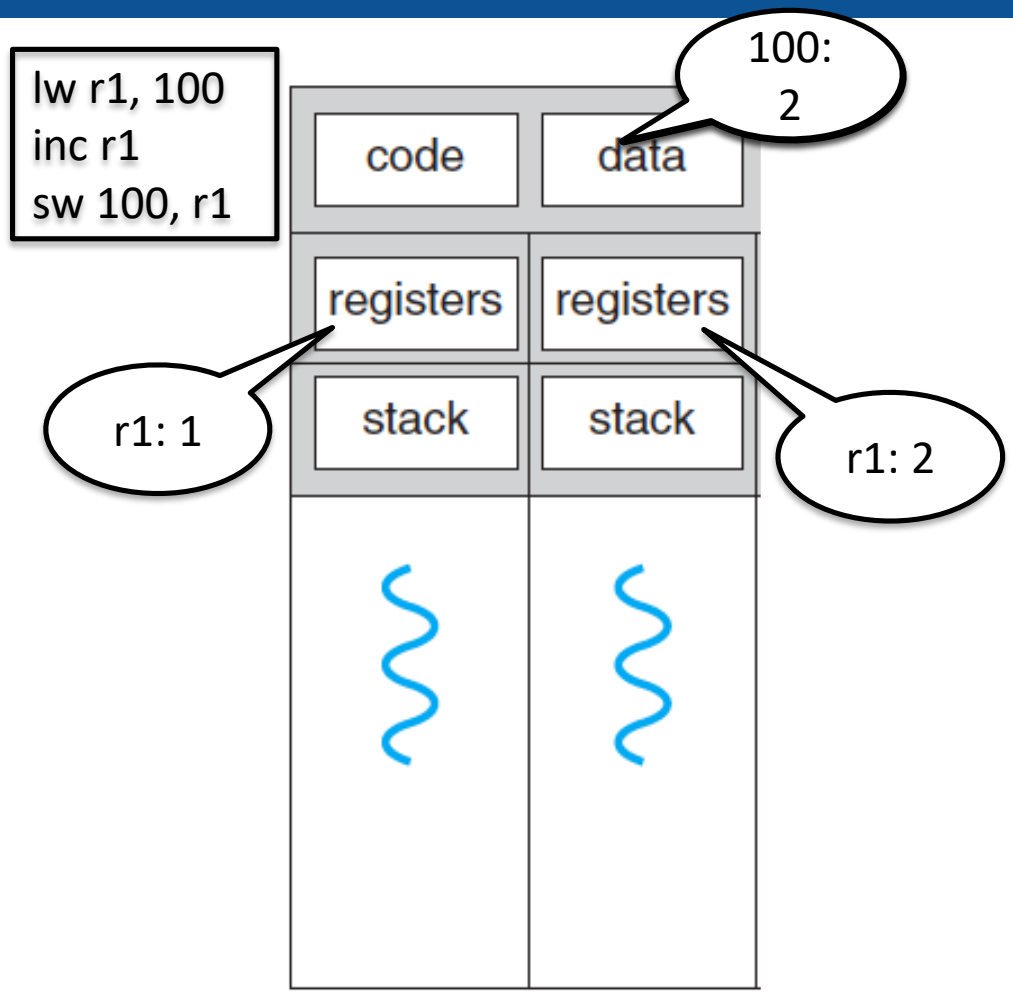
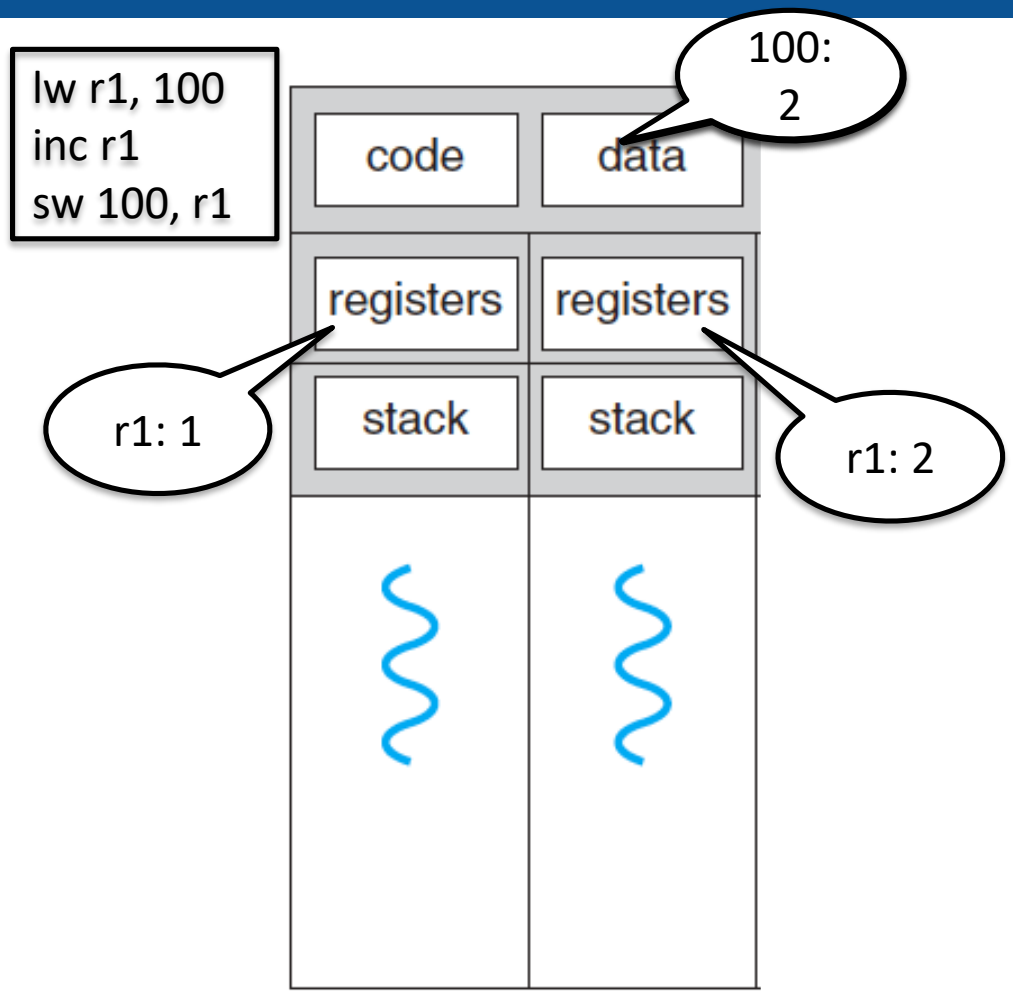
- <Context Switch>
- Thread 2: lw r1, 100
- Thread 2: inc r1

Further Motivation



- Thread 1: lw r1,100
- Thread 1: inc r1
- Thread 1: sw 100,r1
- <Context Switch>
- Thread 2: lw r1, 100
- Thread 2: inc r1
- Thread 2: sw 100, r1

Further Motivation

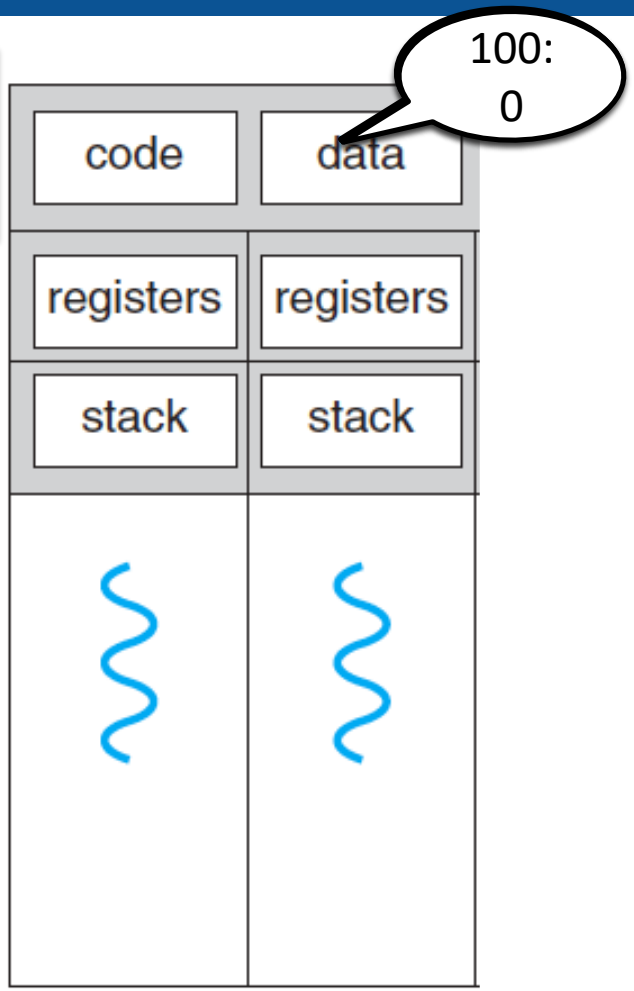


- Thread 1: lw r1,100
- Thread 1: inc r1
- Thread 1: sw 100,r1
- <Context Switch>
- Thread 2: lw r1, 100
- Thread 2: inc r1
- Thread 2: sw 100, r1

→ IN = 2

Further Motivation

```
lw r1, 100
inc r1
sw 100, r1
```



- Thread 1: lw r1,100
- Thread 1: inc r1
- Thread 1: sw 100,r1
- <Context Switch>
- Thread 2: lw r1, 100
- Thread 2: inc r1
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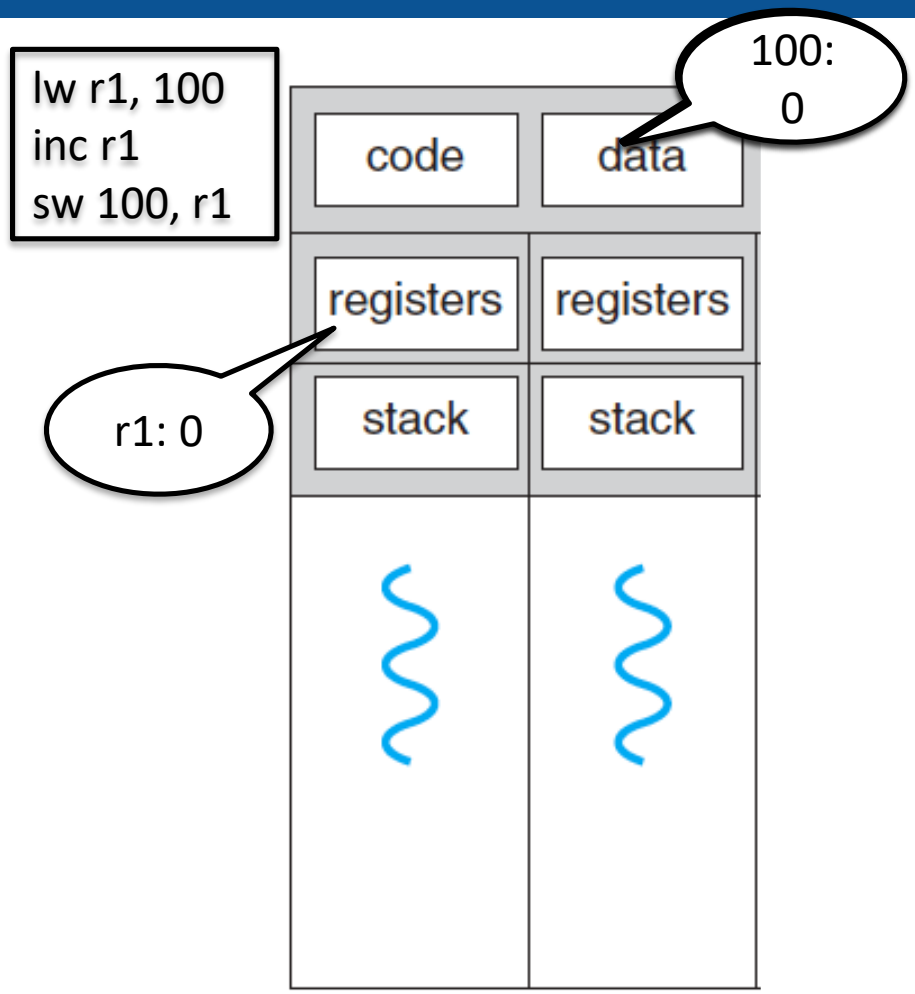
→ IN = 2

Further Motivation

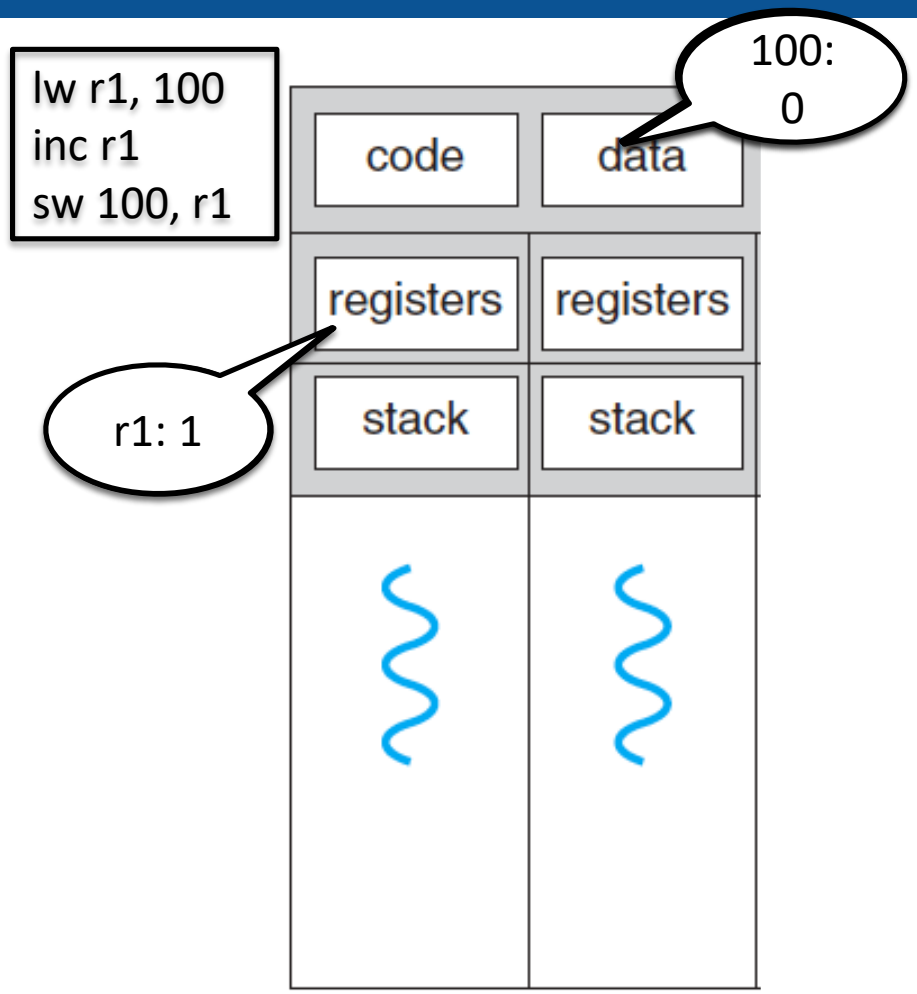


- Thread 1: lw r1,100
- Thread 1: inc r1
- Thread 1: sw 100,r1
- <Context Switch>
- Thread 2: lw r1, 100
- Thread 2: inc r1
- Thread 2: sw 100, r1

→ IN = 2

- Thread 1: lw r1,100

Further Motivation



- Thread 1: lw r1,100
- Thread 1: inc r1
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- <Context Switch>
- Thread 2: lw r1, 100
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- Thread 2: sw 100, r1

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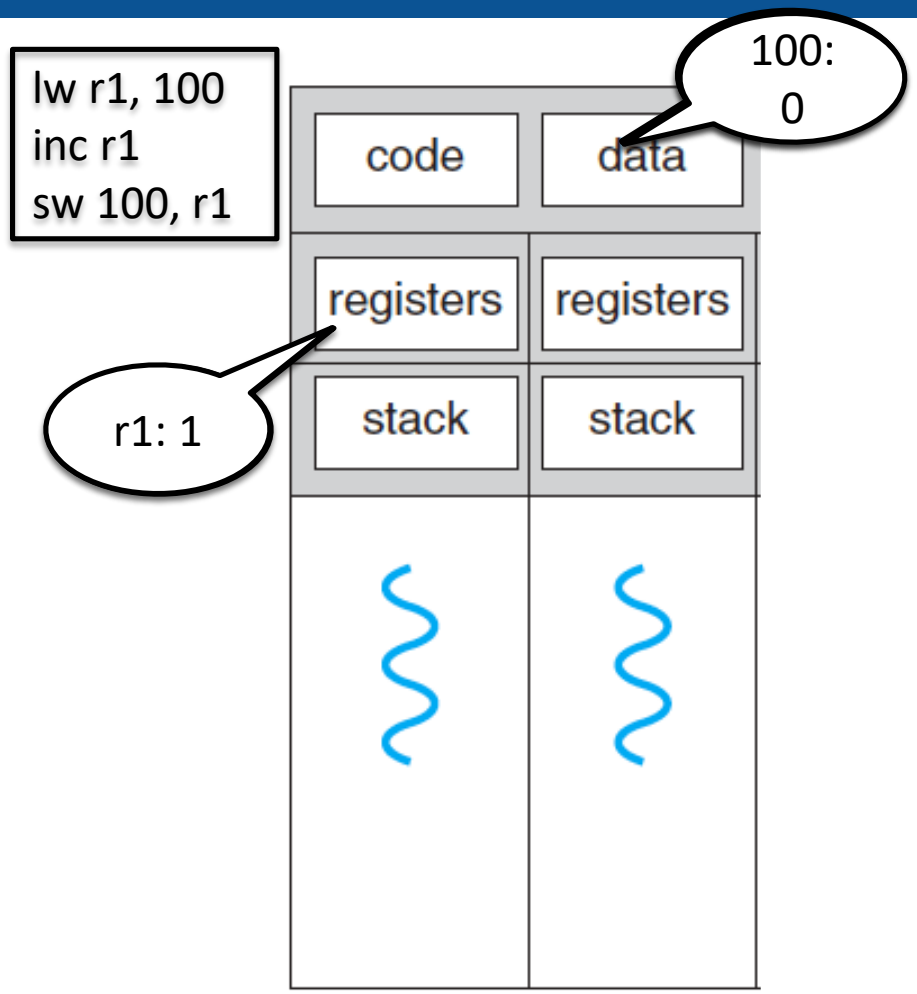

- Thread 1: lw r1,100
- Thread 1: inc r1
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- <Context Switch>
- Thread 2: lw r1, 100
- Thread 2: inc r1
- Thread 2: sw 100, r1

→ IN = 2

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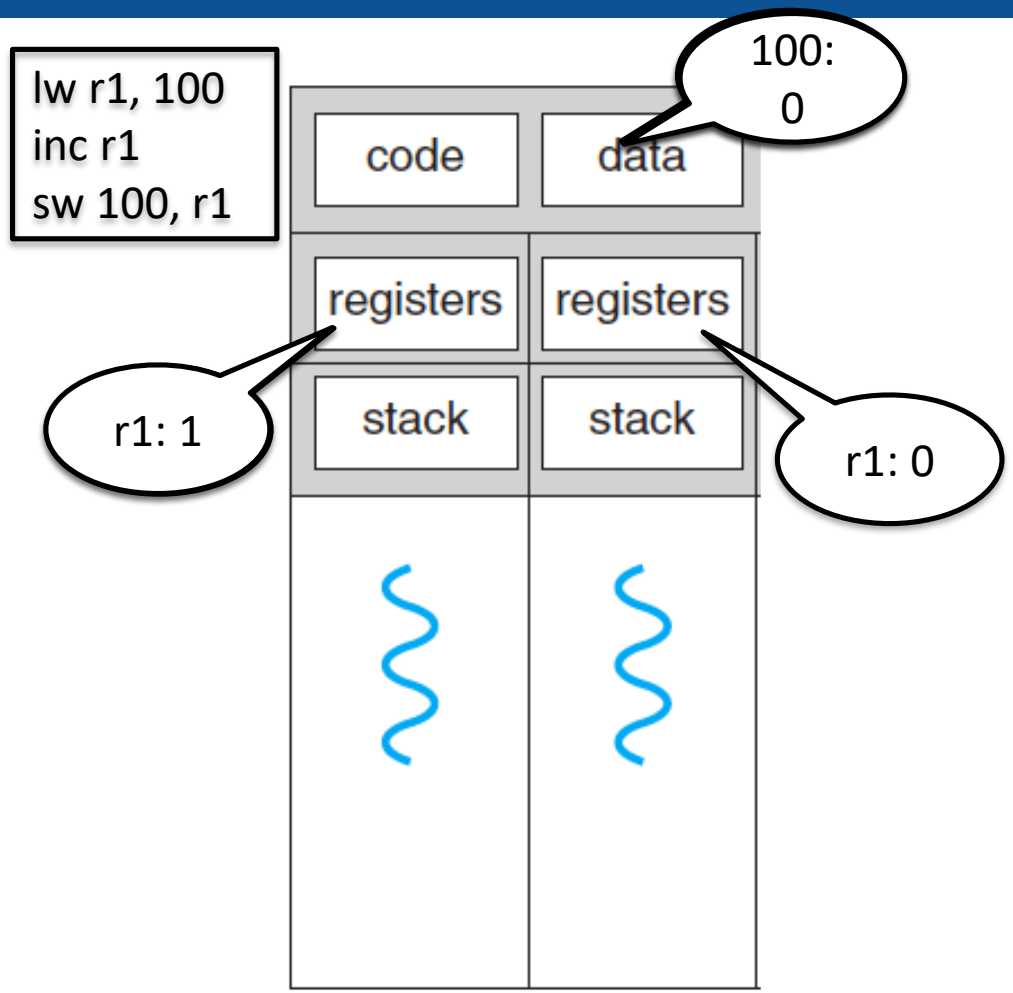
Further Motivation



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→ IN = 2

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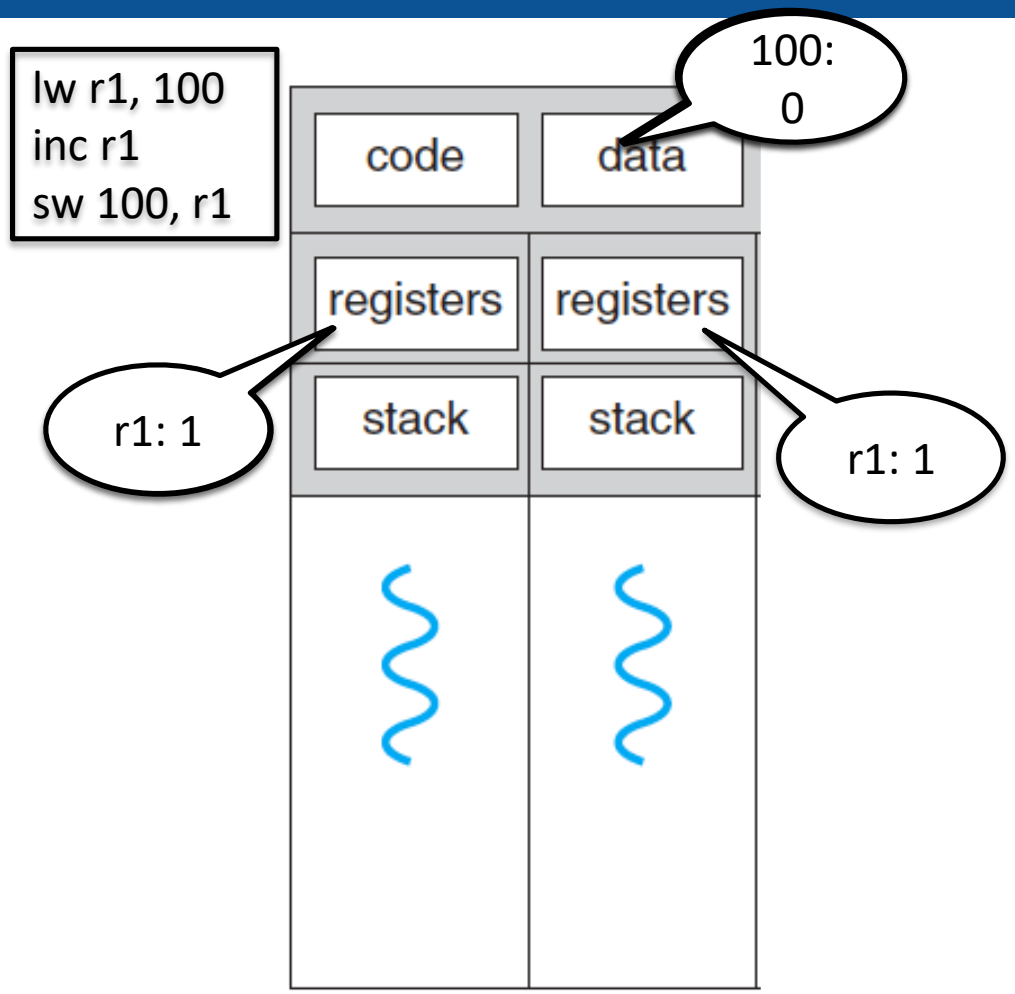

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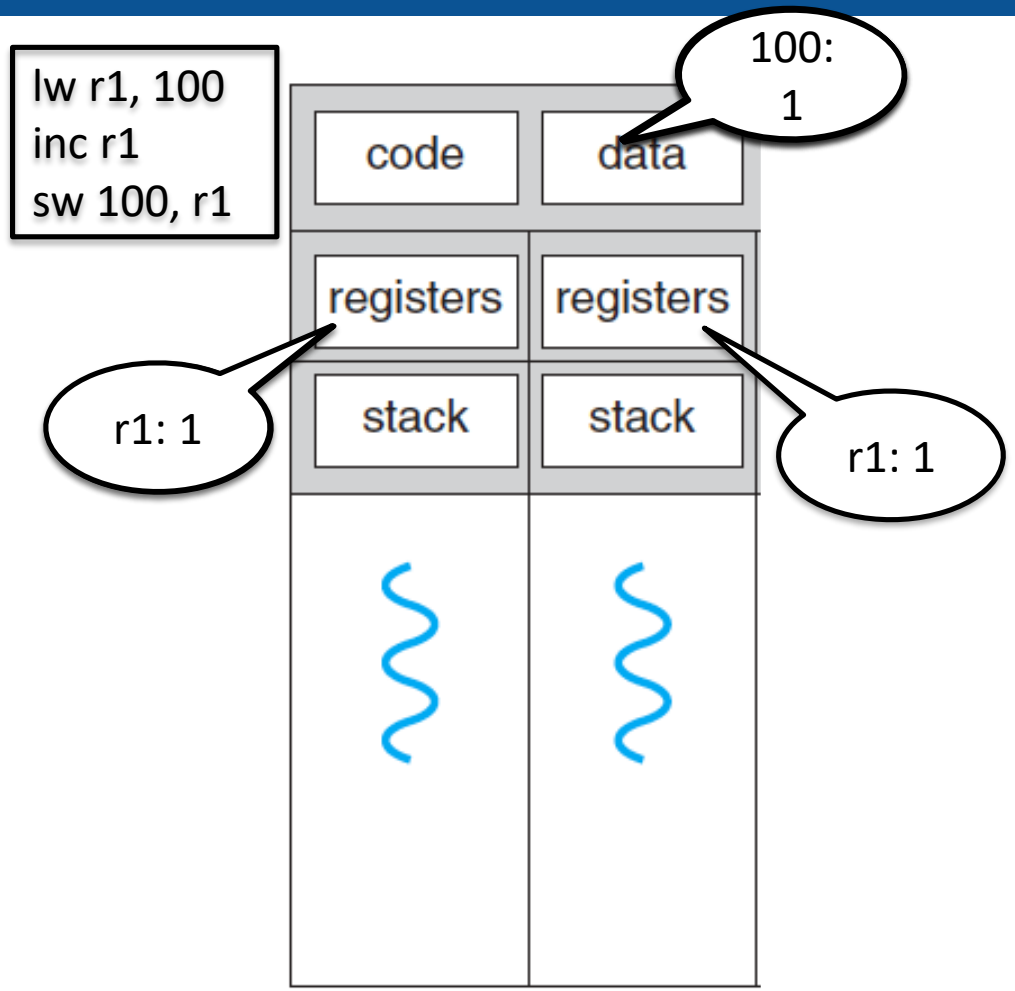

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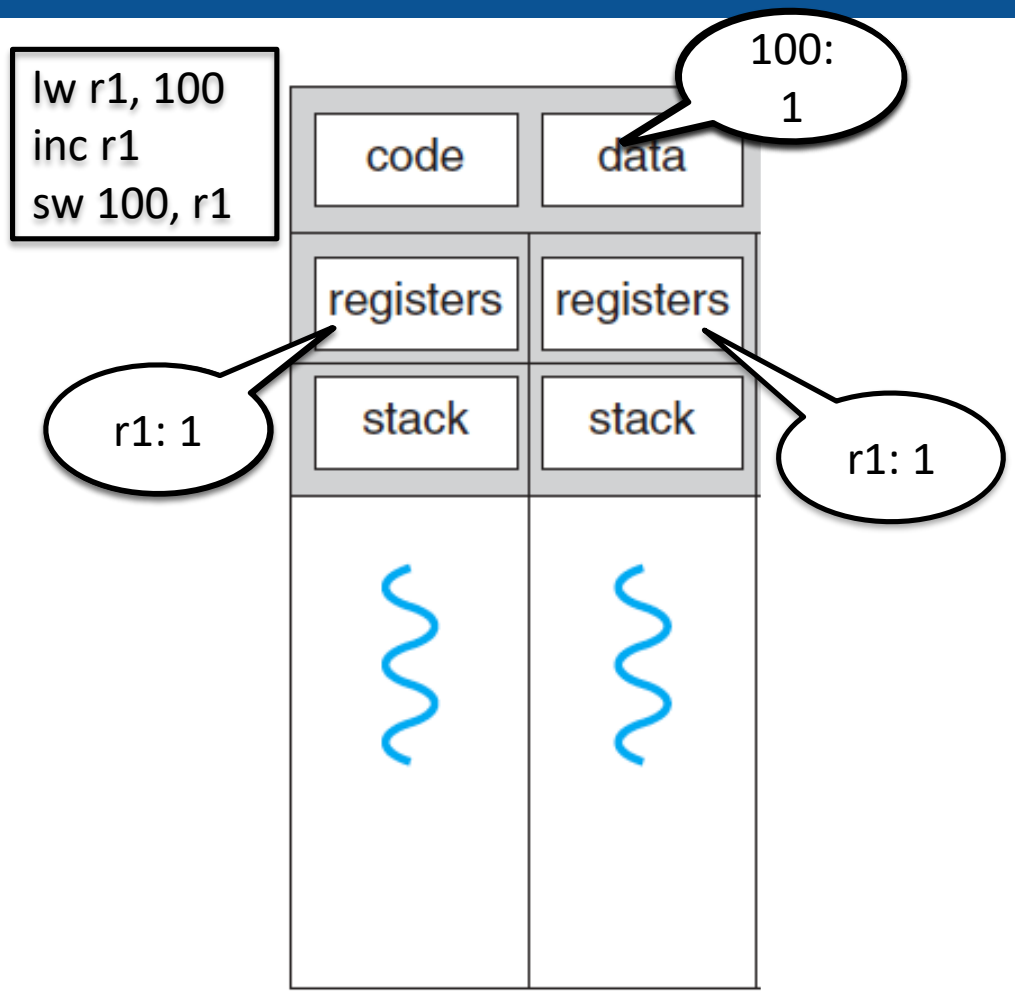

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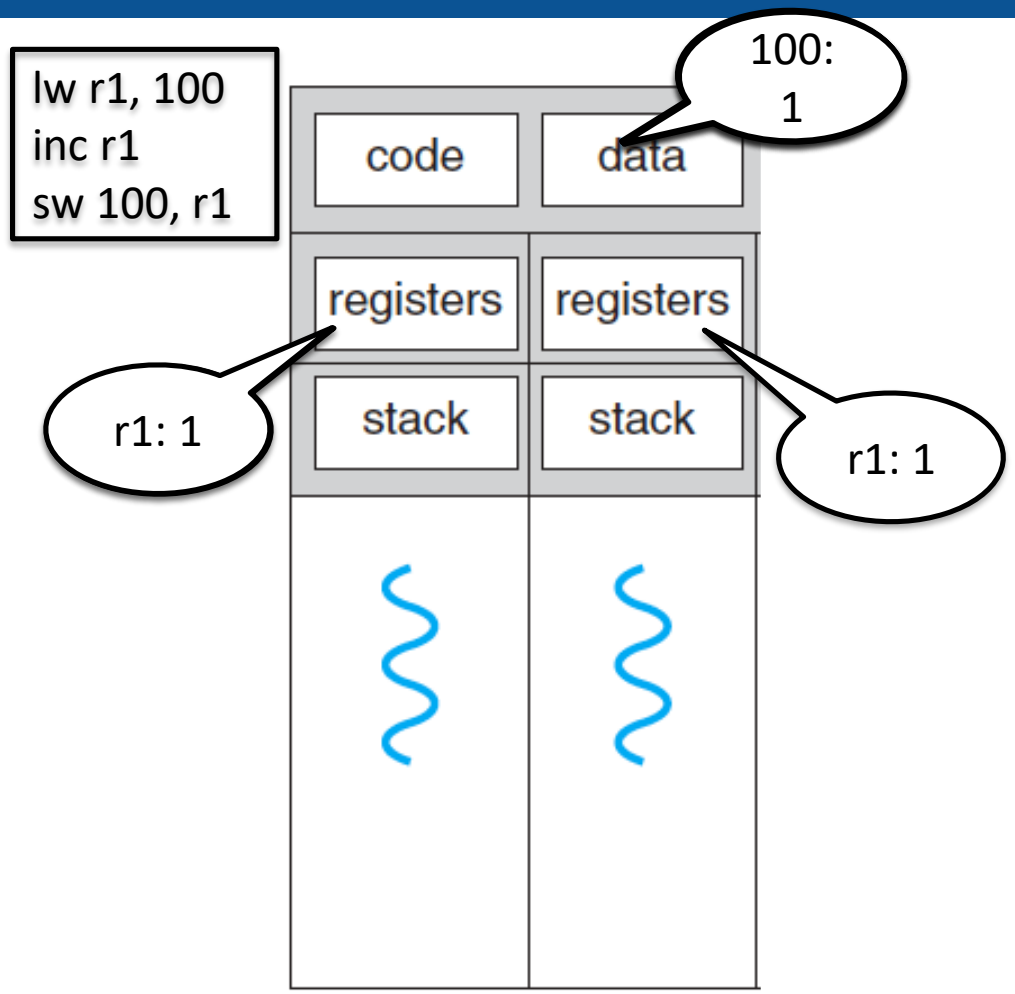

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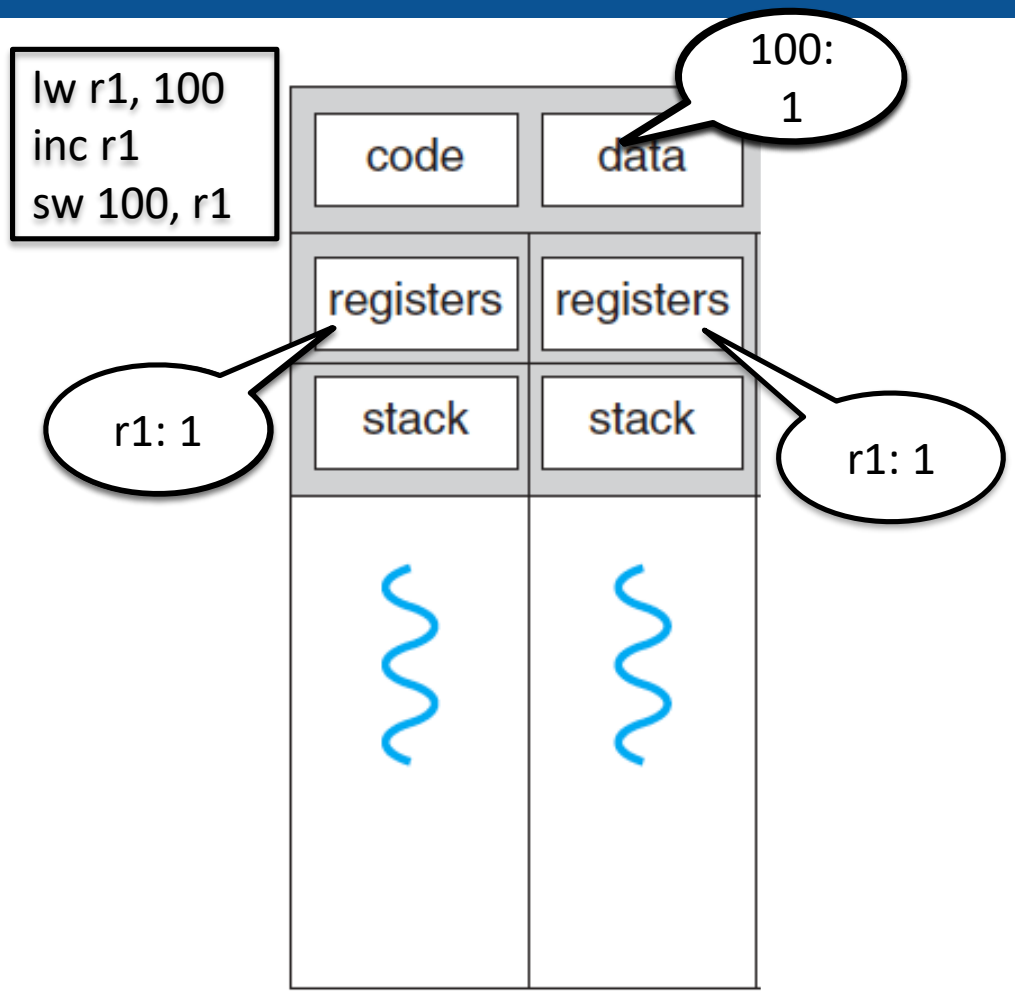

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→ IN = 1

“Too Much Milk”…

Time	You	Your Roommate
3:00	Arrive Home	
3:05	Look in fridge; no milk	
3:10	Leave for grocery	
3:15		Arrive home
3:20	Arrive at grocery	Look in fridge; no milk
3:25	Buy milk	Leave for grocery
3:35	Arrive home; put milk in fridge	
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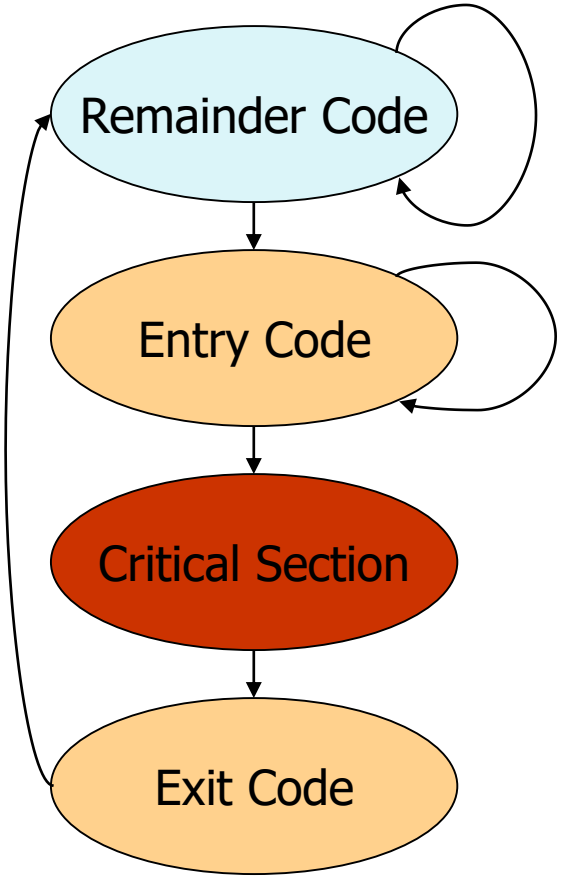
Important: Sometimes it is not enough to ensure mutual exclusion (e.g., when the order of execution matters)

- More on this later

Modeling the Mutual Exclusion Problem

[First modeling by Dijkstra, 1965]



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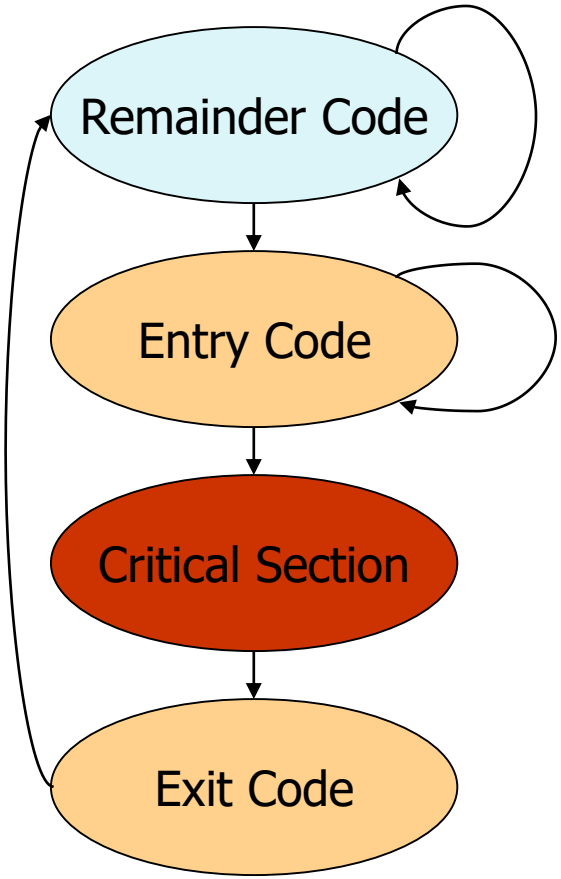

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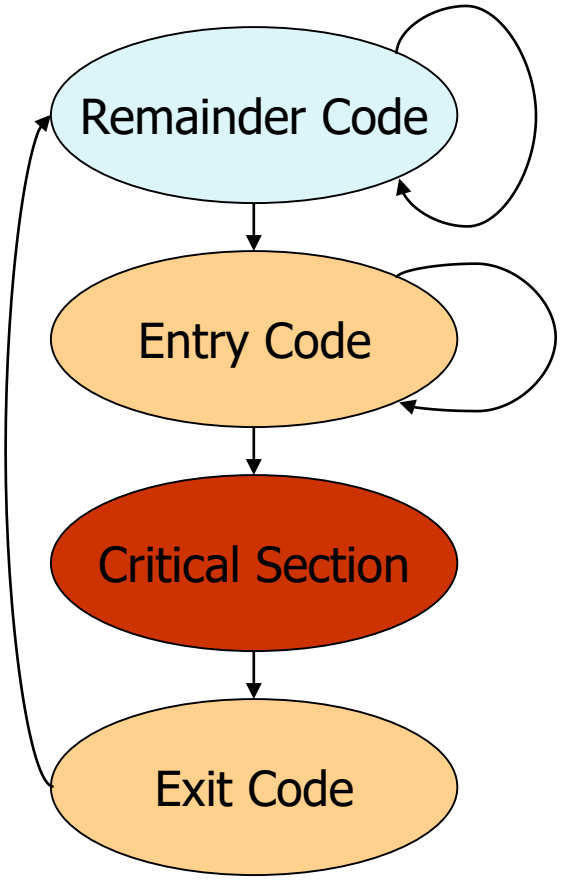
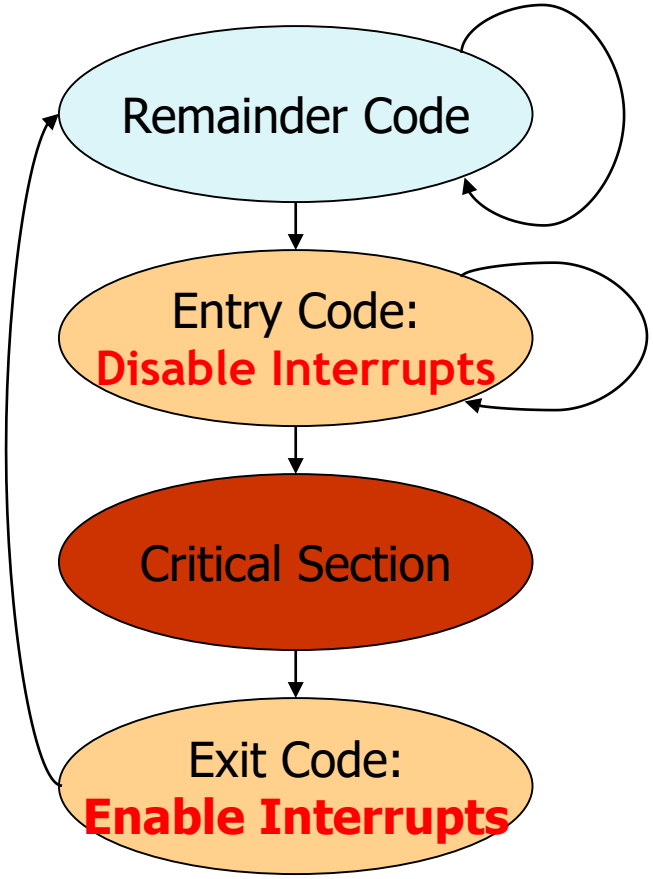


The Problem: Write entry and exit code. We will examine the code against the following properties (the goal is to ensure all of them)

1. **Mutual Exclusion:** No two processes are in their critical section at the same time.
2. **Progress:** If a process in trying to enter the critical section then **some** process must eventually enter the critical section.
3. **Starvation freedom:** If a process in trying to enter the critical section then **this** process must eventually enter the critical section.
4. **Generality:** no assumptions may be made about speeds or the number of participants (threads/processes/cores/CPUs)
5. **No blocking in the remainder** No process running outside its critical section may block other process

First Try: Disabling interrupts



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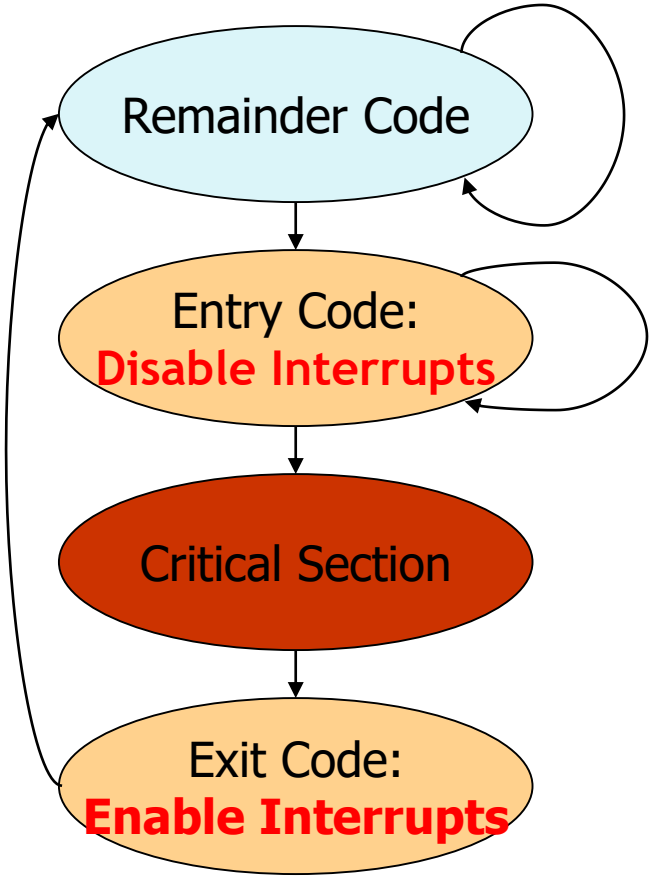

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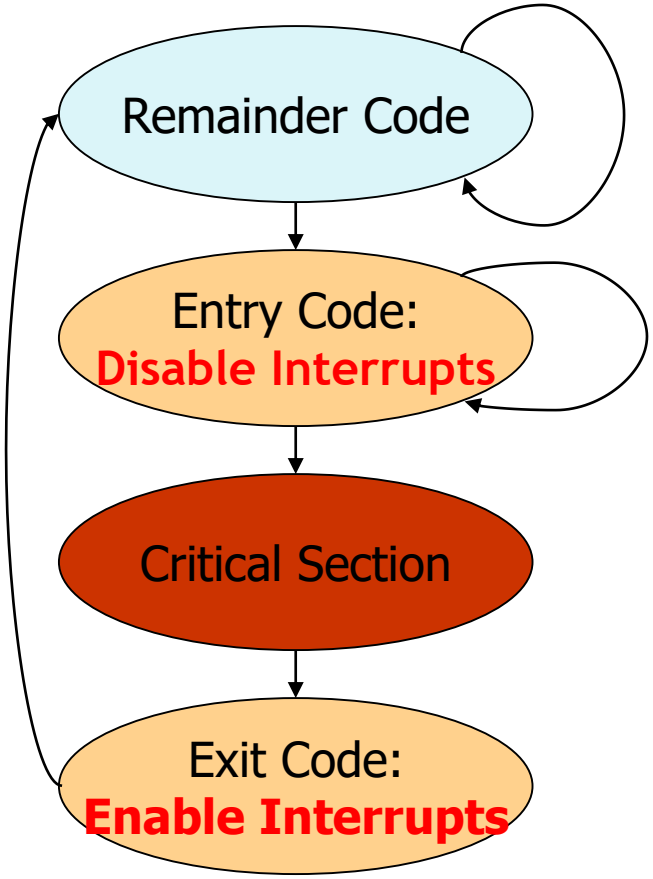

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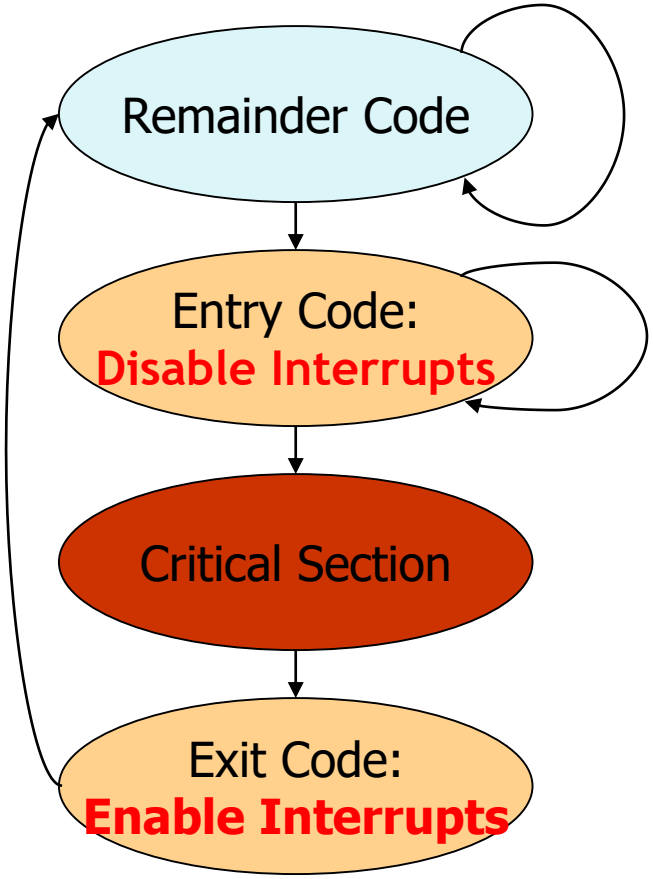

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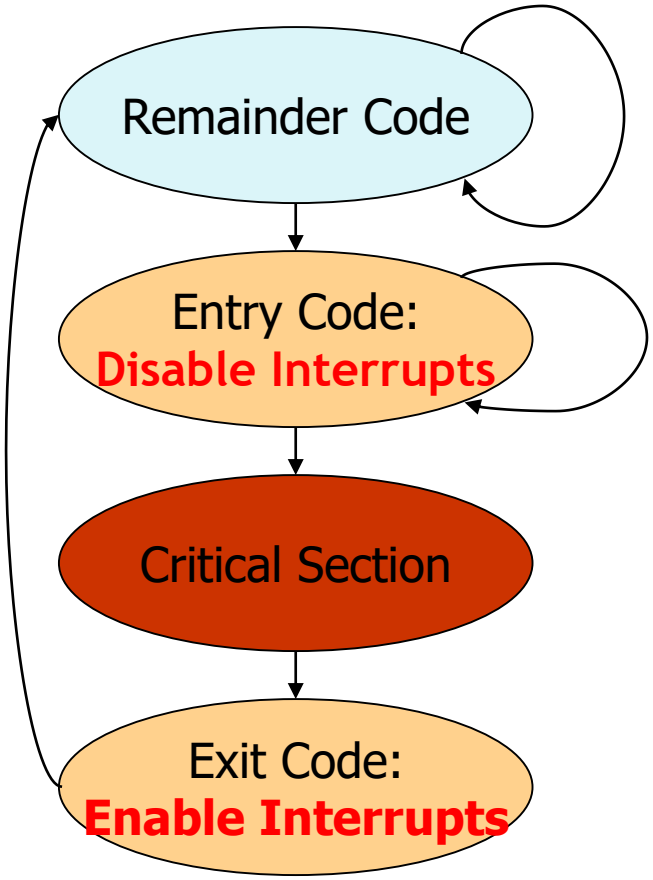

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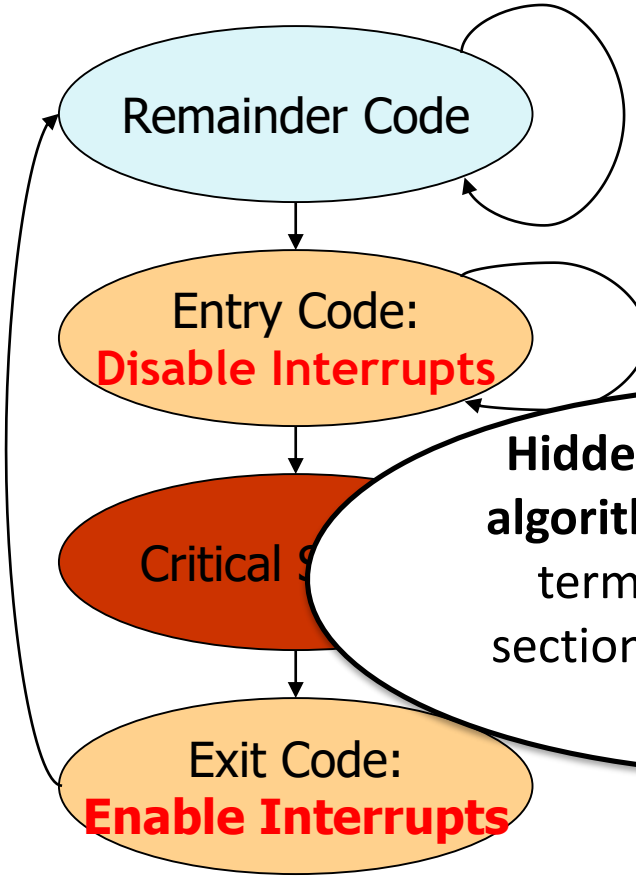

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Hidden assumption for all algorithms: Processes never terminate in the critical section and finish it in finite time

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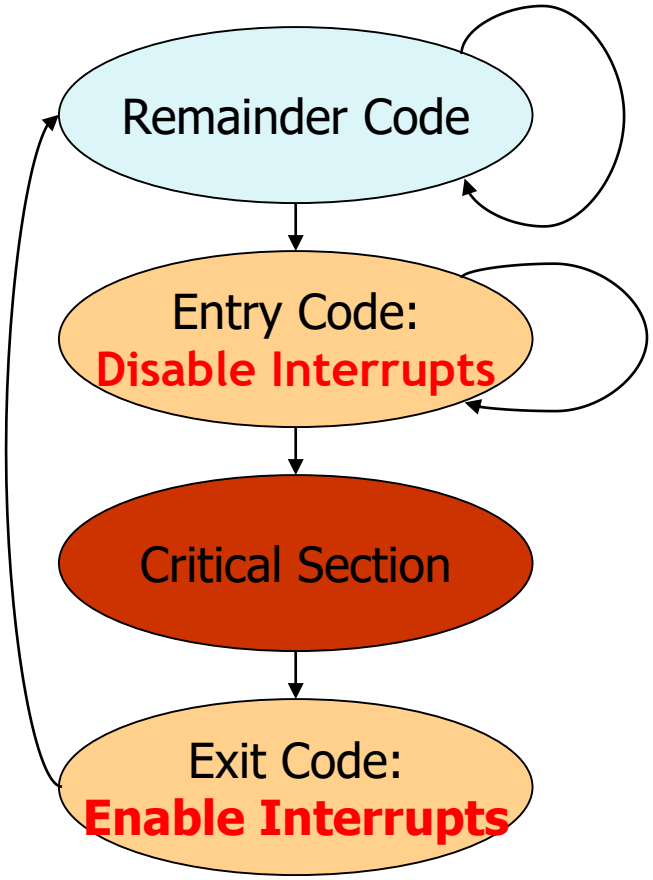

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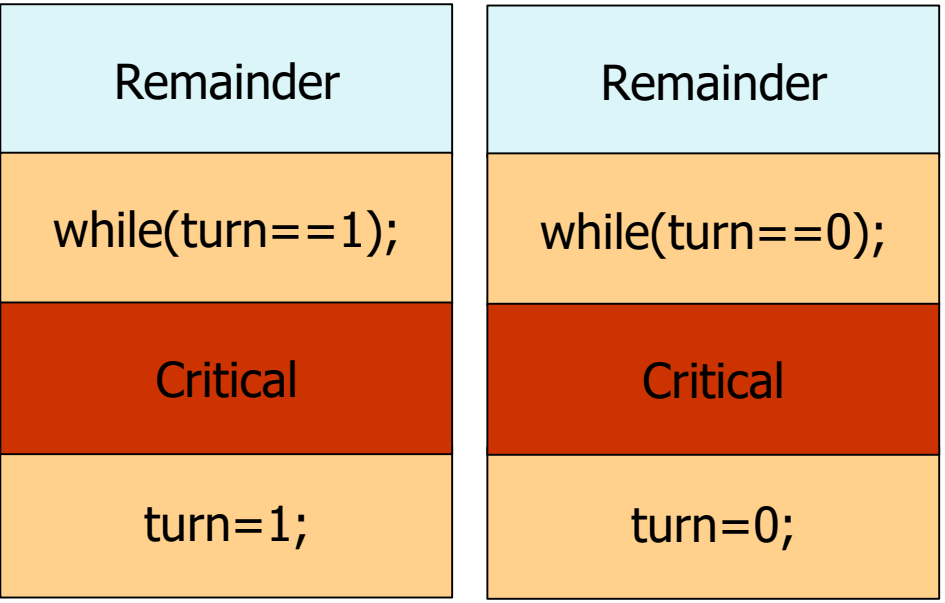

- Algorithm for 2 threads/processes
- Uses global variable (1 bit) named **turn.** Cannot be used in the remainder/critical
- (Slightly) different code for each thread

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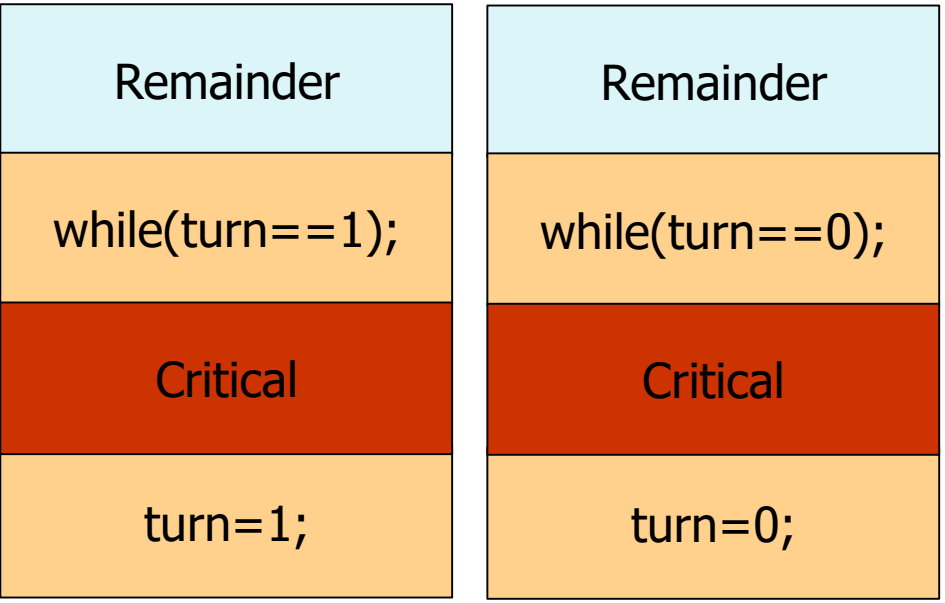

Code for Thread 0 Code for Thread 1

√ **Mutual Exclusion:** Assume that the two of the processes are in the critical condition, and then w.l.o.g. thread 0 left its entry section (and entered the critical section) first → At that point, turn≠1→turn=0. The only place turn can be changed to 1 is when thread 0 exits the critical section, thus turn=0 throughout the entire execution of the critical section by Thread 0→Thread 1 is in its entry code when Thread 0 is the critical section → Contradiction.

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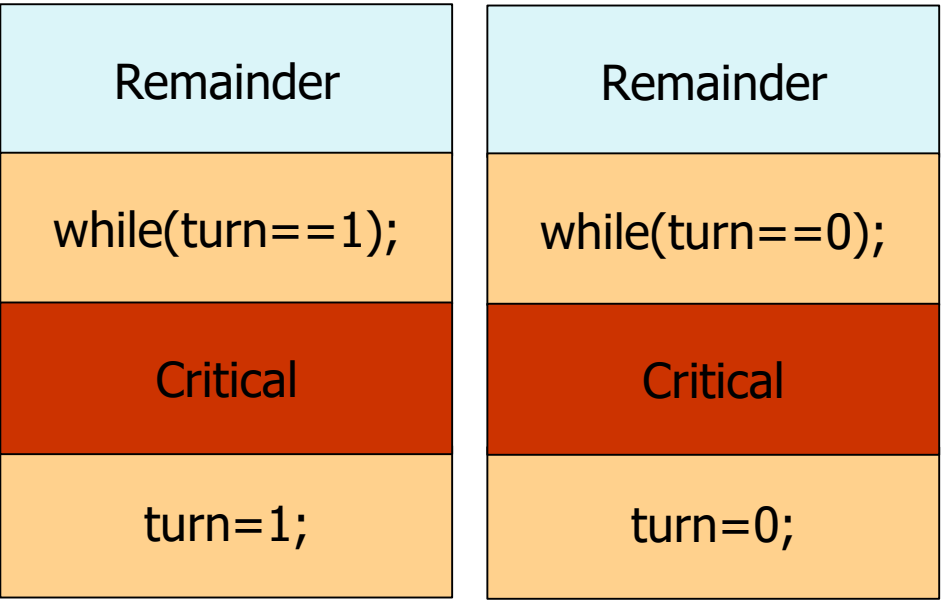

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Bad News:

Progress / no blocking in the remainder does not hold. Thread 1 can simply stay in its remainder and never get to its entry (and therefore exit) code → **Starvation Freedom** does not hold

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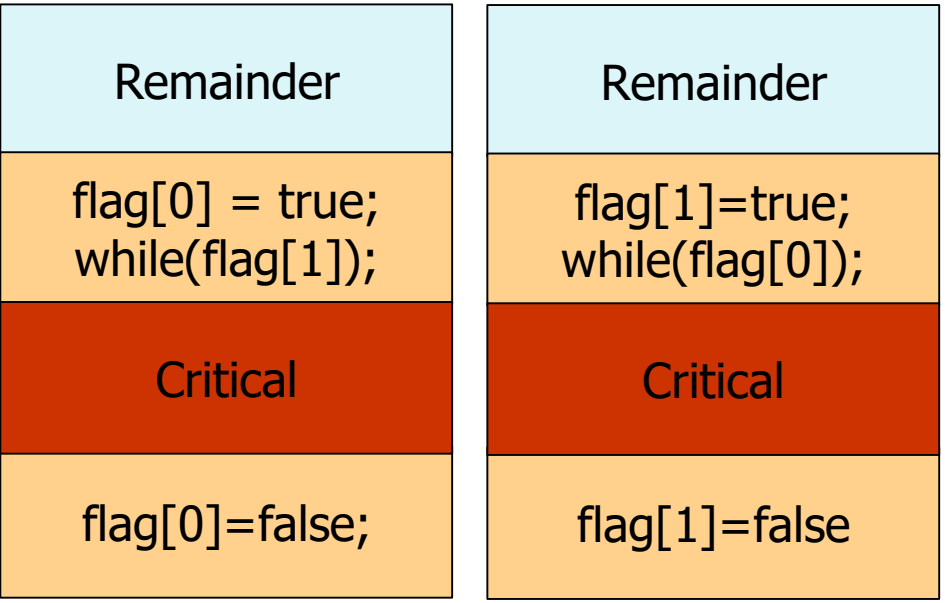

Code for Thread 0 Code for Thread 1

Algorithm for 2 threads/processes

Uses global two global variables (1 bit), named **flag[0], flag[1].** Cannot be used in the remainder/critical section

(Slightly) different code for each thread

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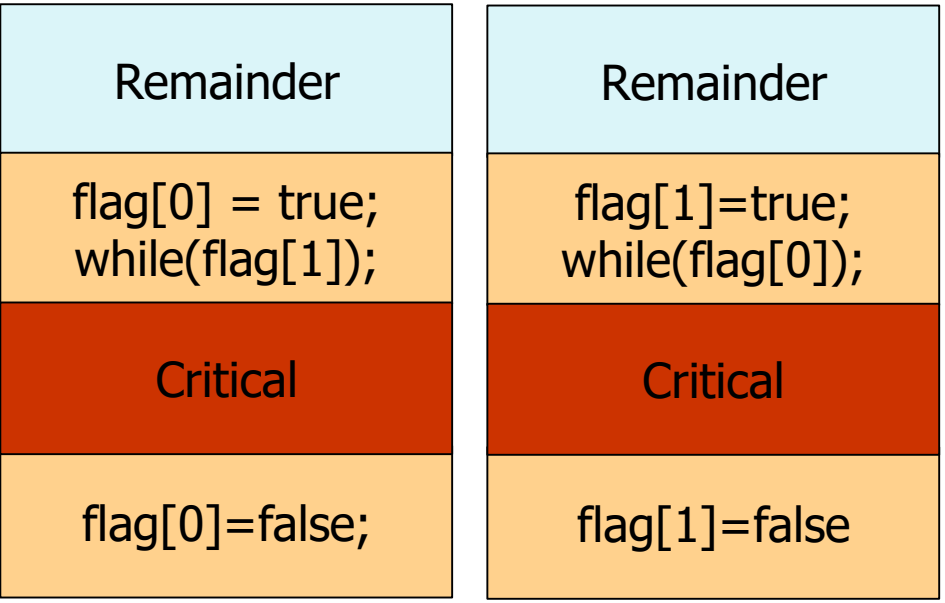

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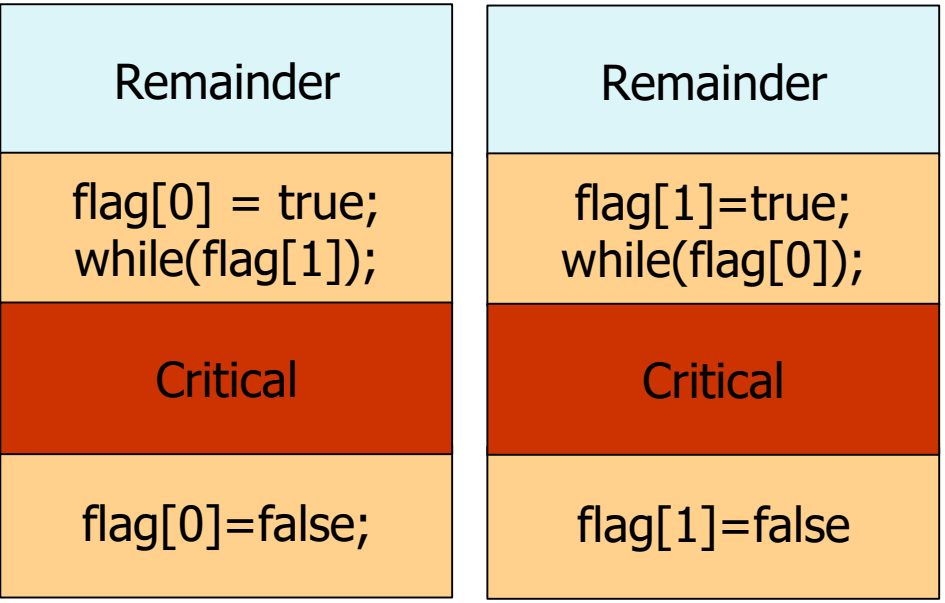

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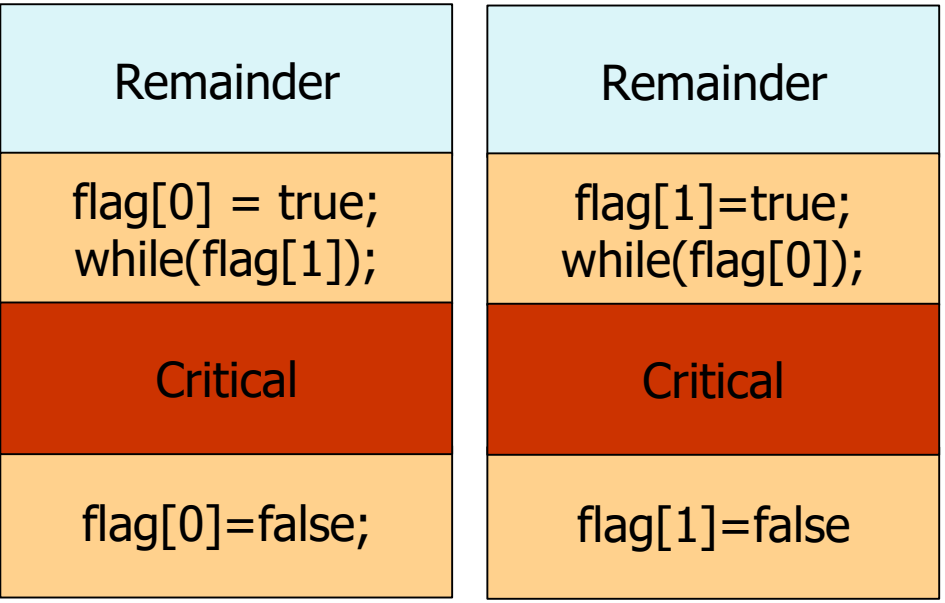

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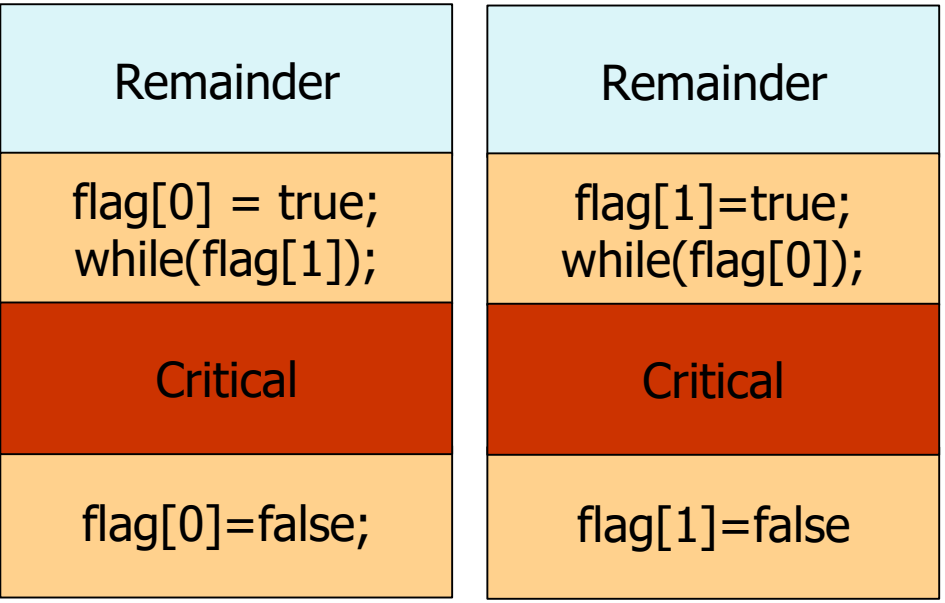

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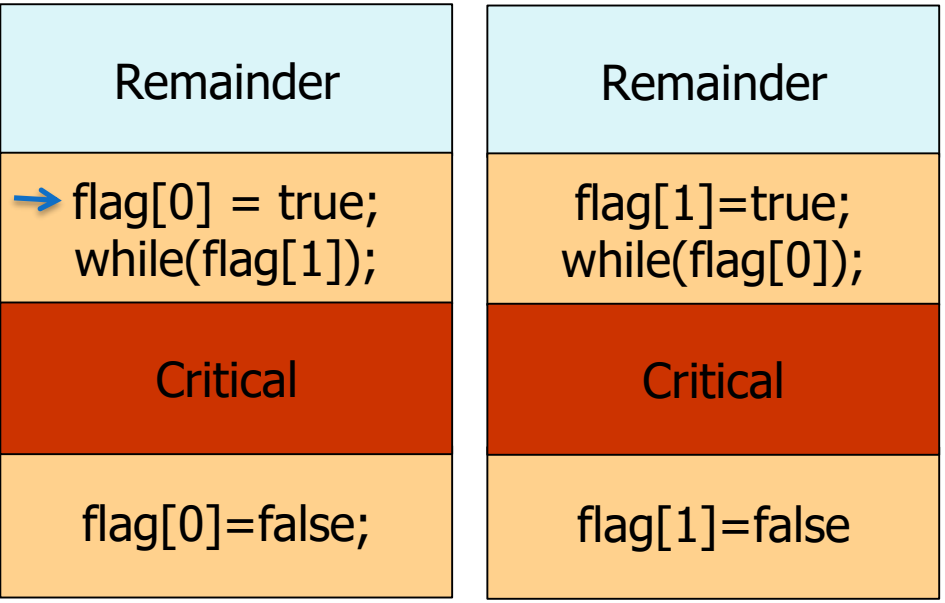

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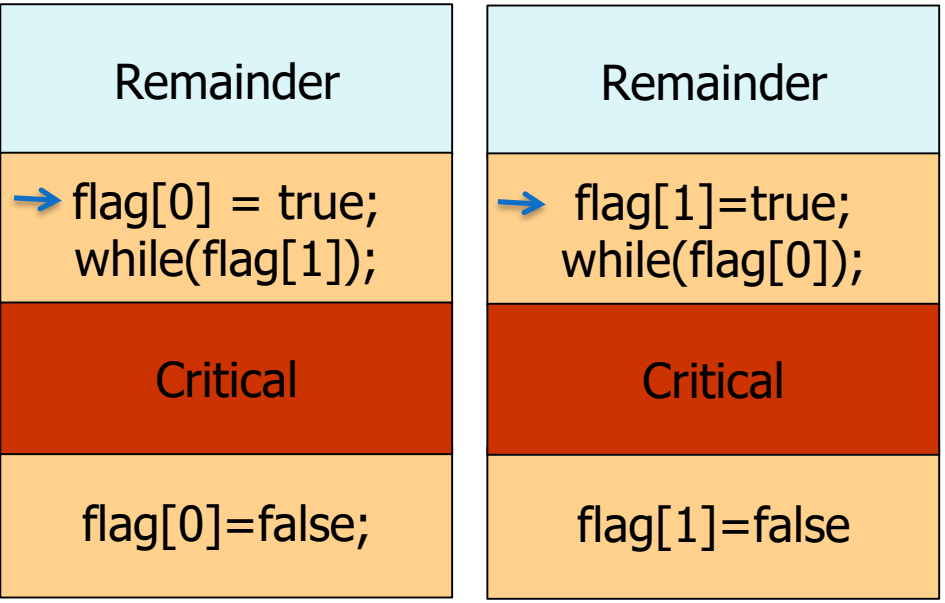

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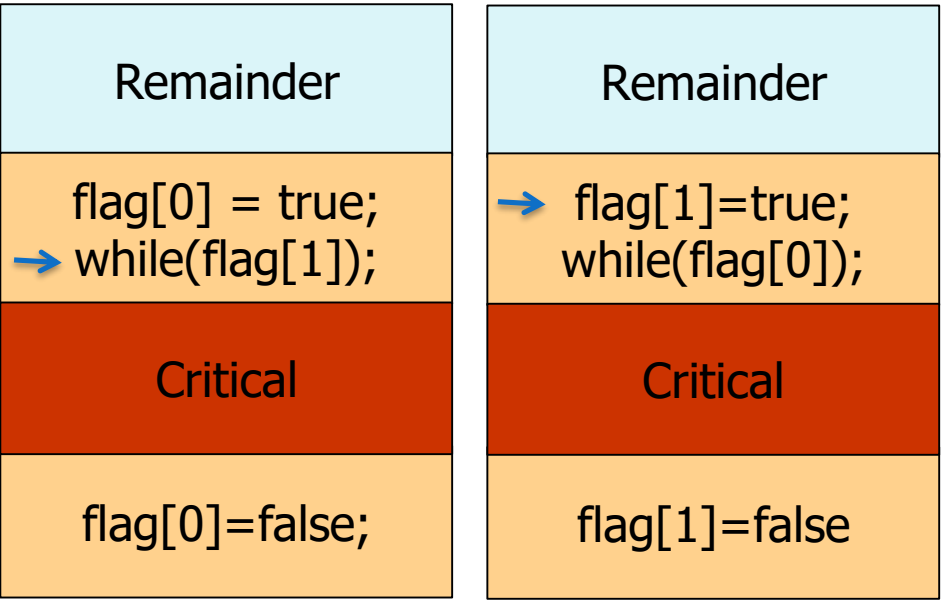

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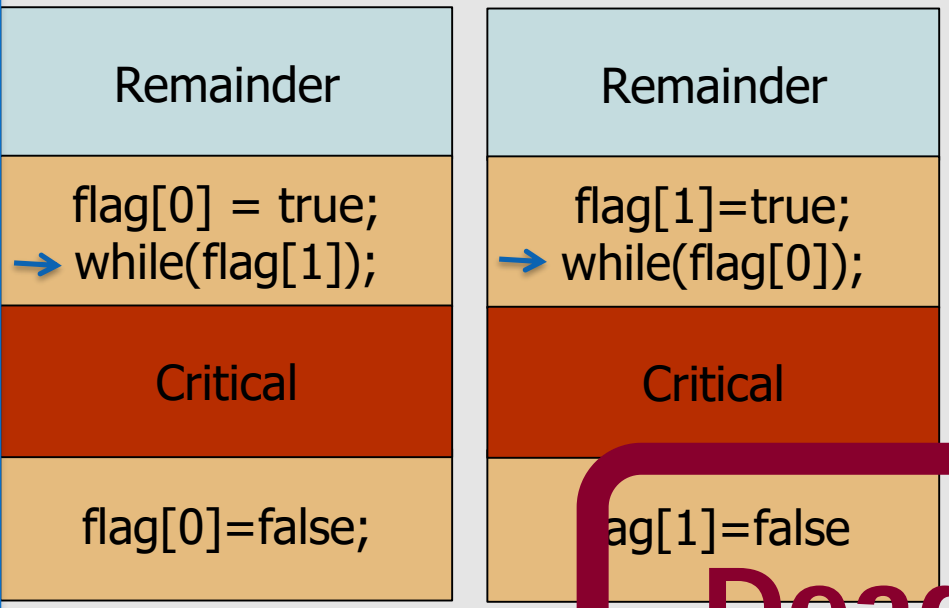


Code for Thread 0 Cod for Thread 1

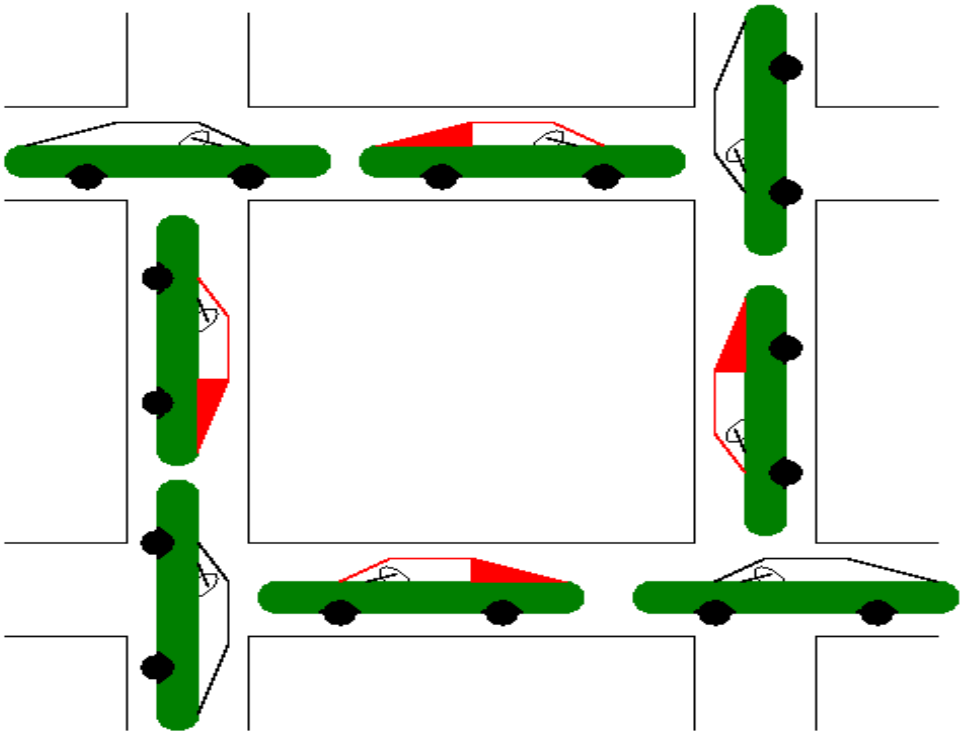
No Blocking in the Remainder: A thread can block another thread only if its flag is true, implying it is either in its entry, critical, or exit section.

But still **Prog ess** does not hold → **Starvation Freedom** does not hold

Deadlock!

√ Mutual Exclusion: Assume that the two of the processes are in the critical section, and then w.l.o.g. thread 0 left its entry section (and entered the critical section) first → At that point, **flag[0]=true** → The only place **flag[0]** can be changed to **false** is when thread 0 exits the critical section, thus **flag[0]=true** throughout the entire execution of the critical section by Thread 0→Thread 1 is in its entry code when Thread 0 is the critical section → Contradiction.

Illustration of Deadlocks



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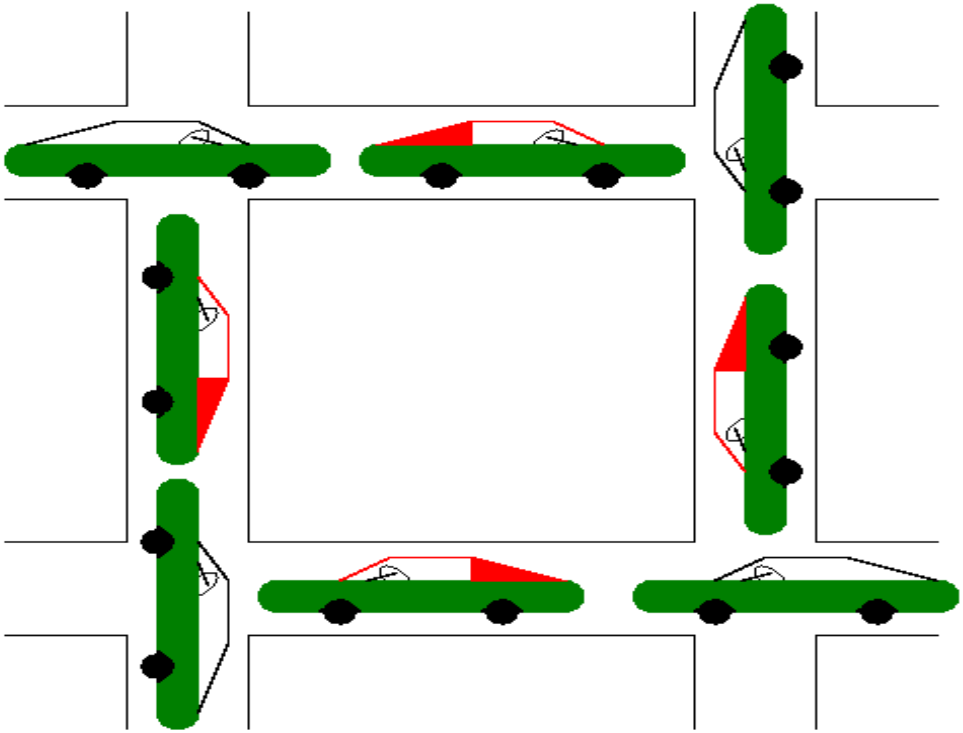
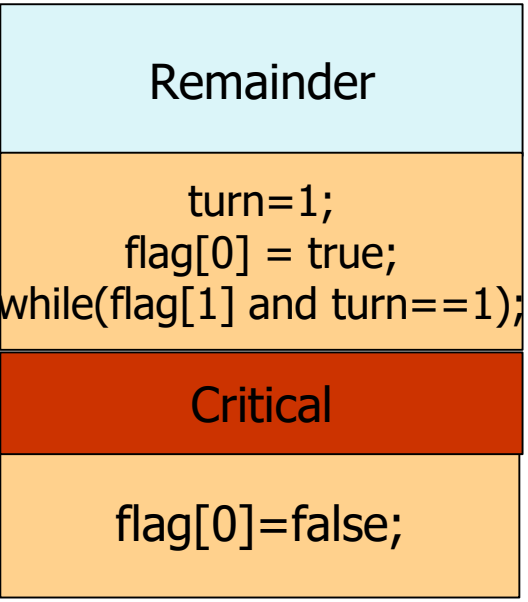


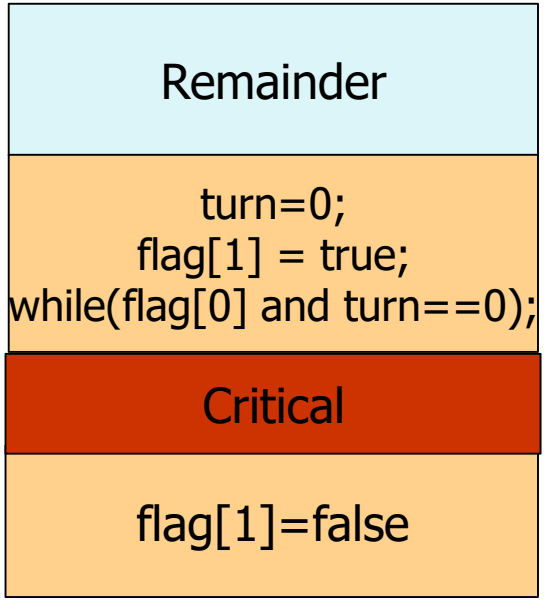
Illustration of Deadlocks

Tel Aviv, Winter 2011

No “Cheating” – Third Try

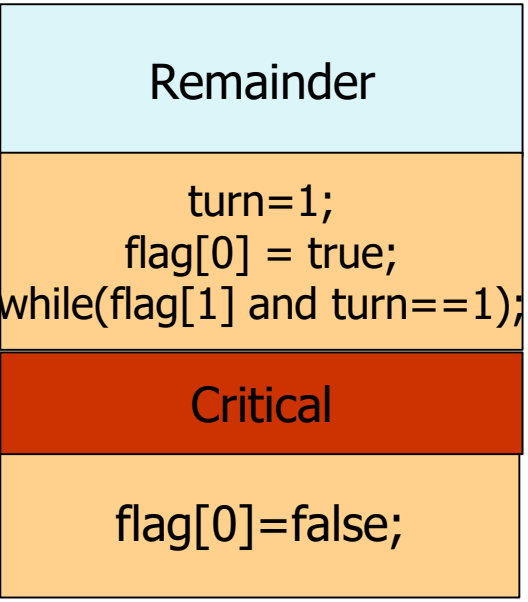


Code for Thread 0



Code for Thread 1

No “Cheating” – Third Try



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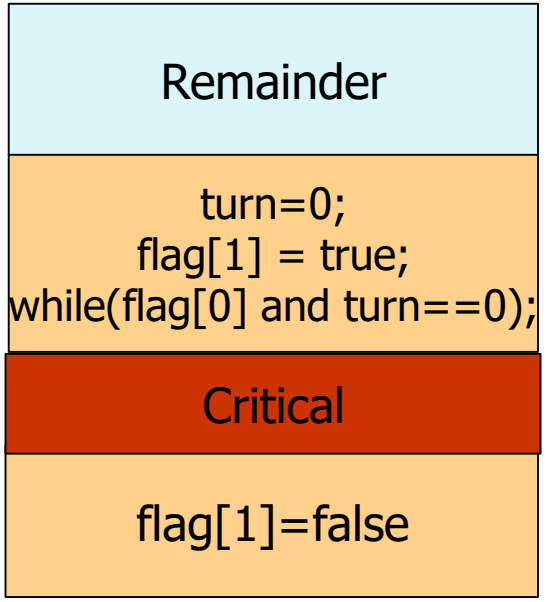

Code for Thread 1

Mutual Exclusion does not hold

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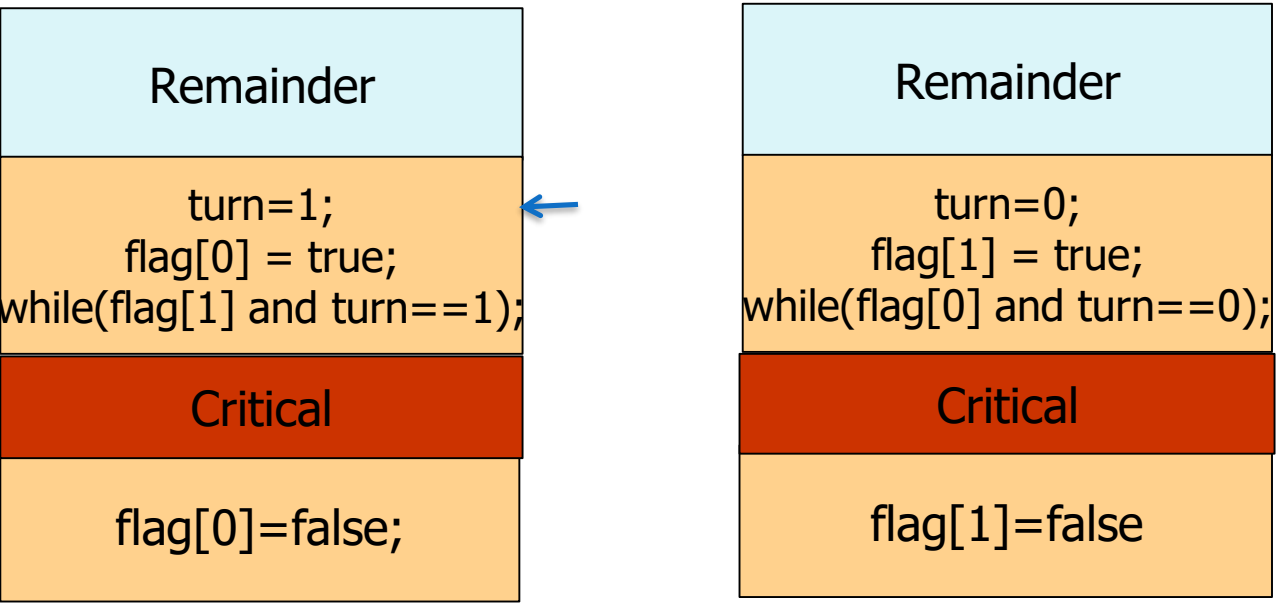

Code for Thread 0

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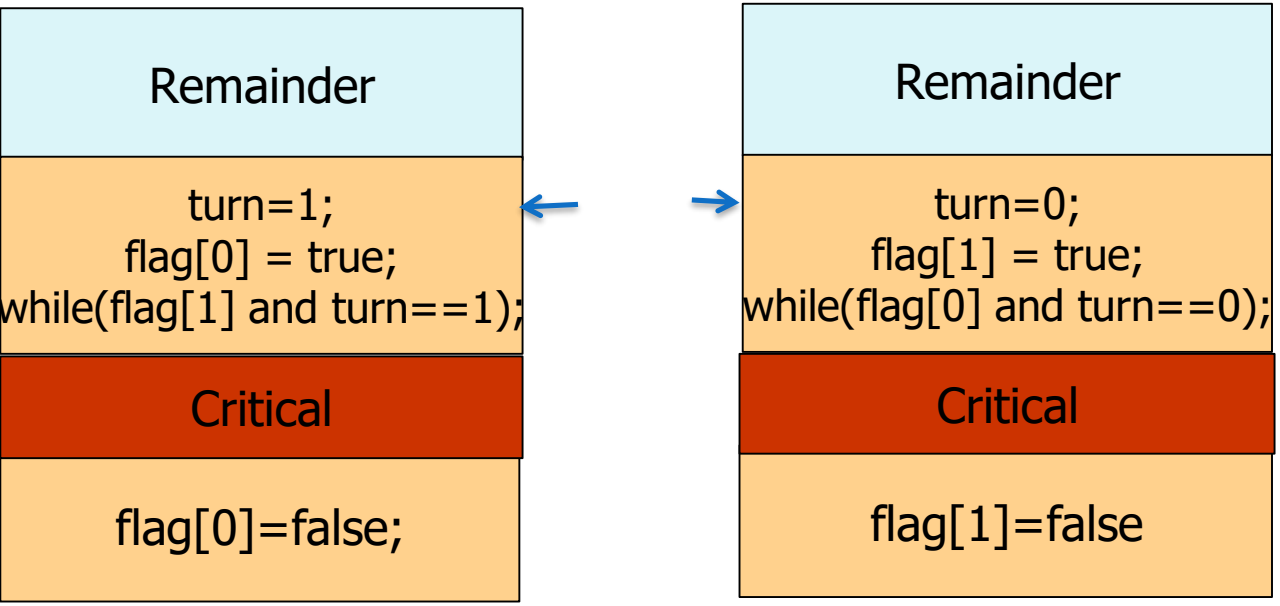

Code for Thread 0

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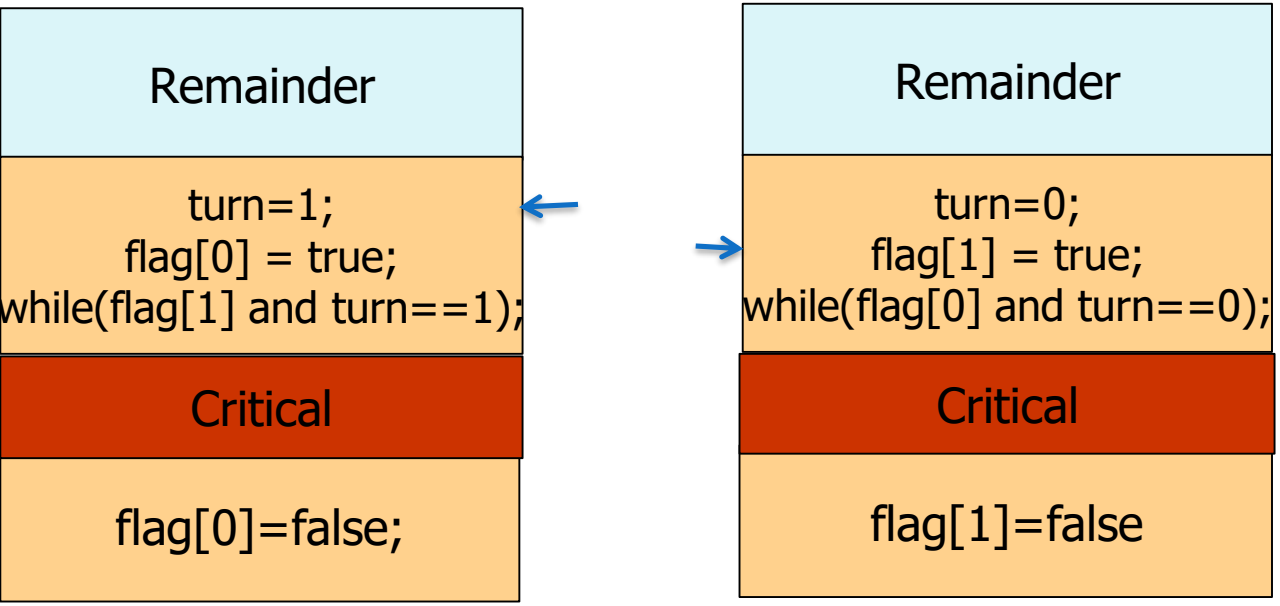

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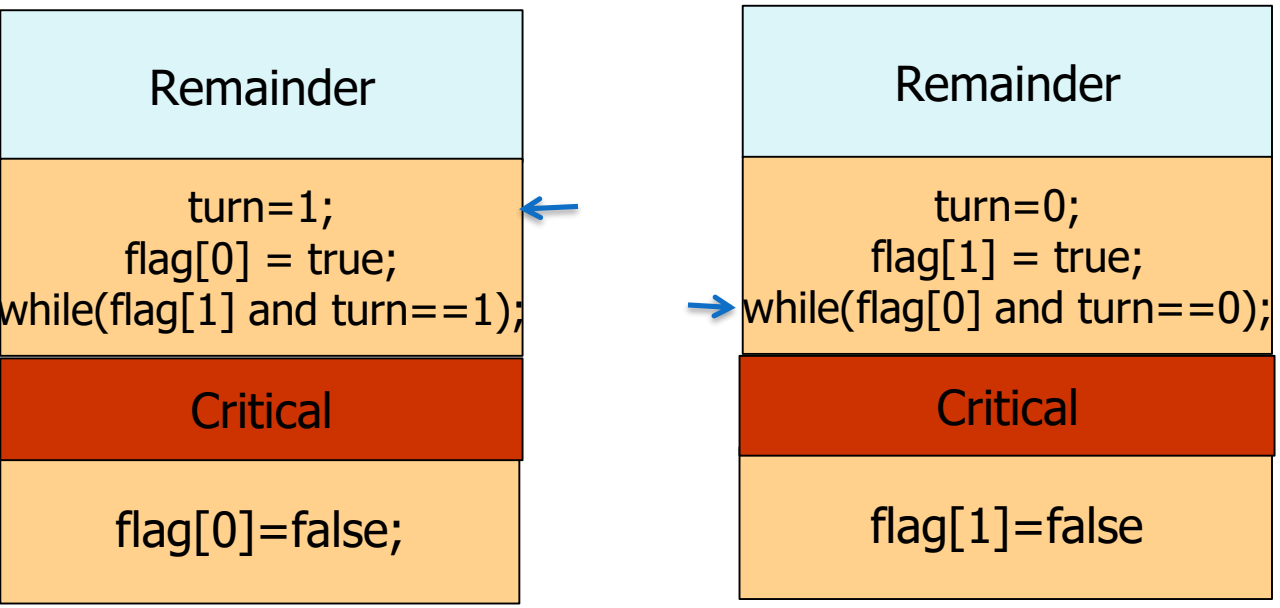

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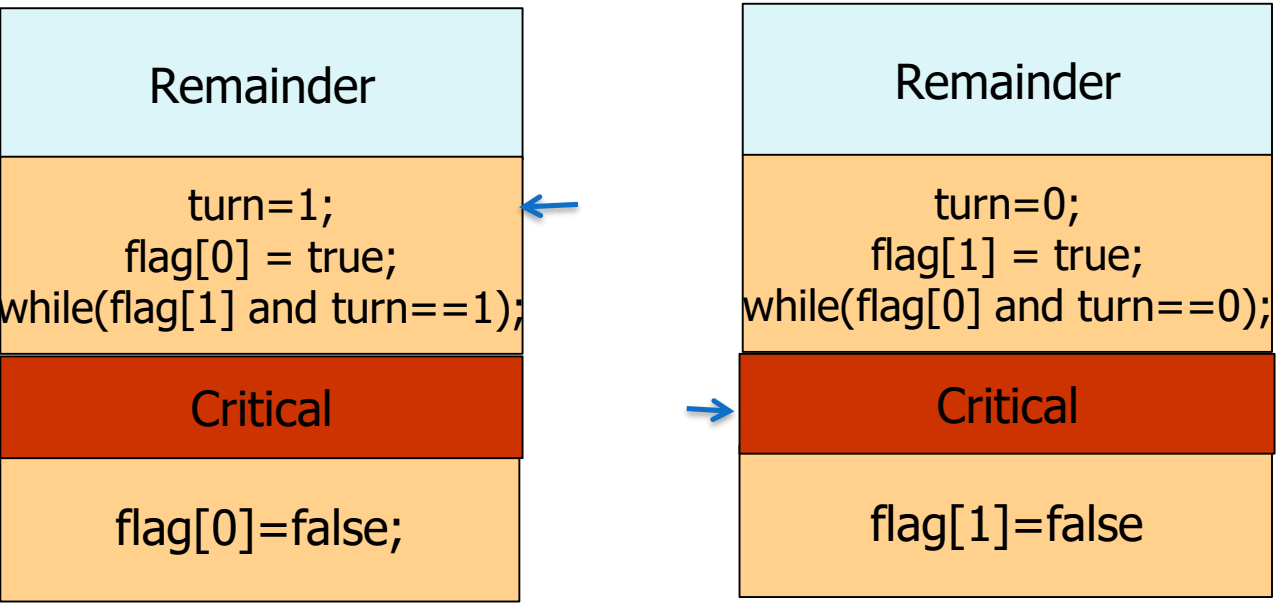

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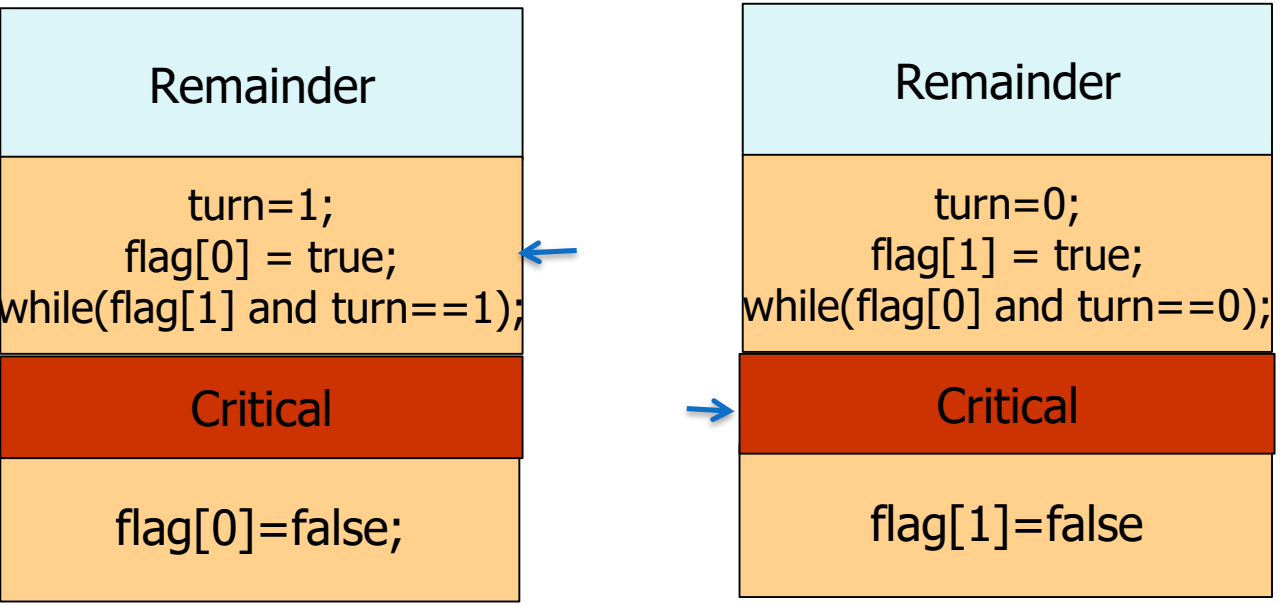

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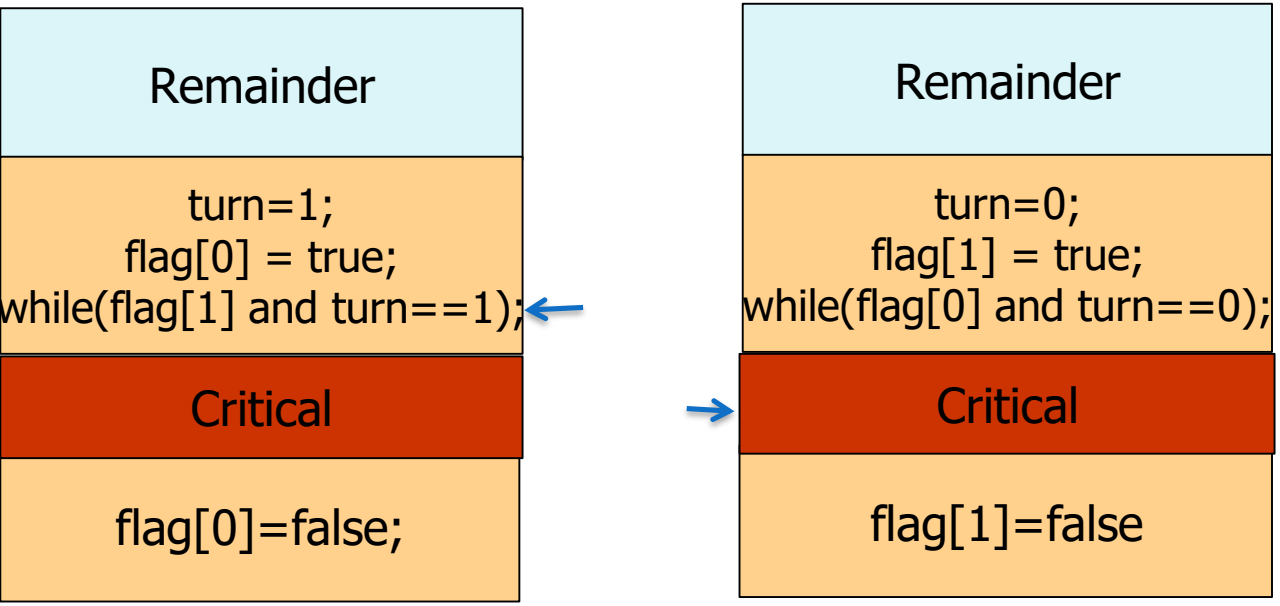

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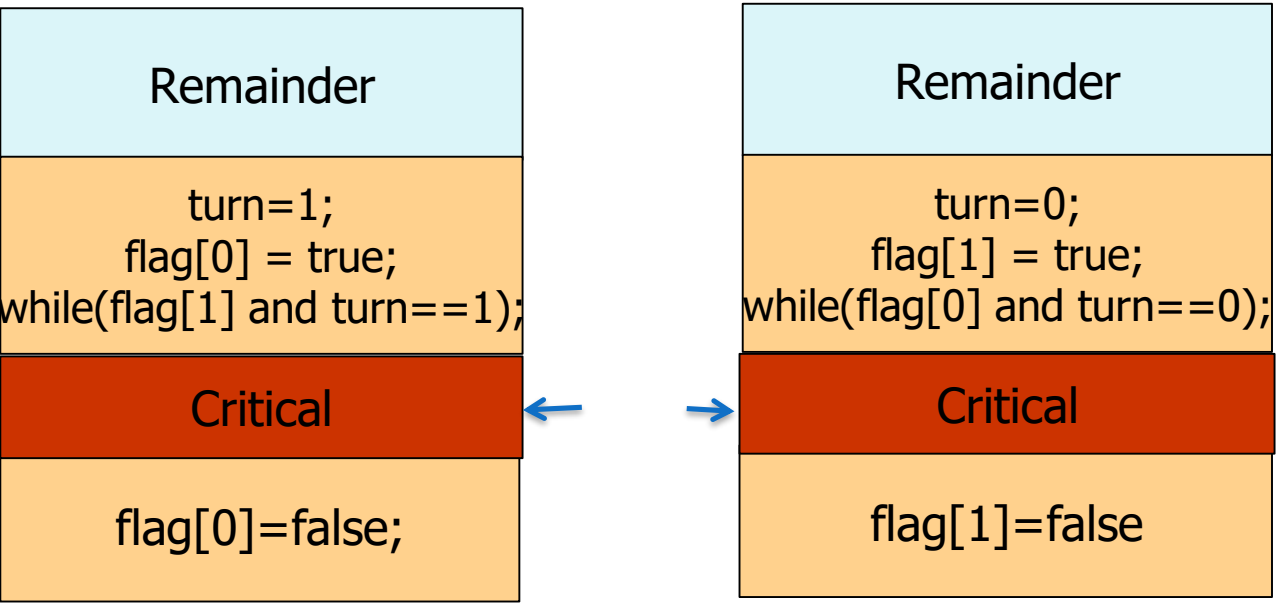

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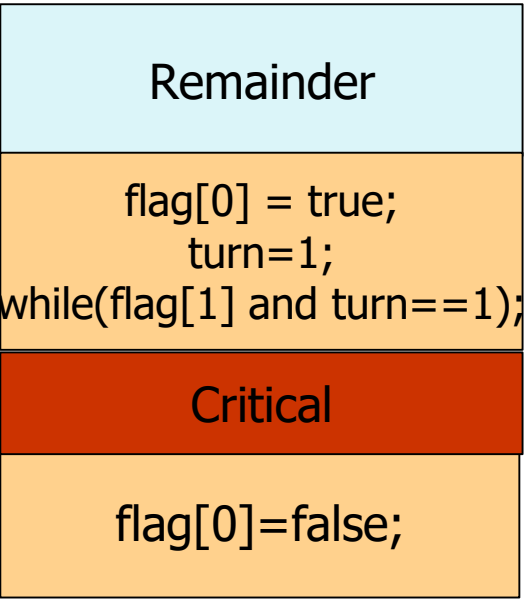
Peterson's Algorithm - 1981



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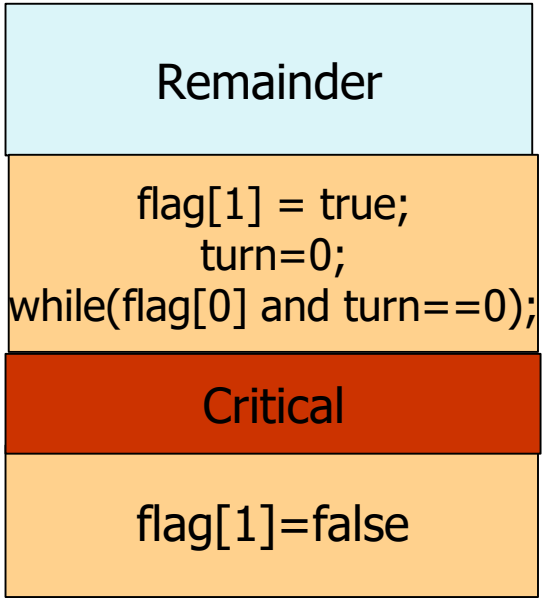

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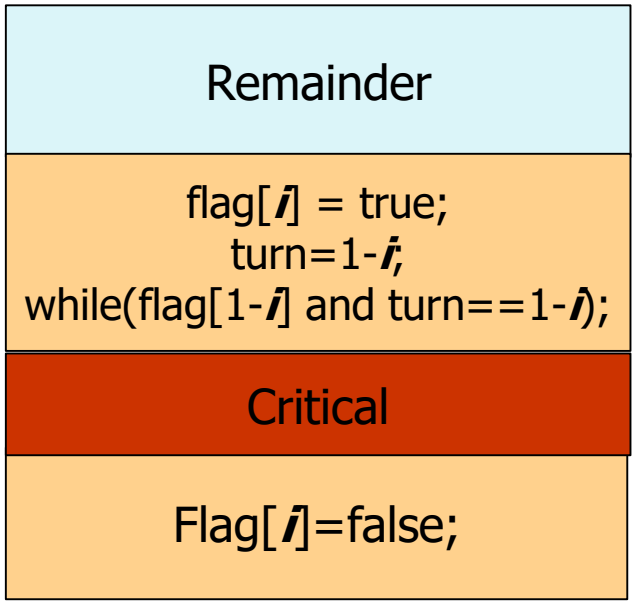

Code for Thread ***i***

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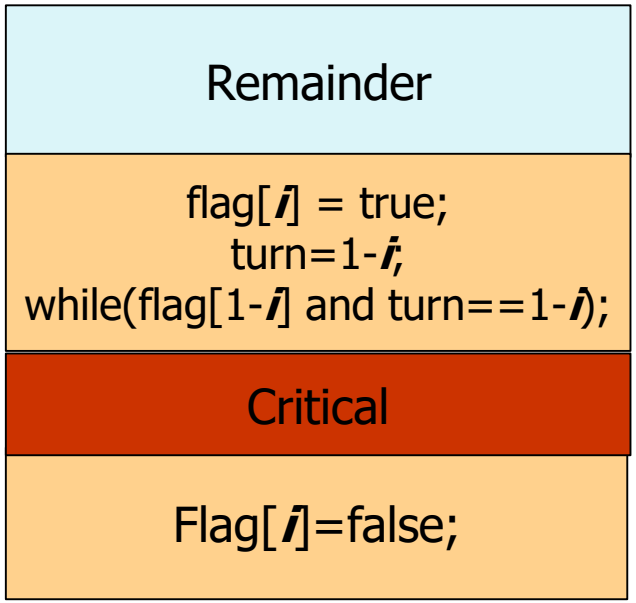

Code for Thread ***i***

√ **Mutual Exclusion:** Assume that the two processes are in the critical section, and then w.l.o.g. thread 0 left its entry section (and entered the critical section) first → At that point, **flag[1]=false or turn=0.**

Case 1: flag[1]=false → Thread 1 has not executed Line 1 of it's entry code → When it will eventually get to Line 3, it will set turn to 0, and wait. The only place **turn** is set to 1, is in Thread's 0 entry code, after it left the critical section → Contradiction.

Case 2: turn=0→Thread 1 executed Line 2 between Thread 0 Line 2 and 3→

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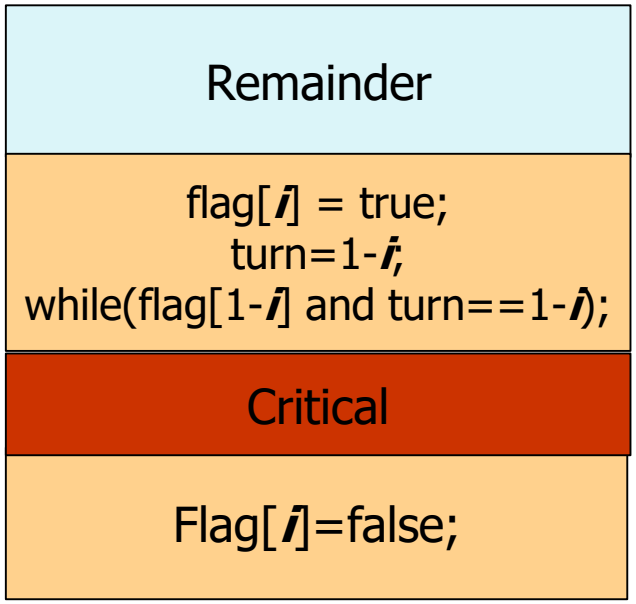

Code for Thread ***i***

√ No blocking in the Remainder

√ Starvation Free: Assume Thread 1 tries to get into the critical section but blocked (on Line 3) for infinite time → Thread 0 enters the critical section infinite number of times → The second time Thread 0 will execute the entry, **flag[0]=true**, **turn=1** and it will block → The next time Thread 1 gets the CPU, the **while** condition does not hold and Thread 1 enters the critical section → Contradiction.

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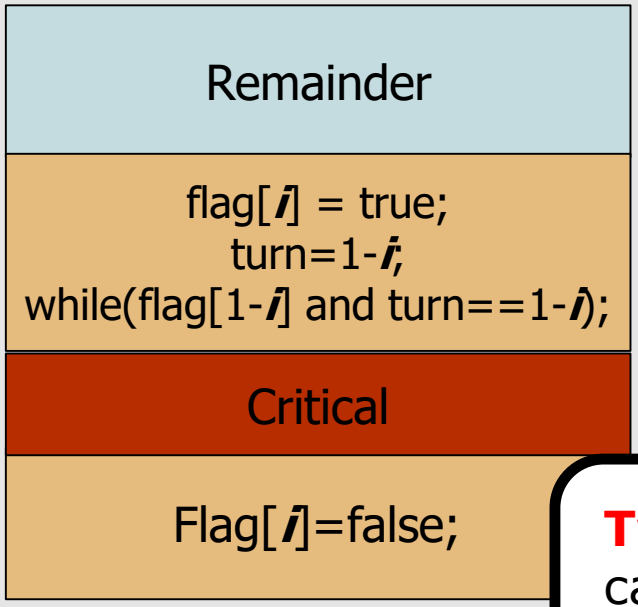

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Two threads only
cannot be easily extended to more
Busy wait (spinning)

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Three Concepts We've Covered

- Race Condition: A situation in which the scheduling of processes/threads (the order of who is getting the CPU) changes the final result
  - Different order → different results
  - Typical scenario: Most of the time everything is OK, but sometime not → very hard to debug
- Atomic Instruction: instruction that completes in a single step relative to other threads
  - x=x+1 was not atomic
  - Read (lw) and write (sw) were atomic
  - Sometimes this doesn't hold (wide words that spans more than one memory address)

Three Concepts We've Covered

- Busy-waiting (spinning, busy-looping): technique in which a process repeatedly checks to see if a condition is true
  - "do nothing" loops: while(flag[1-***i***] and turn==1-***i***);

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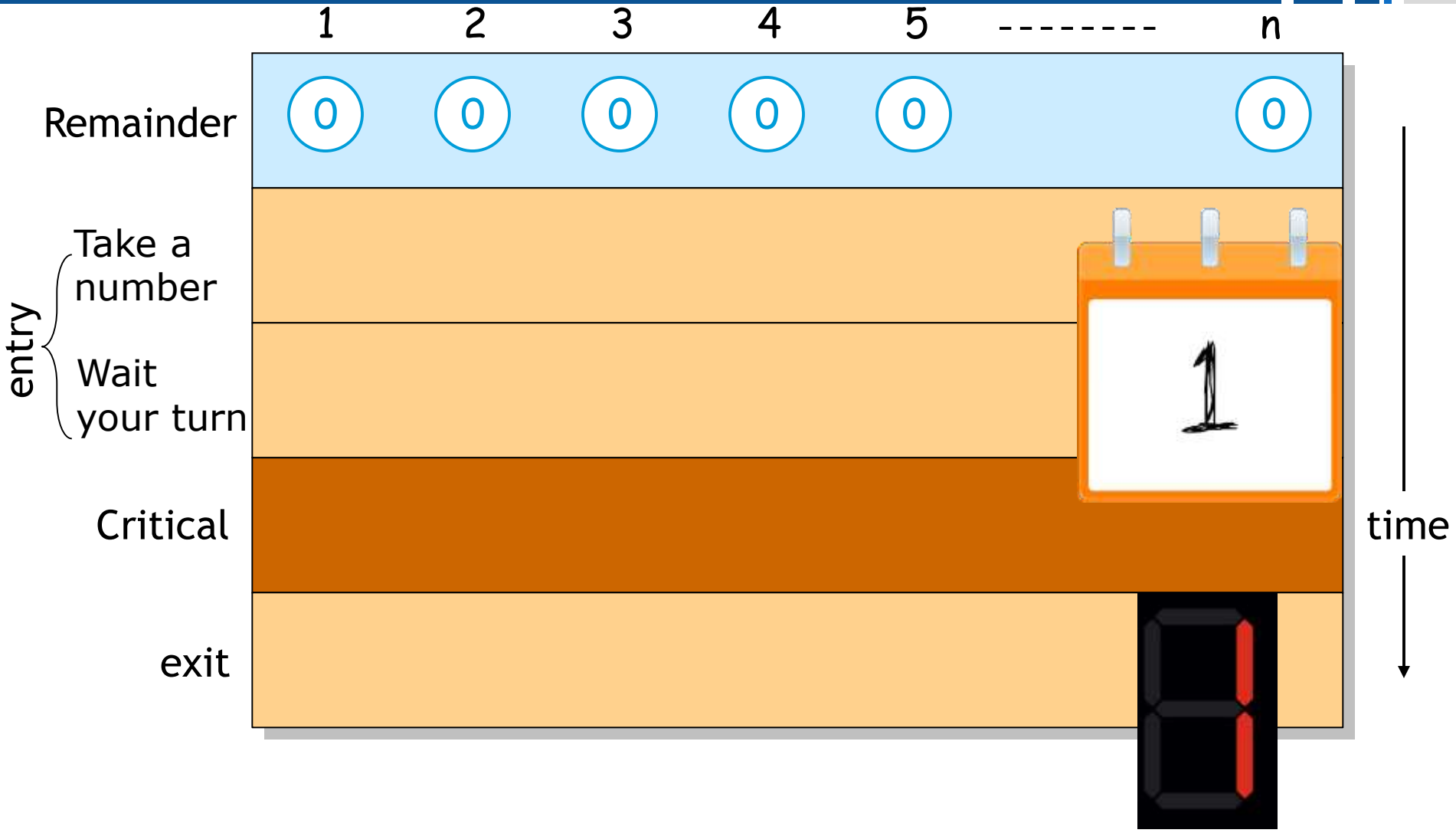
  - We will discuss alternative later

Lamport's Bakery Algorithm - 1974



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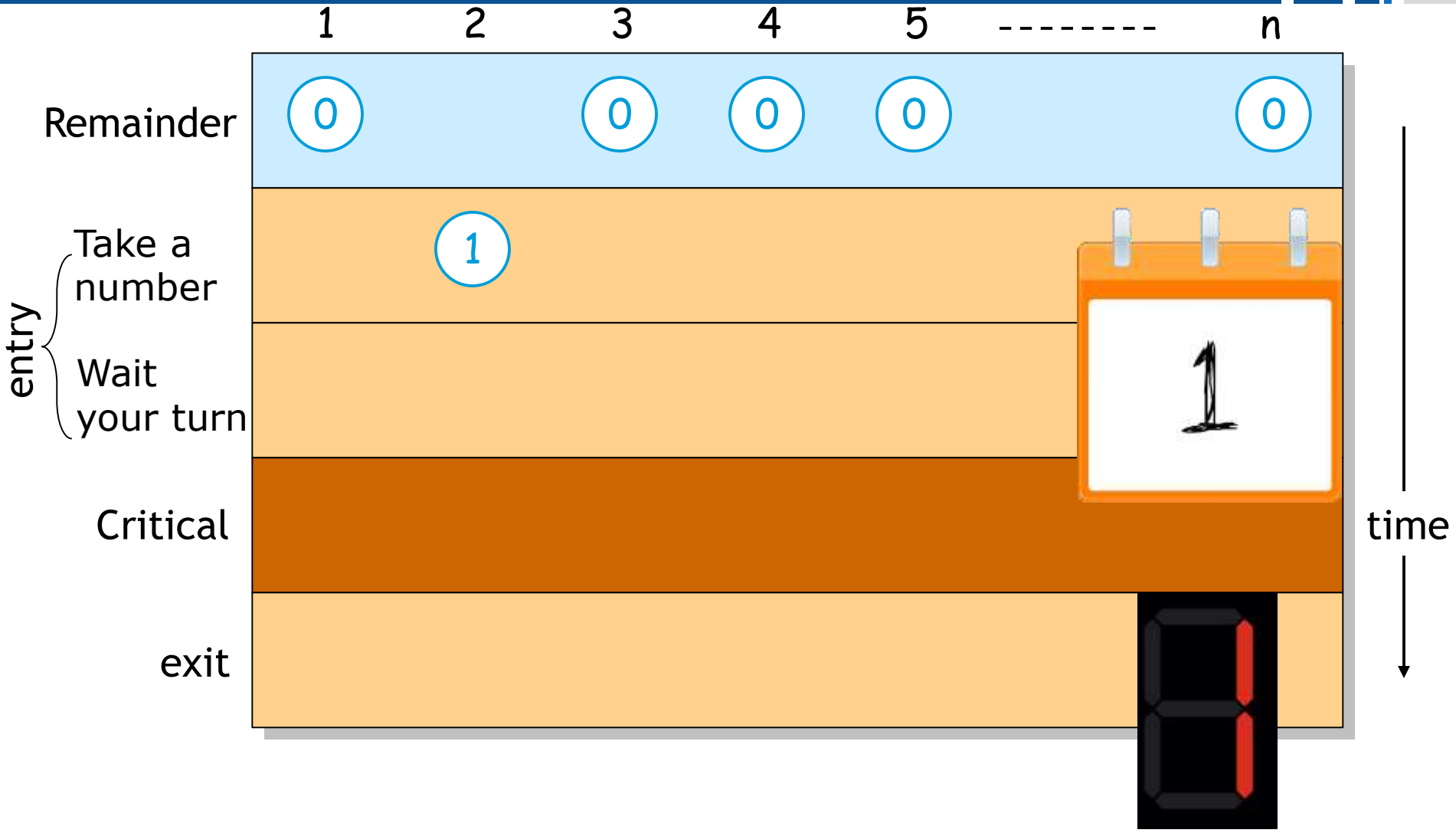

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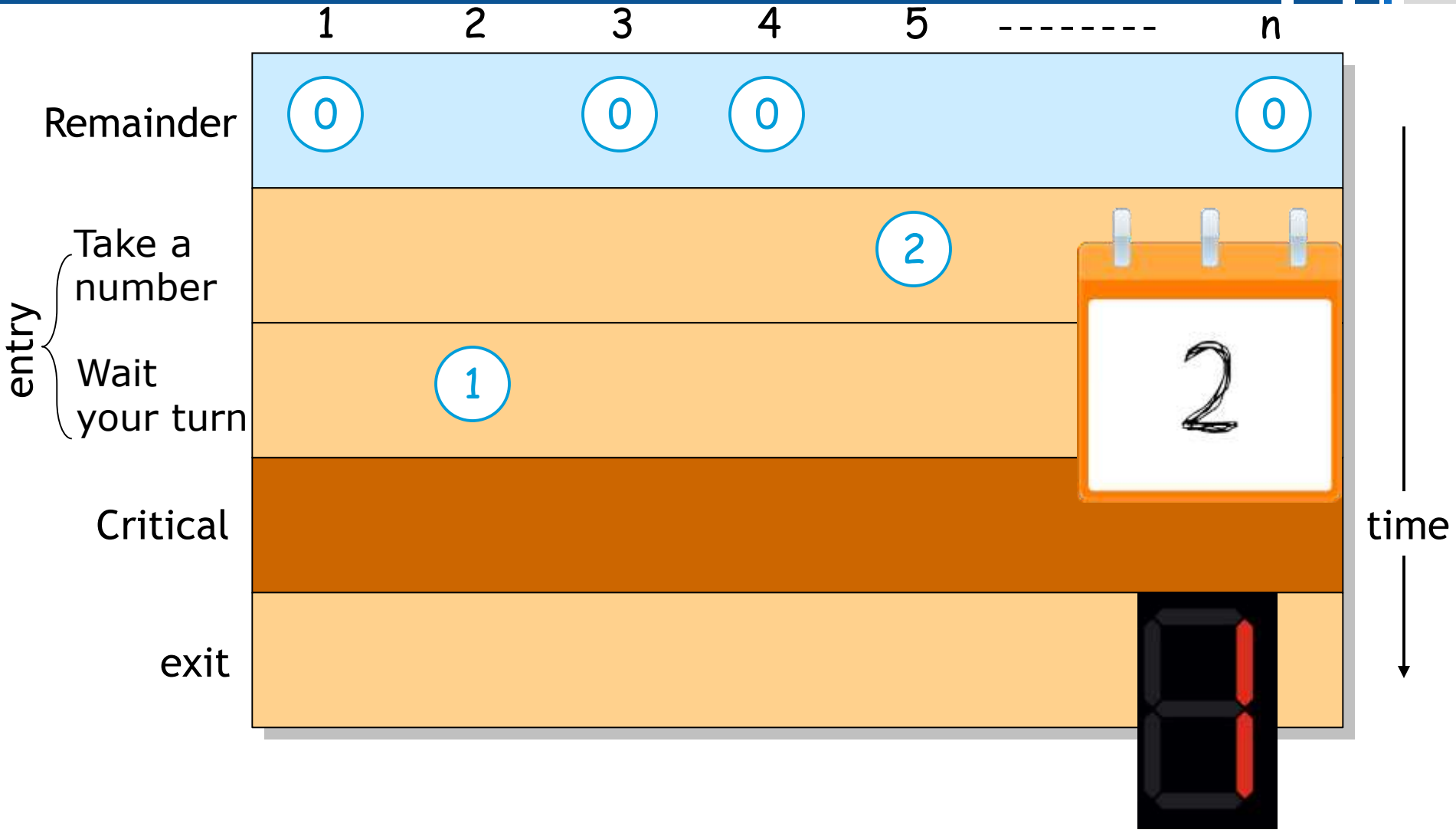

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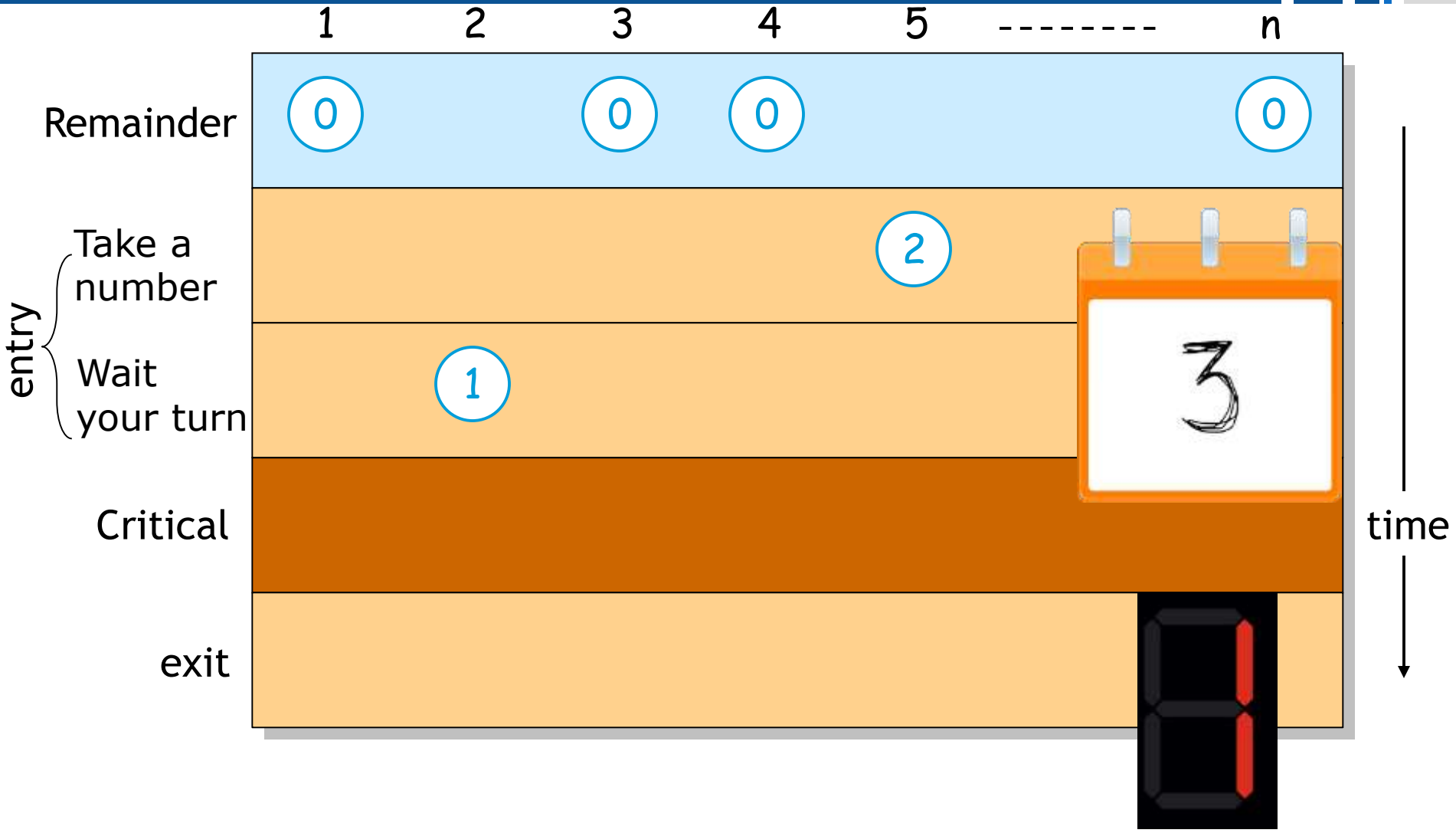

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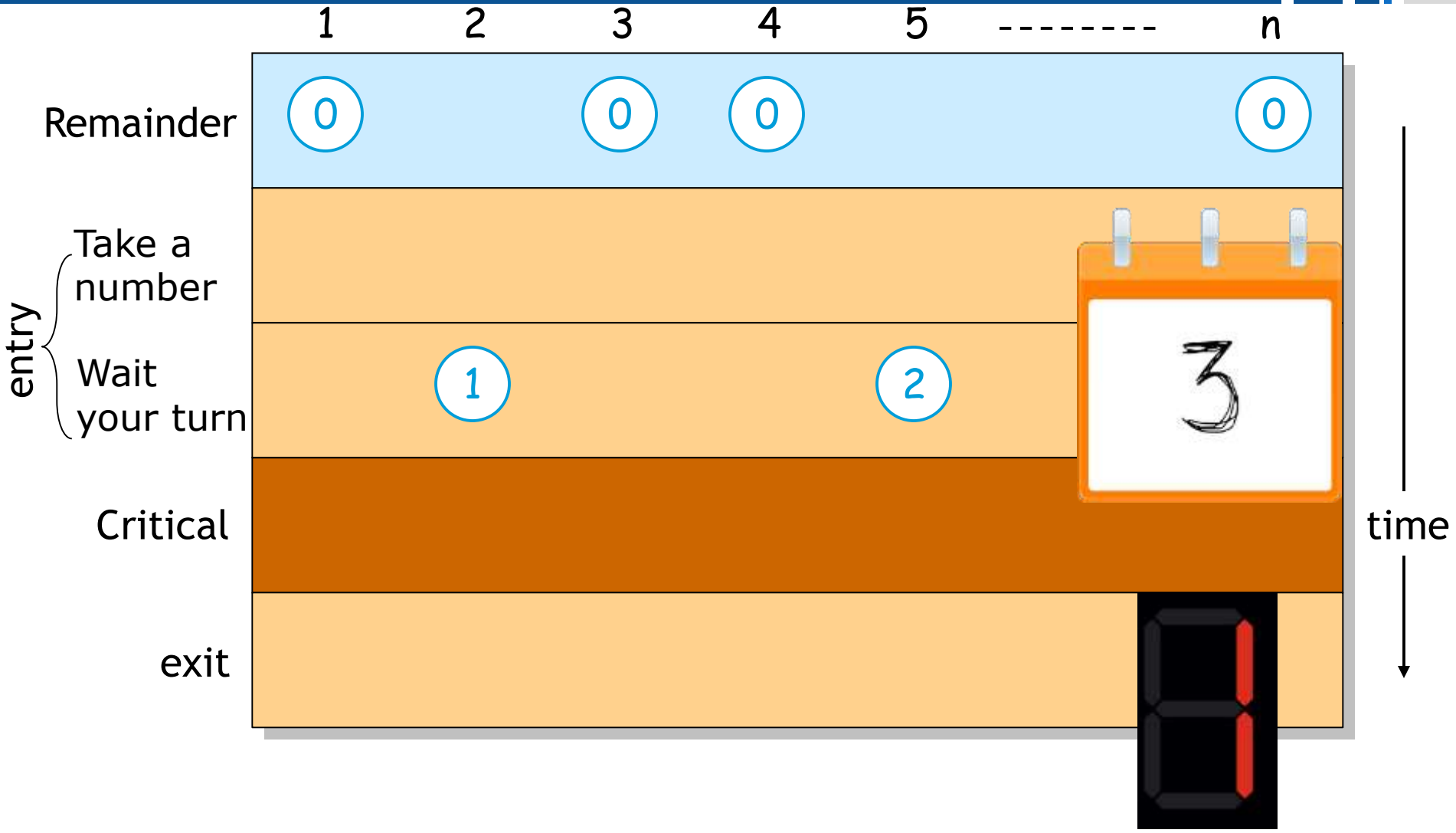

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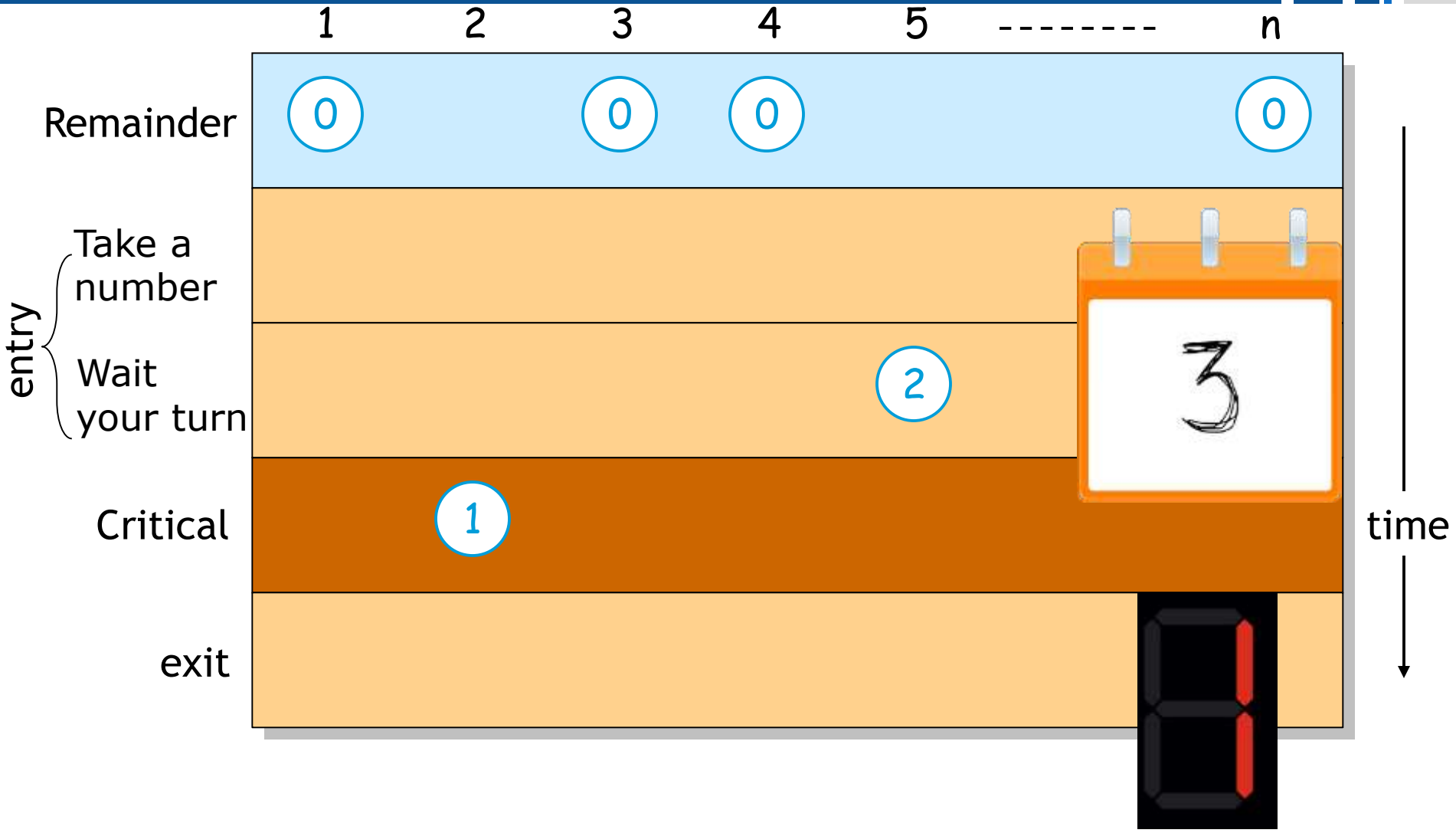

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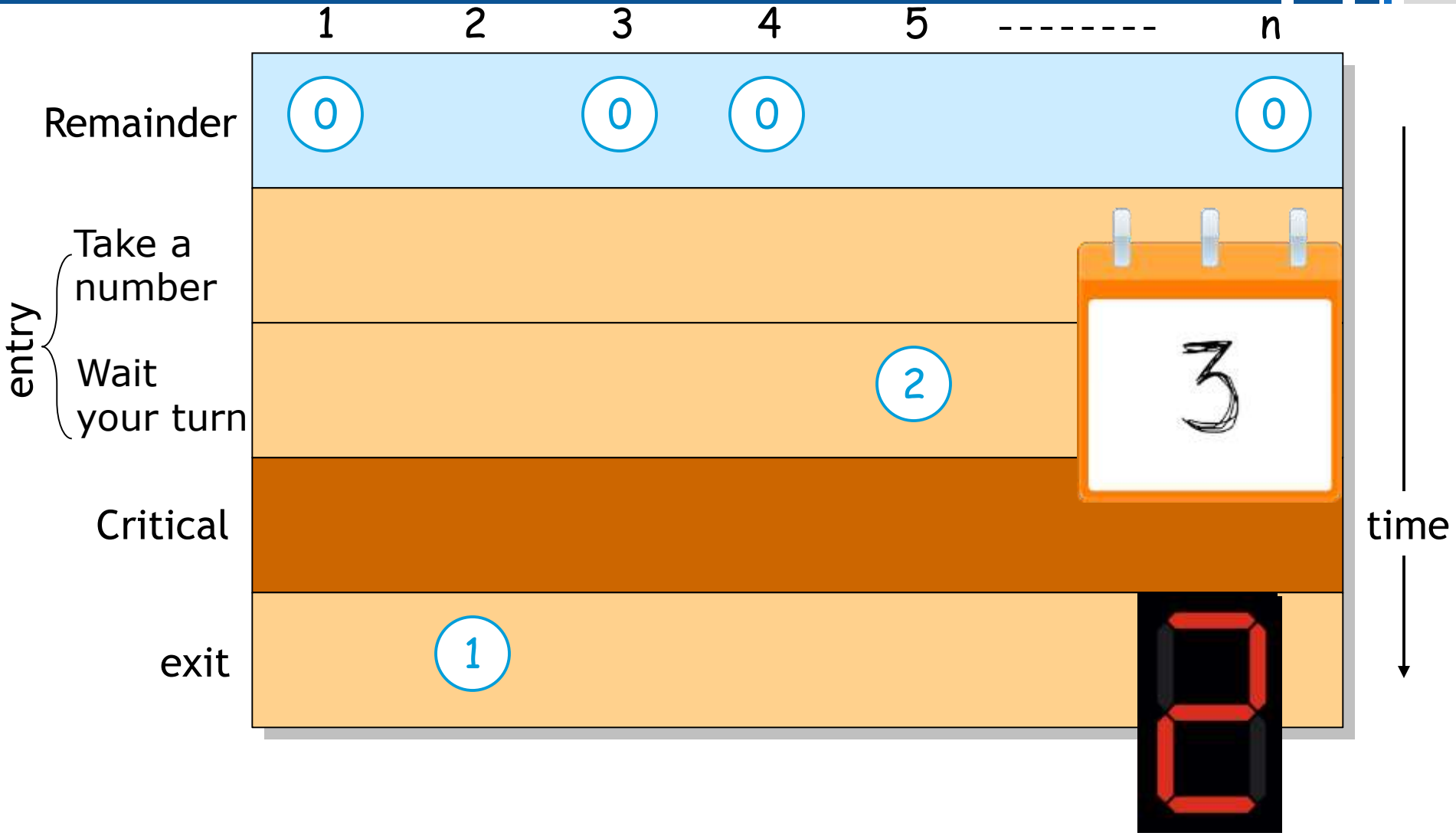

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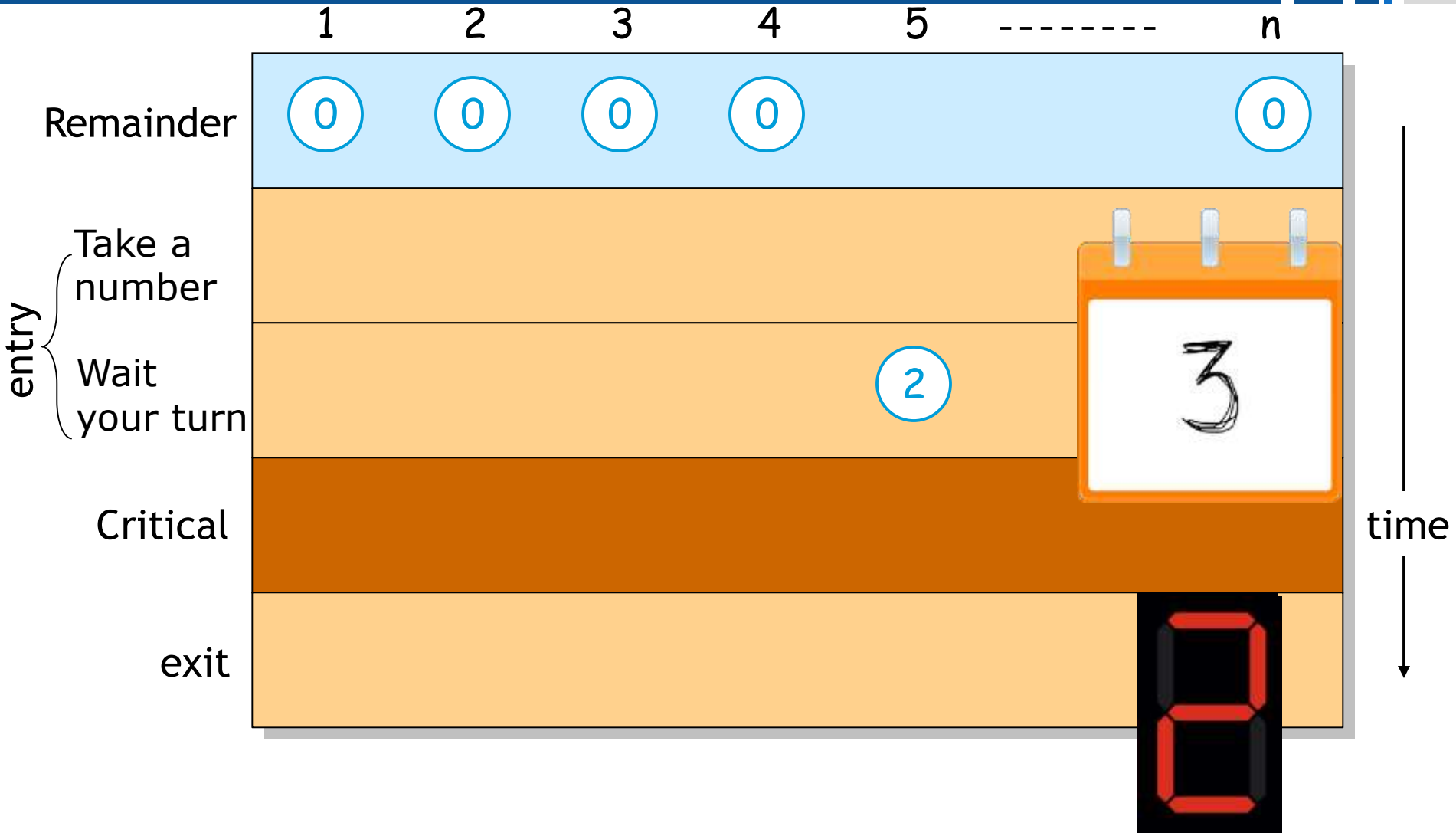

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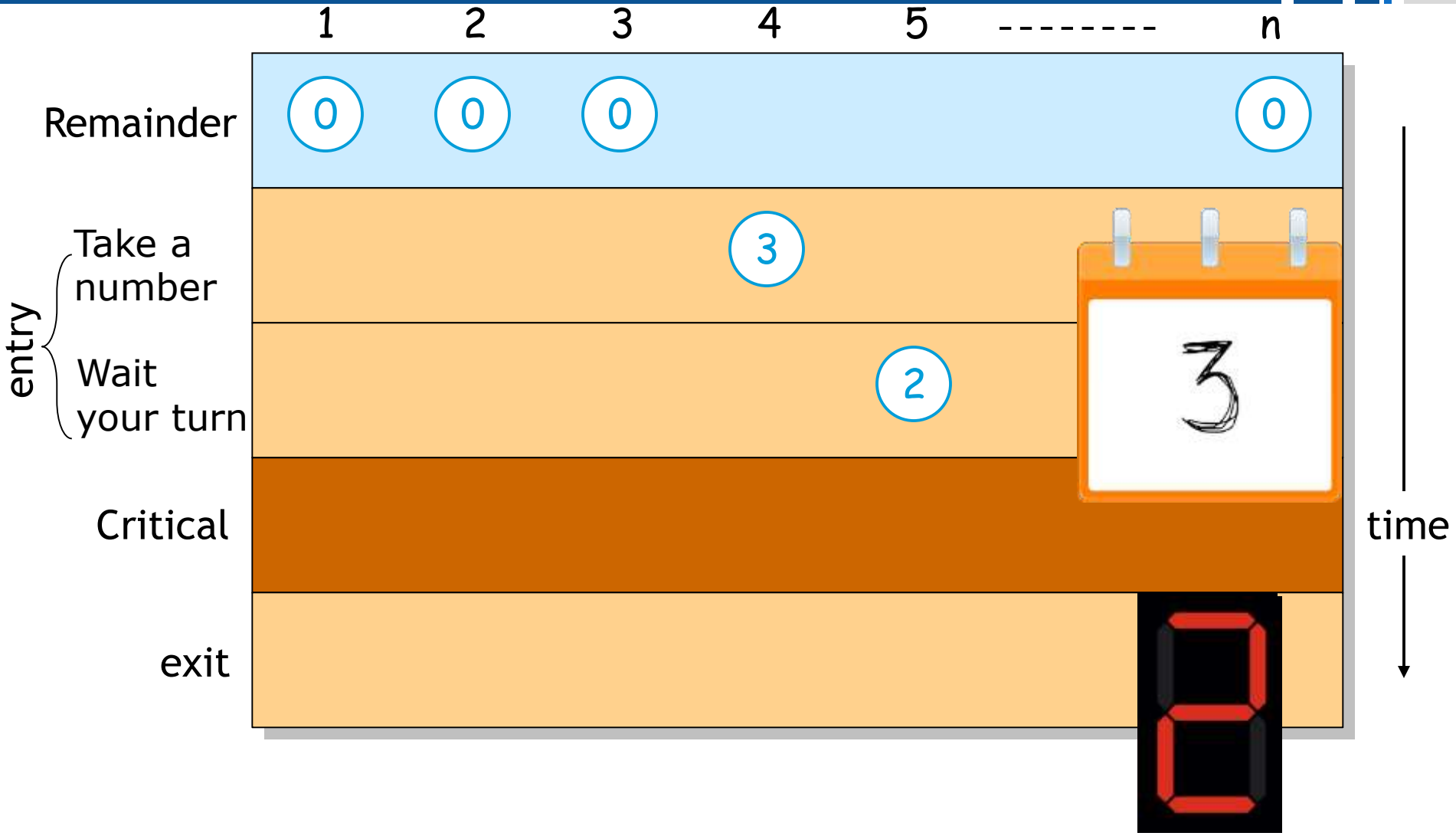

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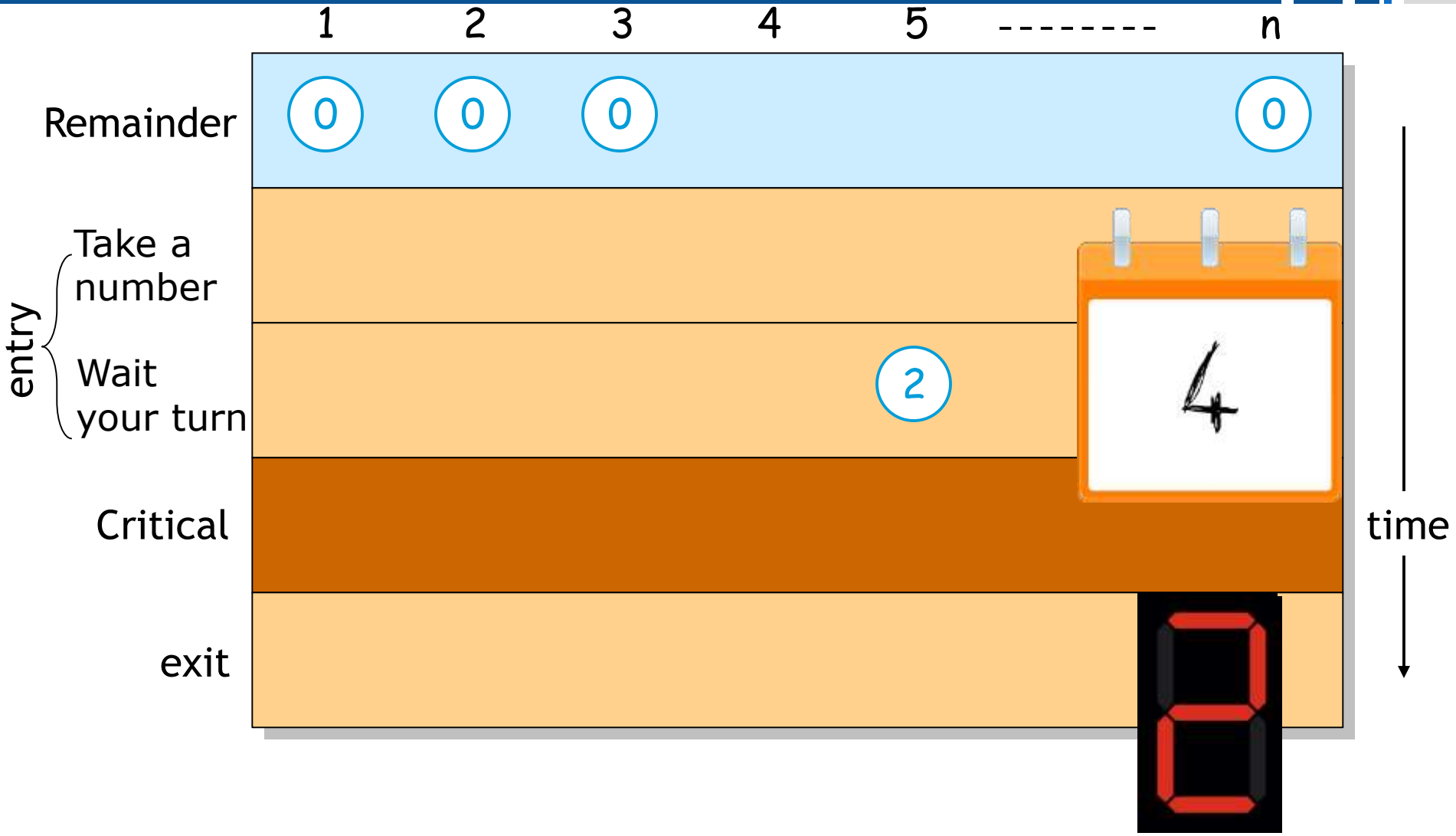

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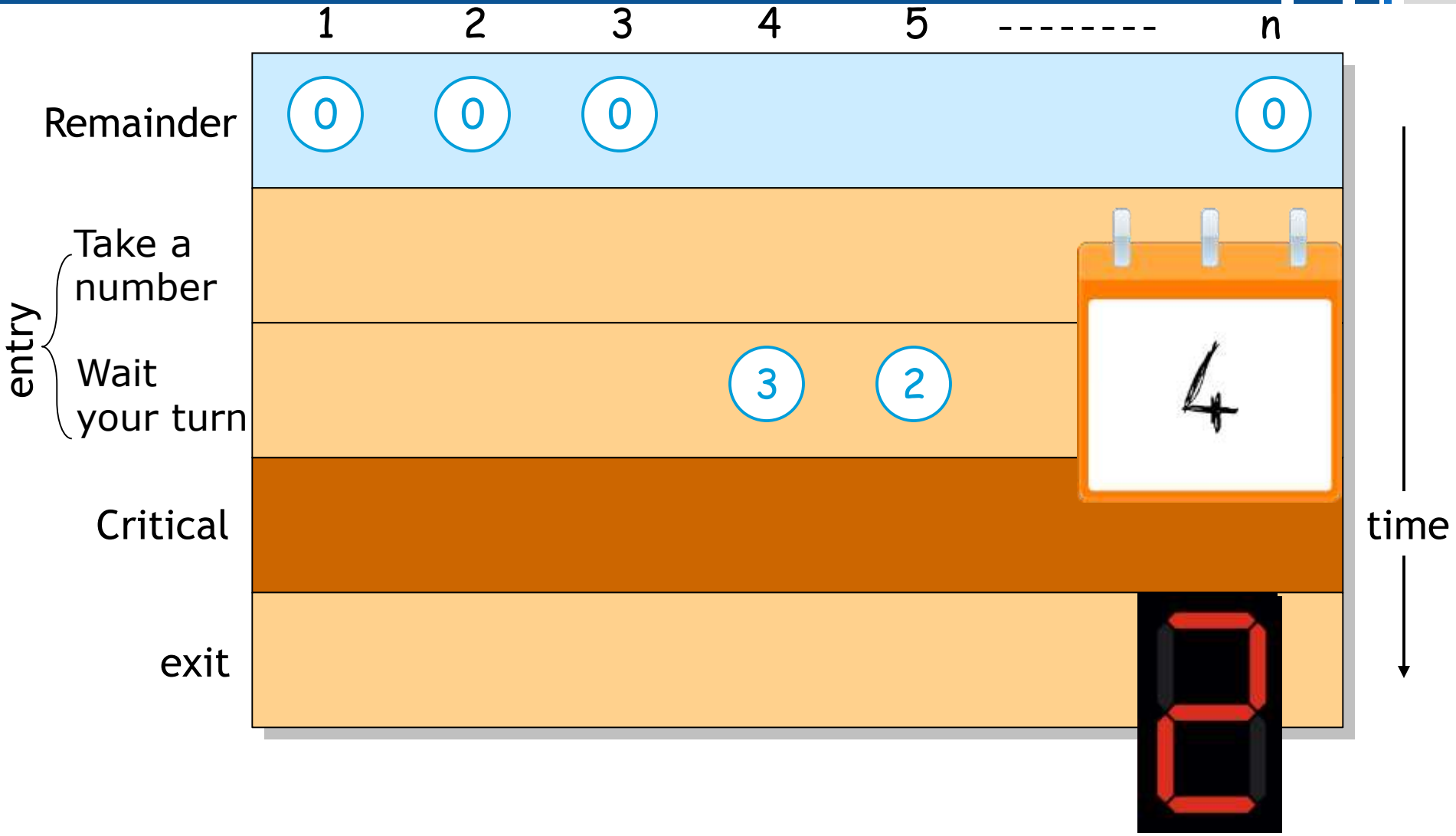

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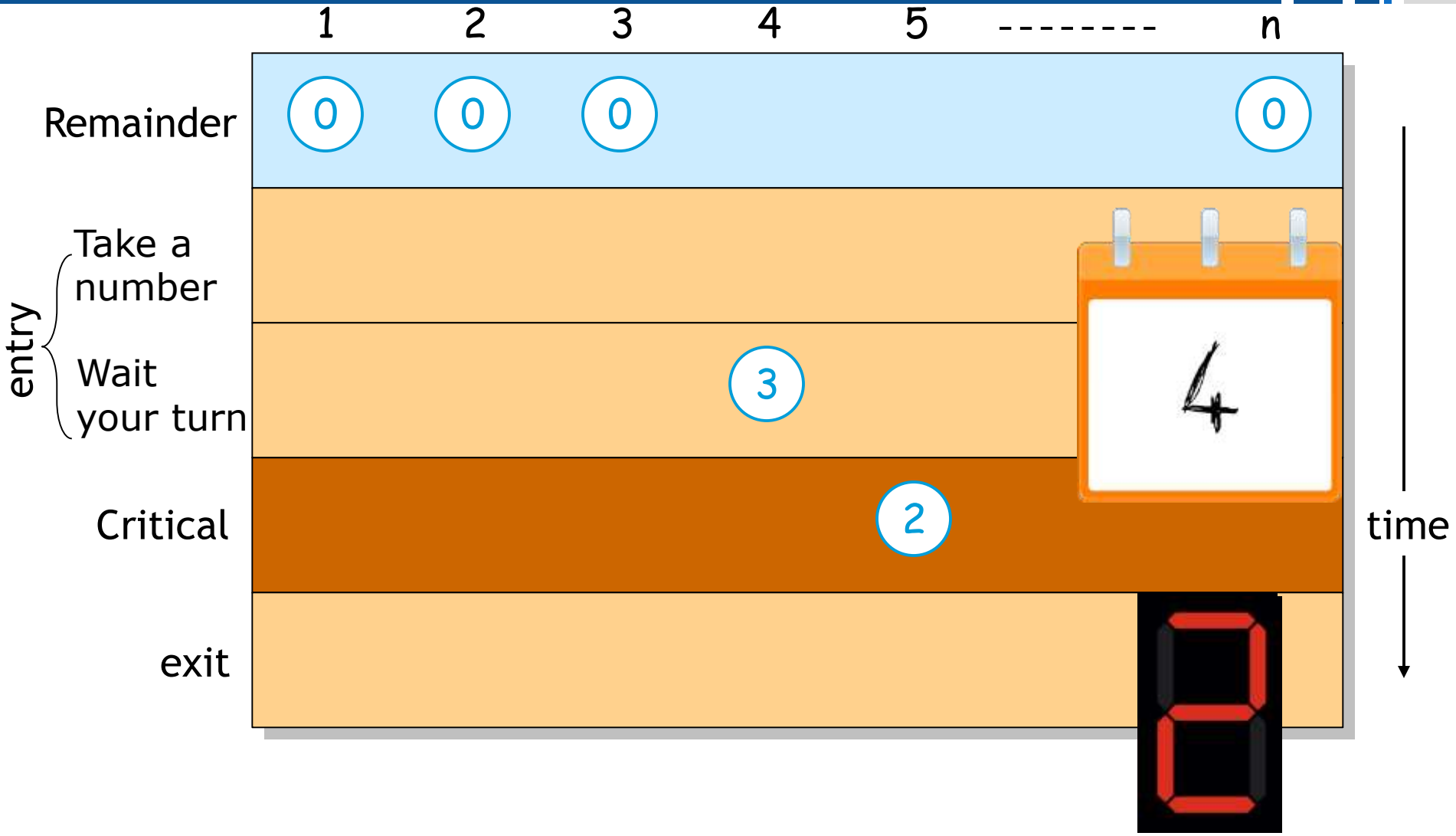

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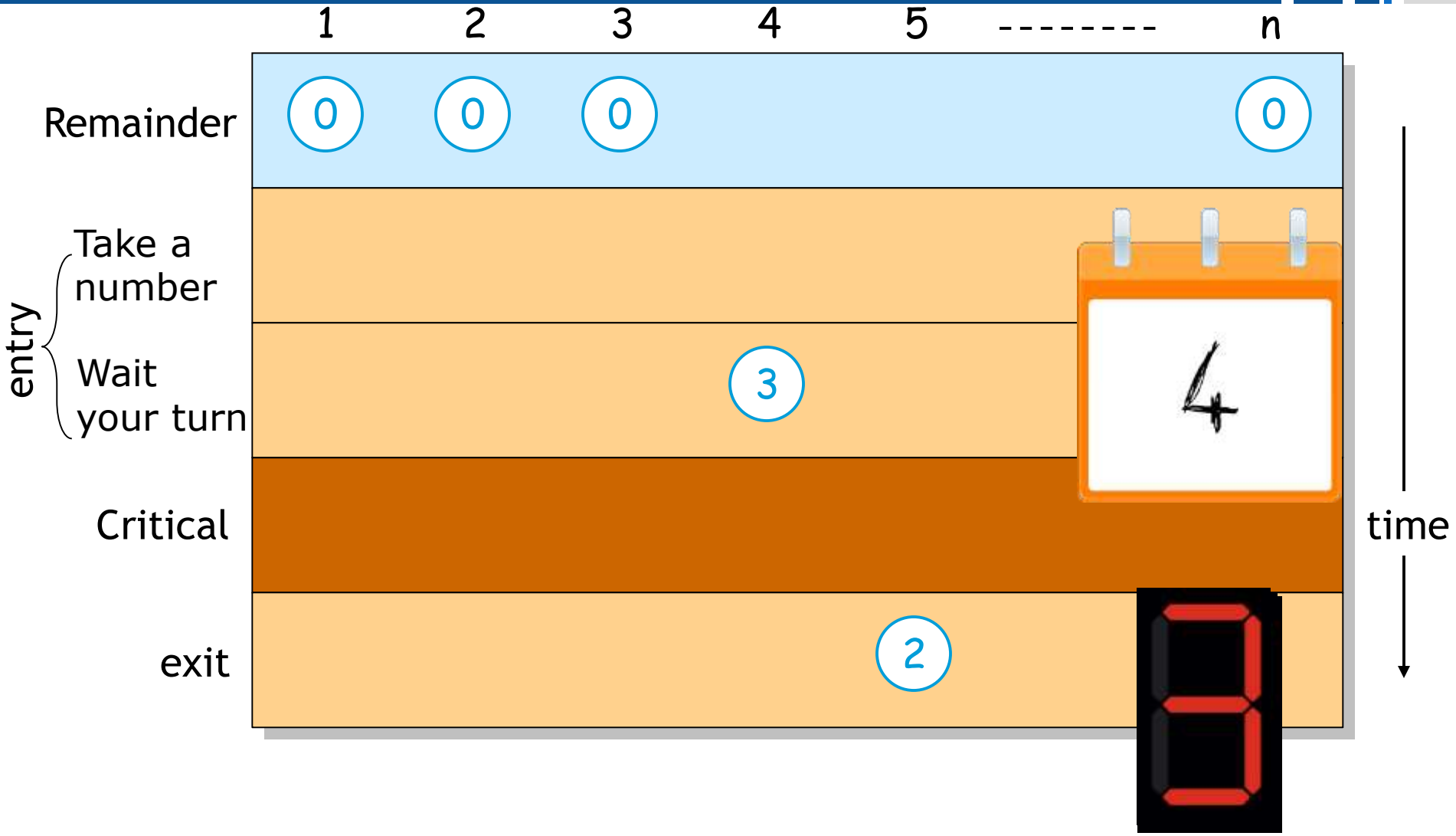

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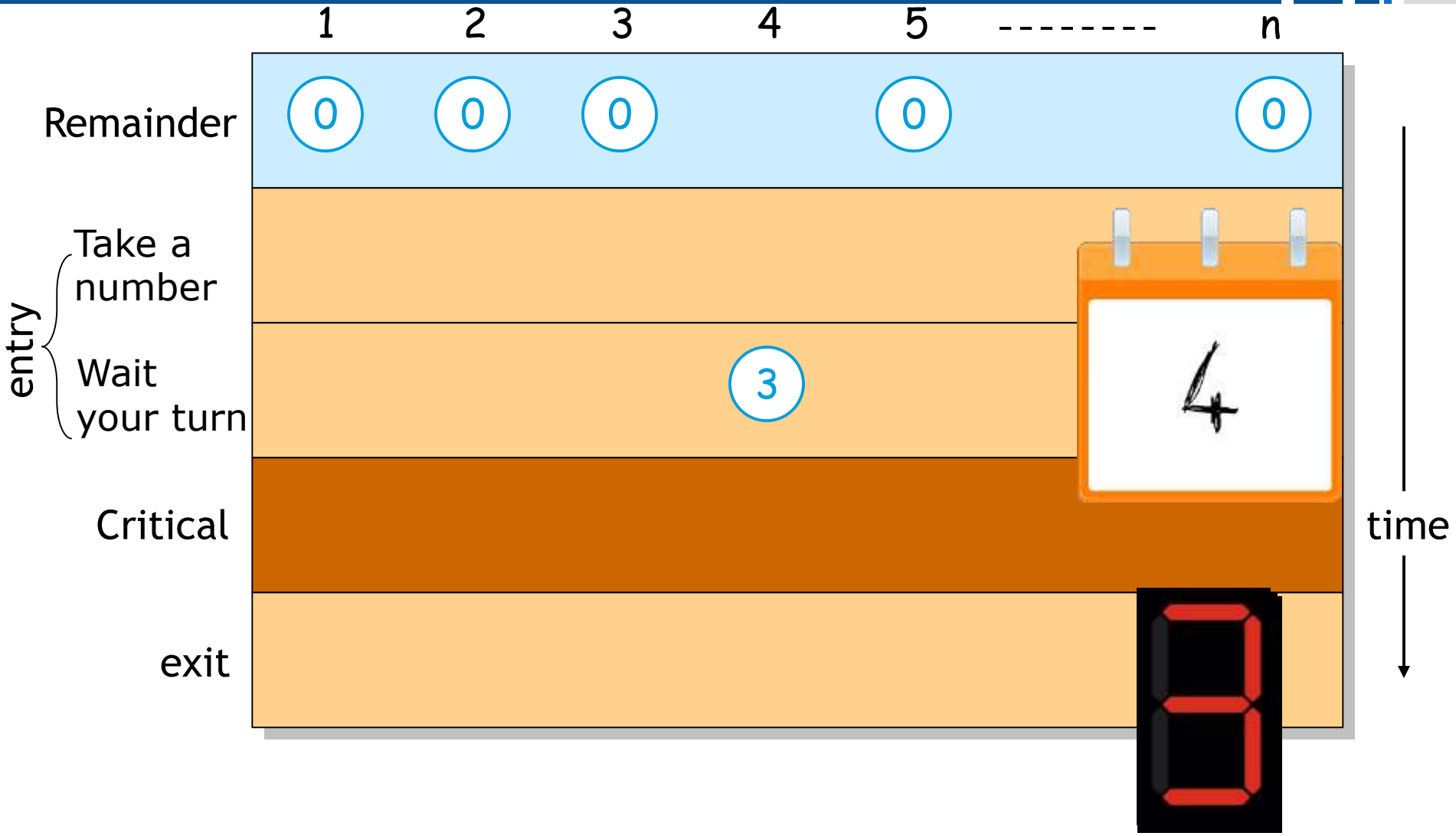

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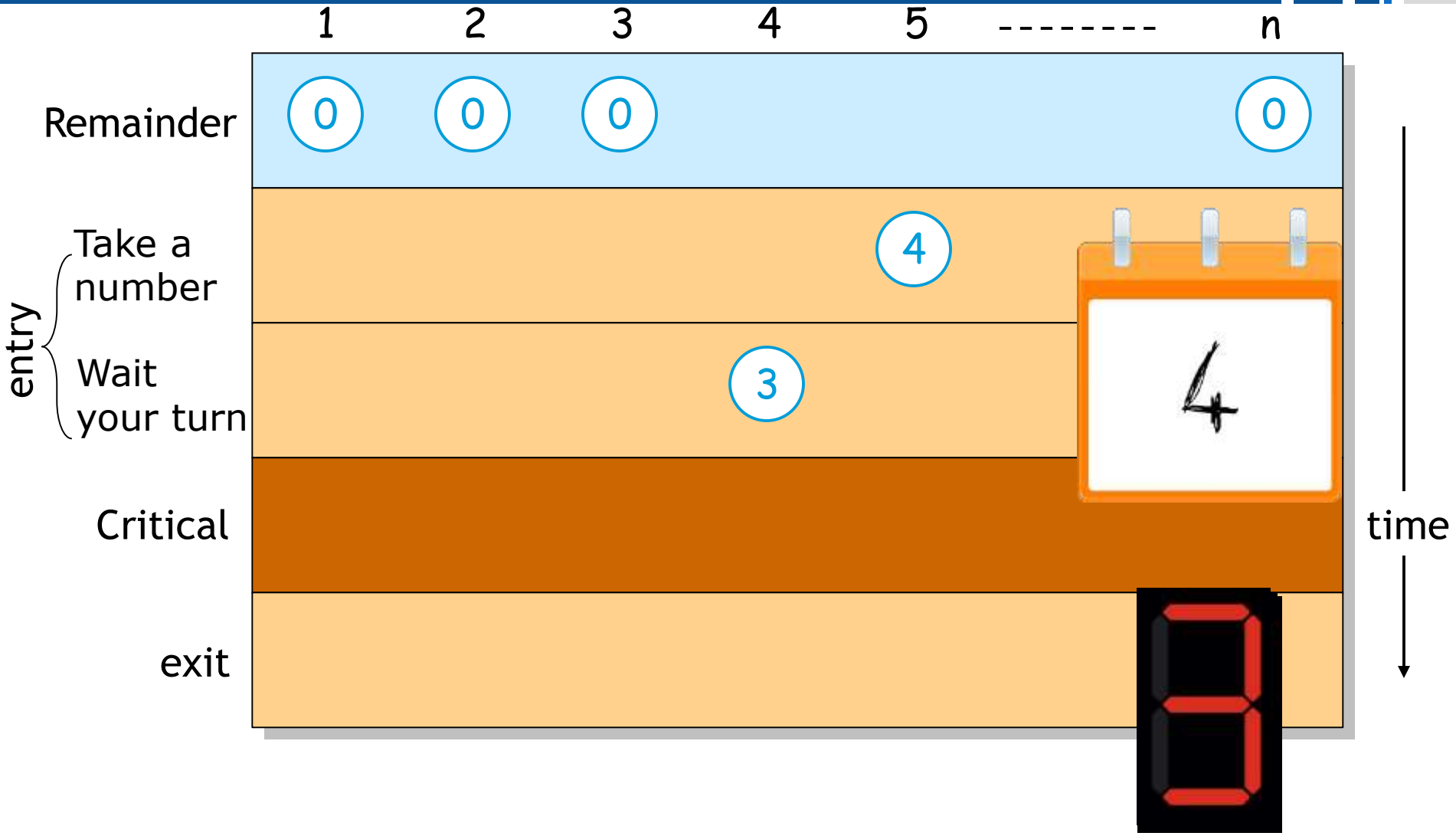

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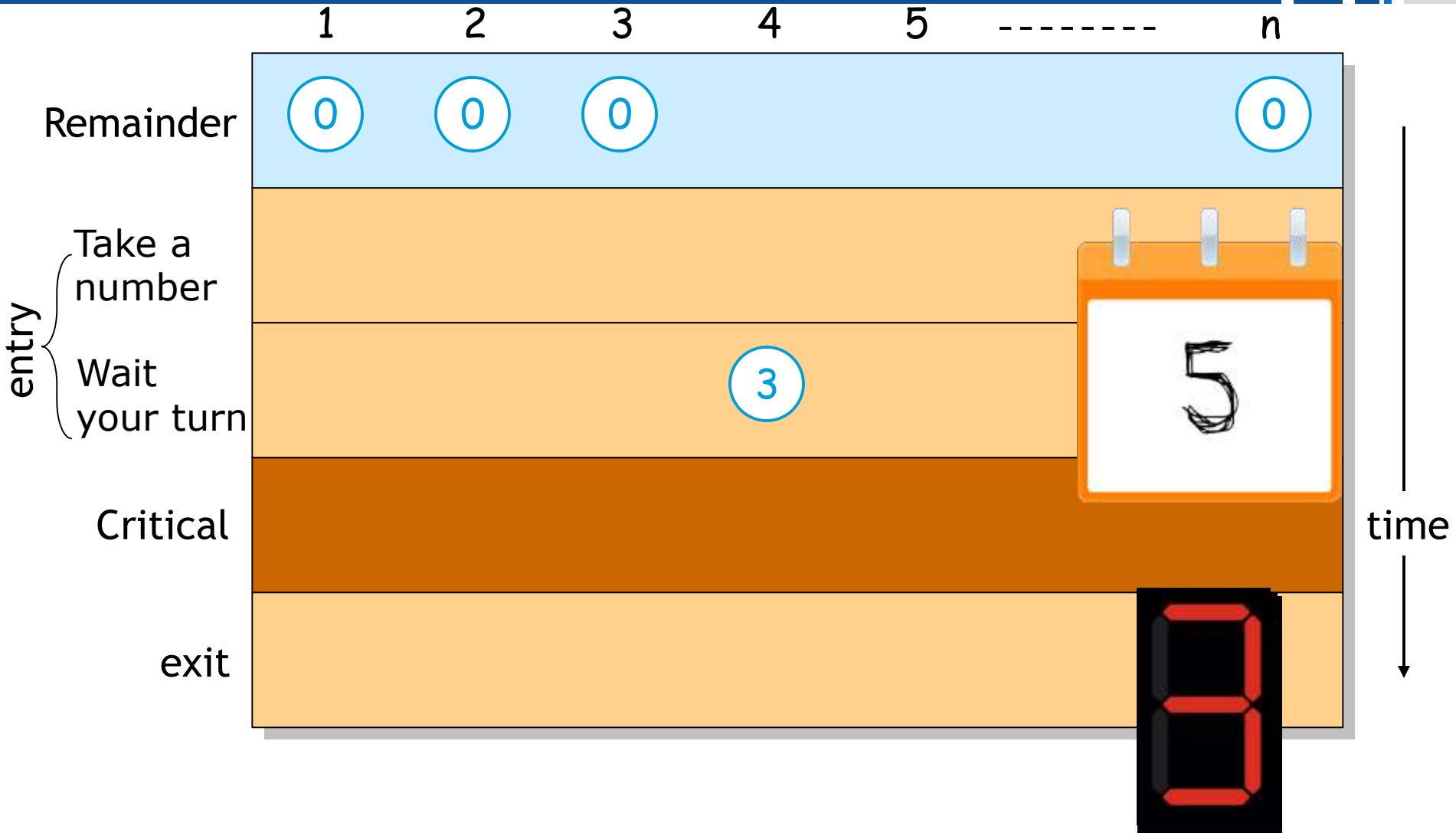

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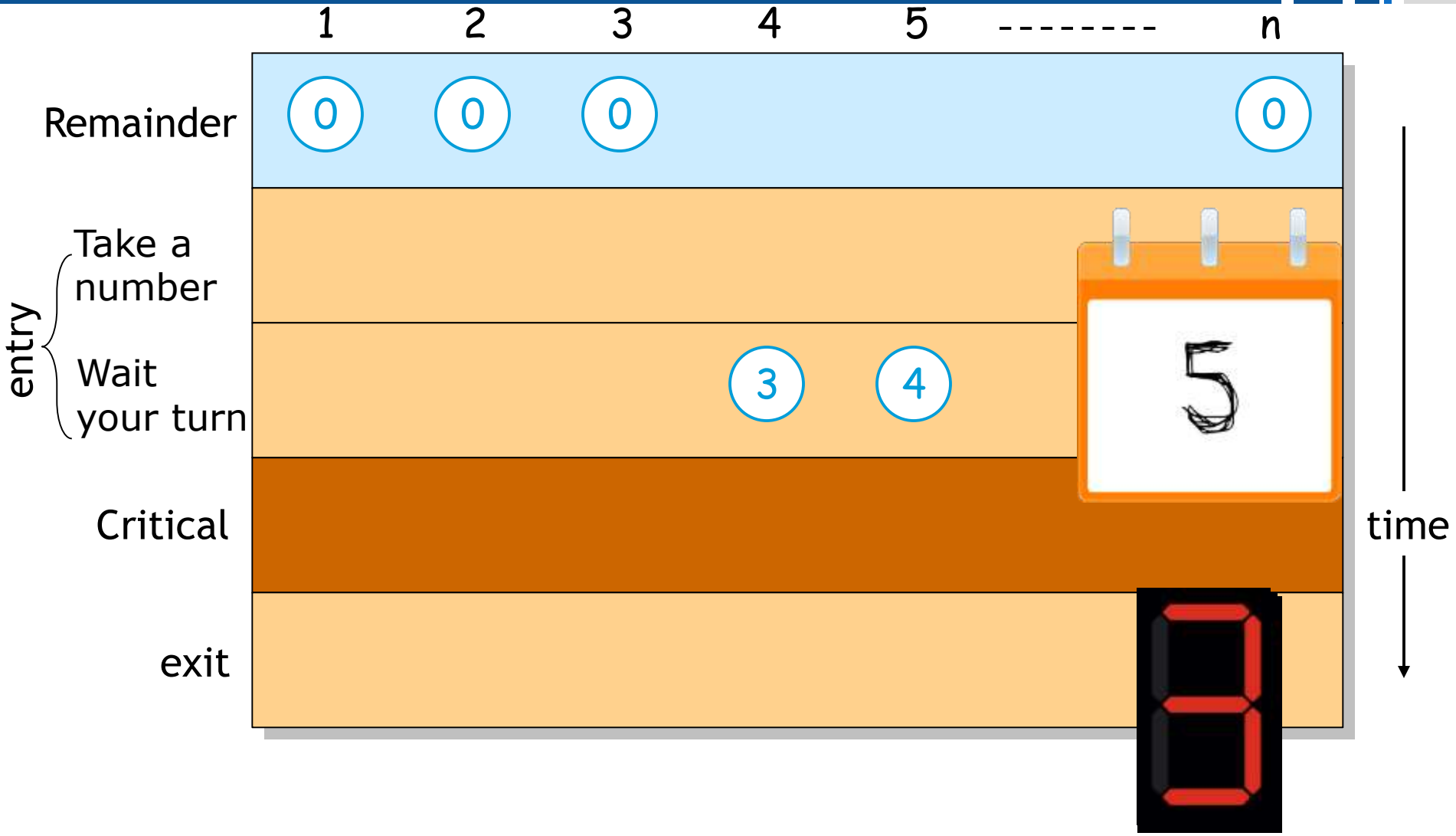
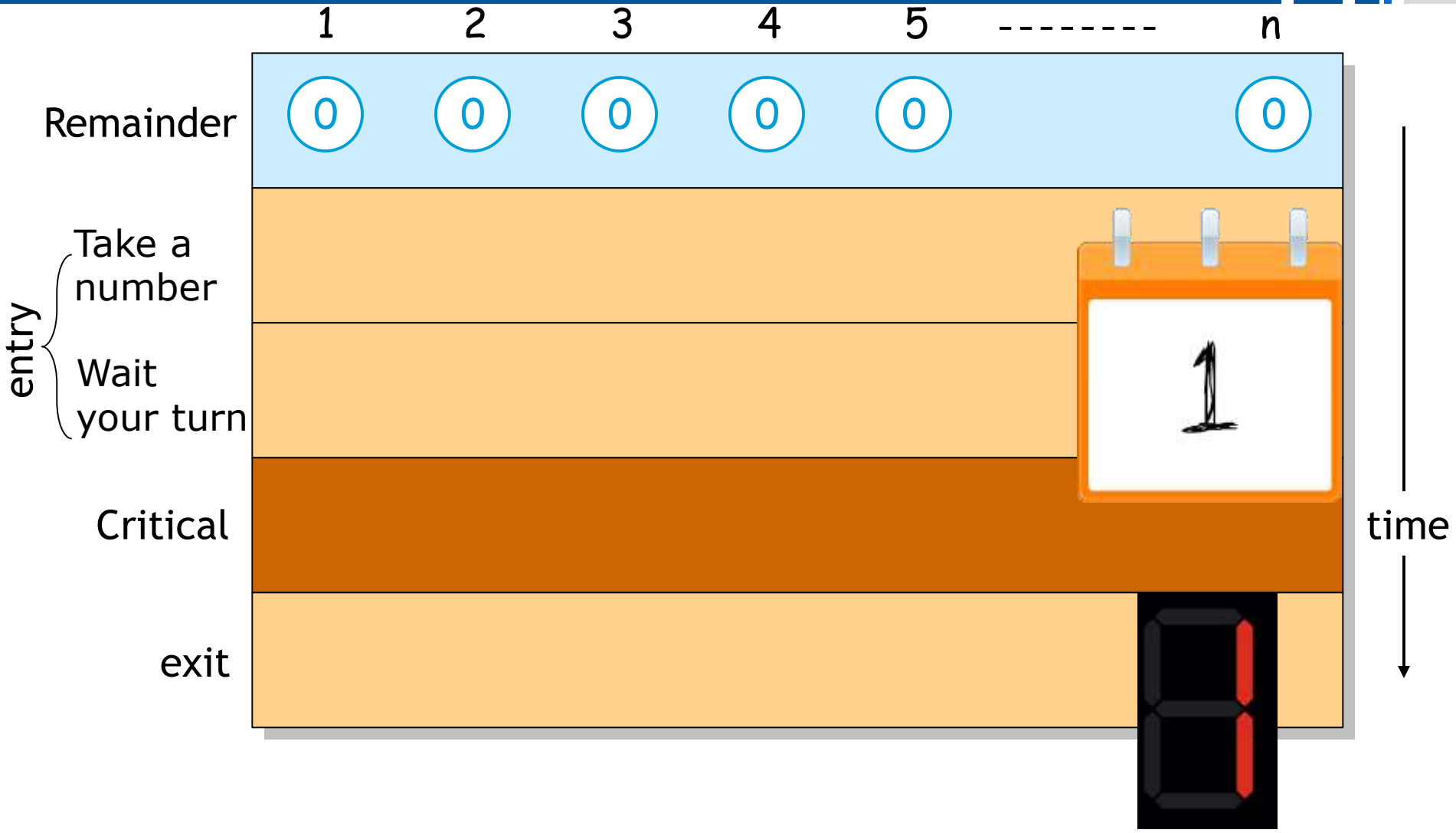


Not quite...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entry
Wait your turn
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Critical
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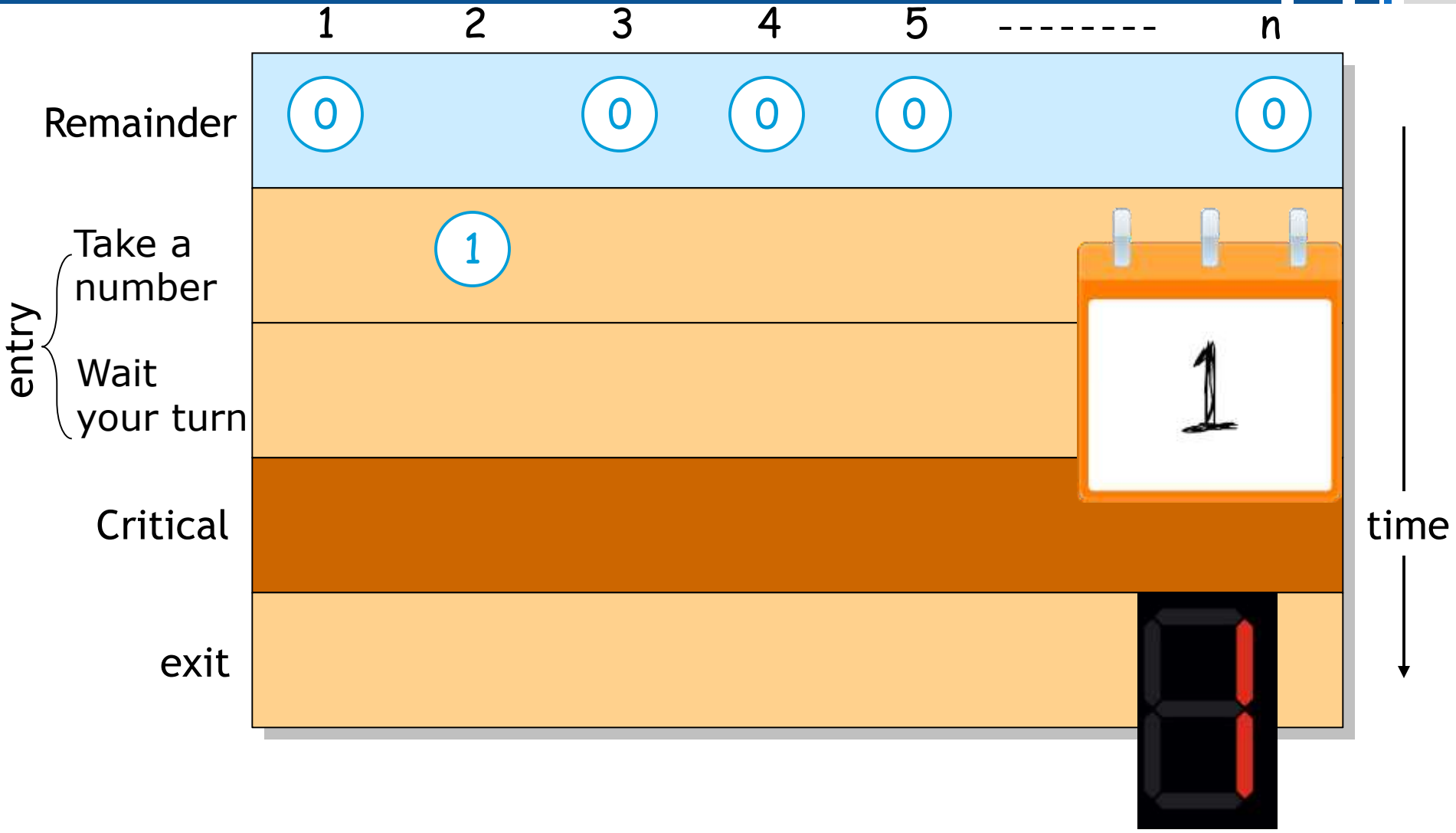
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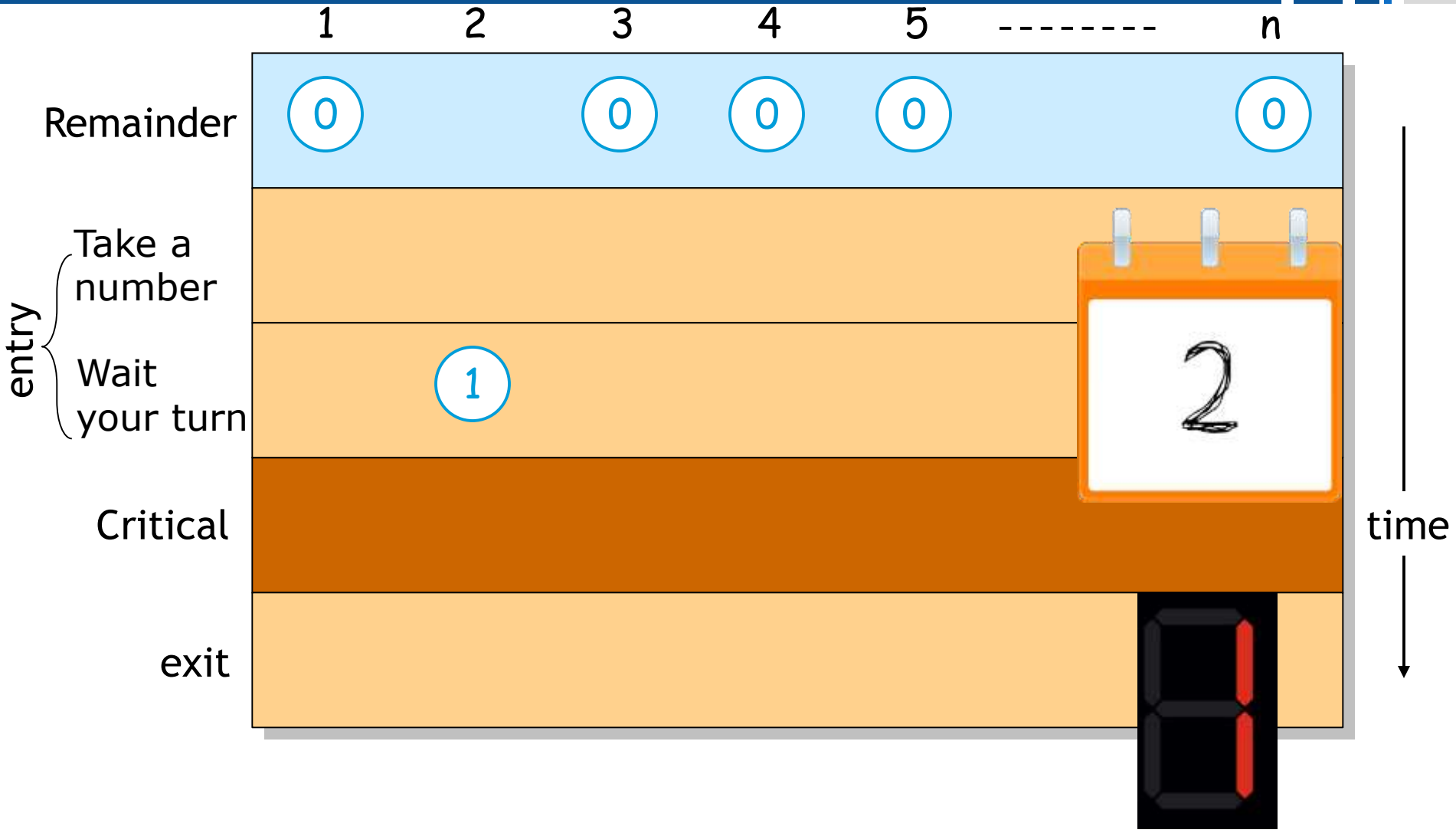
Not quite...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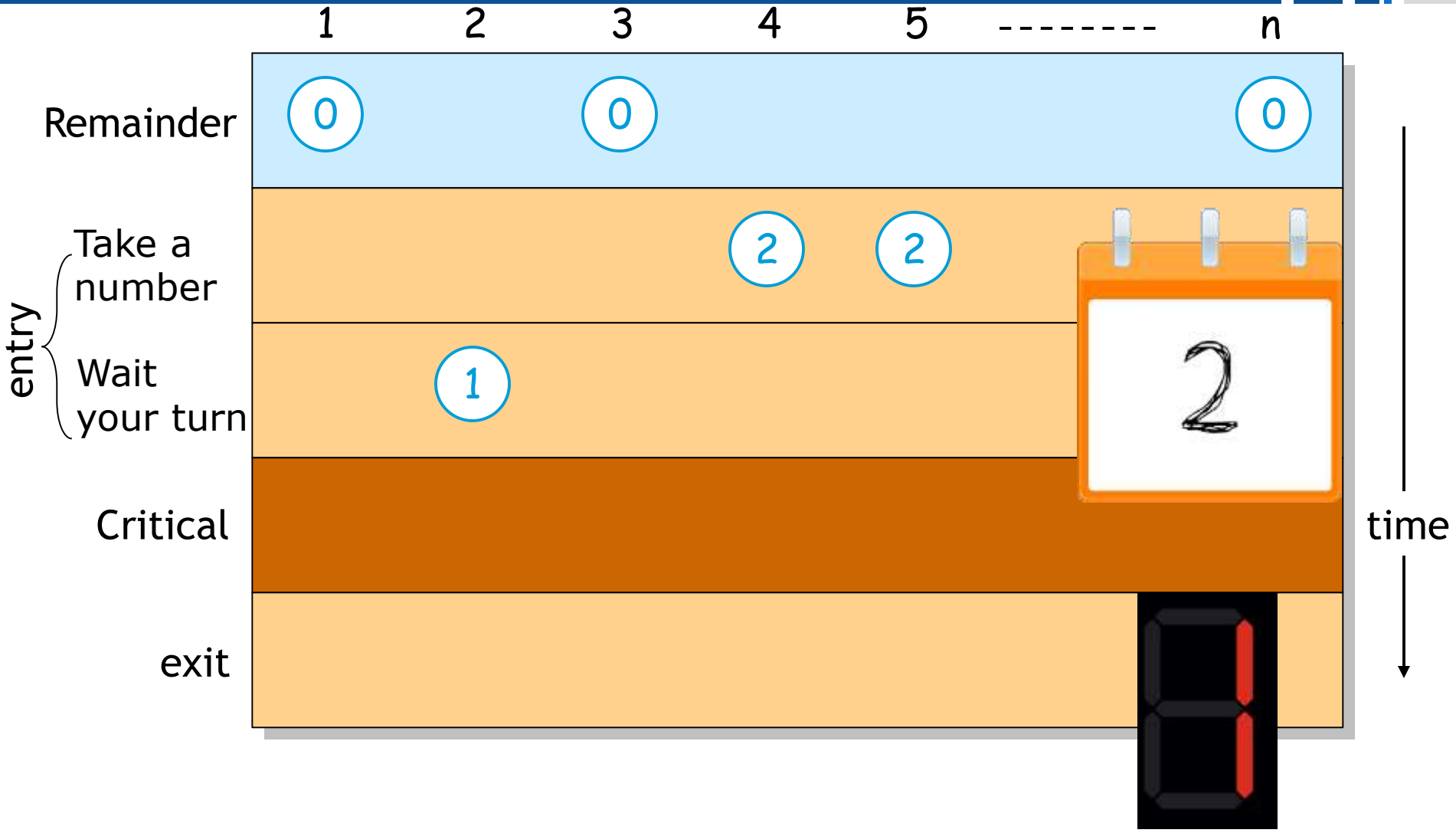
entry
Take a number
Wait your turn
1
2
Critical
exit
time

Not quite...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entry
Take a number
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1
2
Critical
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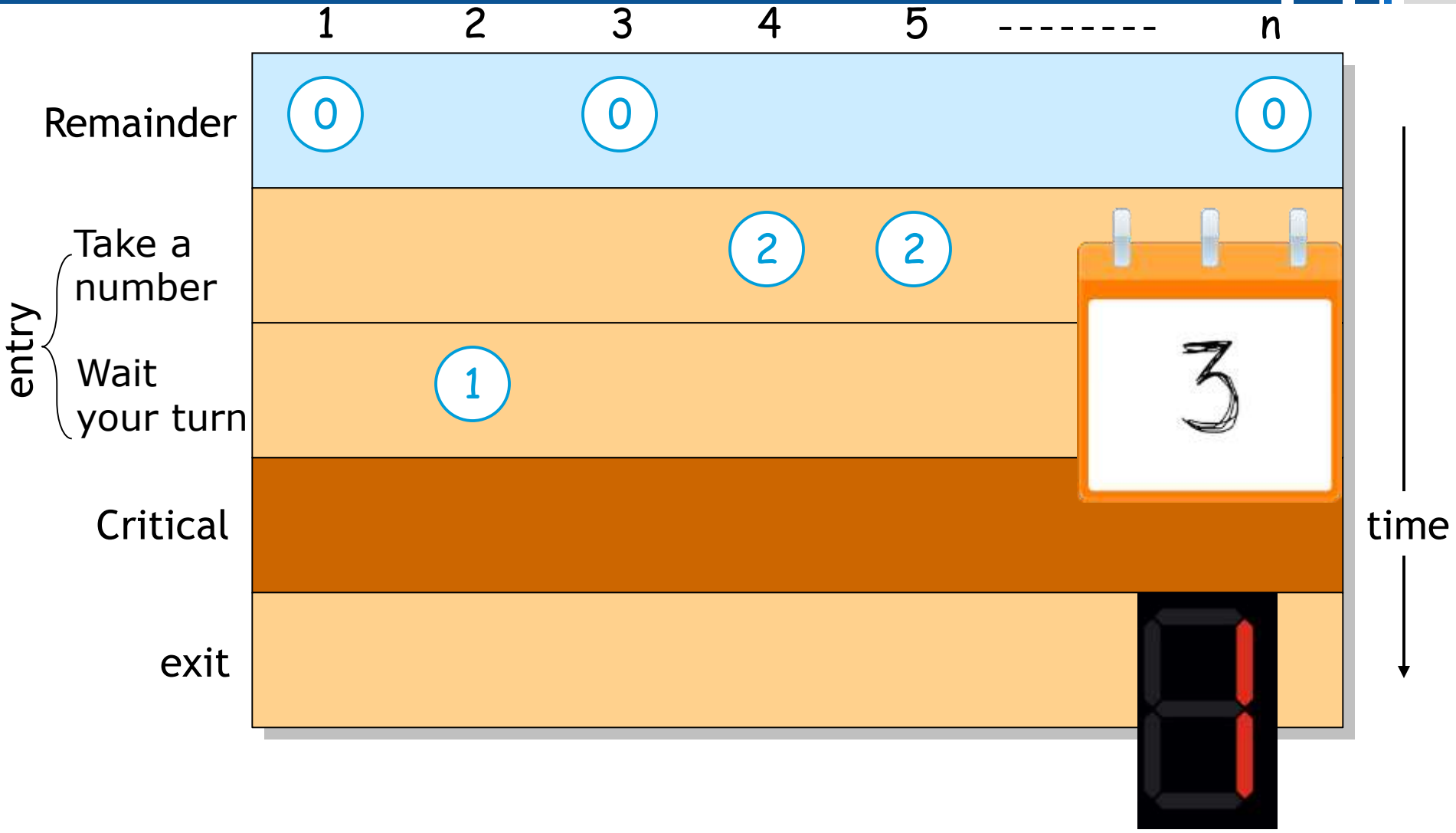
Not quite...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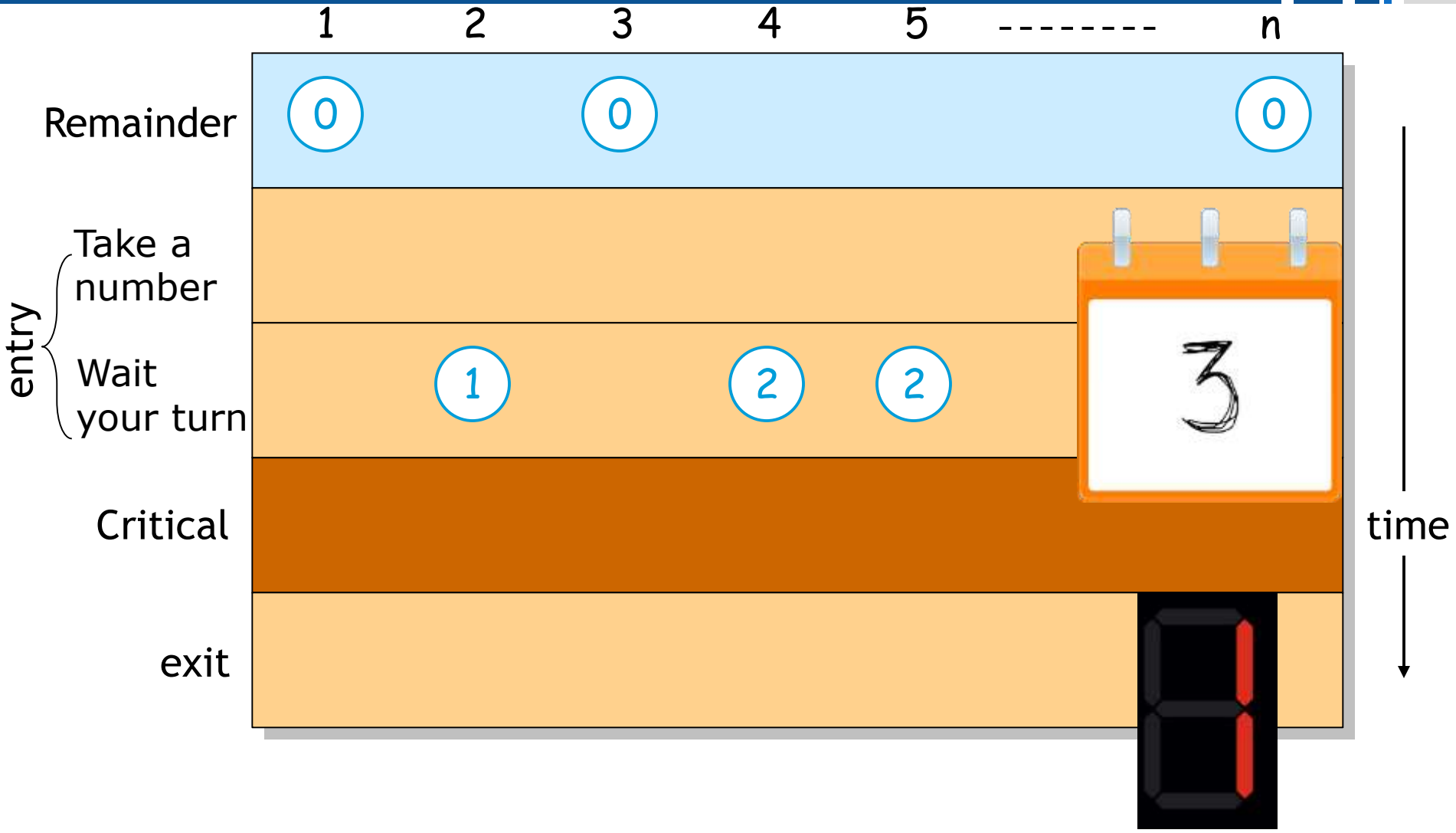
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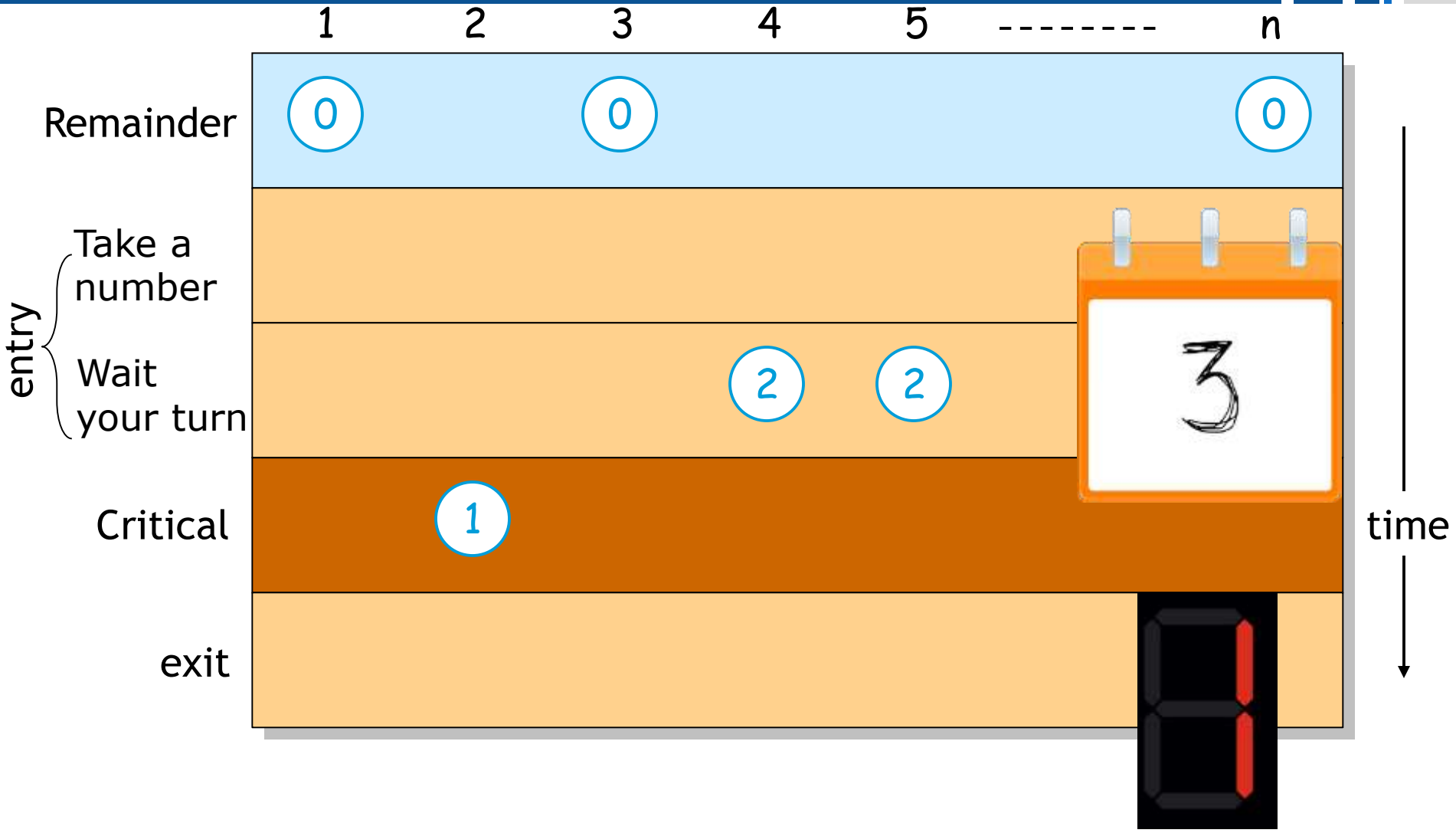
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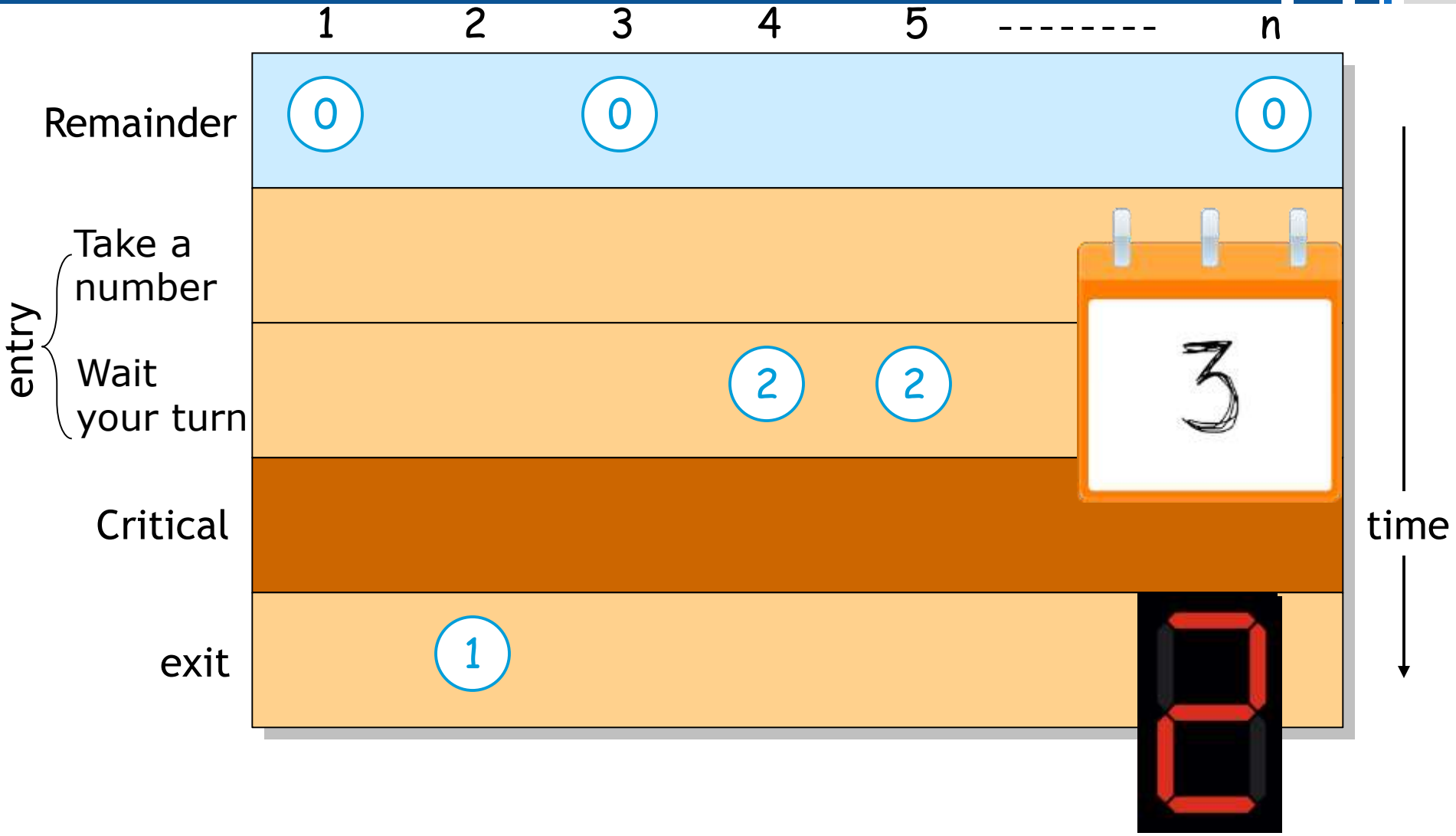
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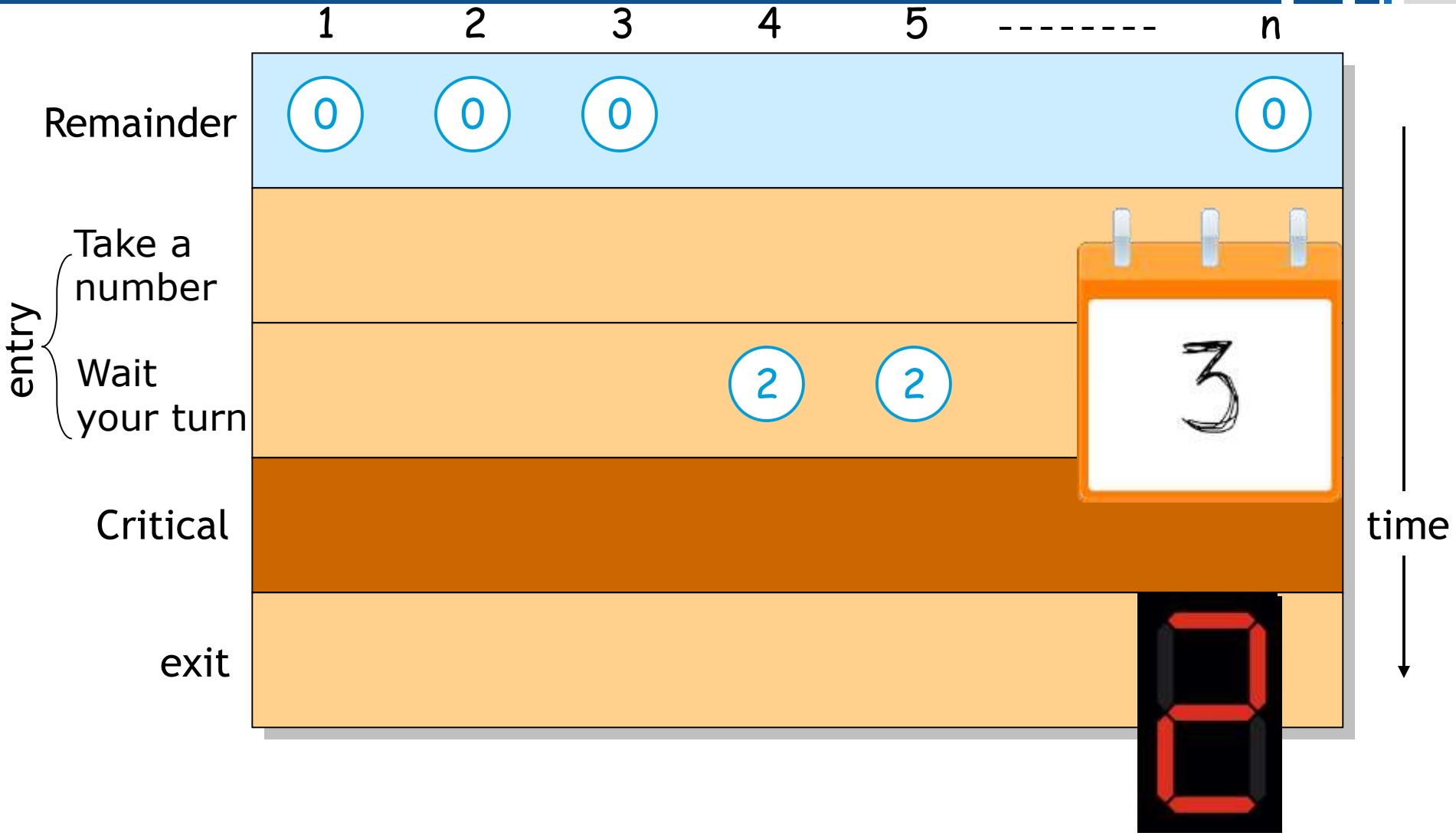
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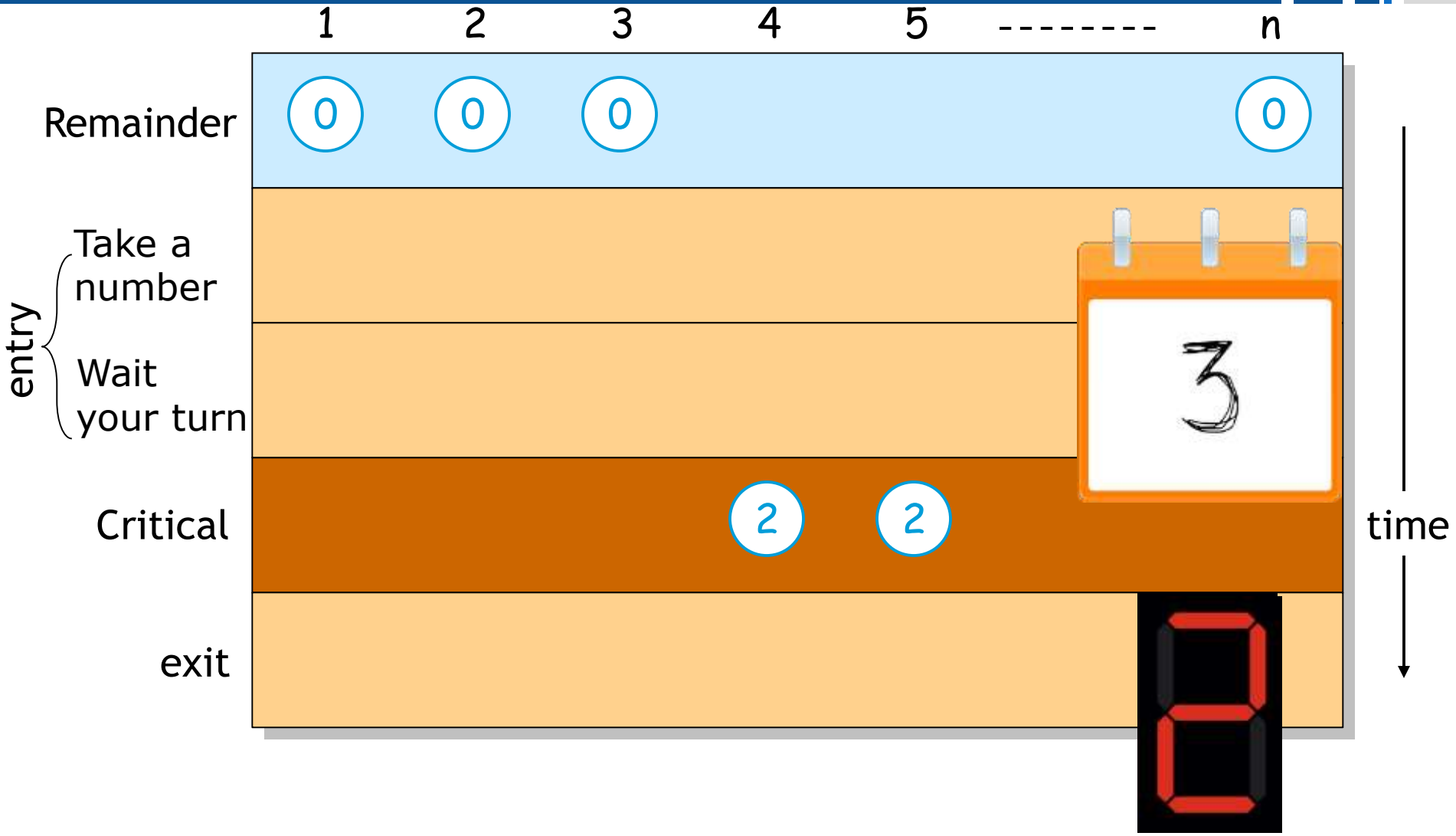
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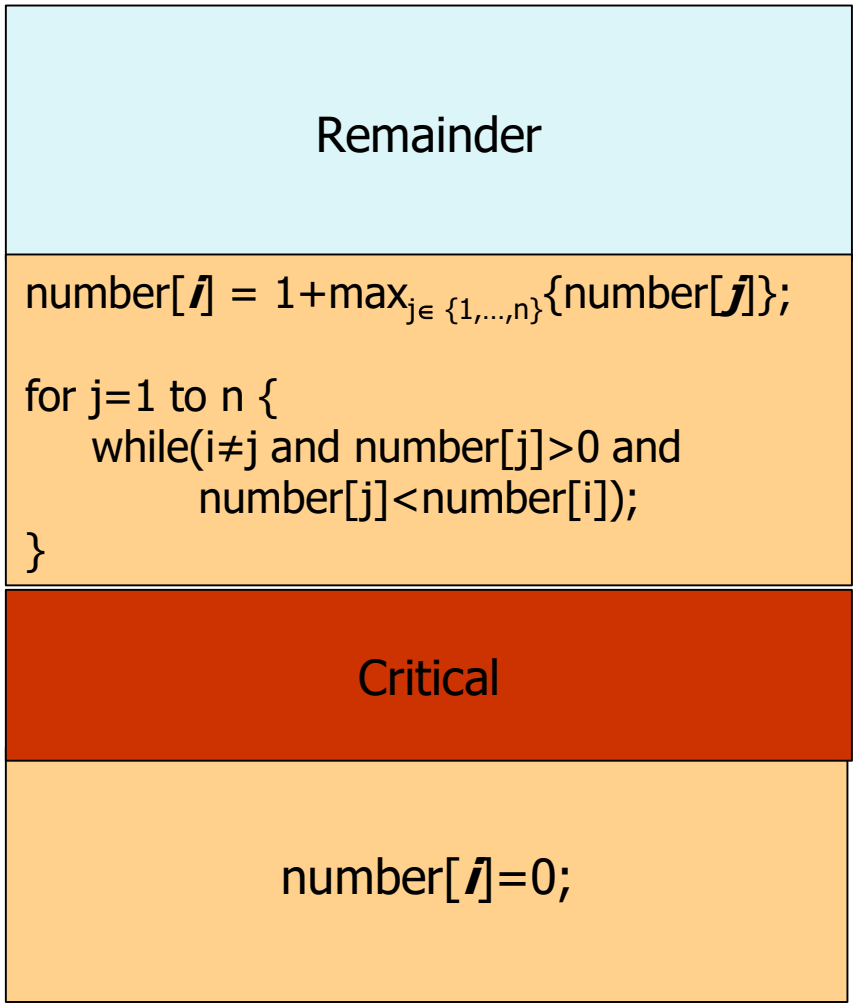
Implementation 1



Code for Thread ***i***
(out of ***n*** threads)

Implementation 1

Remainder

number[***i***] = 1+max$_{j \in \{1,\ldots,n\}}${number[***j***]};

```
for j=1 to n {
    while(i≠j and number[j]>0 and
          number[j]<number[i]);
}
```

Critical

number[***i***]=0;

Code for Thread ***i***
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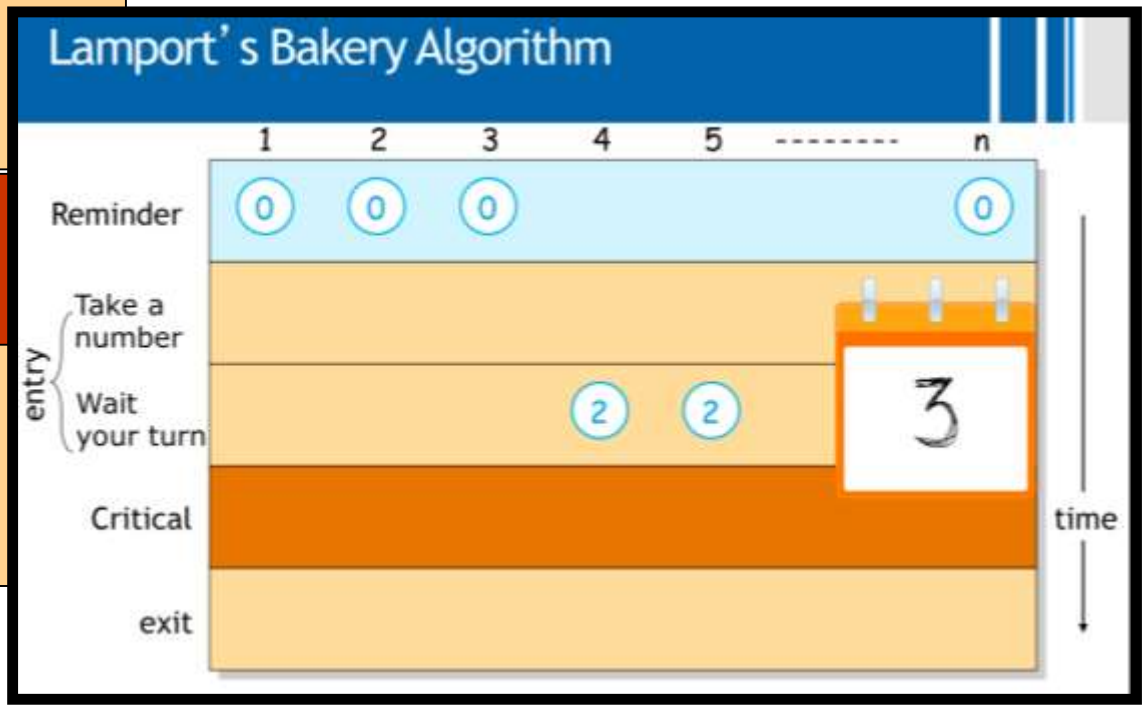

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        number[j] number[i]);
}

Critical

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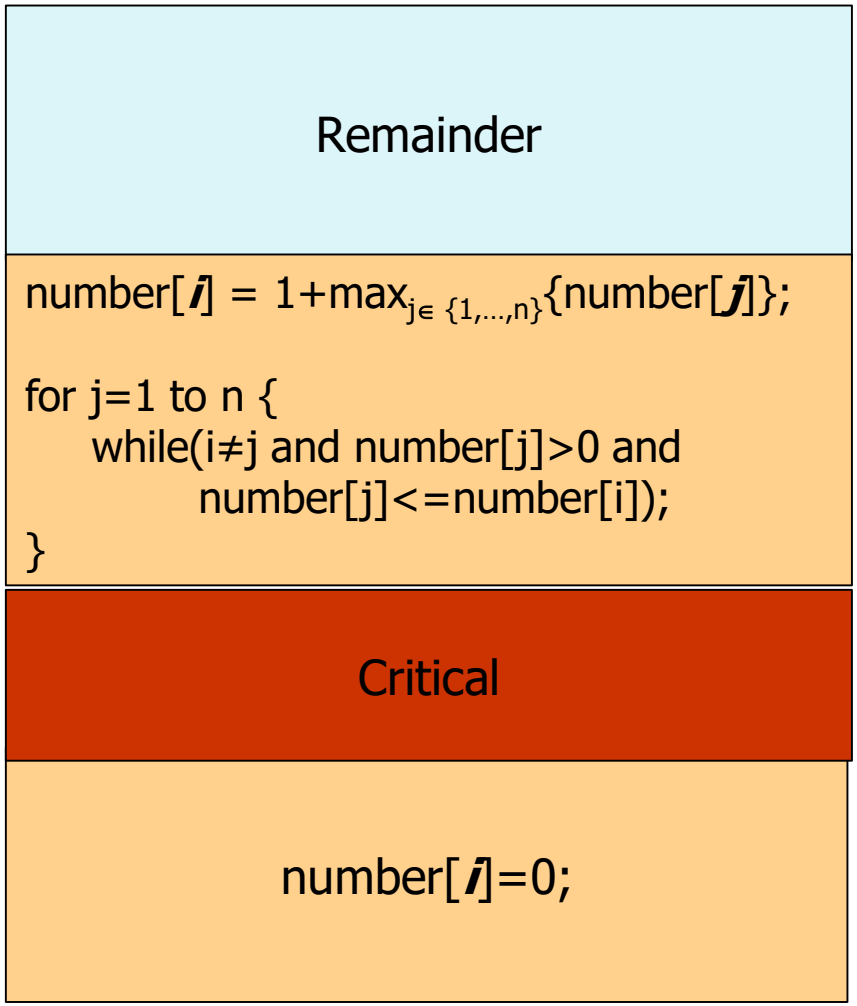
Code for Thread ***i***
(out of ***n*** threads)

No mutual exclusion

Implementation 1.1



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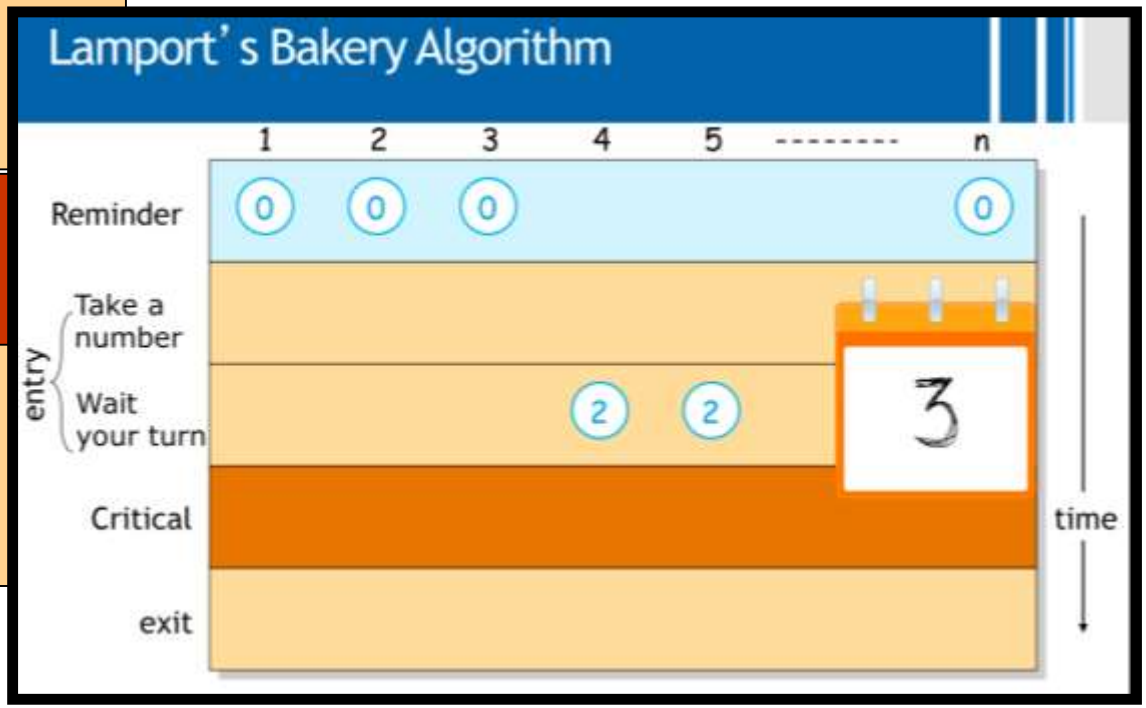

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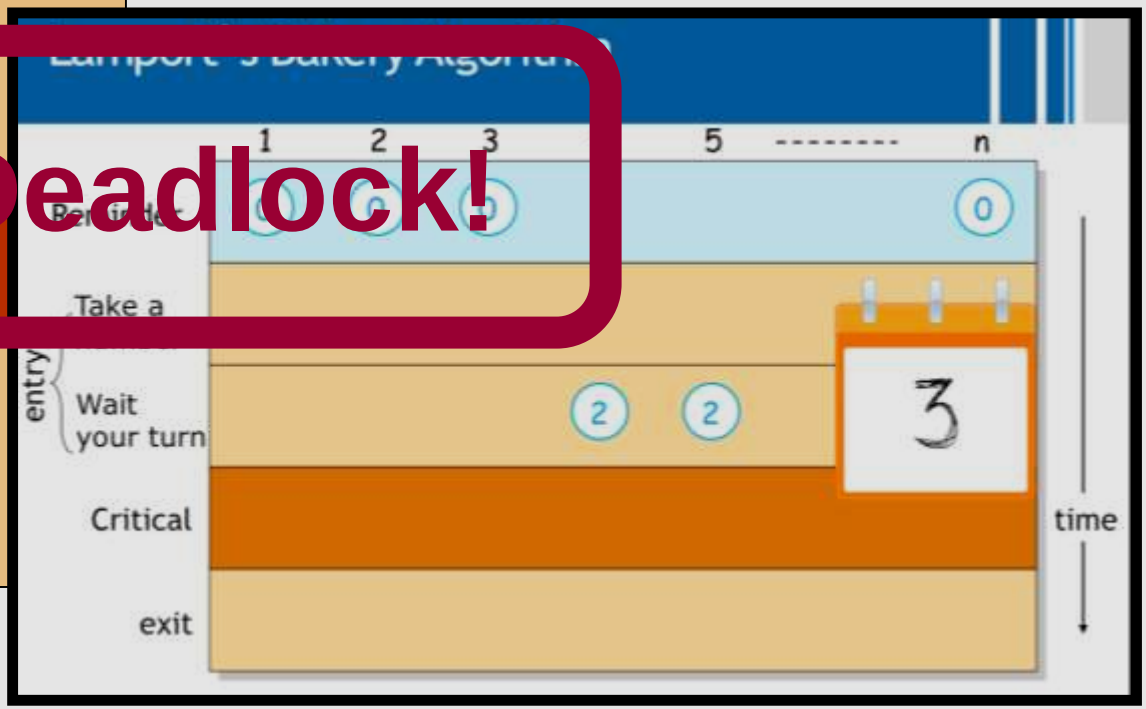
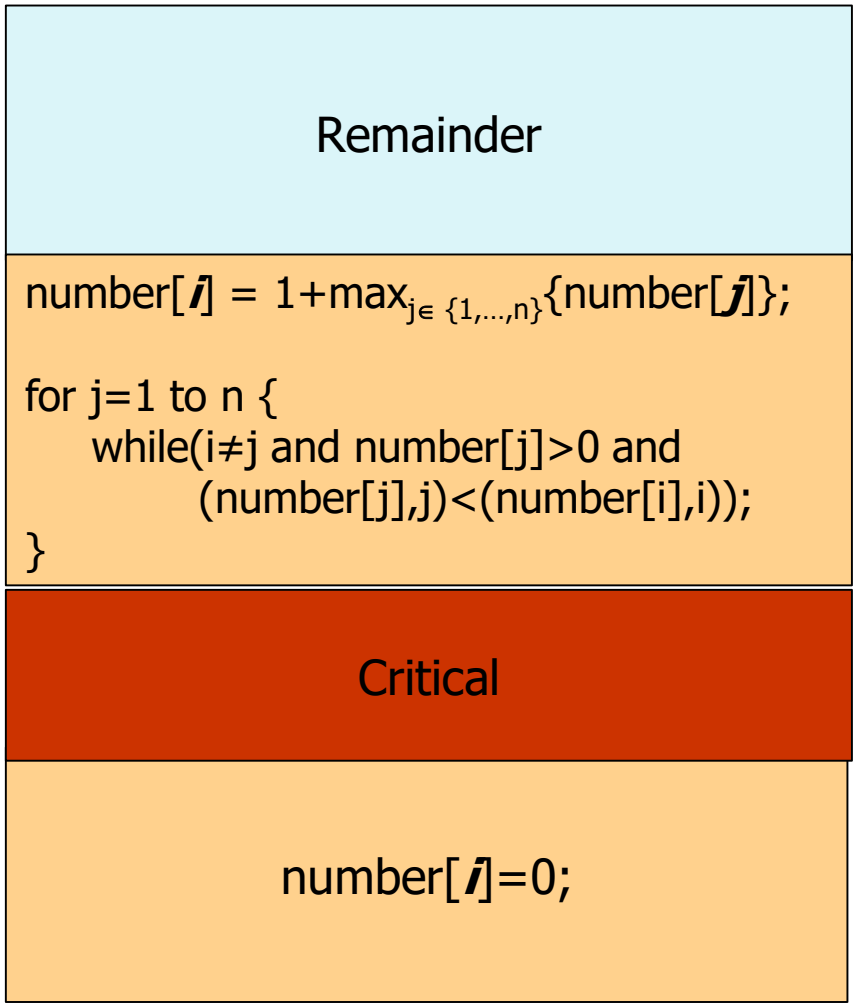


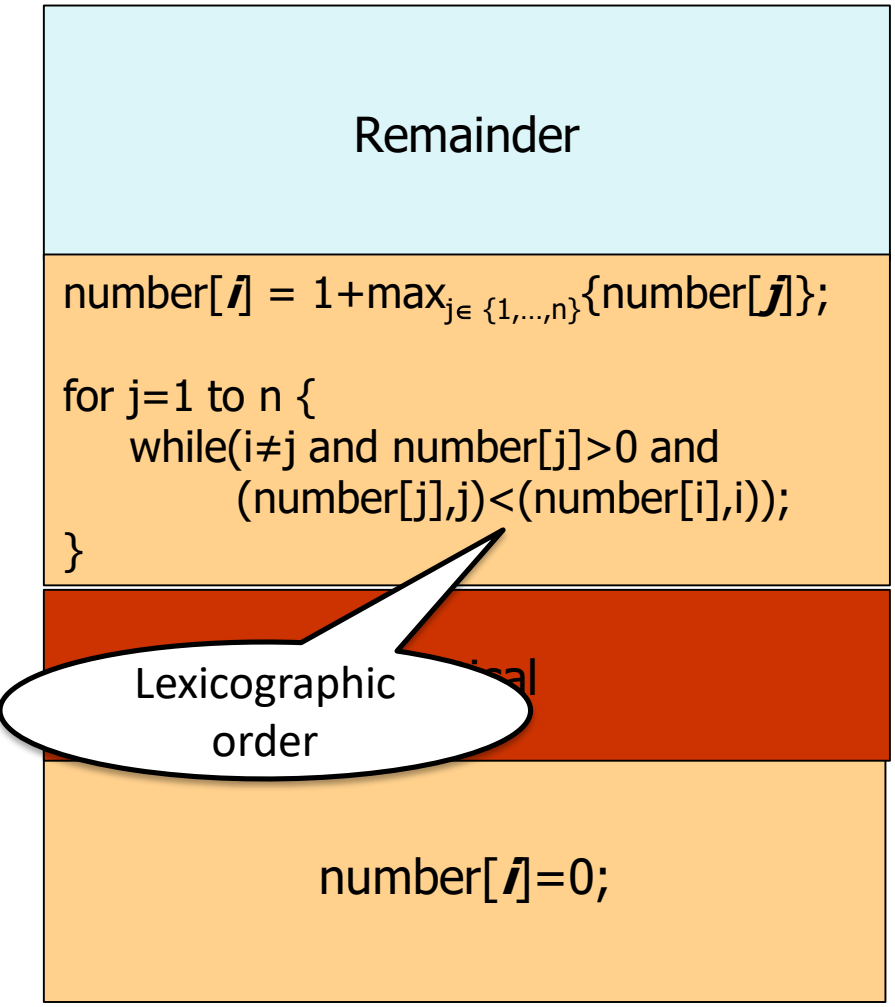
Deadlock!

Implementation 2



Code for Thread ***i***
(out of ***n*** threads)

Implementation 2



Code for Thread ***i***
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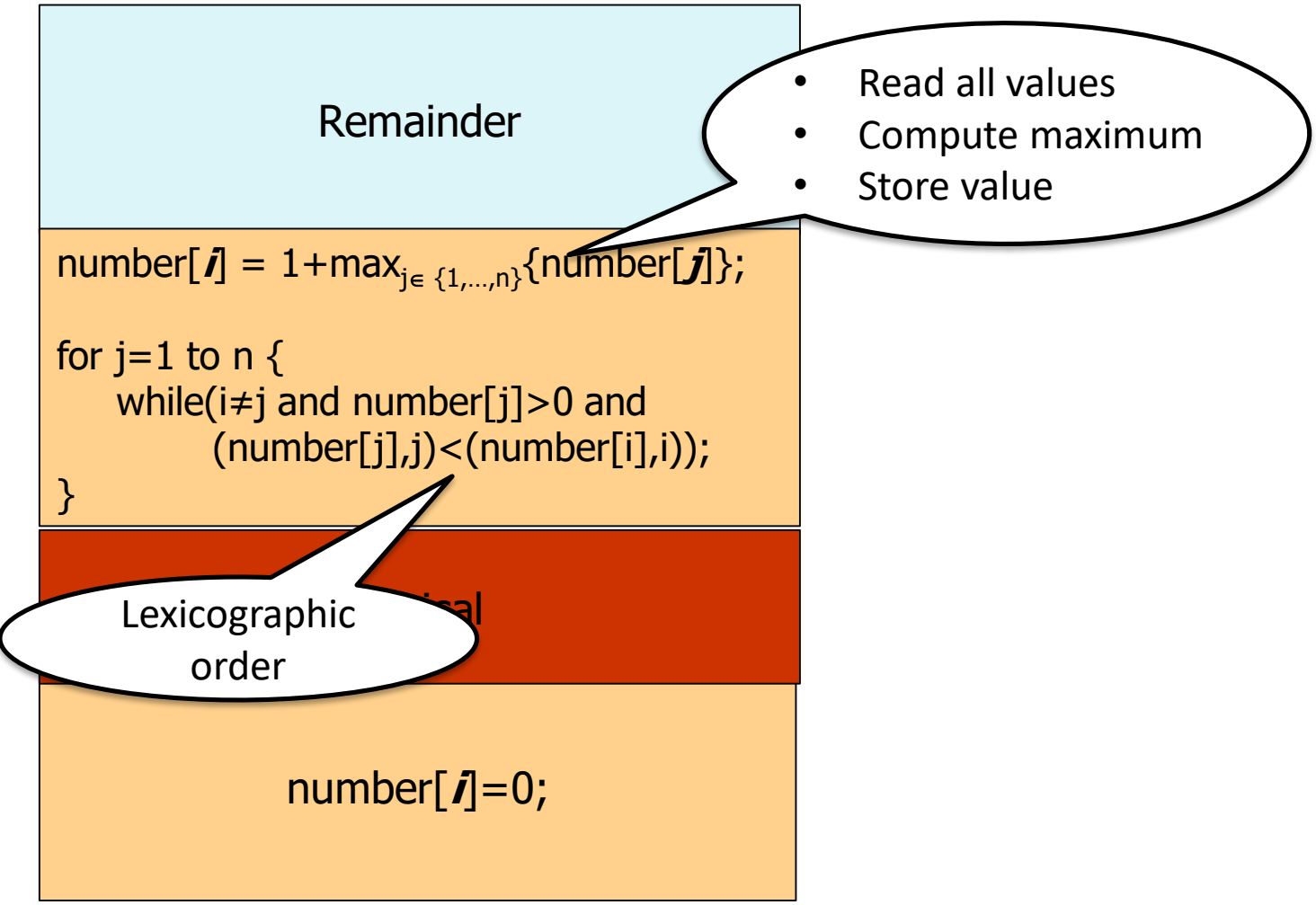
Implementation 2



Code for Thread ***i***
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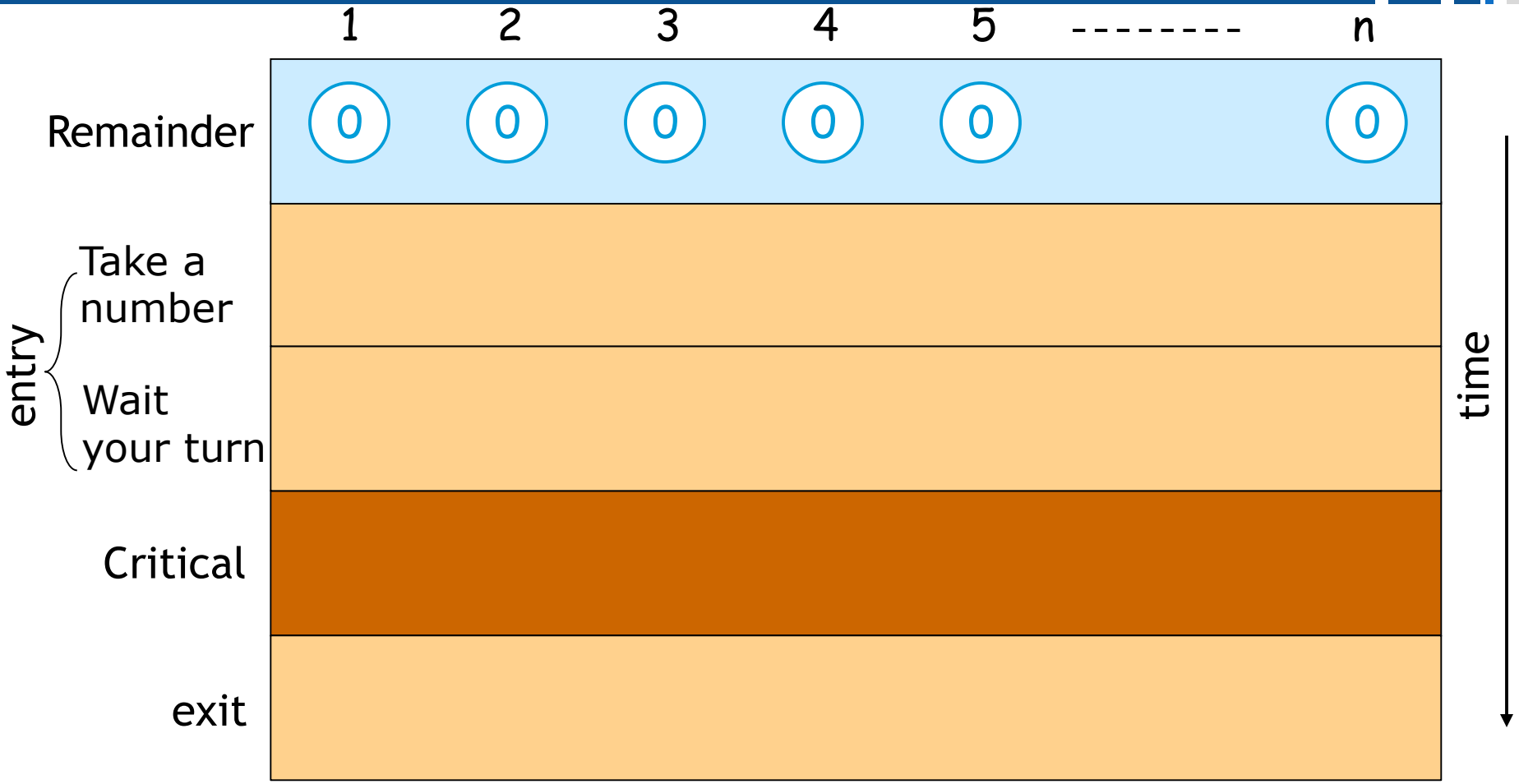
Bakery Algorithm - Implementation 2



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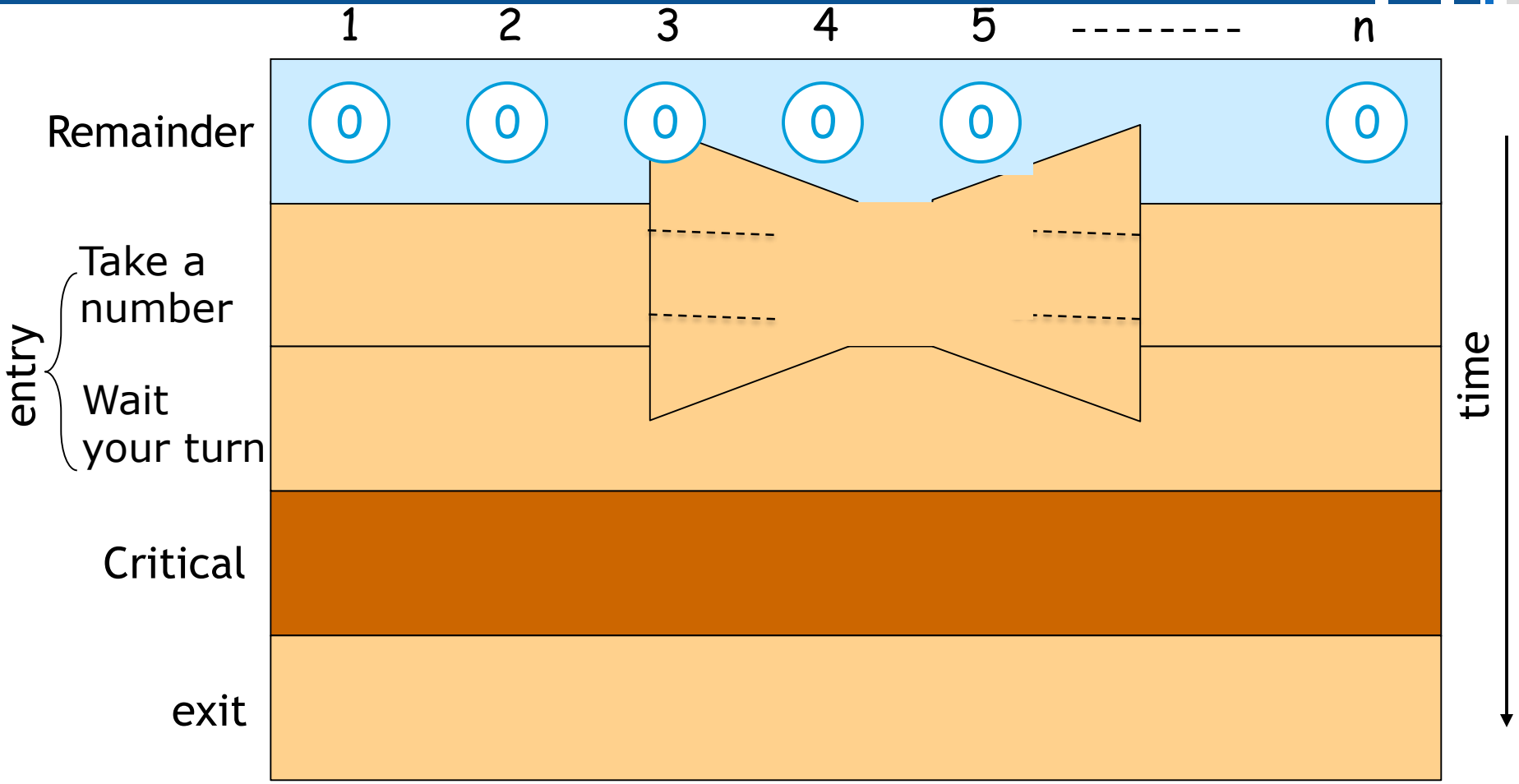

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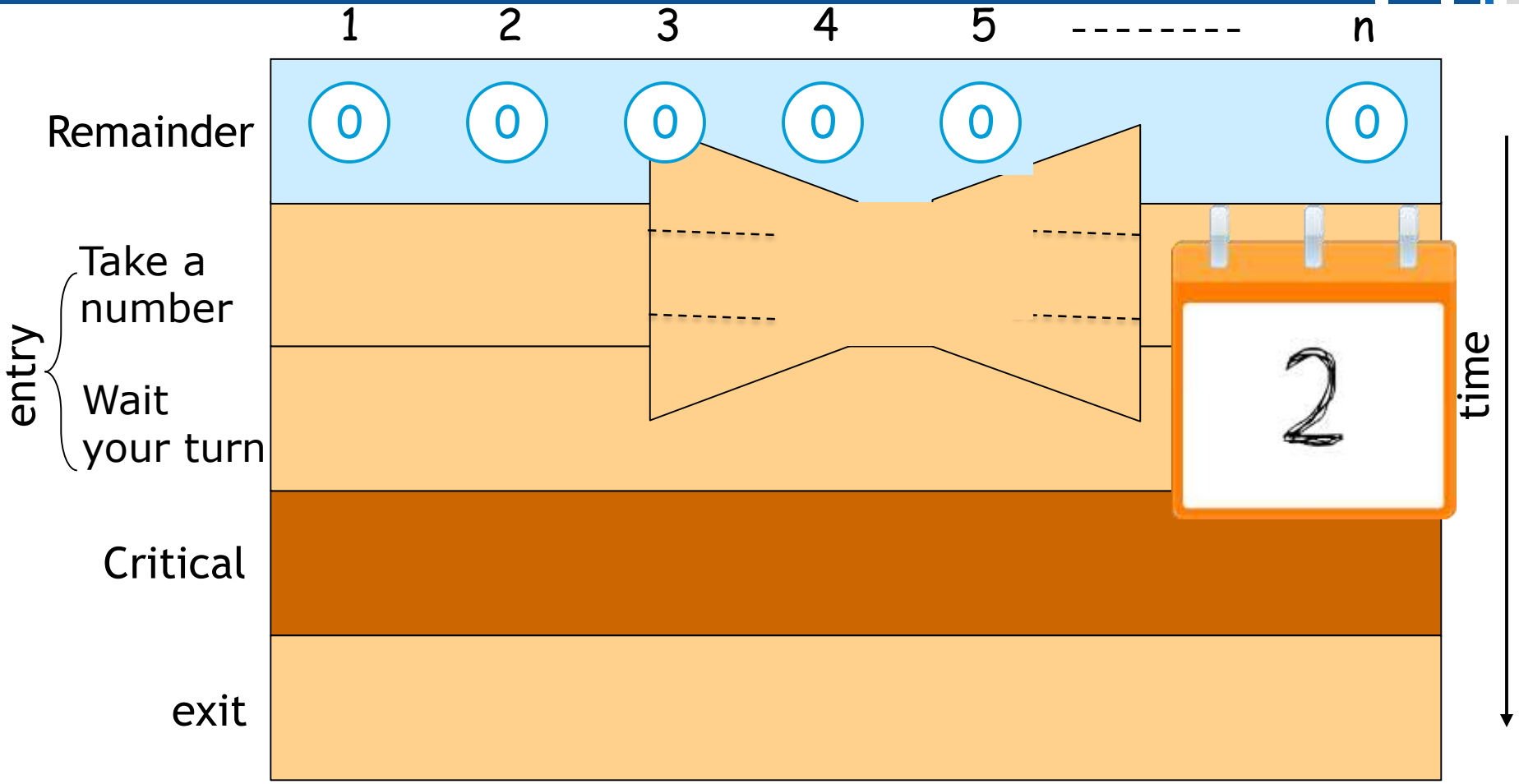

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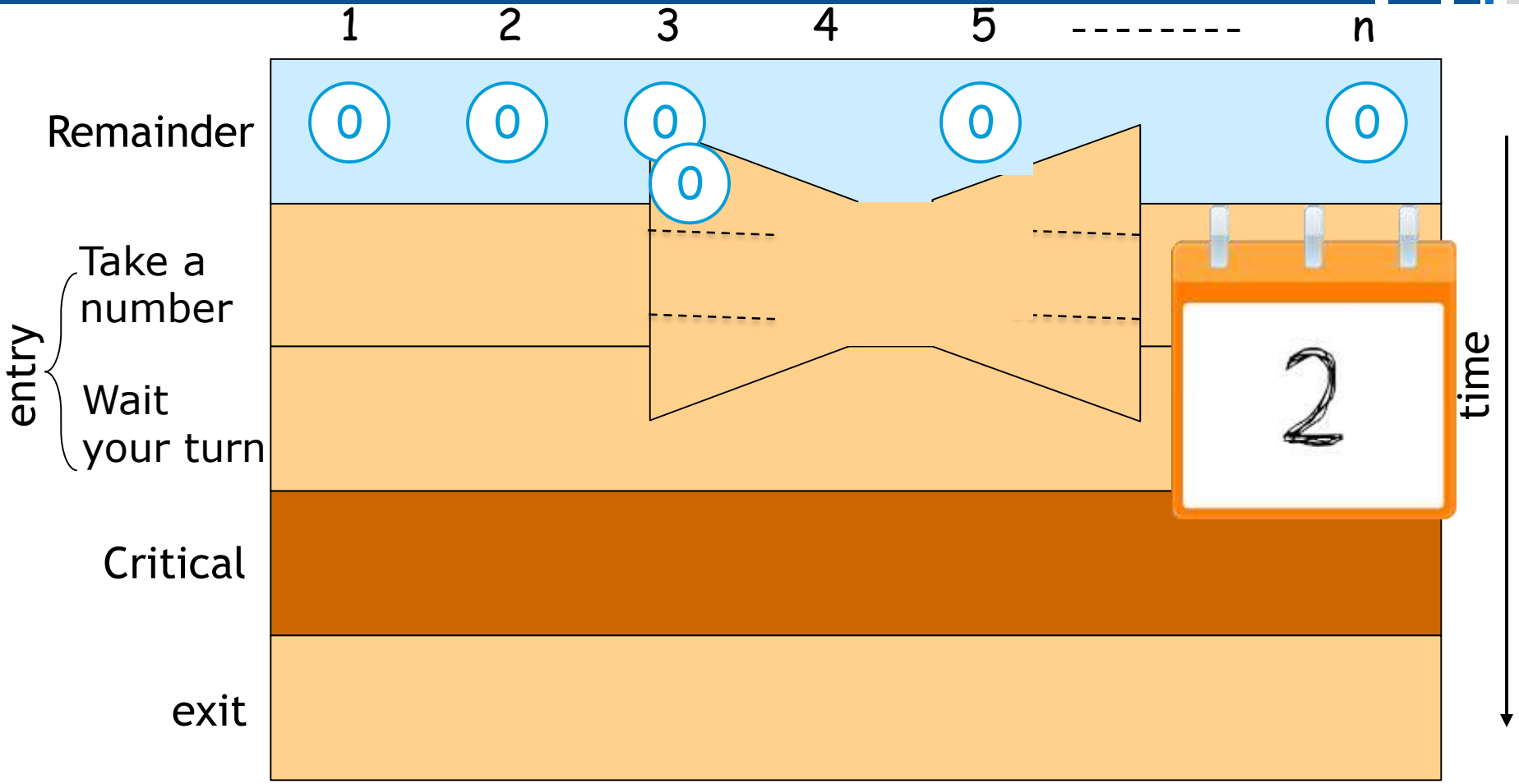

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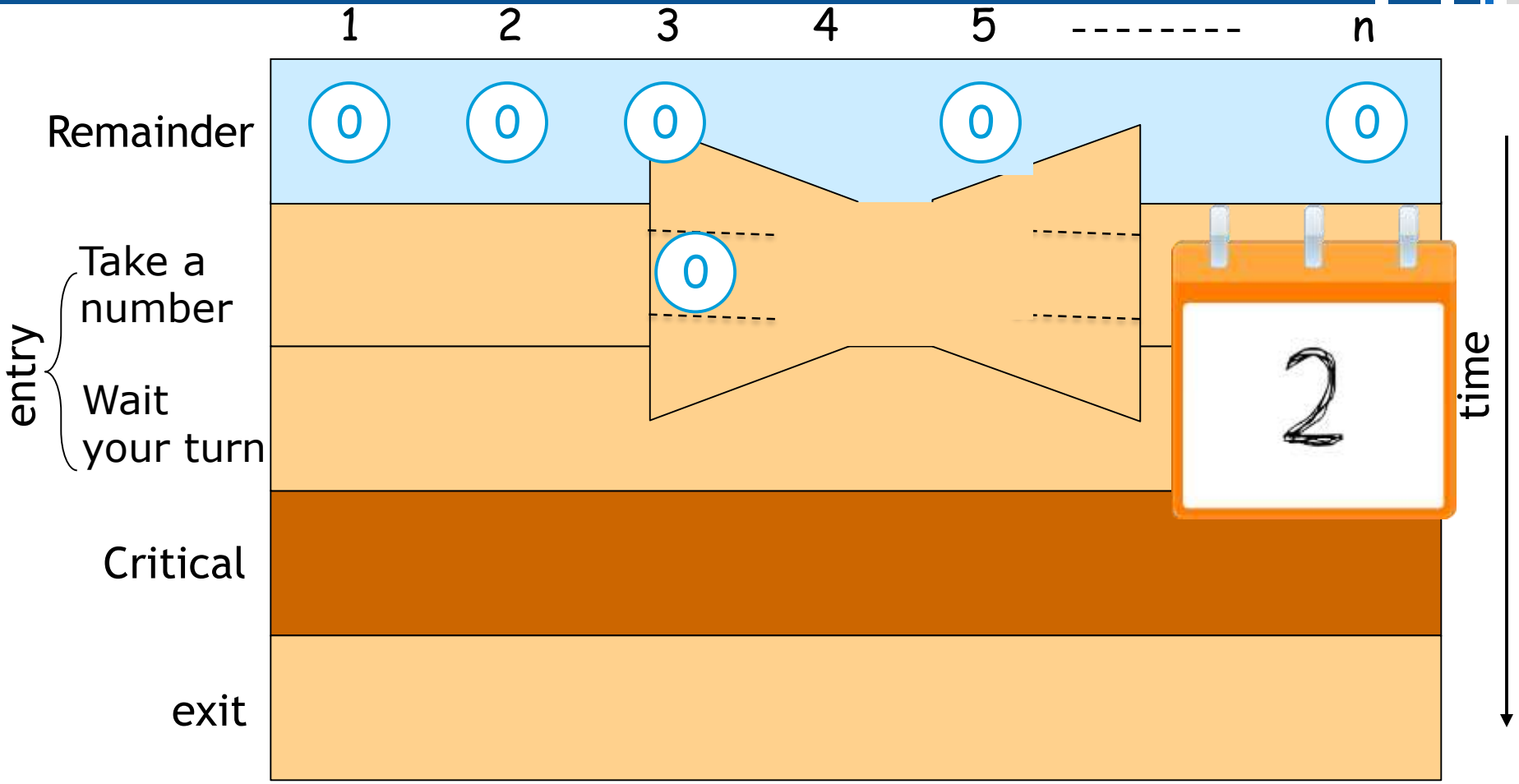

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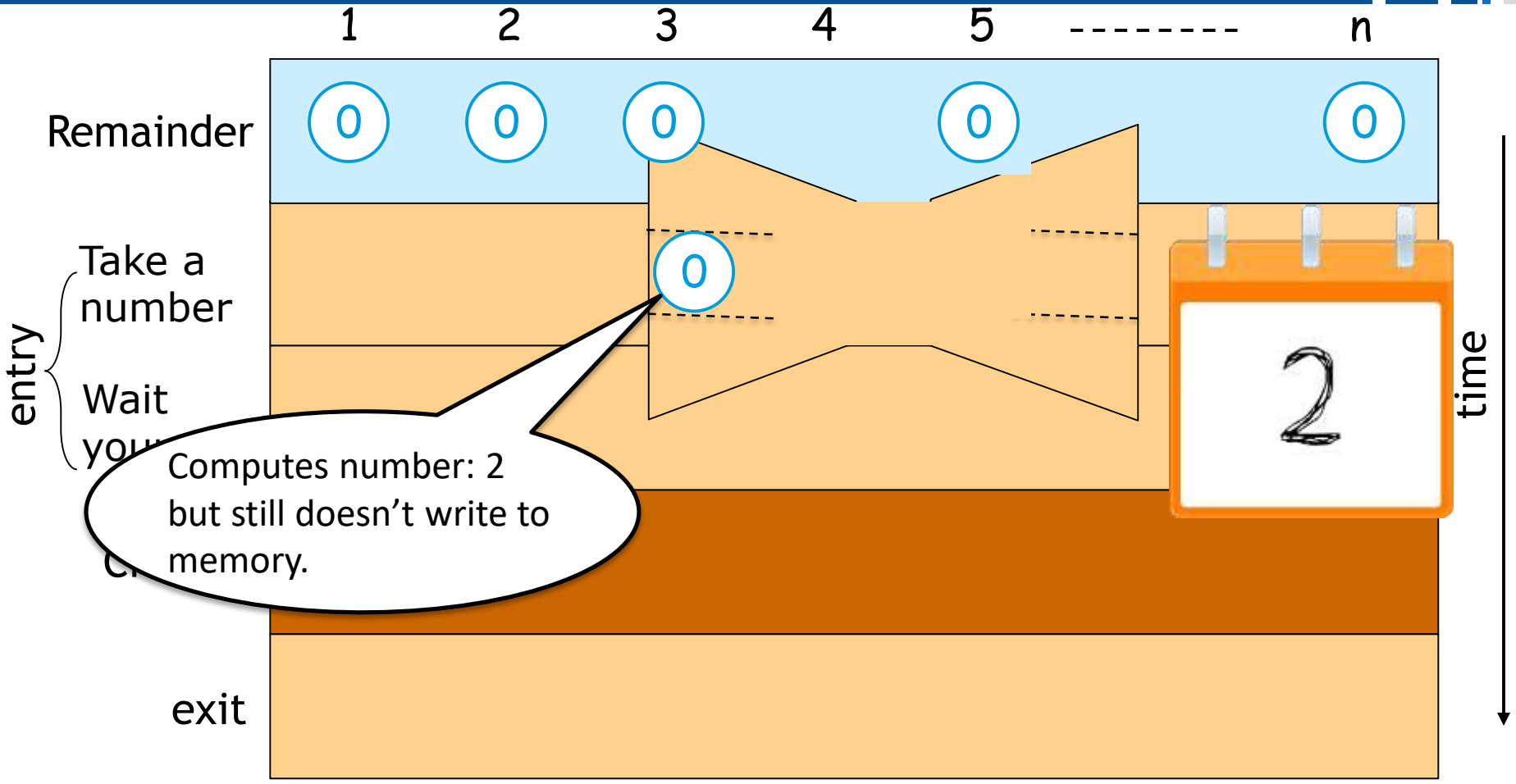

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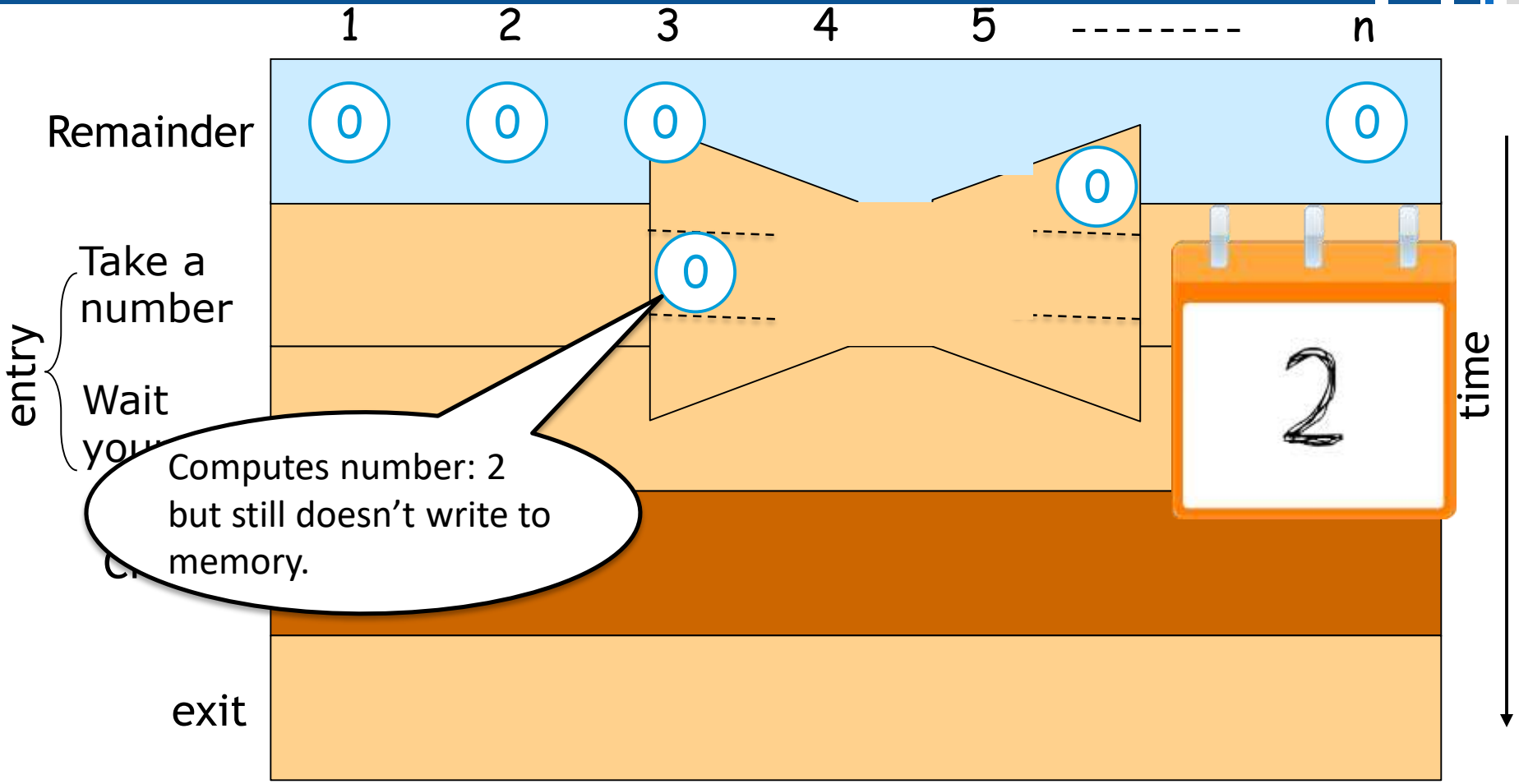

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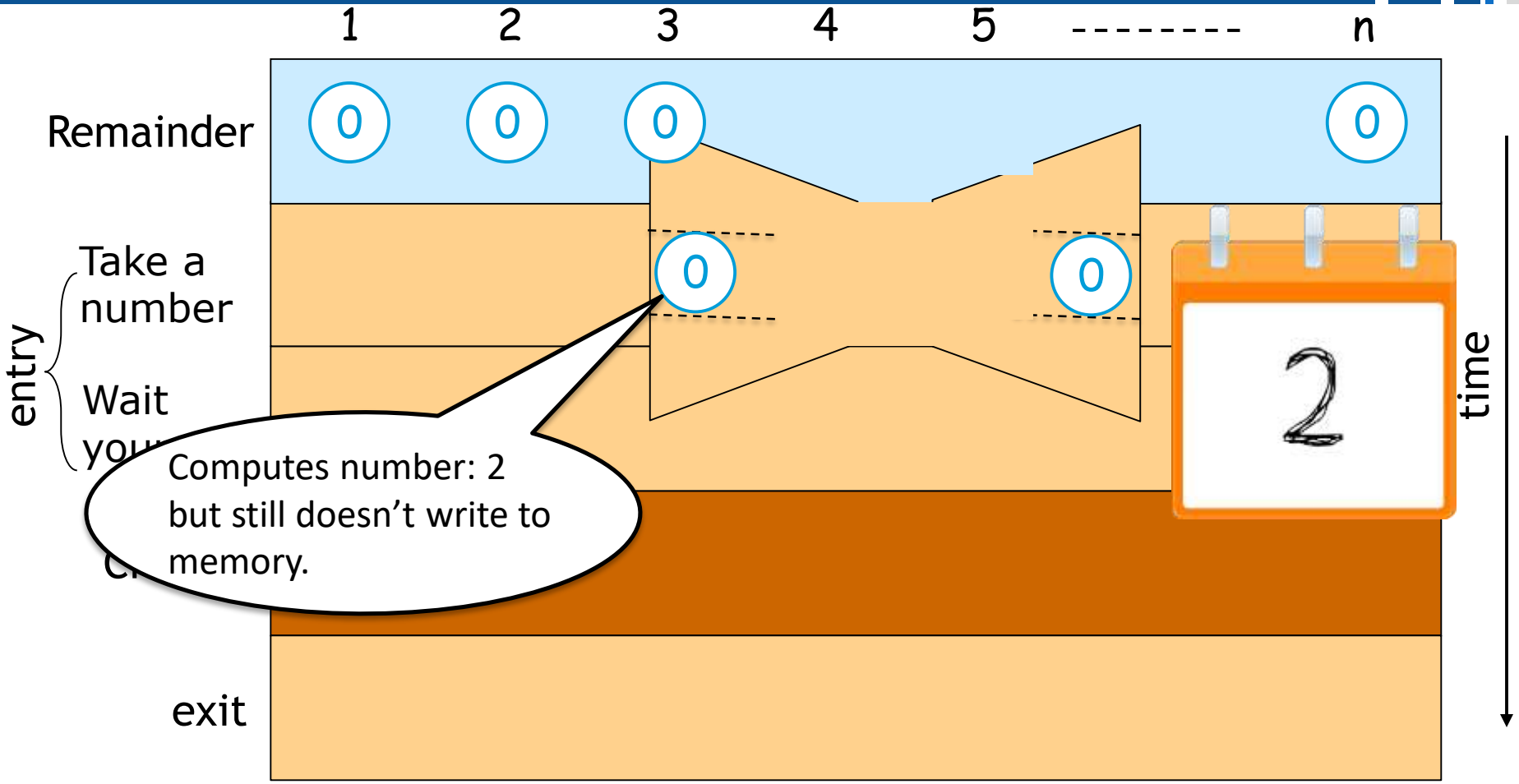

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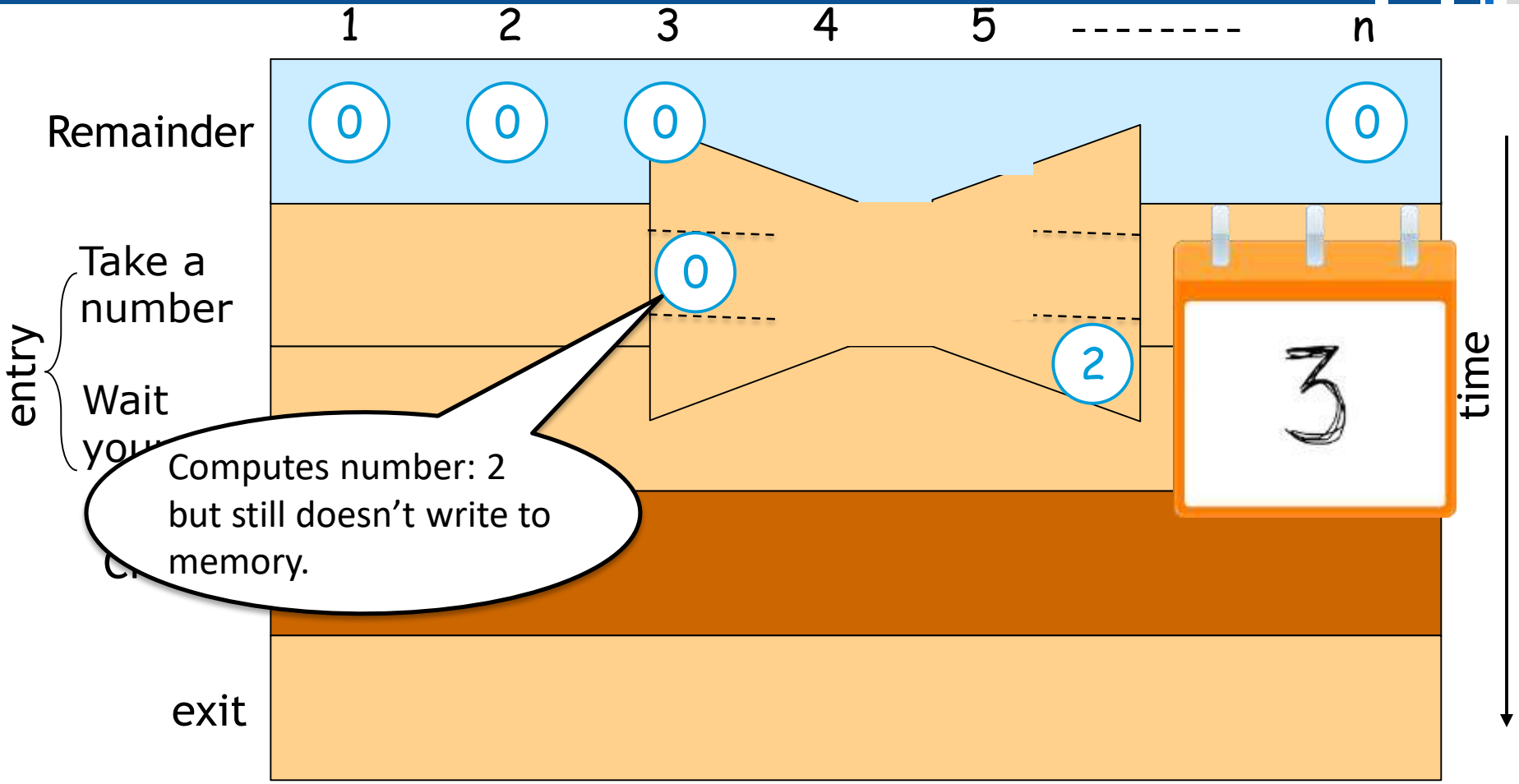

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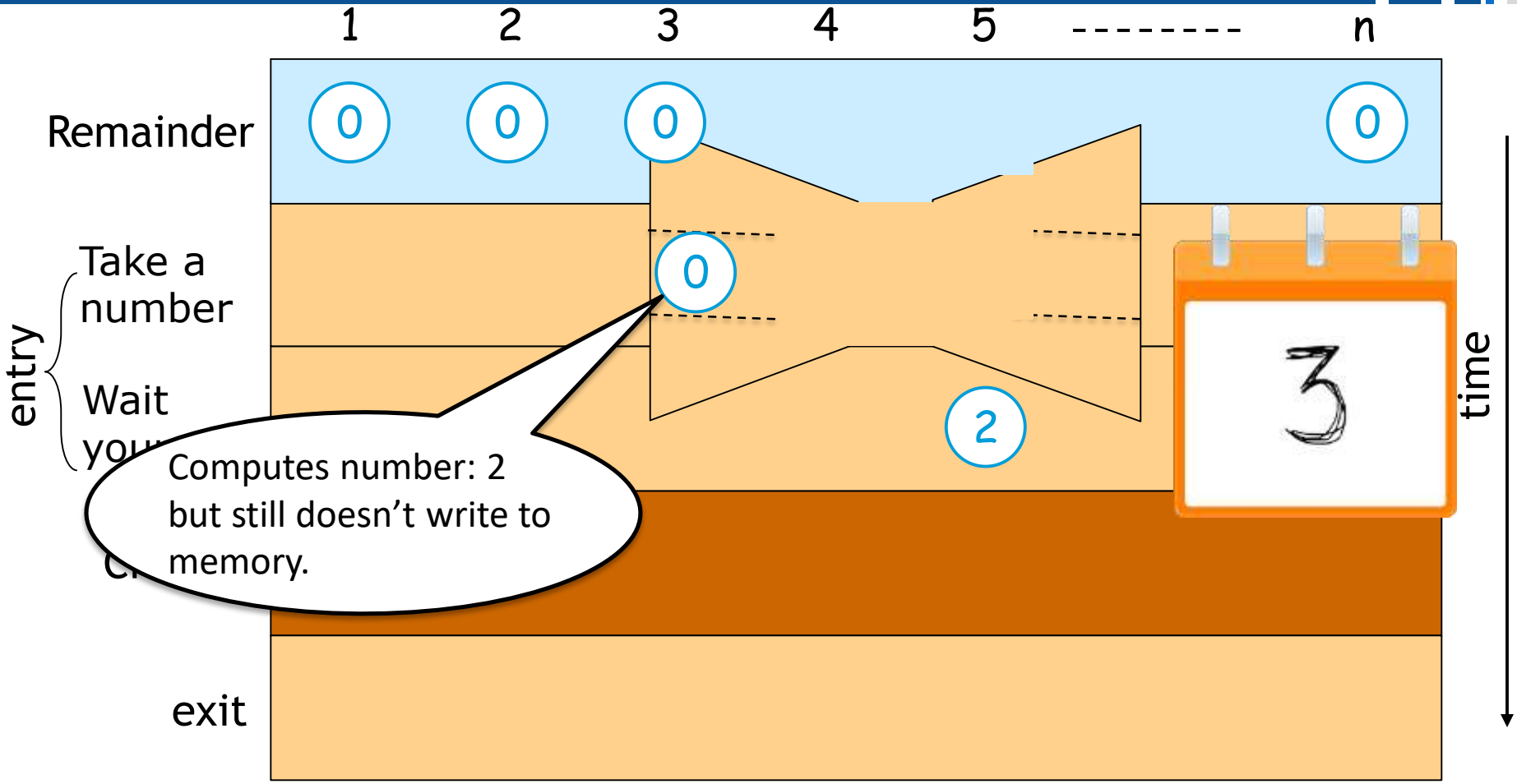

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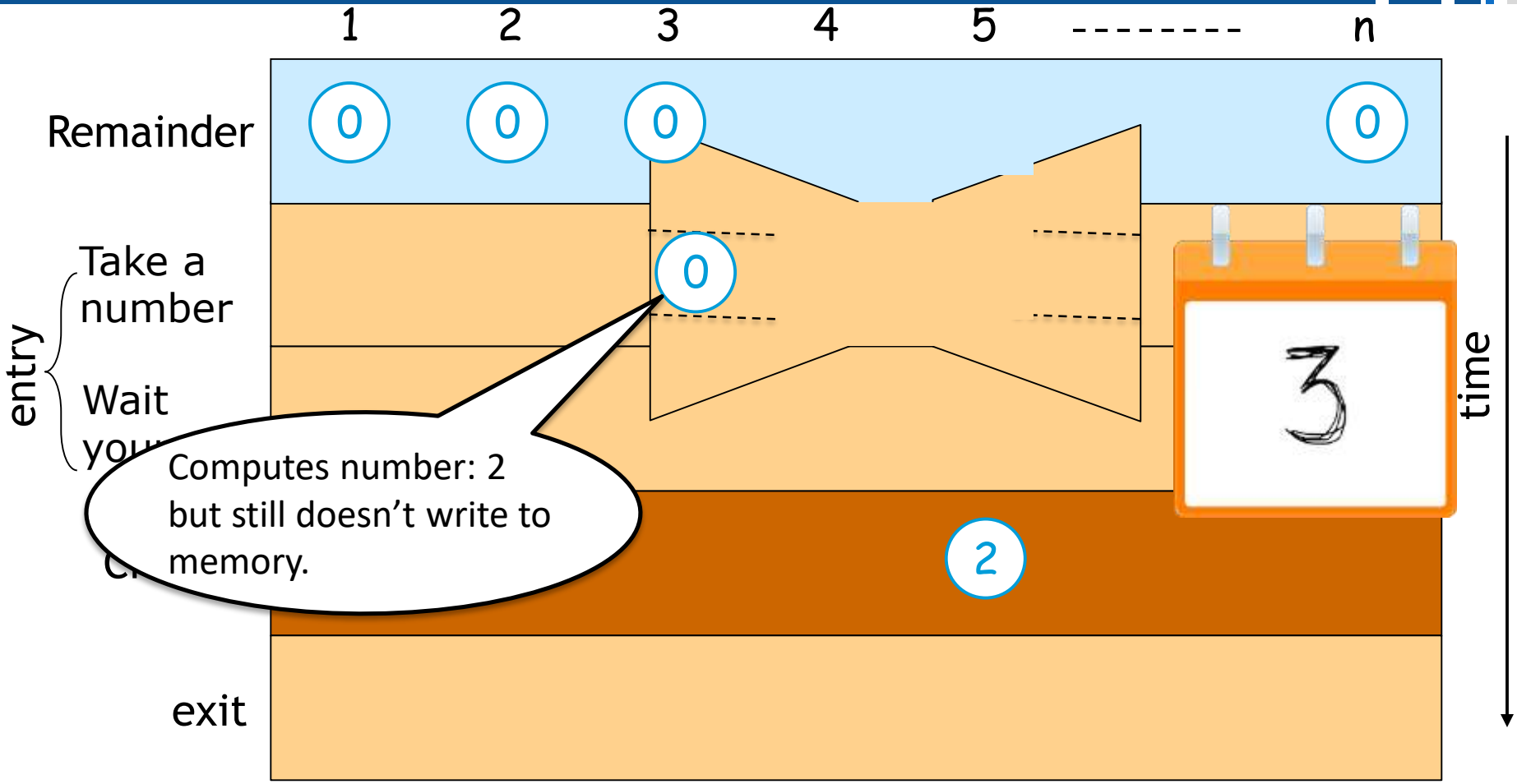

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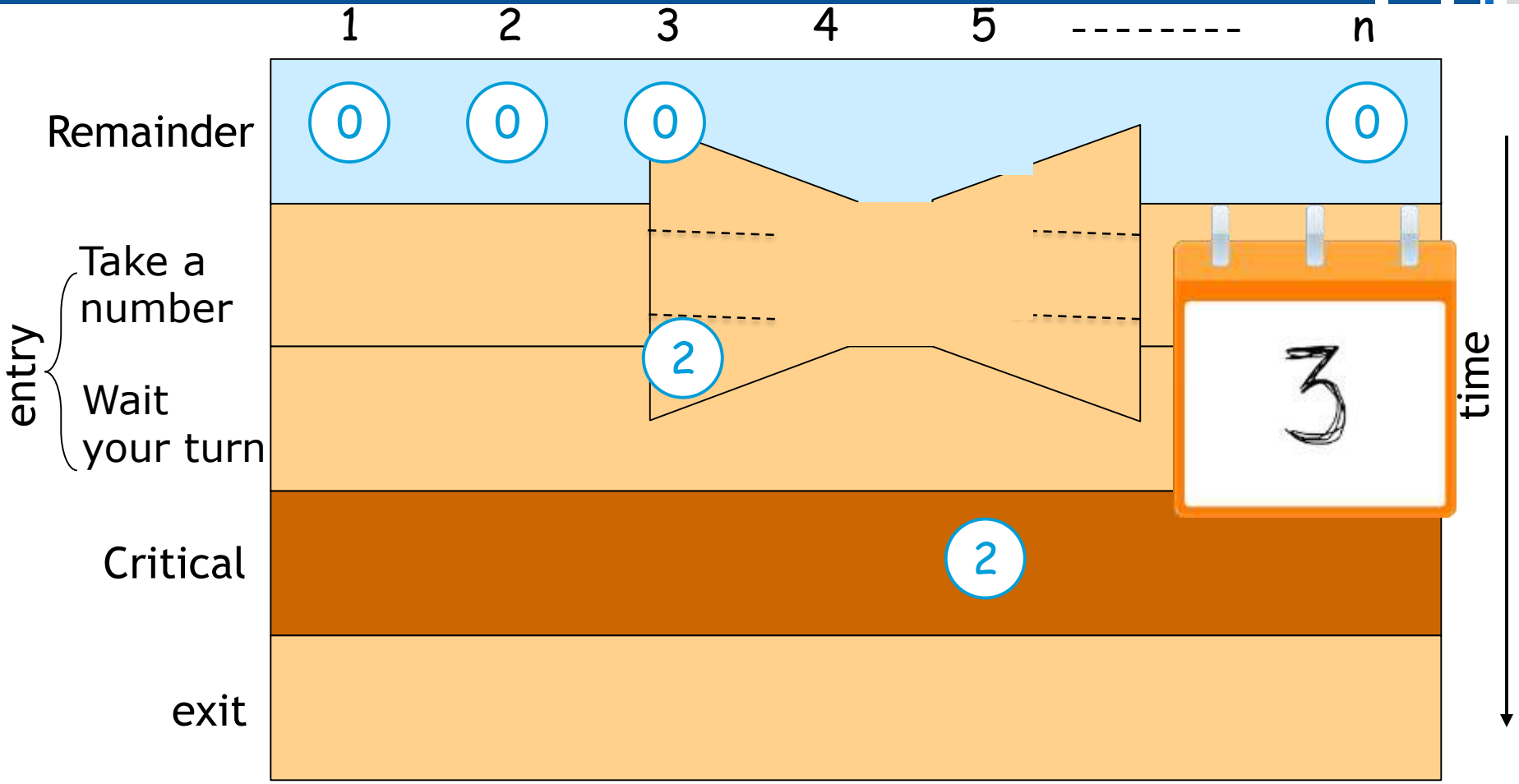

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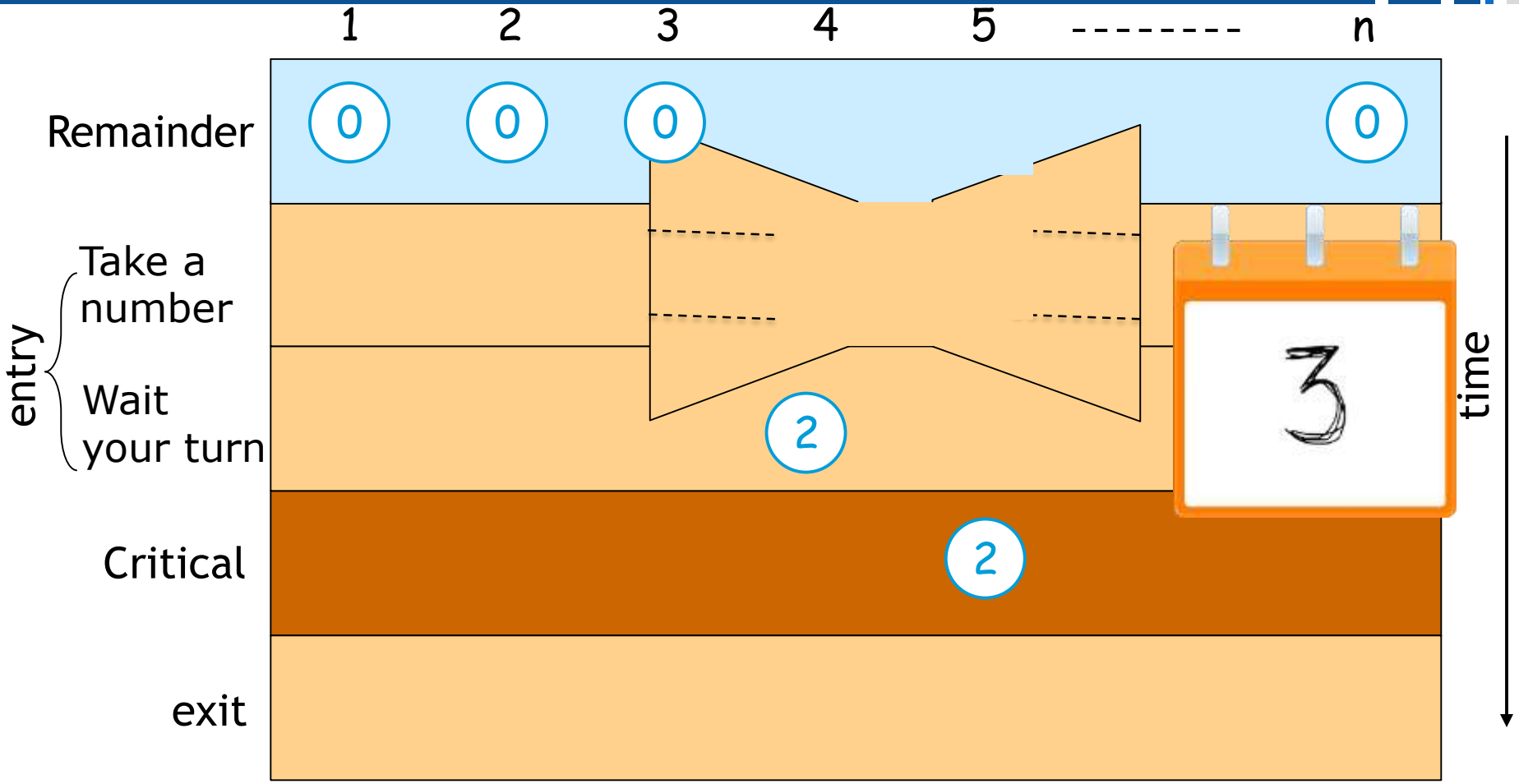

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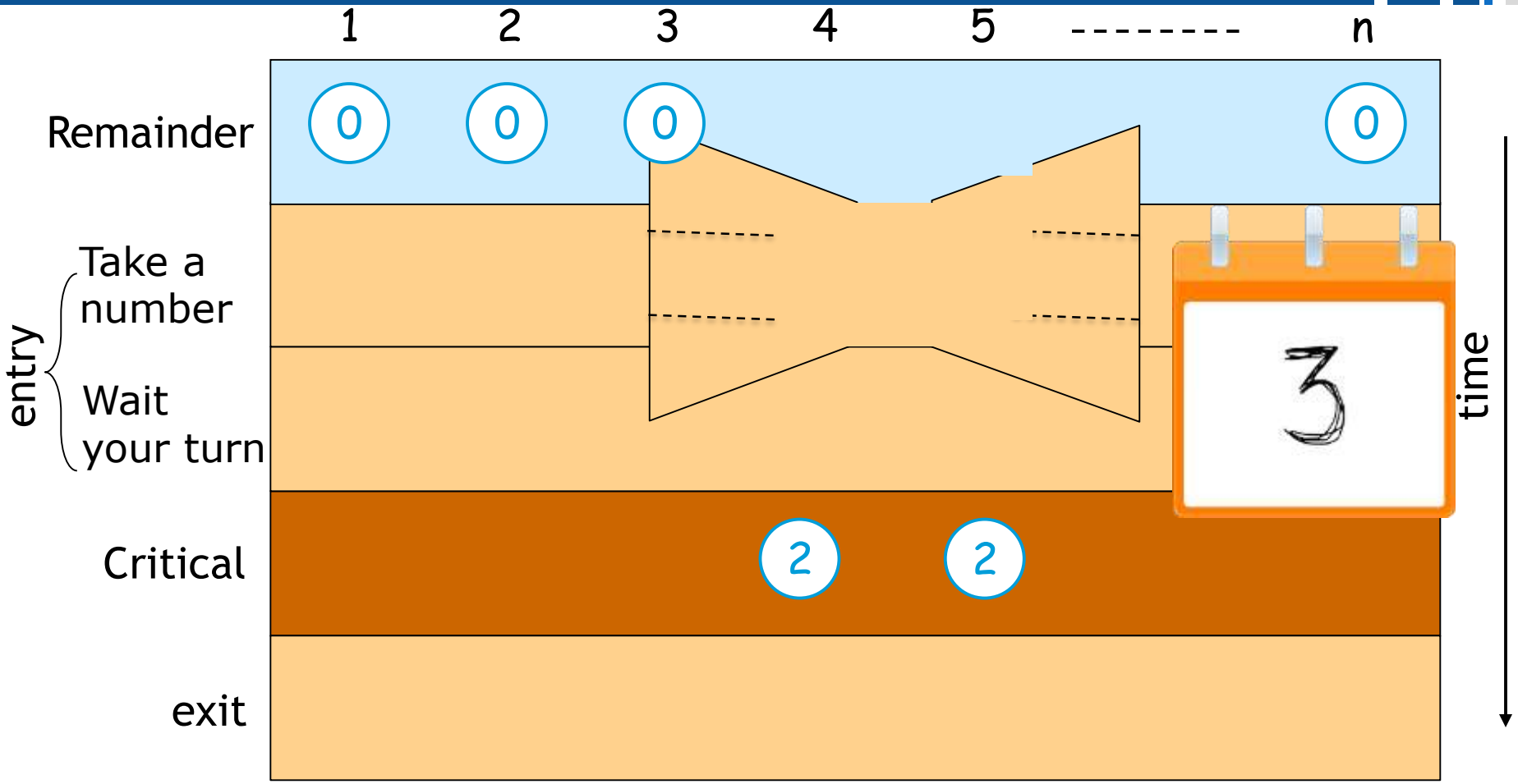
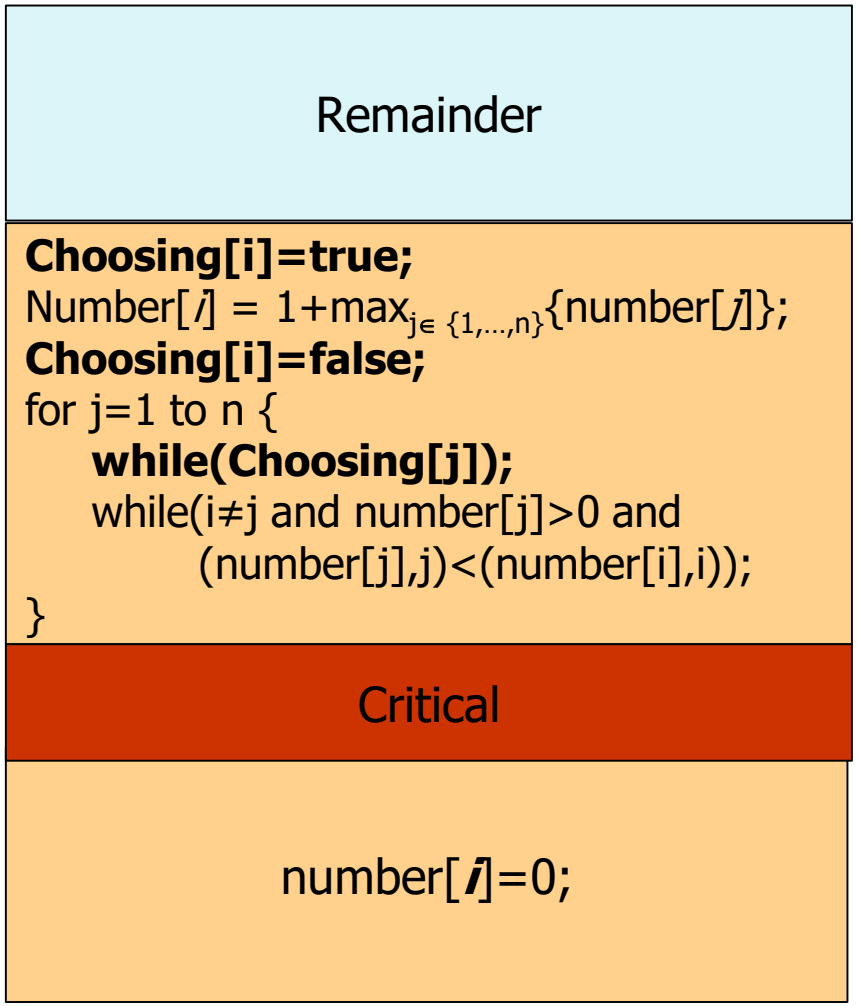


Correct Implementation (1974)



Code for Thread ***i***
(out of ***n*** threads)

Correct Implementation (1974)

Remainder

Choosing[i]=true;
Number[*i*] = 1+max$_{j \in \{1,\ldots,n\}}${number[*j*]};
Choosing[i]=false;
for j=1 to n {
    while(Choosing[j]);
    while(i≠j and number[j]>0 and
        (number[j],j)<(number[i],i));
}

Critical

number[***i***]=0;

Code for Thread ***i***
(out of ***n*** threads)

Also ensures a notion of **First-In-First-Out:**
If a process *i* is waiting (somewhere in the for loop) and thread *j* has not yet started the entry, then *j* will not enter the CS before *i*.

Read-Modify-Write Instructions

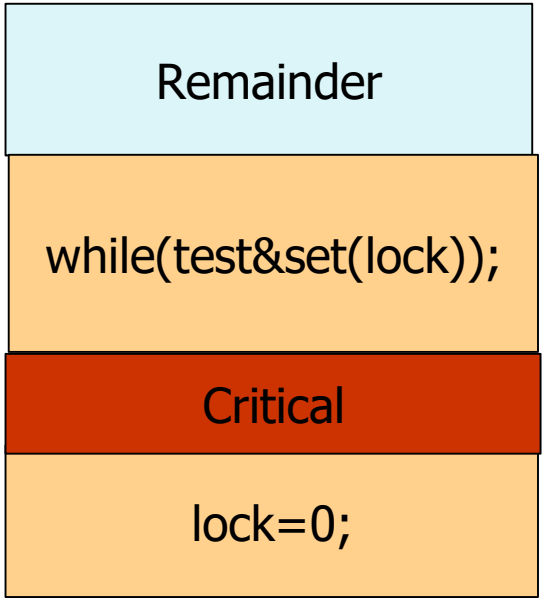
- Up until now we assume that read (load) and write (store) are atomic instructions
  - There might be a context switch between a read and its corresponding write
- Modern CPUs support in **hardware** some RMW instructions:
  - **Test&Set(&lock):**

    {i=*lock; *lock=1; return i;}
  - **Fetch&Add(&p,inc):**

    {val=*p; *p=val+inc; return val}
  - **Compare&Swap(&p,old,new):**

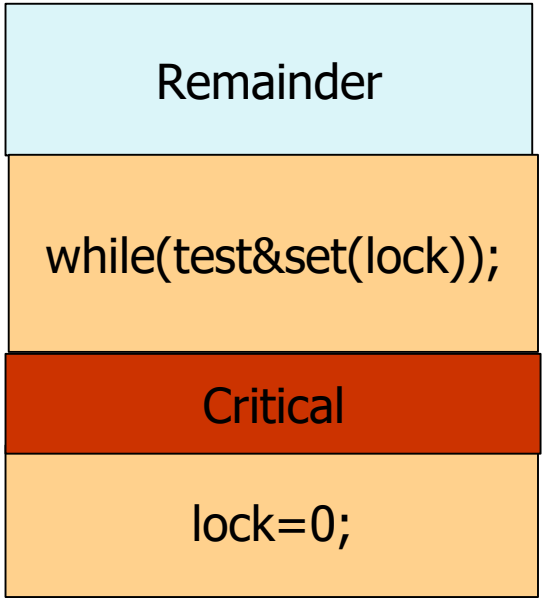
    {if(*p≠old) return false; *p=new; return true;}

Mutual Exclusion with Test&Set



Code for Thread i

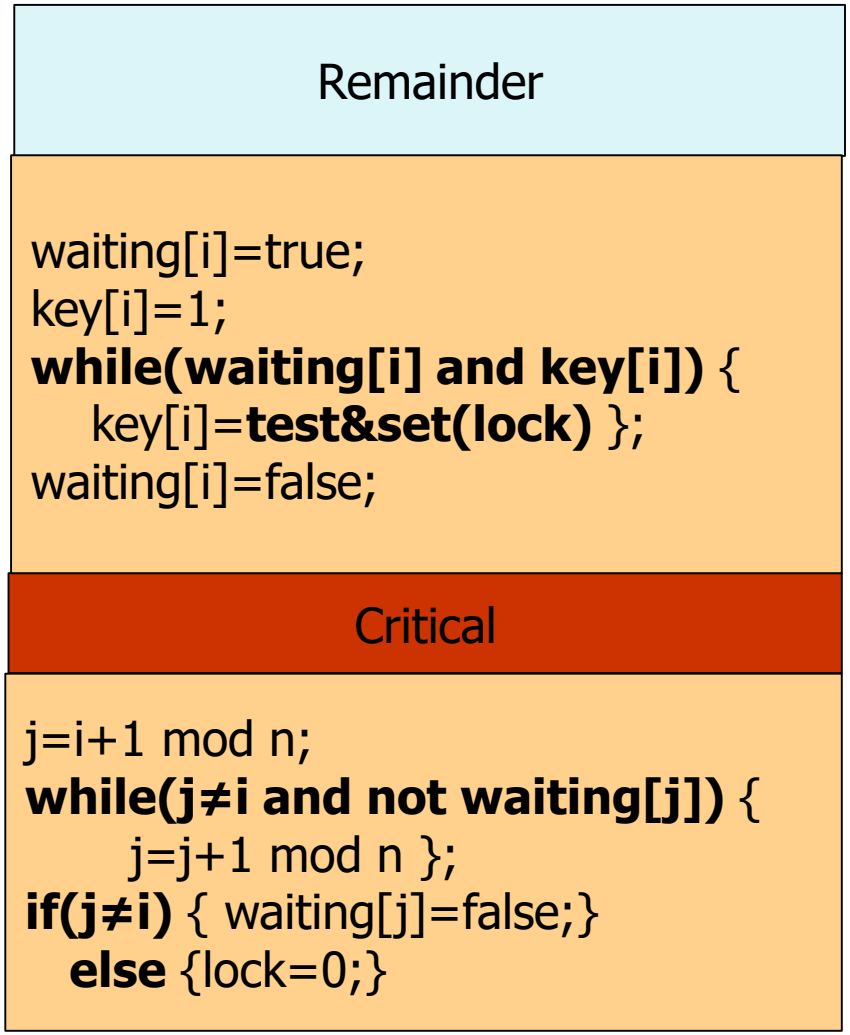
Mutual Exclusion with Test&Set



Code for Thread i

Not so fast: Starvation Freedom condition does not hold!

Burn's Algorithm



Code for Thread i out of n

Up until now…

- We saw several solutions for the **mutual exclusion** problem in different settings
- All the solutions perform busy-waiting:
  - Waste of CPU resources
- Mutual exclusion is only one synchronization problem. There are many more
  - Contention → coordination
  - Some were and will be covered in the tutorials

Next: Synchronization Primitives

- We will define **abstract data types** used to provide synchronization

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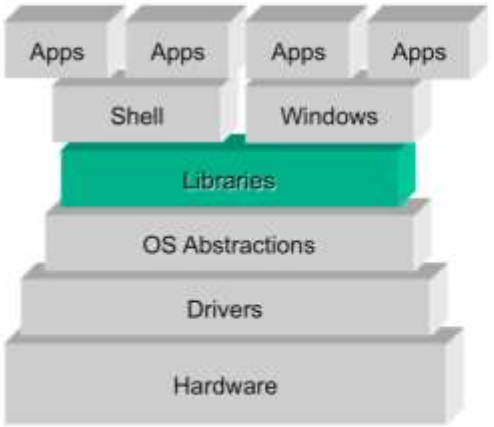
Layers of System



Libraries

- Usually language specific
  - java.io.*, java.net.*
  - stdio.h; stdlib.h
- Often higher level abstractions

Next: Synchronization Primitives

- We will define **abstract data types** used to provide synchronization
- Clear **interface** to the data type
- The data type (and its inner variables) cannot be accessed in any other way
- Usually provide by the programming language with some support of the OS
- The abstract data type may have many implementations

First Data Type: Semaphore

- Record with two fields:
  - value
  - List (L)

First Data Type: Semaphore

- Record with two fields:
  - value
  - List (L)
- Two operations:

Down(S)

S.*value*= S.*value* - 1
if S.*value* < 0 then
{ add this thread to S.*L*;
sleep();}

Up(S)

S.*value*= S.*value* + 1
if S.*value*≤0 then
{remove a thread T from
S.L; Wakeup(T);}

Init(S,v)

S.*value*= v

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- The operations are executed atomically
  - How? Implementation is orthogonal to the definition

First Data Type: Semaphore

- Record with two fields:

In literature, the operations are often called P(s) and V(s).
In the book, wait(s), signal(s)

Down(S)

S.*value*= S.*value* - 1
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  - value
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- Two operations:

Some variations bound the maximum and minimum value (e.g., binary semaphores)

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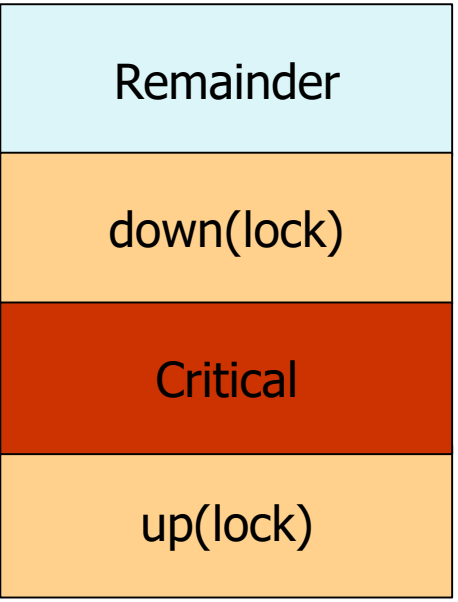
Mutual Exclusion w/ Semaphore



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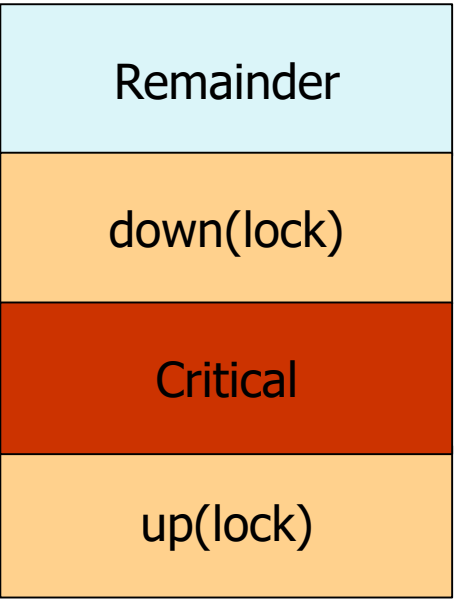

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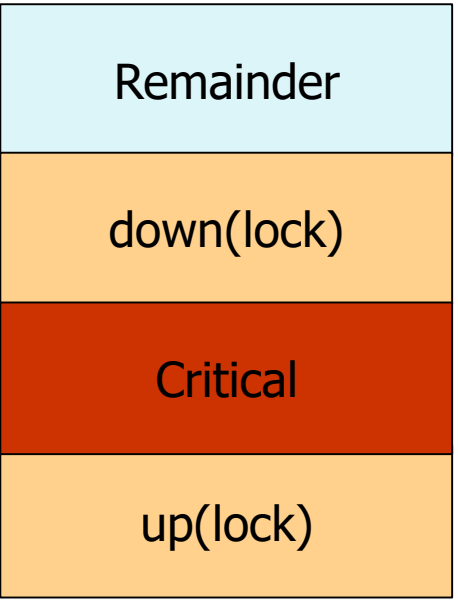

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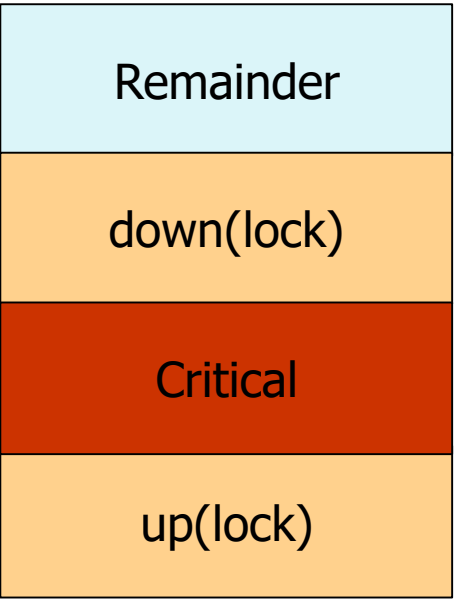

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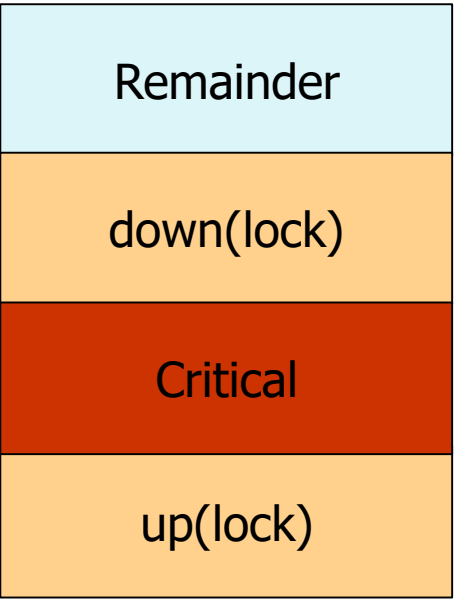

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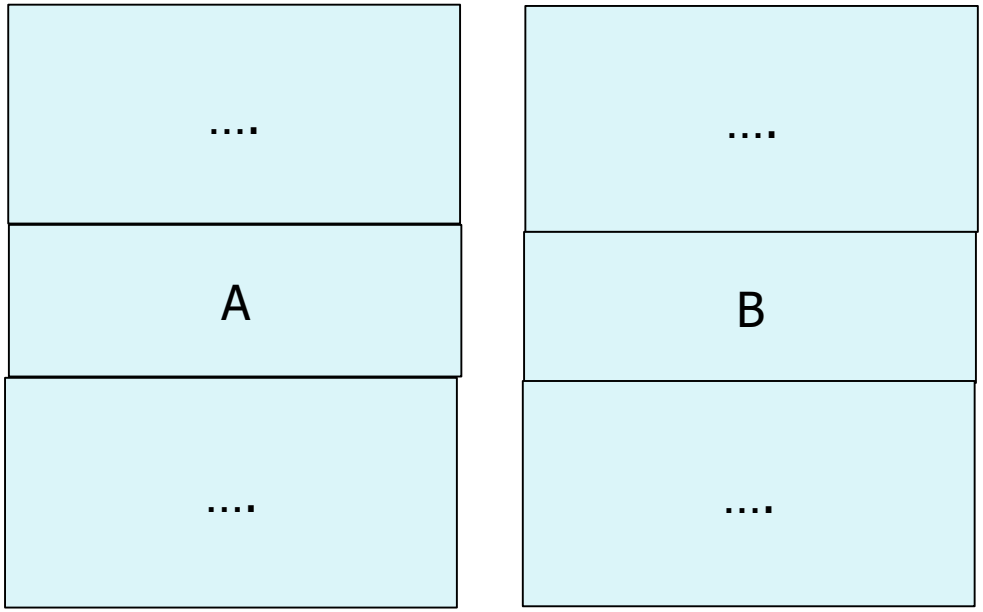
0/1 (binary) semaphore suffices → Binary semaphores data type are often called Mutex objects

“Execute B after A”

- A different synchronization problem
  - Coordination rather than contention
- One process needs to execute code A, before another process executes code B



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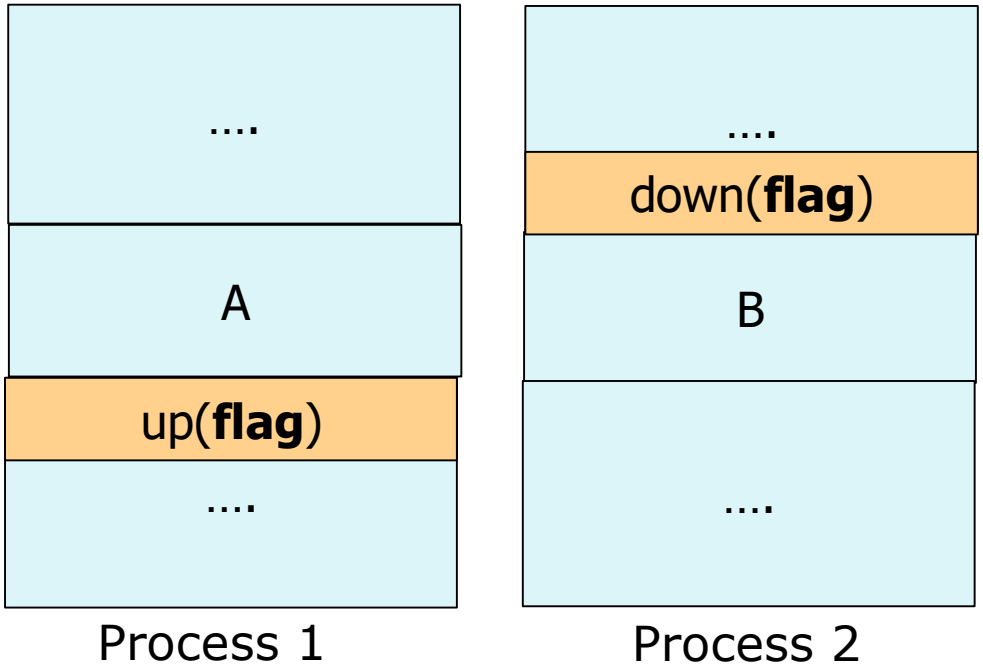

Semaphore **flag**, initialized to 0

Another Problem: Moving Money Between Accounts

Thread 1 transfers money from account A to B, Thread 2 transfers money from B to A.

If executed simultaneously, some errors might occur (e.g., Thread 1 executes A--, while Thread 2 executes A++)

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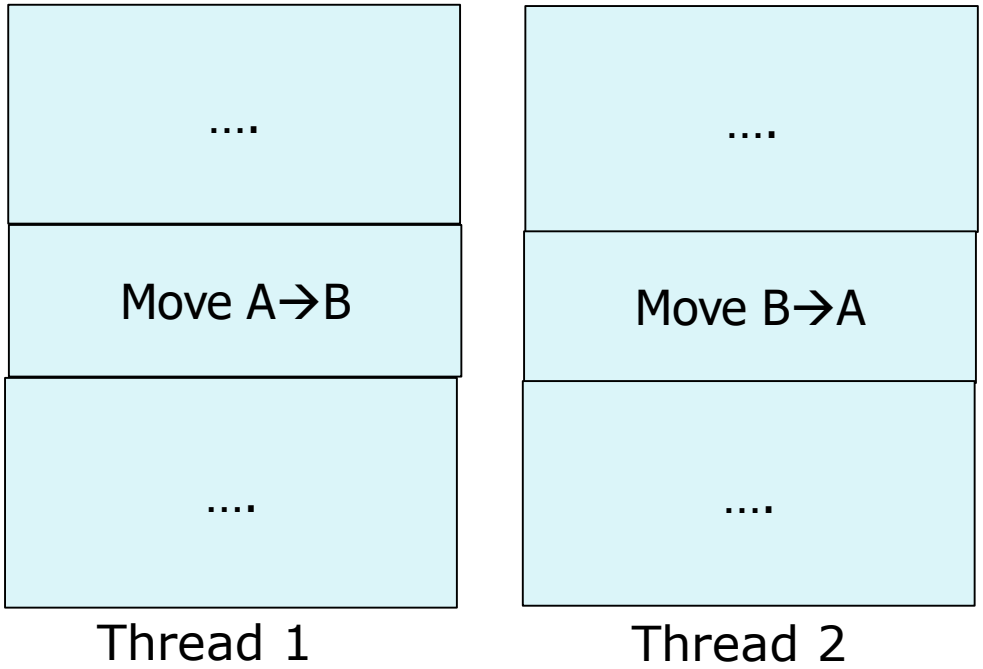

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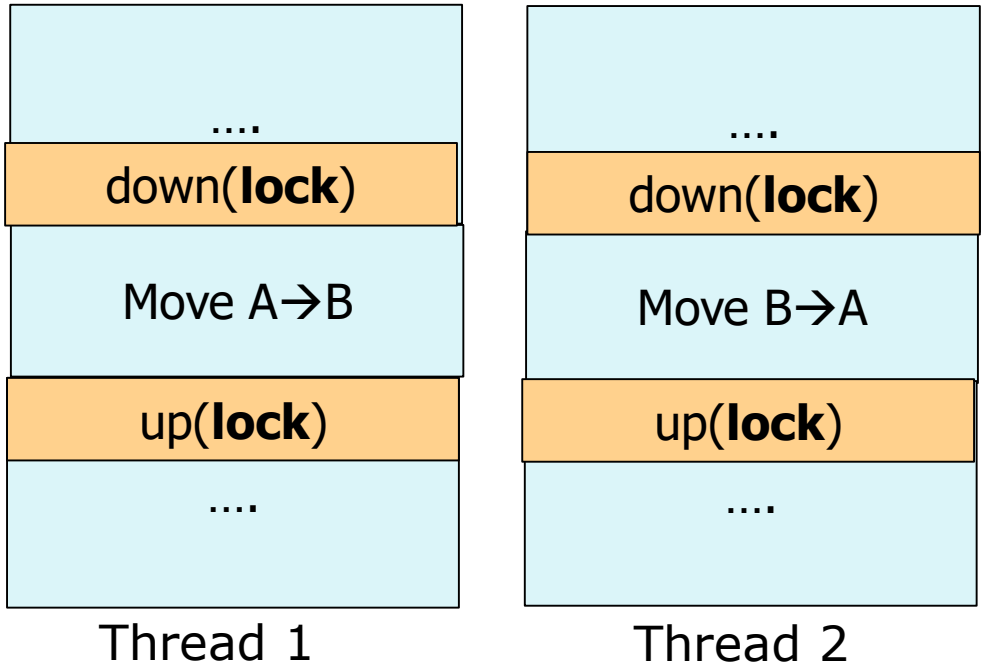

Semaphore **lock**, initialized to 1

Mutual exclusion, where the Move is the critical section

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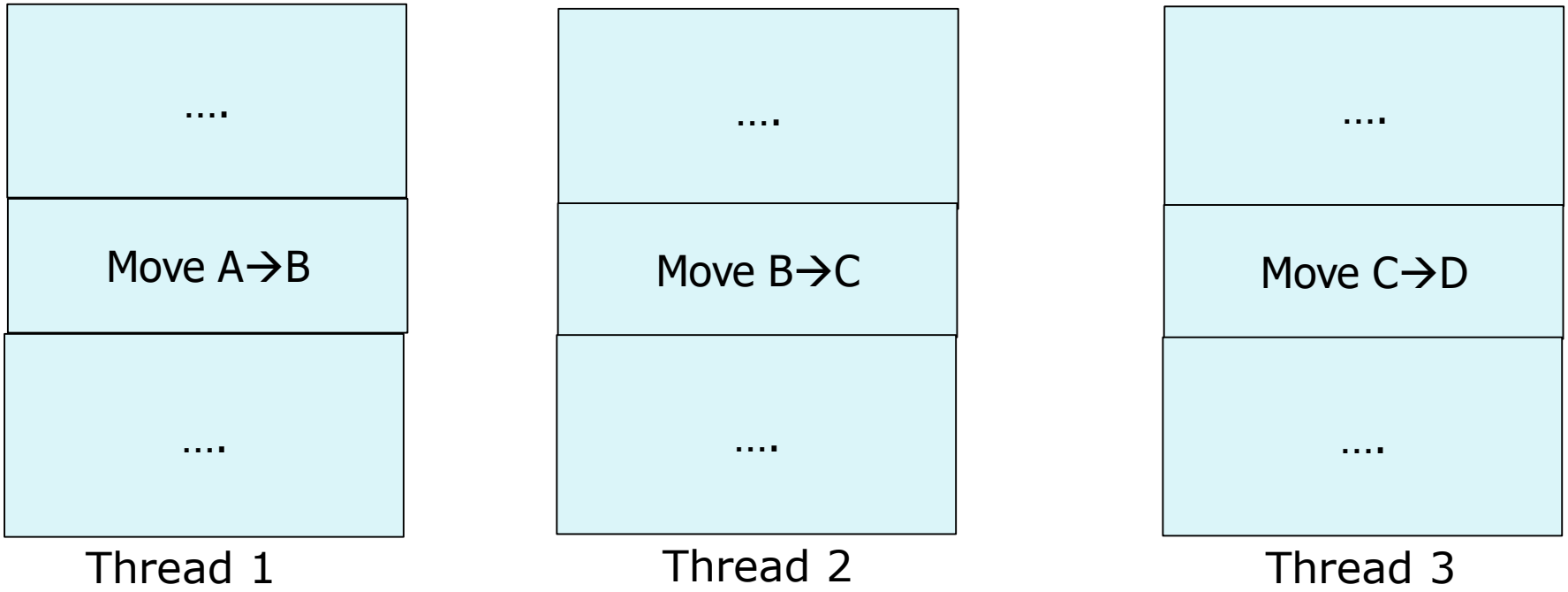
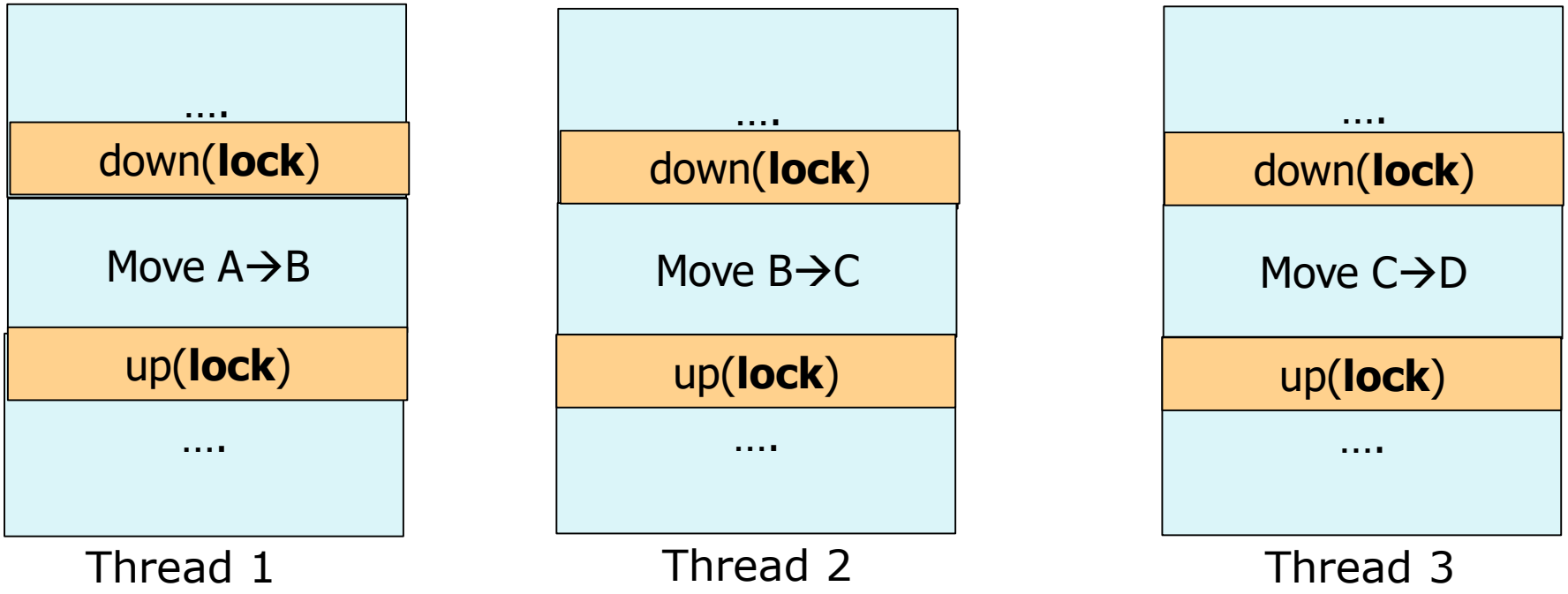
- Three Threads



Another Problem: Moving Money Between Accounts

- Three Threads
- Solution 1: mutual exclusion



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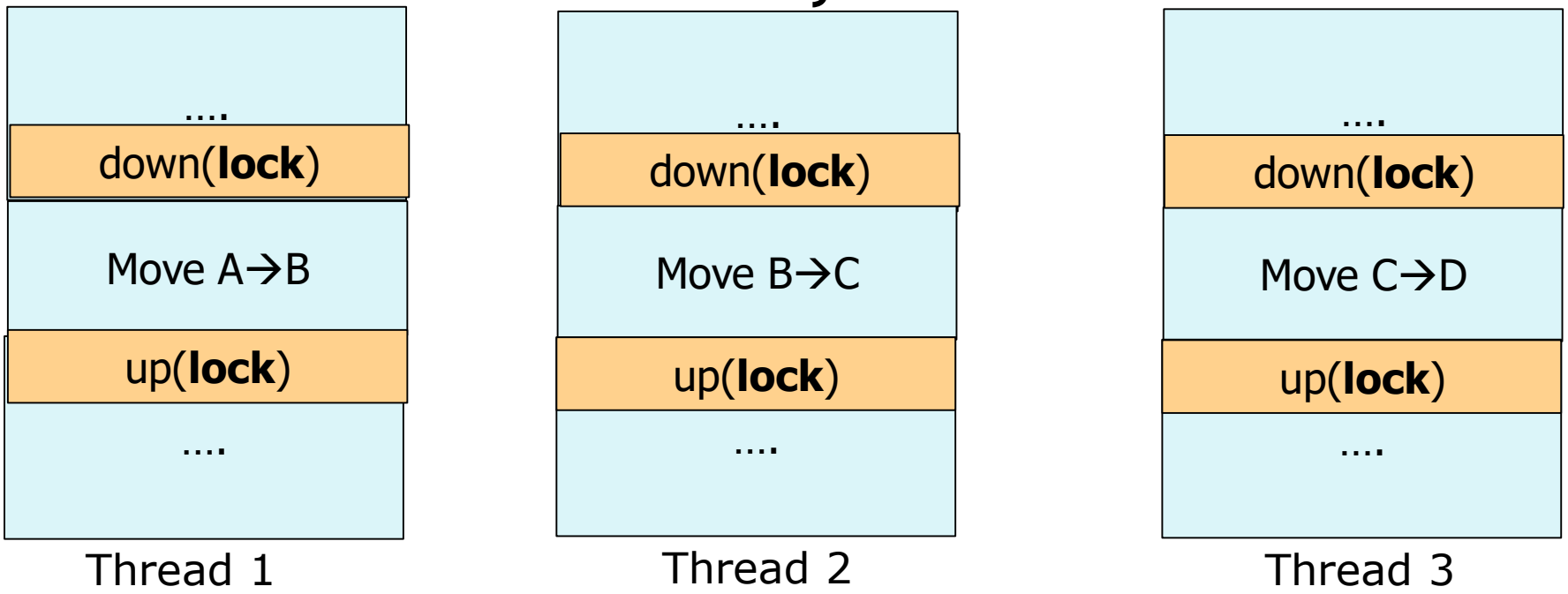
- Three Threads
- Solution 1: mutual exclusion
  - But why Thread 1 and Thread 3 cannot be executed concurrently?



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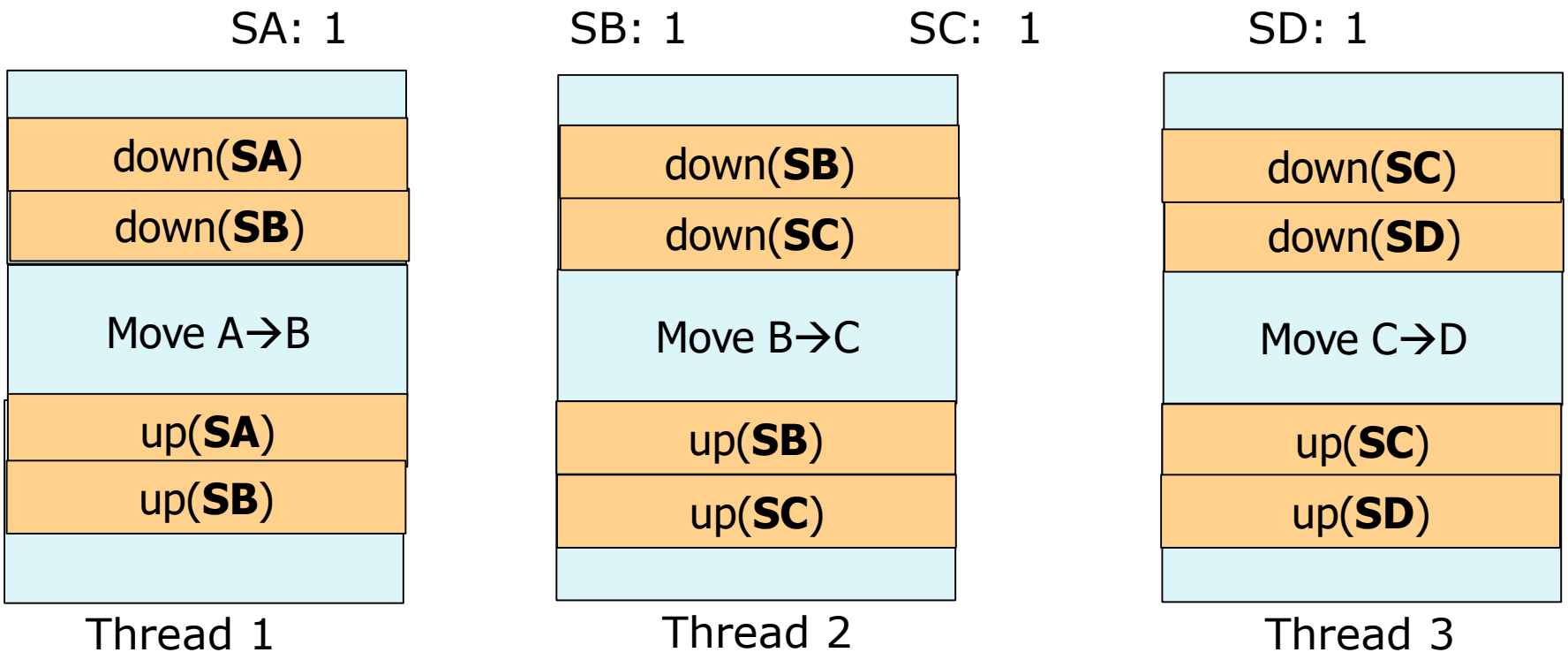
  - Semaphore for each account: SA, SB, SC, SD. All initialized to 1.



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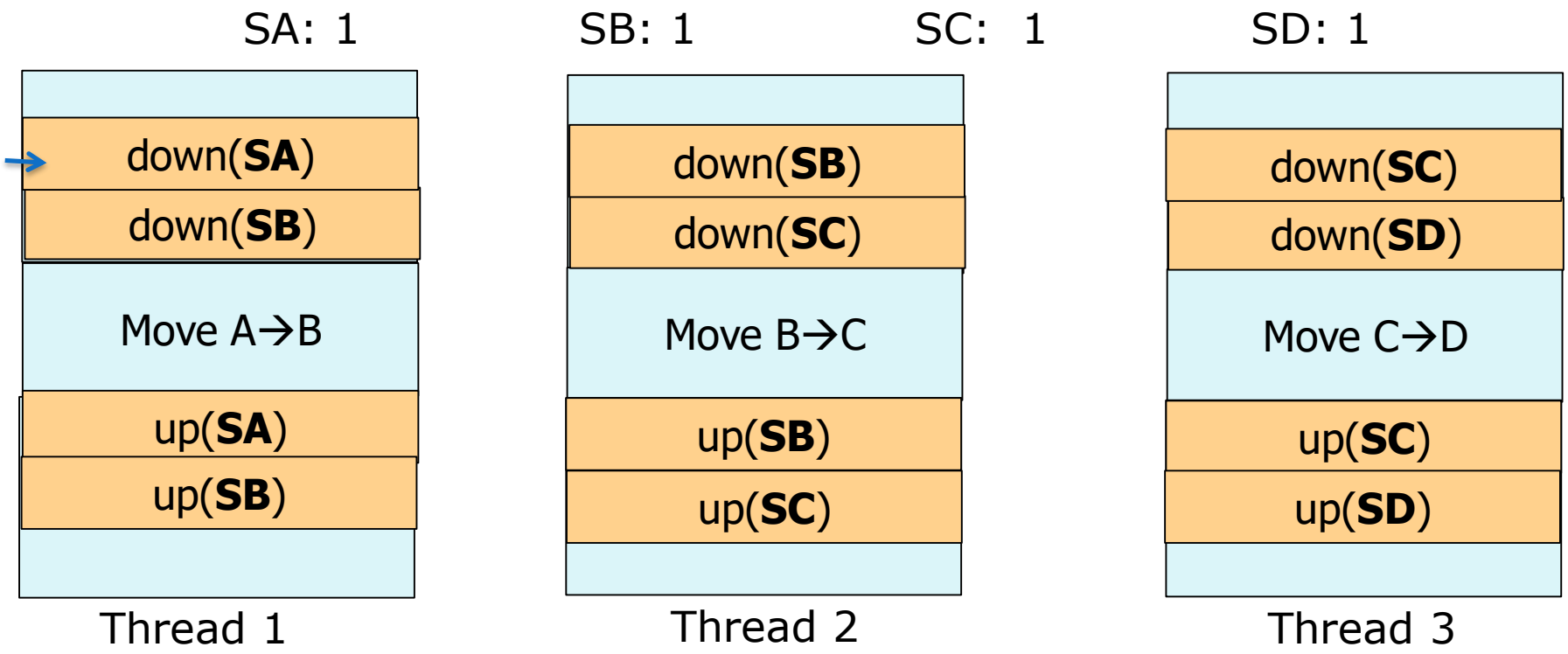

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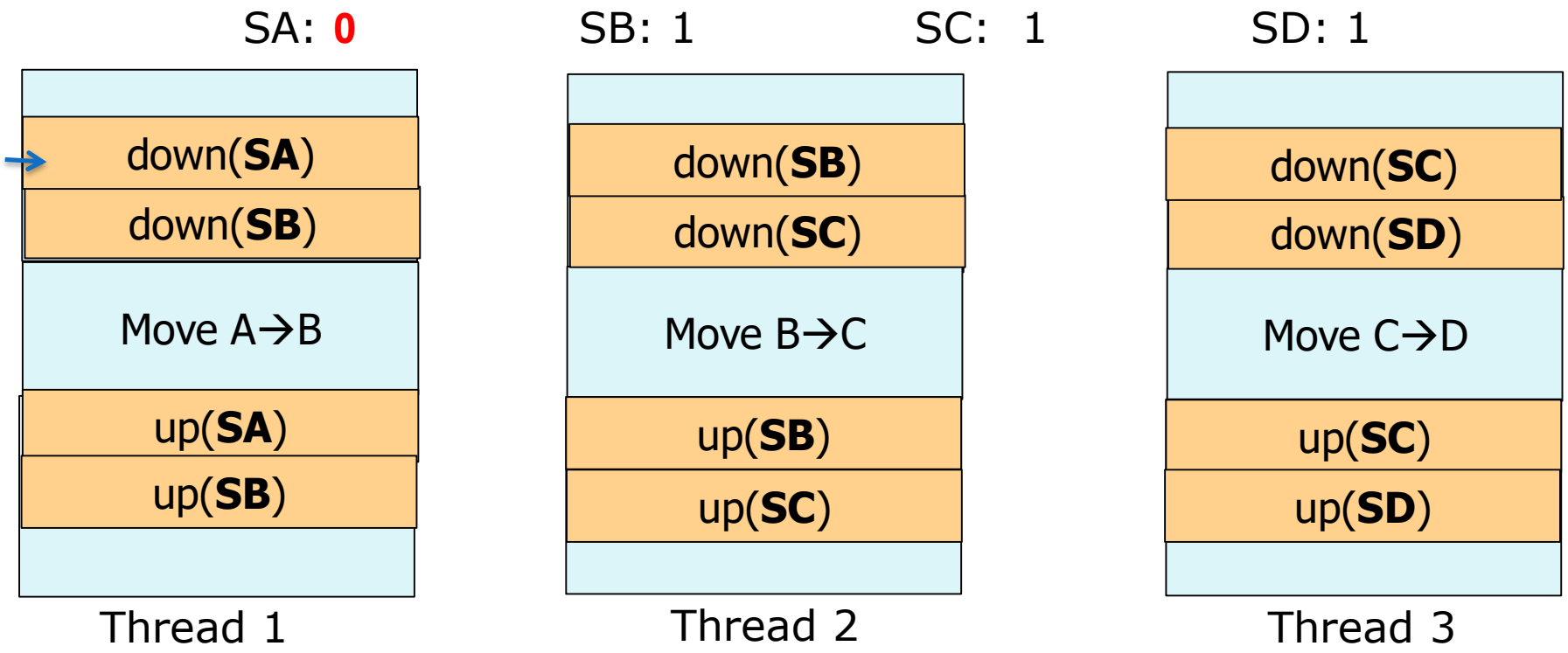

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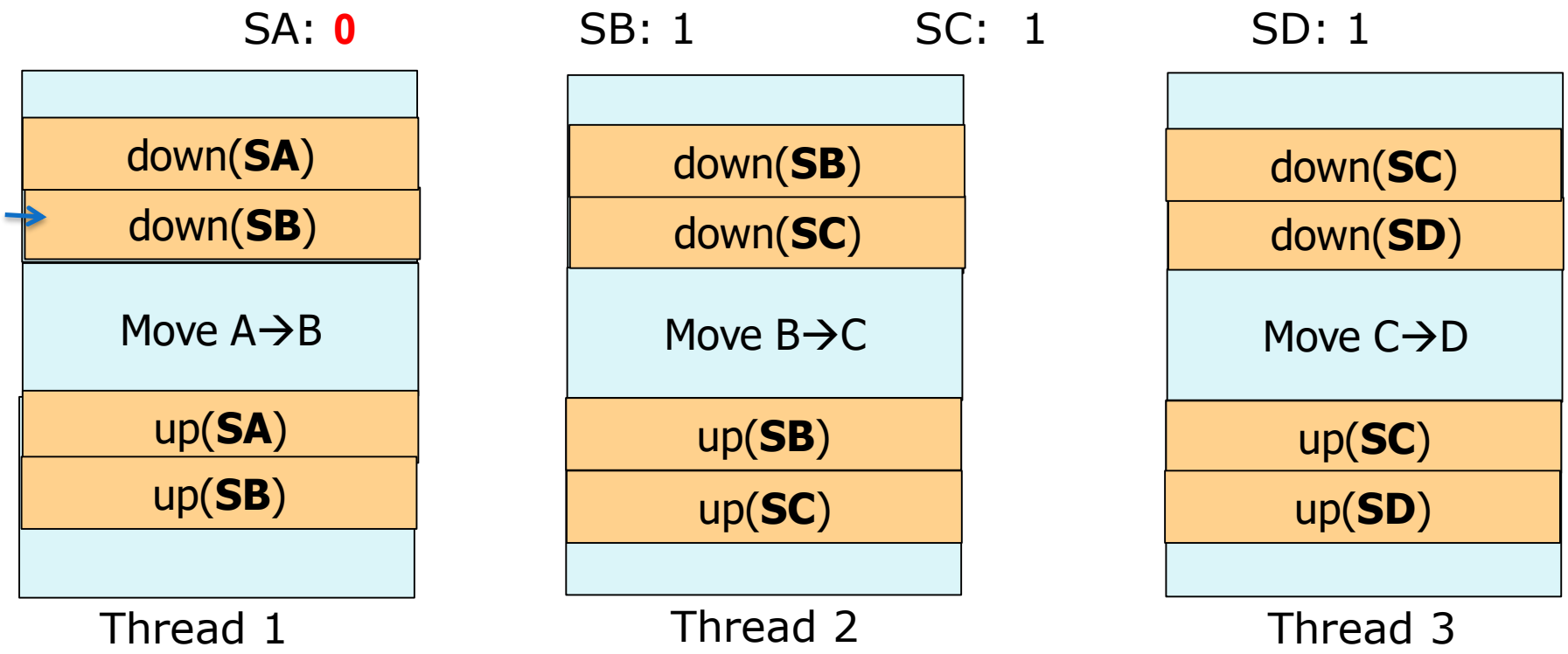

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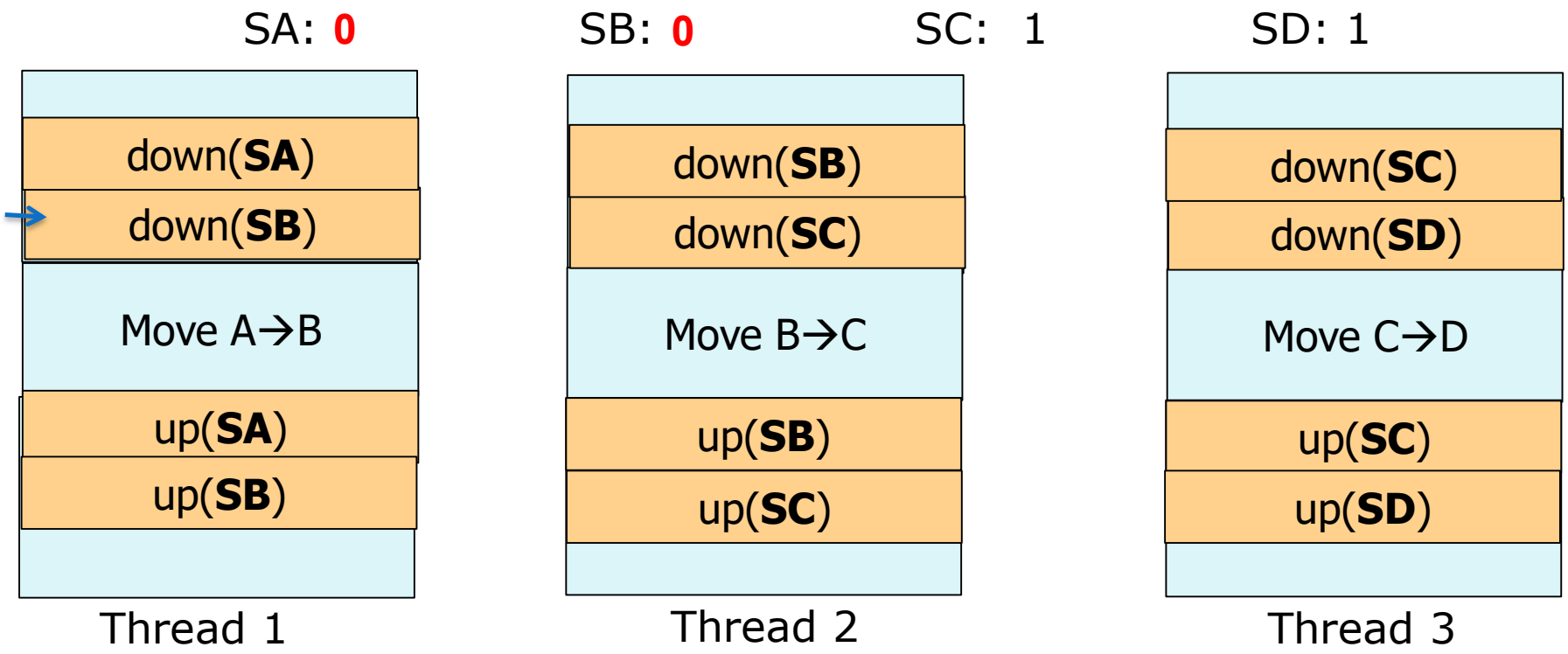

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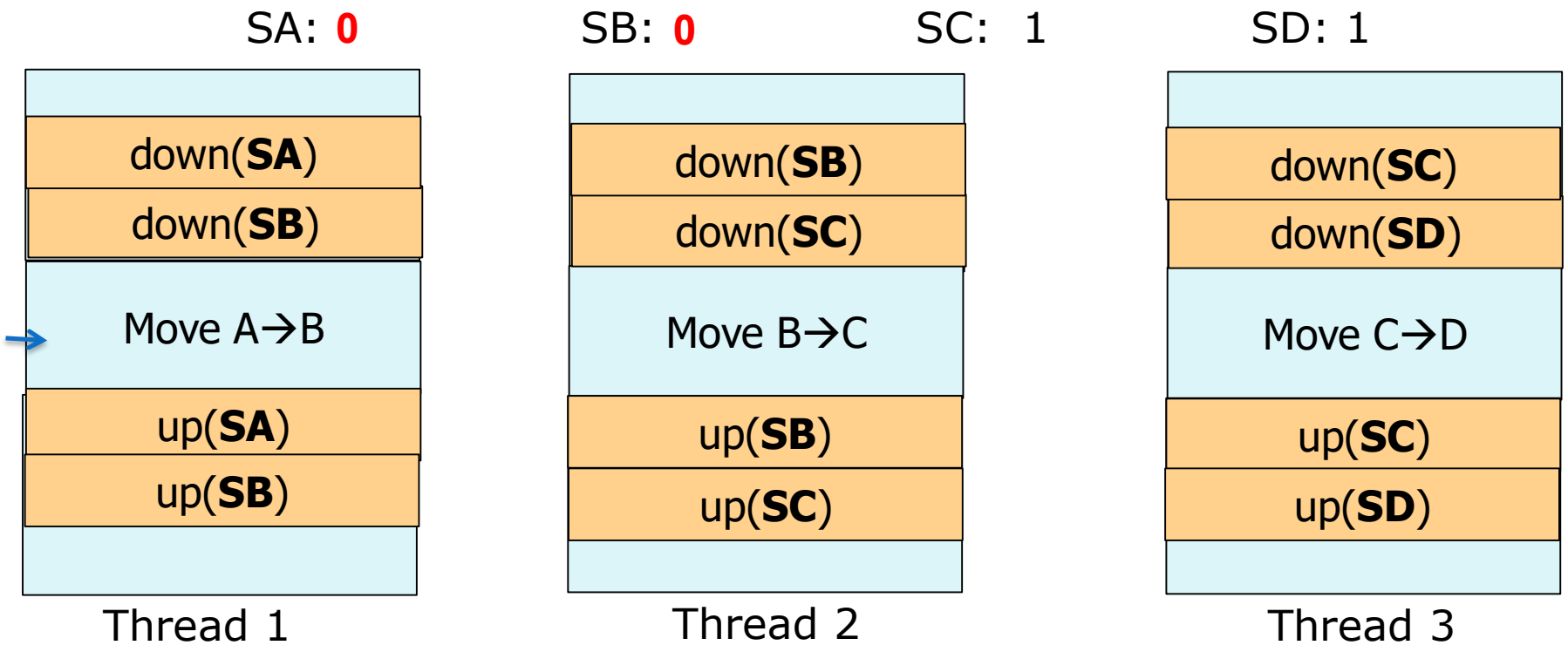

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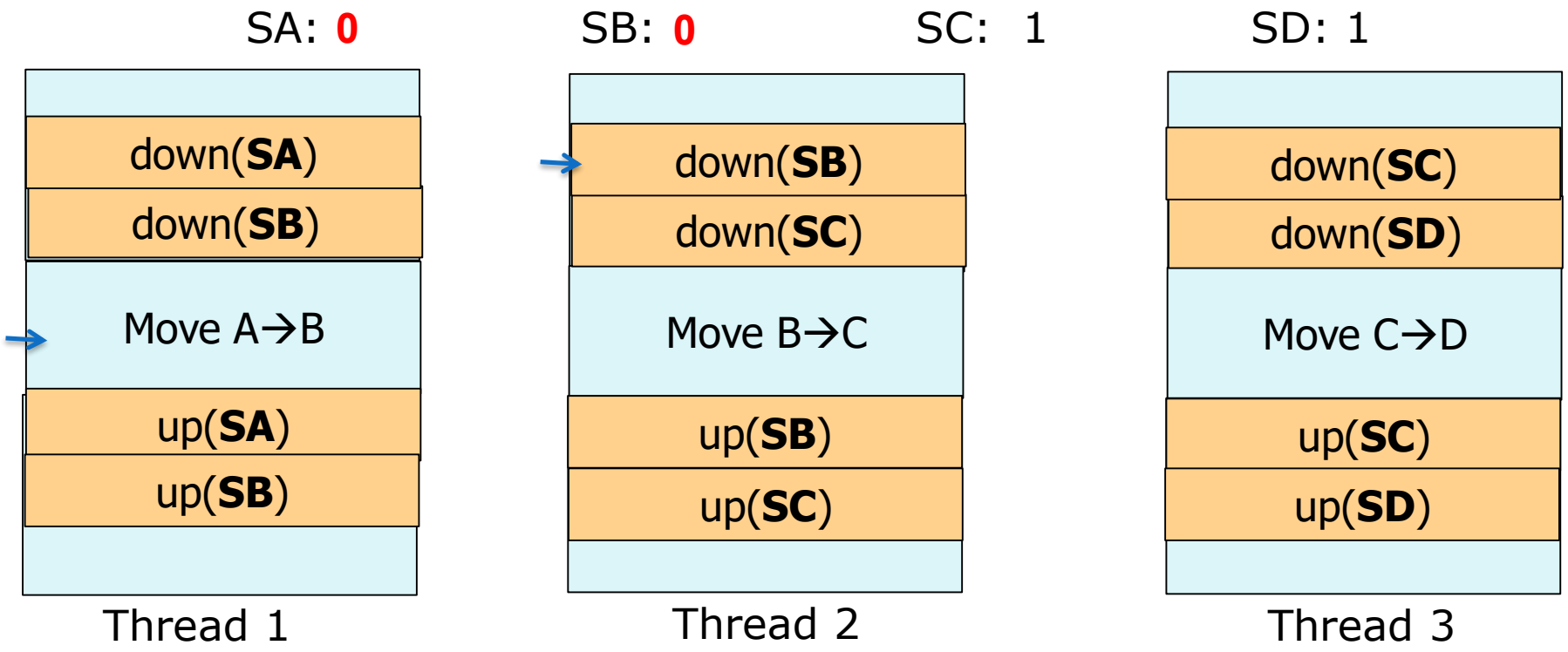

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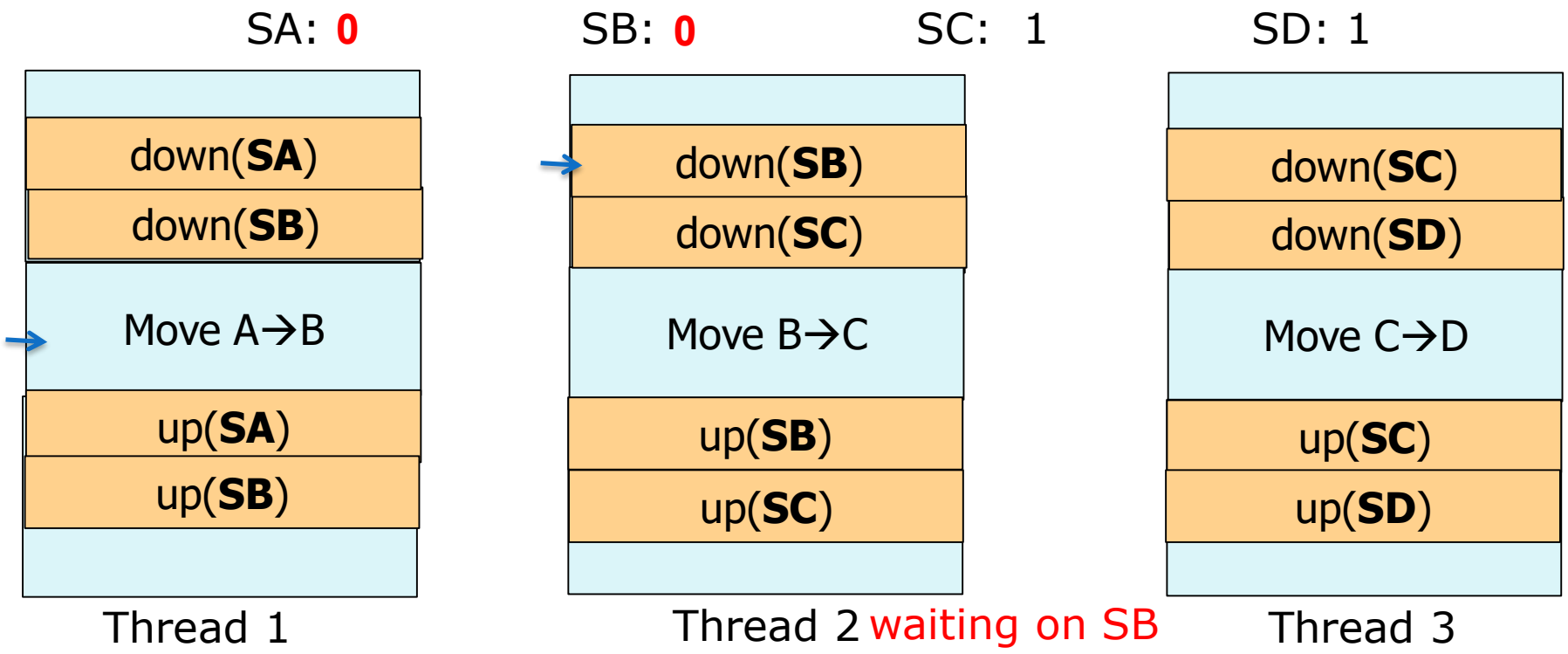

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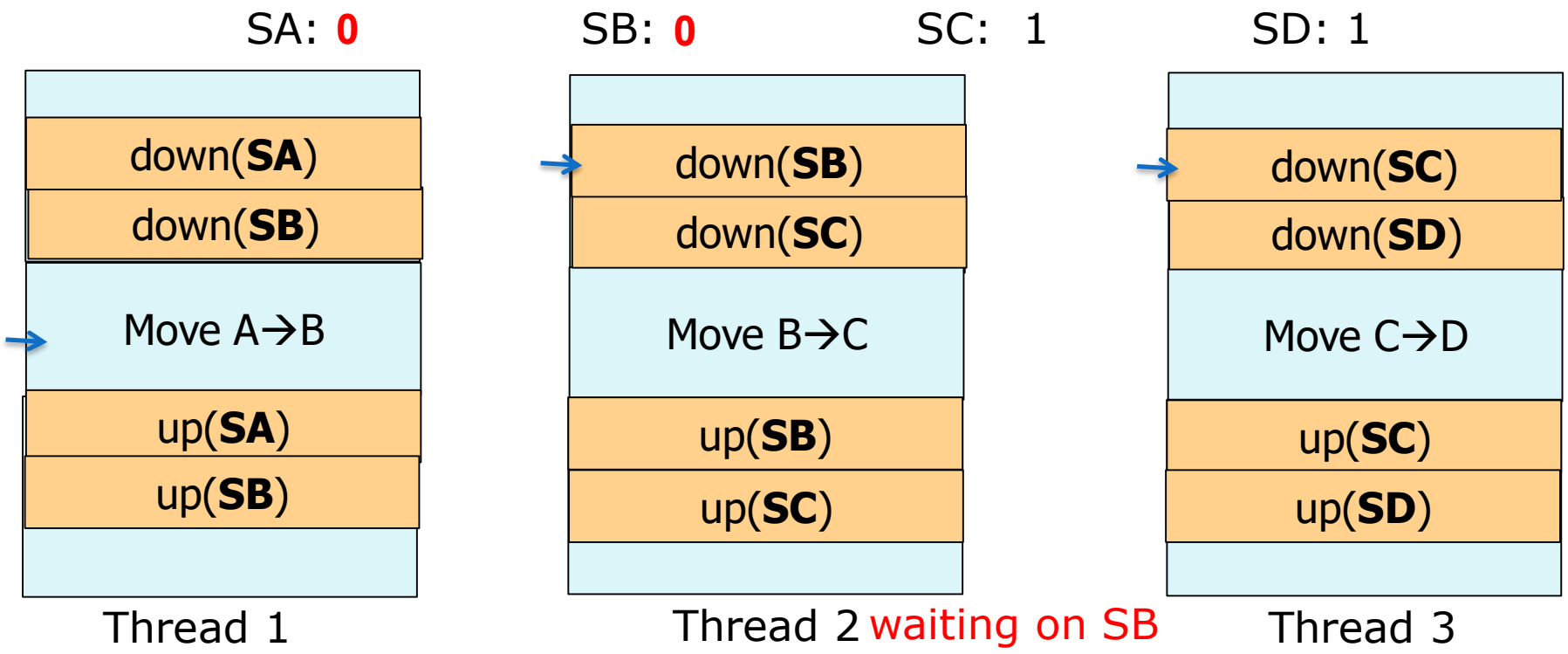

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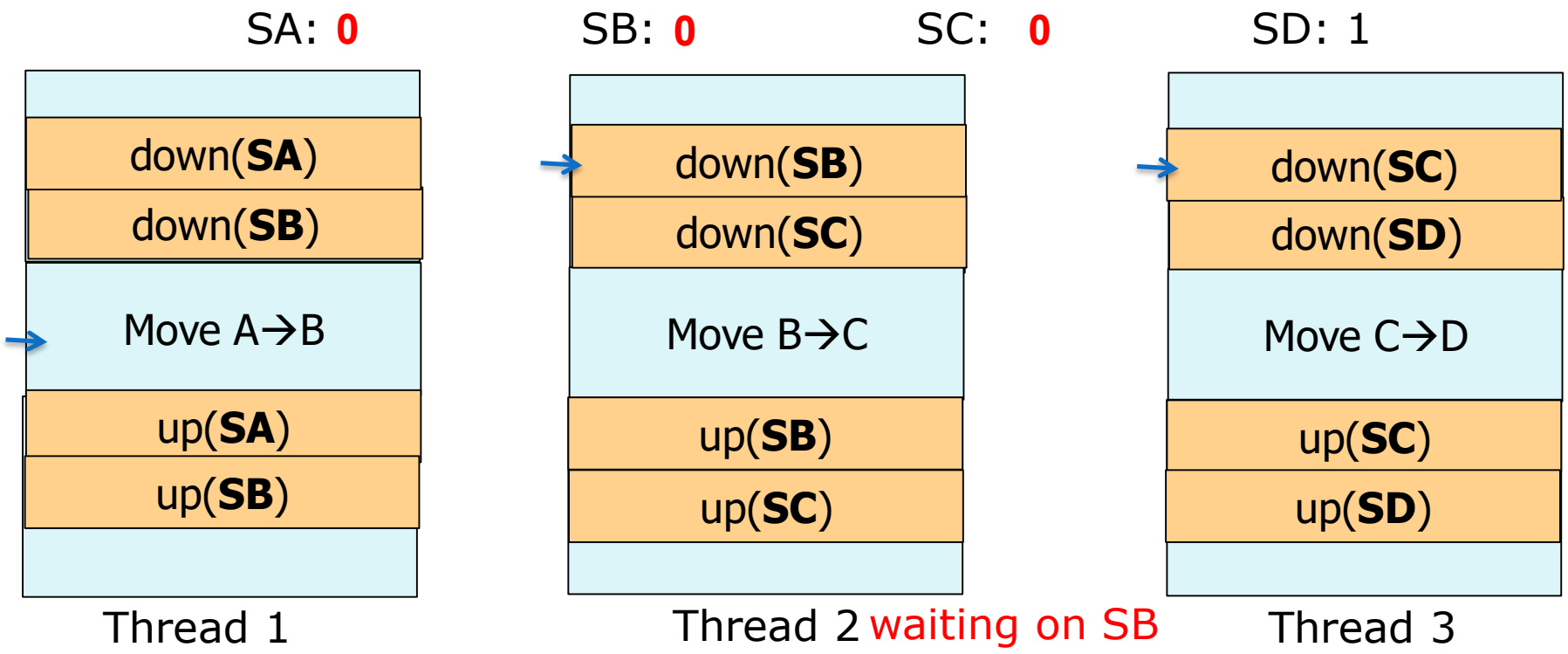

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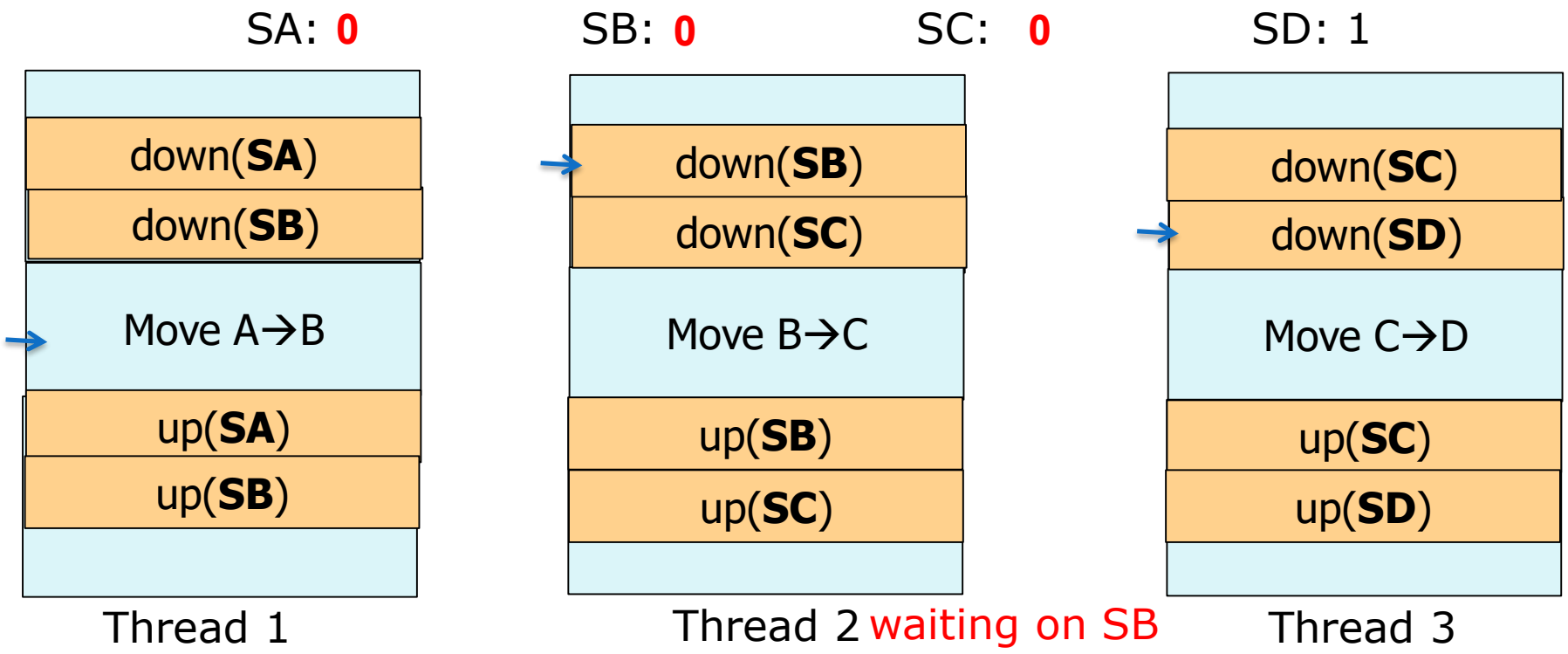

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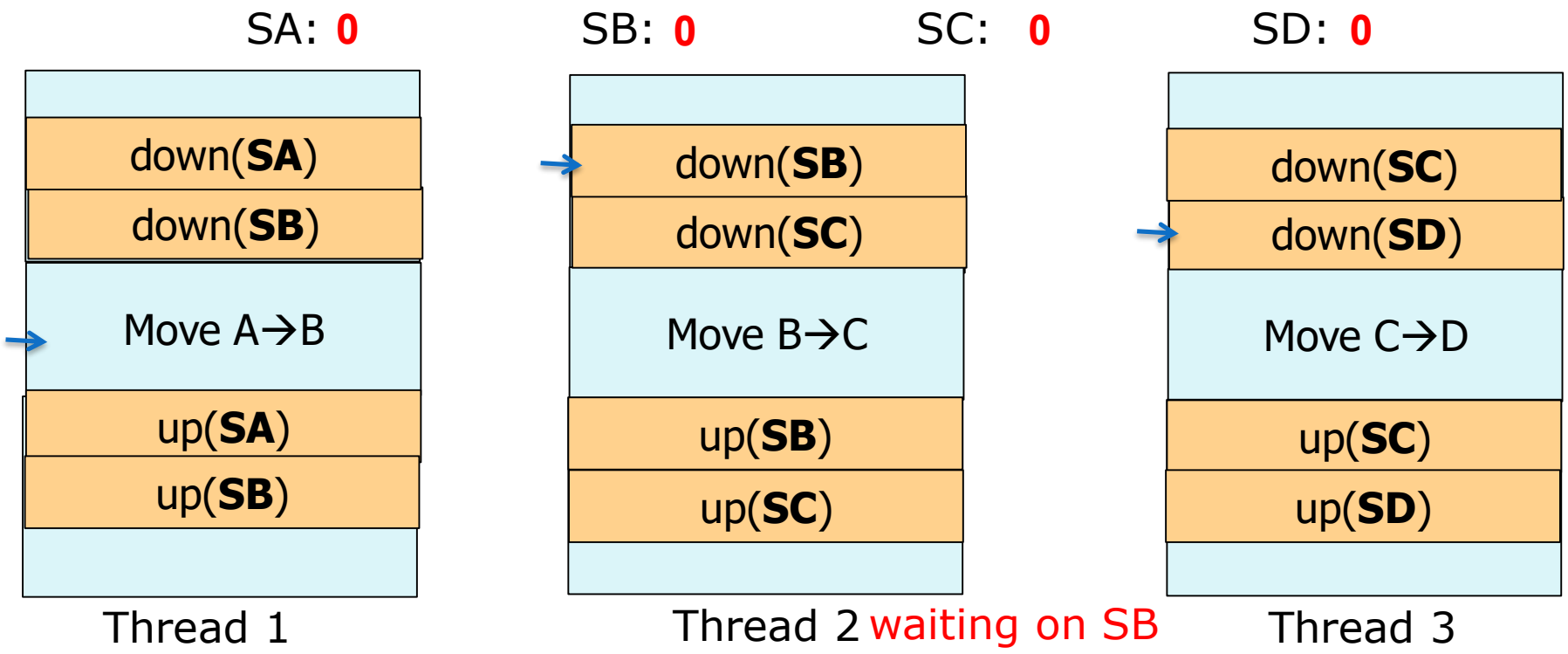

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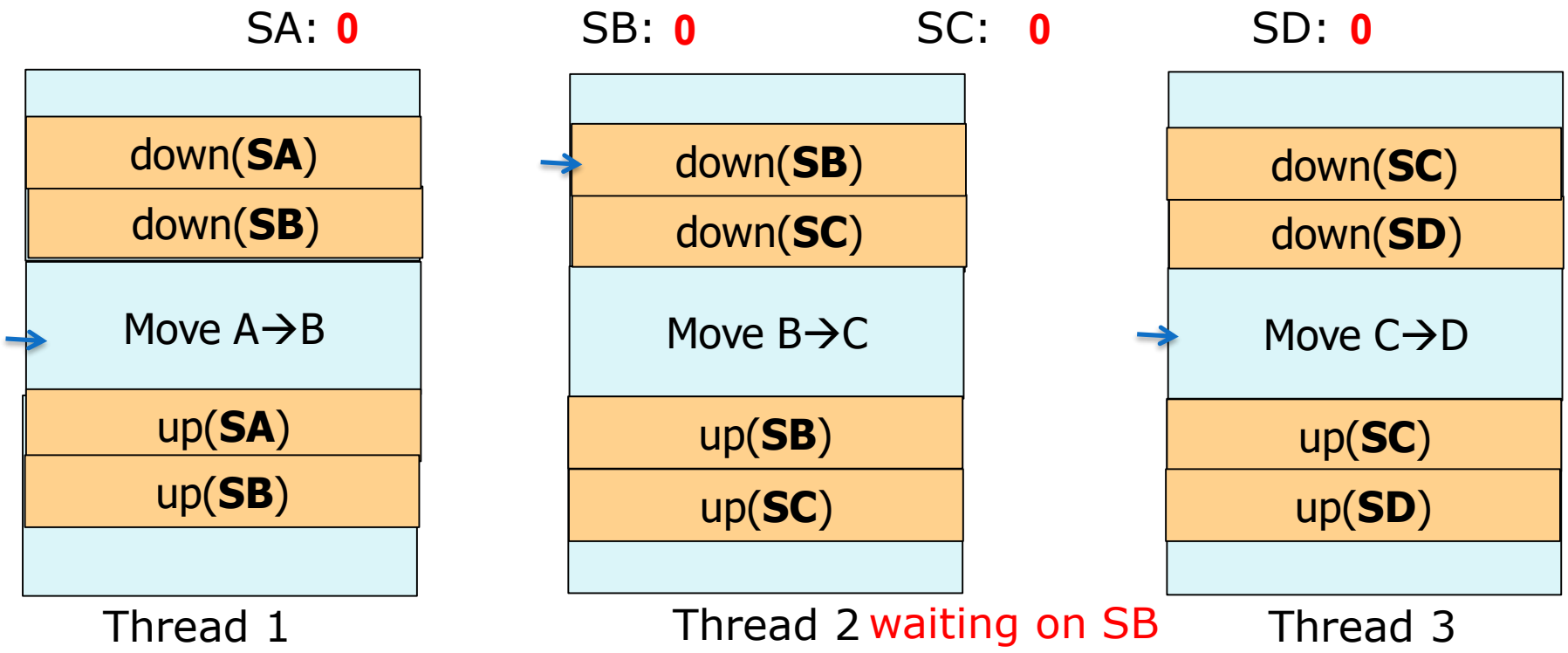
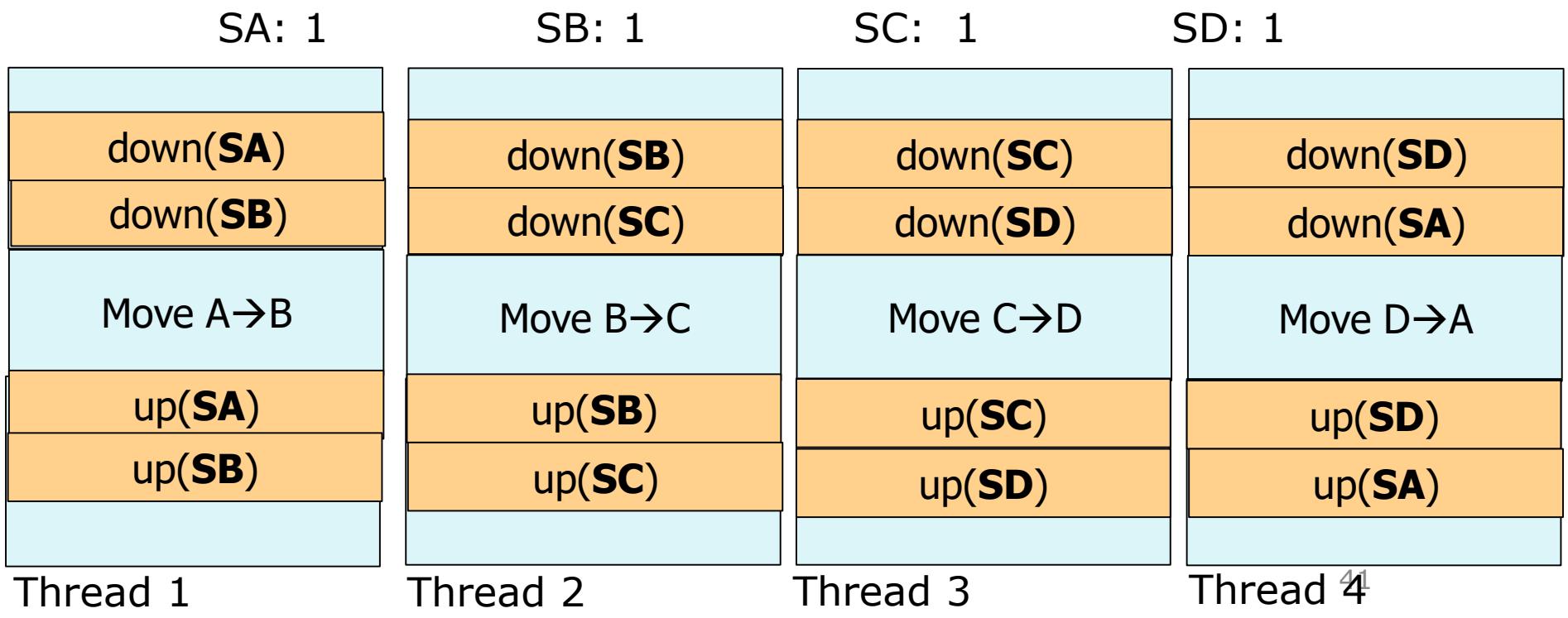


Semaphores are not Silver Bullets



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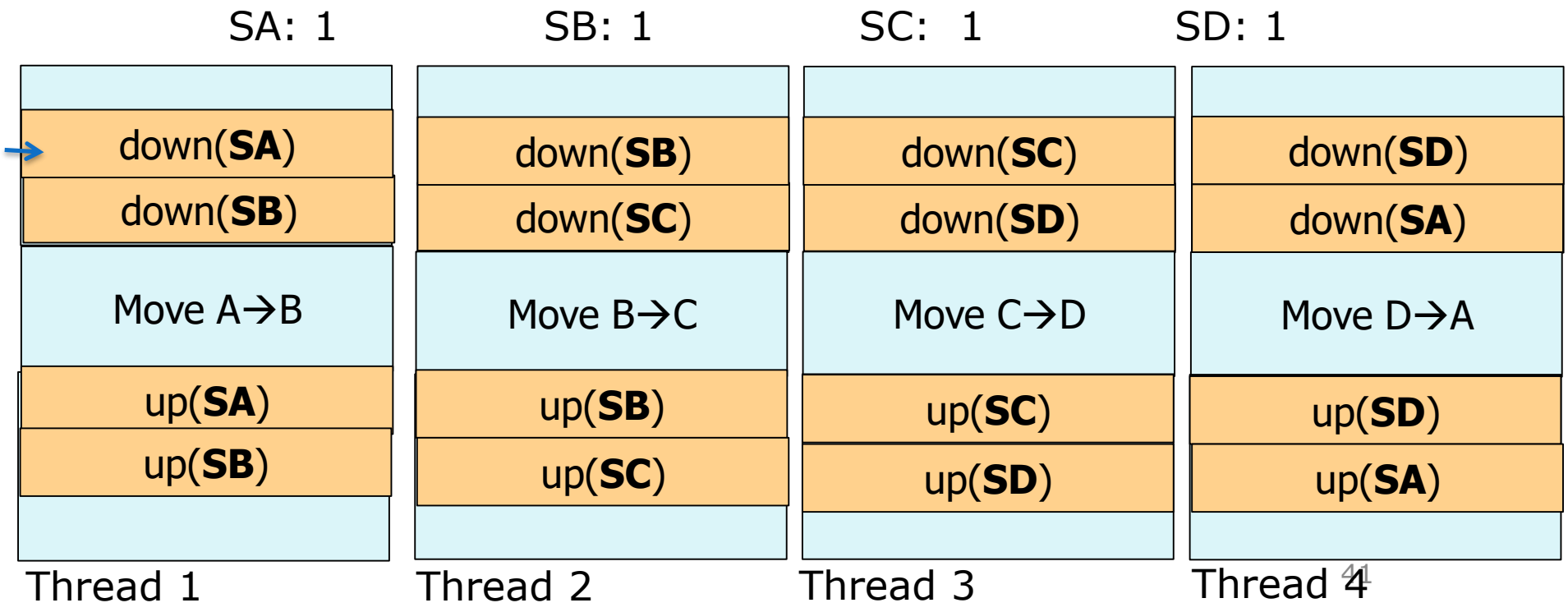

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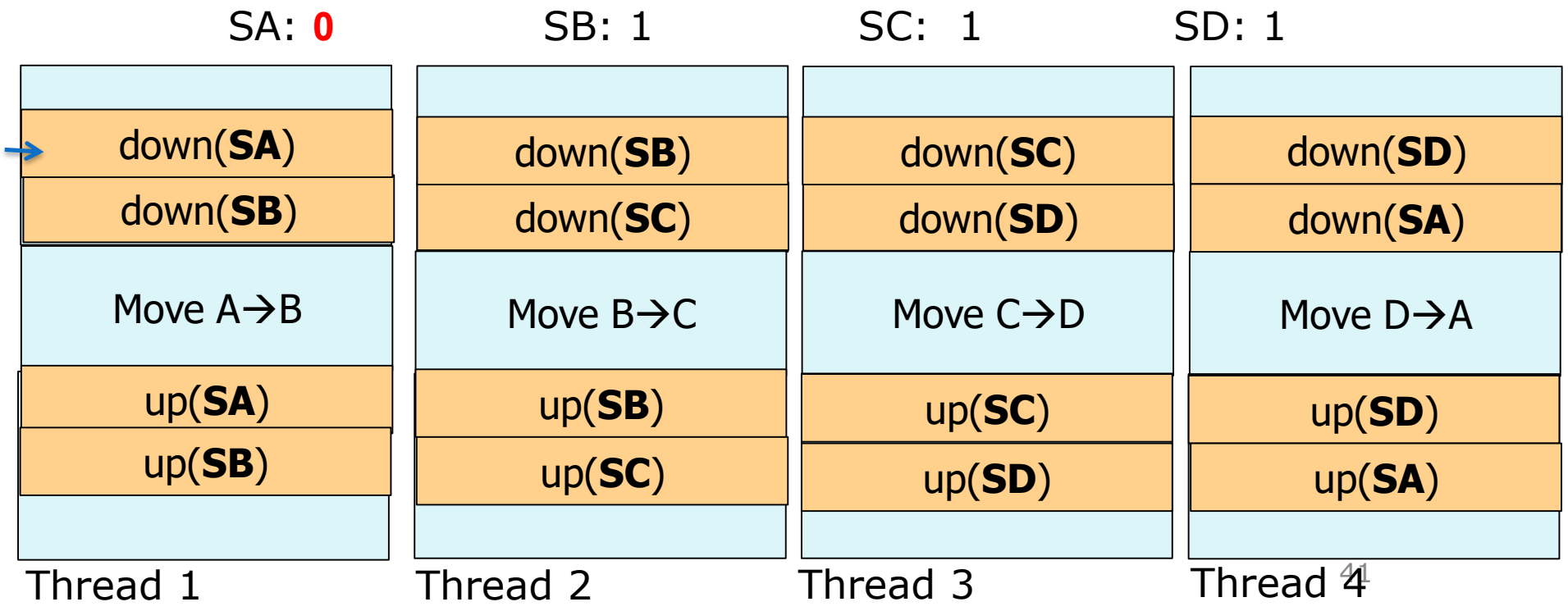

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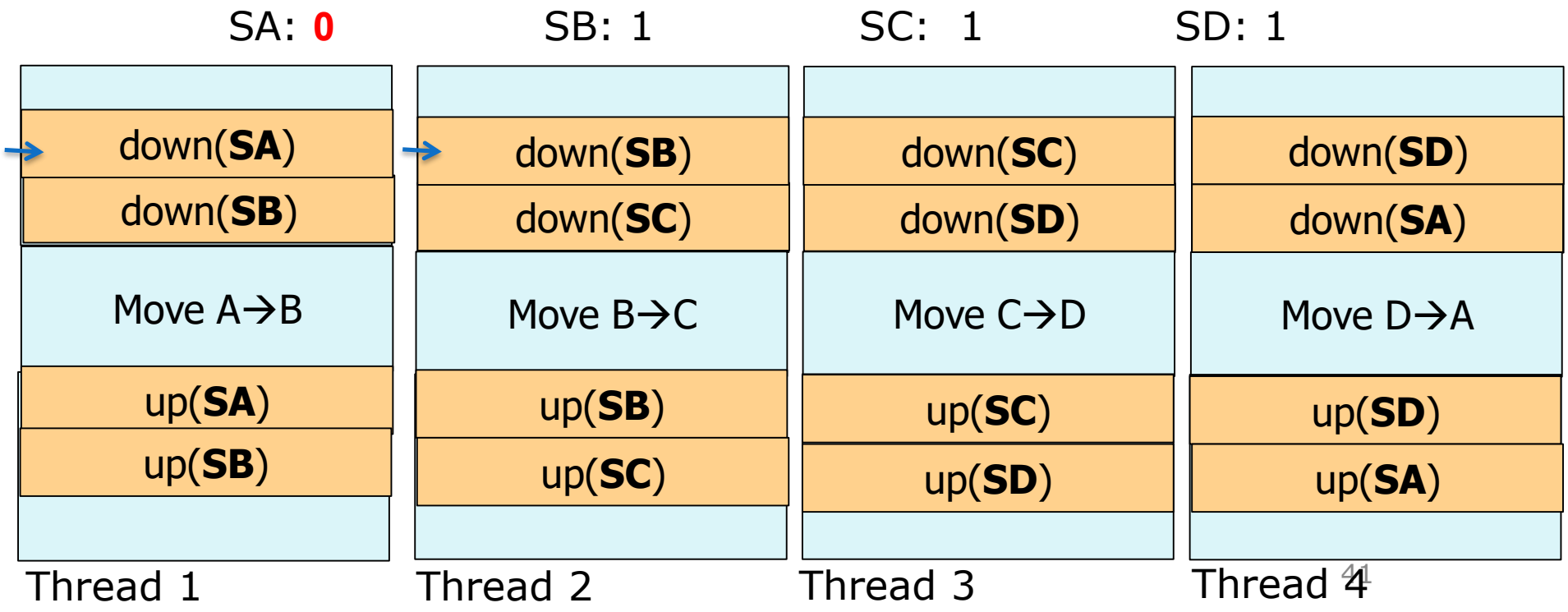

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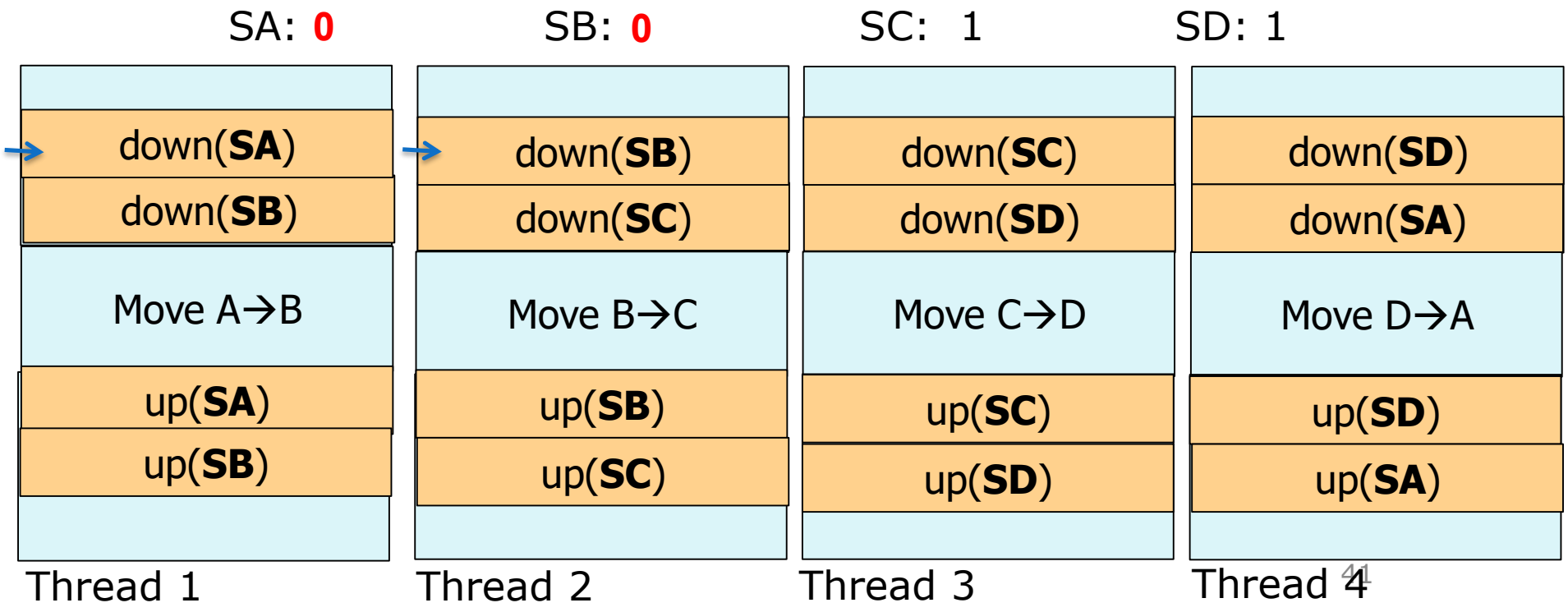

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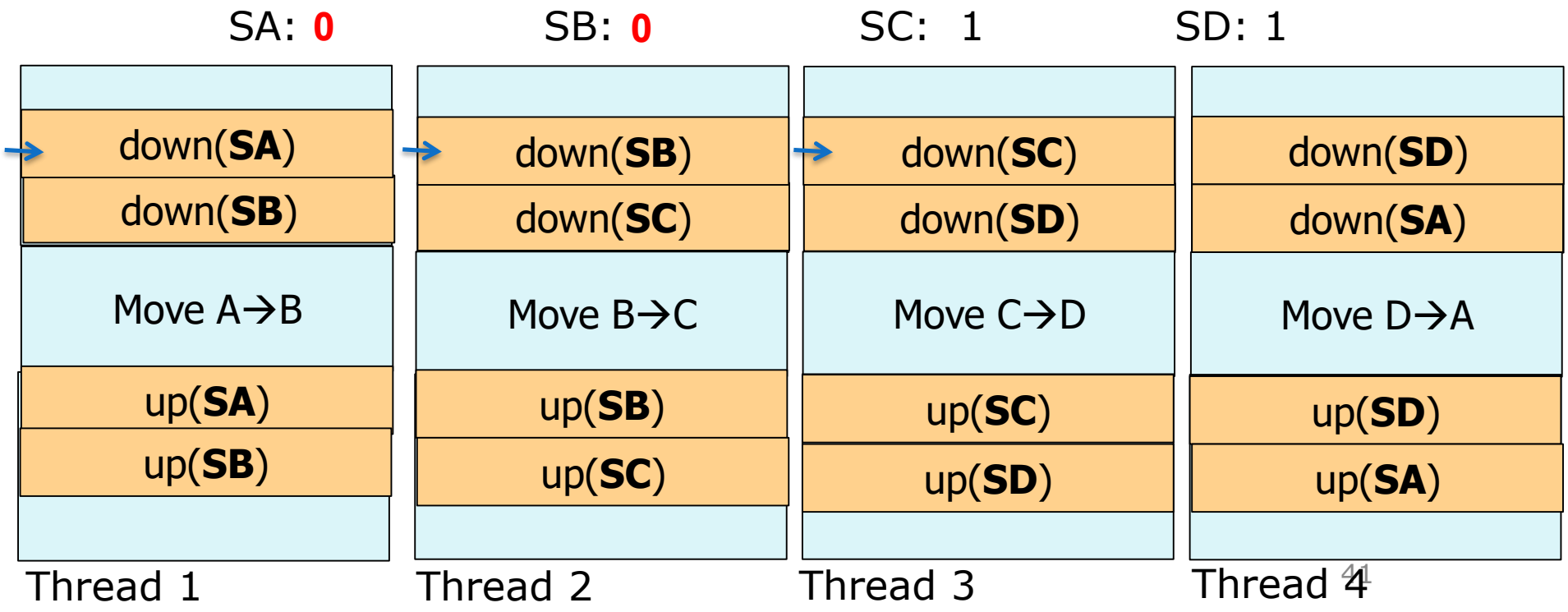

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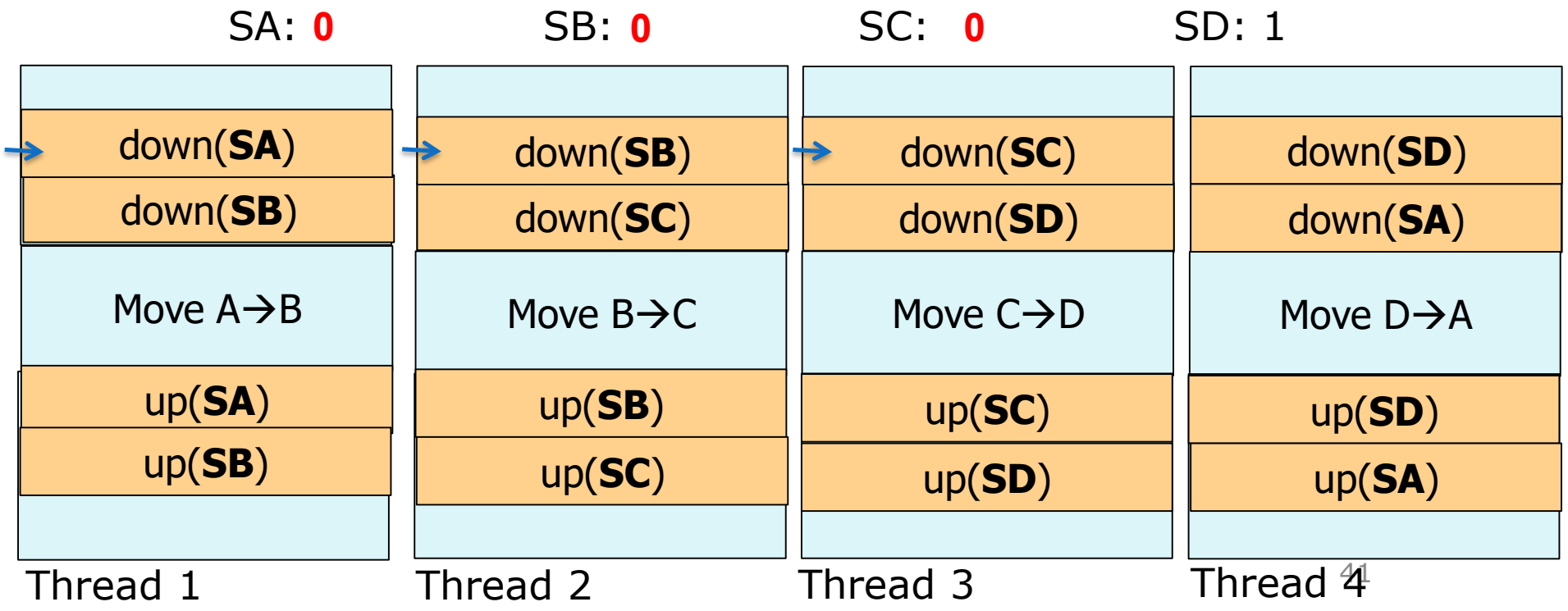

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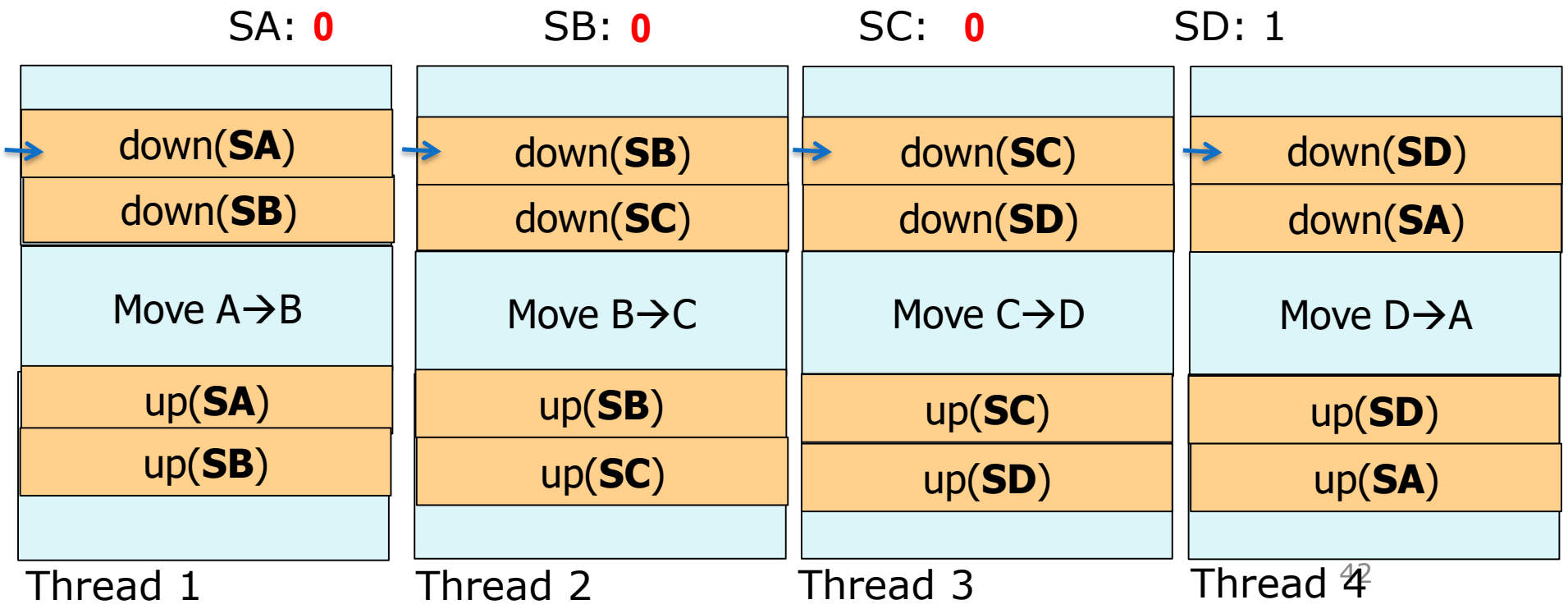

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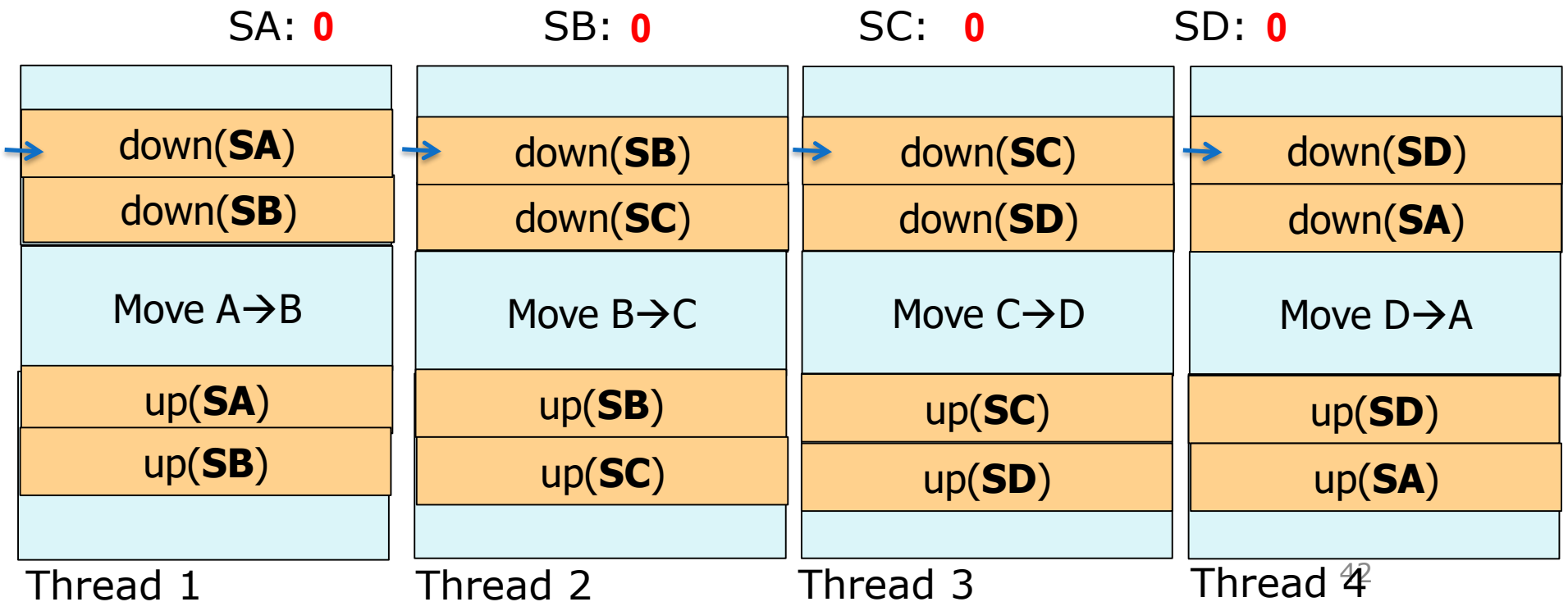

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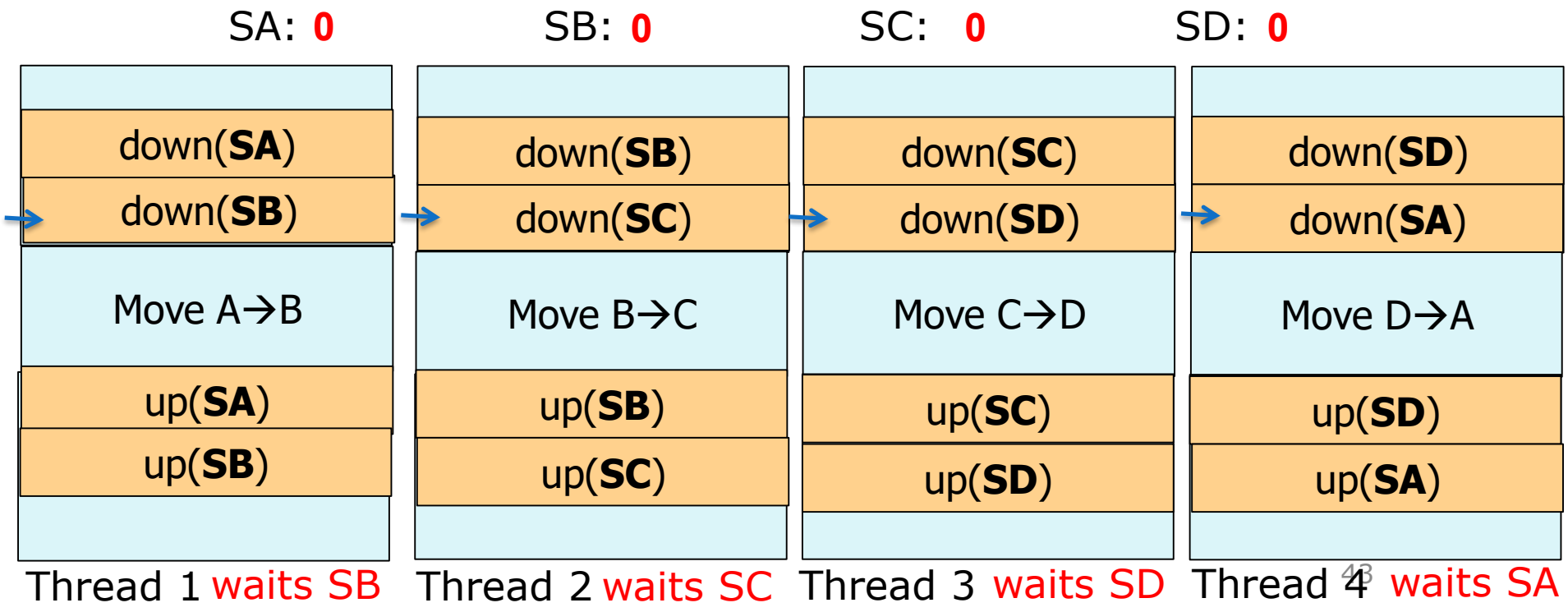

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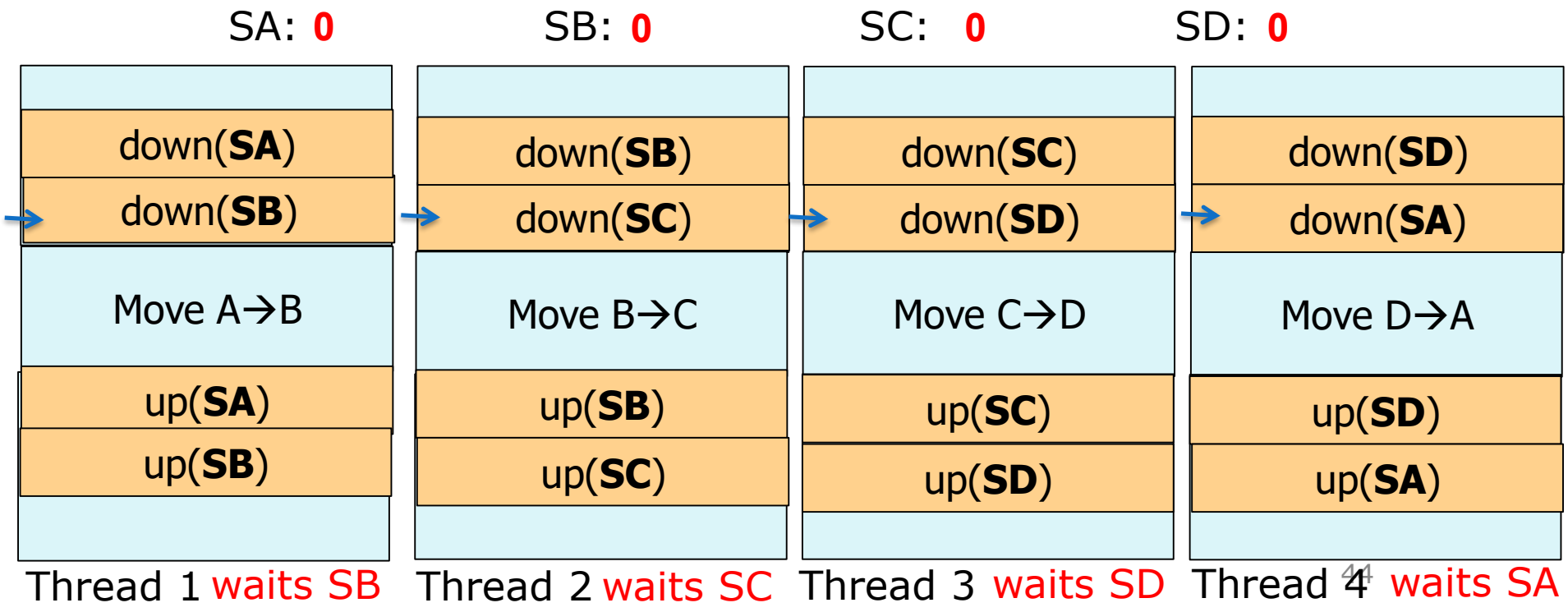

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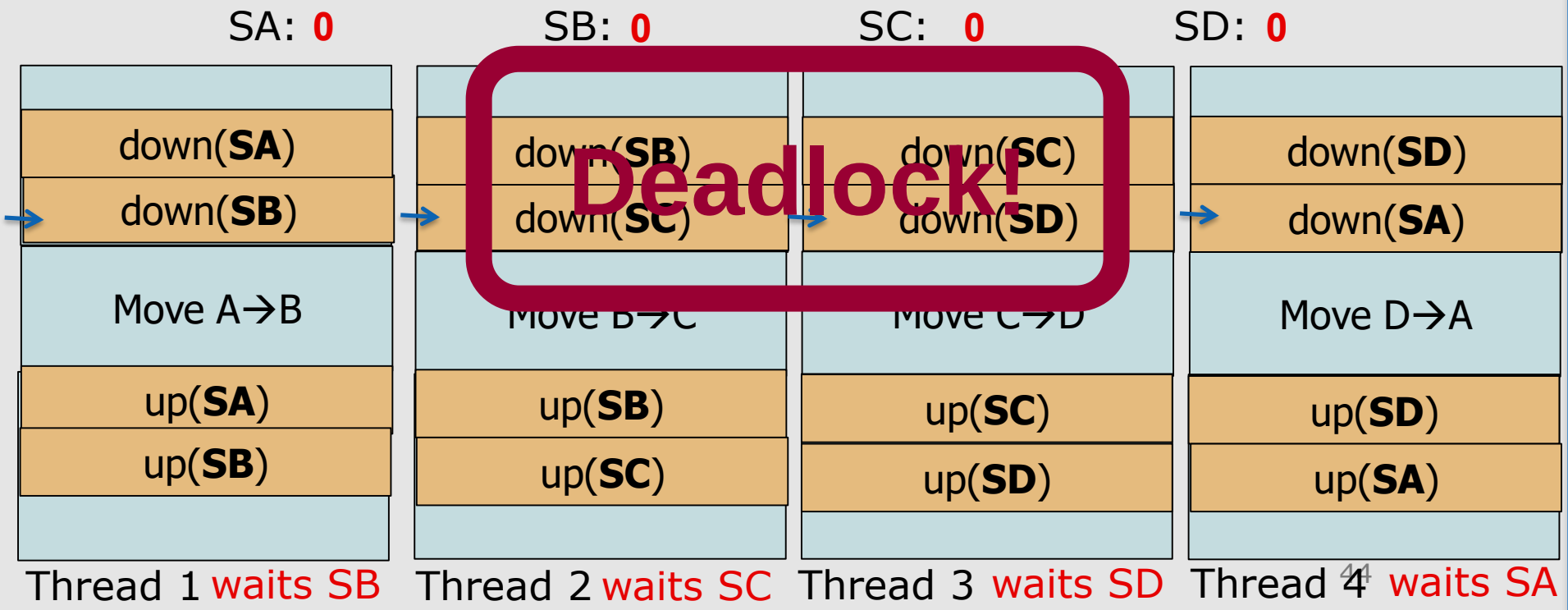

Semaphores are not Silver Bullets

Although it is much easier to work with semaphores than read/write operations, it is still possible to cause problems (e.g., deadlocks, starvation, incorrectness)