Operating Systems

David Hay

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  - List (L)

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  – How? Implementation is orthogonal to the definition

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

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

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Mutual Exclusion w/ Semaphore

Remainder

down(lock)

Critical

up(lock)

Code for Thread i

lock.*value*= lock.*value* - 1
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{ add this thread to S.*L*;
sleep();}

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

Mutual Exclusion w/ Semaphore

- Assume **lock** is a shared semaphore
  - Initially **lock** is 1

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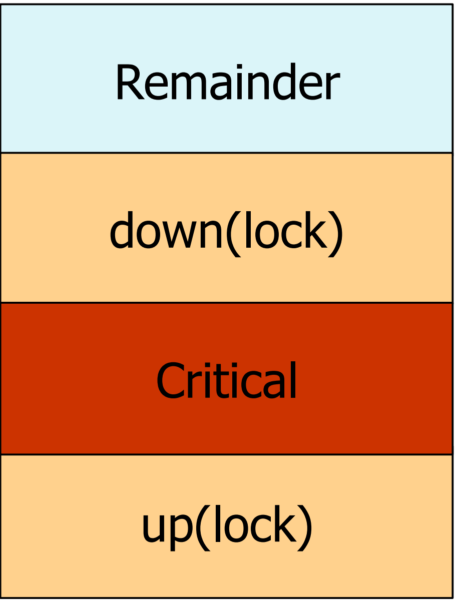
  - Cannot be more than 1
  - 0: one process in Critical Section
  - (-x): x processes are waiting

Mutual Exclusion w/ Semaphore



Code for Thread i

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

```
lock.value= lock.value + 1
If lock.value≤0 then
{remove a thread T from
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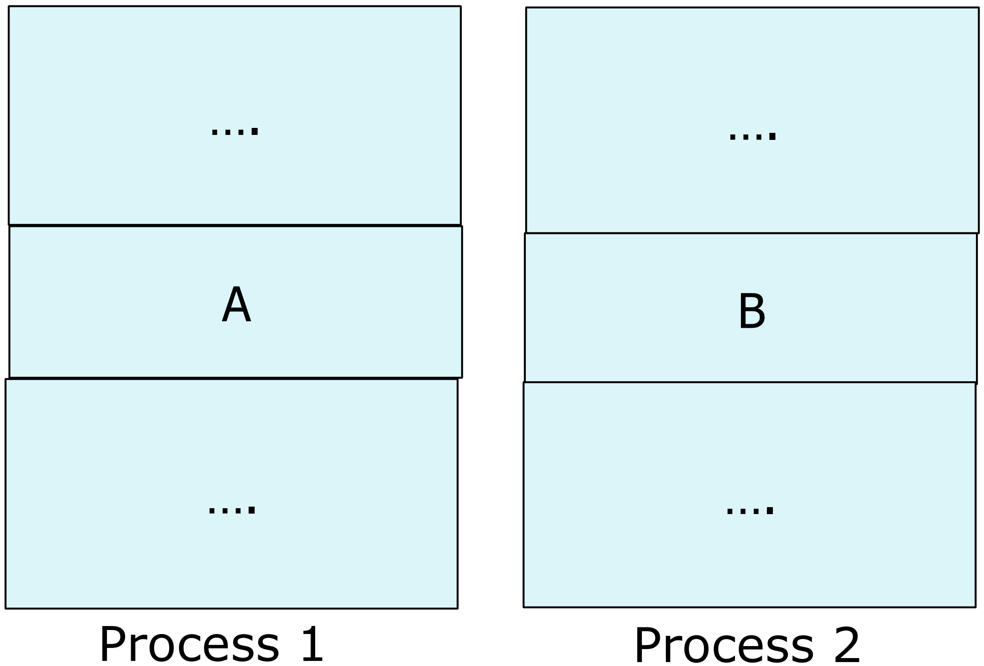
  - If L is a FIFO queue

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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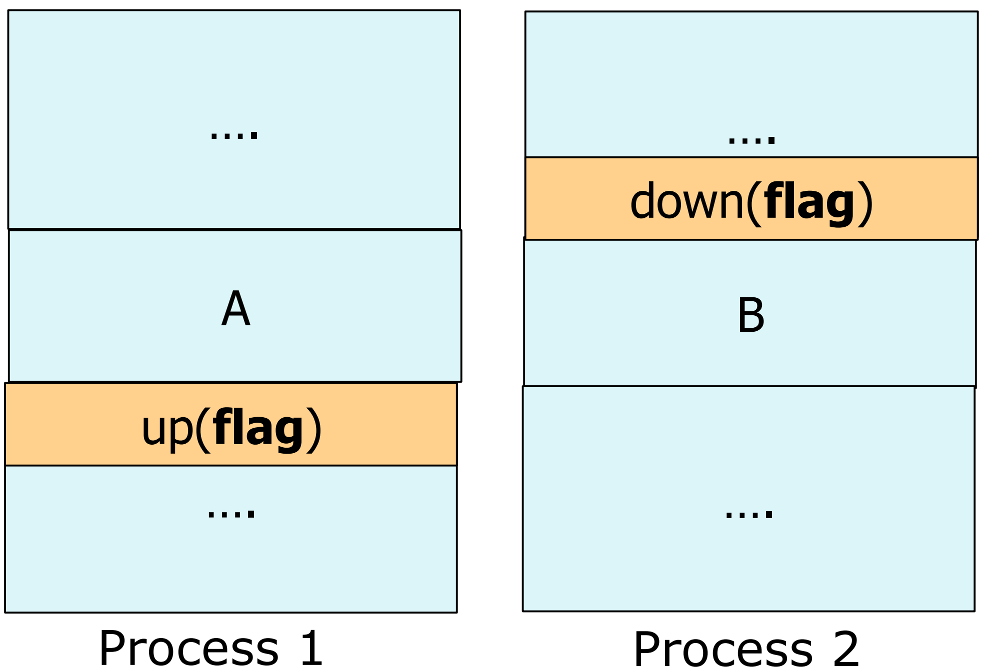

Semaphore **flag**, initialized to 0

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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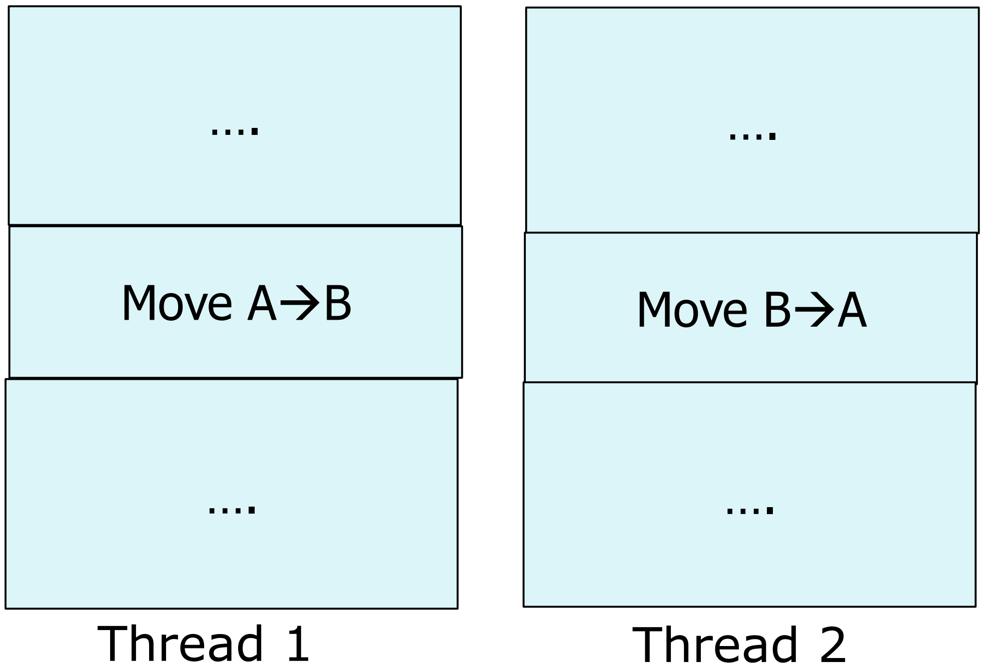

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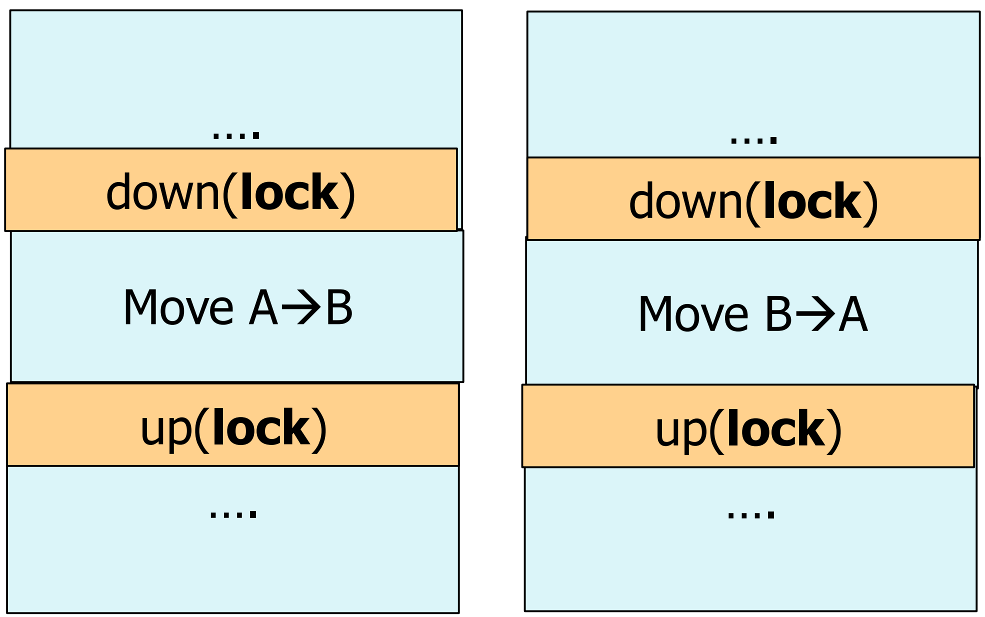


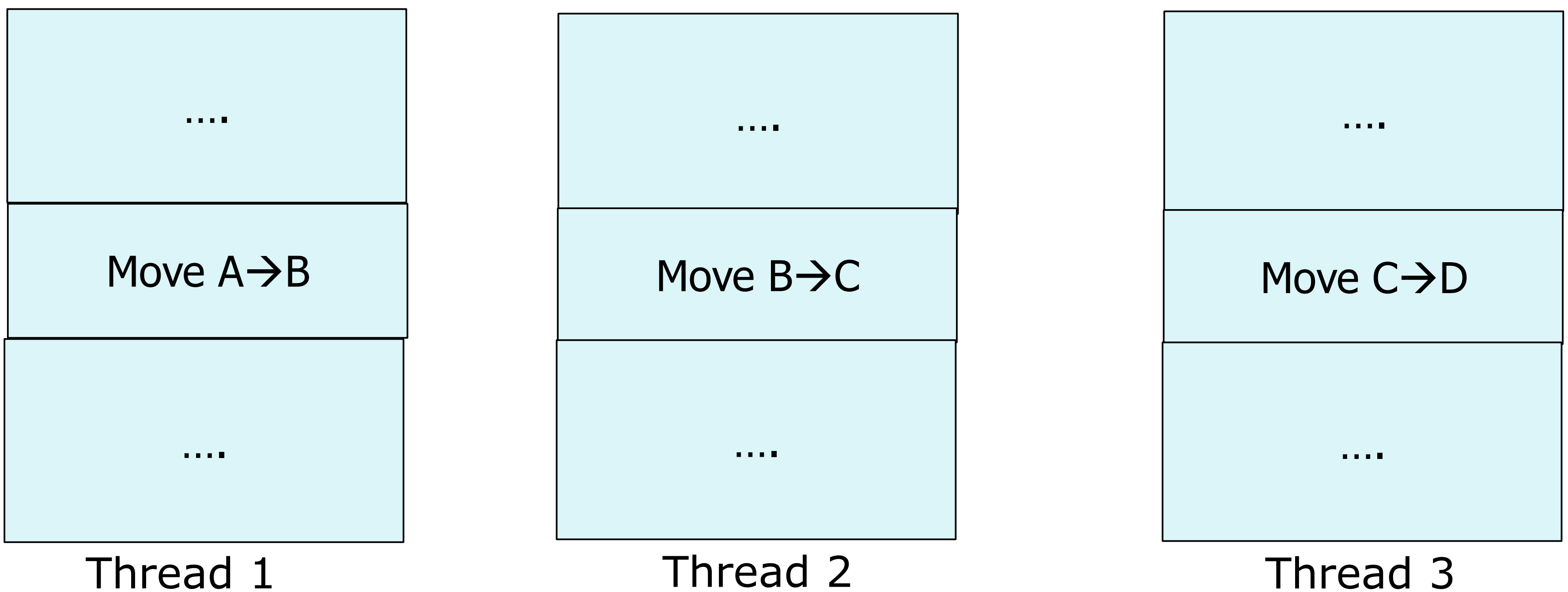
Thread 1 Thread 2

Semaphore **lock**, initialized to 1

Mutual exclusion, where the Move is the critical section

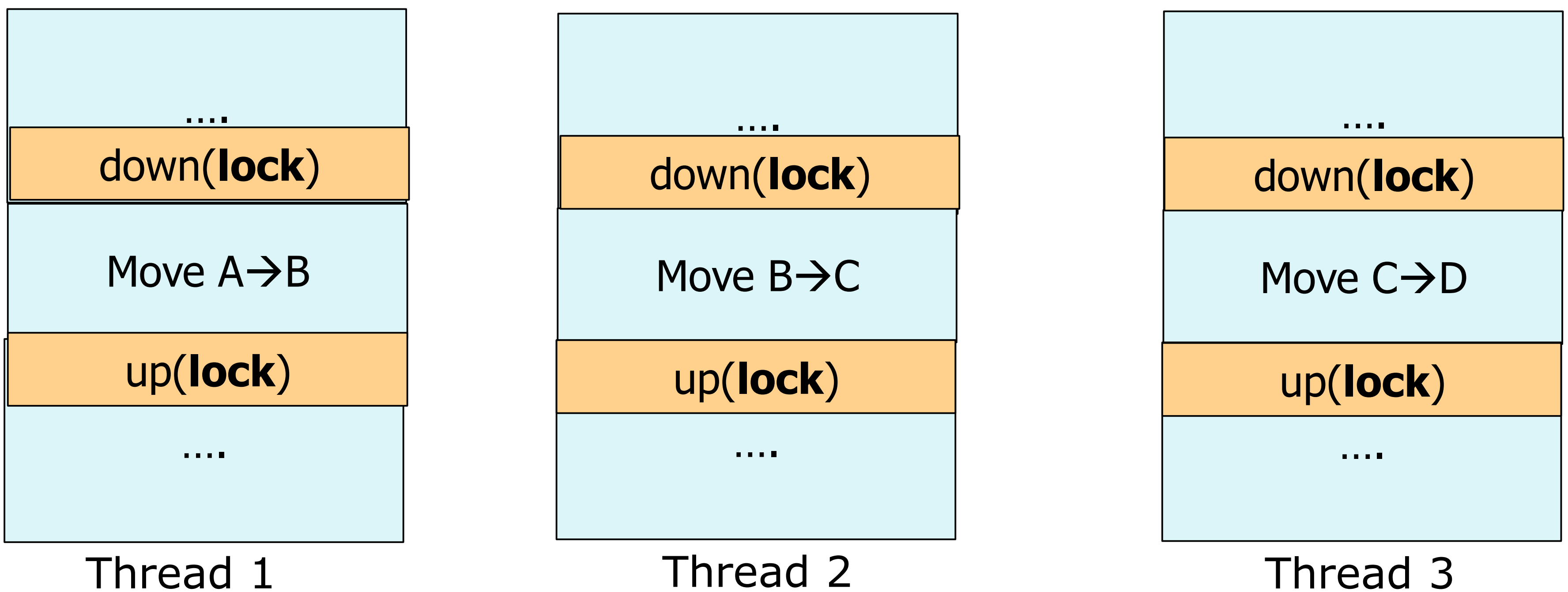
Another Problem: Moving Money Between Accounts

- Three Threads



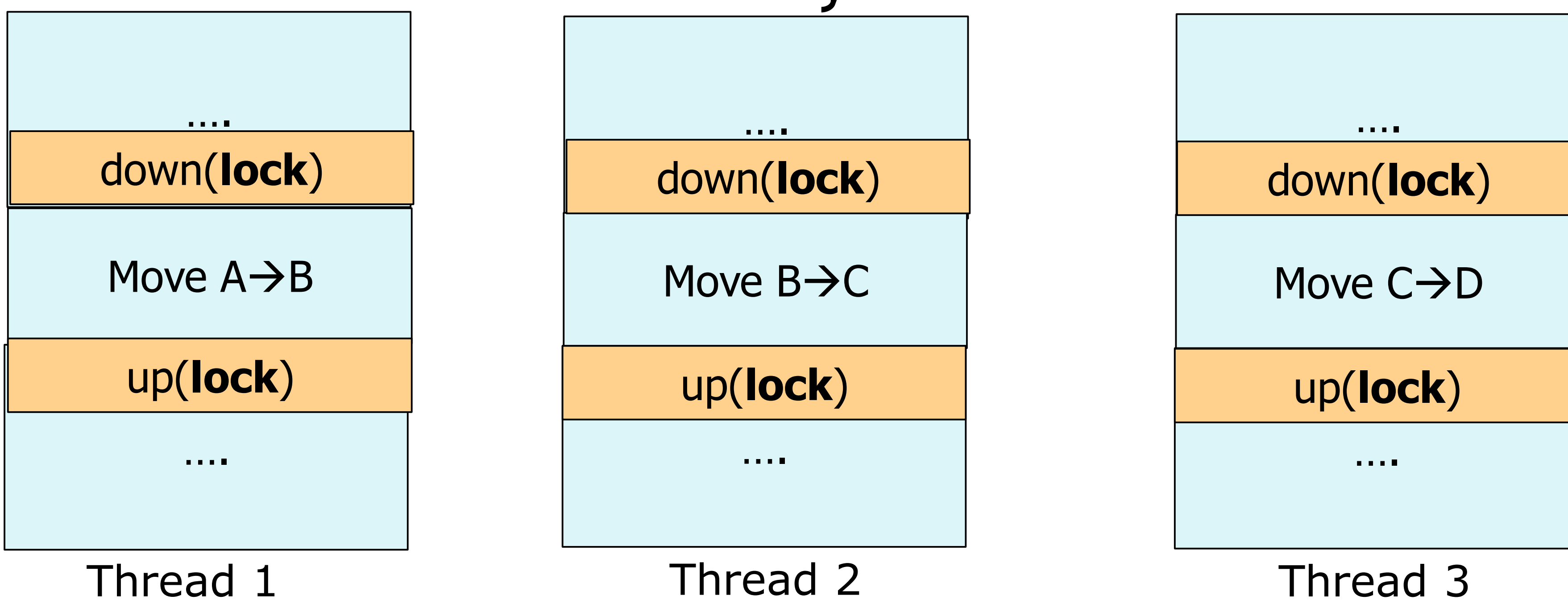
Another Problem: Moving Money Between Accounts

- Three Threads
- Solution 1: mutual exclusion



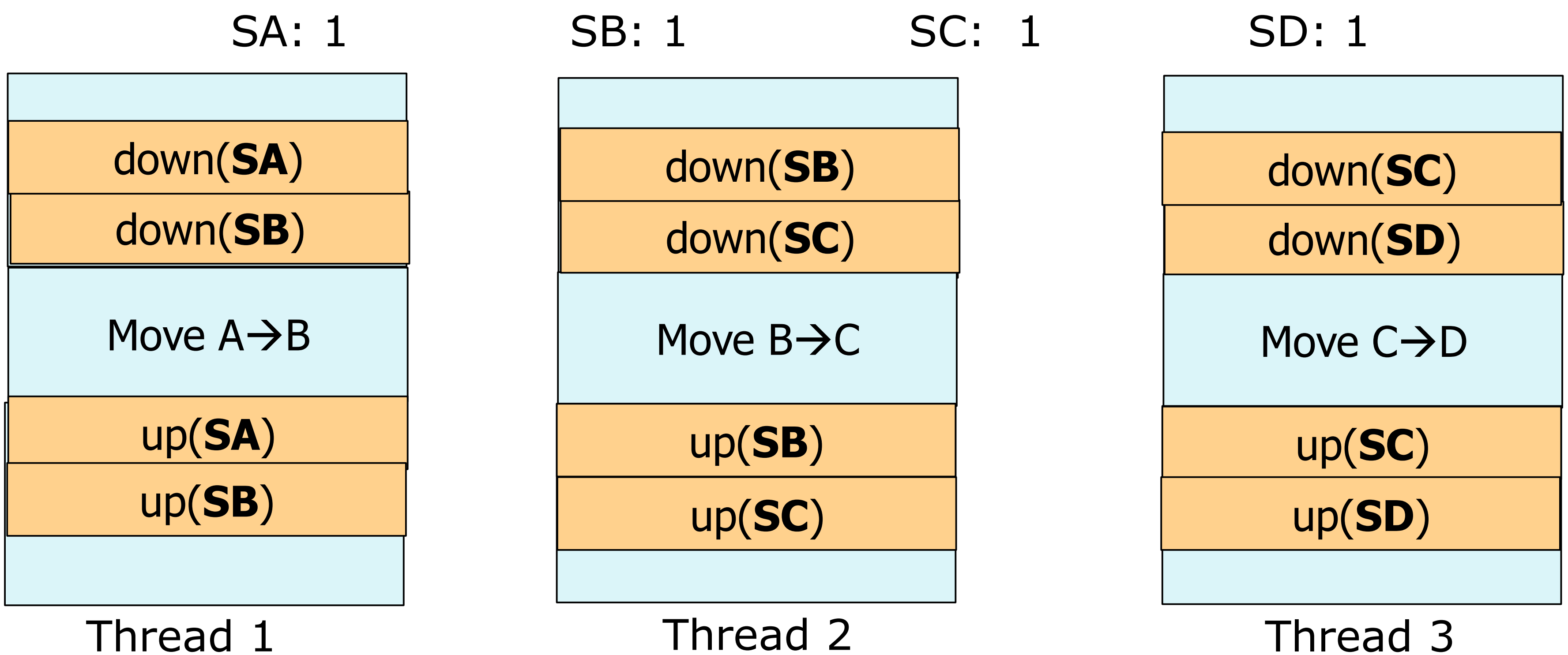
Another Problem: Moving Money Between Accounts

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



Another Problem: Moving Money Between Accounts

- Solution 2: Lock each account separately
  - Semaphore for each account: SA, SB, SC, SD. All initialized to 1.



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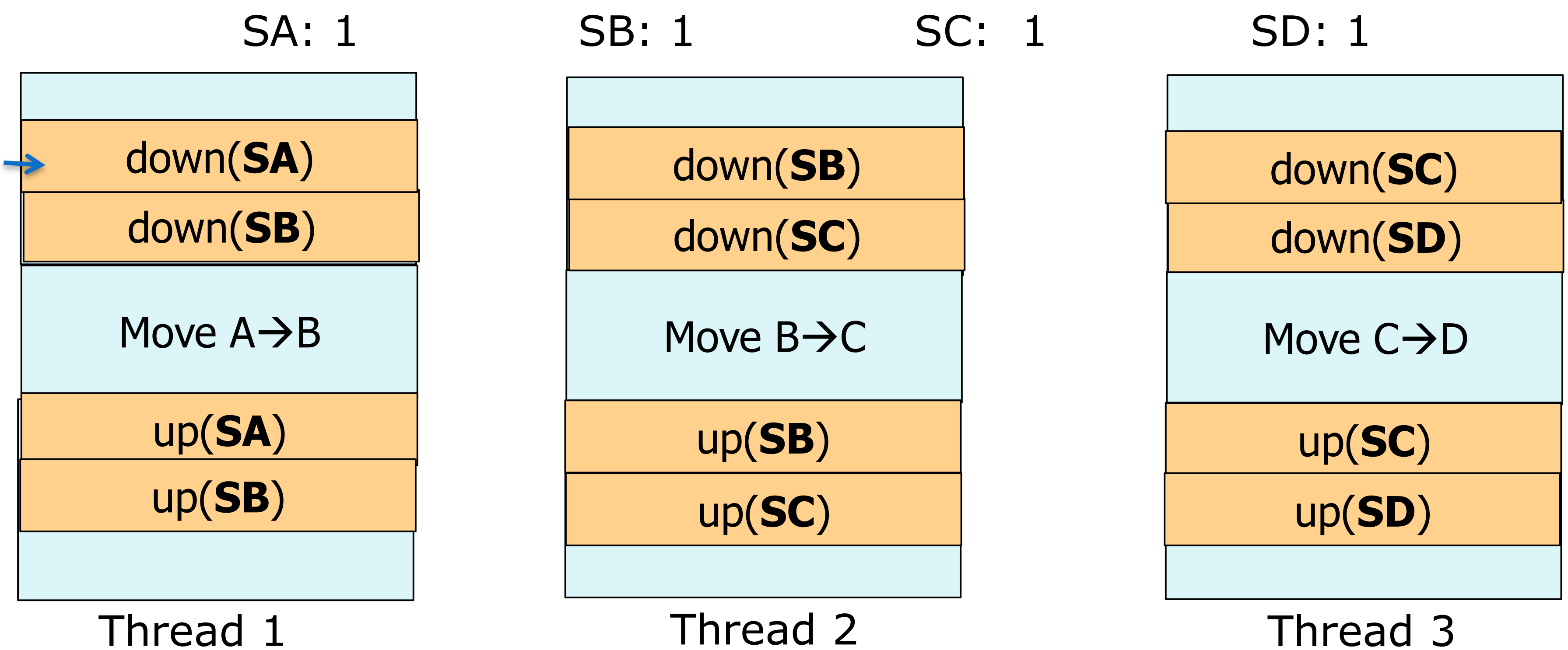

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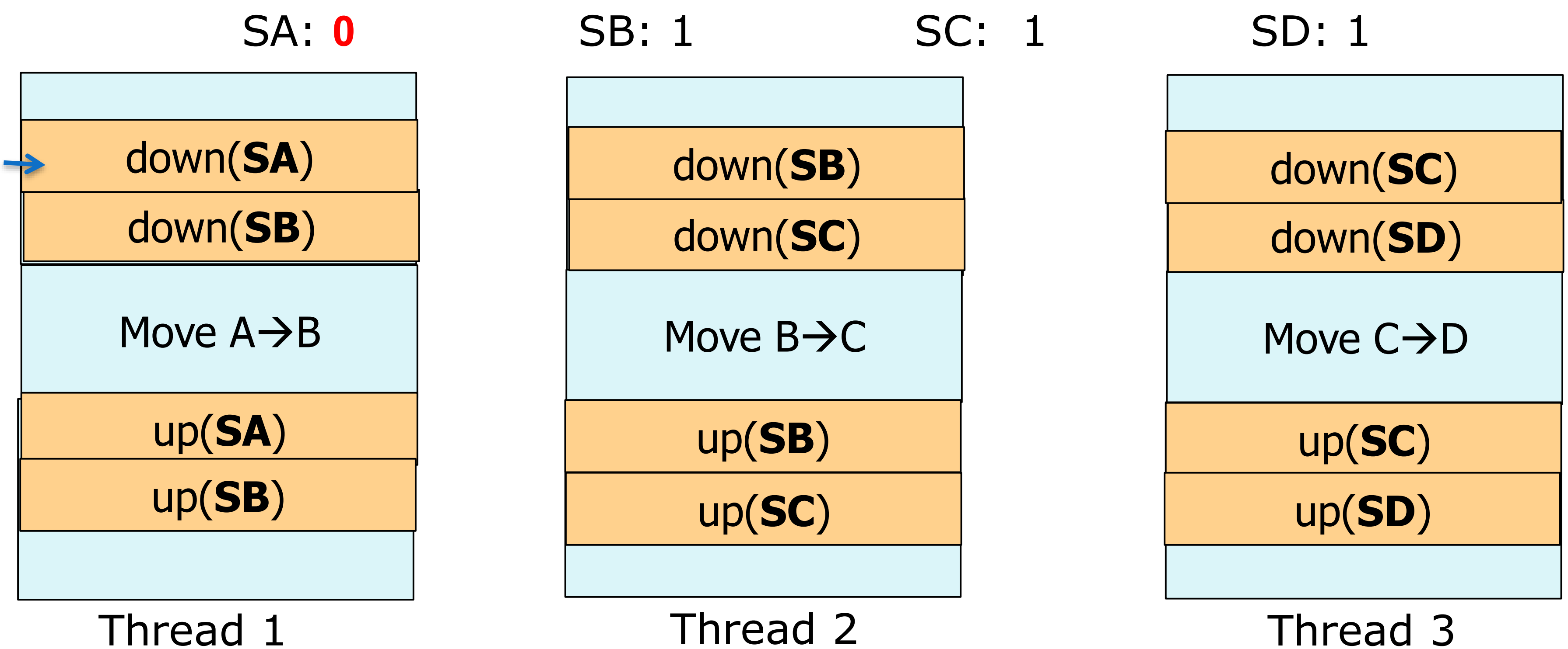

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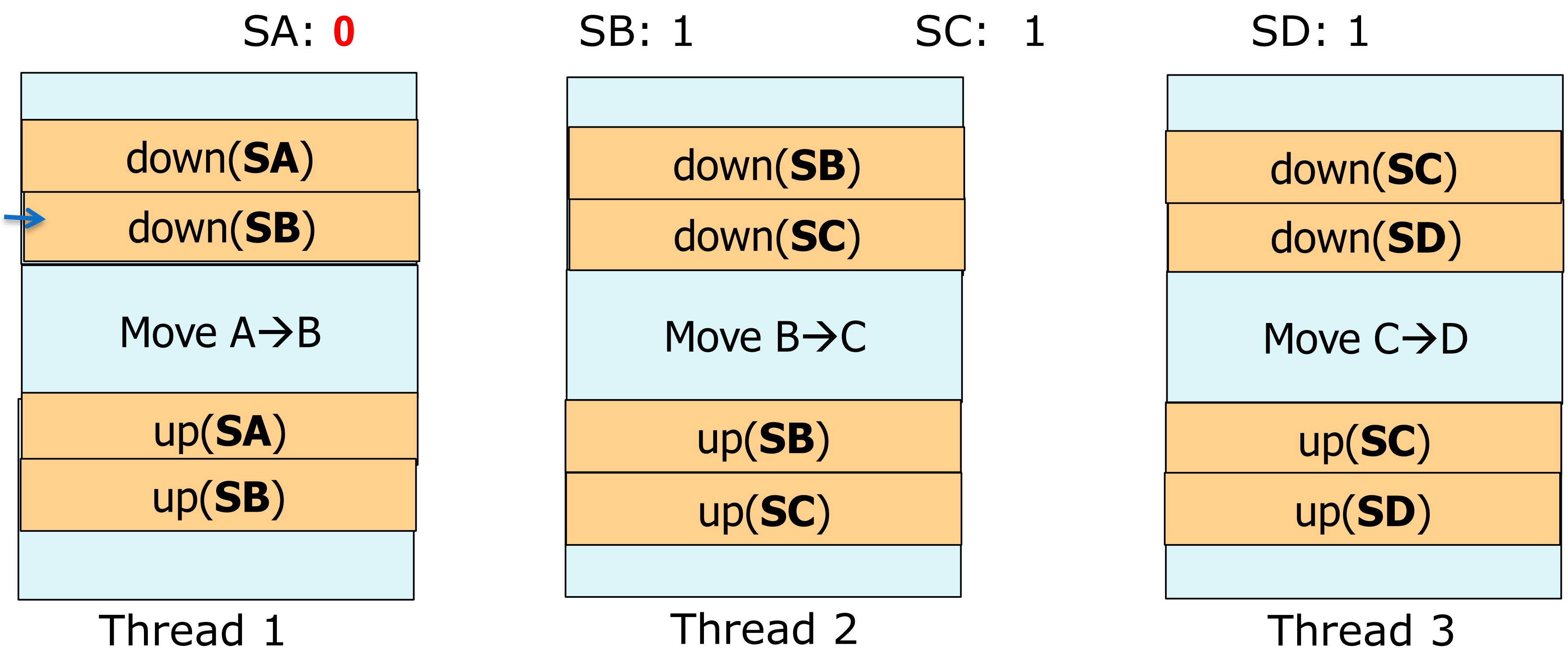

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SA: **0** SB: **0** SC: 1 SD: 1

Thread 1	Thread 2	Thread 3
down(**SA**)	down(**SB**)	down(**SC**)
down(**SB**)	down(**SC**)	down(**SD**)
Move A→B	Move B→C	Move C→D
up(**SA**)	up(**SB**)	up(**SC**)
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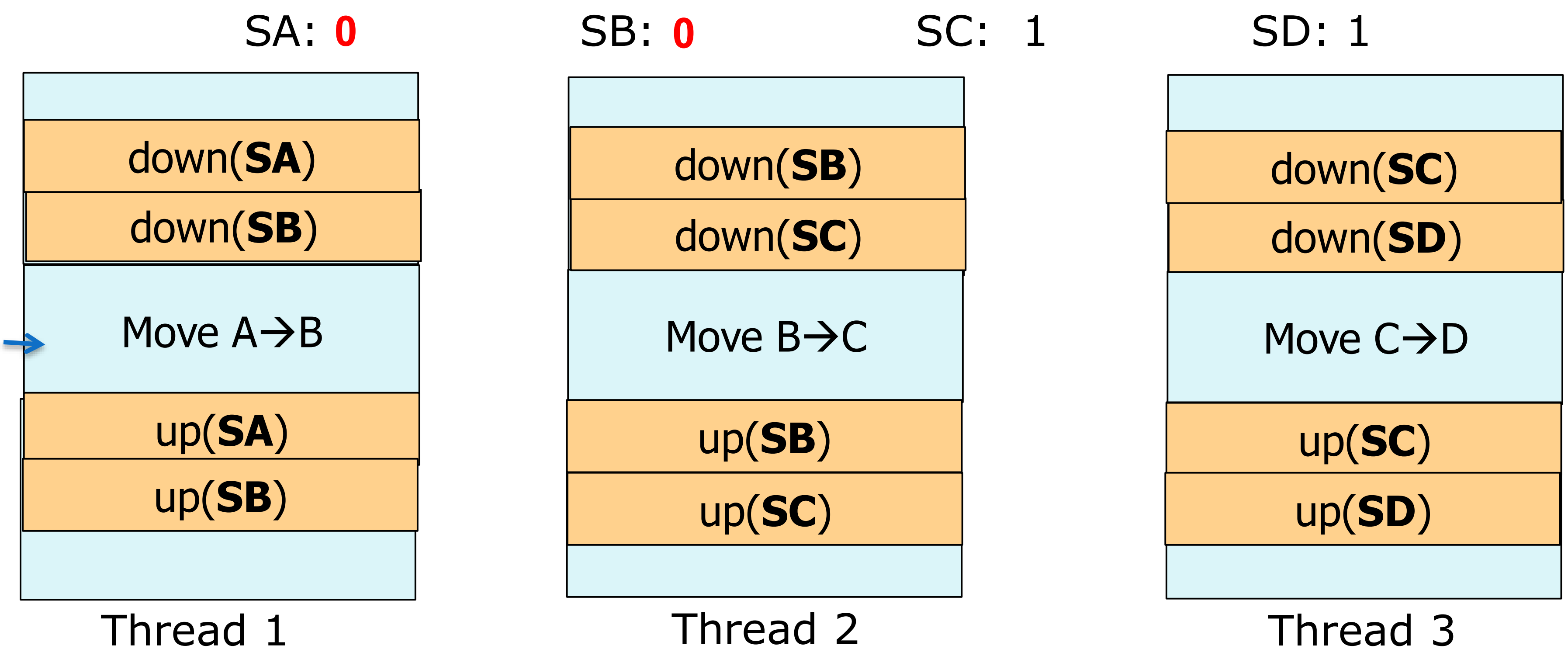

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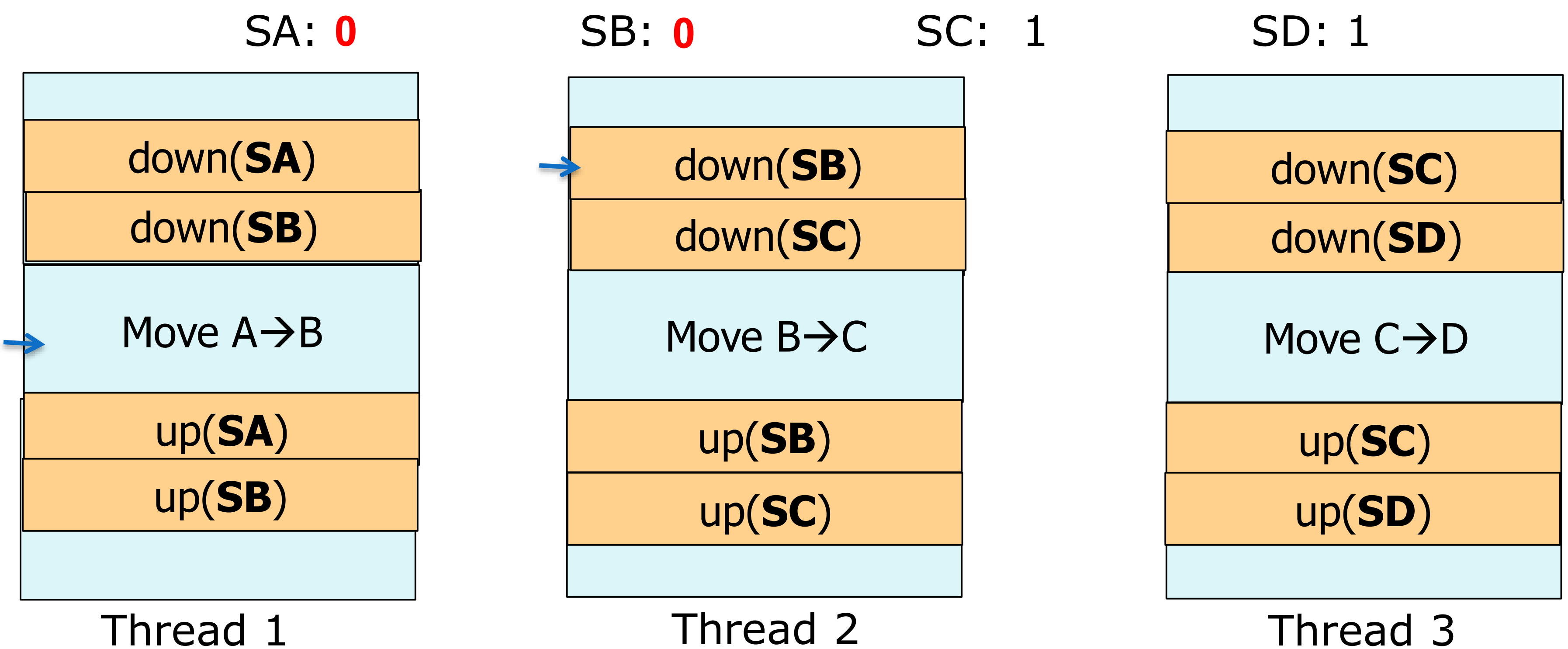

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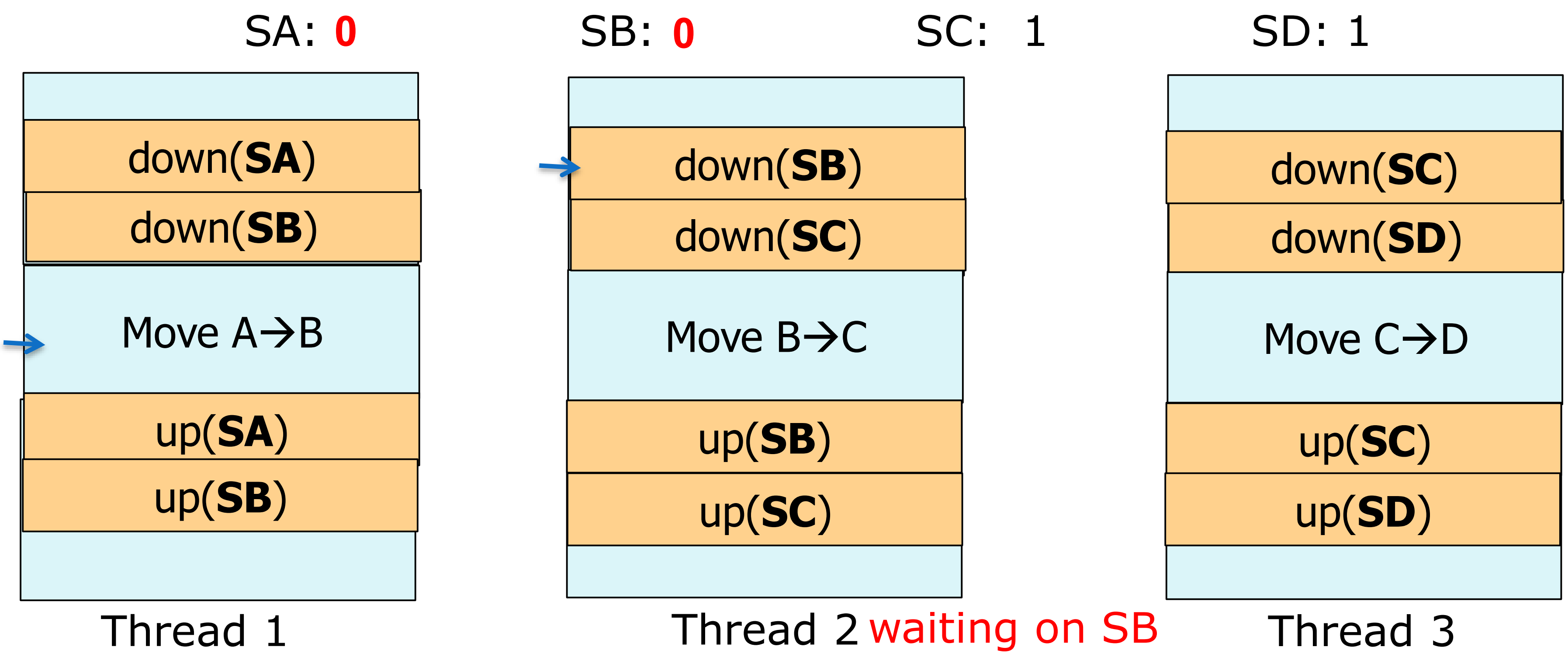

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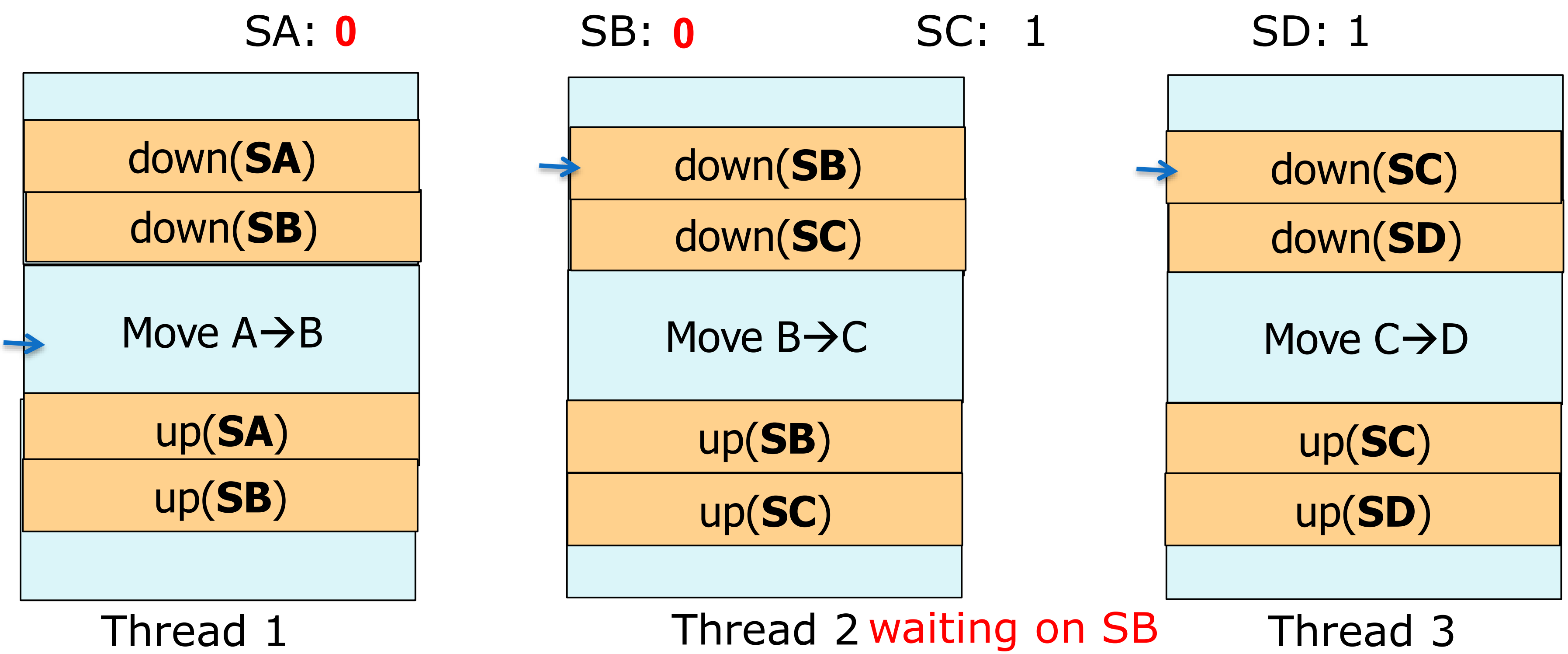

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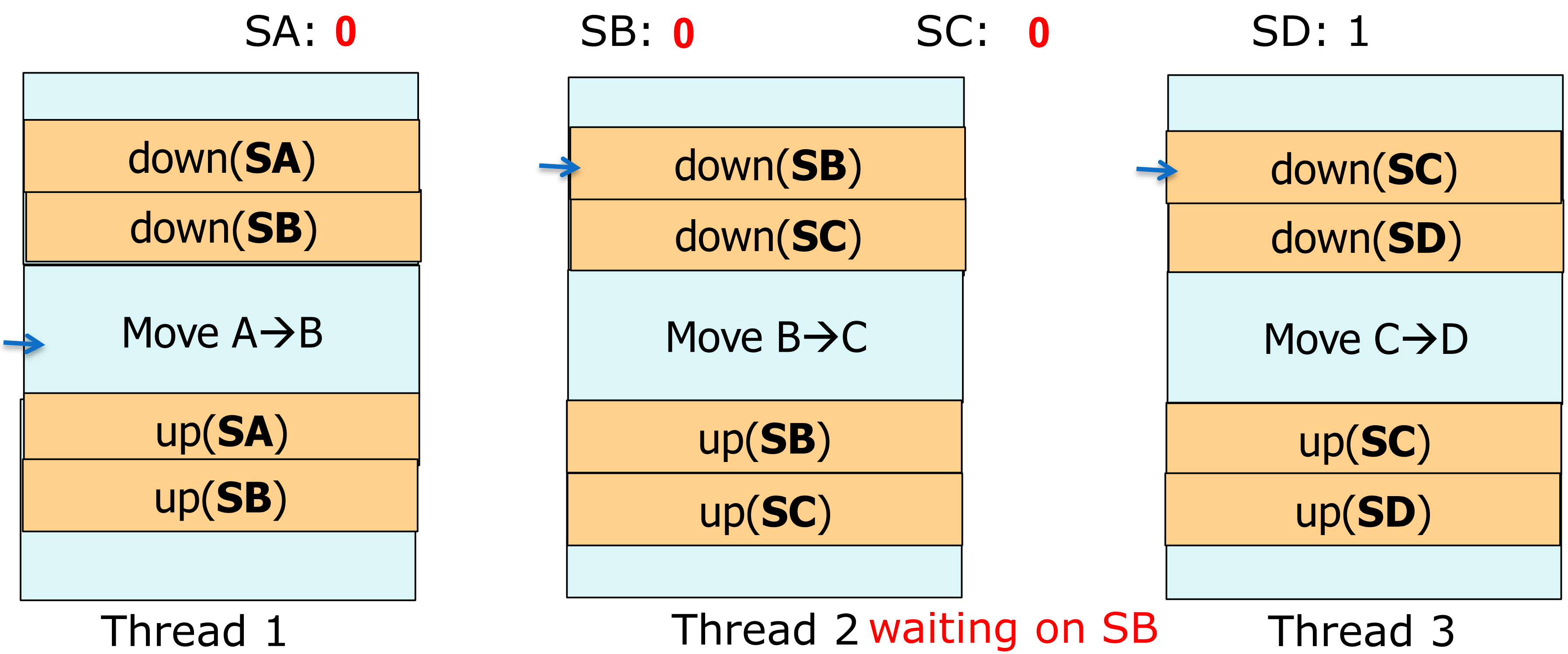

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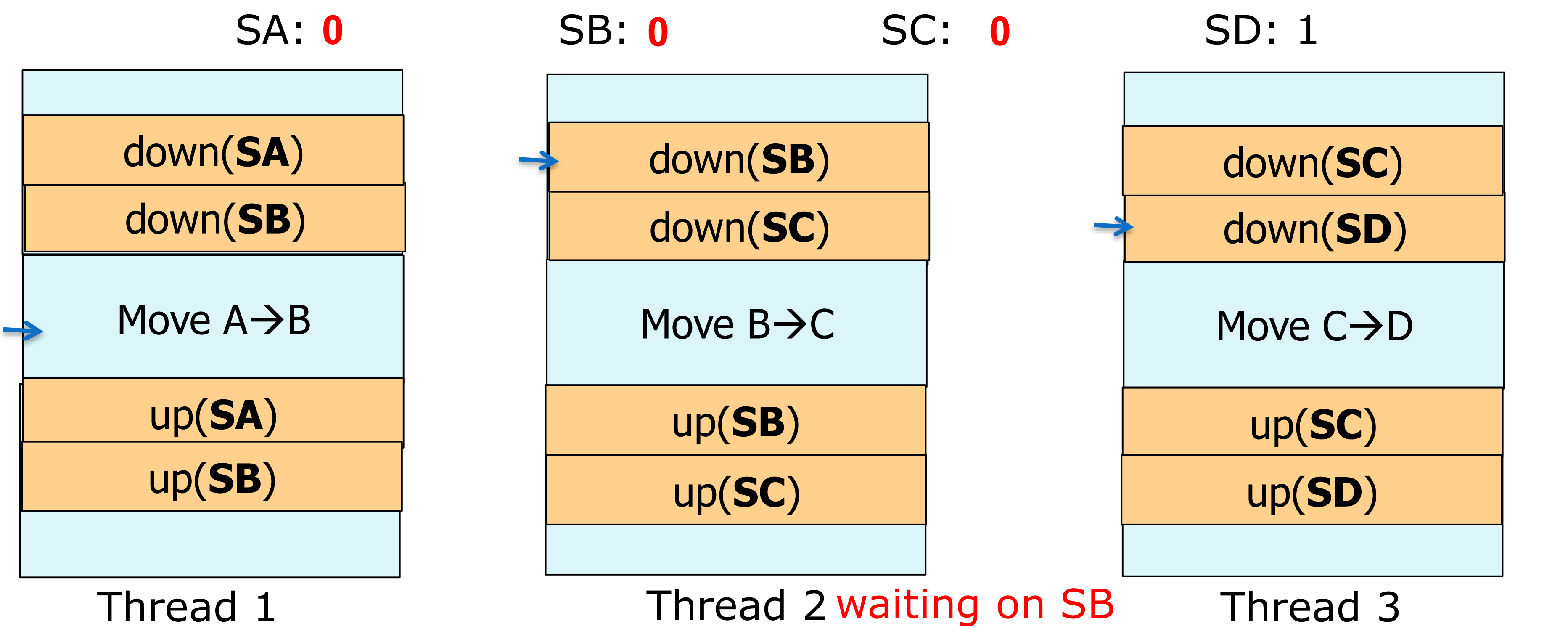

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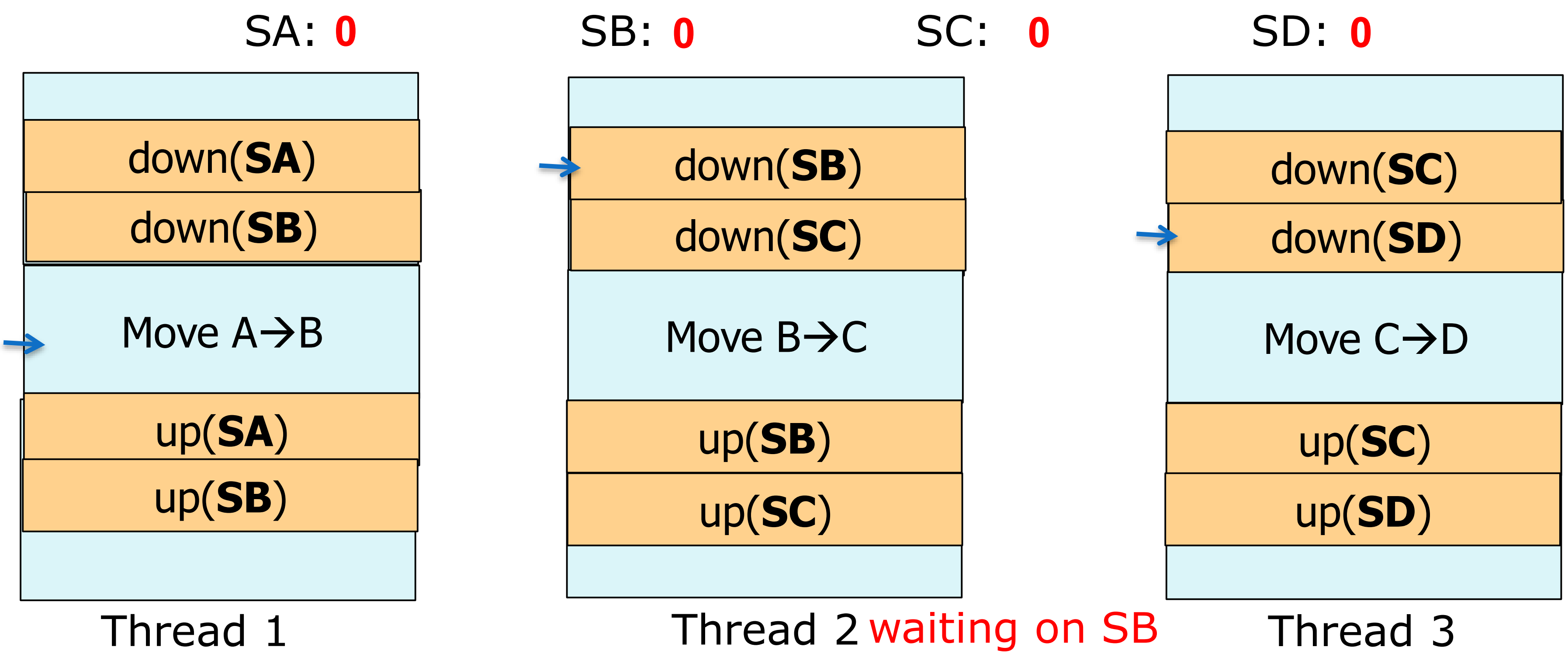

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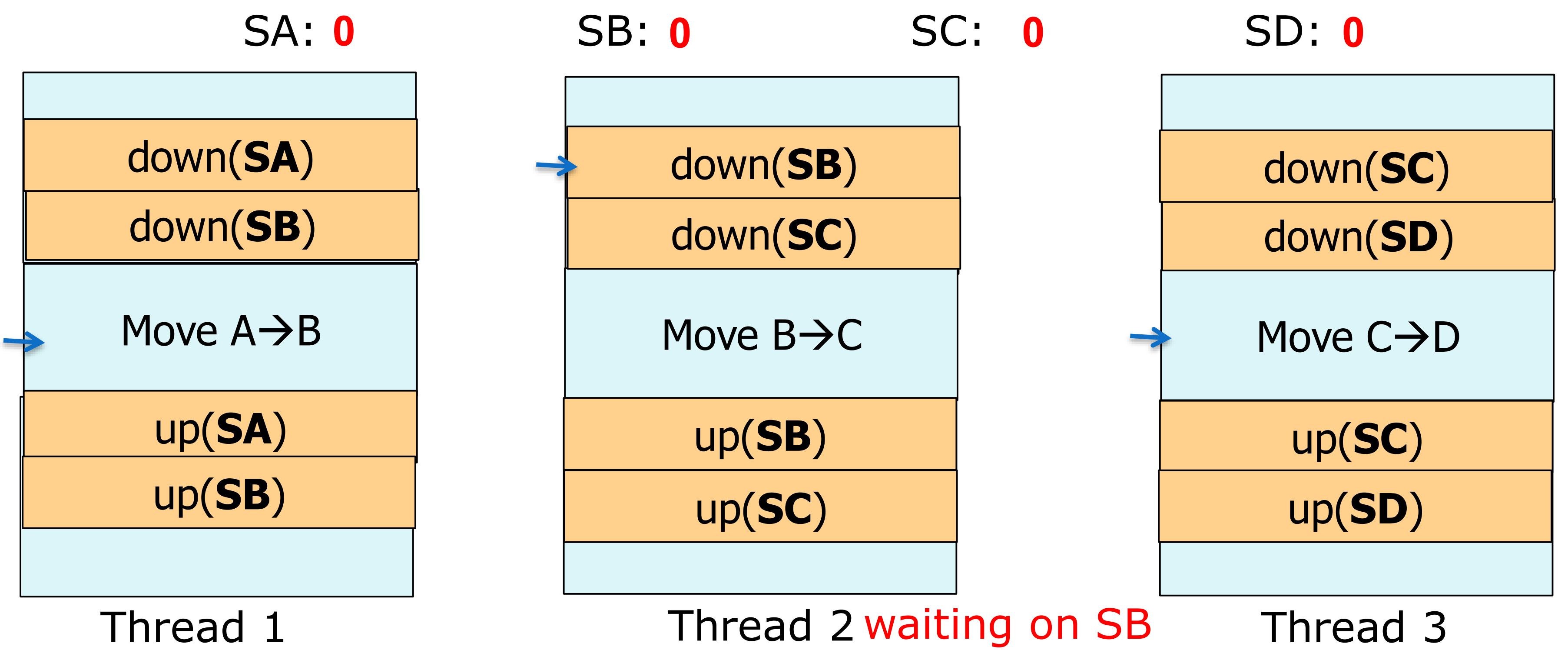
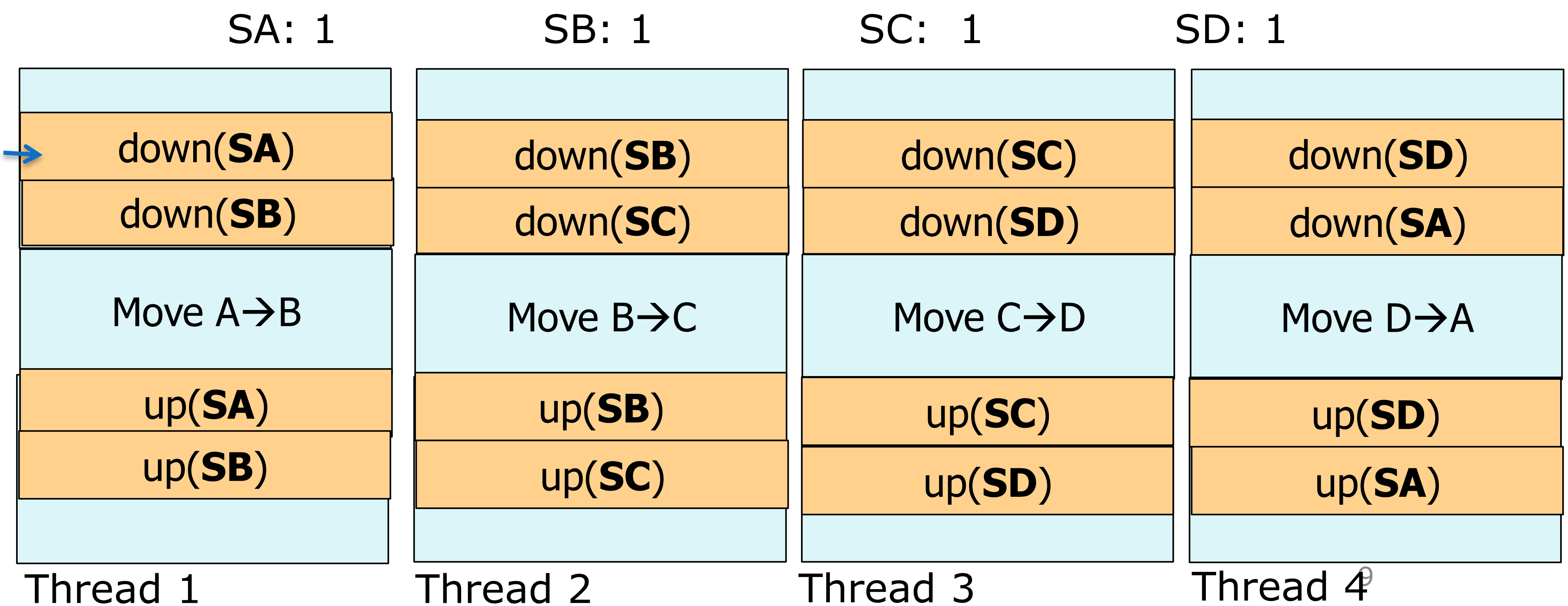


Semaphores are not Silver Bullets

SA: 1	SB: 1	SC: 1	SD: 1
down(**SA**)	down(**SB**)	down(**SC**)	down(**SD**)
down(**SB**)	down(**SC**)	down(**SD**)	down(**SA**)
Move A→B	Move B→C	Move C→D	Move D→A
up(**SA**)	up(**SB**)	up(**SC**)	up(**SD**)
up(**SB**)	up(**SC**)	up(**SD**)	up(**SA**)
Thread 1	Thread 2	Thread 3	Thread 4

Semaphores are not Silver Bullets



Semaphores are not Silver Bullets

SA: 0	SB: 1	SC: 1	SD: 1
down(**SA**)	down(**SB**)	down(**SC**)	down(**SD**)
down(**SB**)	down(**SC**)	down(**SD**)	down(**SA**)
Move A→B	Move B→C	Move C→D	Move D→A
up(**SA**)	up(**SB**)	up(**SC**)	up(**SD**)
up(**SB**)	up(**SC**)	up(**SD**)	up(**SA**)
Thread 1	Thread 2	Thread 3	Thread 4

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Thread 1	Thread 2	Thread 3	Thread 4

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Thread 1	Thread 2	Thread 3	Thread 4

Semaphores are not Silver Bullets

SA: 0	SB: 0	SC: 0	SD: 0
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Thread 1	Thread 2	Thread 3	Thread 4

Semaphores are not Silver Bullets

SA: **0**	SB: **0**	SC: **0**	SD: **0**
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Thread 1 waits SB	Thread 2 waits SC	Thread 3 waits SD	Thread 4 waits SA

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Thread 1 waits SB	Thread 2 waits SC	Thread 3 waits SD	Thread 4 waits SA

Semaphores are not Silver Bullets

SA: **0** SB: **0** SC: **0** SD: **0**

Deadlock!

Thread 1	Thread 2	Thread 3	Thread 4
down(**SA**)	down(**SB**)	down(**SC**)	down(**SD**)
→ down(**SB**)	→ down(**SC**)	→ down(**SD**)	→ down(**SA**)
Move A→B	Move B→C	Move C→D	Move D→A
up(**SA**)	up(**SB**)	up(**SC**)	up(**SD**)
up(**SB**)	up(**SC**)	up(**SD**)	up(**SA**)
Thread 1 waits SB	Thread 2 waits SC	Thread 3 waits SD	Thread 4 waits SA

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)

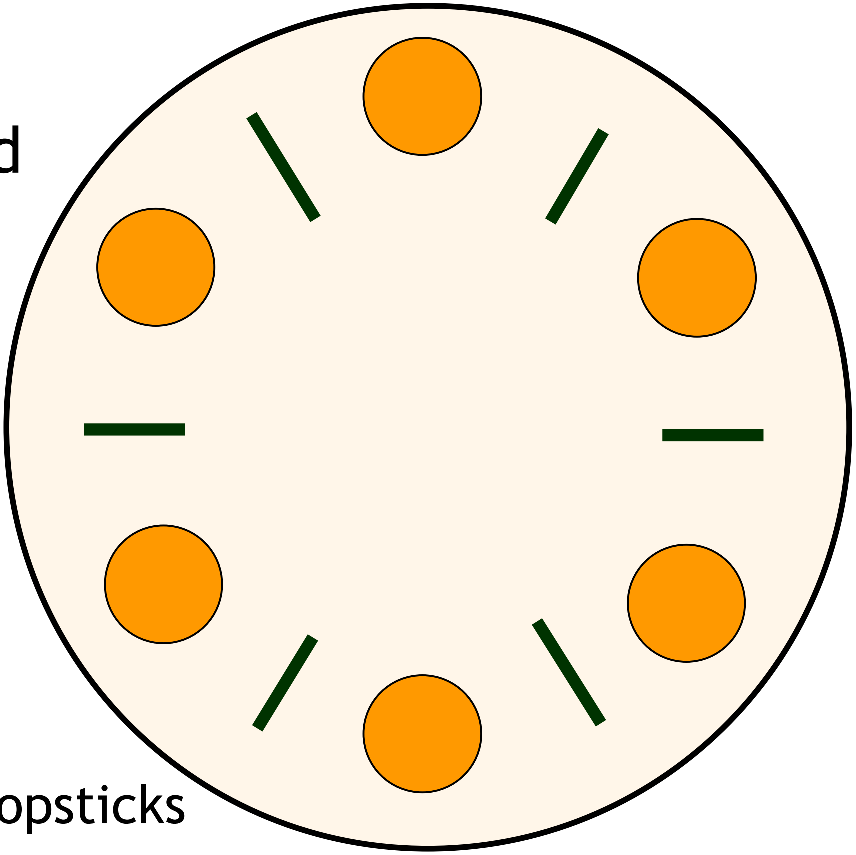
SA: **0**	SB: **0**	SC: **0**	SD: **0**
down(**SA**)	down(**SB**)	down(**SC**)	down(**SD**)
down(**SB**)	down(**SC**)	down(**SD**)	down(**SA**)
Move A→B	Move B→C	Move C→D	Move D→A
up(**SA**)	up(**SB**)	up(**SC**)	up(**SD**)
up(**SB**)	up(**SC**)	up(**SD**)	up(**SA**)
Thread 1 waits SB	Thread 2 waits SC	Thread 3 waits SD	Thread 4 waits SA

Dining Philosophers

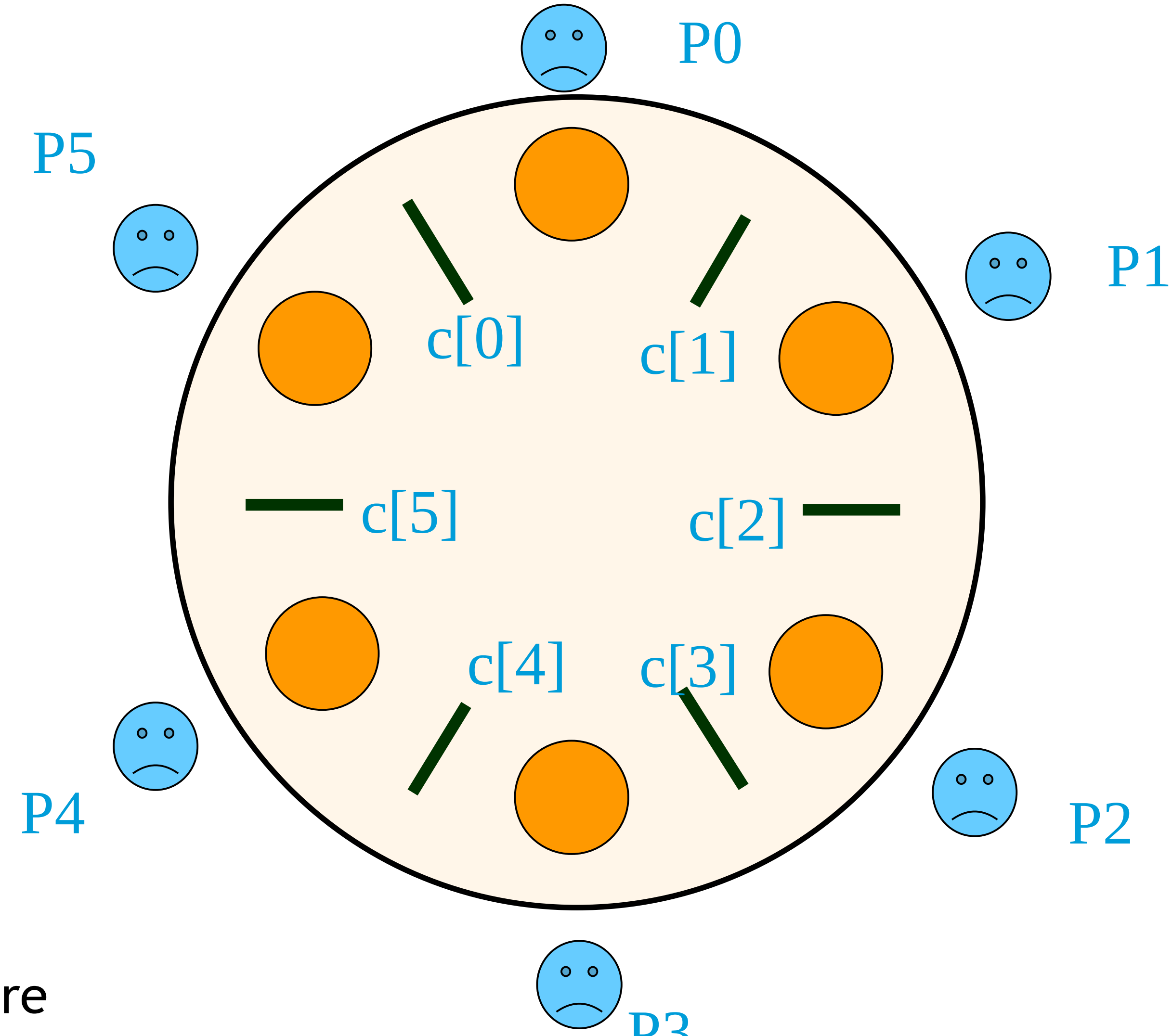
- Philosophers spend their life alternating between **eating** and **thinking**

- Eating requires 2 chopsticks:
  - take chopsticks
  - eat
  - put chopsticks
  - think

- Problem setting:
  1. Philosophers sit in the circle, chopsticks between them
  2. Pick one adjacent chopstick at a time
  3. Two philosophers cannot hold a chopstick together.



Code

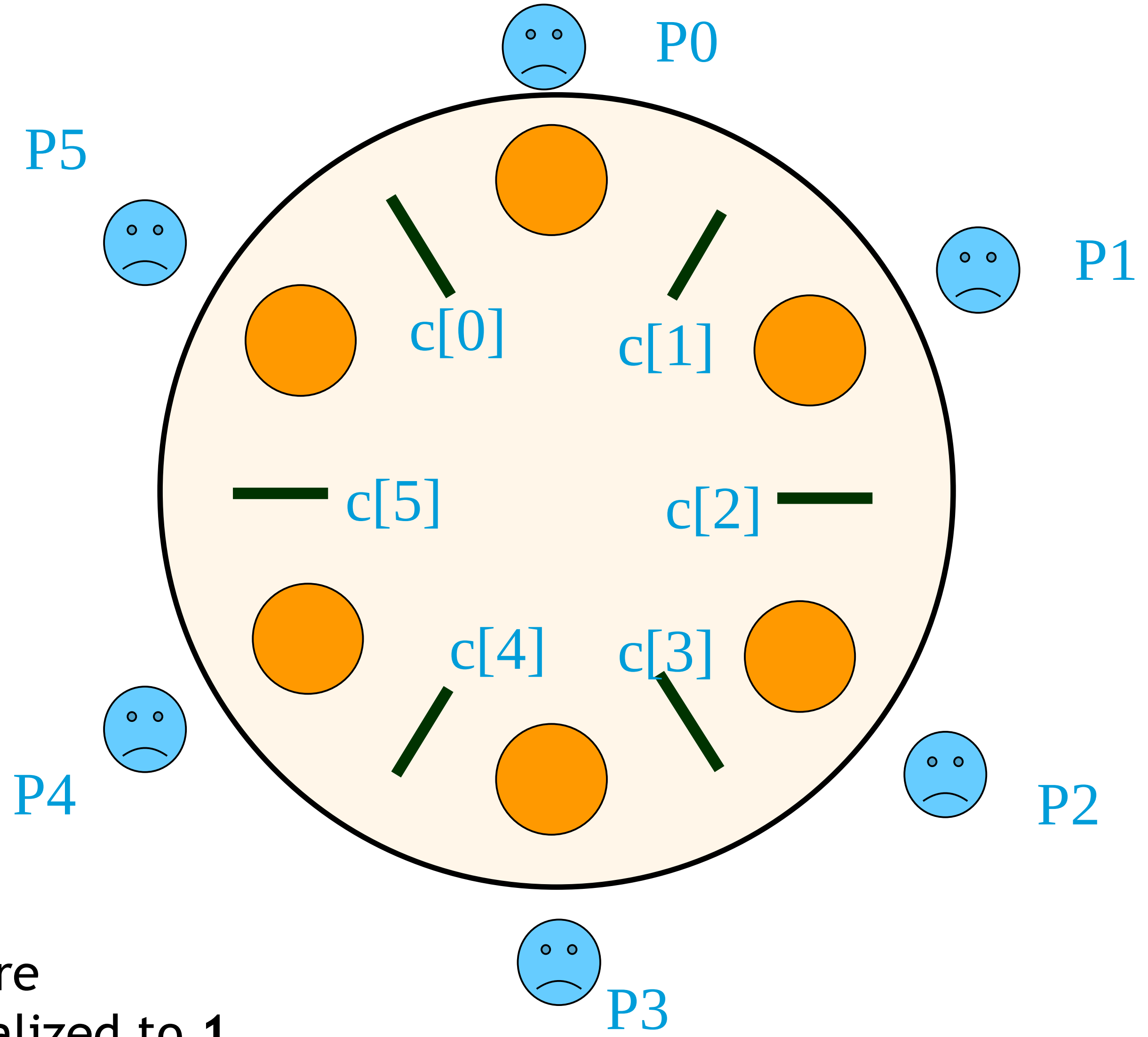


chopstick[0]…chopstick[5] are shared semaphores, all initialized to 1

Code that reaches a deadlock

down(**chopstick[(i+1)mode 6]**)
down(**chopstick[(i)]**)
Eat
up(**chopstick[(i+1)mode 6]**)
up(**chopstick[(i)]**)
Think

Code for philosopher i



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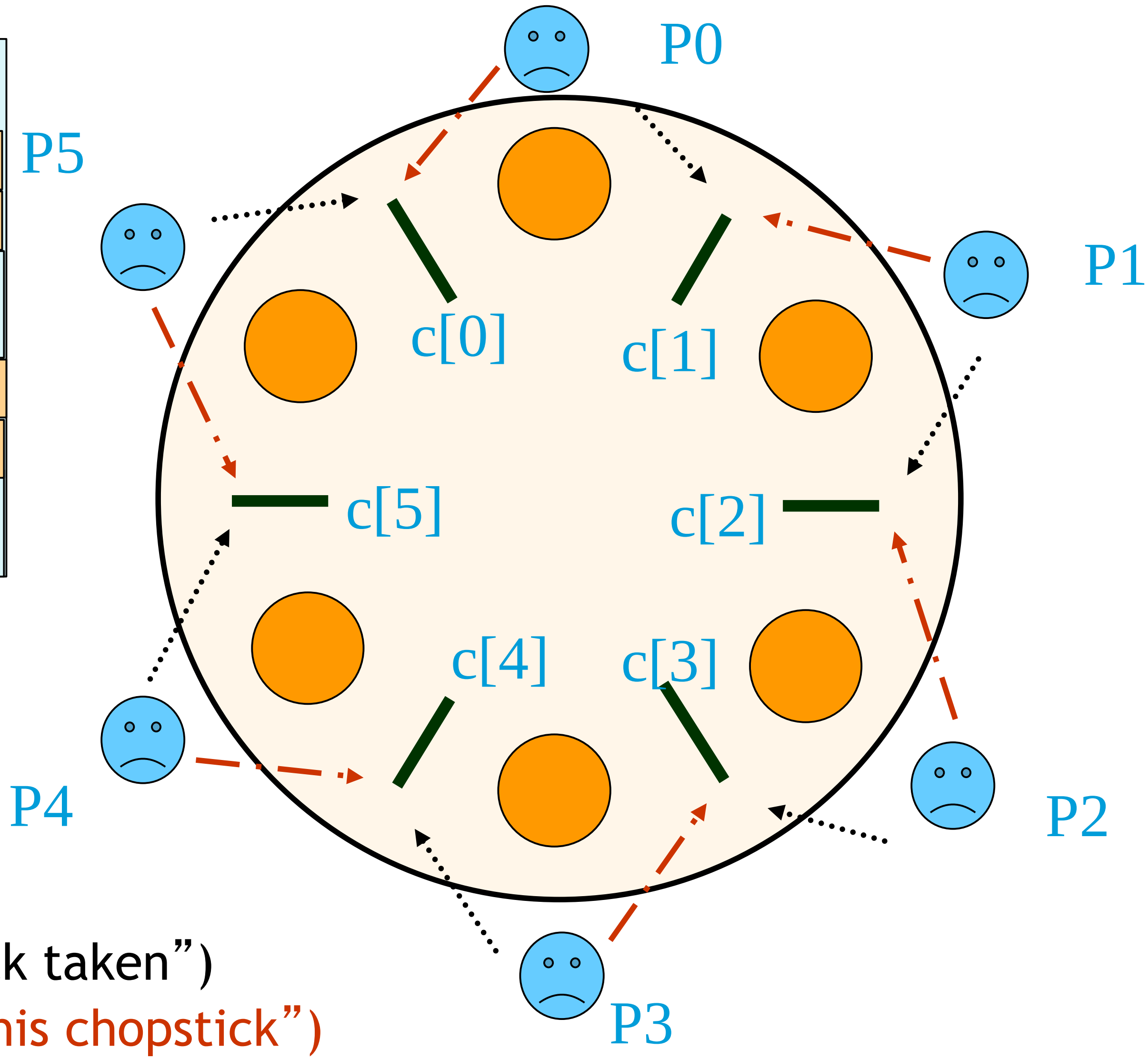
up(**chopstick[(i+1)mode 6]**)
up(**chopstick[(i])**)
Think

Code for philosopher i



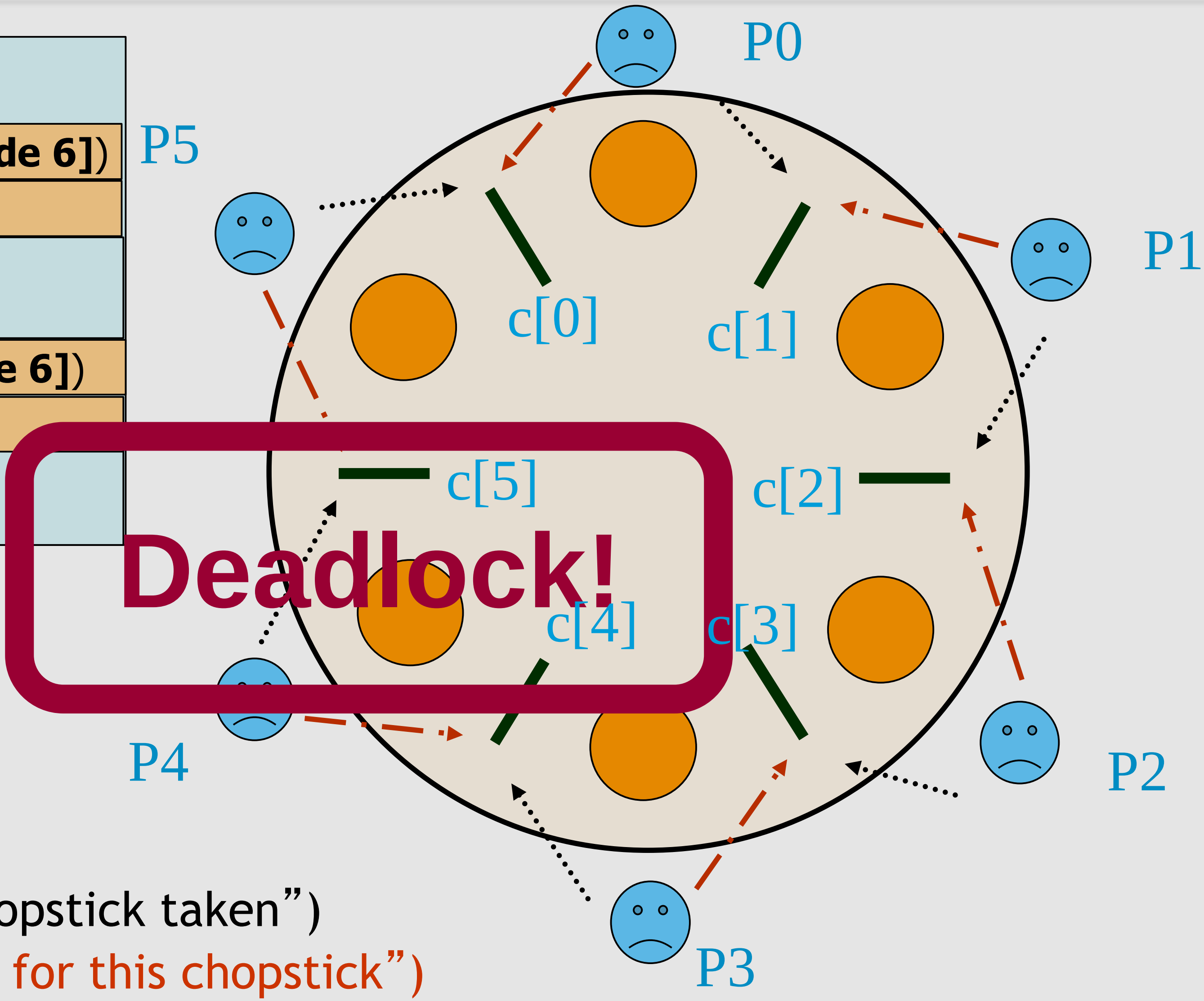
(means "first chopstick taken")

(means "waiting for this chopstick")

Code that reaches a deadlock

down(**chopstick[(i+1)mode 6]**)
down(**chopstick[(i]**)
Eat
up(**chopstick[(i+1)mode 6]**)
up(**chopstick[(i]**)
Think

Code for philosopher i



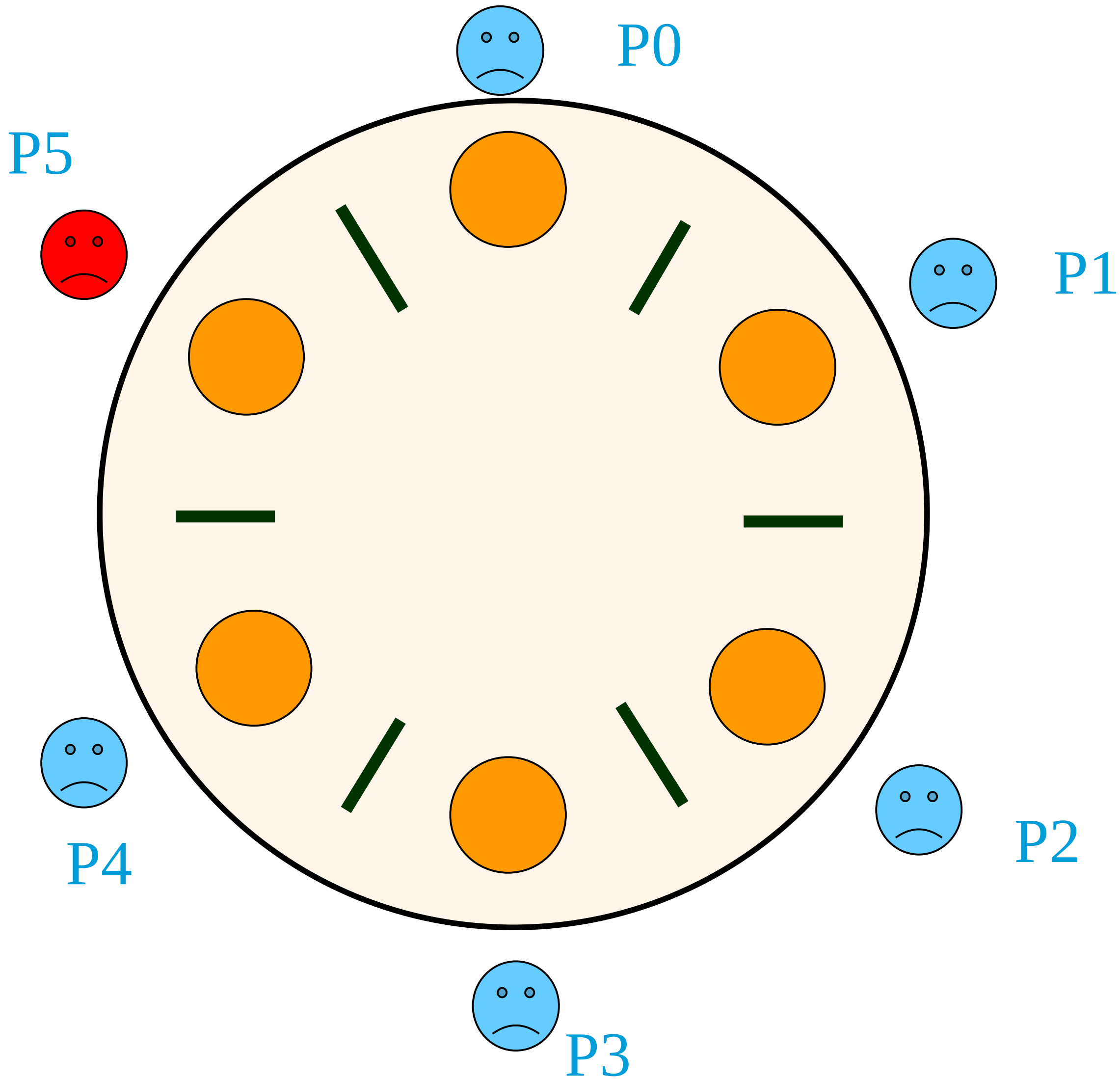
(⋯⋯→ means "first chopstick taken")

(— ·→ means "waiting for this chopstick")

Different code for philosopher 5

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i]**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

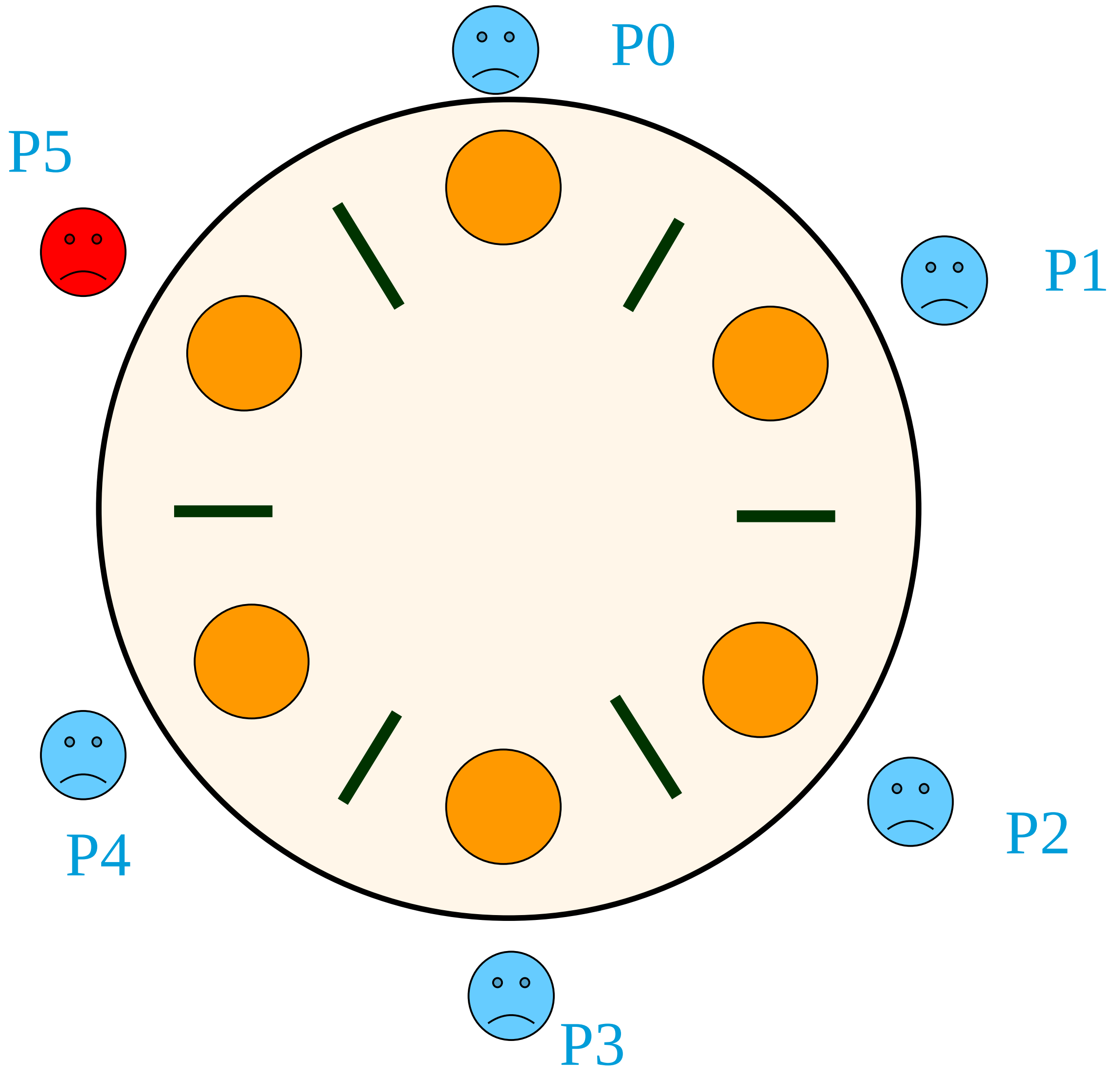
down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chopstick[0]**)
up(**chopstick[5]**)
Think



Different code for philosopher 5

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i]**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chopstick[0]**)
up(**chopstick[5]**)
Think

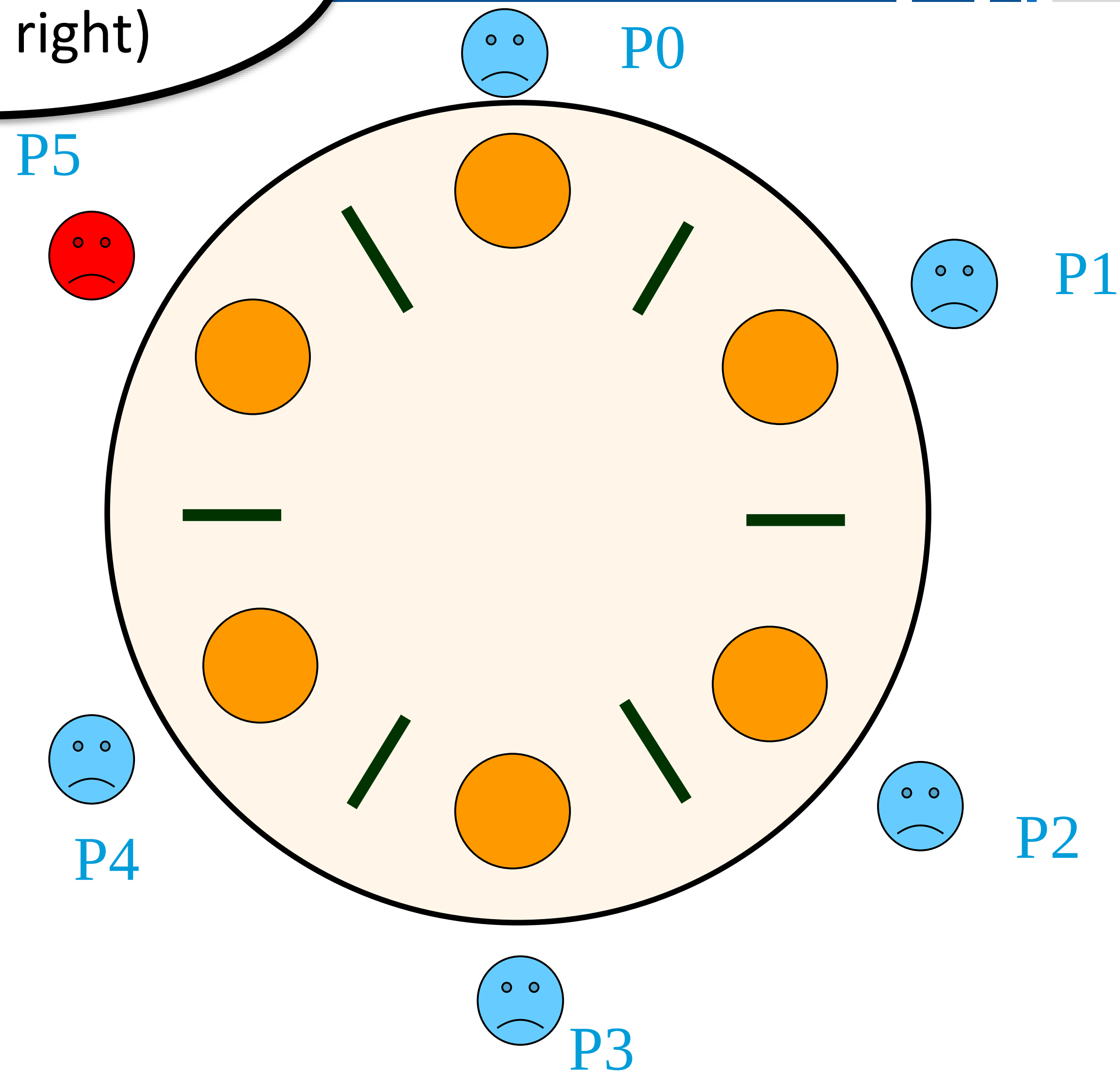


Differen ilosopher 5

Same code for philosophers 0,…,4 (left before right)

```
down(chopstick[(i+1)mod 6])
down(chopstick[(i)])
Eat
up(chopstick[(i+1)mod 6])
up(chopstick[i])
Think
```

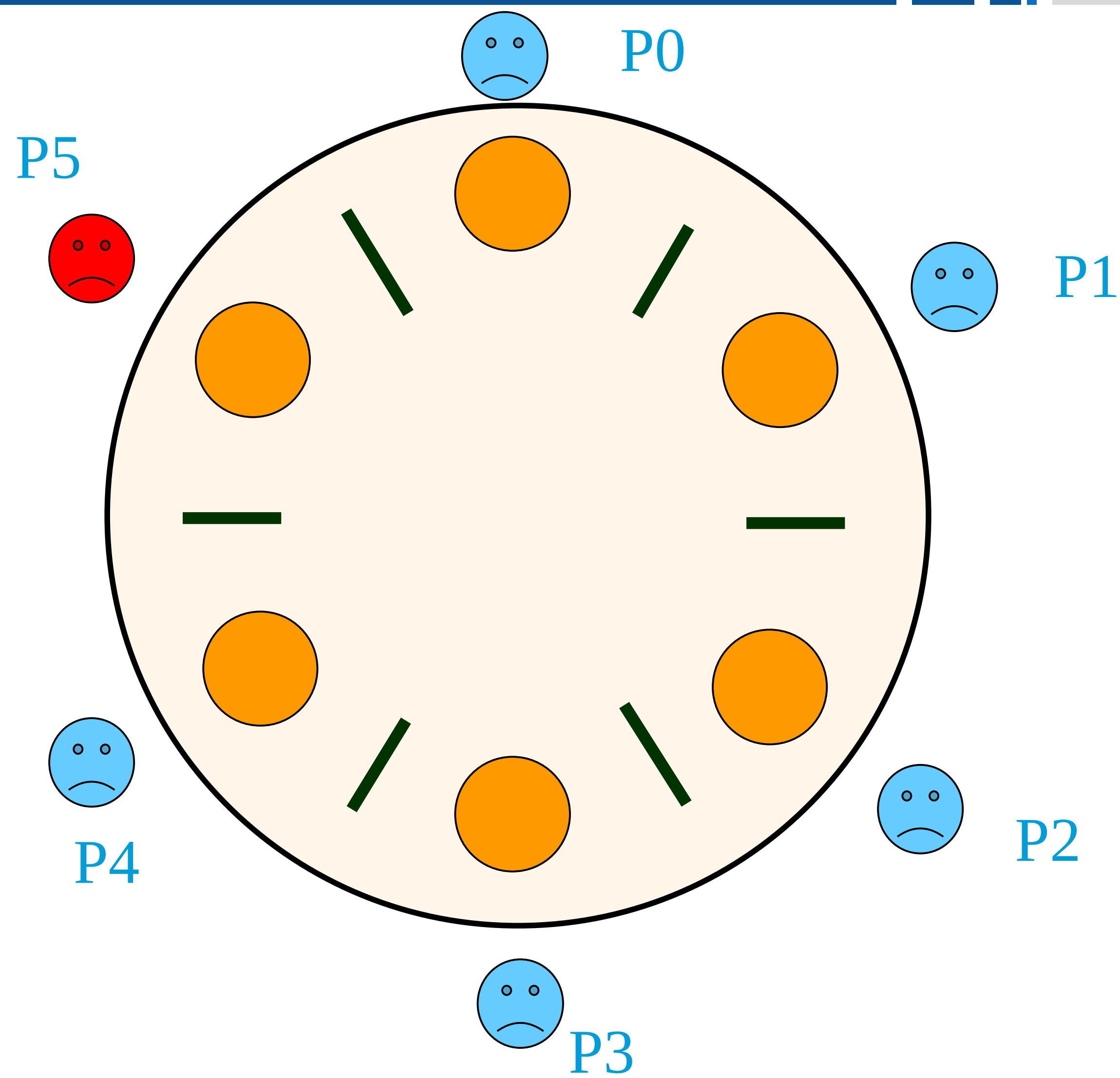
```
down(chopstick[5])
down(chopstick[0])
Eat
up(chopstick[0])
up(chopstick[5])
Think
```



Different code for philosopher 5

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i]**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

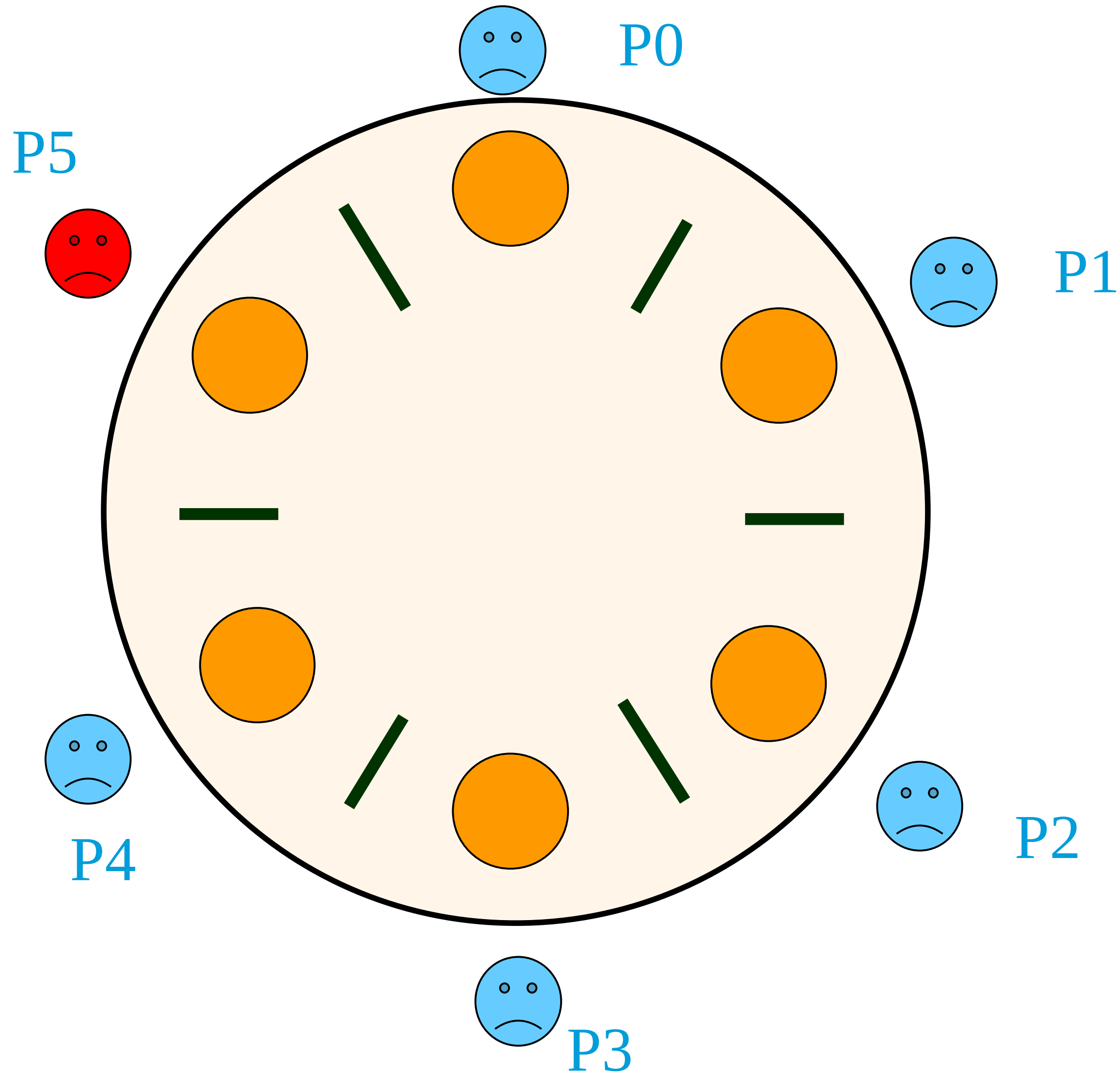
down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chopstick[0]**)
up(**chopstick[5]**)
Think



Different code for philosopher 5

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i]**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

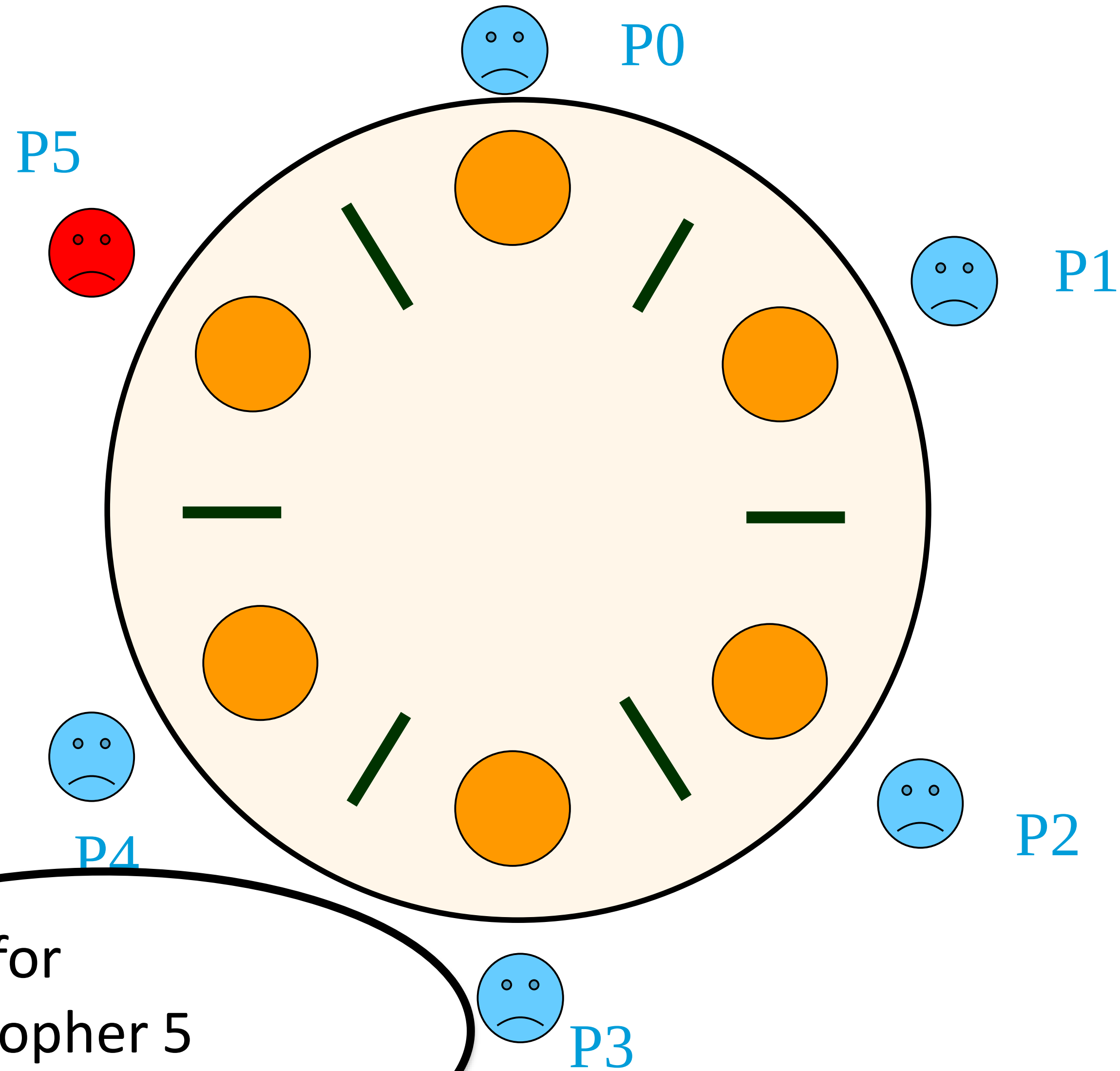
down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chopstick[0]**)
up(**chopstick[5]**)
Think



Different code for philosopher 5

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i]**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chops**
up(**chopstick[5**
Think

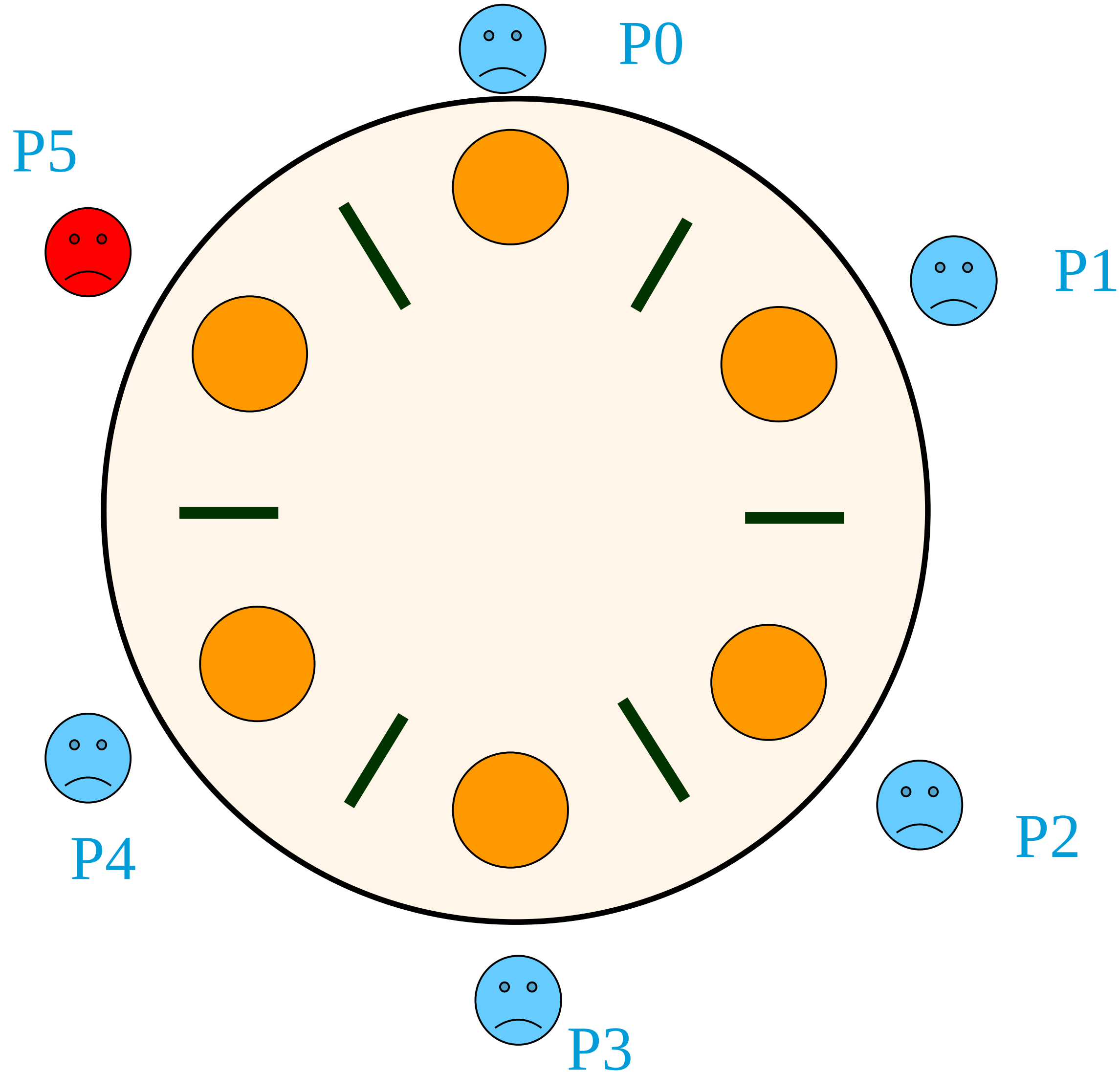


Code for philosopher 5 (right before left)

Different code for philosopher 5

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i]**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chopstick[0]**)
up(**chopstick[5]**)
Think



Progress

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i]**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chopstick[0]**)
up(**chopstick[5]**)
Think

If a philosopher tries to take a chopstick, then eventually some philosopher will eat.

Assume philosopher i tries to take a chopstick but no philosopher will be eating → no philosopher was able to grab the second chopstick.

Progress

down(**chopstick[(i+1)mod 6]**)

down(**chopstick[(i]**)

Eat

up(**chopstick[(i+1)mod 6]**)

up(**chopstick[i]**)

Think

down(**chopstick[5]**)

down(**chopstick[0]**)

Eat

up(**chopstick[0]**)

up(**chopstick[5]**)

Think

i is either 0,1,2, or 3

- i tries to takes the chopstick i+1, but does not succeed → philosopher i+1 took chopstick i+1(its second one) → Contradiction.
- i took chopstick i+1 and wait for chopstick i → philosopher i-1 took chopstick i and wait for i-1 → … → philosopher 0 took 1 and wait for 0 → philosopher 5 took 0 → philosopher 5 will eat

Progress

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i])**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chopstick[0]**)
up(**chopstick[5]**)
Think

i = 4

- Philosopher 4 tries to takes the chopstick 5, but does not succeed → philosopher 5 took chopstick 5 and wait for 0 → philosopher 0 took chopstick 0 (his second one). Contradiction.
- i took chopstick i+1 and wait for chopstick i → philosopher i-1 took chopstick i and wait for i-1 → … → philosopher 0 took 1 and wait for 0 → philosopher 5 took 0 → philosopher 5 will eat

Progress

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i])**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chopstick[0]**)
up(**chopstick[5]**)
Think

i = 4

- Philosopher 4 tries to takes the chopstick 5, but does not succeed → philosopher 5 took chopstick 5 and wait for 0 → philosopher 0 took chopstick 0 (his second one). Contradiction.
- i took chopstick i+1 and wait for chopstick i → philosopher i-1 took chopstick i and wait for i-1 → … → philosopher 0 took 1 and wait for 0 → philosopher 5 took 0 → philosopher 5 will eat

Progress

down(**chopstick[(i+1)mod 6]**)
down(**chopstick[(i])**)
Eat
up(**chopstick[(i+1)mod 6]**)
up(**chopstick[i]**)
Think

down(**chopstick[5]**)
down(**chopstick[0]**)
Eat
up(**chopstick[0]**)
up(**chopstick[5]**)
Think

i = 5

- Philosopher 5 tries to takes the chopstick 0, but does not succeed → philosopher 0 took chopstick 0 (his second one). Contradiction.
- Philosopher 5 tries to takes the chopstick 5, but does not succeed → philosopher 4 took chopstick 5 and wait for 4 → … → philosopher 0 took chopstick 1 and waits for 0, but 0 cannot be taken as philosopher 5 still waits on chopstick 5 → philosopher 0 will grab chopstick 0. Contradiction.

(Necessary) Conditions for Deadlock (Coffman Conditions)

1. Mutual Exclusion

   At least one resource must be held in a non-shareable mode

2. Hold and Wait

   A thread is holding one resource and is requesting a resource that is held by another thread

3. Non-Preemptive Allocation

   A resource can be released only voluntarily by the process holding it

4. Circular Wait

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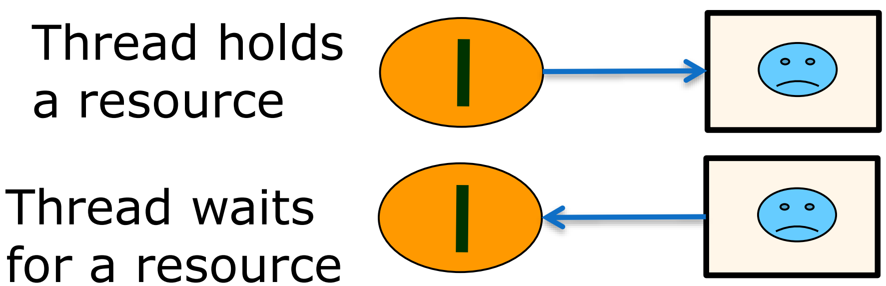
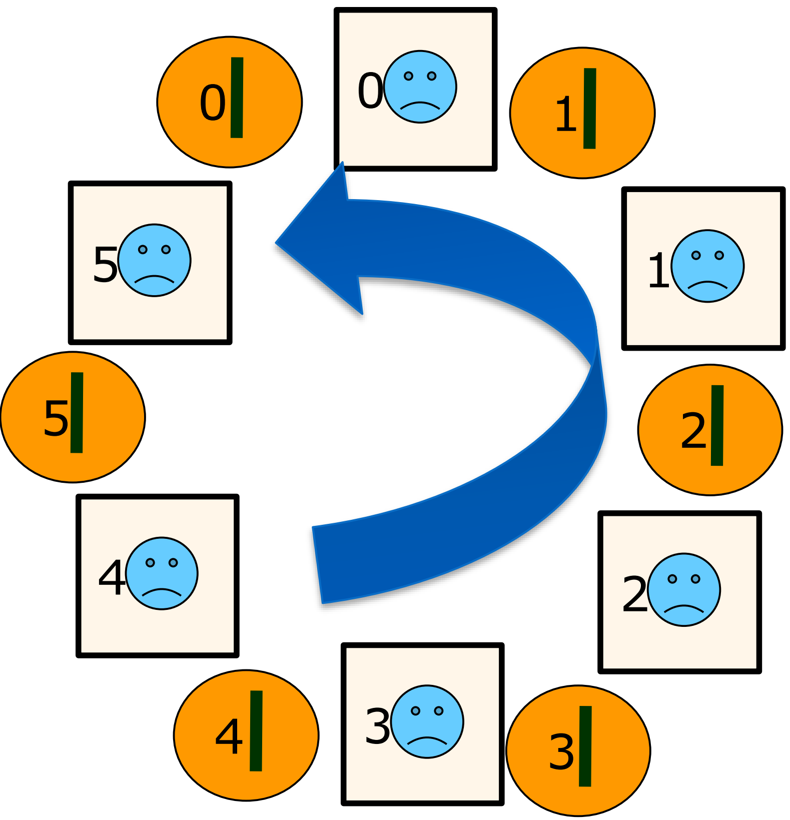
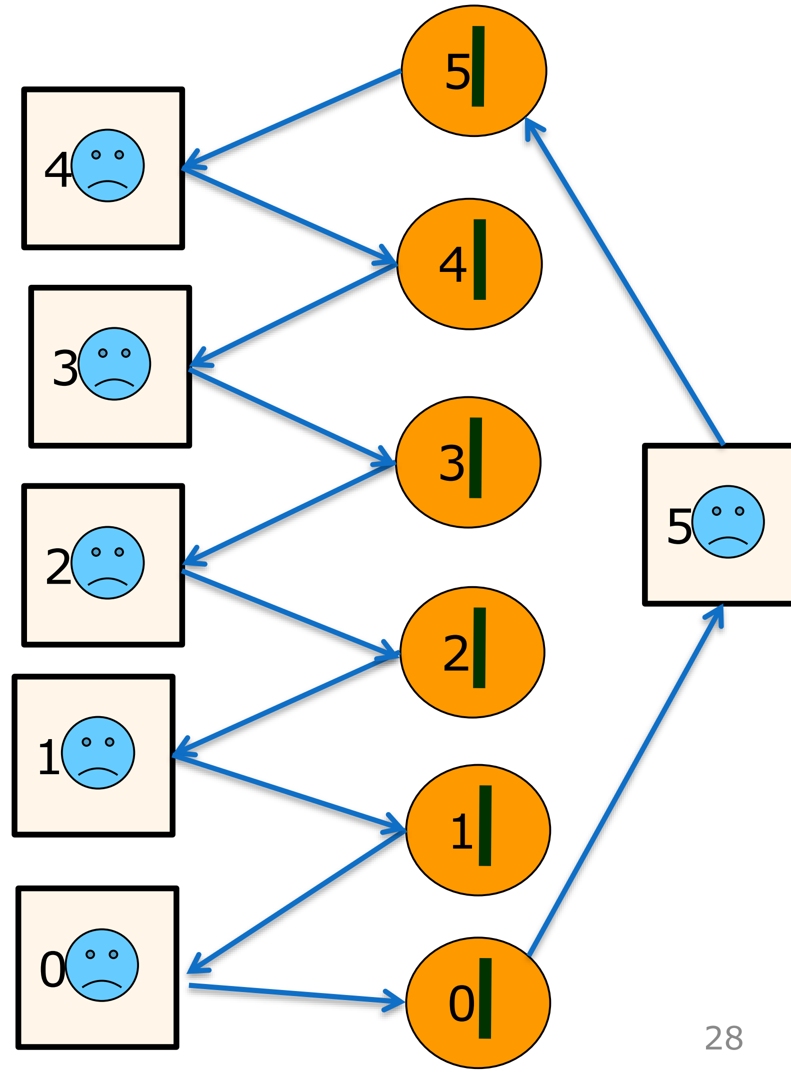


Dinning Philosophers' Circular Wait





Better Solution: Breaking Symmetry (a.k.a. the LR solution)

Odd threads	Even threads
down(**chopstick[(i+1)mod 6]**)	down(**chopstick[(i]**)
down(**chopstick[(i]**)	down(**chopstick[(i+1)mod 6]**)
Eat	Eat
up(**chopstick[(i+1)mod 6]**)	up(**chopstick[(i+1)mod 6]**)
up(**chopstick[(i]**)	up(**chopstick[(i]**)
Think	Think

- Provides better concurrency (2 philosophers can always eat concurrently, instead of just one)

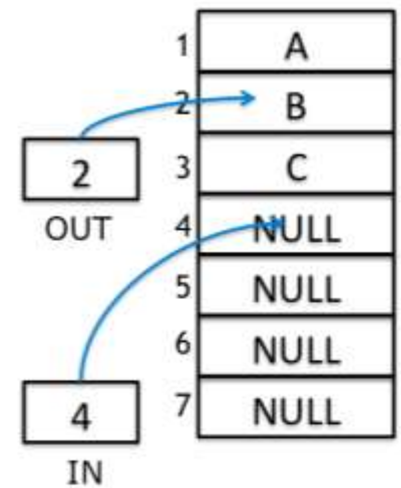
Final word about deadlocks

- Usually, cannot be detected by the OS
- Do not happen in every execution
  - Very tricky bug!
- Good practice:
  1. Order the resources
  2. Always lock the resources in the same order
     - E.g. from high to low
  3. Release resources in reverse order

Next Problem: Producer-Consumer

Motivation: Two processes (or threads) want to print

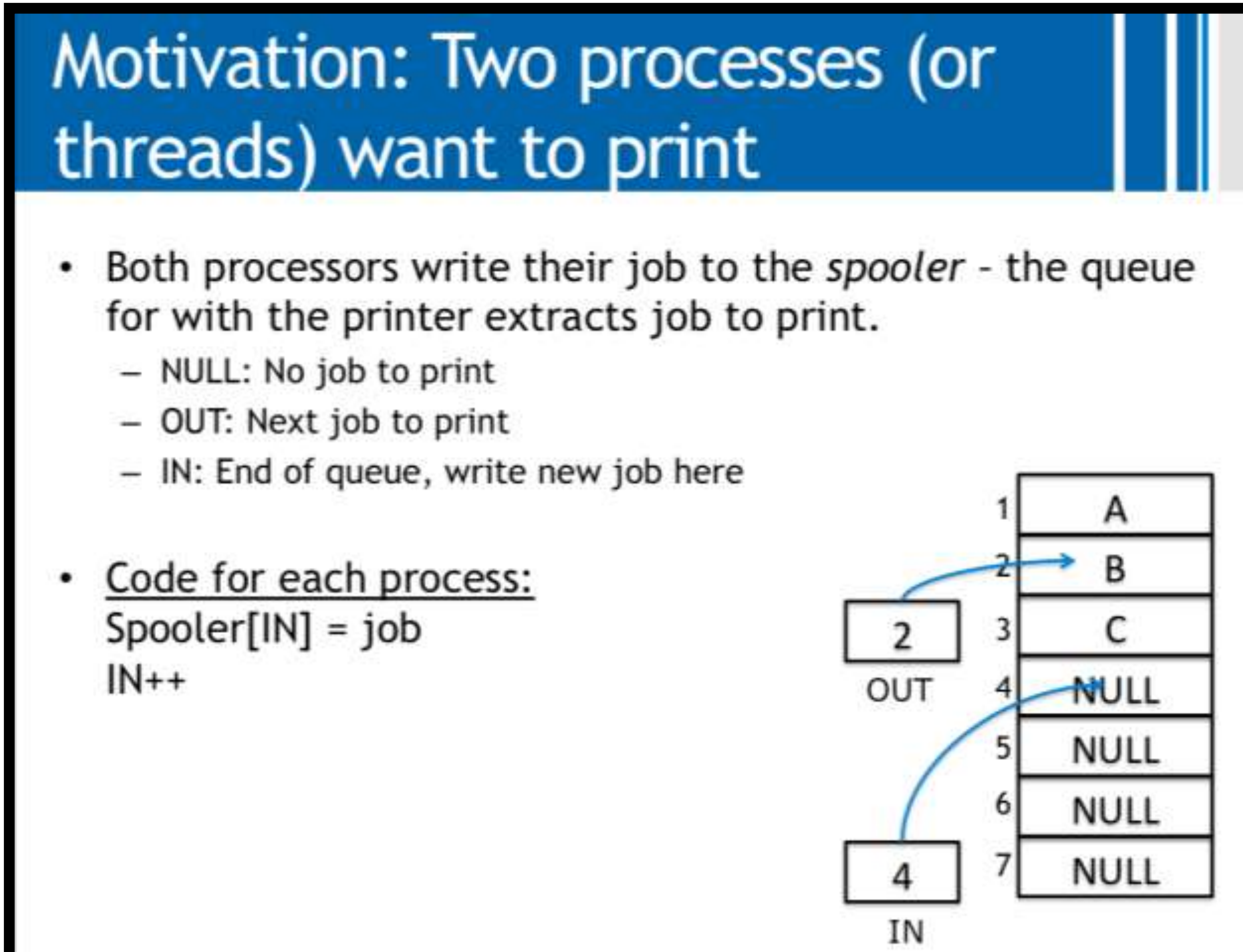
- Both processors write their job to the *spooler* - the queue for with the printer extracts job to print.
  - NULL: No job to print
  - OUT: Next job to print
  - IN: End of queue, write new job here
- <u>Code for each process:</u>
  Spooler[IN] = job
  IN++



Next Problem: Producer-Consumer

We already saw that half of the problem:

A contention between two printing processes (**producers**) on the IN counter can lead to overriding jobs and gaps in the array (**buffer**)



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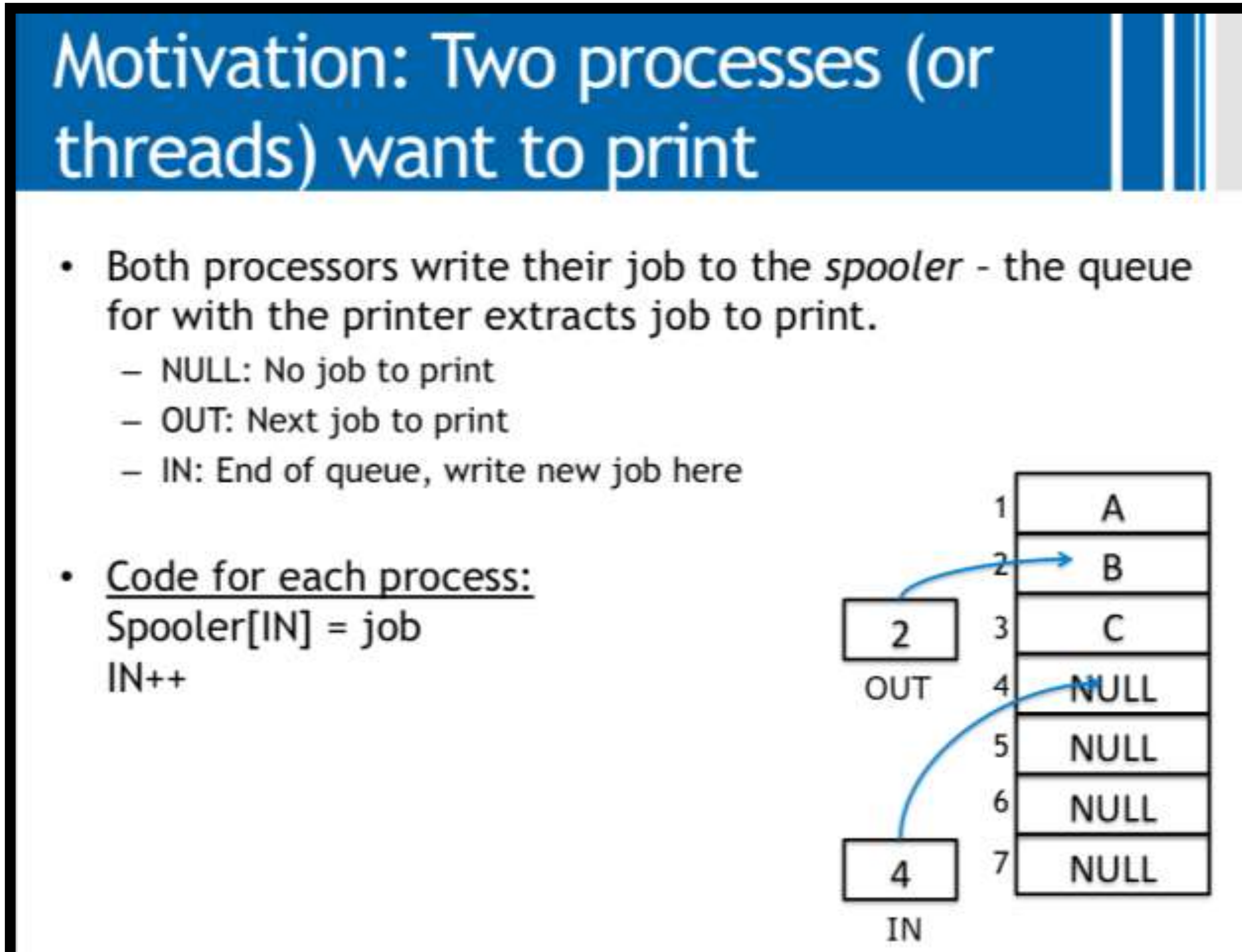
A contention between two printing processes (**producers**) on the IN counter can lead to overriding jobs and gaps in the array (**buffer**)

Similar situations can happen on the OUT variables in case there is more than one printer process (**consumers**)



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- Code for each process:
  Spooler[IN] = job
  IN++

In case the **buffer** is of **bounded** size, how it is managed (cyclic operation) and how empty/full buffers are handled.

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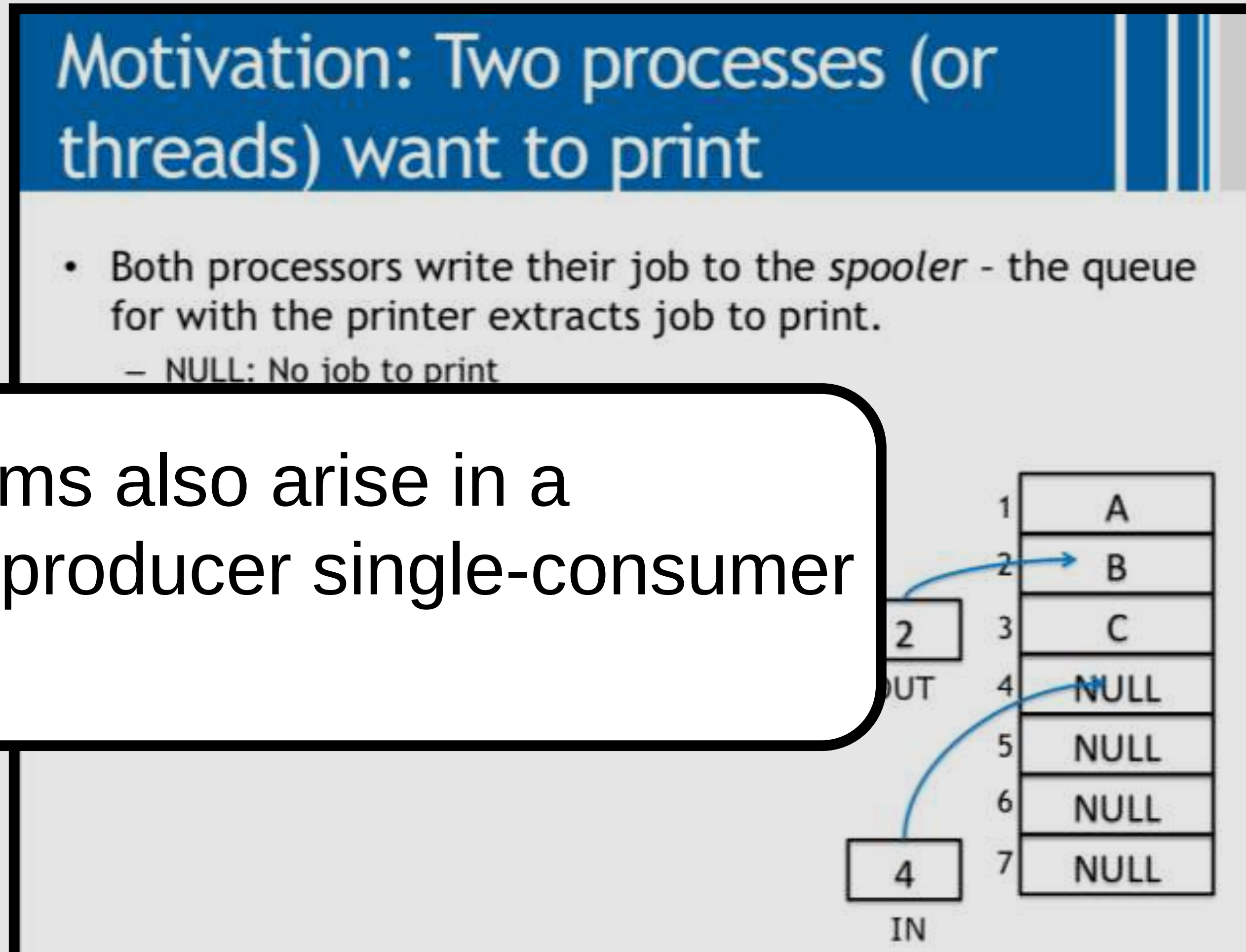
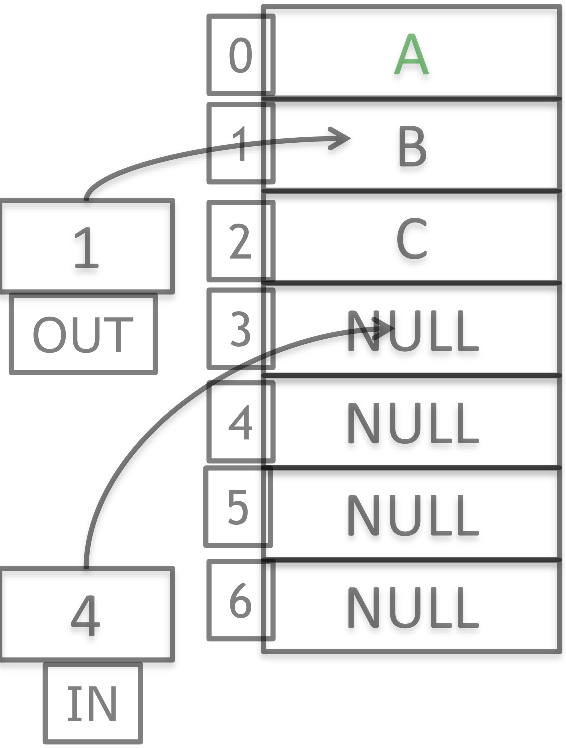


Problems also arise in a single-producer single-consumer setting

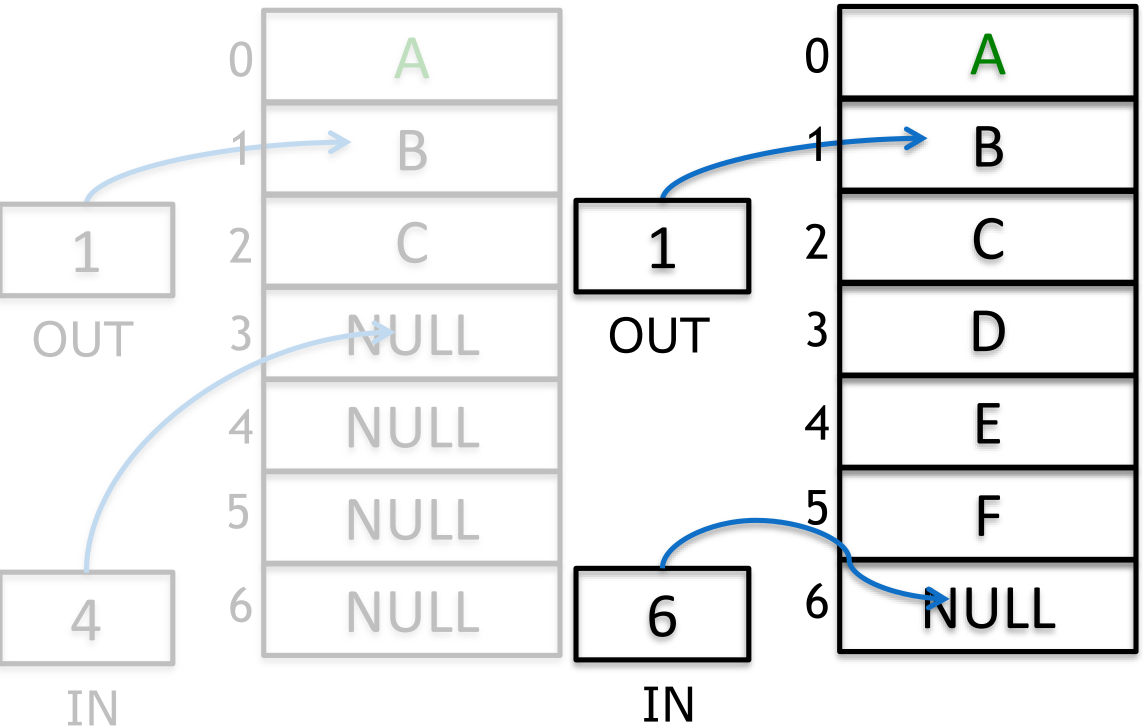
In case the **buffer** is of **bounded** size, how it is managed (cyclic operation) and how empty/full buffers are handled.

Cyclic Buffers

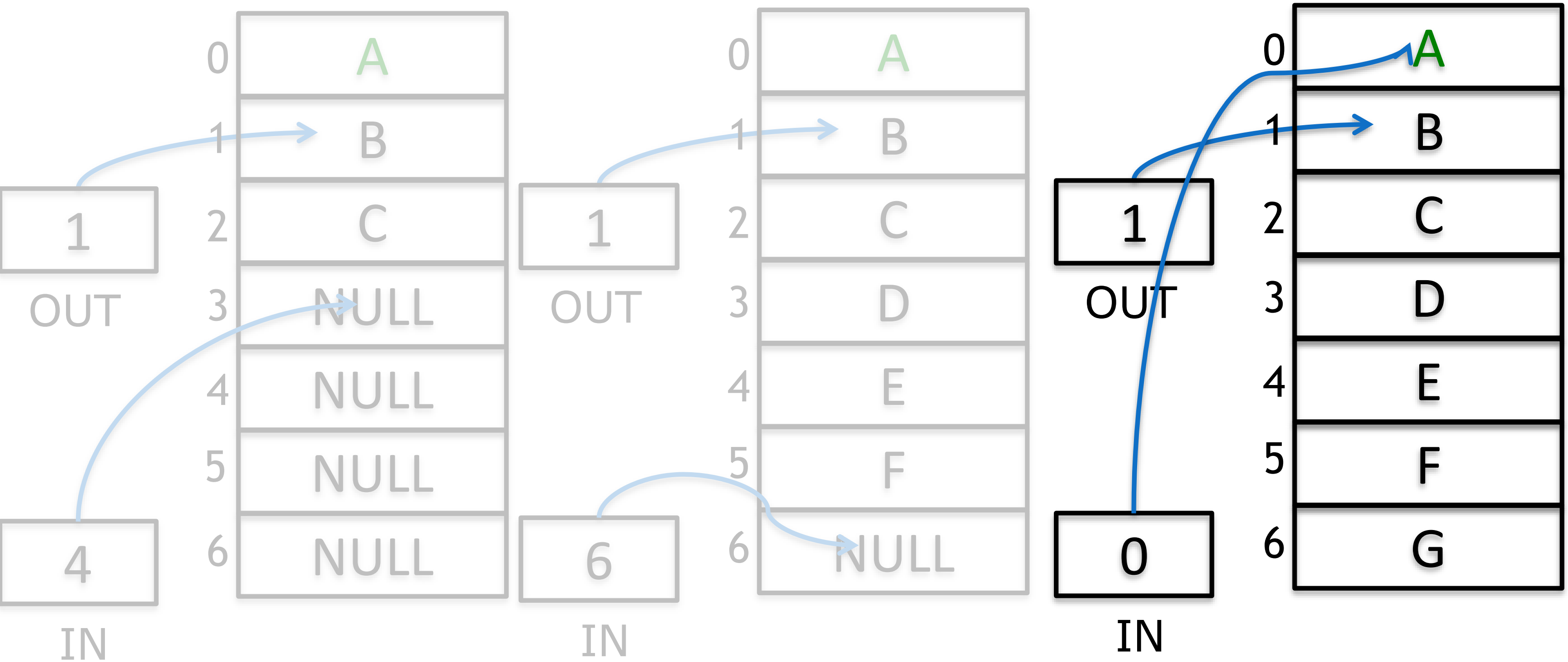
Cyclic Buffers



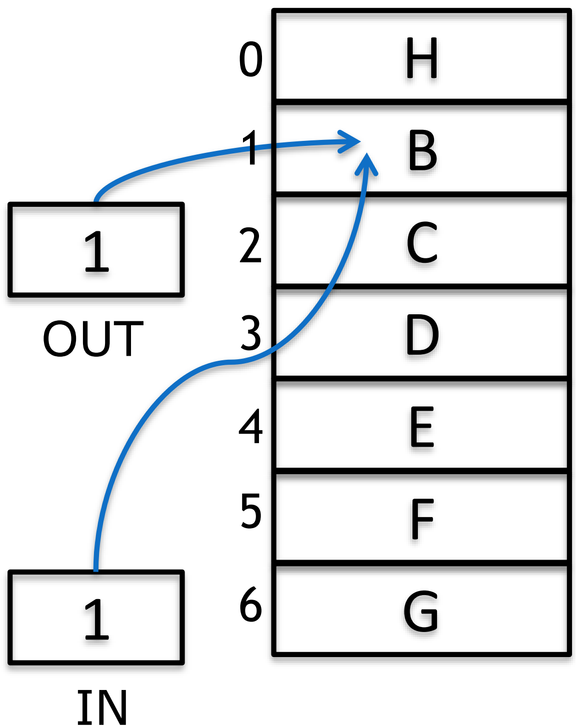
Cyclic Buffers



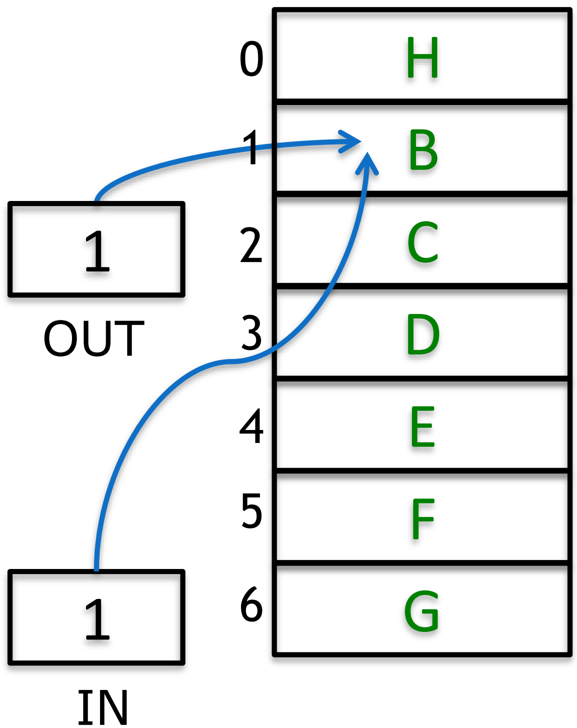
Cyclic Buffers



Cyclic Buffers

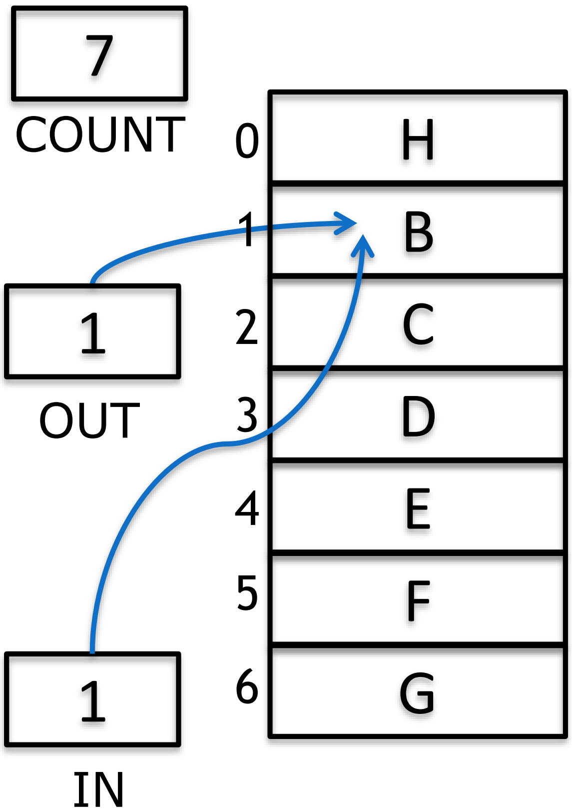


Buffer is full

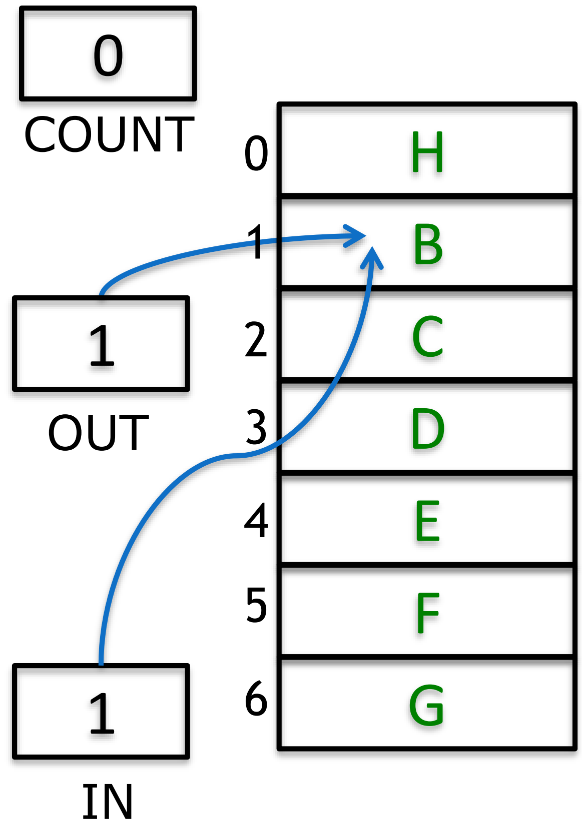


Buffer is empty

Cyclic Buffers



Buffer is full



Buffer is empty

Single Producer- Single Consumer Code

Producer
(e.g., sending printing job)

```
while (COUNT==n);

buffer [IN]=job;
IN=IN+1 mod n;
COUNT++;
```

Consumer
(e.g., printer)

```
while (COUNT==0);

job=buffer [OUT];
OUT=OUT+1 mod n;
COUNT--;
```

Single Producer- Single Consumer Code

Producer
(e.g., sending printing job)

```
while (COUNT==n);

buffer [IN]=job;
IN=IN+1 mod n;
COUNT++;
```

Must be atomic

Consumer
(e.g., printer)

```
while (COUNT==0);

job=buffer [OUT];
OUT=OUT+1 mod n;
COUNT--;
```

Single Producer- Single Consumer Code

Producer
(e.g., sending printing job)

while (COUNT==n);

buffer [IN]=job;
IN=IN+1 mod n;
COUNT++;

Consumer
(e.g., printer)

while (COUNT==0);

job=buffer [OUT];
OUT=OUT+1 mod n;
COUNT--;

Use semaphore
(mutual exclusion)

Must be atomic

Single Producer- Single Consumer Code

Producer
(e.g., sending prin

Busy wait

while (COUNT==n);

buffer [IN]=job;
IN=IN+1 mod n;
COUNT++;

Must be atomic

Consumer
g., printer)

while (COUNT==0);

job=buffer [OUT];
OUT=OUT+1 mod n;
COUNT--;

Use semaphore
(mutual exclusion)

Alternative Solution: Producers-Consumers w/ Semaphores

Producer
(e.g., sending printing job)

down(empty)
down(mutex)

buffer [IN]=job;
IN=IN+1 mod n;

up(mutex)
up(full)

Consumer
(e.g., printer)

down(full)
down(mutex)

job=buffer [OUT];
OUT=OUT+1 mod n;

up(mutex)
up(empty)

Initial values:

mutex	1
empty	n
full	0

Alternative Solution: Producers-Consumers w/ Semaphores

Producer
(e.g., sending printing job)

down(empty)
down(mutex)

buffer [IN]=job;
IN=IN+1 mod n;

up(mutex)
up(full)

Consumer
(e.g., printer)

down(full)
down(mutex)

job=buffer [OUT];
OUT=OUT+1 mod n;

up(mutex)
up(empty)

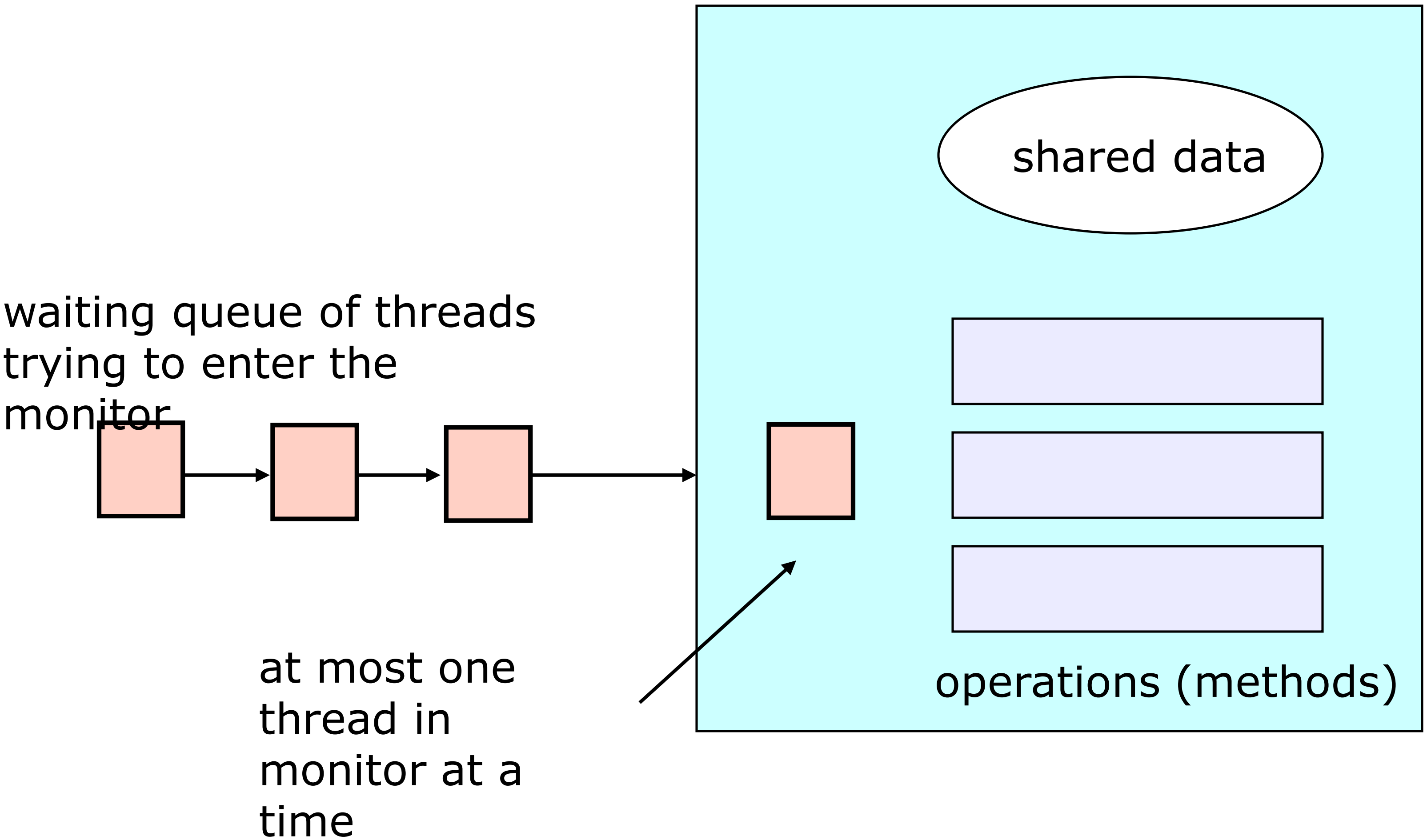
Initial values:

mutex	1
empty	n
full	0

One More Approach: Monitors

- A *monitor* is a <u>programming language</u> construct that supports controlled access to shared data
  - synchronization code is added by the compiler
    - why does this help?
- A monitor encapsulates:
  - shared data structures
  - procedures that operate on the shared data
  - synchronization between concurrent threads that invoke those procedures
- Data can only be accessed from within the monitor, using the provided procedures
  - protects the data from unstructured access
- Addresses the key usability issues that arise with semaphores

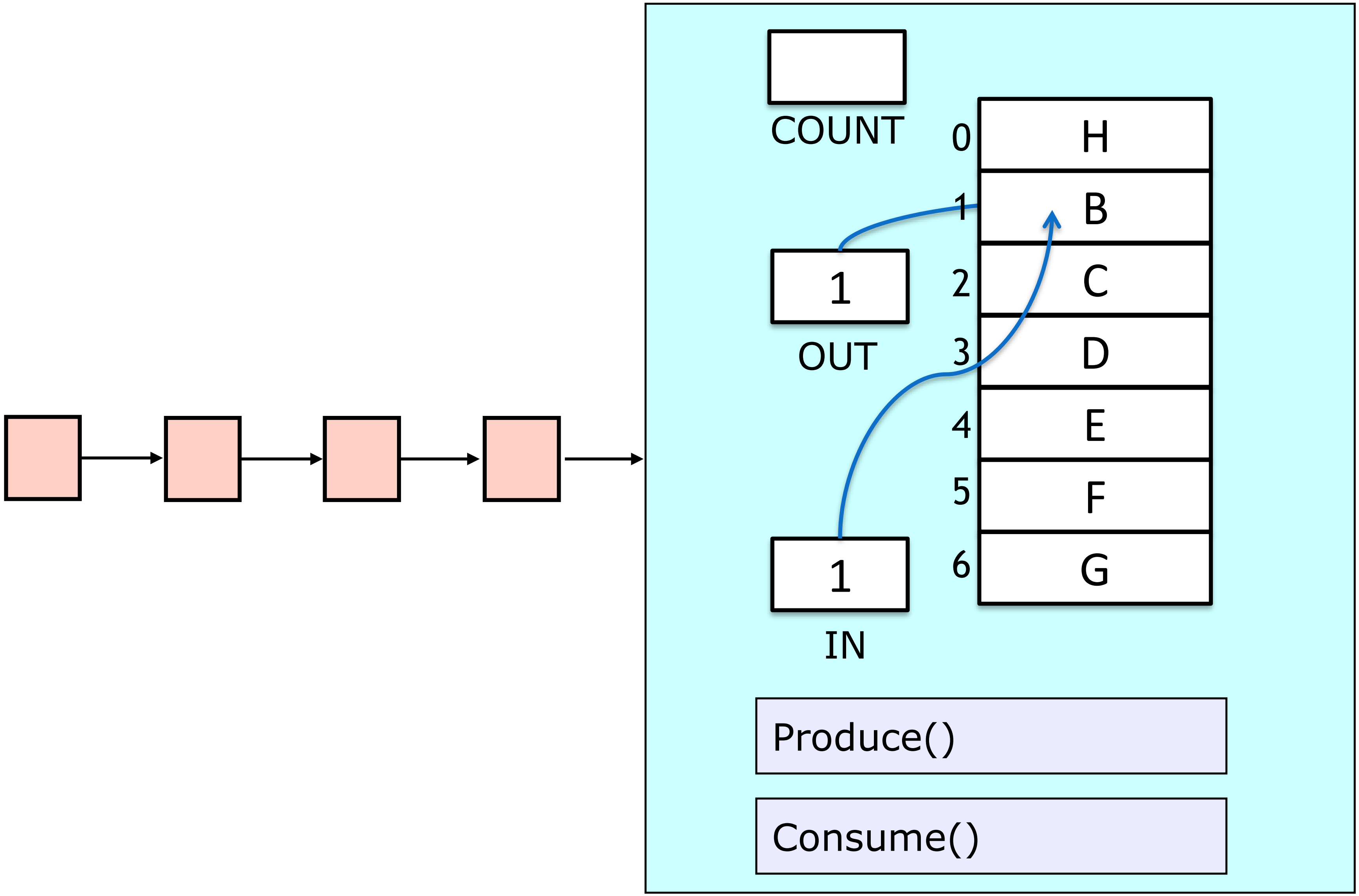
A monitor


shared data
waiting queue of threads trying to enter the monitor
at most one thread in monitor at a time
operations (methods)

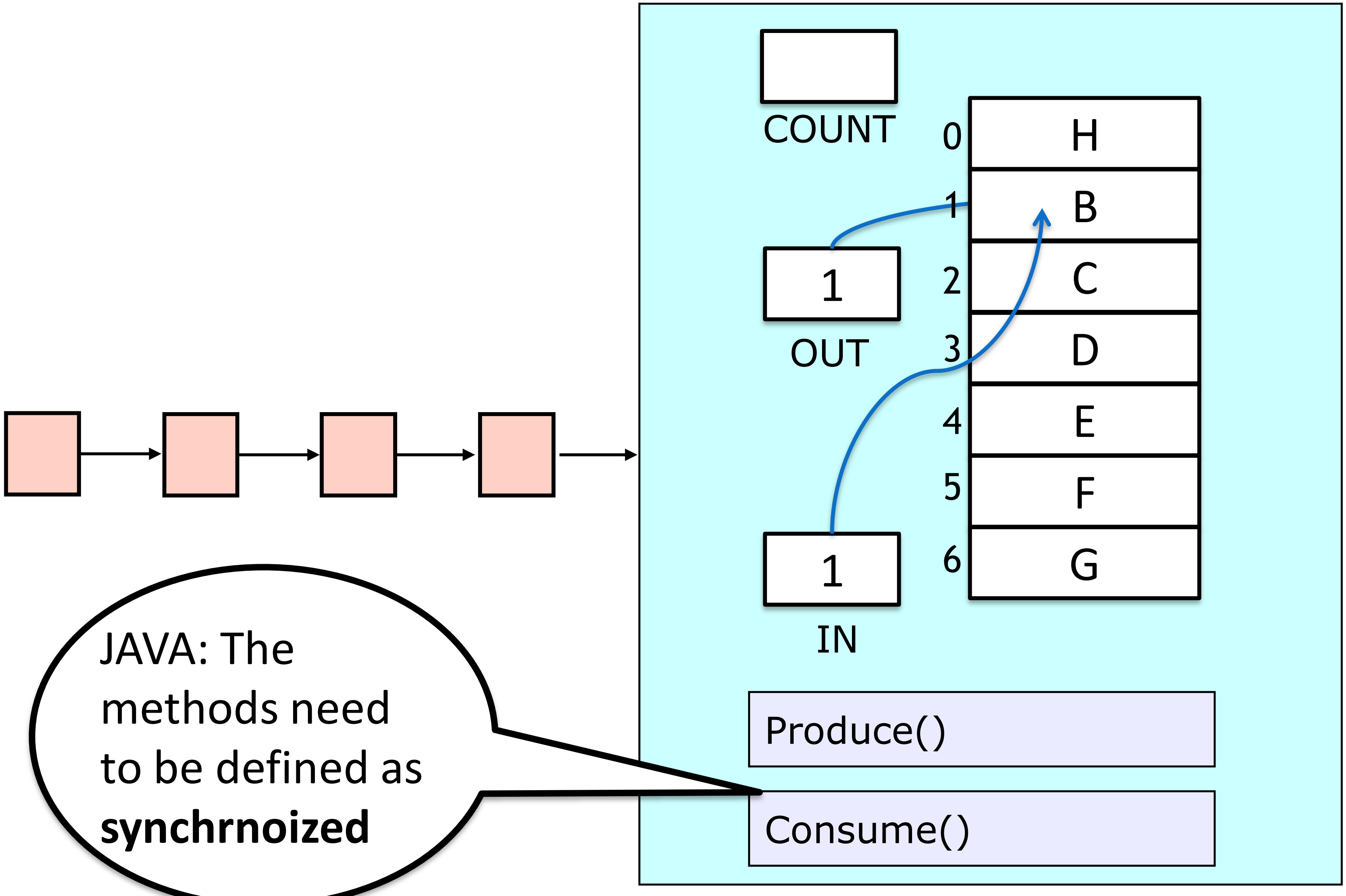
Monitor facilities

- "Automatic" mutual exclusion
  - only one thread can be executing inside at any time
    - thus, synchronization is implicitly associated with the monitor – it "comes for free"
  - if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor
    - more restrictive than semaphores
    - but easier to use (most of the time)
- But, there is a problem…

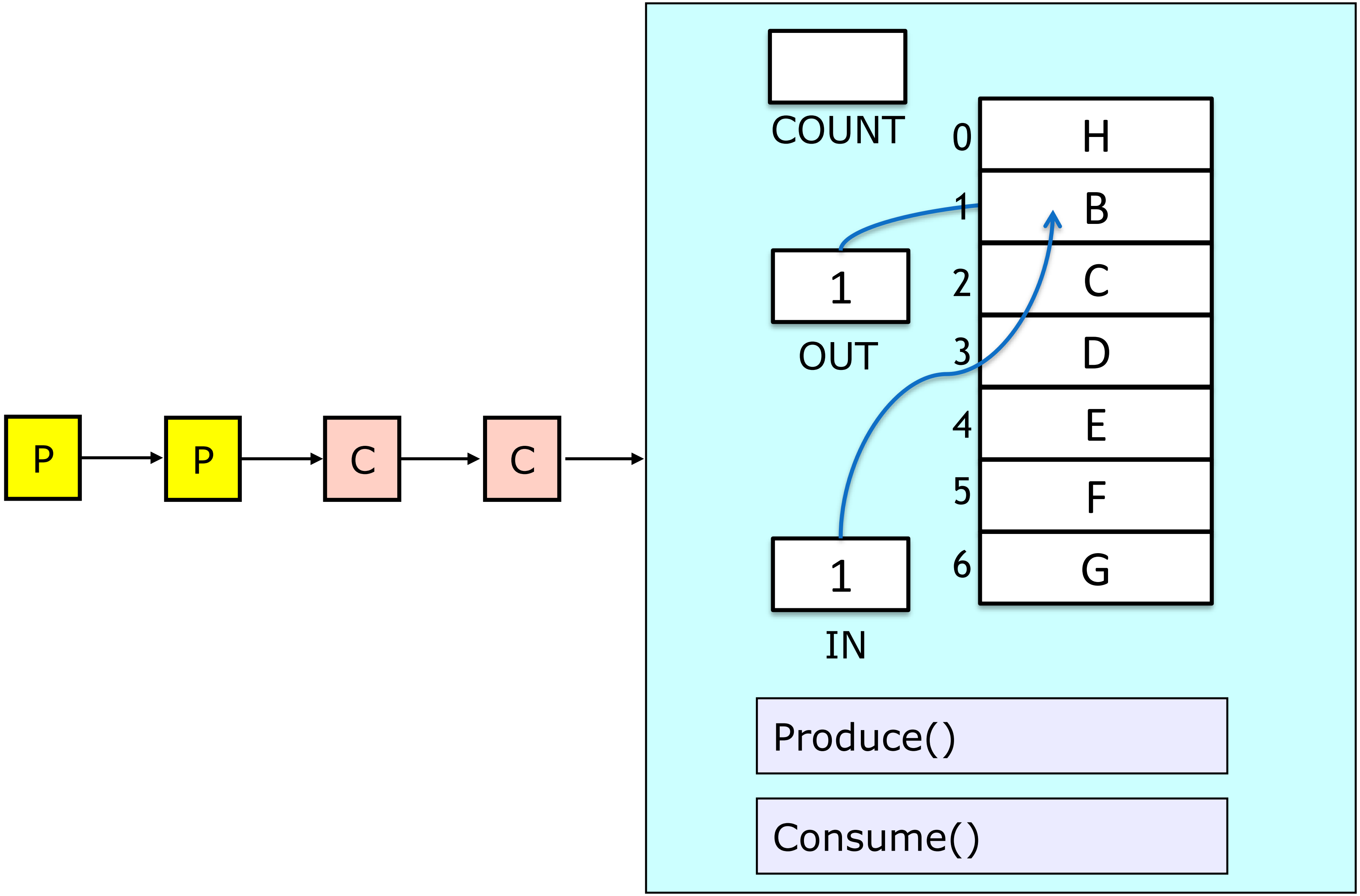
Producers/Consumers Monitor



Producers/Consumers Monitor



Producers/Consumers Monitor



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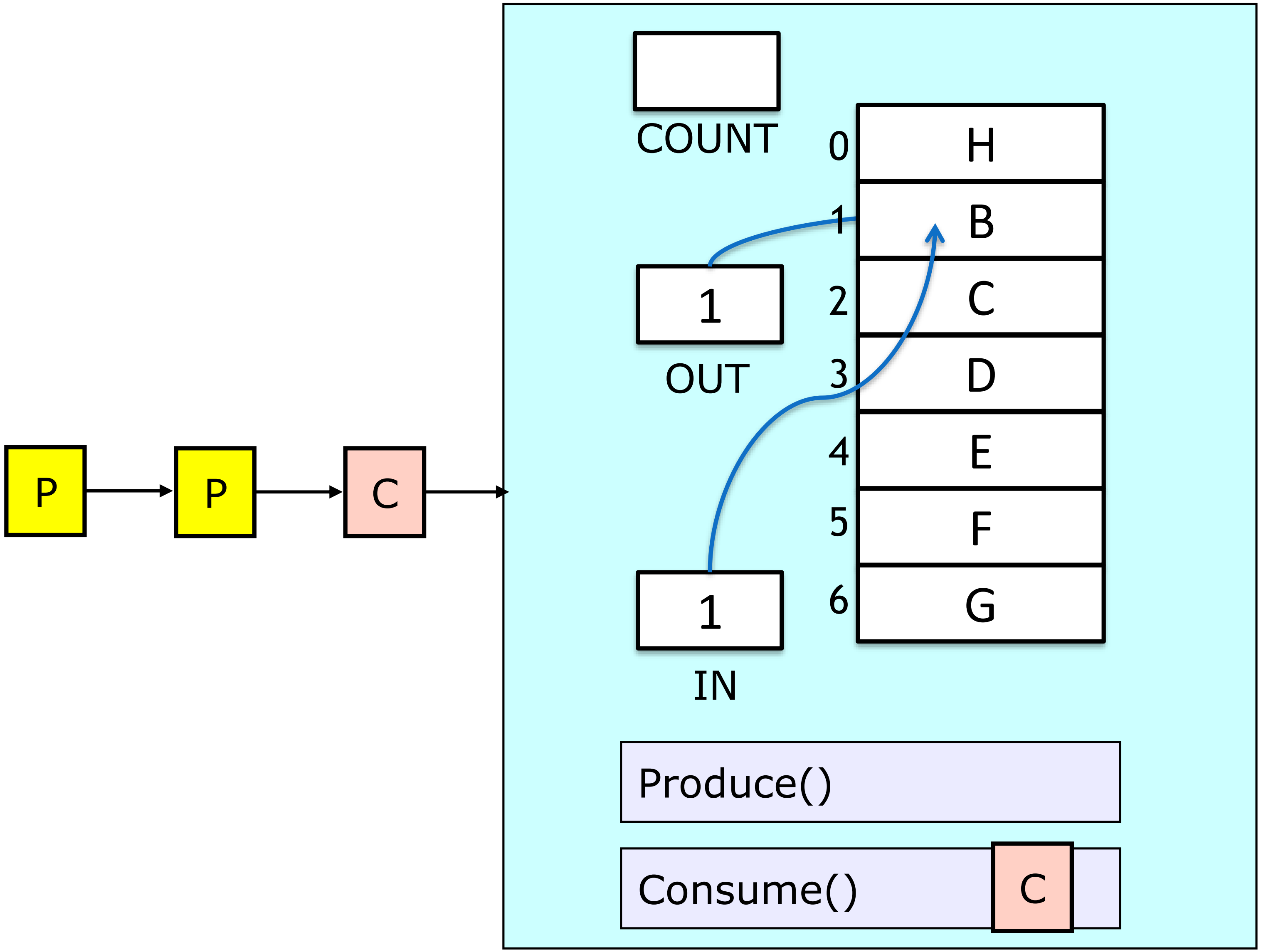

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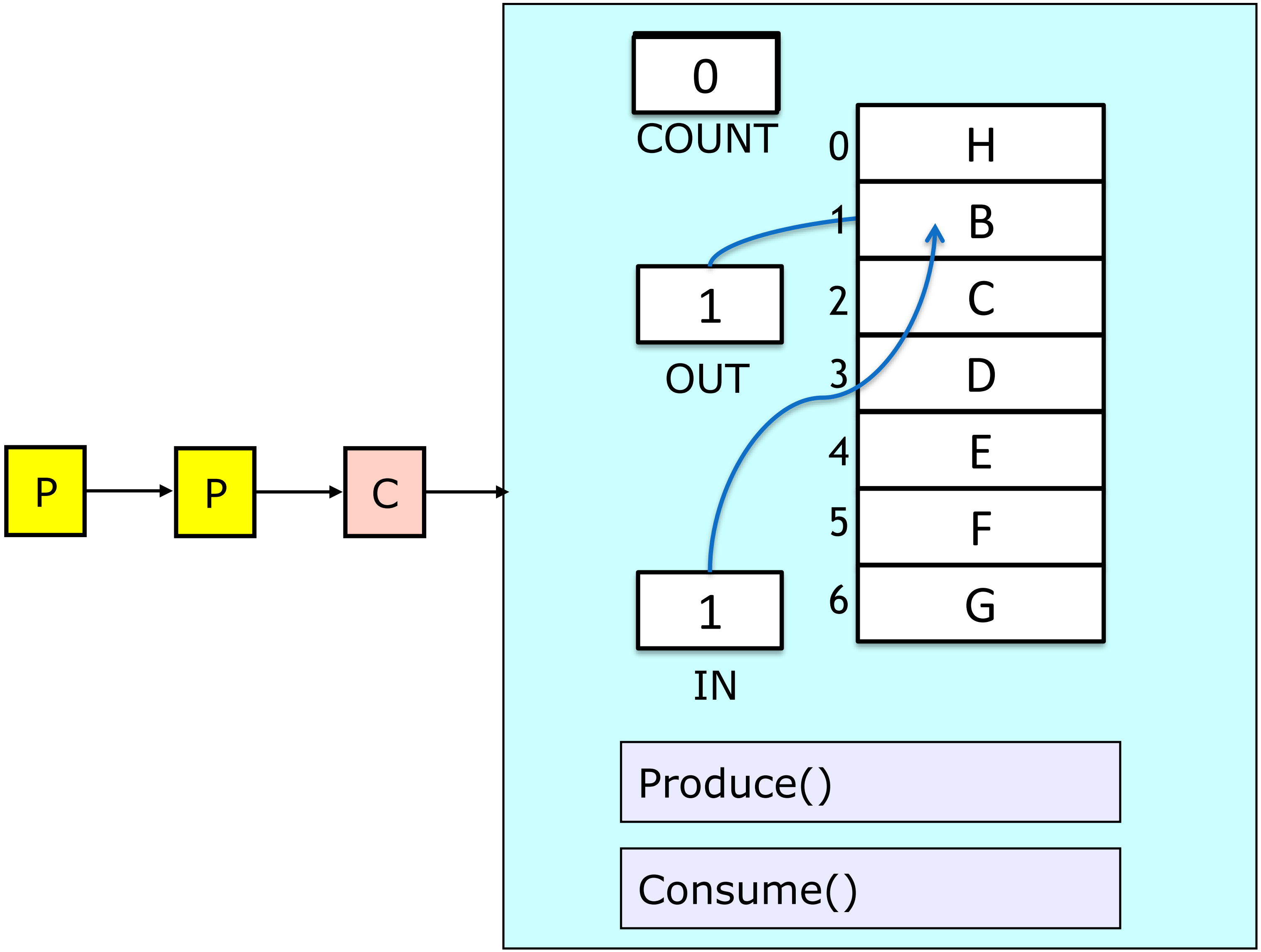

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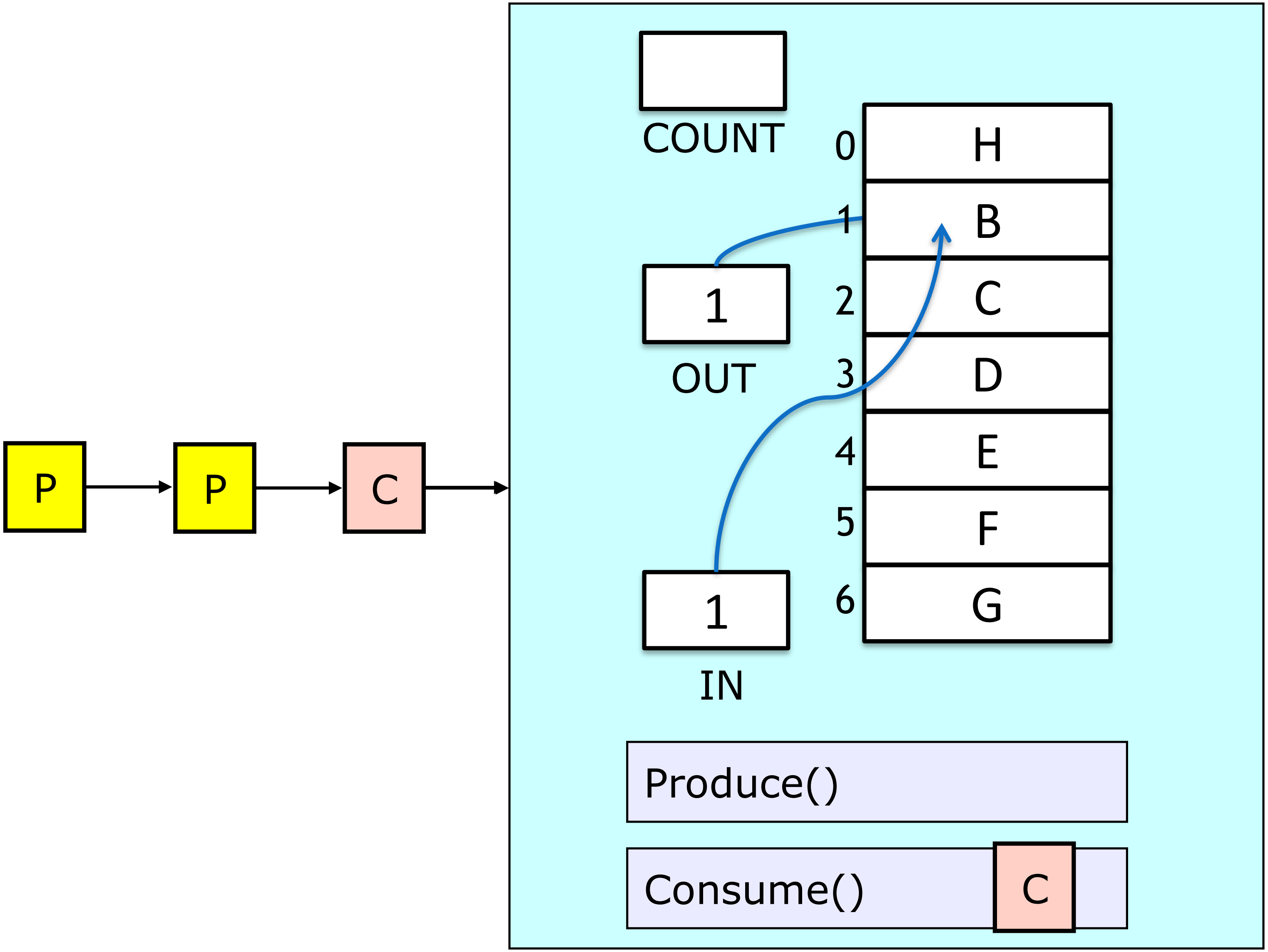

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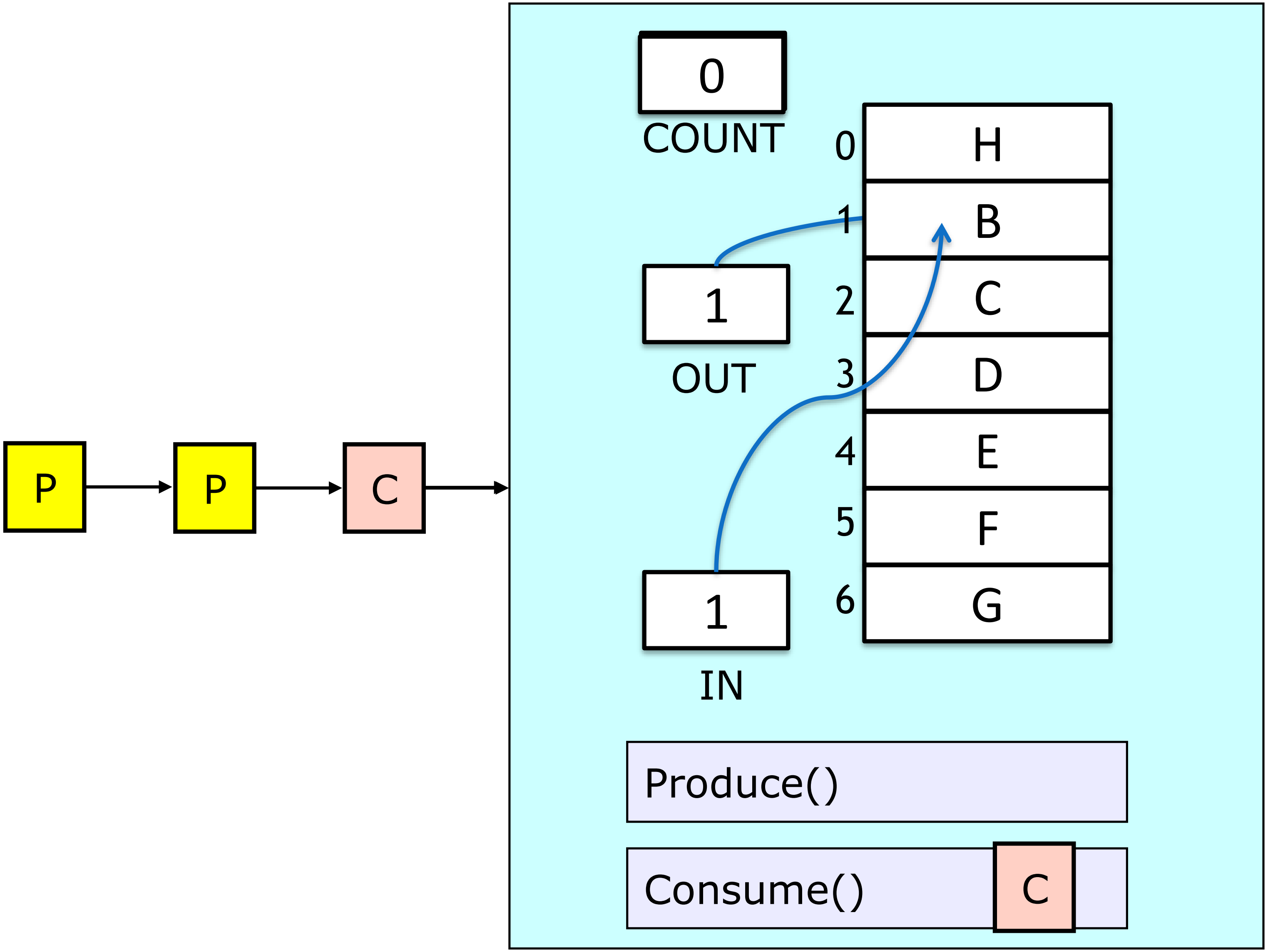

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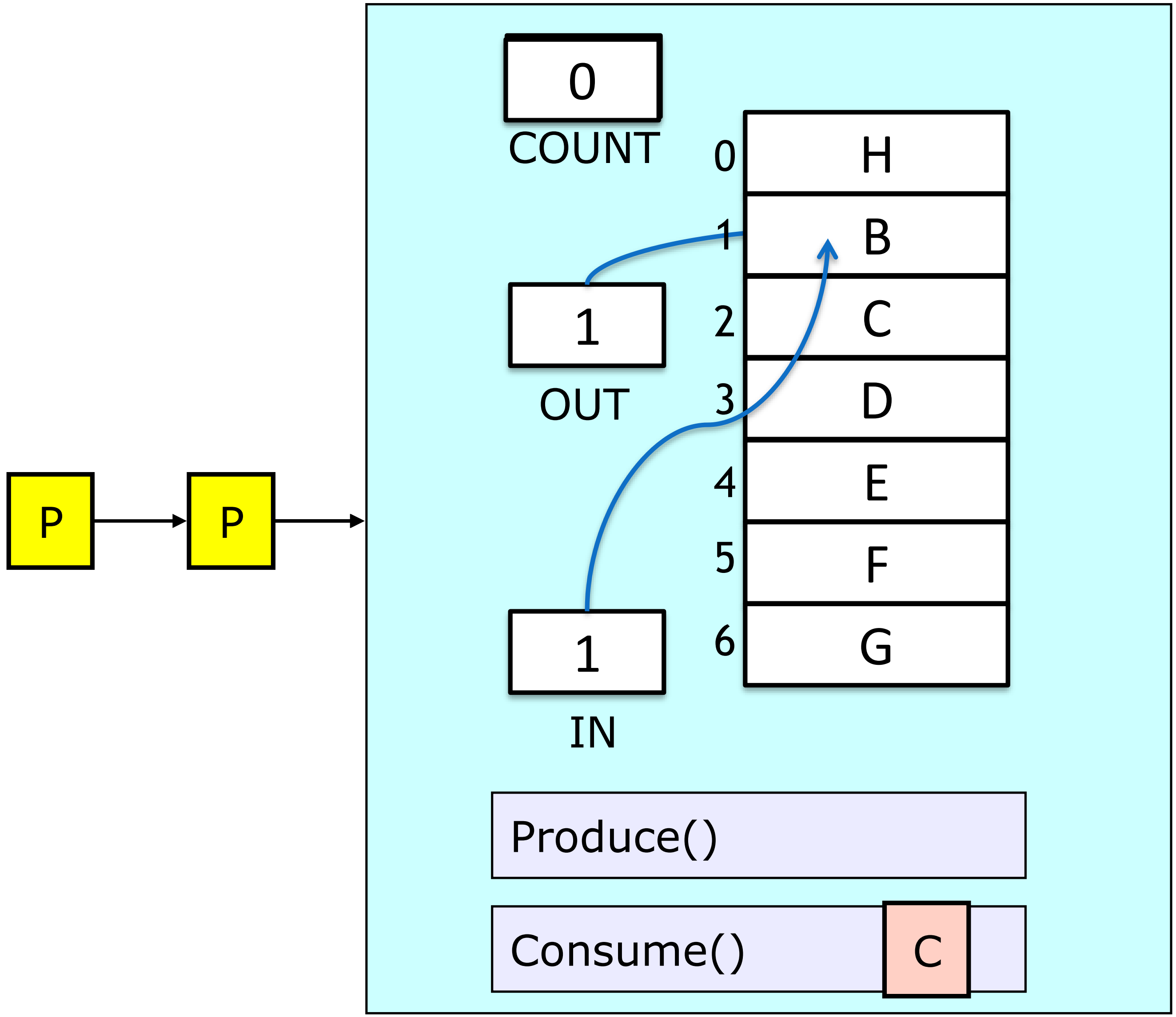

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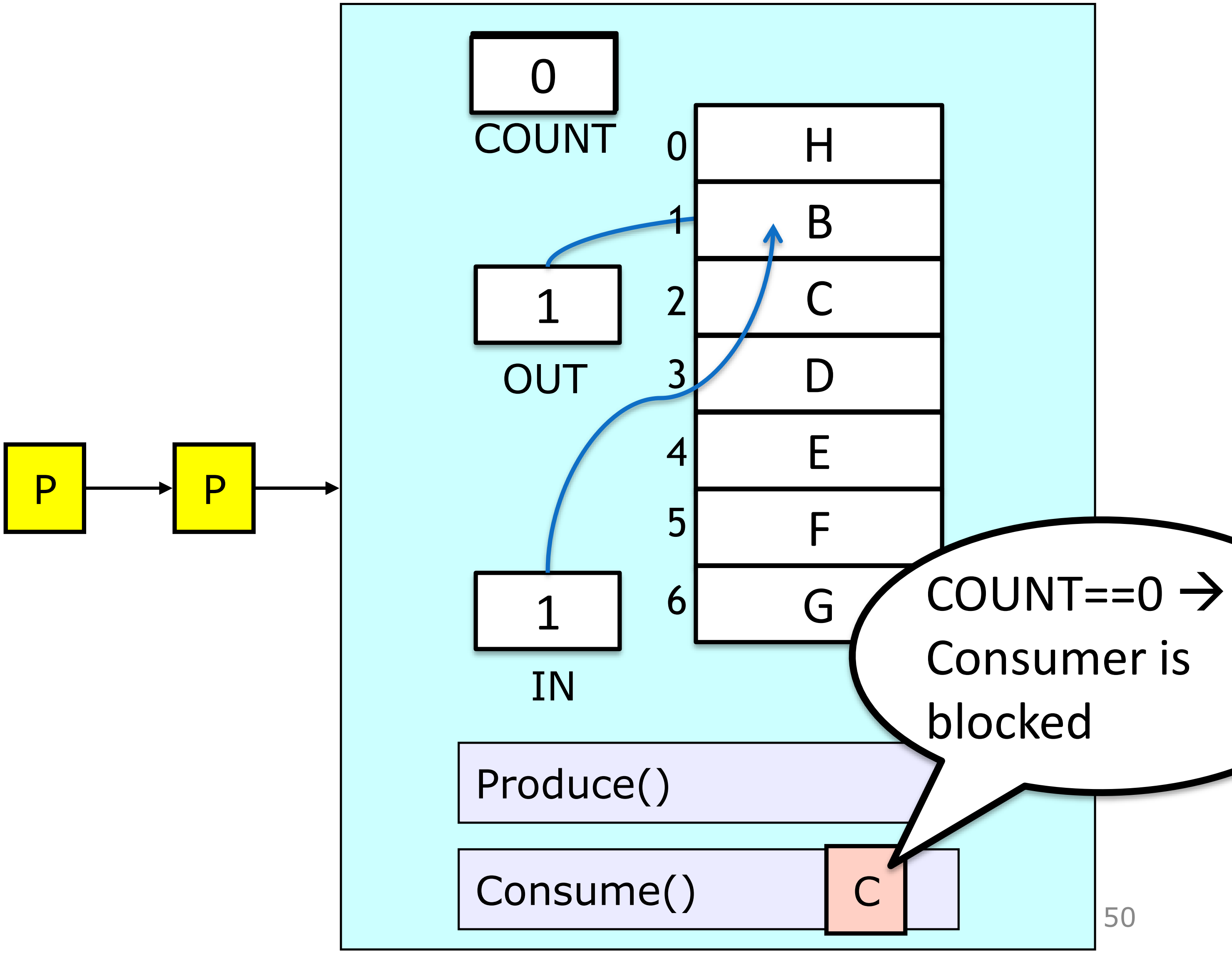

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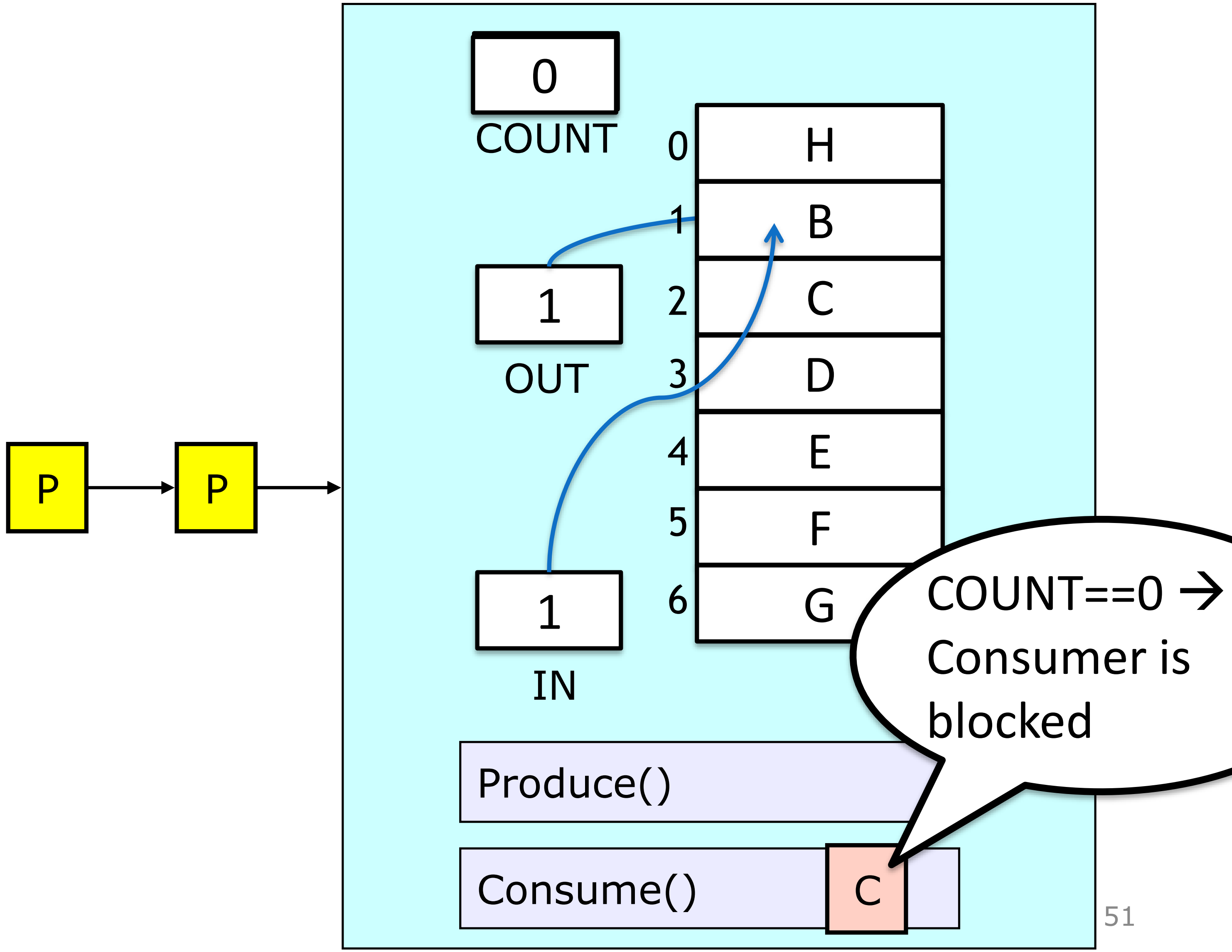

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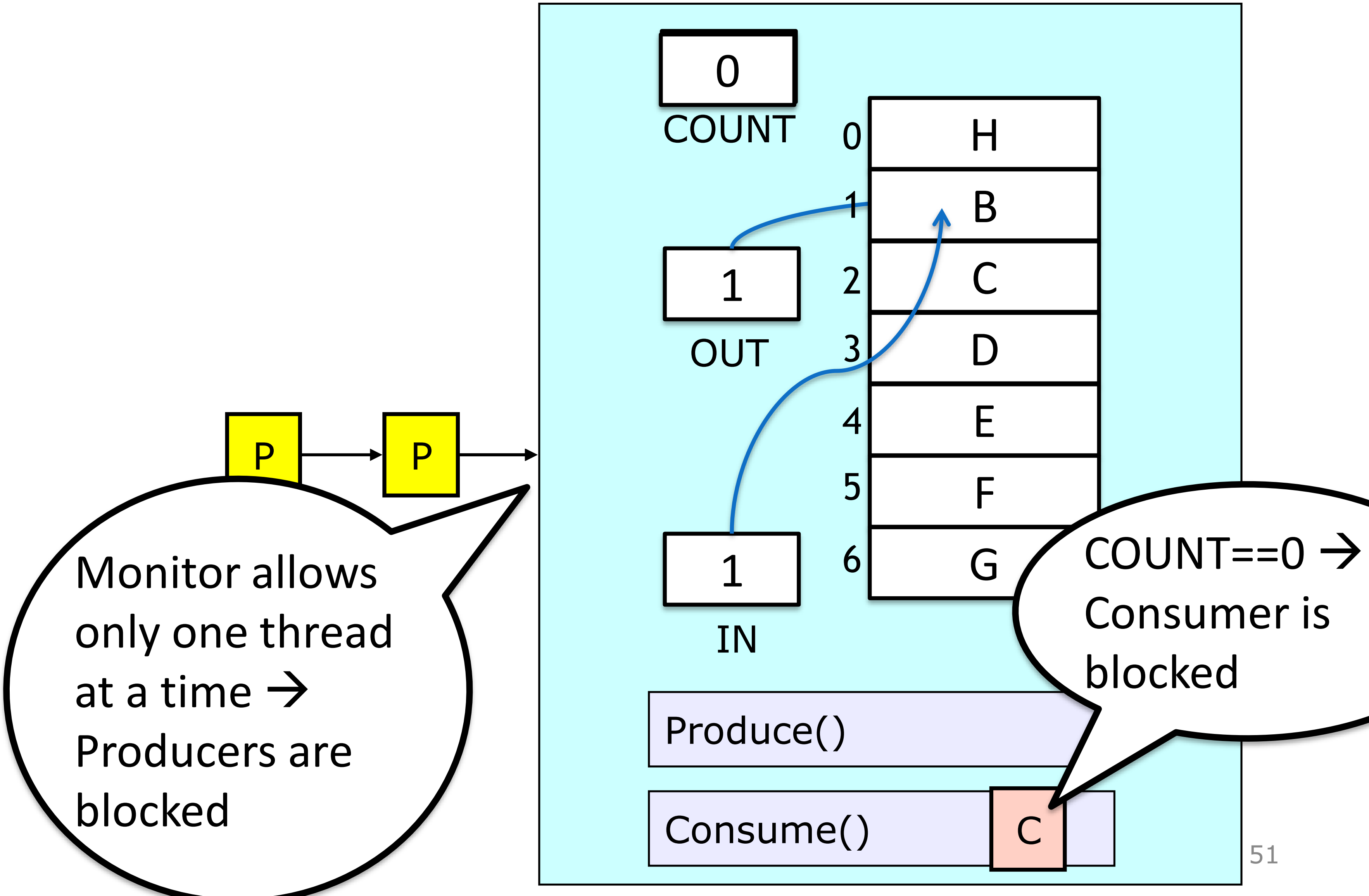
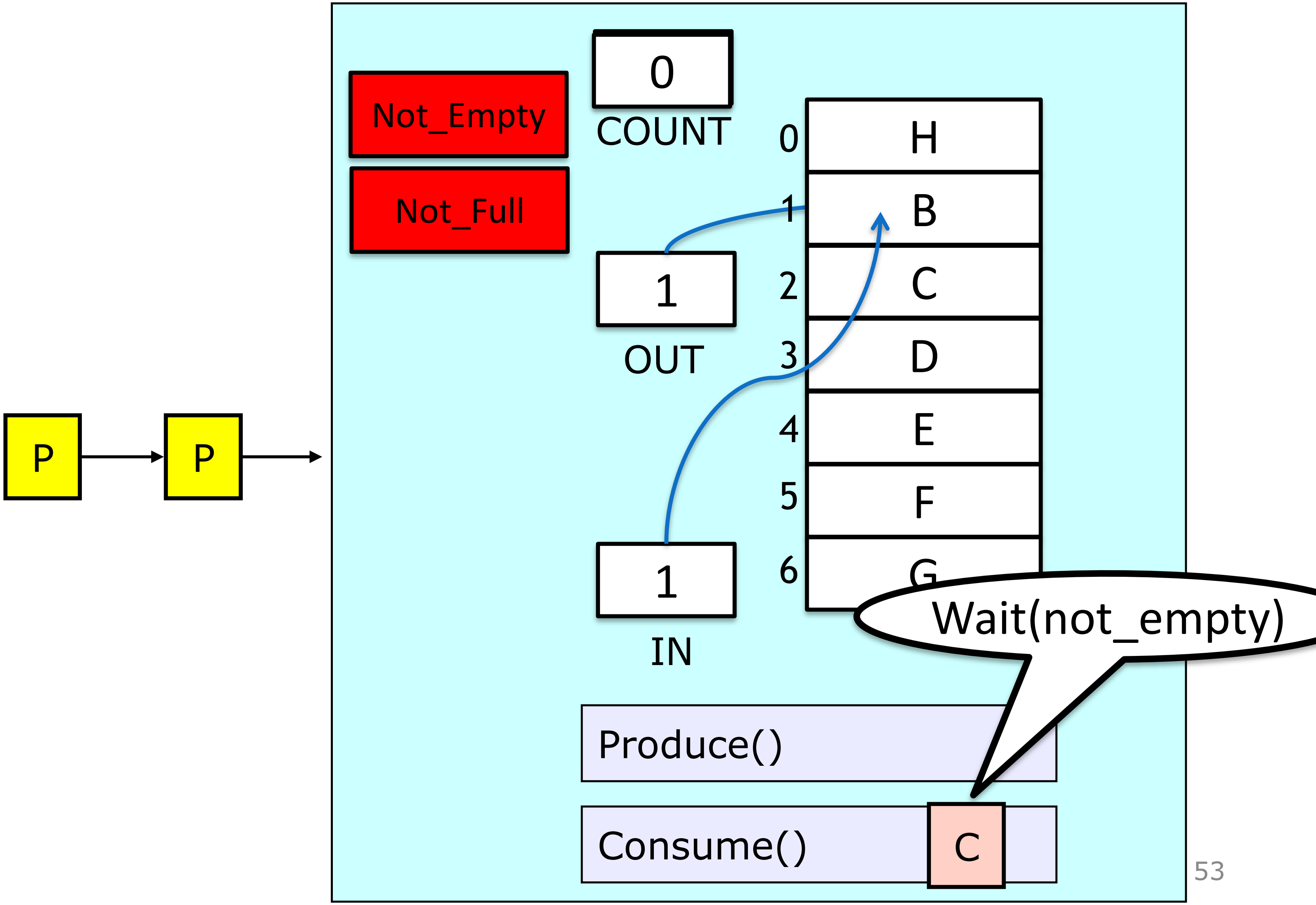


Condition variables (a.k.a. Rendezvous Points)

- “A place to wait”
- “Required” for monitors
  - So useful they’re often provided even when monitors aren’t available
- Three operations on condition variables
  - wait(c) – java: c.wait()
    - release monitor lock, so somebody else can get in
    - wait for somebody else to signal condition
    - thus, condition variables have associated wait queues
  - signal(c) – java: c.notify()
    - wake up at most one waiting thread
    - if no waiting threads, signal is lost
      - this is different than semaphores: no history!
  - broadcast(c) – java: c.NofityAll()
    - wake up all waiting threads

Producers/Consumers Monitor



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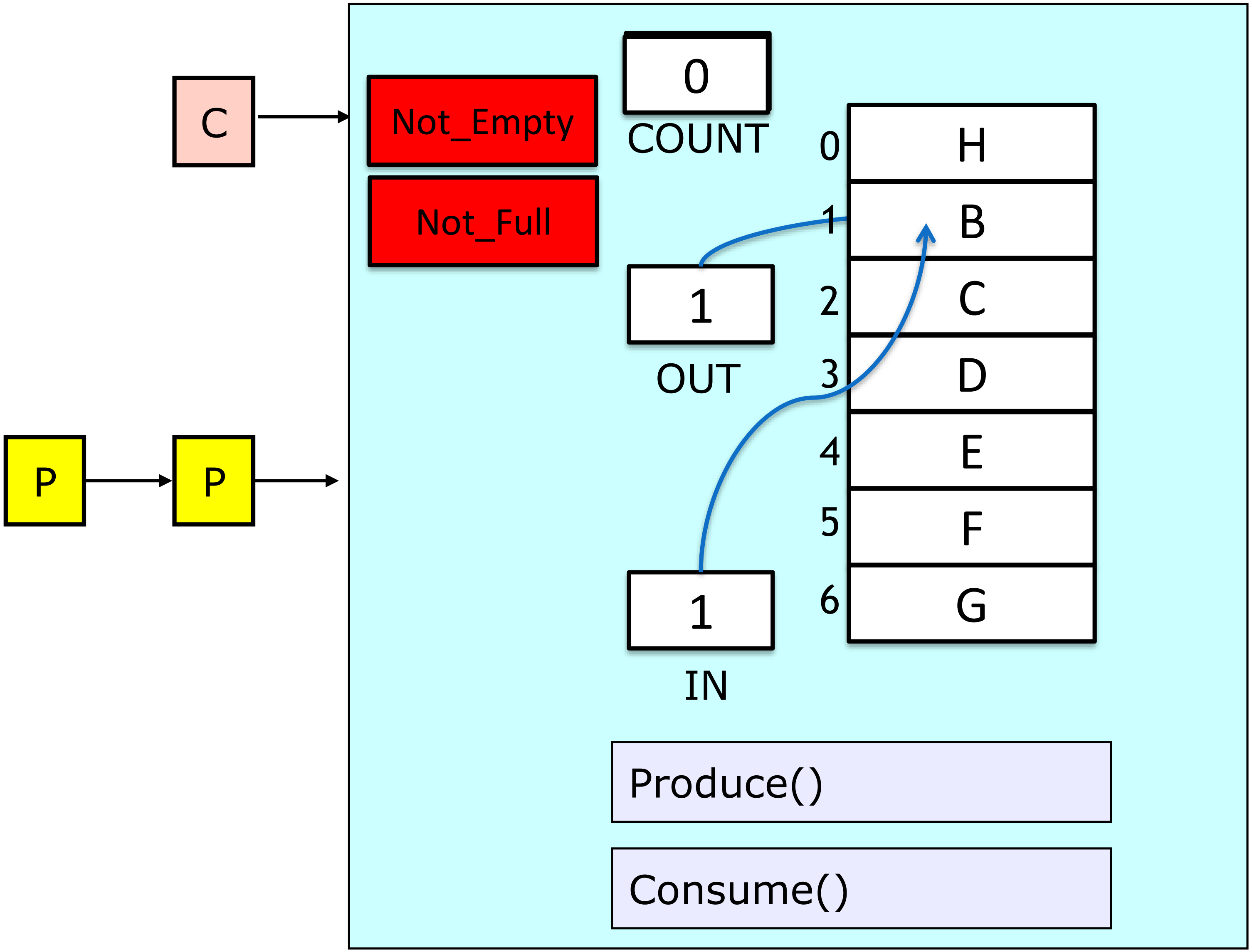

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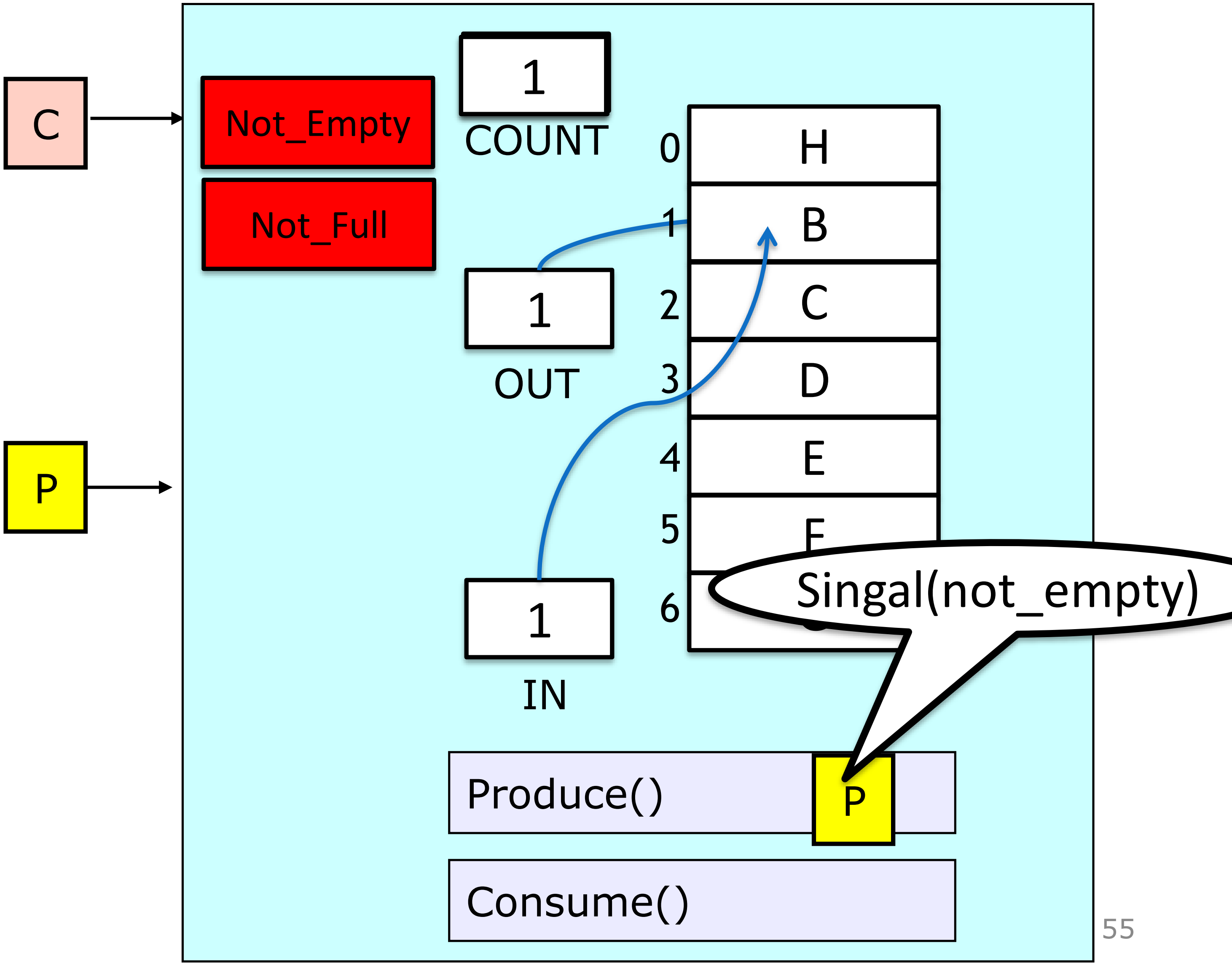

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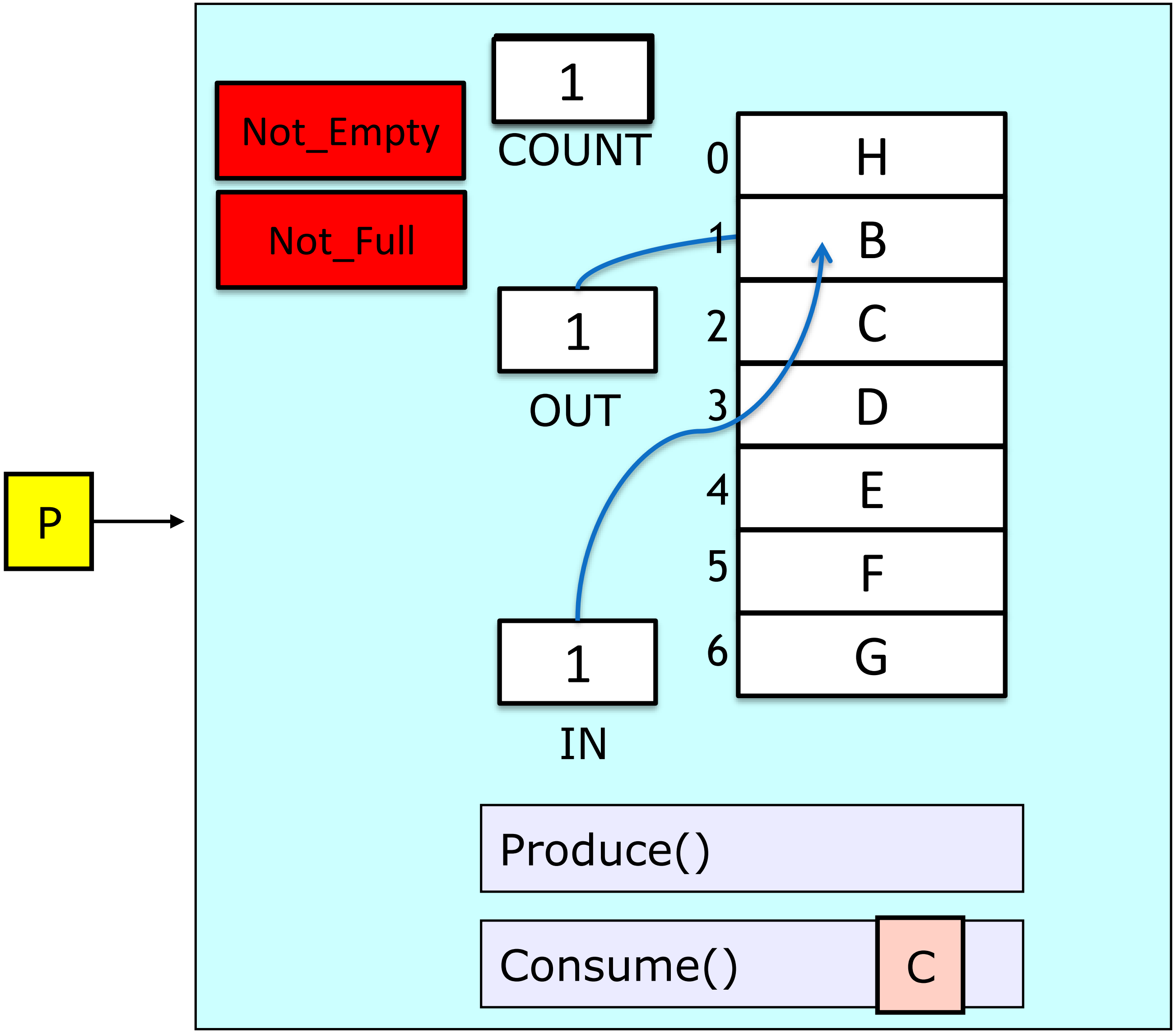

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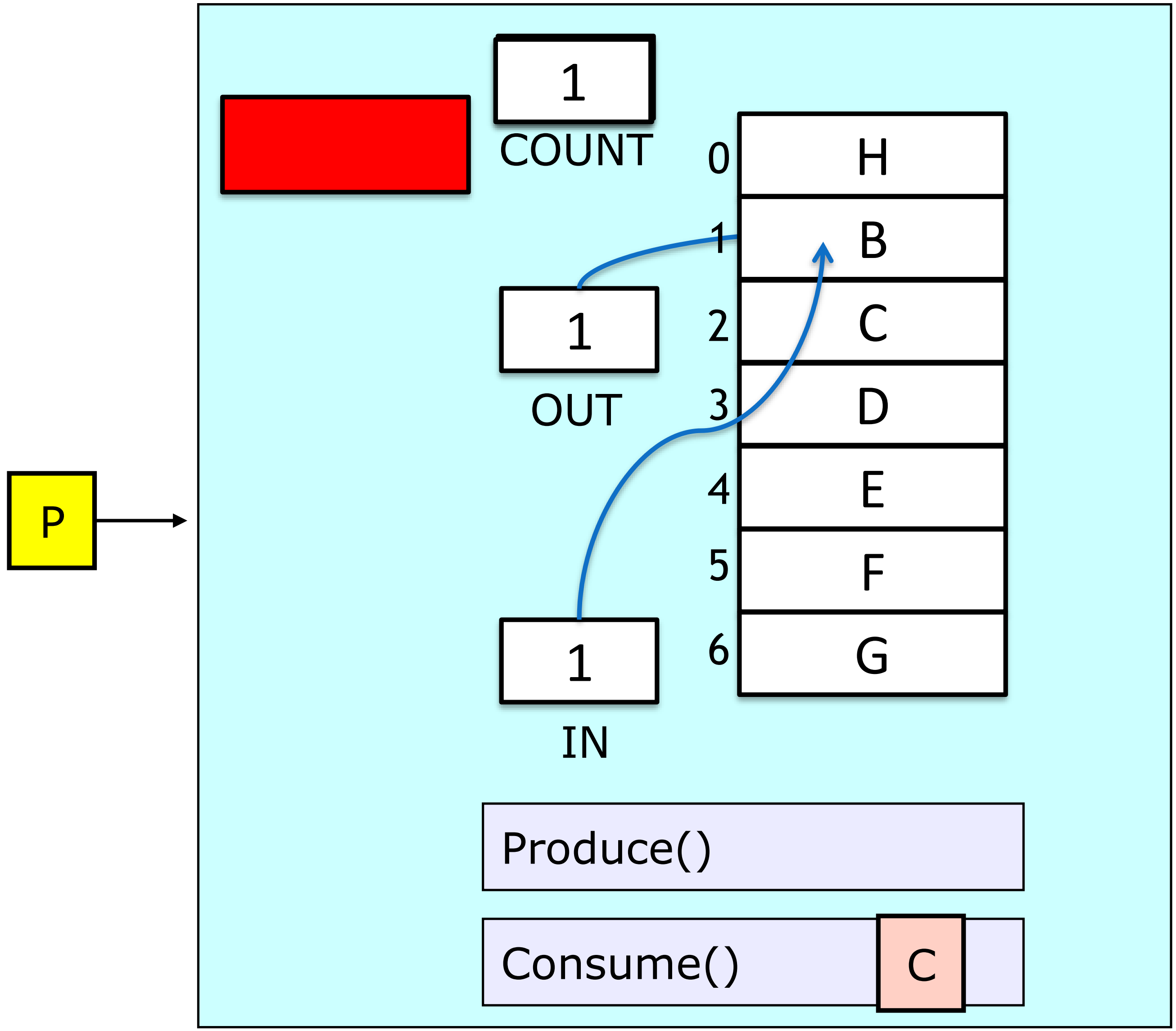

Shared Memory vs. Message Passing Models

- In the course we assume two threads or two processes are communicating through **shared resources** – mostly shared memory
- Another way to communicate: send and receive **messages**
- Similar problems arise, but the solutions are quite different
- More about it in the “Distributed Algorithms” course