

# Synchronisation problems

## Module 4 self study material

Bounded buffer  
Reader and writers  
Priority inversion

---

**Operating systems 2018**

**1DT044 and 1DT096**

# **Classical problems of synchronization**

- ★ The bounded buffer problem
- ★ The readers and writers problem
- ★ Priority inversion

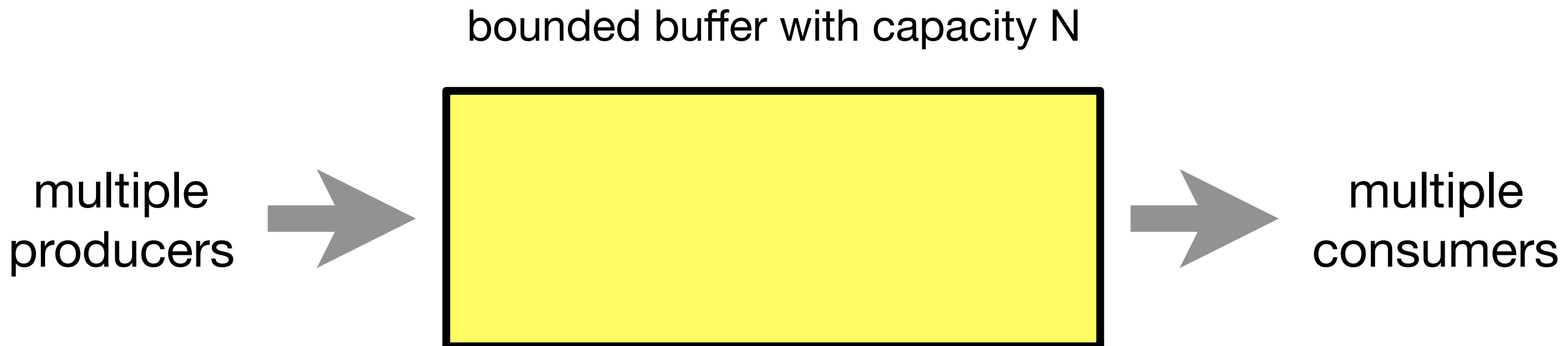
**Bounded**

**buffer**

# Bounded buffer

A bounded buffer lets multiple **producers** and multiple **consumers** share a buffer. Producers write data to the buffer and consumers read data from the buffer.

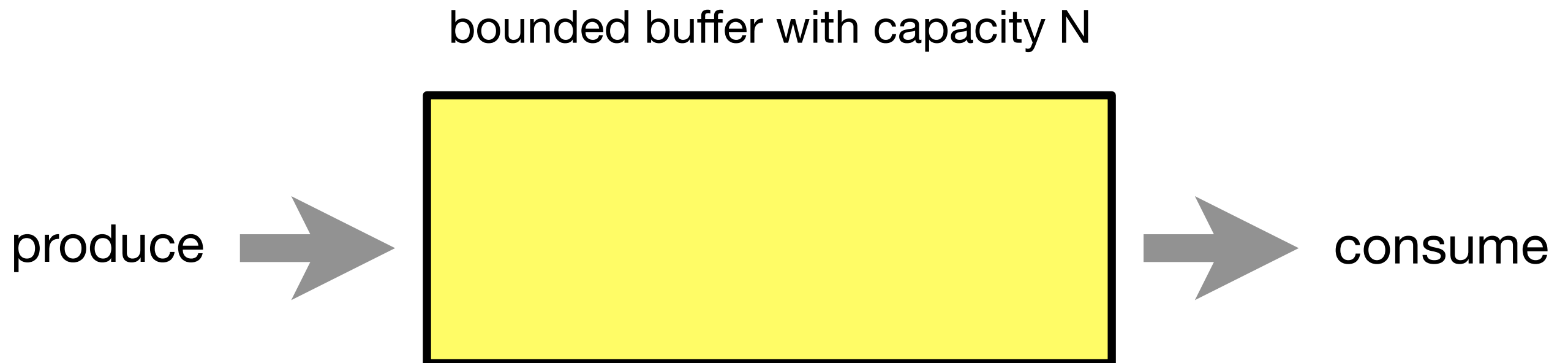
- ★ **Producers** must **block** if the buffer is **full**.
- ★ **Consumers** must **block** if buffer is **empty**.



# Bounded buffer

A bounded buffer lets multiple **producers** and multiple **consumers** share a buffer. Producers write data to the buffer and consumers read data from the buffer.

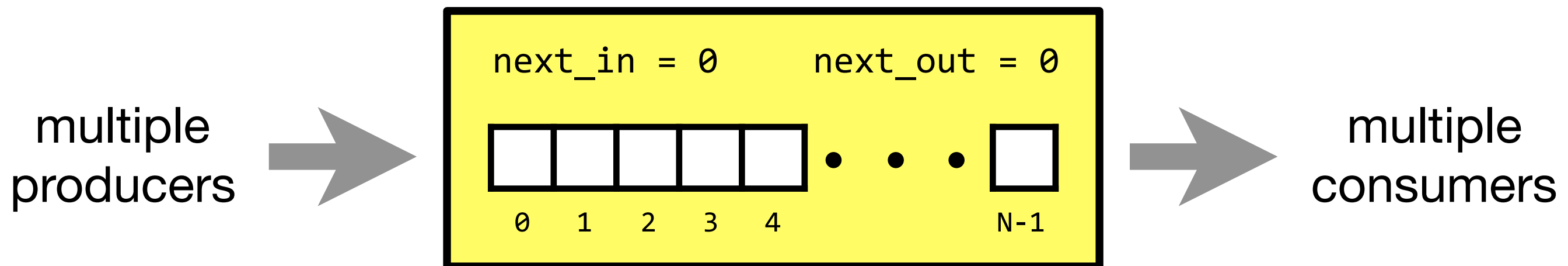
- ★ **Producers** must **block** if the buffer is **full**.
- ★ **Consumers** must **block** if buffer is **empty**.



# Implementation

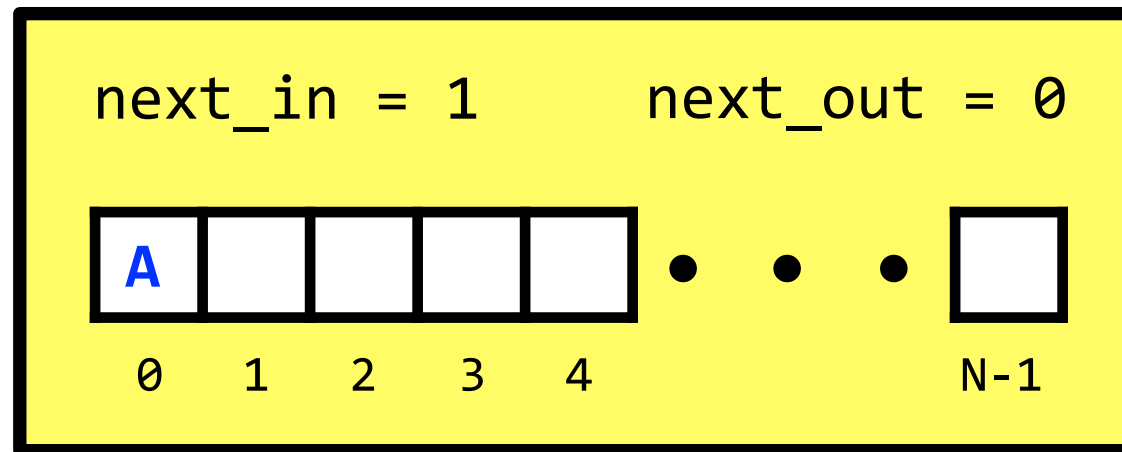
Use an **array** of size **N** to store the data in the buffer. Must keep track of where to produce next item and where to consume next item using two indices **next\_in** and **next\_out**.

bounded buffer with capacity N

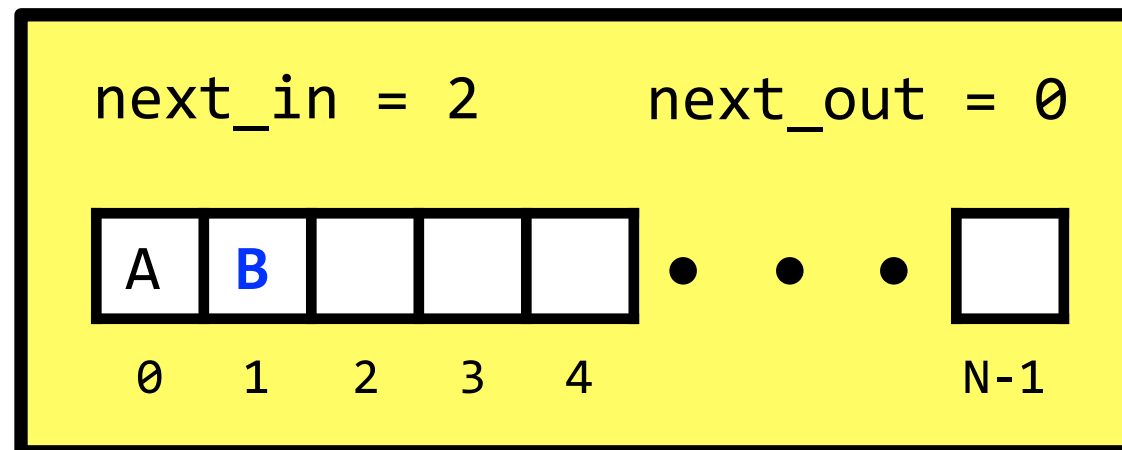


The **next\_in** index must be **incremented** after every **write** to the buffer.

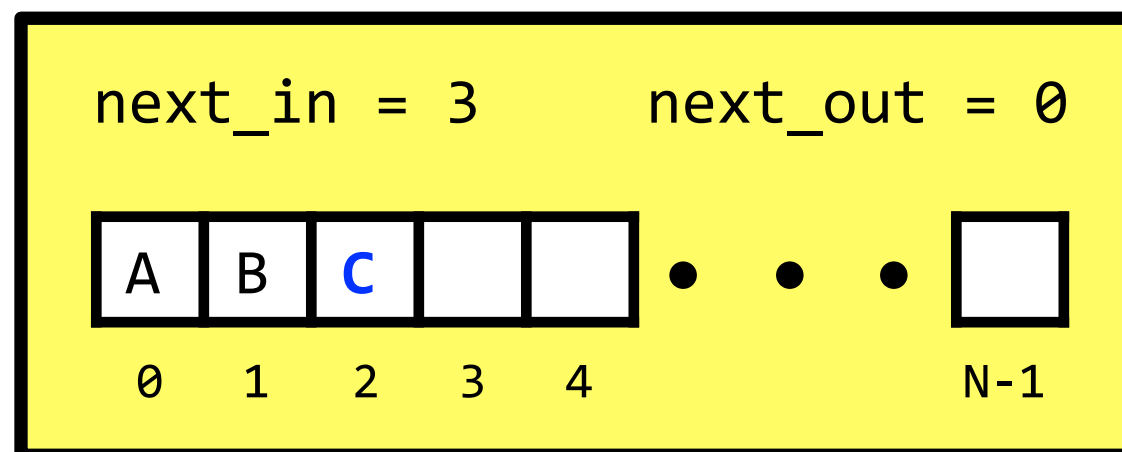
A →



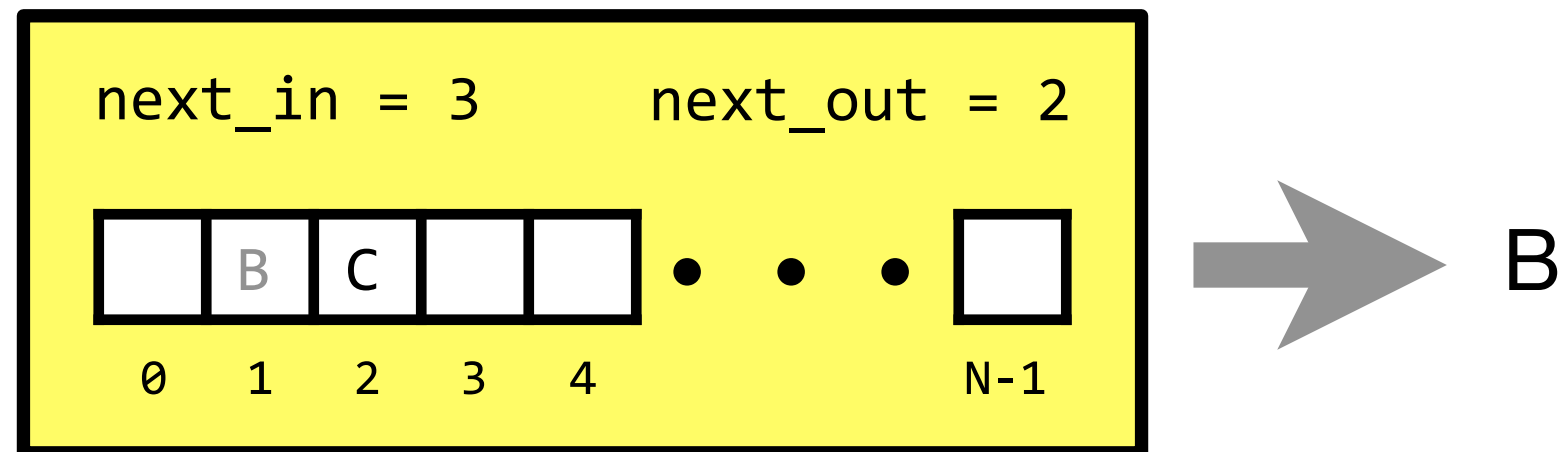
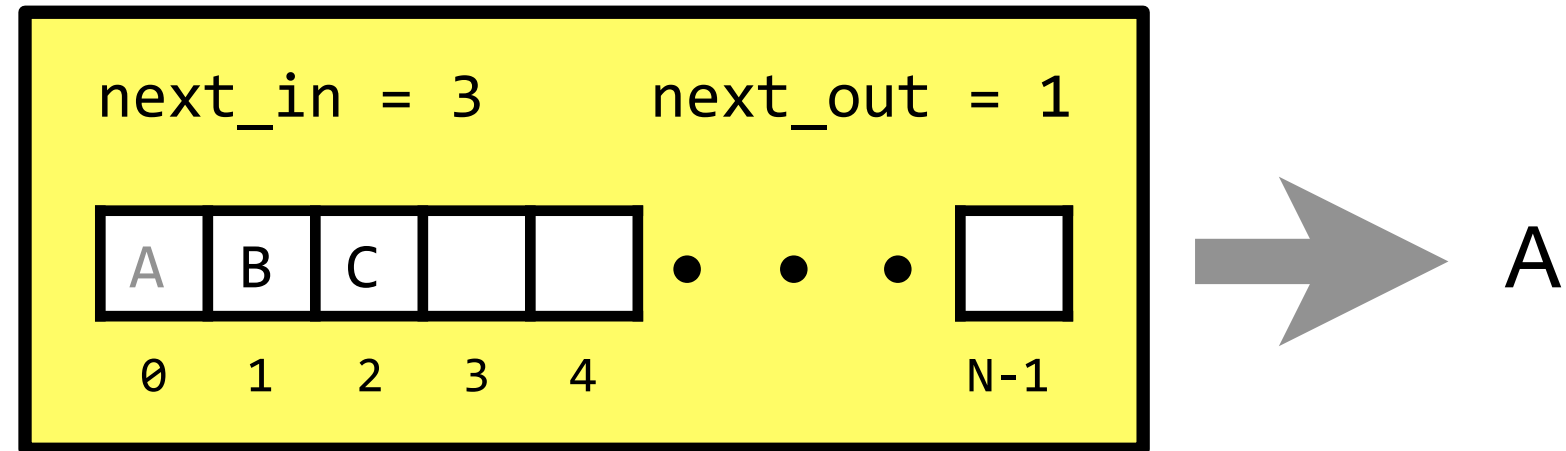
B →



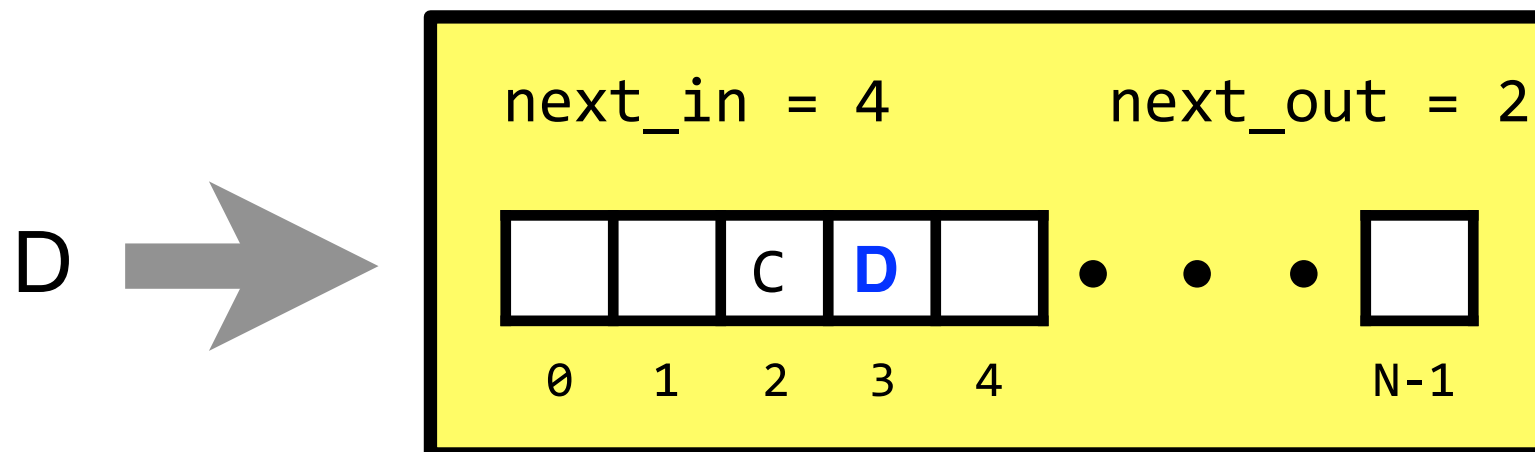
C →



The **next\_out** index must be **incremented** after every **read** from the buffer.

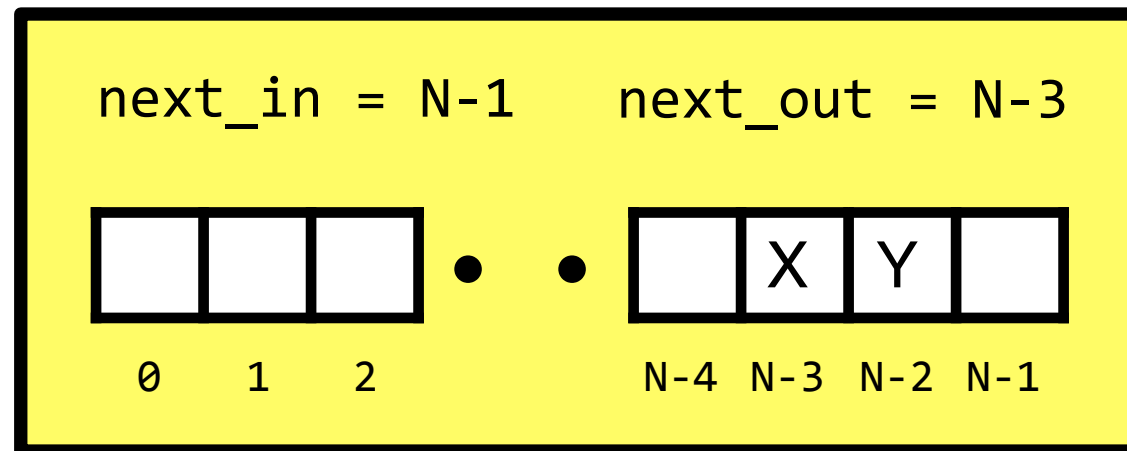


Let's make an additional write to the buffer.



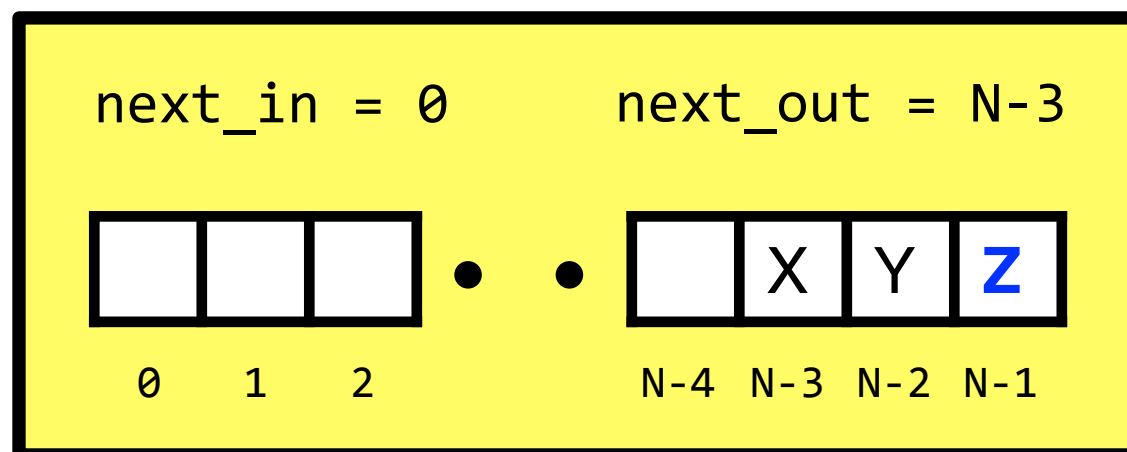


The buffer **wraps around** in a **circular** manner.



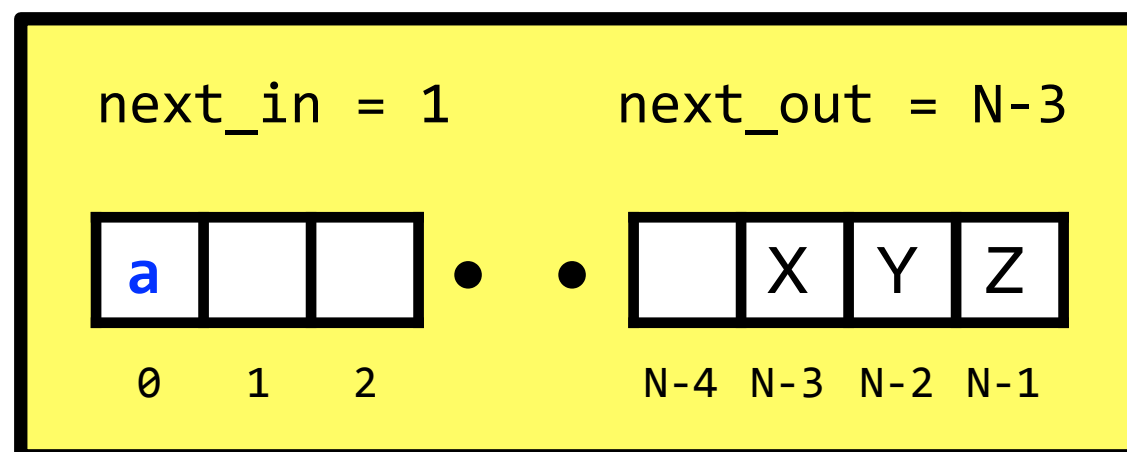
Assume the buffer is in the following state. The next write will be to the last element of the array.

Z →



The next write will be to the first element of the array.

a →



The next write will be to the second element of the array.

# Wrap around

Use the modulo operator `%` to make the index `next_in` wrap around after `N` writes and the index `next_out` wrap around after `N` reads.

## Producer

$$\text{next\_in} = (\text{next\_in} + 1) \% N$$

## Consumer

$$\text{next\_out} = (\text{next\_out} + 1) \% N$$

# Mutual exclusion

All updates to the buffer state must be done in a critical section. More specifically, mutual exclusion must be enforced between the following **critical sections**:

- ★ A **producer** writing to a buffer slot and **updating** `next_in`.
- ★ A **consumer** reading from a buffer slot and **updating** `next_out`

A **binary semaphore** or a **mutex lock** can be used to protect access to the critical sections.

# Synchronisation

**Producers** must **block** if the buffer is **full**. **Consumers** must **block** if the buffer is **empty**.

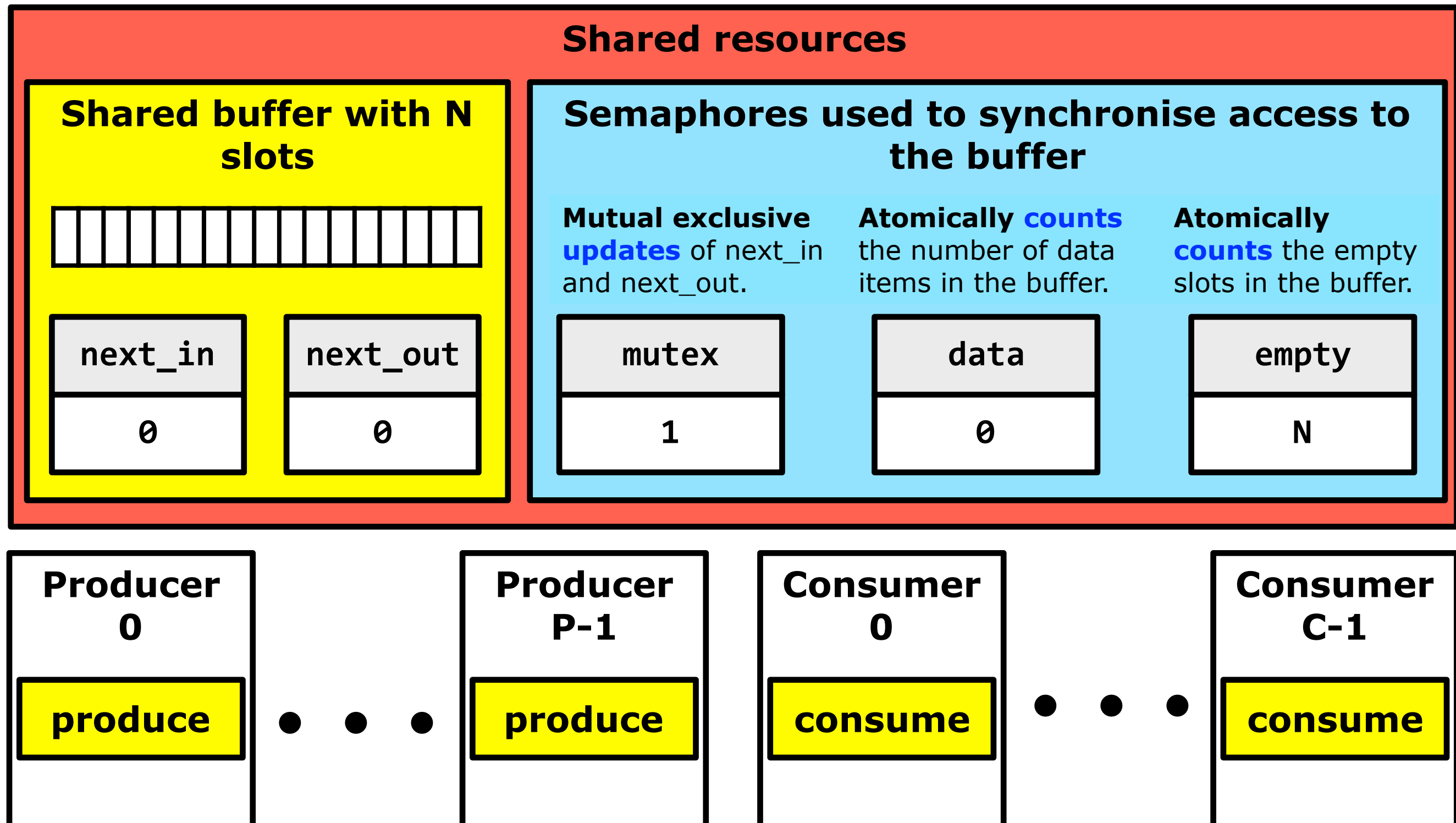
Use one **semaphore** named **empty** to count the empty slots in the buffer.

- ▶ **Initialise** this semaphore to **N**.
- ▶ A **producer** must **wait** on this semaphore before writing to the buffer.
- ▶ A **consumer** will **signal** this semaphore after reading from the buffer.

Use one **semaphore** named **data** to count the number of data items in the buffer.

- ▶ **Initialise** this semaphore to **0**.
- ▶ A **consumer** must **wait** on this semaphore before reading from the buffer.
- ▶ A **producer** will **signal** this semaphore after writing to the buffer.

**P** producers and **C** consumers using a shared bounded buffer of size **N**. Producers writes to buffer at index **next\_in** and consumer reads at index **next\_out**.



## Shared resources

### Shared buffer with N slots



next\_in

next\_out

### Semaphores used to synchronize access to the buffer

Provides mutual exclusive updates of next\_in and next\_out.

mutex

1

Counts the number of data items in the buffer.

data

0

Counts the number of empty slots in the buffer.

empty

N

```
produce(buffer, *data) {
```

1

```
  wait(empty)
```

2

```
  wait(mutex)
```

3

```
  buffer[next_in] = copy(data)
```

4

```
  next_in = next_in + 1 % N
```

5

```
  signal(mutex)
```

6

```
  signal(data)
```

```
}
```

1. **Block** if buffer is **full**, otherwise atomically decrement the empty counter.
2. **Enter critical section**, i.e., make sure no other producer or consumer updates the buffer at the same time.
3. **Copy** data to slot in **buffer**.
4. **Update** **next\_in**.
5. **Leave the critical section**.
6. **Atomically increment** the **data** counter.

## Shared

### Shared buffer with N slots



next\_in

next\_out

### Semaphores used to synchronize access to the buffer

Provides mutual exclusive updates of next\_in and next\_out.

mutex

1

Counts the number of data items in the buffer.

data

0

Counts the number of empty slots in the buffer.

empty

N

```
consume(buffer, *data) {
```

1

```
  wait(data)
```

2

```
  wait(mutex)
```

3

```
  data = copy(buffer[next_out])
```

4

```
  next_out = next_out + 1 % N
```

5

```
  signal(mutex)
```

6

```
  signal(empty)
```

```
}
```

1. **Block** if buffer is **empty**, otherwise atomically decrement data counter.
2. **Enter critical section**, i.e., make sure no other producer or consumer updates the buffer at the same time.
3. **Copy** data **from** slot in **buffer**.
4. **Update** **next\_out**.
5. **Leave** the **critical section**.
6. **Atomically** increment the **empty** counter.

## Shared

### Shared buffer with N slots



next\_in

next\_out

### Semaphores used to synchronize access to the buffer

Provides mutual exclusive updates of next\_in and next\_out.

mutex

1

Counts the number of data items in the buffer.

data

0

Counts the number of empty slots in the buffer.

empty

N

```
produce(buffer, *data) {  
    wait(empty)  
    wait(mutex)
```

```
    buffer[next_in] = copy(data)  
    next_in = next_in + 1 % N
```

```
    signal(mutex)  
    signal(data)
```

```
}
```

```
consume(buffer, *data) {  
    wait(data)  
    wait(mutex)
```

```
    data = copy(buffer[next_out])  
    next_out = next_out + 1 % N
```

```
    signal(mutex)  
    signal(empty)
```

```
}
```





**A pipe is a bounded buffer**

**ls | grep .txt | wc**

# Concurrent writes to a pipe

Is a single write to a pipe atomic, i.e., is the whole amount written in a single write operation not interleaved with data written by any other process?

## POSIX.1-200

- Using `write()` to write less than `PIPE_BUF` bytes **must** be **atomic**: the output data is written to the pipe as a contiguous sequence.
- Writes of **more than** `PIPE_BUF` bytes **may** be **nonatomic**: the kernel may interleave the data, on arbitrary boundaries, with data written by other processes.

The value of `PIPE_BUF` is defined by each implementation, but the minimum is **512** bytes (see `limits.h`).

On Linux:

- `PIPE_BUF` = **4096**.
- The value of `PIPE_BUF` is a consequence of other logic in the kernel, it is not a configuration parameter.

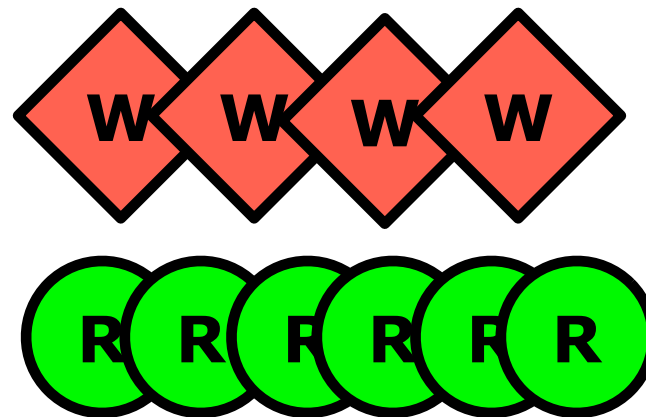
**Readers  
and writers**

# Readers-Writers Problem

A data set is shared among a number of concurrent processes. Readers only read the data set; they do not perform any updates. Writers can both read and write.

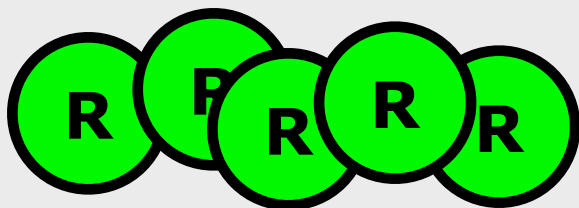
Only one single writer can access the shared data at the same time, any other writers or readers must be blocked.

Shared data accessed by  
readers and writers

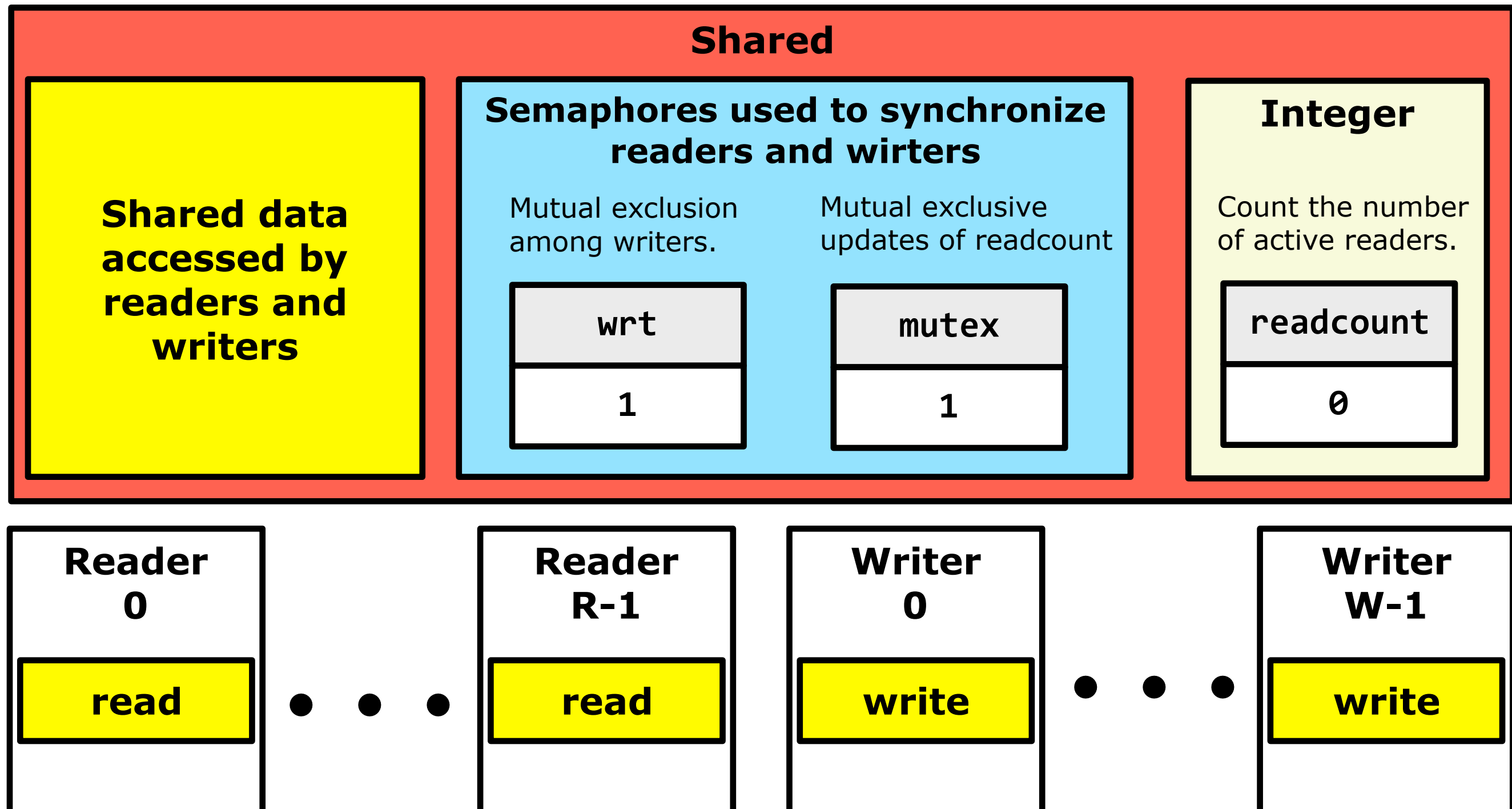


Allow multiple readers to read at the same time, any writers must be blocked

Shared data accessed by  
readers and writers



**R** readers and **W** writers access the same shared data set.  
Allow multiple readers to read at the same time.  
Only one single writer can access the shared data at the same time.



## Shared

**Shared data  
accessed by  
readers and  
writers**

**Semaphores used to synchronize  
readers and writers**

Mutual exclusion  
among writers.

wrt

Mutual exclusive  
updates of readcount

mutex

**Integer**

Count the number  
of active readers.

readcount

```
write(buffer, *data) {
```

① `wait(wrt);`

② `// Write shared data`

③ `signal(wrt);`

```
}
```

1. Enter critical section, block if other task is writing.
2. Inside critical section, write to shared data structure.
3. Leave critical section.

```
read(buffer, *data) {  
    wait(mutex);  
  
    readcount++;  
    if readcount == 1:  
        wait(wrt);  
  
    signal(mutex);  
  
    // Read shared data  
  
    wait(mutex);  
  
    readcount--;  
    if readcount == 0:  
        signal(wrt);  
  
    signal(mutex);  
}
```

## Semaphores

mutex

wrt

## Integral counter

readcount

### Entering

All readers need to mutually exclusively increment readcount when entering.

The first reader also need to block if a writer is active.

### Leaving

All readers need to mutually exclusively decrement readcount when leaving.

The last reader also need to unblock any waiting writer.

# Readers-Writers Problem

A data set is shared among a number of concurrent processes.

- Only one single writer can access the shared data at the same time, any other writers or readers must be blocked.
- Allow multiple readers to read at the same time, any writers must be blocked.

**Semaphores `mutex`** and **`wrt`**, both initialized to 1.

**Integer `readcount`** initialized to 0.

```
write(buffer, *data) {
```

```
    wait(wrt);
```

```
    // Write shared data
```

```
    signal(wrt);
```

```
}
```

```
read(buffer, *data) {
```

```
    wait(mutex);
```

```
    readcount++;
```

```
    if readcount == 1:
```

```
        wait(wrt);
```

```
    signal(mutex);
```

```
    // Read shared data
```

```
    wait(mutex);
```

```
    readcount--;
```

```
    if readcount == 0:
```

```
        signal(wrt);
```

```
    signal(mutex);
```

```
}
```



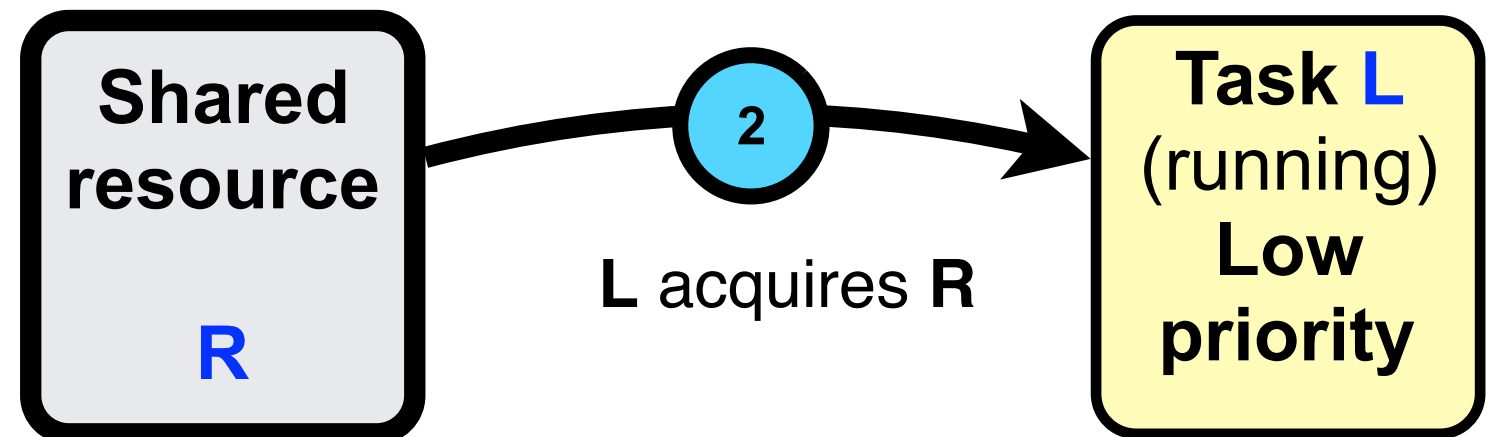
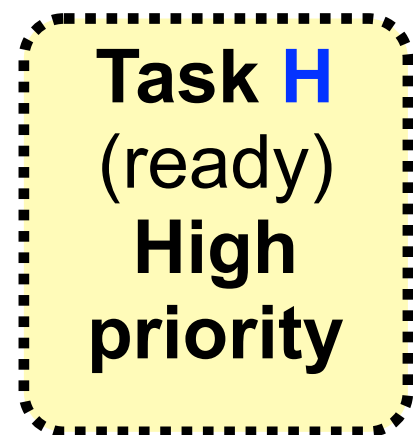
# **Priority inversion**

# Scenario

(1)

A high priority task **H** is blocked due to a low priority task **L** holding a shared resource **R** (for example a binary semaphore) **H** wants to acquire.

- 1) Consider two tasks H and L, of high and low priority respectively, either of which can acquire exclusive use of a shared resource R.
- 2) L acquires R.

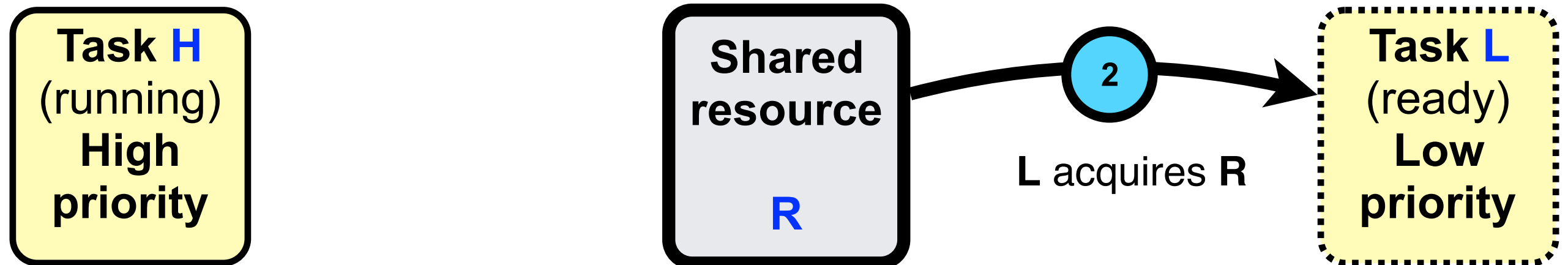


# Scenario

(1)

A high priority task **H** is blocked due to a low priority task **L** holding a shared resource **R** (for example a binary semaphore) **H** wants to acquire.

- 1) Consider two tasks H and L, of high and low priority respectively, either of which can acquire exclusive use of a shared resource R.
- 2) L acquires R.

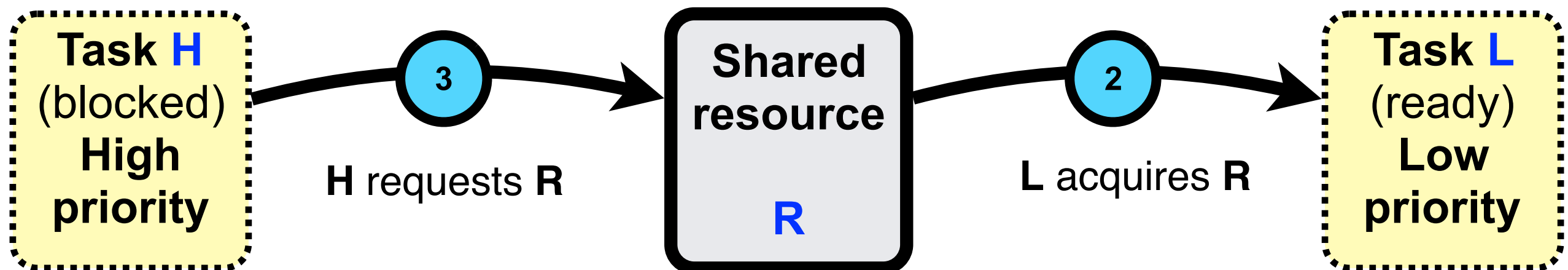


# Scenario

(1)

A high priority task **H** is blocked due to a low priority task **L** holding a shared resource **R** (for example a binary semaphore) **H** wants to acquire.

- 1) Consider two tasks H and L, of high and low priority respectively, either of which can acquire exclusive use of a shared resource R.
- 2) L acquires R.
- 3) If H attempts to acquire R after L has acquired it, then H becomes blocked until L relinquishes the resource.



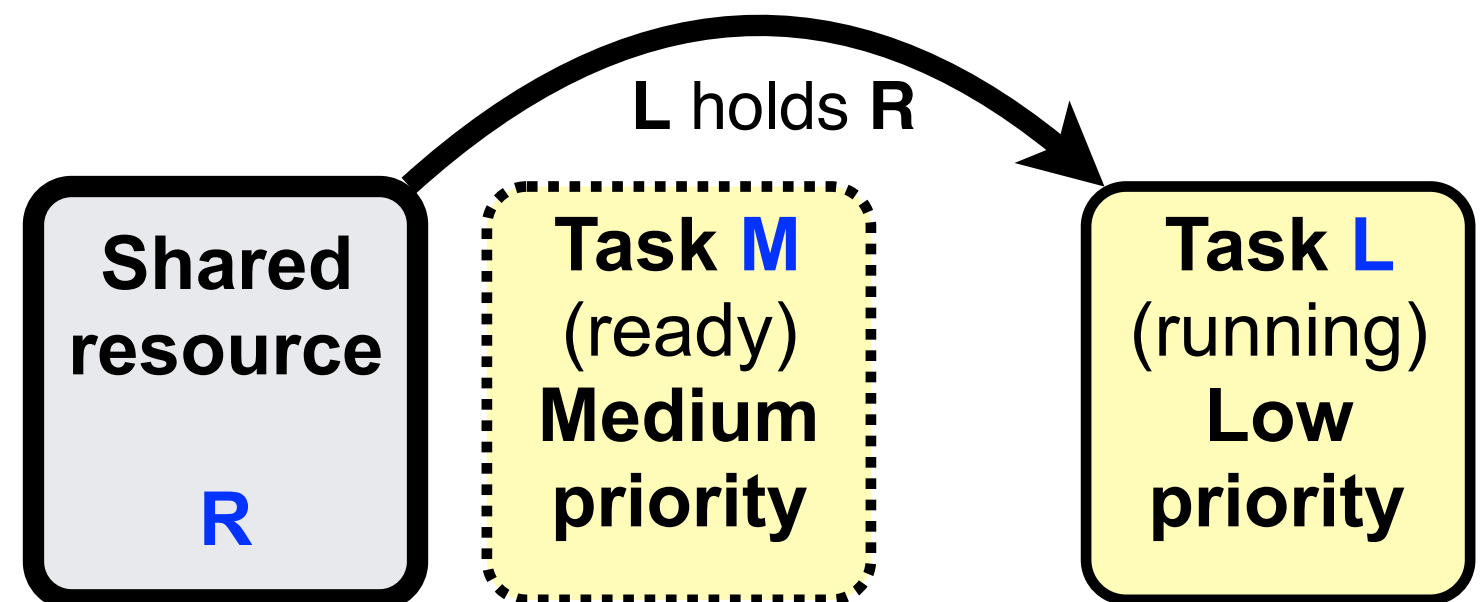
- 4) Sharing an exclusive-use resource (R in this case) in a well-designed system typically involves L relinquishing R promptly so that H (a higher priority task) does not stay blocked for excessive periods of time.

# Scenario

(2)

Let's introduce a **medium priority task M**, i.e., a task with priority between **high priority task H** and **low priority task L**.

Task M of medium priority ( $p(L) < p(M) < p(H)$ , where  $p(x)$  represents the priority for task  $x$ ) becomes ready (to run) during L's use of R.



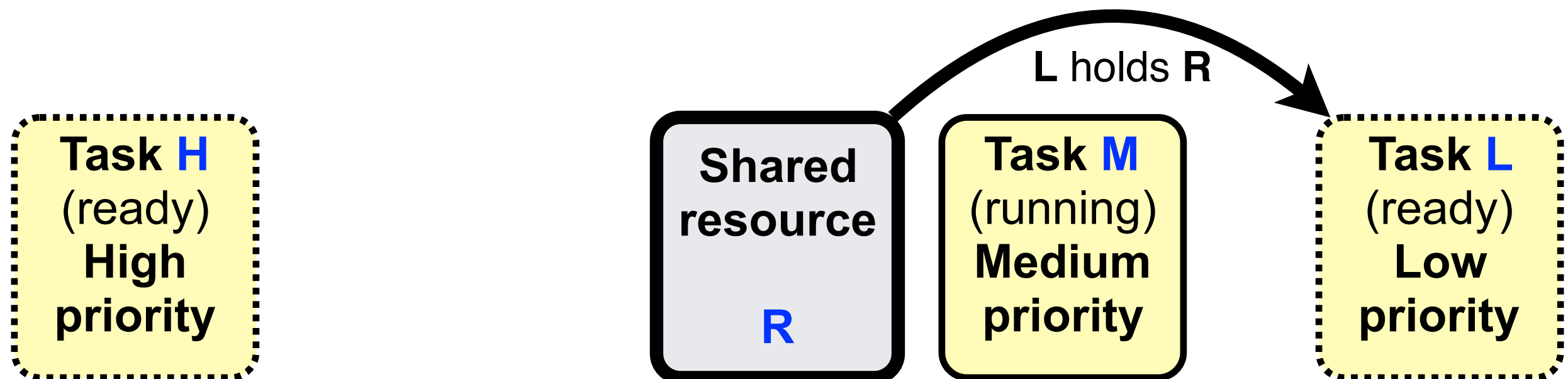
# Scenario

(2)

Let's introduce a third task **M** with **medium priority**, i.e., a priority between **high priority task H** and **low priority task L**.

Task M of medium priority ( $p(L) < p(M) < p(H)$ , where  $p(x)$  represents the priority for task  $x$ ) becomes ready (to run) during L's use of R.

- 1) M being higher in priority than L preempts R, causing L to not be able to relinquish R promptly.
- 2) H becomes ready to run.



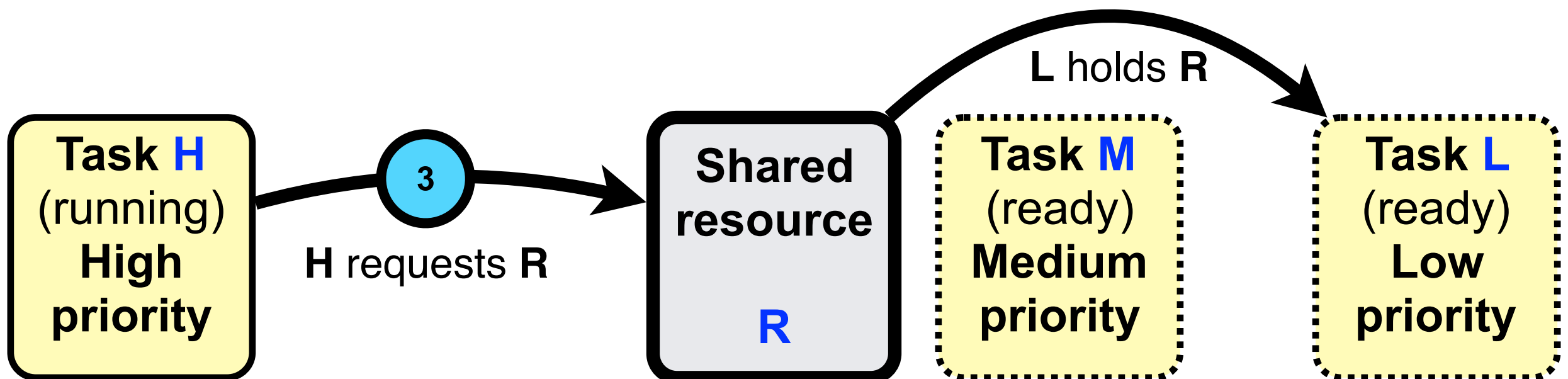
# Scenario

(2)

Let's introduce a third task **M** with **medium priority**, i.e., a priority between **high priority task H** and **low priority task L**.

Task M of medium priority ( $p(L) < p(M) < p(H)$ , where  $p(x)$  represents the priority for task  $x$ ) becomes ready (to run) during L's use of R.

- 1) M being higher in priority than L preempts R, causing L to not be able to relinquish R promptly.
- 2) H becomes ready to run.
- 3) H request to acquire R.



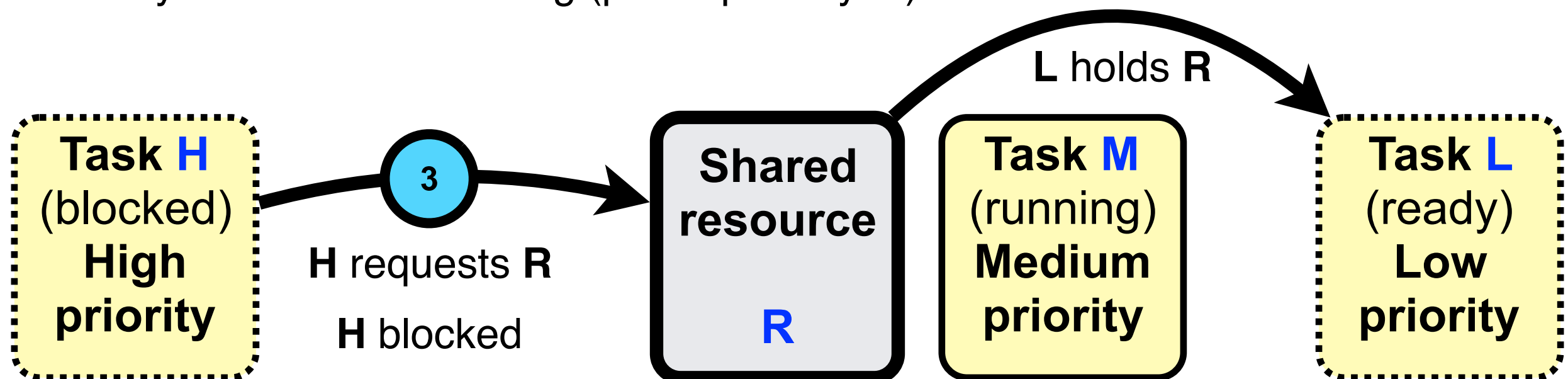
# Scenario

(2)

Let's introduce a third task **M** with **medium priority**, i.e., a priority between **high priority task H** and **low priority task L**.

Task M of medium priority ( $p(L) < p(M) < p(H)$ , where  $p(x)$  represents the priority for task  $x$ ) becomes ready (to run) during L's use of R.

- 1) M being higher in priority than L preempts R, causing L to not be able to relinquish R promptly.
- 2) H becomes ready to run.
- 3) H request to acquire R.
- 4) H (the highest priority process) becomes blocked since H cannot acquire R hold by L but L is not running (preempted by M).



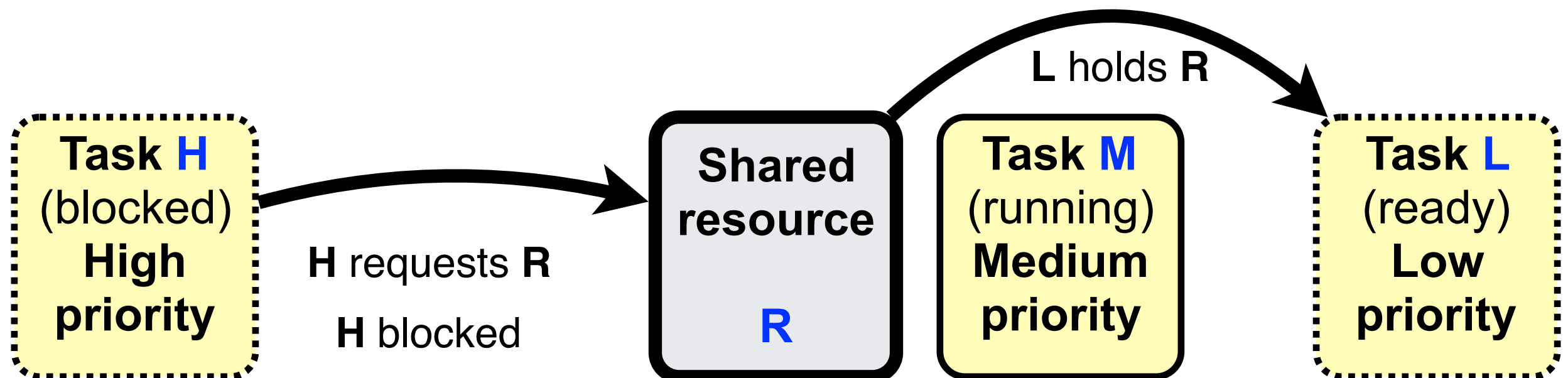


# Priority inversion

A higher priority task is “preempted” by a lower priority one.

A medium priority task **M** preempts a low priority task **L** holding a shared resource **R**. A high priority task **H** is not able to run, although it has higher priority than **M** and **H** and **M** does not compete for **R**.

Solution to the priority inversion problem?



# Priority inheritance protocol

When a task blocks one or more high-priority tasks, it ignores its original priority assignment and executes its critical section at an elevated priority level. After executing its critical section and releasing its locks, the process returns to its original priority level.

- ★ Suppose **H** is blocked by **L** for some shared resource **R**.
- ★ The priority inheritance protocol requires that **L** executes its critical section at **H**'s (high) priority.
- ★ As a result, **M** will be unable to preempt **L** and **M** will be blocked.
- ★ That is, the higher-priority job **M** must wait for the critical section of the lower priority job **L** to be executed, because **L** has inherited **H**'s priority.
- ★ When **L** exits its critical section, it regains its original (low) priority and awakens **H** (which was blocked by **L**).
- ★ **H**, having high priority, preempts **L** and runs to completion. This enables **M** and **L** to resume in succession and run to completion.

# Priority inheritance and mutexes

What if a higher priority task is blocked on a mutex hold (owned) by a lower priority task?

- ★ By default, if a task with a higher priority than the mutex owner attempts to lock a mutex, then the effective priority of the current owner is increased to that of the higher-priority blocked thread waiting for the mutex.
- ★ The current owner's effective priority is again adjusted when it unlocks the mutex; its new priority is the maximum of its own priority and the priorities of those threads it still blocks, either directly or indirectly.