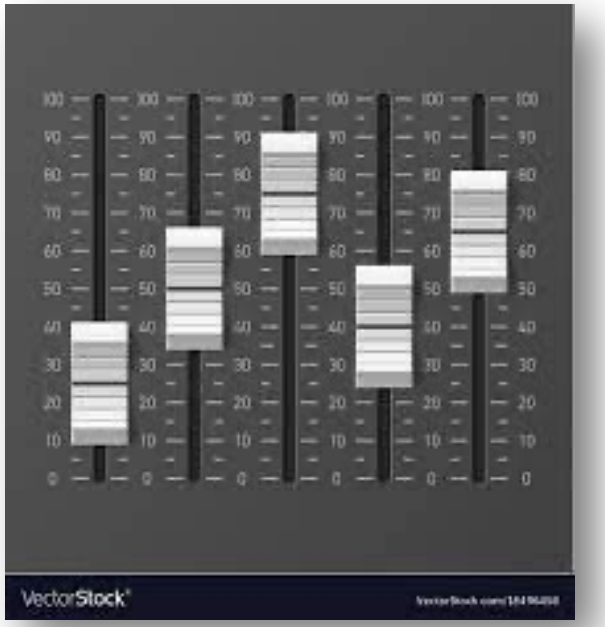
CSE113: Parallel Programming

Feb. 2, 2022

- **Topics**:
  - Concurrent data structure specifications
    - Breaking sequential consistency
    - Linearizability
  - Input/output concurrent queues



Announcements

- Expect HW1 grades by Friday
  - Let us know if there are any issues ASAP
  - Sanya is traveling so there may be some delay

- Homework 2 is due on Friday
  - Please use office hours or piazza if you have questions
  - Remember, nights and weekends have no guarantees of responses. Get started ASAP!
  - I have office hours tomorrow. They are hybrid; please indicate on the sign up sheet if you are in person or remote.
  - Reese has office hours after class today; Tim has office hours on Thursday. Sanya has them on Friday

Announcements

- Homework 3 assigned on Friday by midnight
  - Should have material to get started by end of Friday lecture

- Midterm is released in 1 week
  - asynchronous, 1 week (no time limit)
  - Open note, open internet (to a reasonable extent: no googling exact questions or asking questions on forums)
  - do not discuss with classmates AT ALL while the test is active
  - **No late tests will be accepted.**

Homework clarifications

- Conditional variables
  - They are **not** allowed in your solution, but they are interesting
  - https://en.cppreference.com/w/cpp/thread/condition_variable

- Part 2: reader/writer
  - You cannot significantly slow down readers in isolation

- Part 3: keeping the structure:
  - you can re-arrange functions, just no changing the high-level implementation

Homework clarifications

- You can share results, but not code

Today’s Quiz

- Due Tomorrow by midnight

Previous quiz

It is impossible to use objects that are not thread-safe in a concurrent program.

- ◯ True
- ◯ False

Previous quiz

Non-locking objects do not use mutexes in their implementation. This is beneficial because:

- ◯ it is potentially faster
- ◯ it is easier to reason about
- ◯ it is easier to extend

Previous quiz

When multiple threads access a concurrent object, only 1 possible execution is allowed. We reason about that execution by sequentializing object method calls and it is called sequential consistency

- ◯ True
- ◯ False

Previous quiz

Write a few sentences about the pros and cons of using a concurrent data structure vs. using mutexes to protect data structures that are not thread-safe.

Review

Concurrent Data Structures

Shared memory concurrent objects

```
printf("hello world\n");
```

How does it actually work?

```
printf("h");
printf("e");
printf("l");
printf("l");
printf("o");
```

concurrent queue

```
terminal:
$ ./a.out
```

./a.out

terminal display

You can force a flush with: `fflush(stdout)`

Bank account example

global variables:

```
int tylers_account = 0;
```

Tyler's coffee addiction:

```
for (int i = 0; i < HOURS; i++) {
   tylers_account -= 1;
}
```

Tyler's employer

```
for (int j = 0; j < HOURS; j++) {
   tylers_account += 1;
}
```

Bank account example

global variables:

```
bank_account tylers_account;
```

Tyler's coffee addiction:

```
for (int i = 0; i < HOURS; i++) {
   tylers_account.buy_coffee();
}
```

Tyler's employer

```
for (int j = 0; j < HOURS; j++) {
   tylers_account.get_paid();
}
```

```
class bank_account {
  public:
    bank_account() {
      balance = 0;
    }

    void buy_coffee() {
      balance -= 1;
    }

    void get_paid() {
      balance += 1;
    }

  private:
    int balance;
};
```

Bank account example

global variables:

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for (int i = 0; i < HOURS; i++) {
   tylers_account.buy_coffee();
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Tyler's employer

```
for (int j = 0; j < HOURS; j++) {
   tylers_account.get_paid();
}
```

what happens if we run these concurrently?

```
class bank_account {
  public:
    bank_account() {
      balance = 0;
    }

    void buy_coffee() {
      balance -= 1;
    }

    void get_paid() {
      balance += 1;
    }

  private:
    int balance;
};
```

Non-thread-Safe Data Structures

global variables:

```
bank_account tylers_account;
mutex m;
```

Tyler's coffee addiction:

```
for (int i = 0; i < HOURS; i++) {
   m.lock();
   tylers_account.buy_coffee();
   m.unlock();
}
```

Tyler's employer

```
for (int j = 0; j < HOURS; j++) {
   m.lock();
   tylers_account.get_paid();
   m.unlock();
}
```

```
class bank_account {
  public:
    bank_account() {
      balance = 0;
    }

    void buy_coffee() {
      balance -= 1;
    }

    void get_paid() {
      balance += 1;
    }

  private:
    int balance;
};
```

The object is not "thread safe"

Thread-safe Data Structures

Bank account example

global variables:

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bank_account tylers_account;
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Tyler's coffee addiction:

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for (int i = 0; i < HOURS; i++) {
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class bank_account {
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    bank_account() {
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    }

    void buy_coffee() {
      m.lock();
      balance -= 1;
      m.unlock();
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    void get_paid() {
      m.lock();
      balance += 1;
      m.unlock();
    }

  private:
    int balance;
    mutex m;
};
```

Non-locking Concurrent Data Stuctures

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global variables:

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bank_account tylers_account;
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for (int i = 0; i < HOURS; i++) {
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```

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```
for (int j = 0; j < HOURS; j++) {
   tylers_account.get_paid();
}
```

```
class bank_account {
  public:
    bank_account() {
      balance = 0;
    }

    void buy_coffee() {
      atomic_fetch_add(&balance, -1);
    }

    void get_paid() {
      atomic_fetch_add(&balance, 1);
    }

  private:
    atomic_int balance;
};
```

Sequential Consistency

Global variable:

```
CQueue<int> q;
```

Thread 0:

```
q.enq(6);
q.enq(7);
```

Thread 1:

```
int t0 = q.deq();
int t1 = q.deq();
```


Can t0 == 0 and t1 == 6?

Global variable:

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CQueue<int> q;
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Thread 0:

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int t0 = q.deq();
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q.enq(6);
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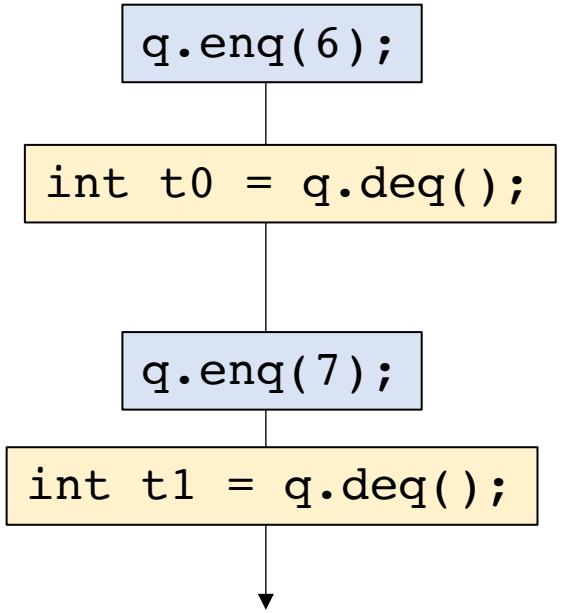

Can t0 == 0 and t1 == 6?

Valid execution!

Are there others?

Next example

Global variable:

```
CQueue<int> s;
```

Thread 0:

```
s.enq(7);
int t0 = q.dec();
```

Thread 1:

```
int t1 = q.dec();
```

Is it possible for both t0 and t1 to be 0 at the end?

Global variable:

```
CQueue<int> s;
```

Thread 0:

```
s.enq(7);
int t0 = q.dec();
```

Thread 1:

```
int t1 = q.dec();
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```
q.enq(7);
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int t0 = q.deq();
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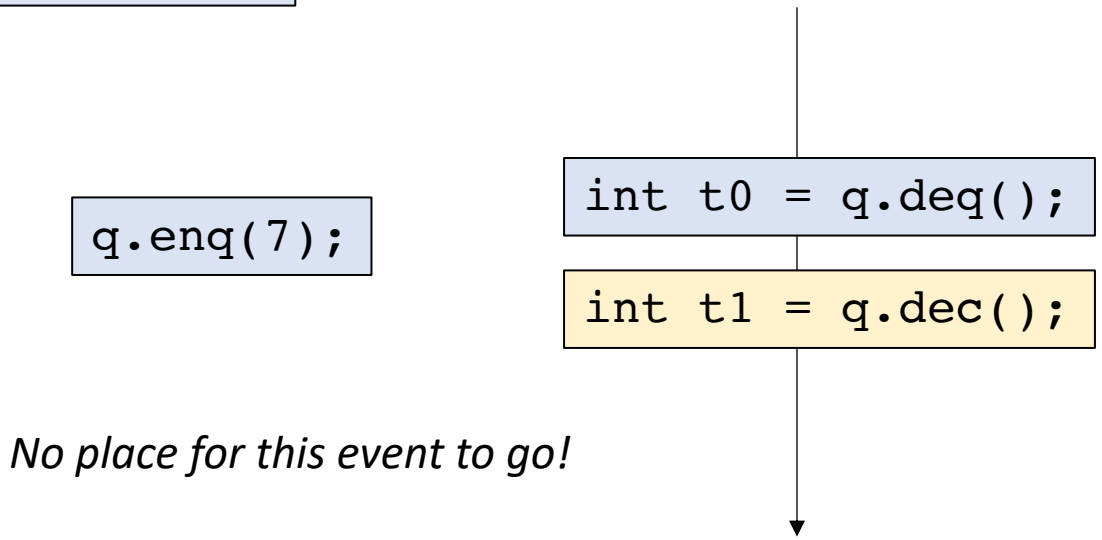


No place for this event to go!

Is it possible for both t0 and t1 to be 0 at the end?

New material!

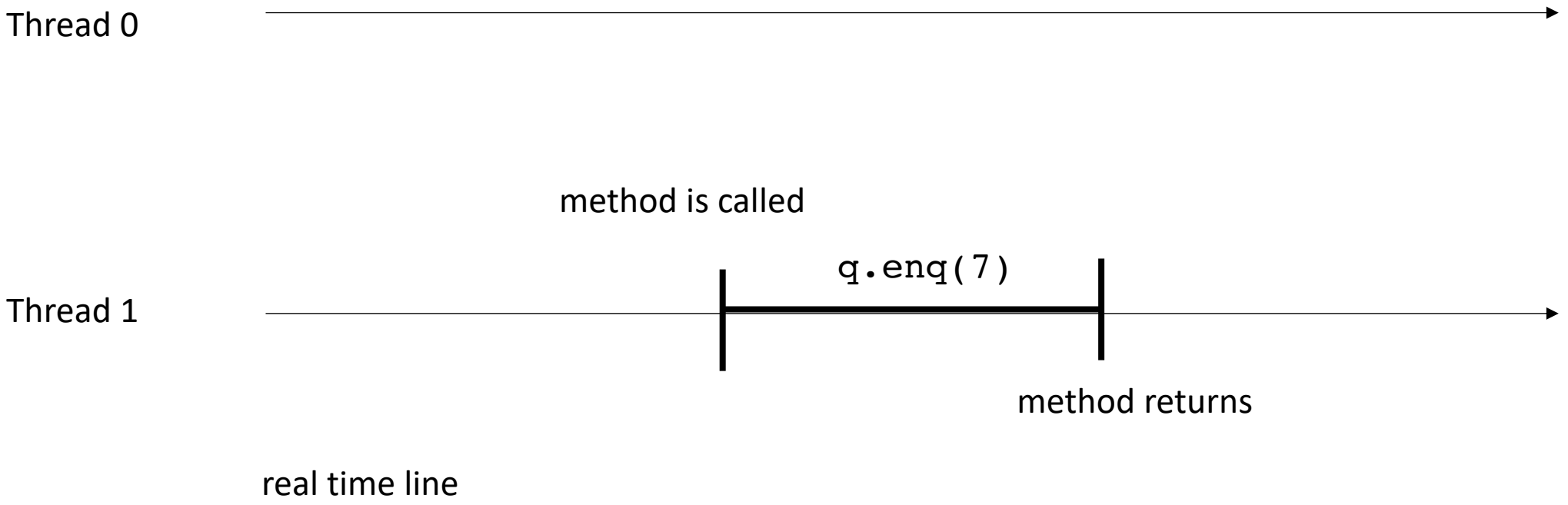
Schedule

- **Problems with sequential consistency**
- Linearizability
- Specialized concurrent queues

Sequential consistency and real time

- Add in real time:

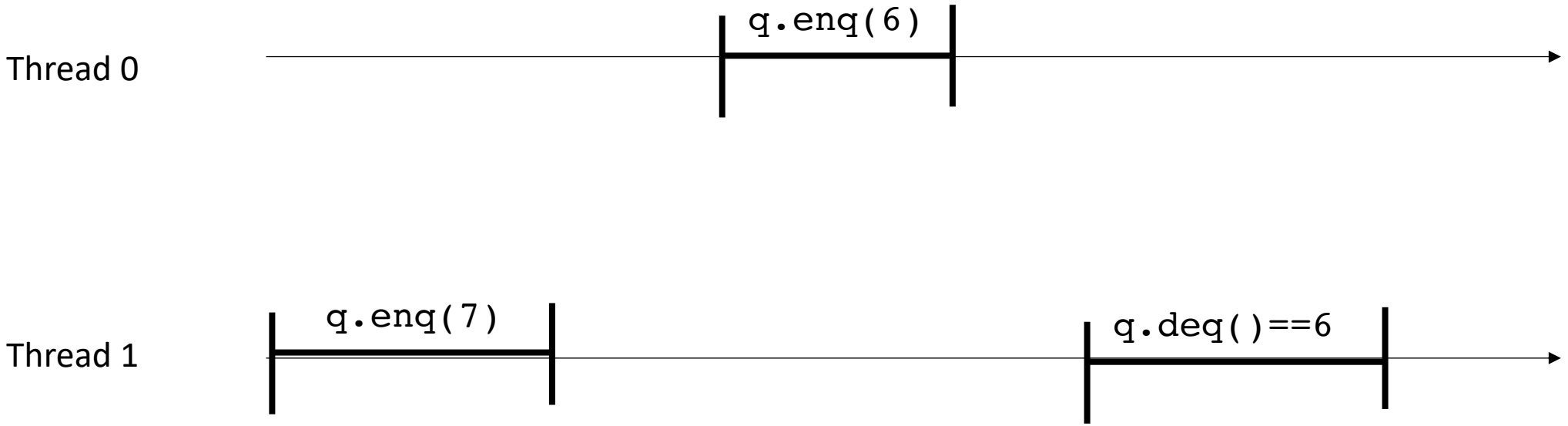
each method as a start, and end time stamp



Sequential consistency and real time

- Add in real time:

This timeline seems strange...

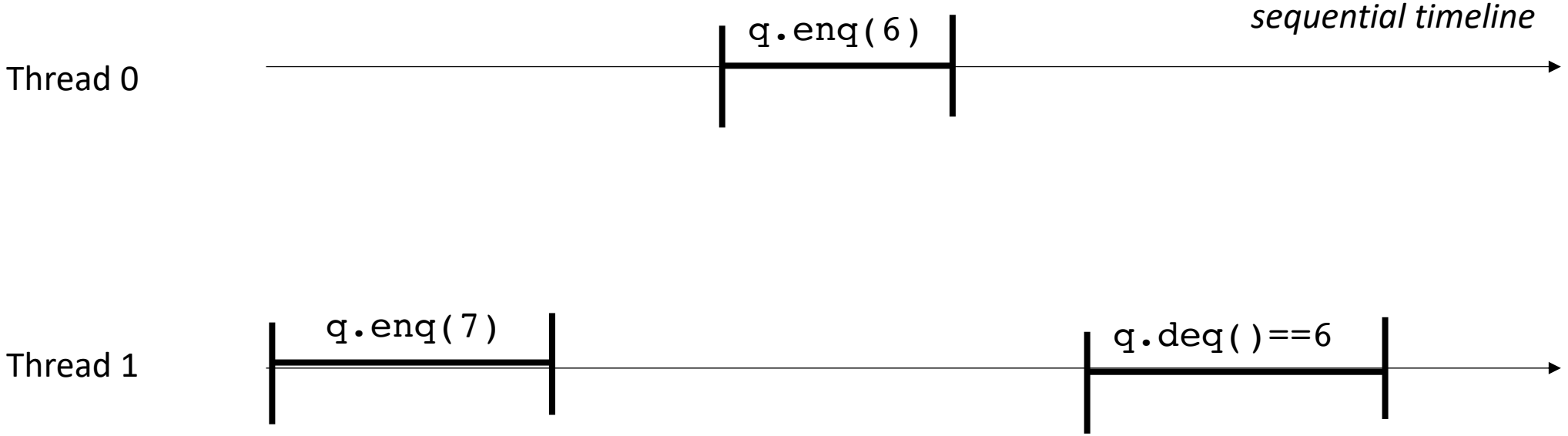


Sequential consistency and real time

- Add in real time:

This execution is allowed in sequential consistency!

SC doesn't care about real time, only if it can construct its virtual sequential timeline



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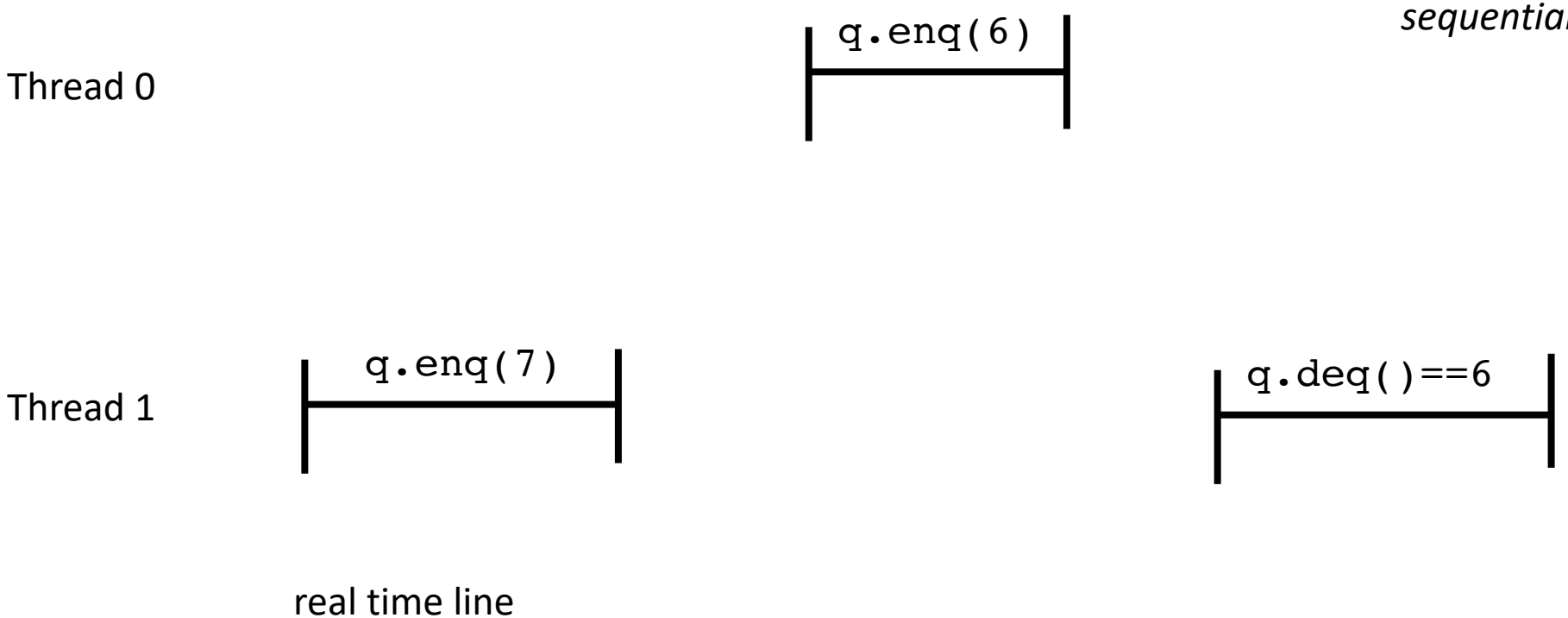

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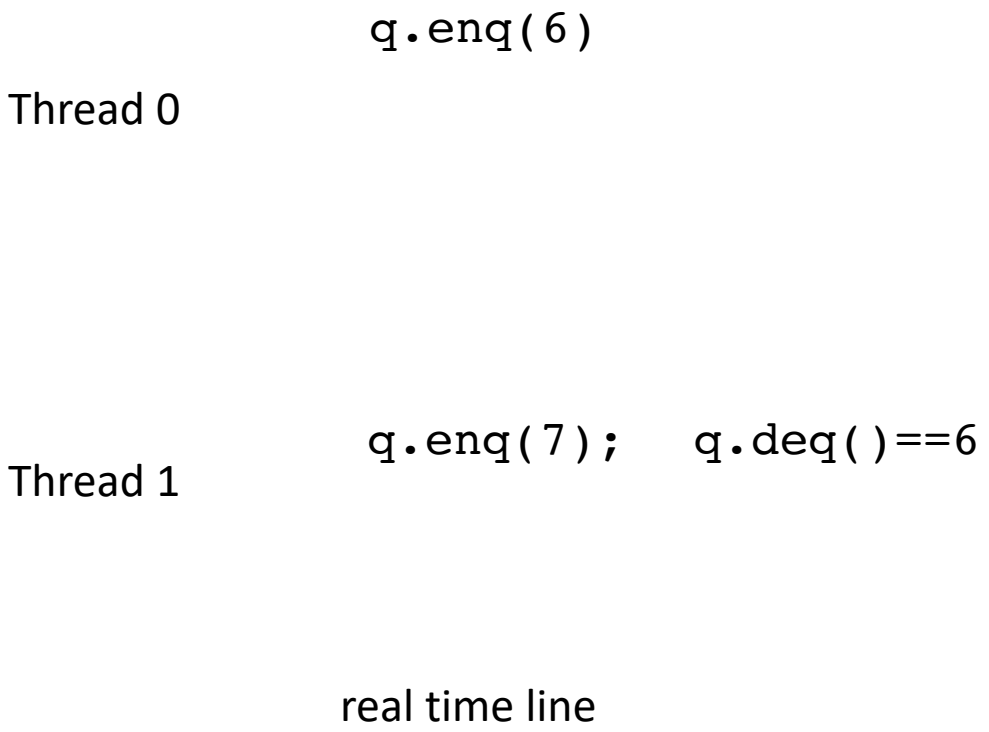

Sequential consistency and real time

- Add in real time:

```
                q.enq(6)
Thread 0

                q.enq(7);   q.deq()==6
Thread 1

real time line
```

This execution is allowed in sequential consistency!

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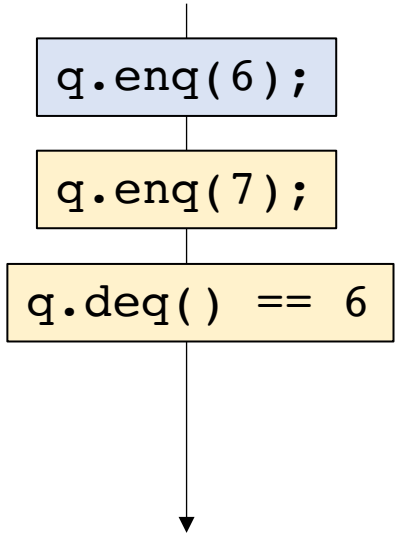
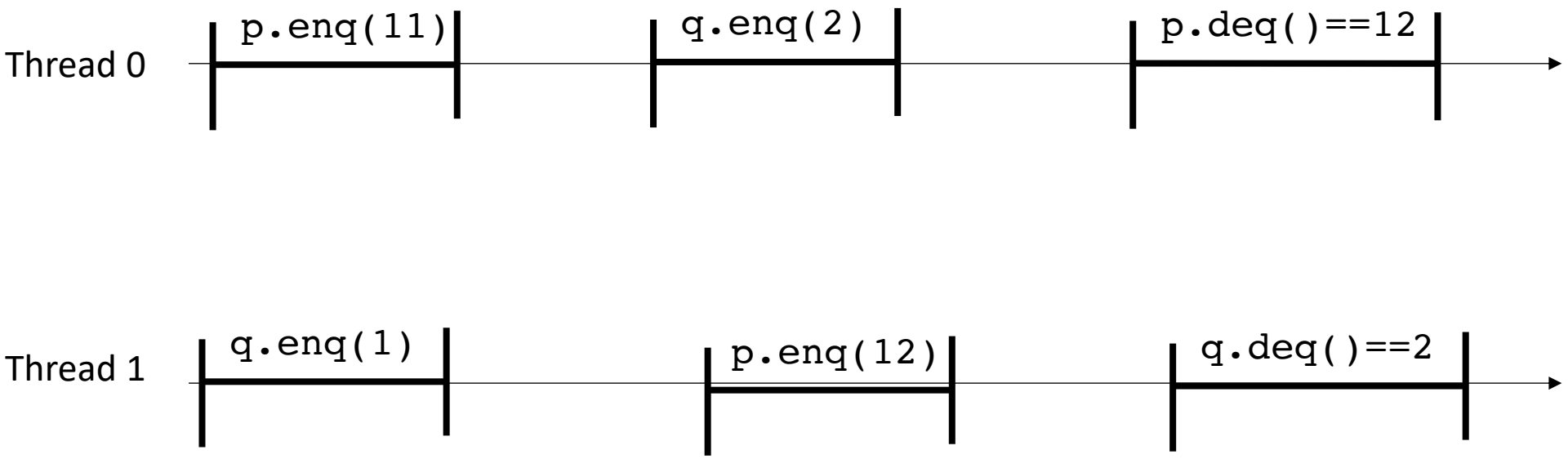


Sequential consistency and real time

- Add in real time:

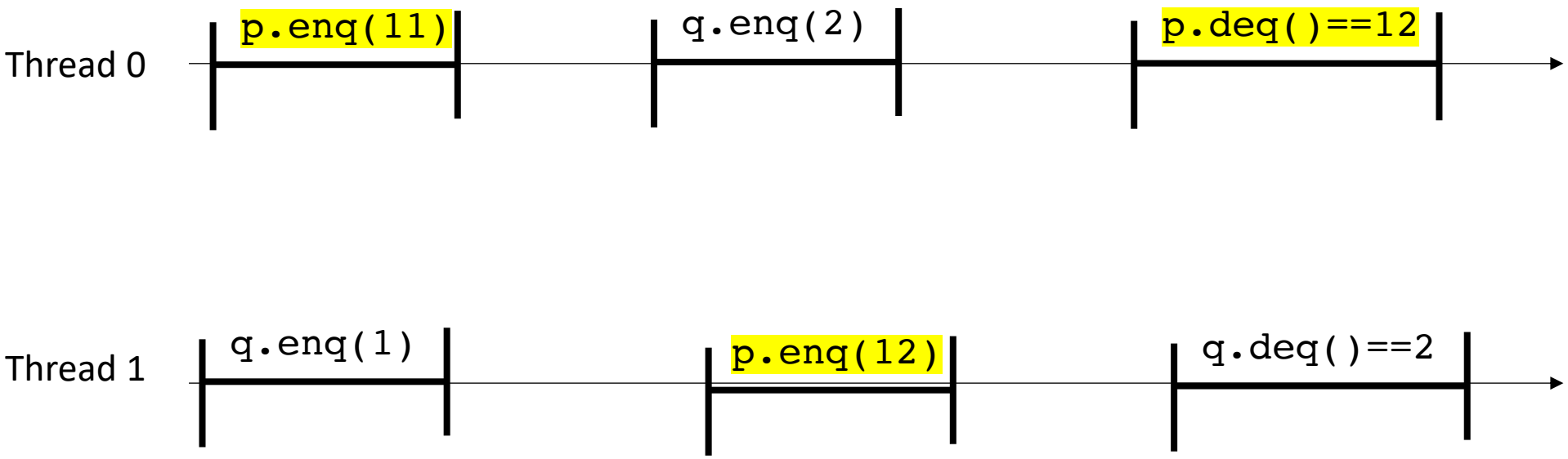
2 objects now: p and q



Sequential consistency and real time

- Add in real time:

2 objects now: p and q
Consider each object in isolation



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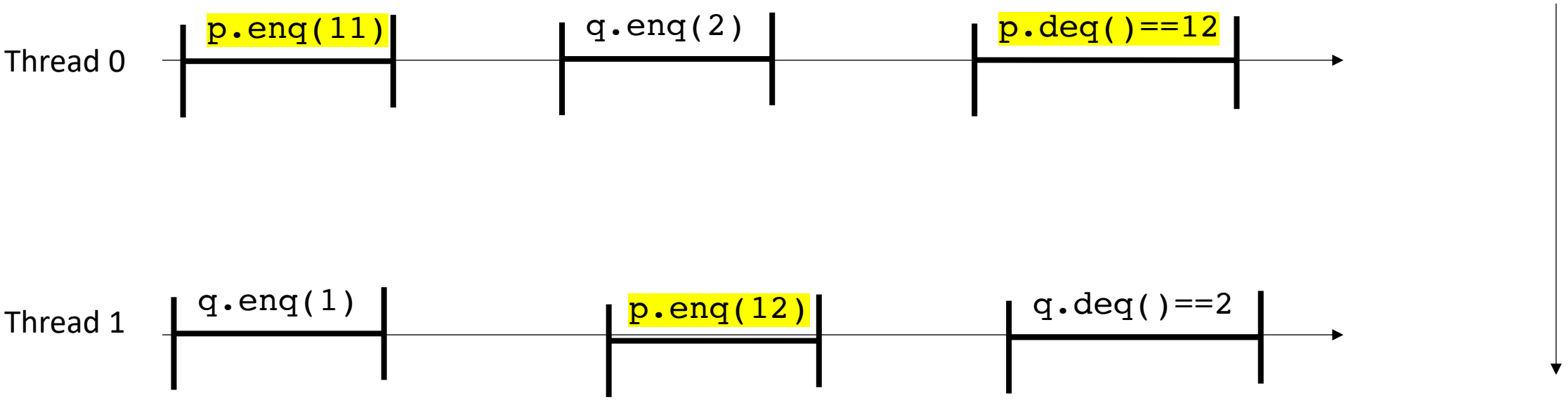

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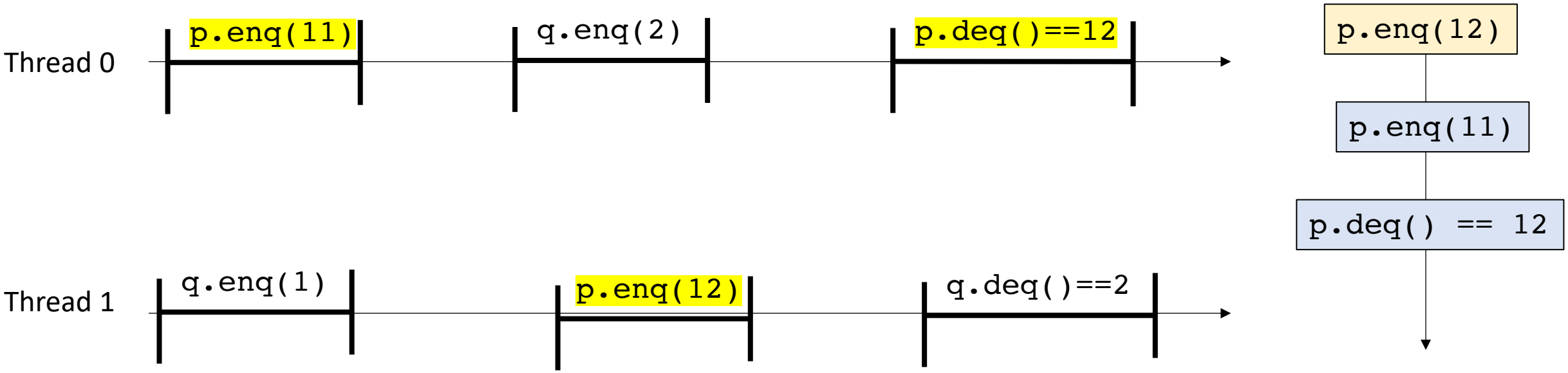

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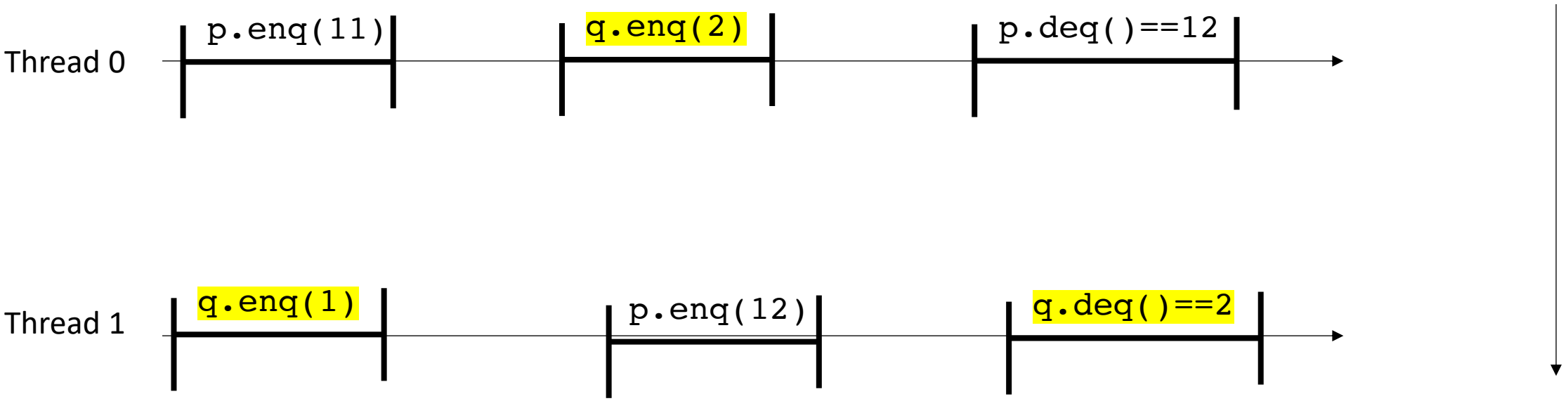

Sequential consistency and real time

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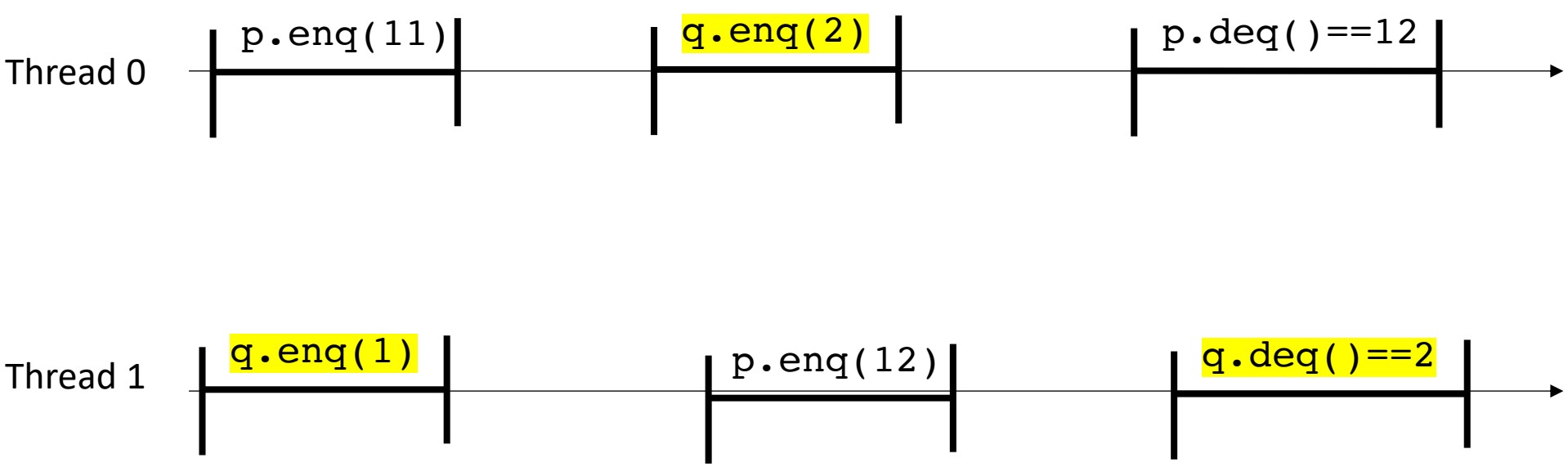
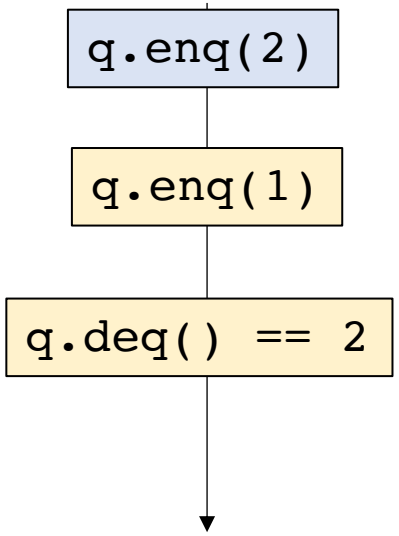
2 objects now: p and q
Consider each object in isolation

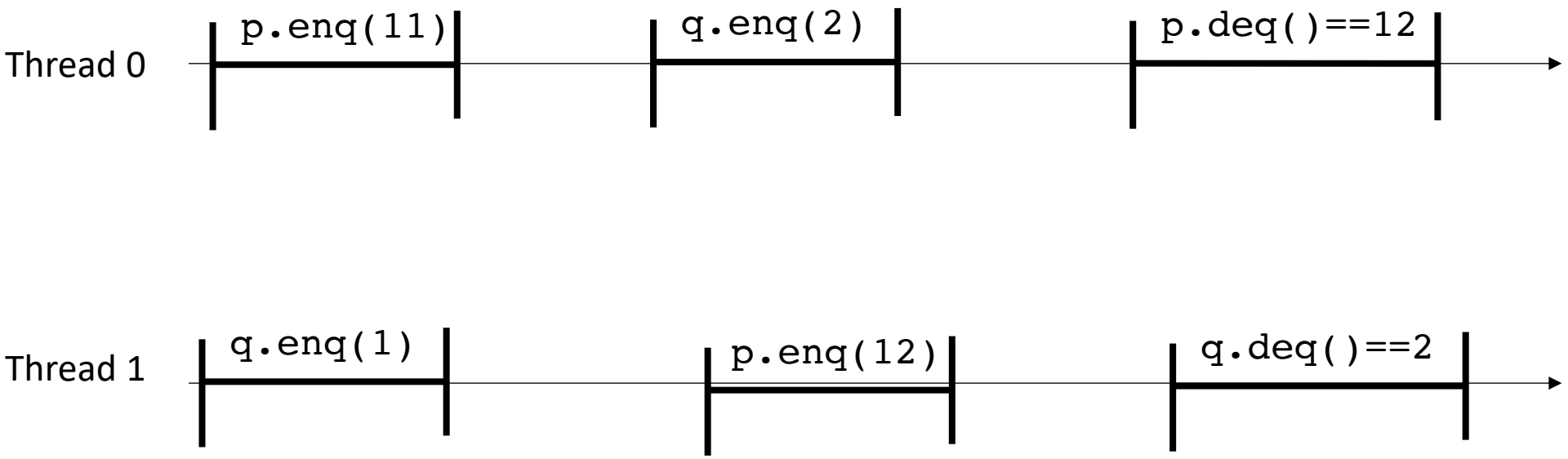




Sequential consistency and real time

- Add in real time:

Now consider them all together



Global variable:

```
CQueue<int> p,q;
```

Thread 0:

```
p.enq(11)
q.enq(2)
p.deq()==12
```


Thread 1:

```
q.enq(1)
p.enq(12)
q.deq()==2
```

Global variable:

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CQueue<int> p,q;
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p.enq(11)
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```
p.enq(11);
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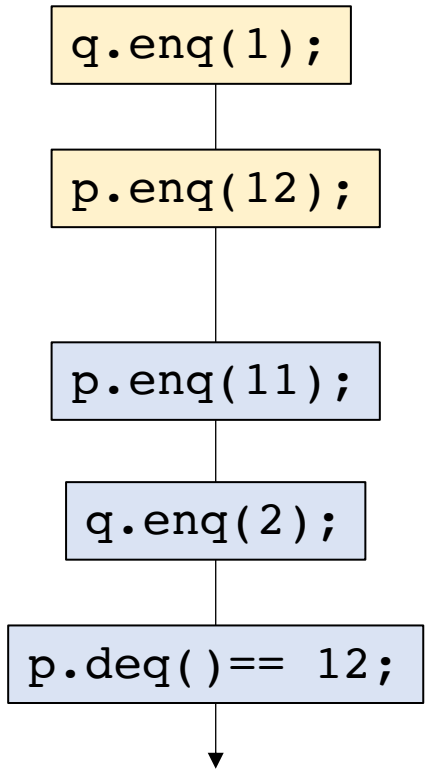


Thread 1:

```
q.enq(1)
p.enq(12)
q.deq()==2
```

```
q.deq()== 2;
```

No place for this one to go!

What does this mean?

- Even if objects in isolation are sequentially consistent
- Programs composed of multiple objects might not be!
- We would like to be able to use more than 1 object in our programs!

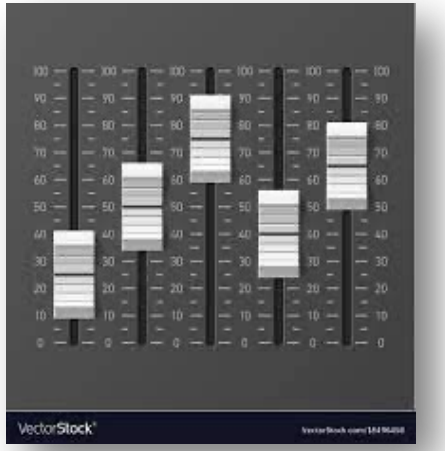
Schedule

- Problems with sequential consistency
- **Linearizability**
- Specialized concurrent queues

Linearizability

- Linearizability
  - Defined in term of real-time histories
  - We want to ask if an execution is allowed under linearizability

- Slightly different game:
  - sequential consistency is a game about stacking lego bricks
  - linearizability is about sliders



Linearizability

each operation has a linearizability point

- does not overlap with other with other linearizability points
- indivisible computation (critical section, atomic RMW, atomic load, atomic store)
- object update (or read) occurs exactly at this point

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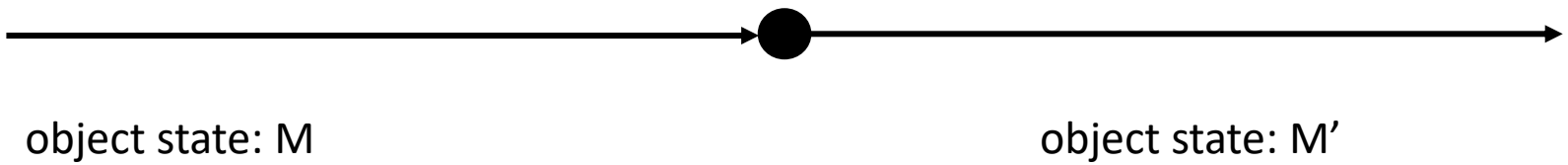

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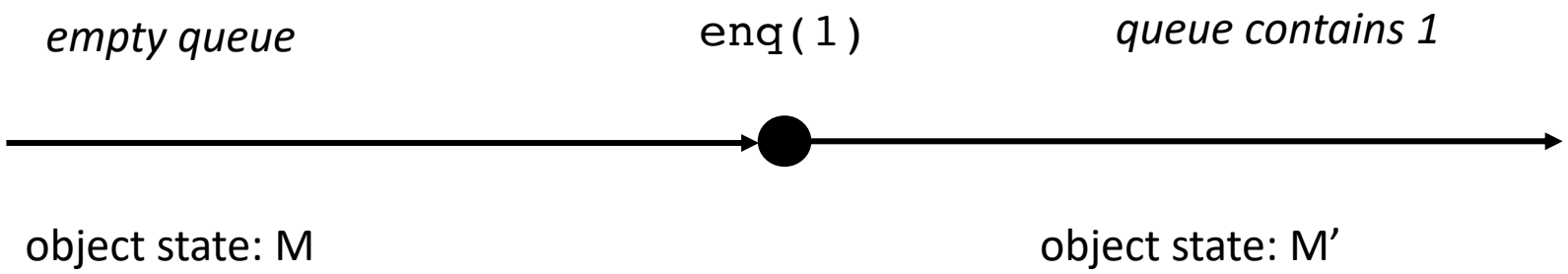

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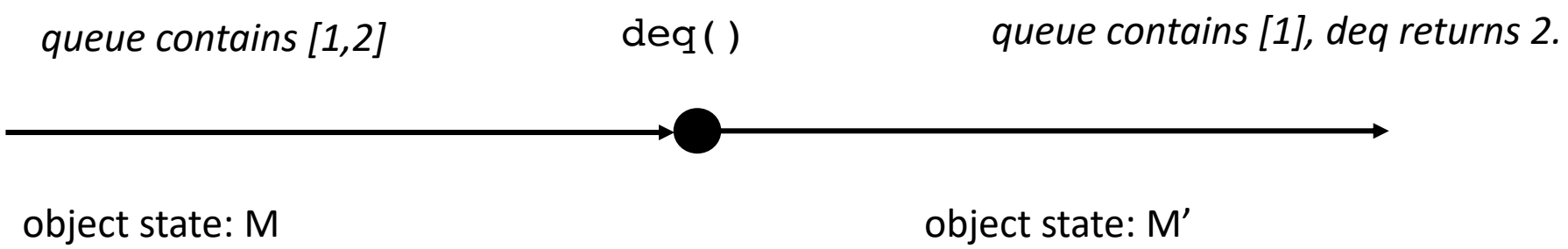

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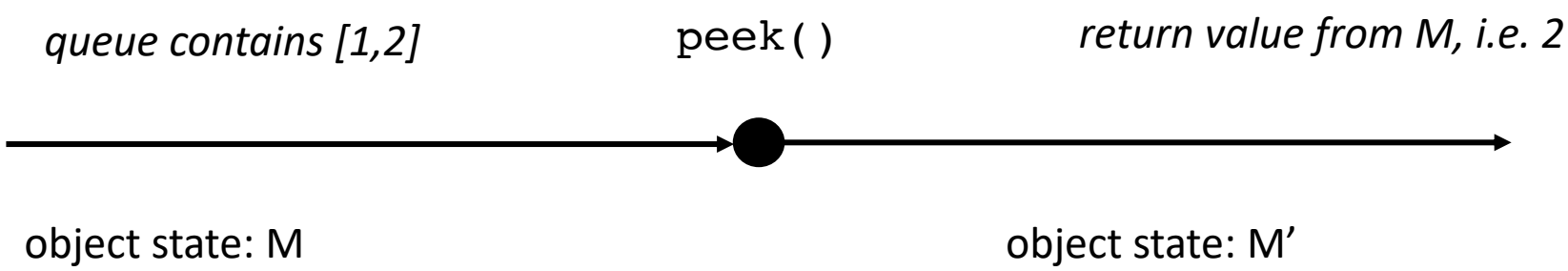
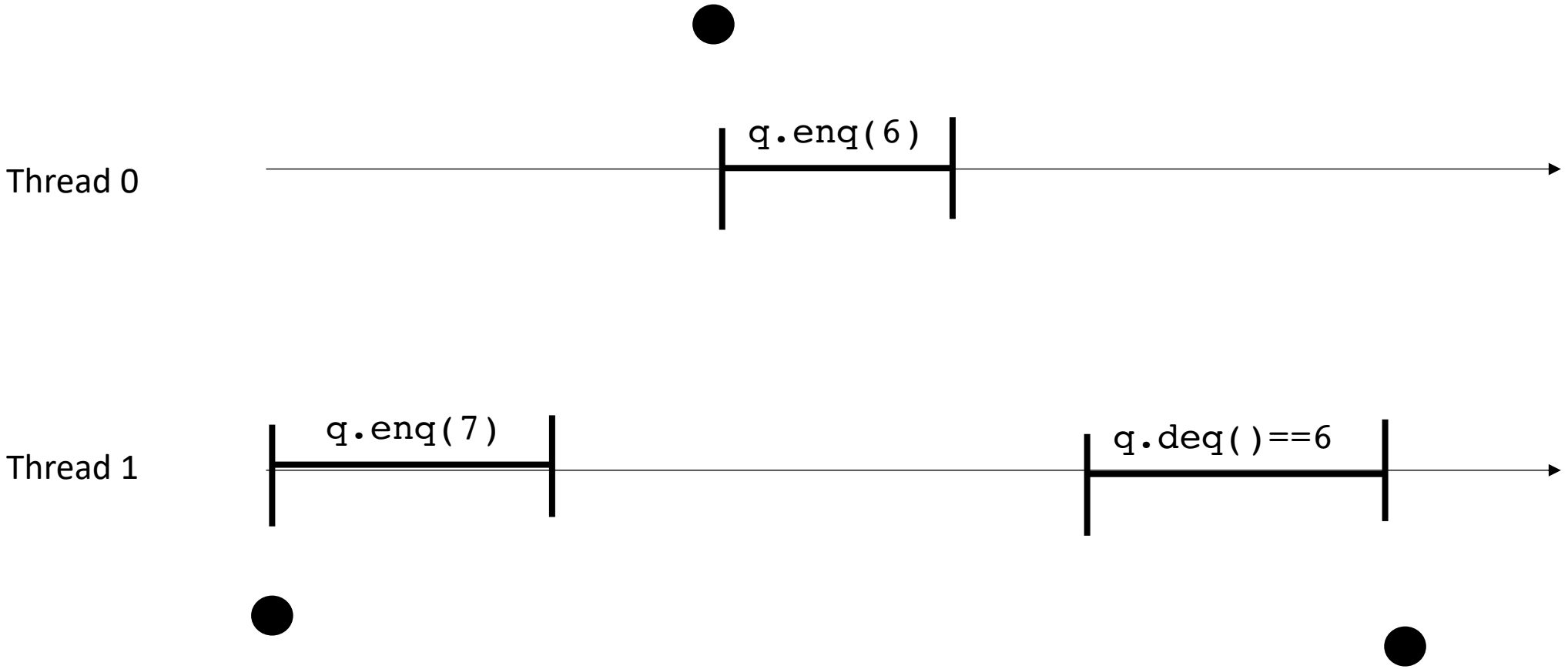


Linearizability

each command gets a linearization point.

You can place the point any where between its innovation and response!



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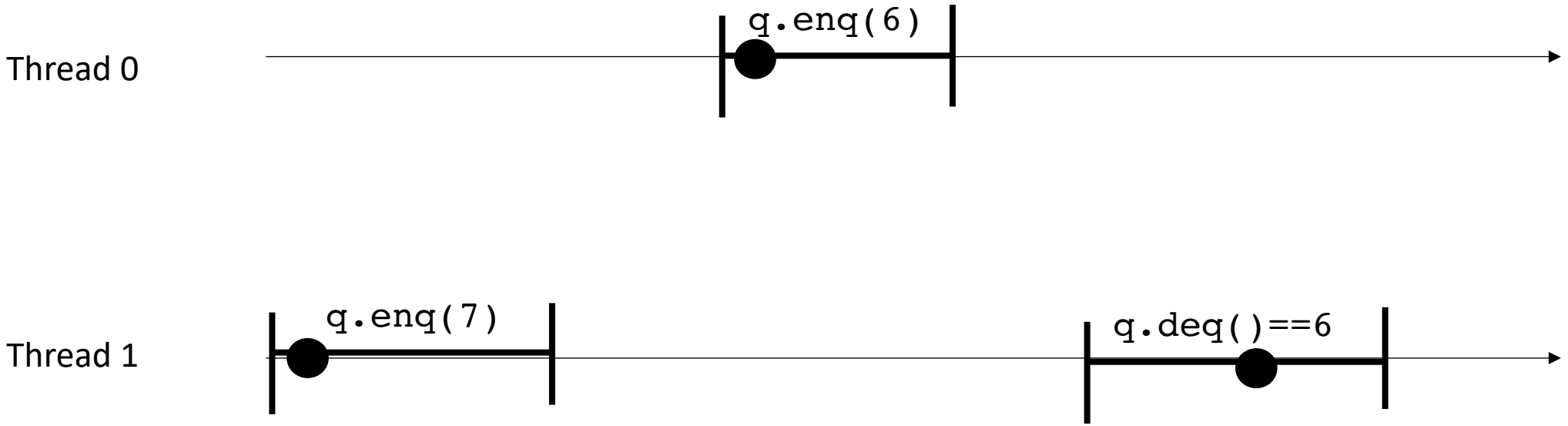

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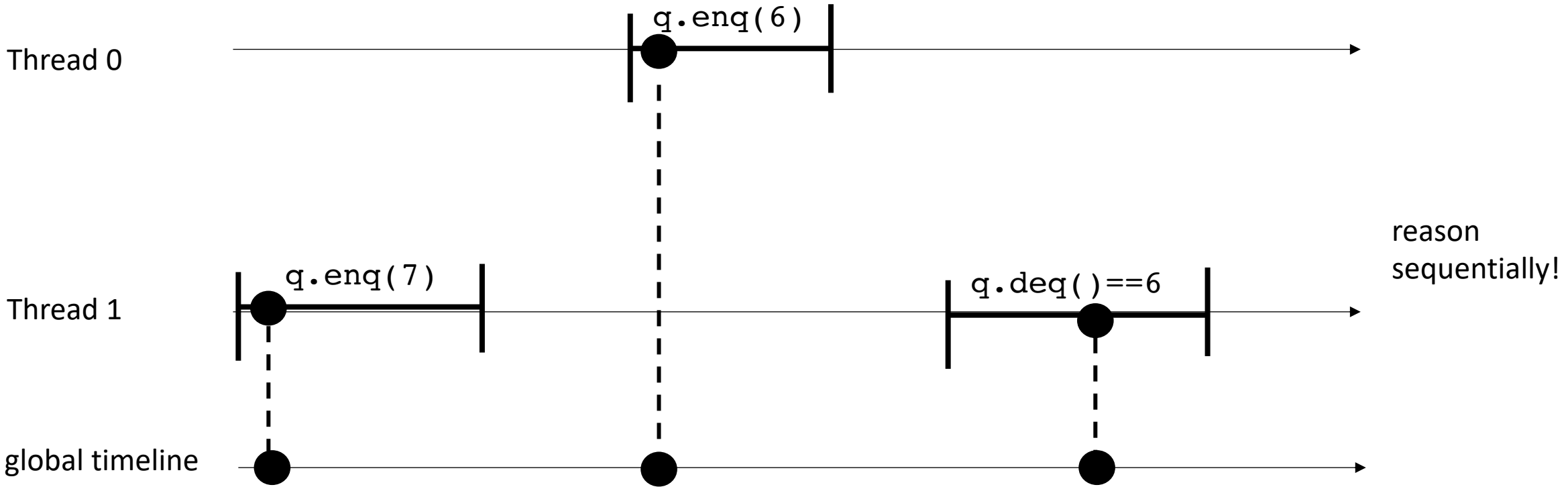
Project the linearization points to a global timeline



reason sequentially!

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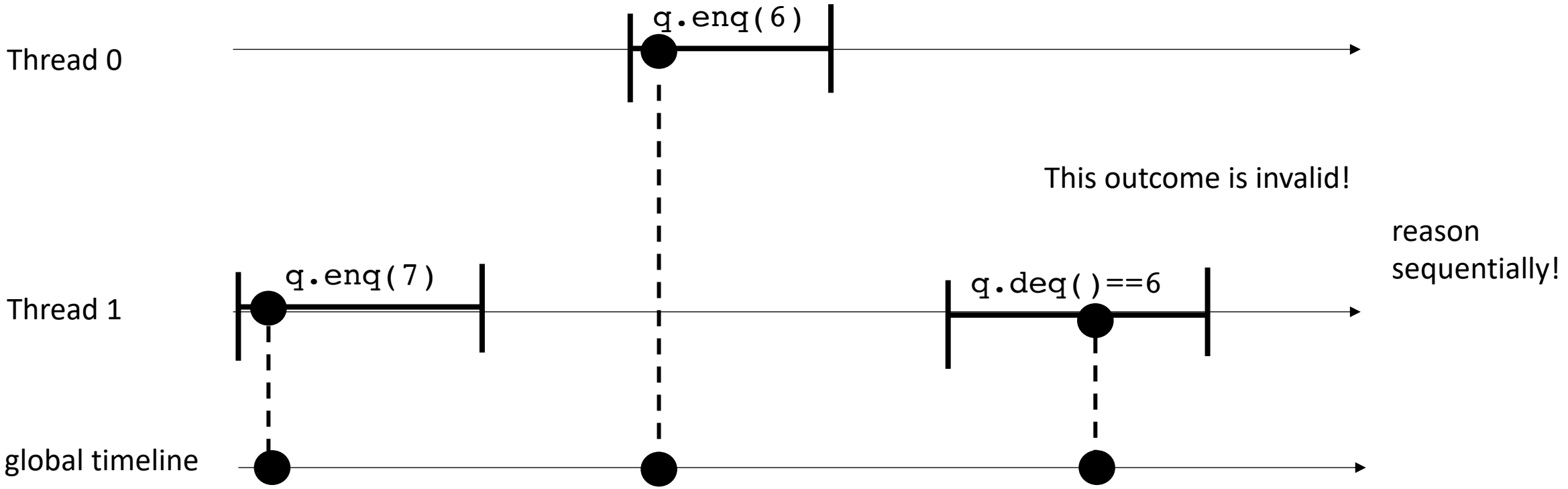

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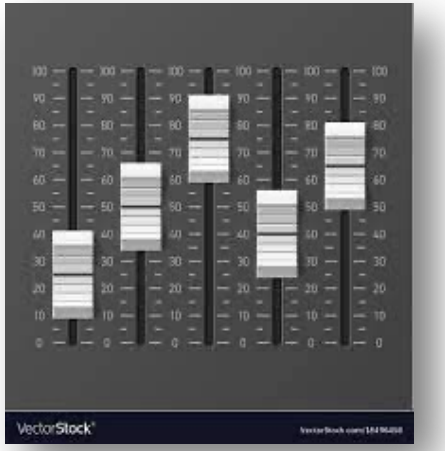

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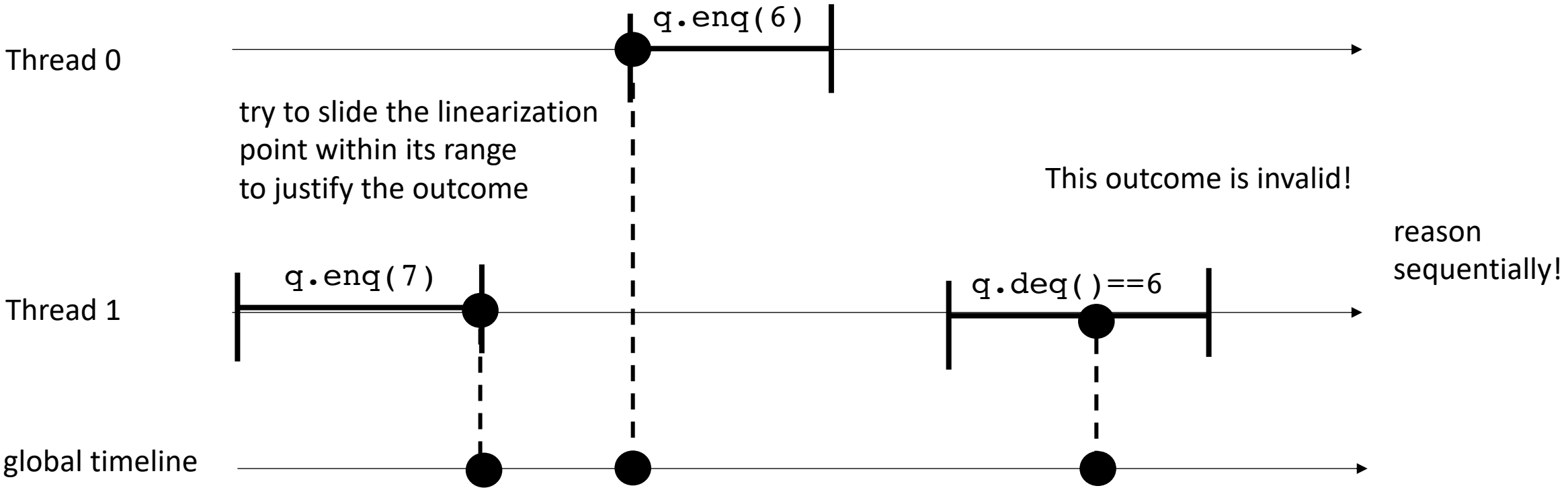
Project the linearization points to a global timeline

slider game!



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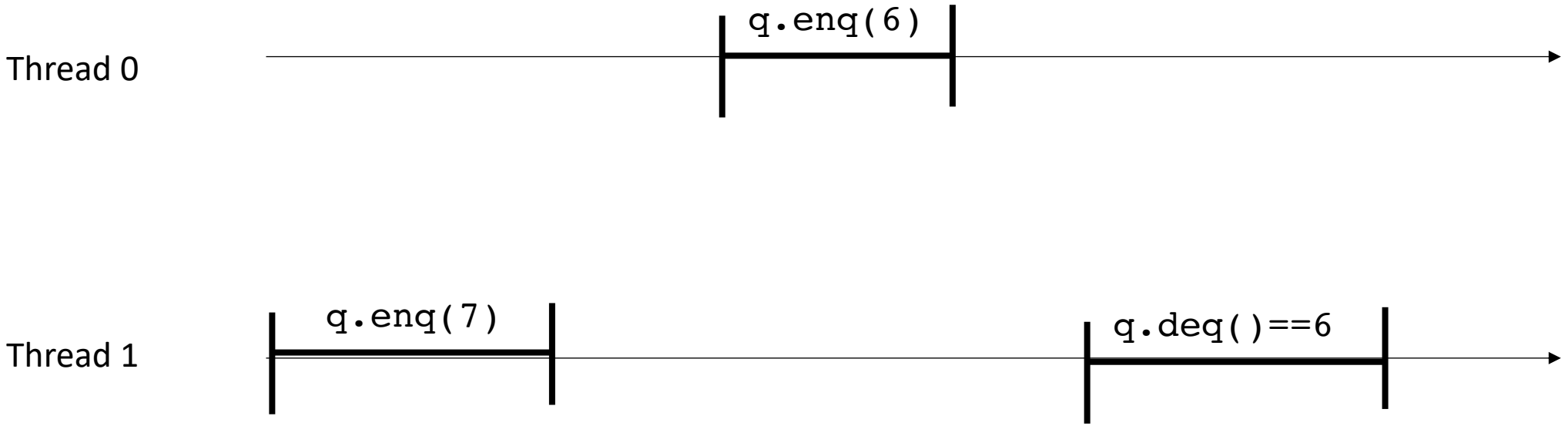
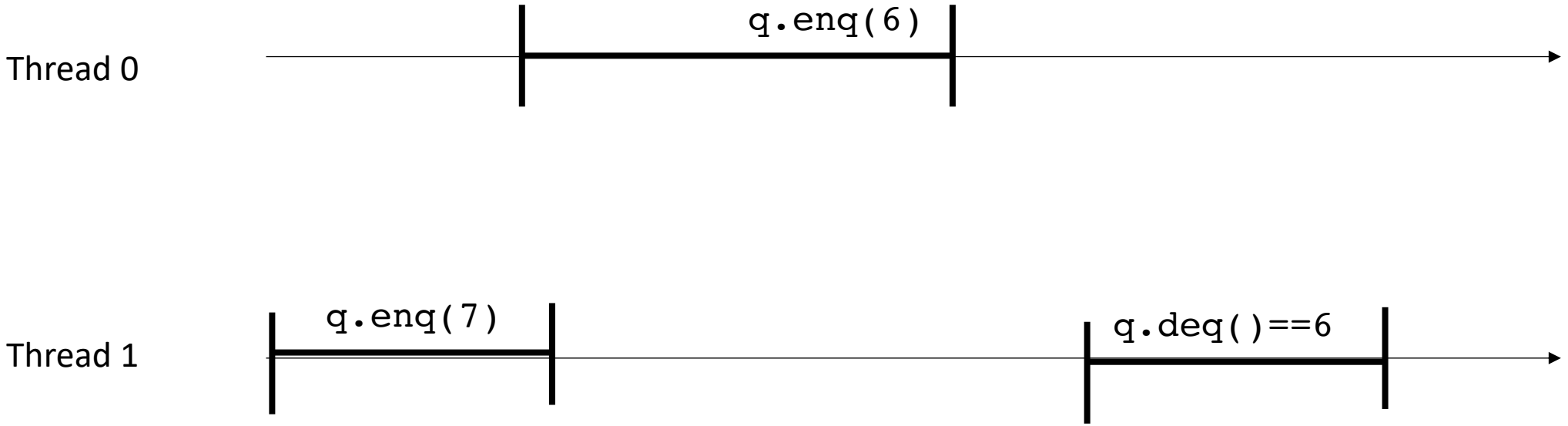


Linearizability



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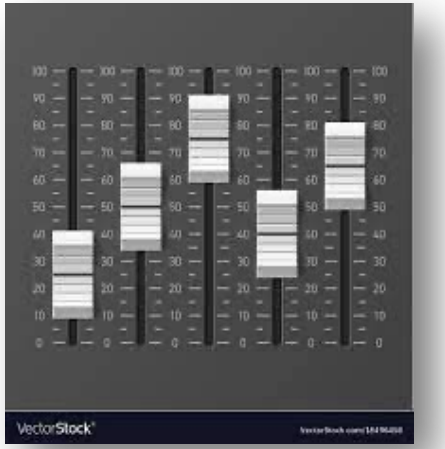

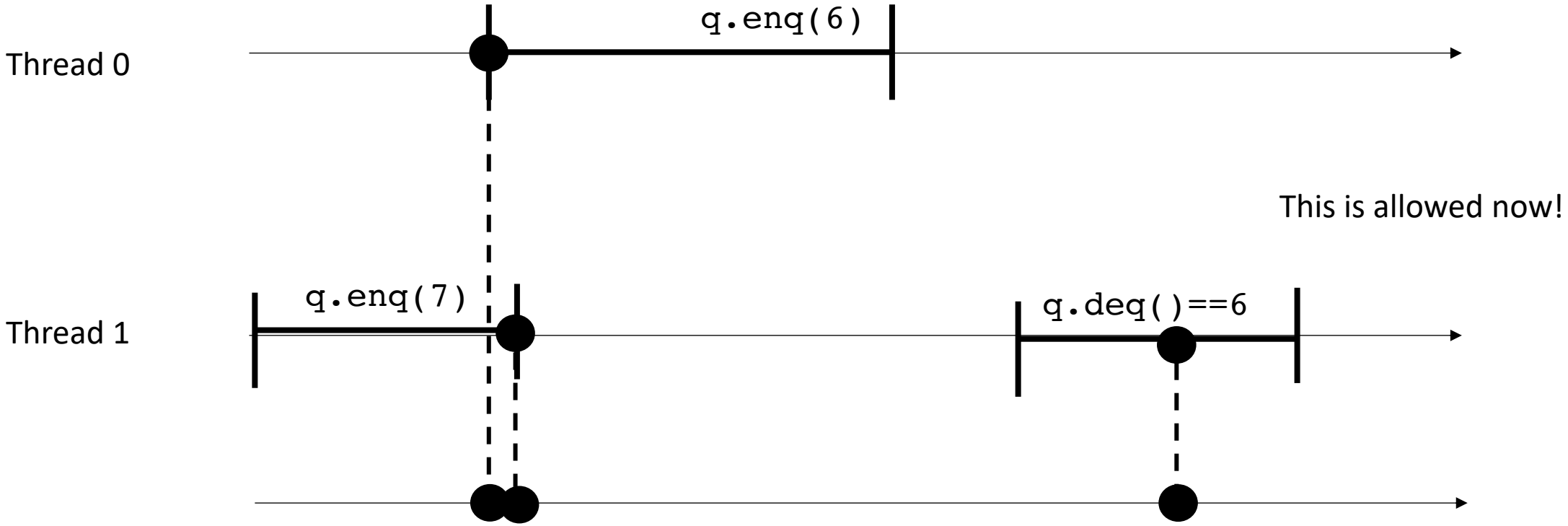

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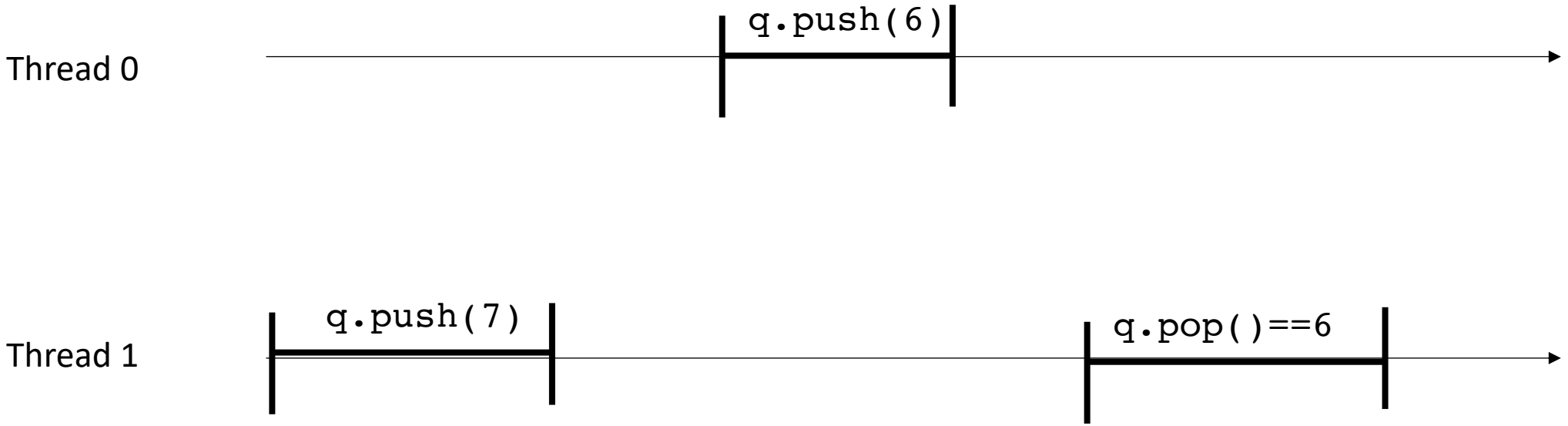
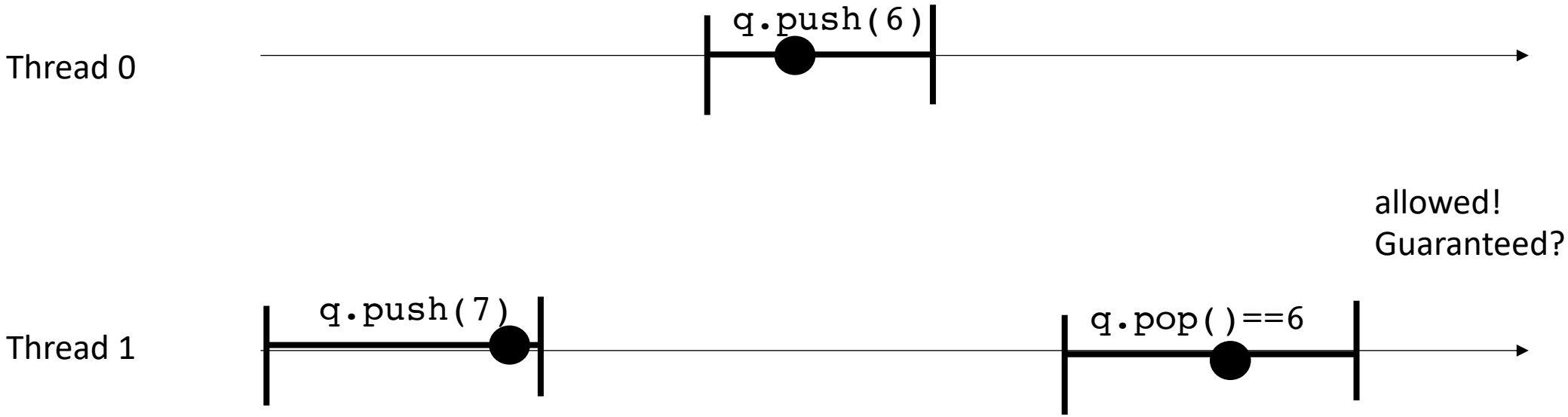
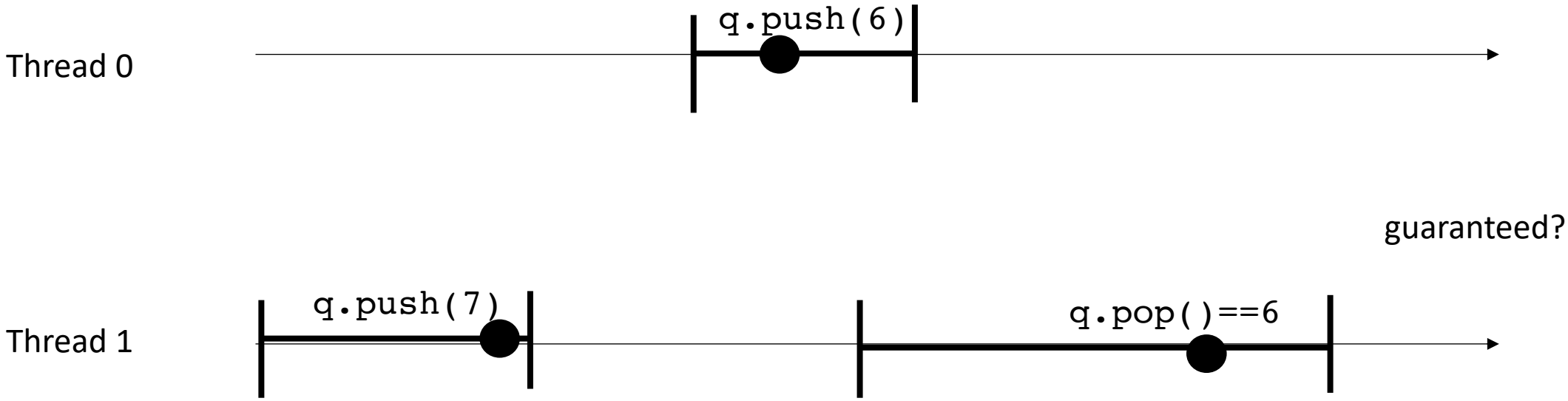


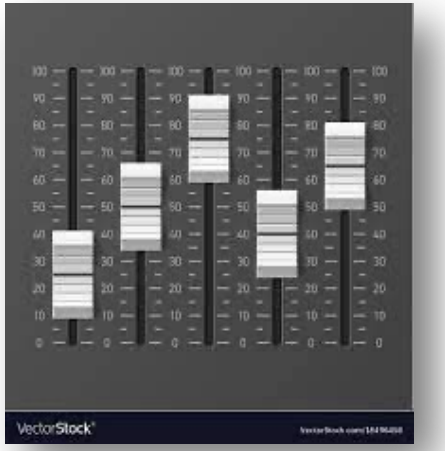
Linearizability

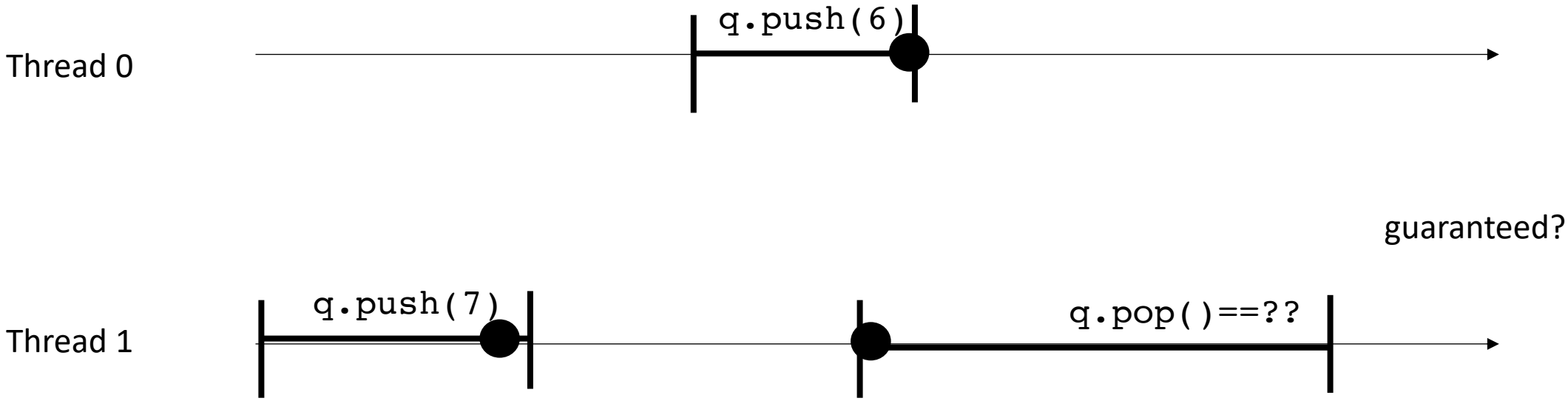


Linearizability



Linearizability



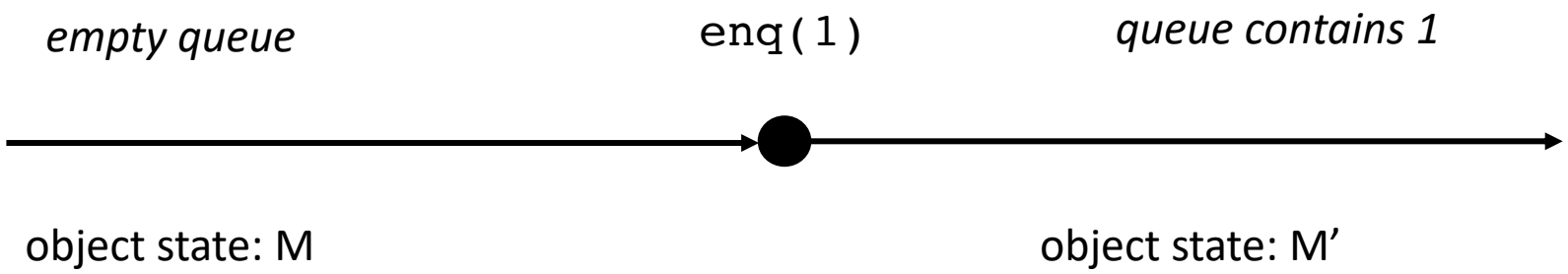


Linearizability

- We spent a bunch of time on SC... did we waste our time?
  - No!
  - Linearizability is strictly stronger than SC. Every linearizable execution is SC, but not the other way around.
  - If a behavior is disallowed under SC, it is also disallowed under linearizability.
- Overall strategy:
  - Write our objects to be linearizable: need to identify linearizable points
  - Reason about our programs using SC: no need for timelines, just need code

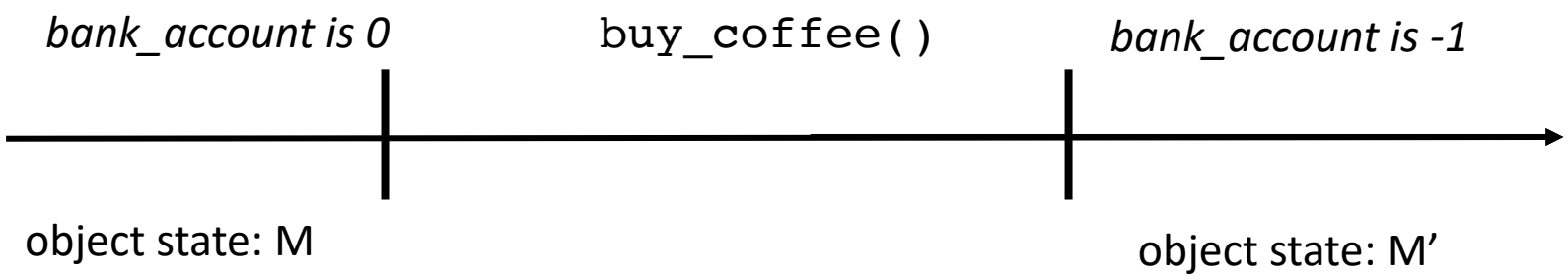
Linearizability

- How do we write our programs to be linearizable?
  - Identify the linearizability point
  - One indivisible region (e.g. an atomic store, atomic load, atomic RMW, or critical section) where the method call takes effect. Modeled as a point.



Linearizability

- Locked data structures are linearizable.




```
class bank_account {
  public:
    bank_account() {
      balance = 0;
    }

    void buy_coffee() {
      m.lock();
      balance -= 1;
      m.unlock();
    }

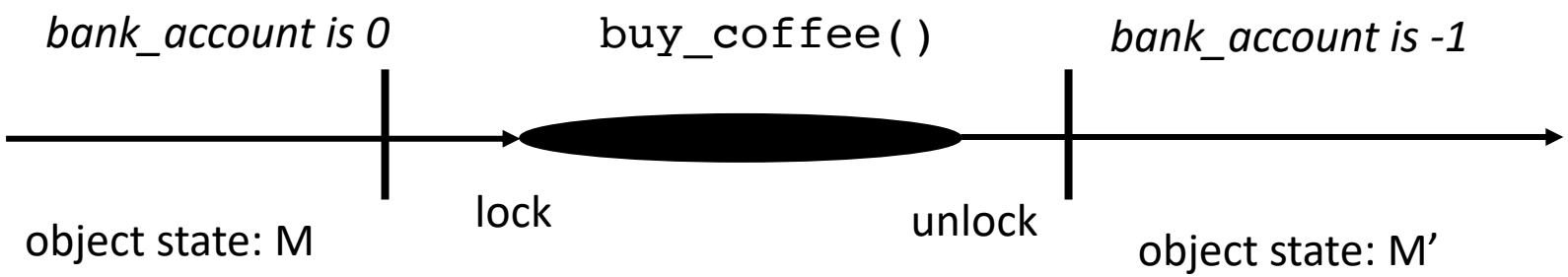
    void get_paid() {
      m.lock();
      balance += 1;
      m.unlock();
    }

  private:
    int balance;
    mutex m;
};
```

Linearizability

- Locked data structures are linearizable.

typically modeled as the point the lock is acquired or released

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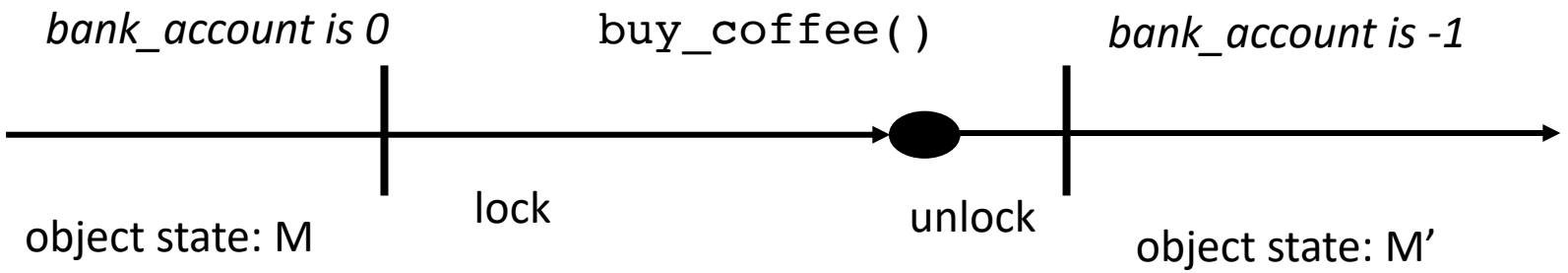
Linearizability

- Locked data structures are linearizable.

typically modeled as the point the lock is acquired or released lets say released.

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      m.unlock();
    }

  private:
    int balance;
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};
```

Linearizability

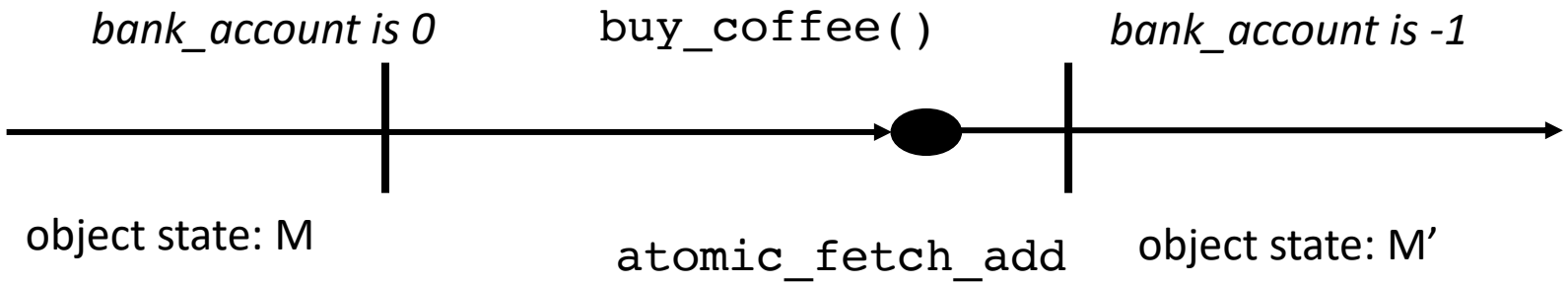
- Our lock-free bank account is linearizable:
  - The atomic operation is the linearizable point

```
class bank_account {
  public:
    bank_account() {
      balance = 0;
    }

    void buy_coffee() {
      atomic_fetch_add(&balance, -1);
    }

    void get_paid() {
      atomic_fetch_add(&balance, 1);
    }

  private:
    atomic_int balance;
};
```



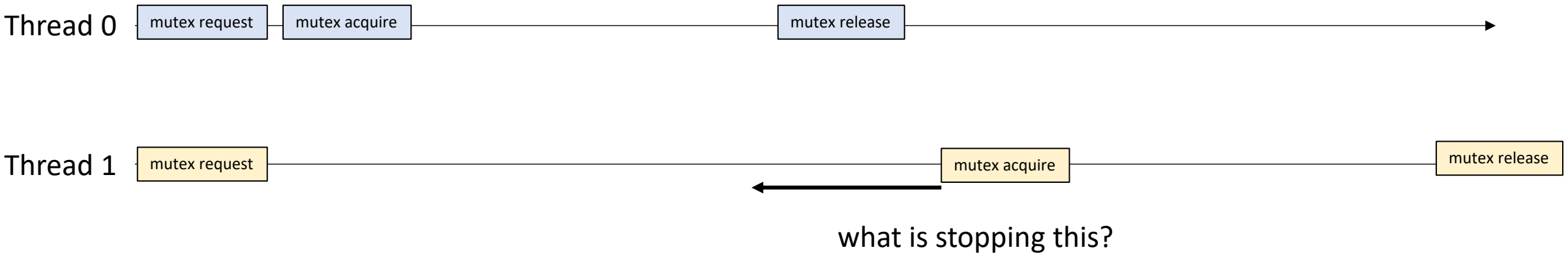
Lecture schedule

- Revisiting sequential consistency
- Linearizablity
- **Progress Properties**
- Implementing a set

Progress properties

- Going back to specifications:

Recall the mutex

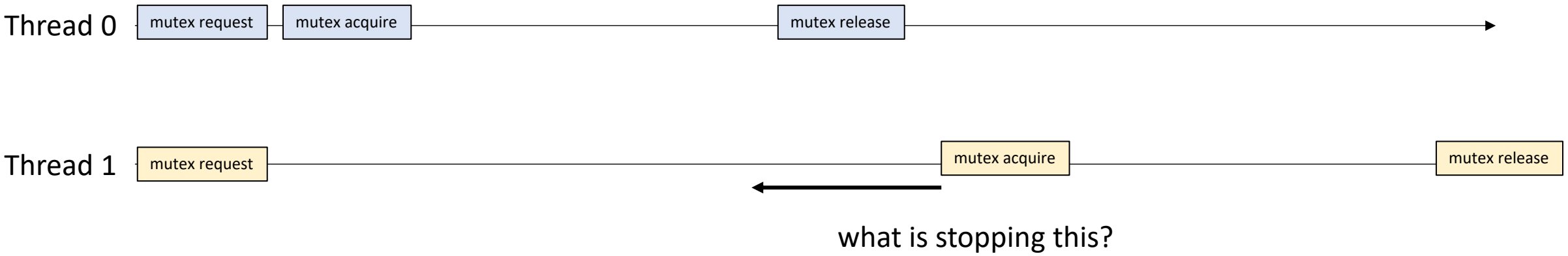


Progress properties

- Going back to specifications:

Thread 0 is stopping Thread 1 from making progress.
If delays in one thread can cause delays in other threads, we say that it is blocking

Recall the mutex



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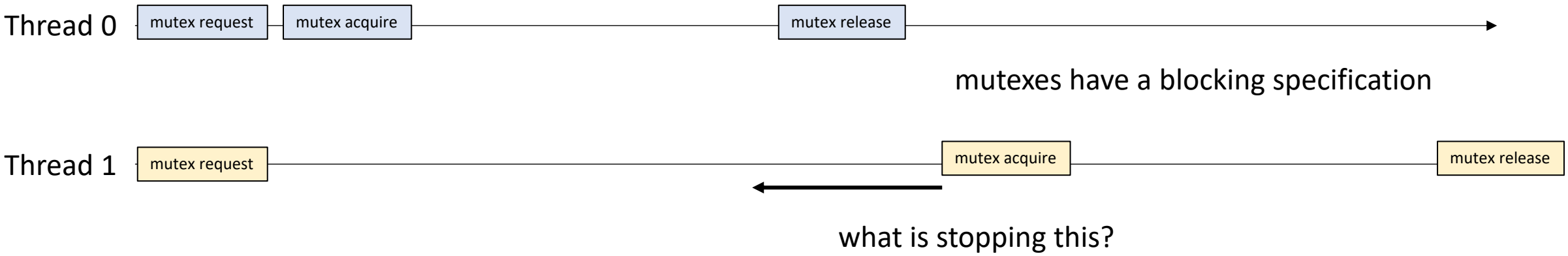

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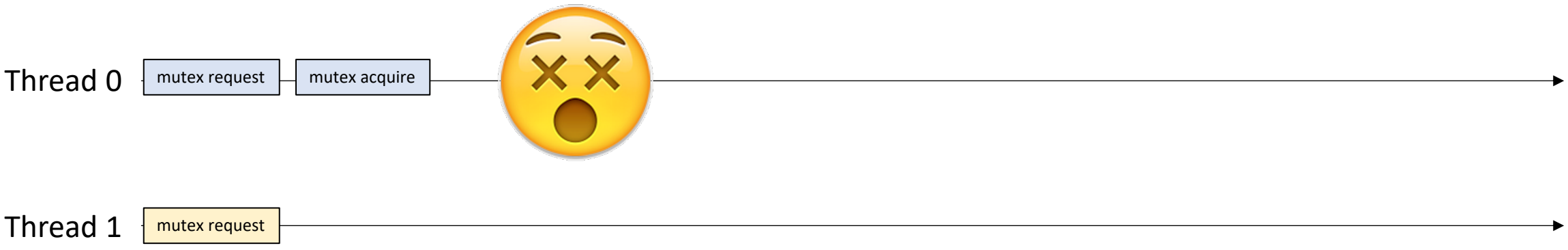
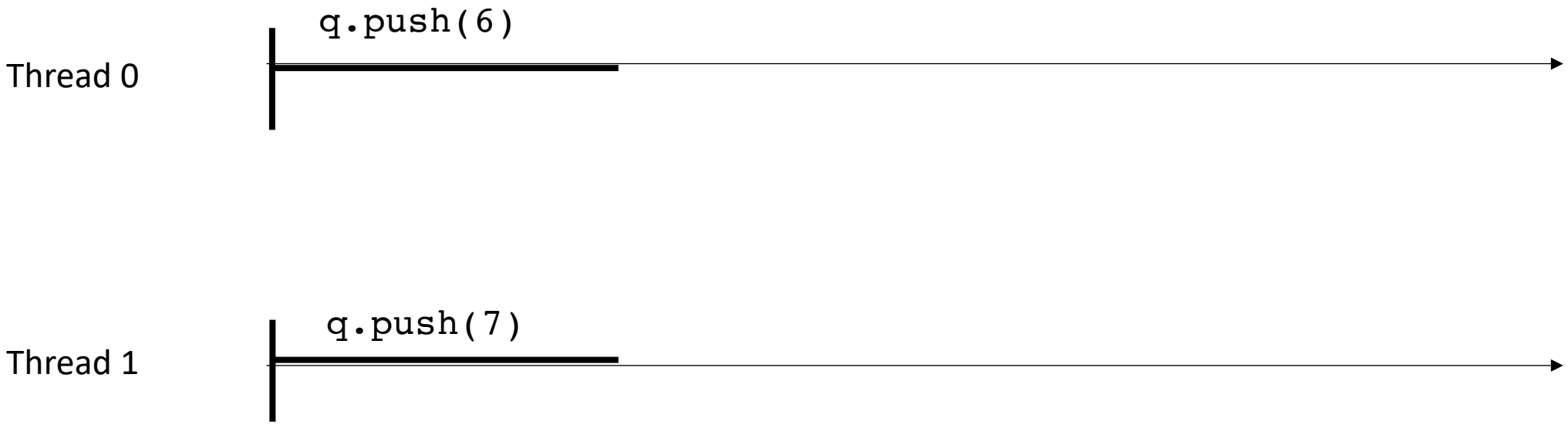


What now?!

Linearizability

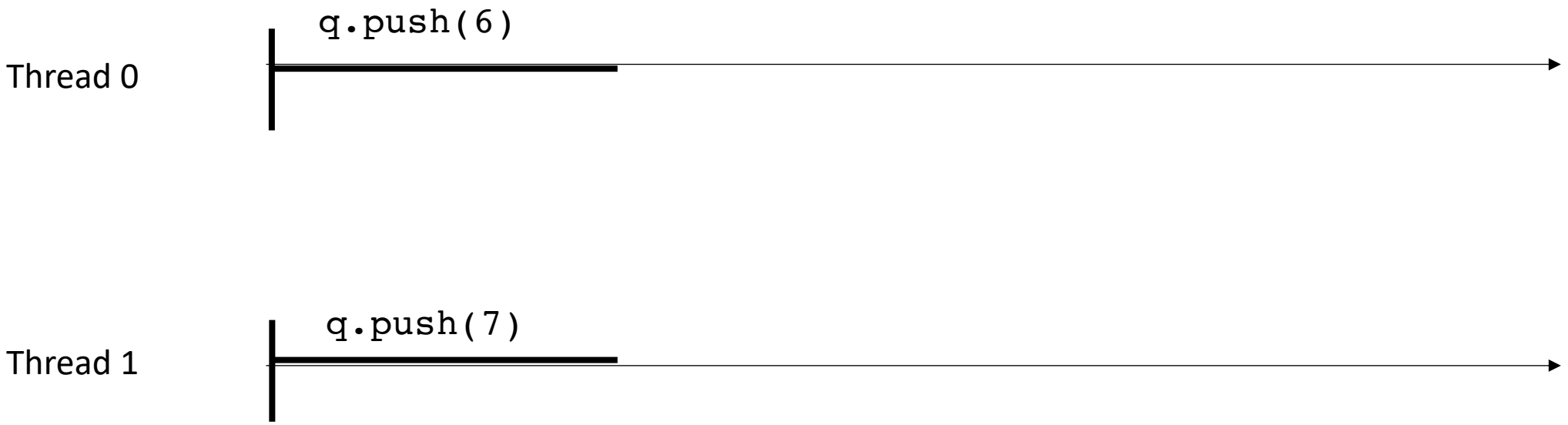
Two unfinished commands.



Linearizability

Two unfinished commands.

Linearizability does not dictate that one needs to wait for another



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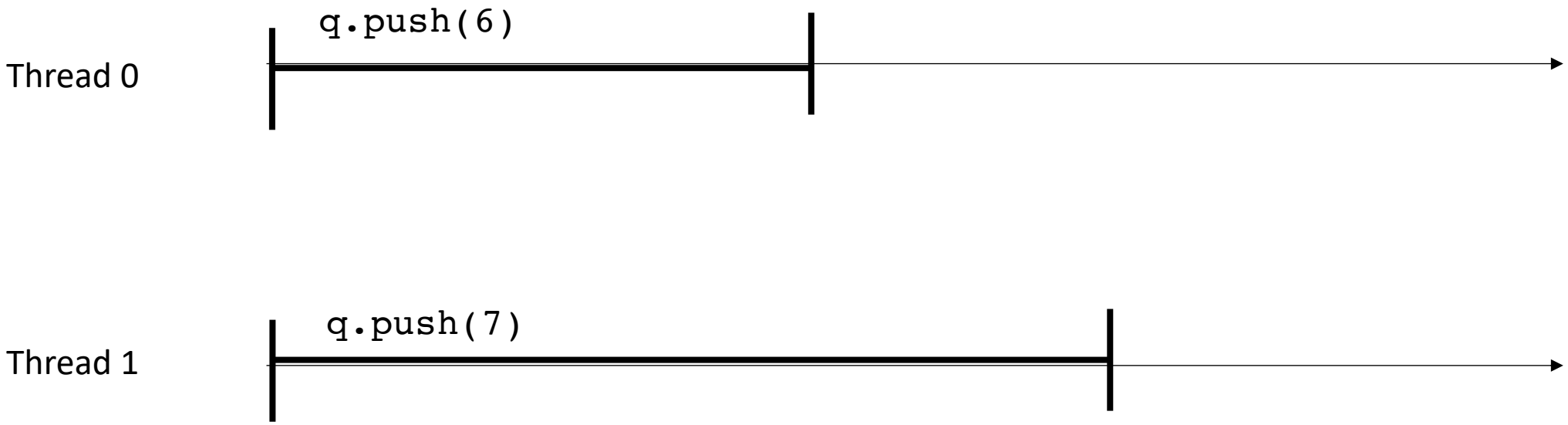

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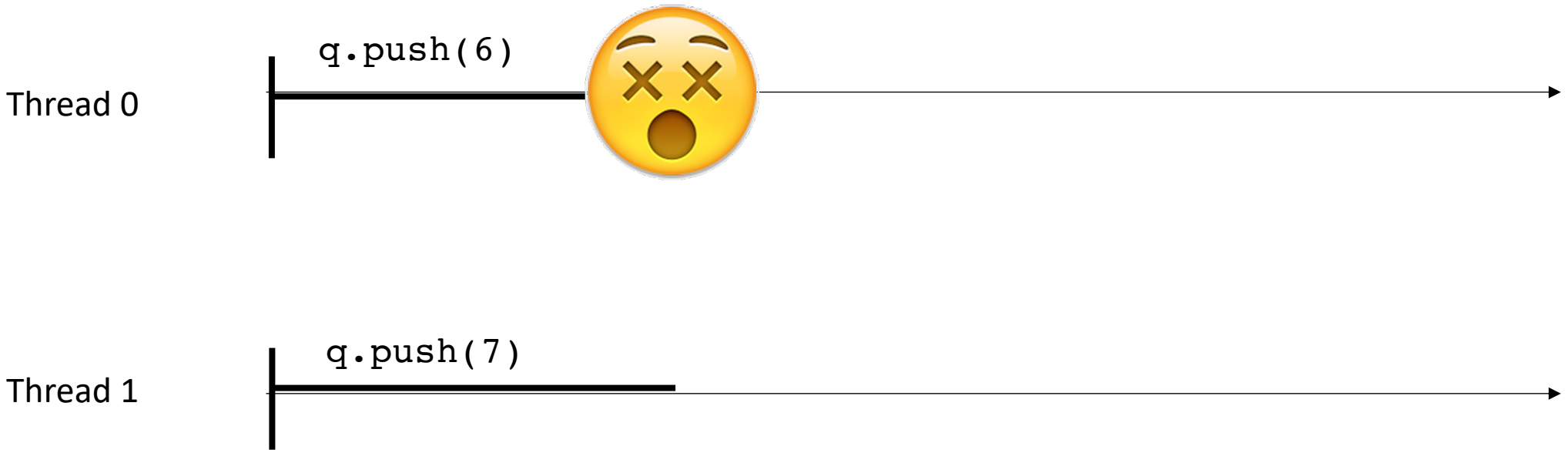

for mutexes, the specification required that the system hang.

Linearizability

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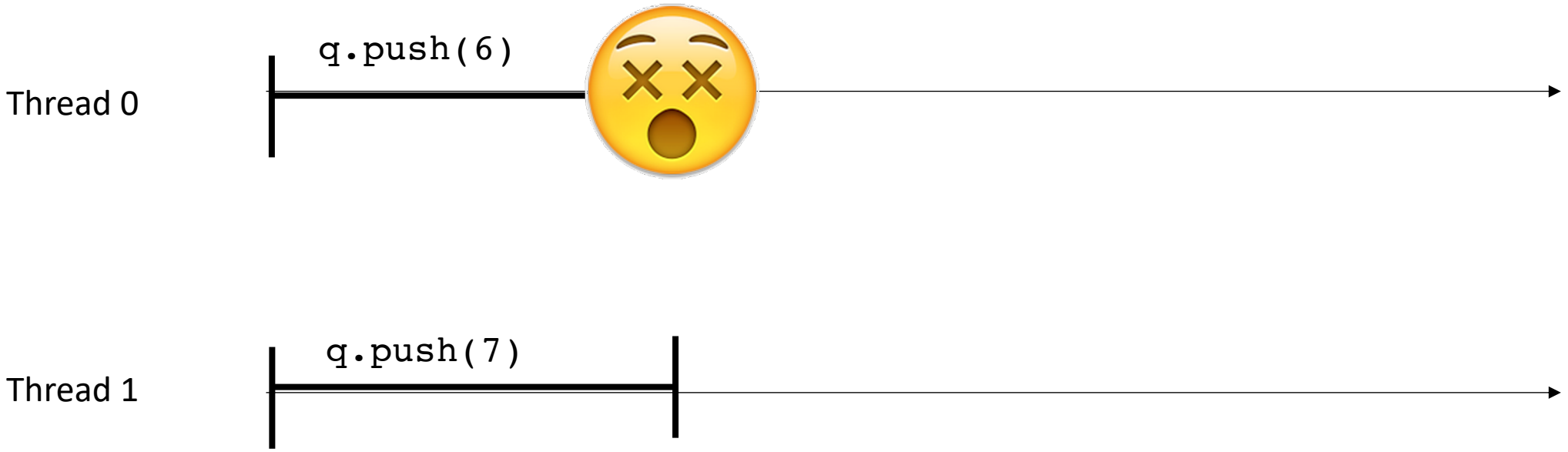
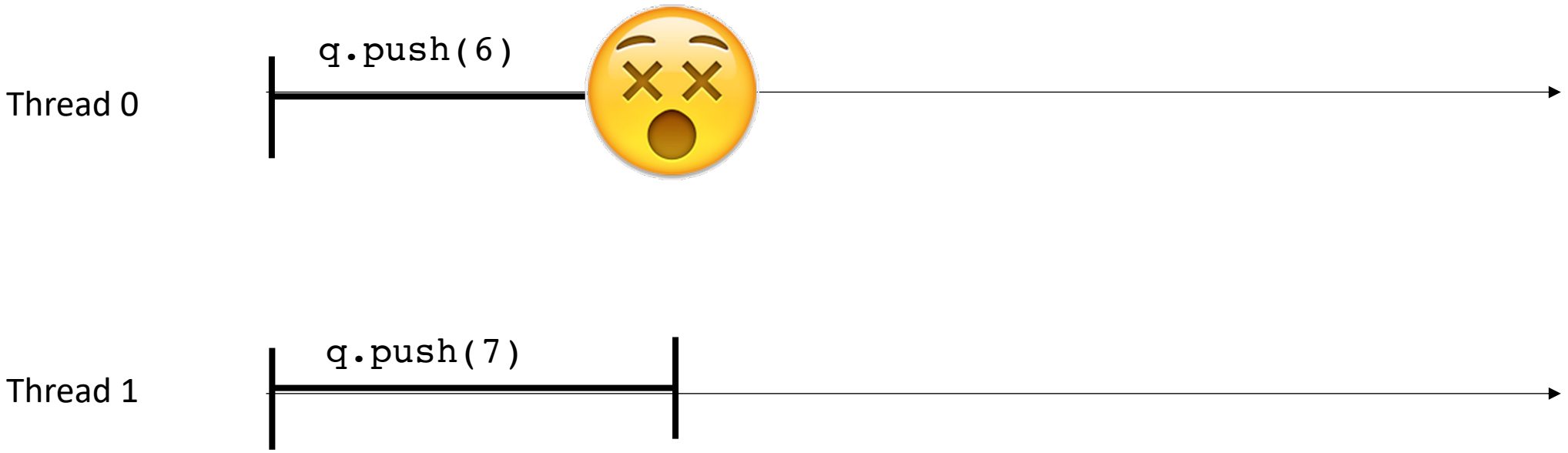


for mutexes, the specification required that the system hang.
no such specification here.

Linearizability

Non-blocking specification:
Every thread is allowed to continue executing
REGARDLESS of the behavior of other threads



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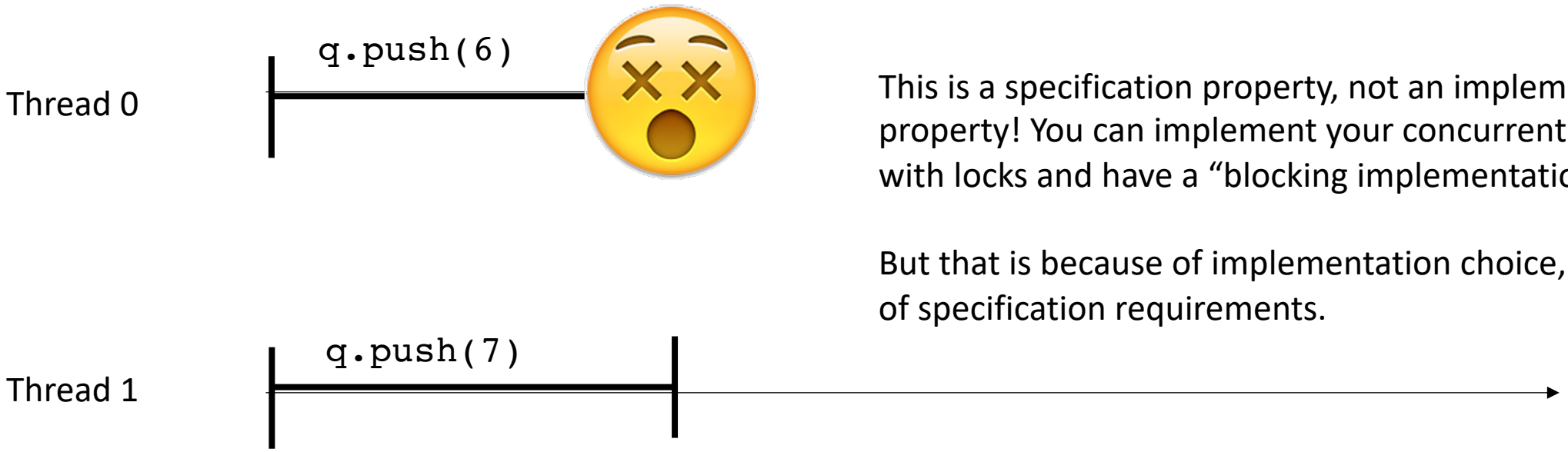


This is a specification property, not an implementation property! You can implement your concurrent objects with locks and have a “blocking implementation”.

But that is because of implementation choice, not because of specification requirements.

Terminology overview

- Thread-safe object:
- Lock-free object:
- Blocking specification:
- Non-blocking specification:
- (non-)blocking implementation:

Terminology overview

- Sequential consistency:
- Linearizability:
- Linearizability point:

Schedule

- Problems with sequential consistency
- Linearizability
- **Specialized concurrent queues**

Concurrent Queues

- List of items, accessed in a first-in first-out (FIFO) way
- *duplicates allowed*
- Methods
  - **`enq(x)`** put **`x`** in the list at the end
  - **`deq()`** remove the item at the front of the queue and return it.
  - **`size()`** returns how many items are in the queue

Concurrent Queues

- General implementation given in Chapter 10 of the book.
- Similar types of reasoning as the linked list
  - Lots of reasoning about node insertion, node deletion
  - Using atomic RMWs (CAS) in clever ways

- We will think about specialized queues
  - Implementations can be simplified!

Input/Output Queues

- Queue in which multiple threads read (deq), or write (enq), but not both.

- Why would we want a thing?

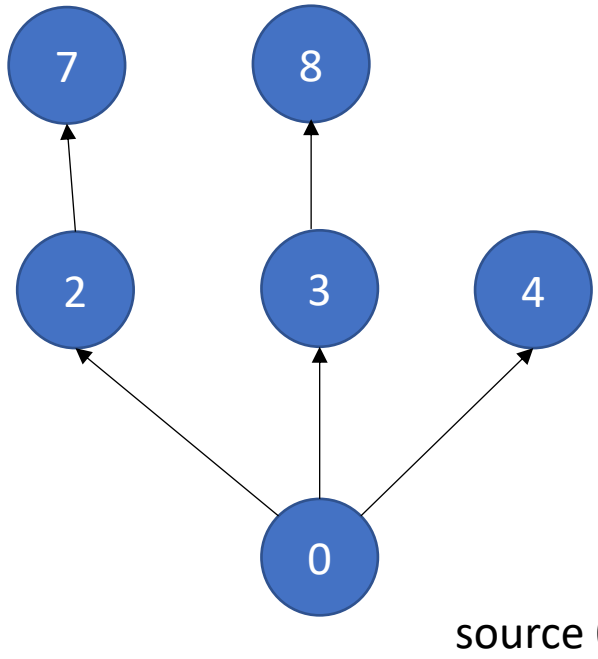
- Computation done in phases:
  - First phase prepares the queue (by writing into it)
  - All threads join
  - Second phase reads values from the queue.

Input/Output Queues

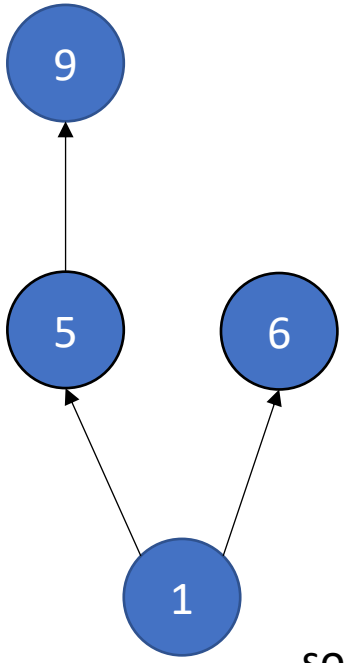
- Example: Information flow in graph applications:

Input/Output Queues

- Example: Information flow in graph applications:



source 0



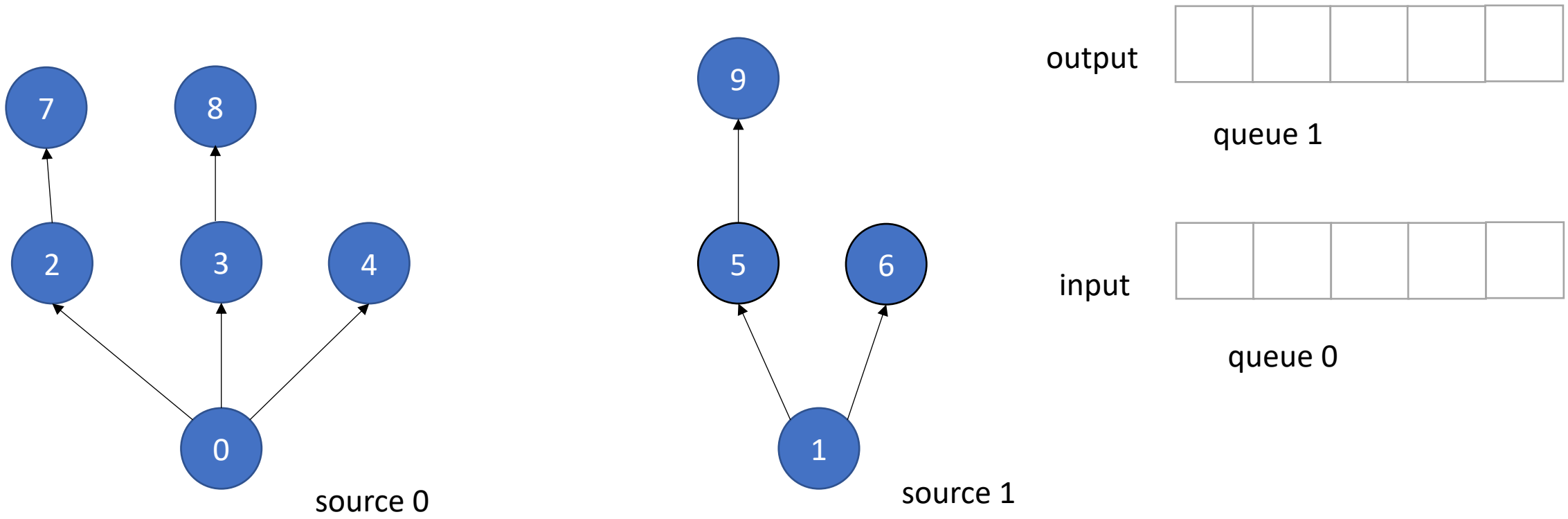
source 1

queue 1

queue 0

Input/Output Queues

- Example: Information flow in graph applications:



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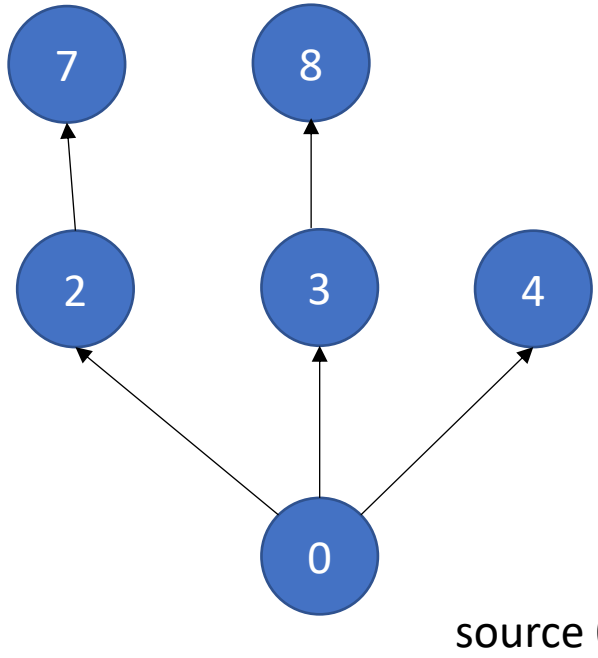

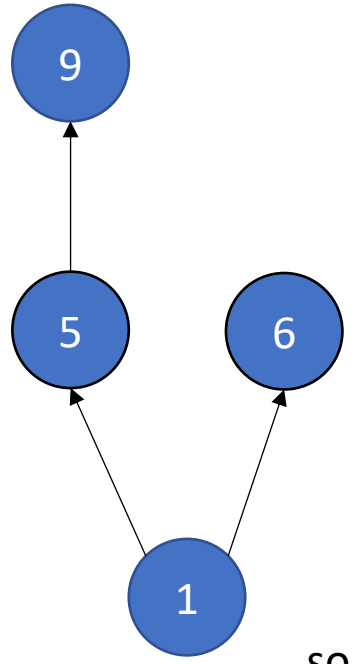

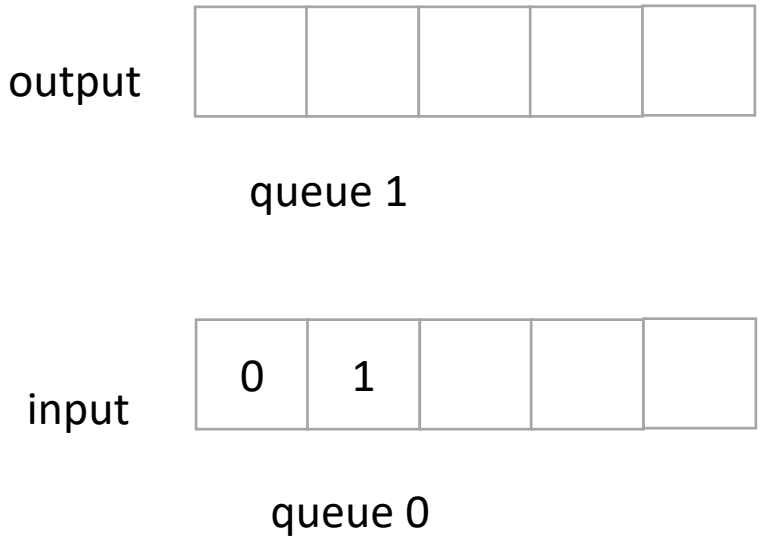

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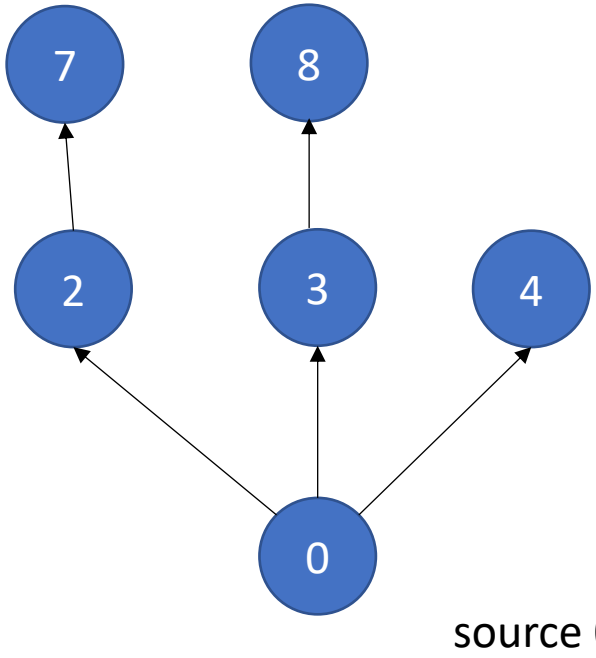

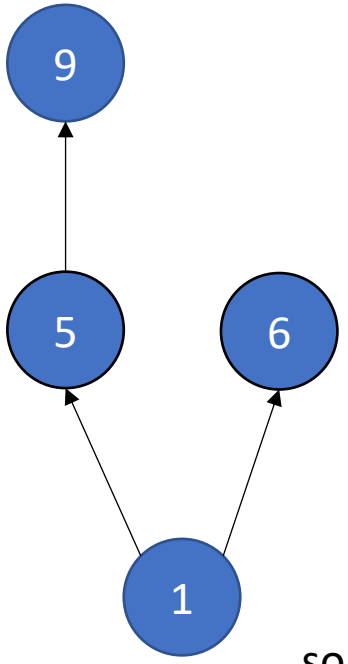

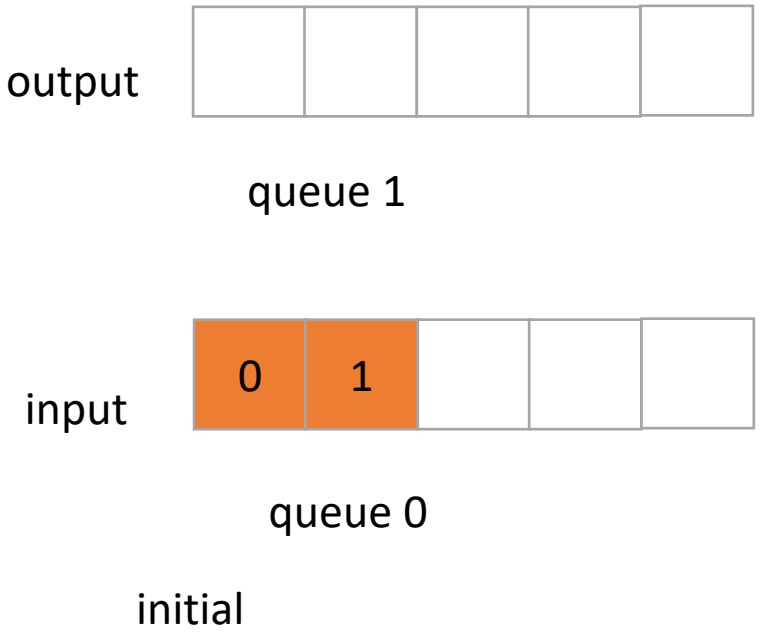

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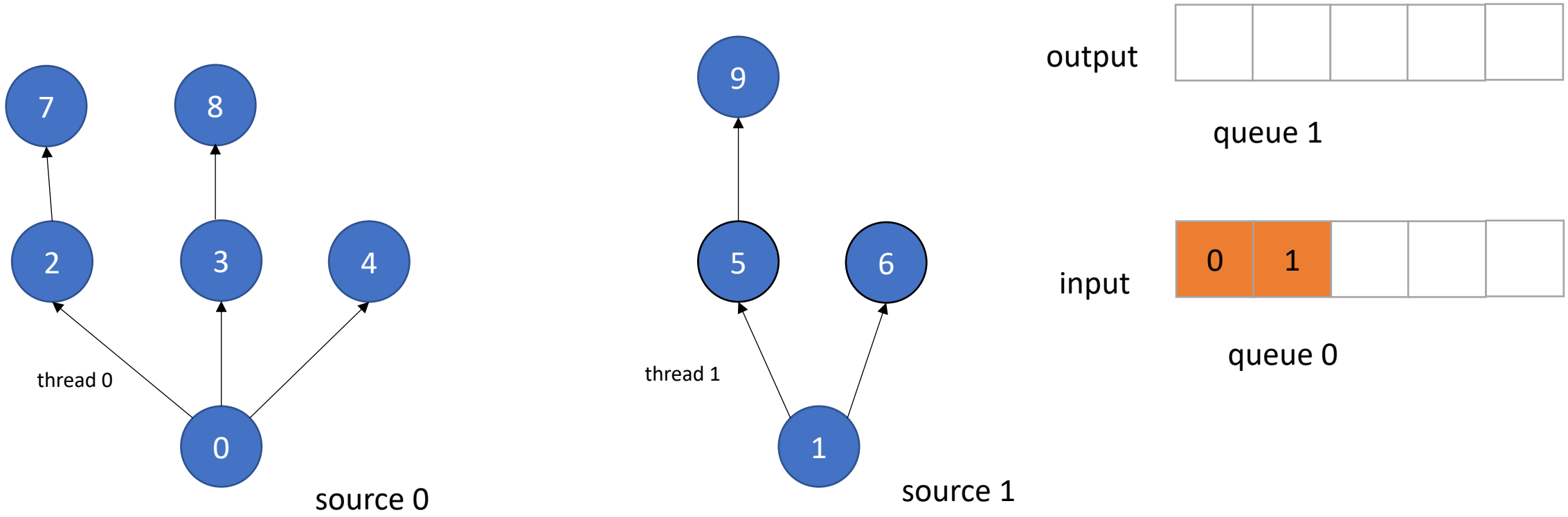

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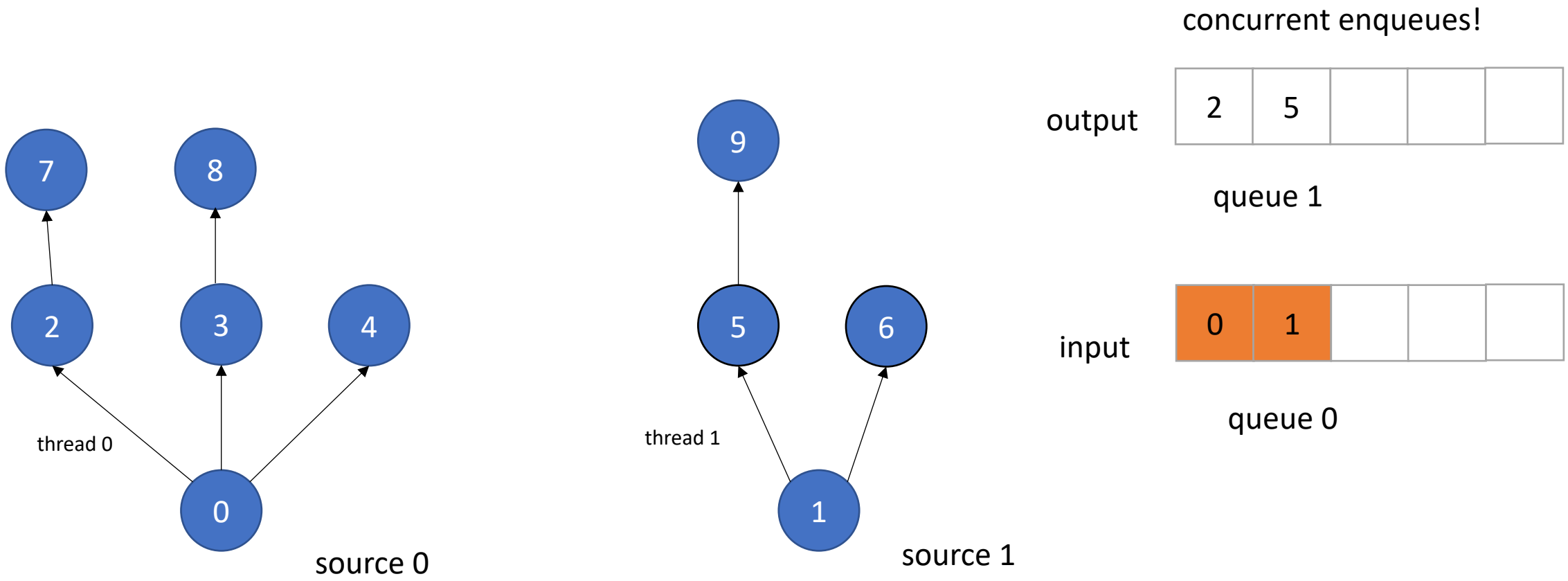

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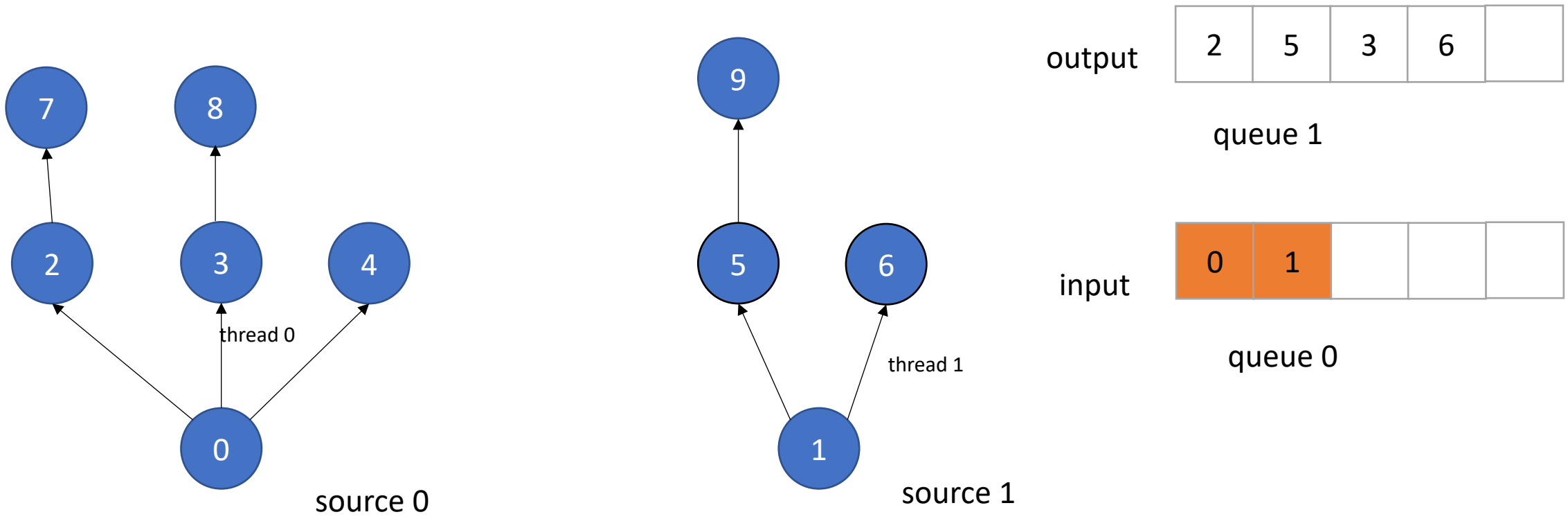

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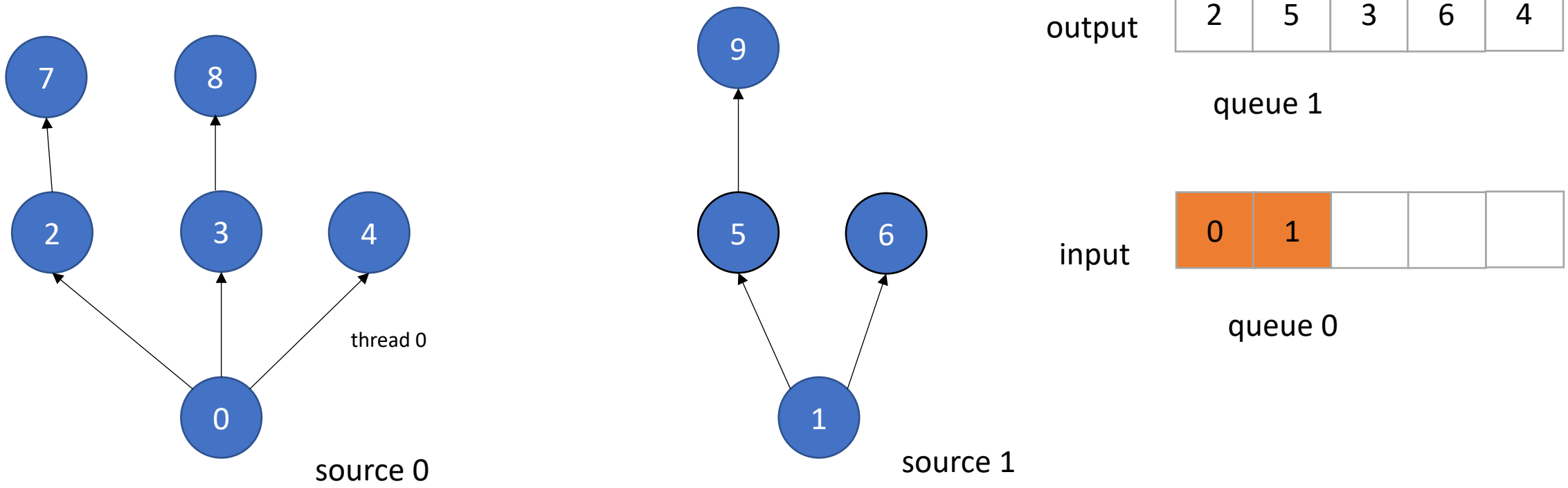

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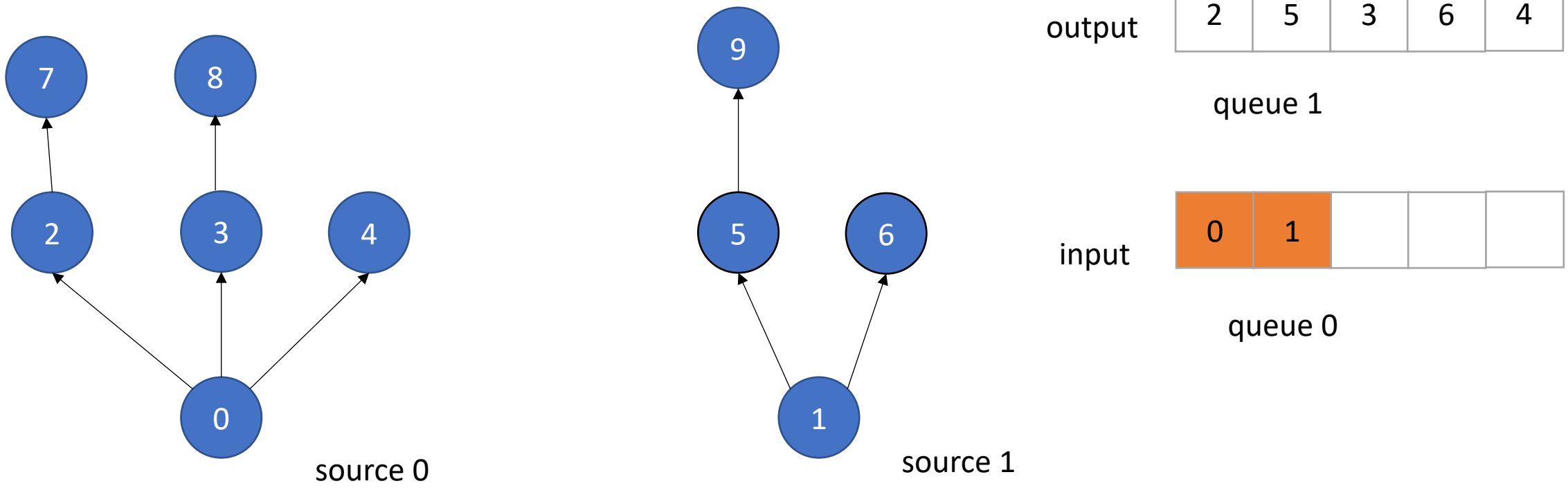

Input/Output Queues

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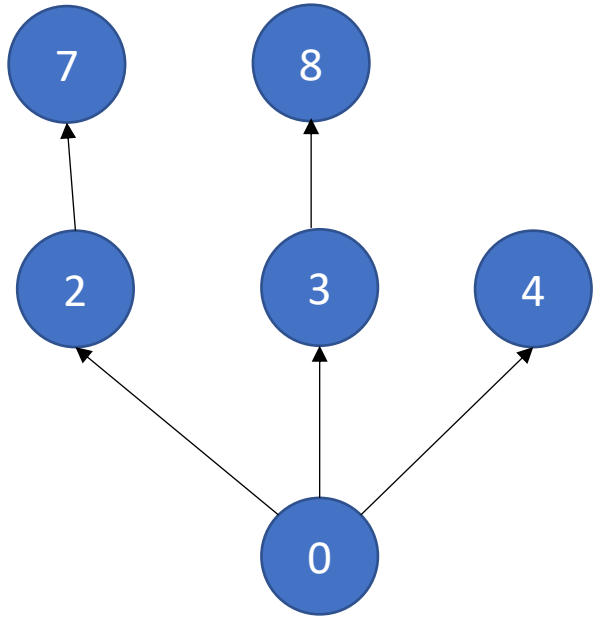
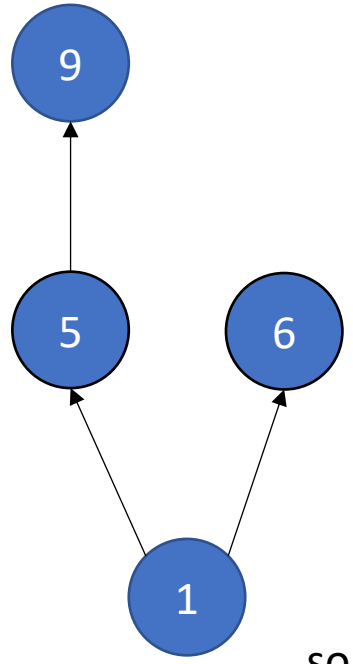
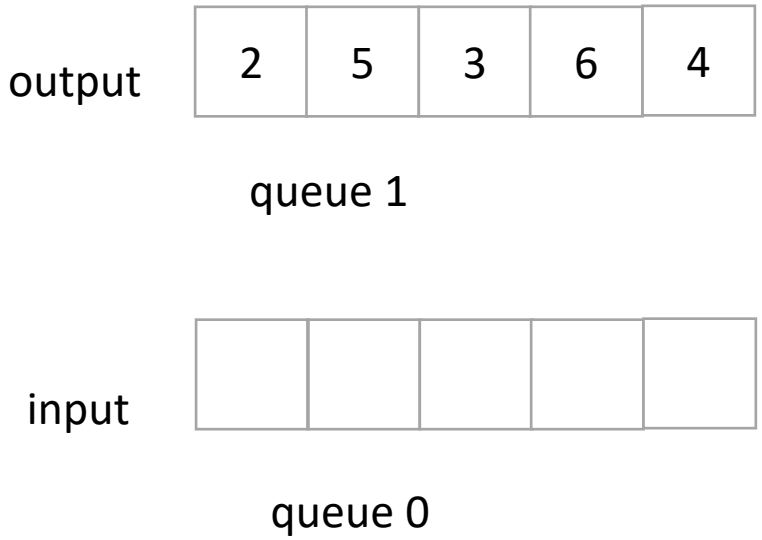


source 0



source 1



join all threads and clear input

Input/Output Queues

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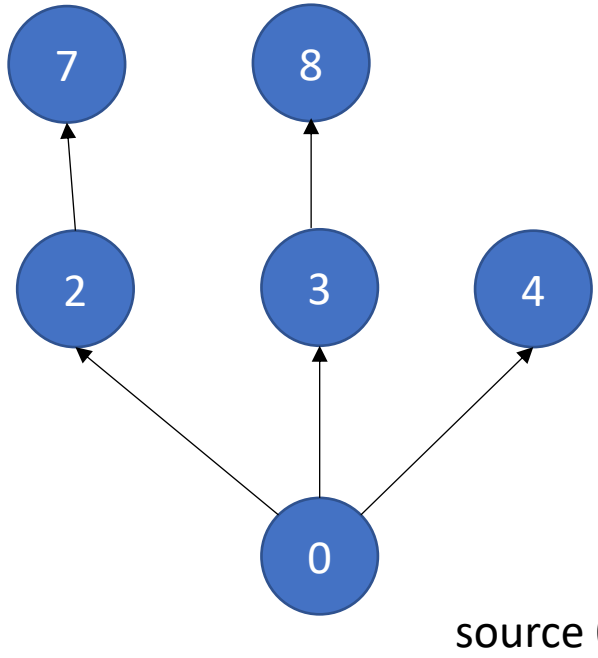

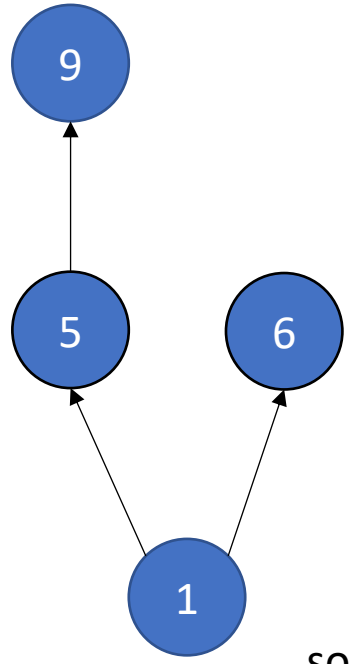

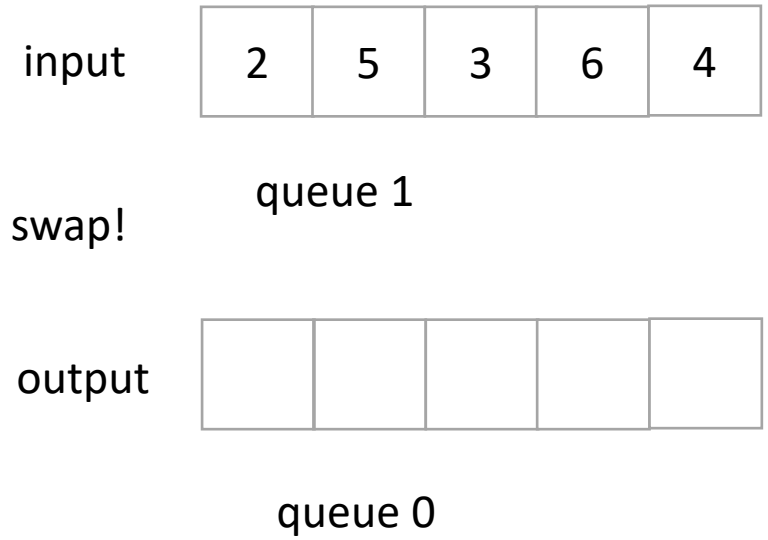

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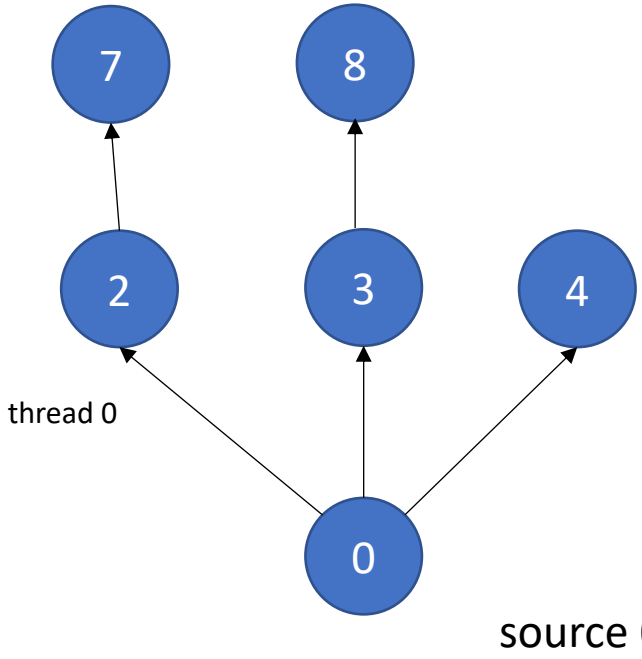
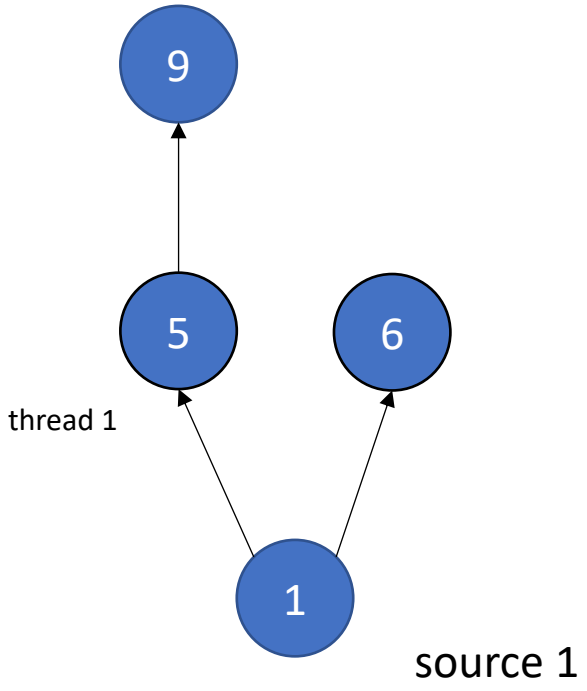
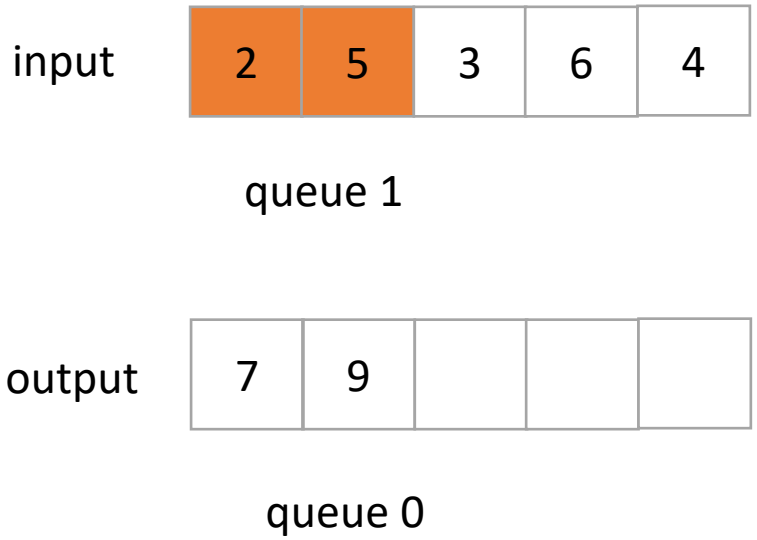
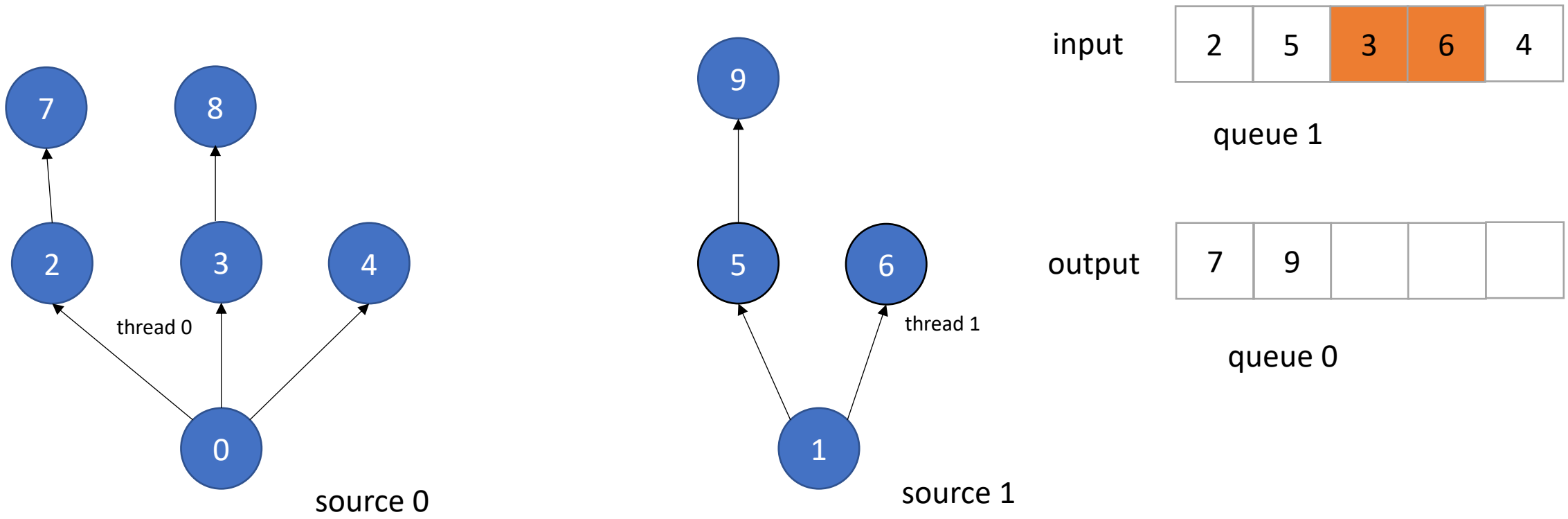






Input/Output Queues

- Example: Information flow in graph applications:



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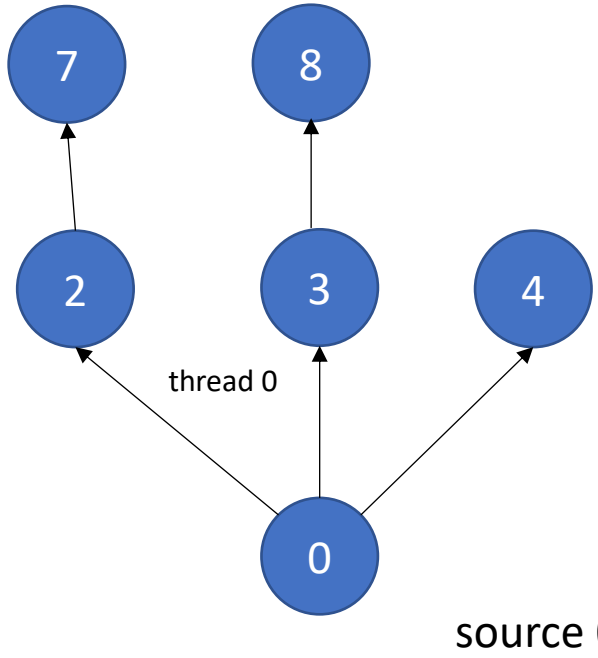

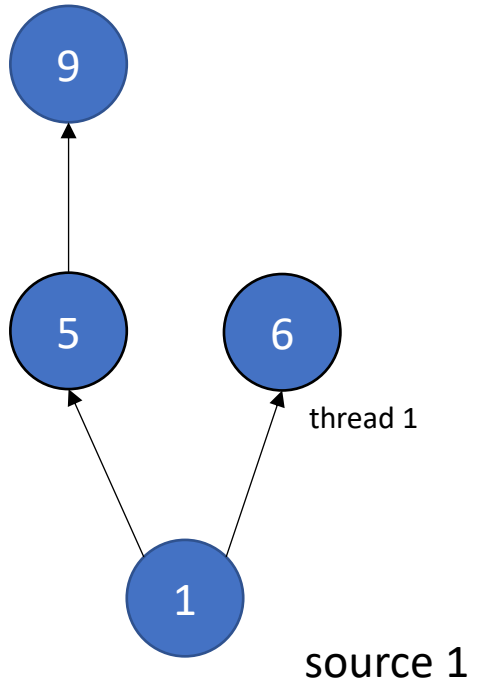

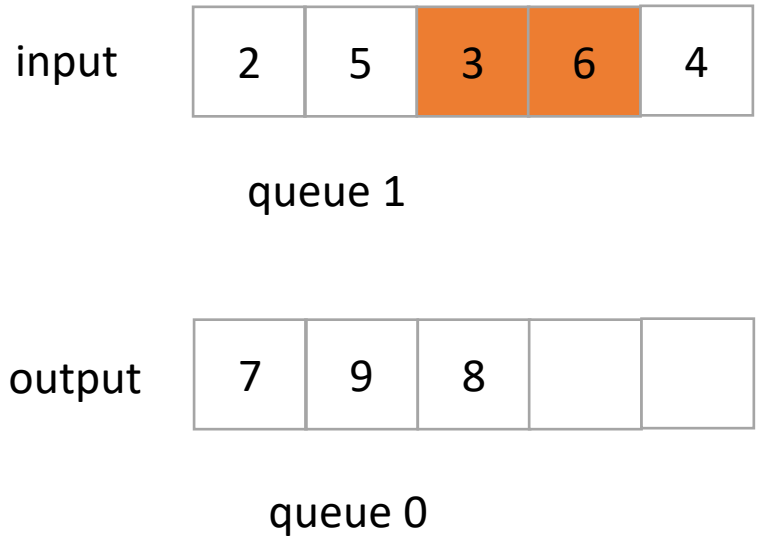

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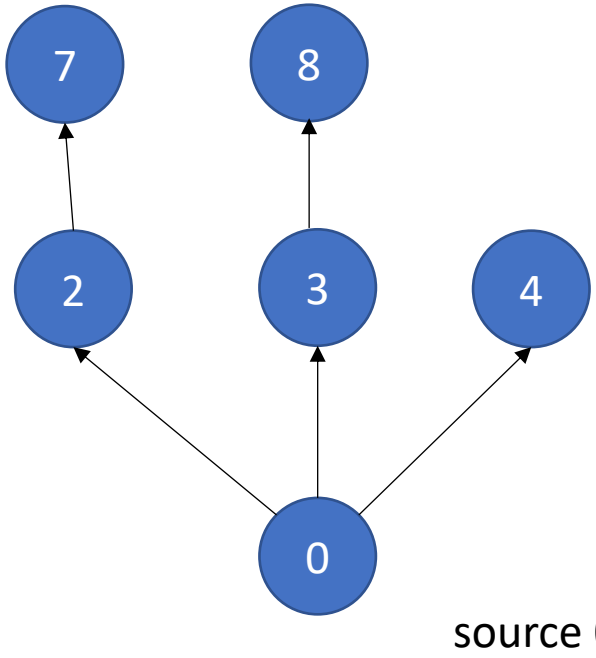

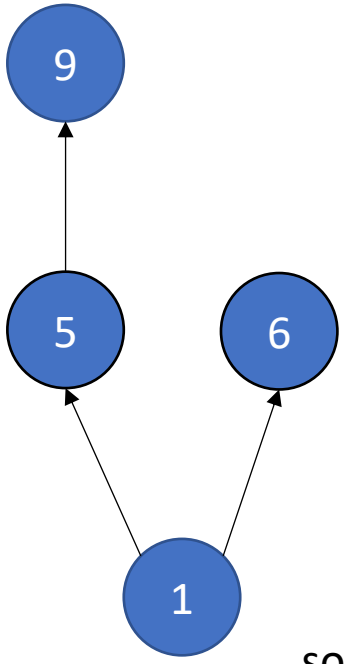

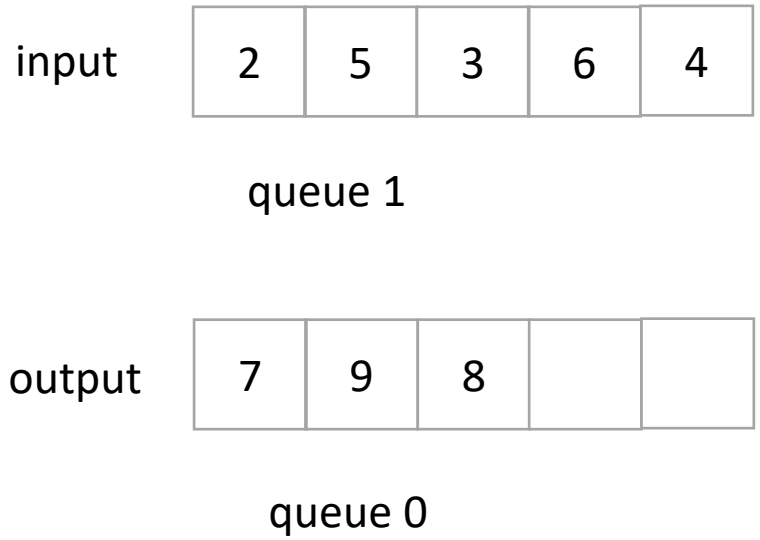

Input/Output Queues

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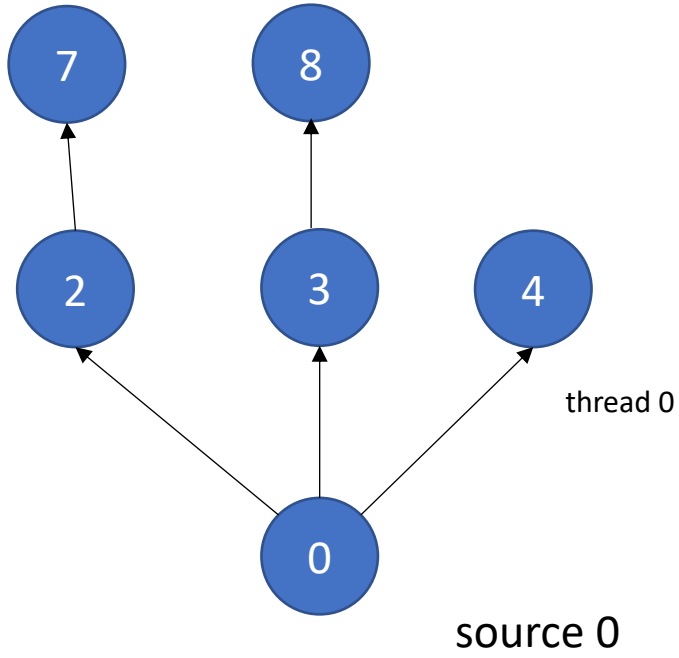

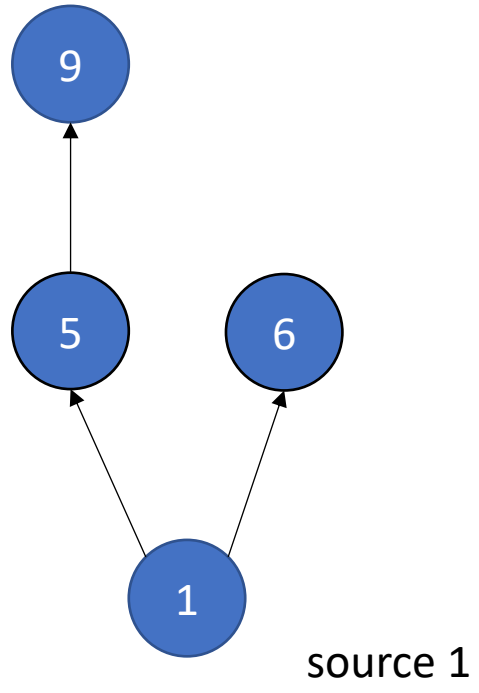

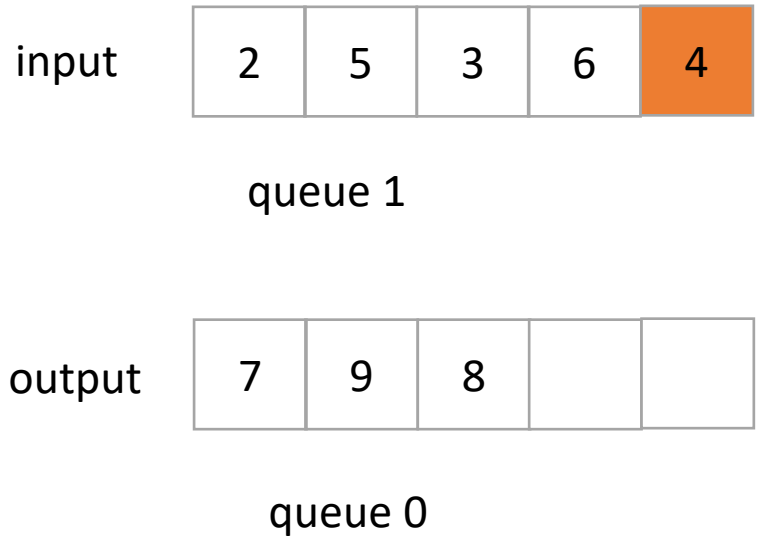

Input/Output Queues

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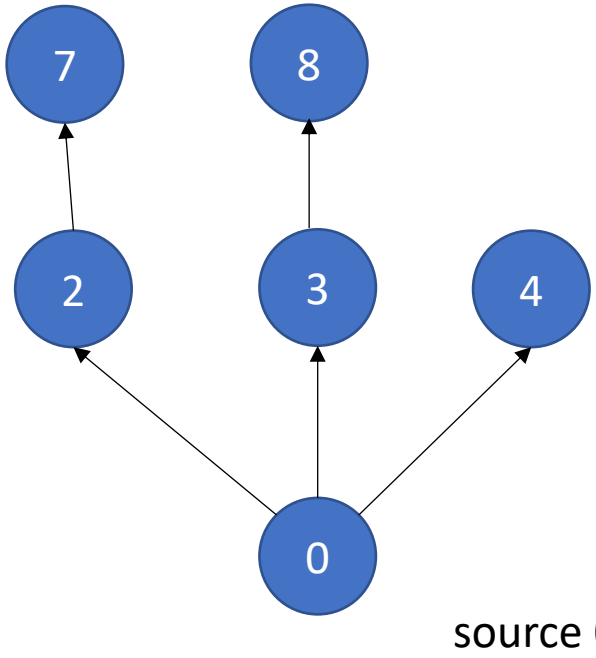

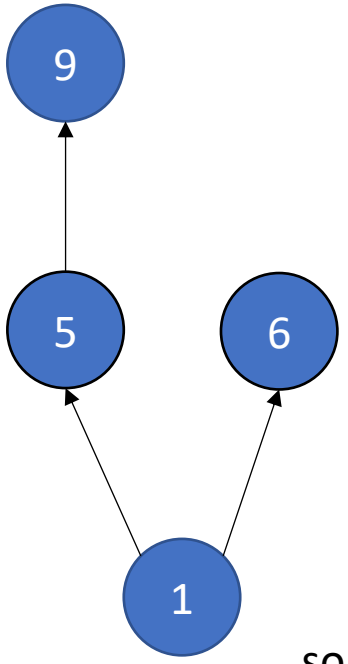

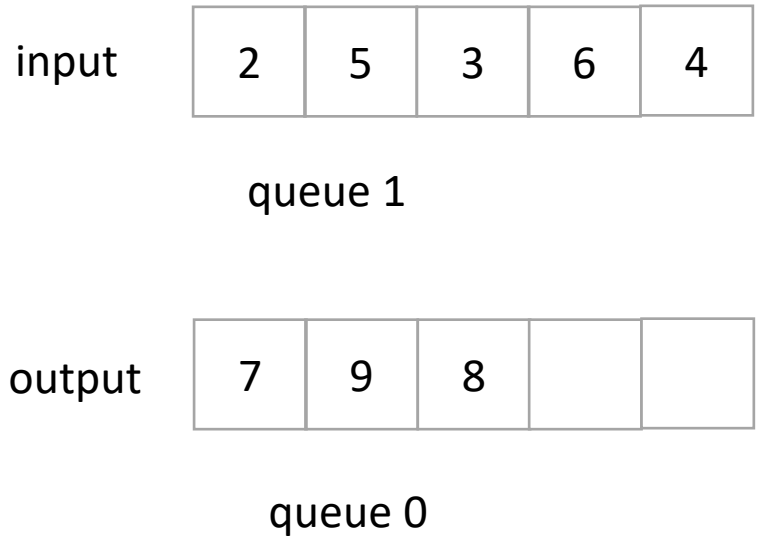

Input/Output Queues

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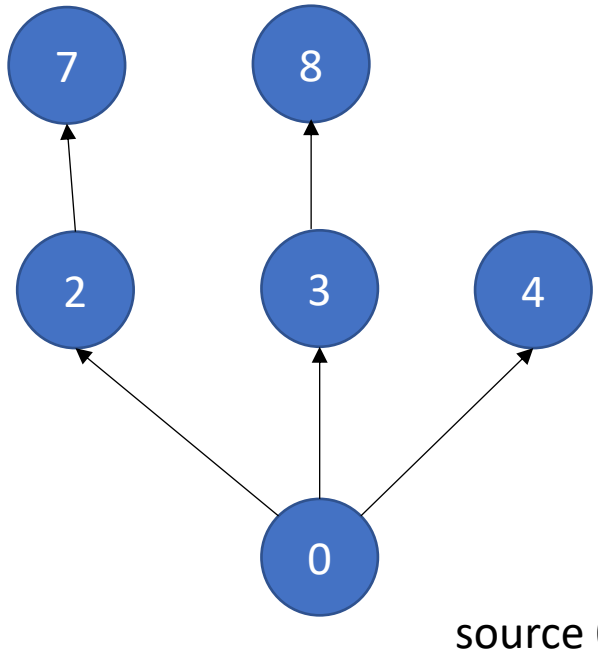
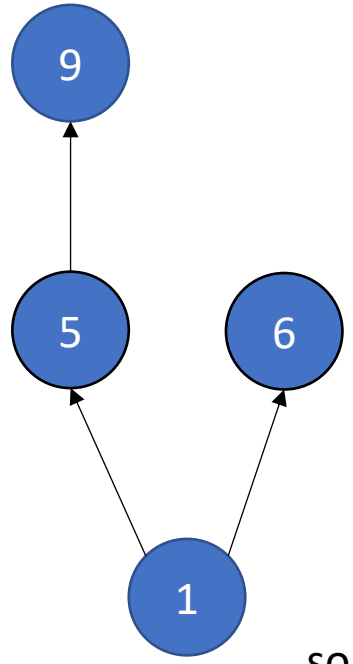




and so on...

output

queue 1

input

7 9 8

queue 0

Implementation

Implementation

Allocate a contiguous array

Pros:
?

Cons:
?

Implementation

Allocate a contiguous array

Pros:
+ fast!
+ we can use indexes instead of addresses

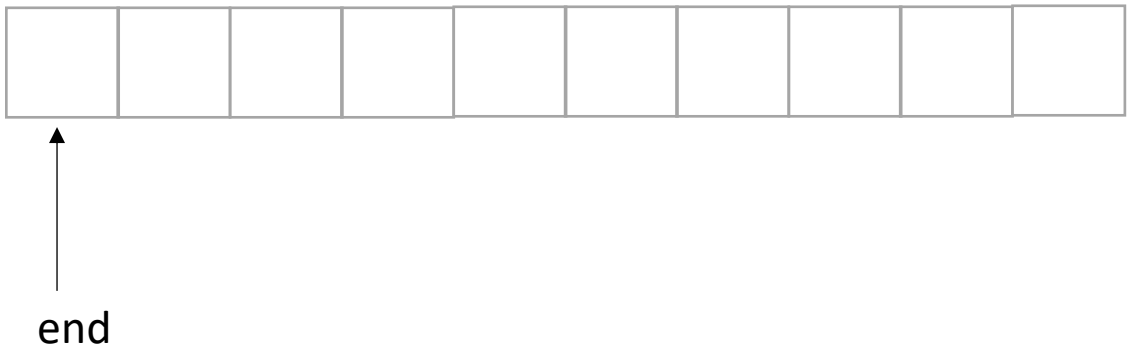
Cons:
- need to reason about overflow!

Note on terminology

- Head/tail - often used in queue implementations, but switches when we start doing circular buffers.

- Front/end - To avoid confusion, we will use front/end for input/output queues.

Implementation



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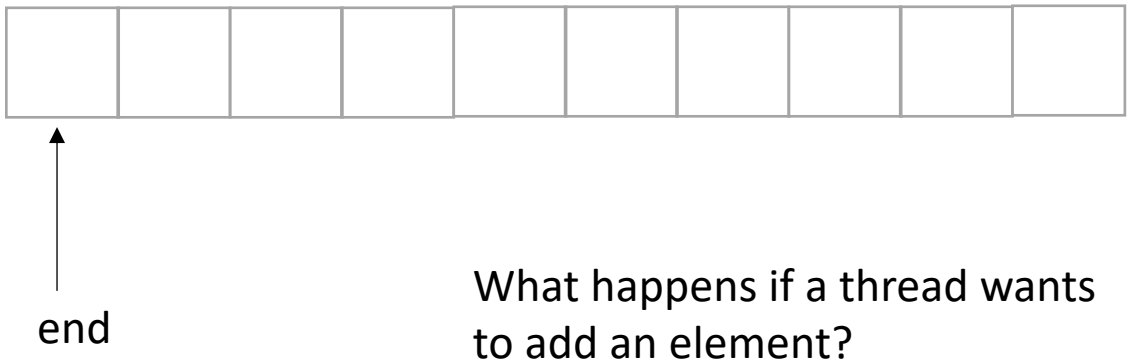

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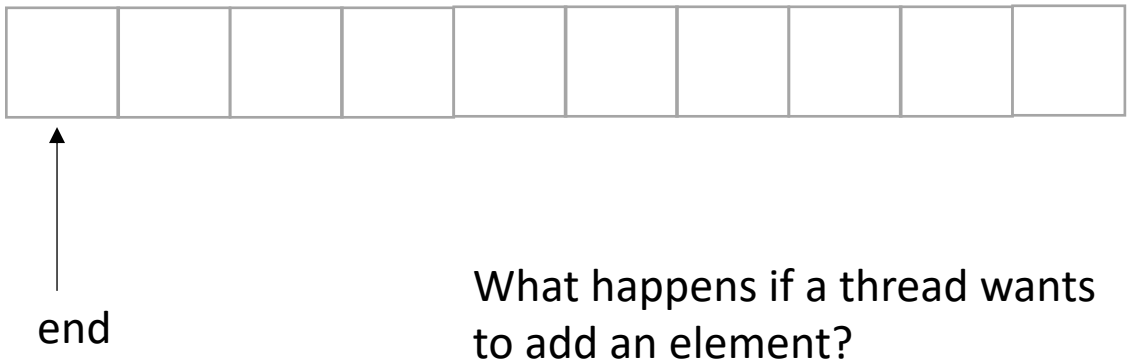
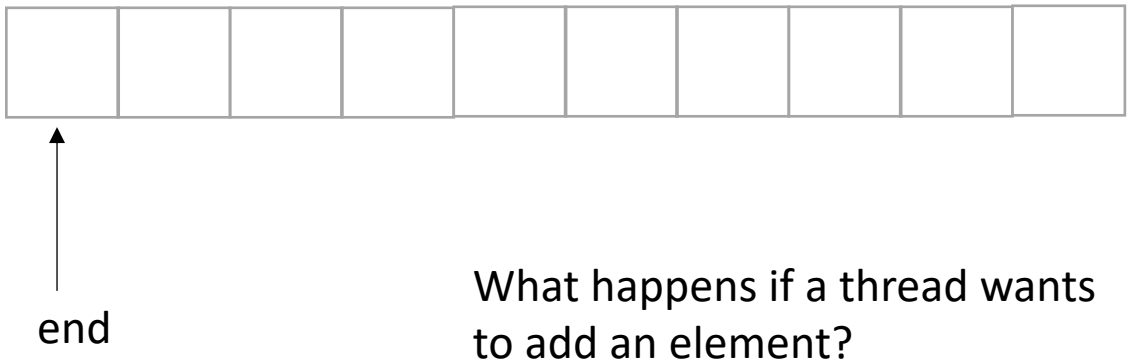


What happens if a thread wants to add an element?

Think sequentially:

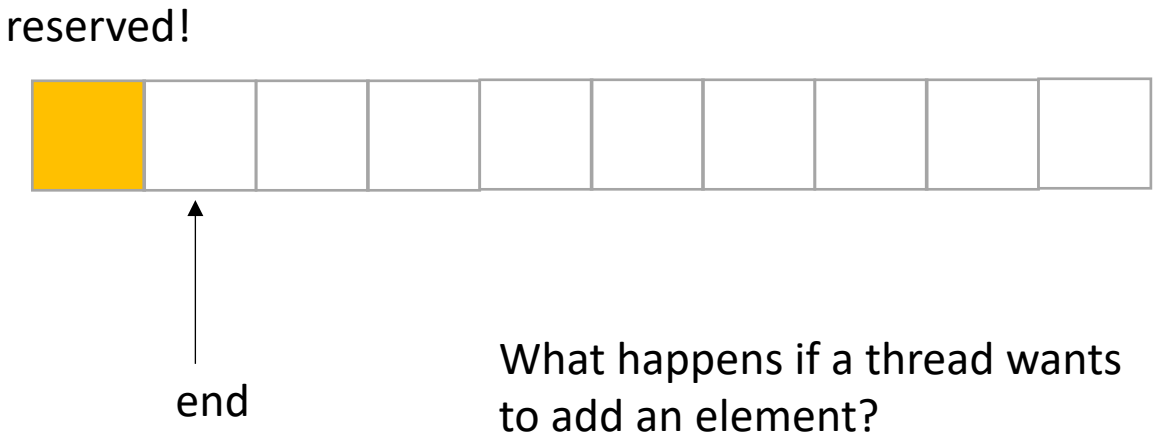
Implementation



What happens if a thread wants to add an element?

Think sequentially:
*reserve a space - increment end

Implementation



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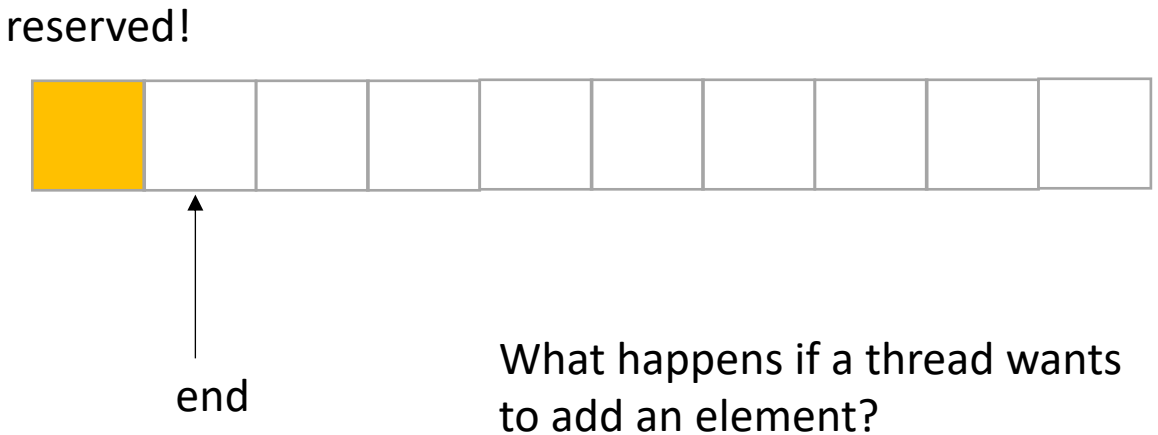

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Think sequentially:
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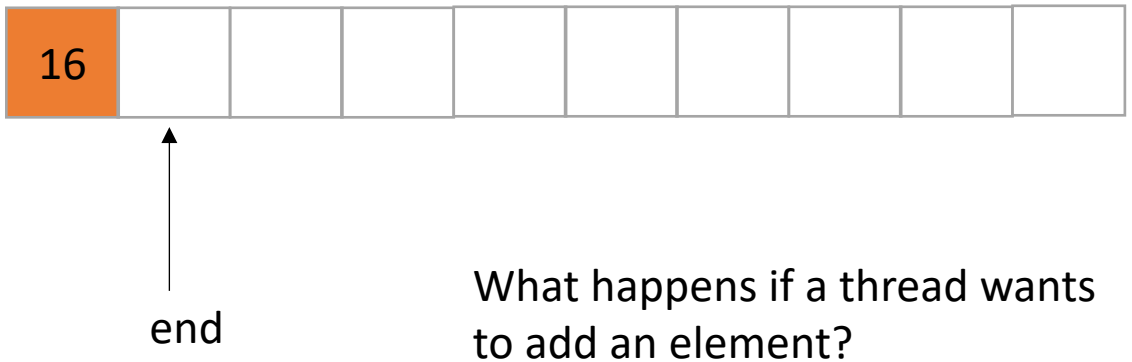
Implementation



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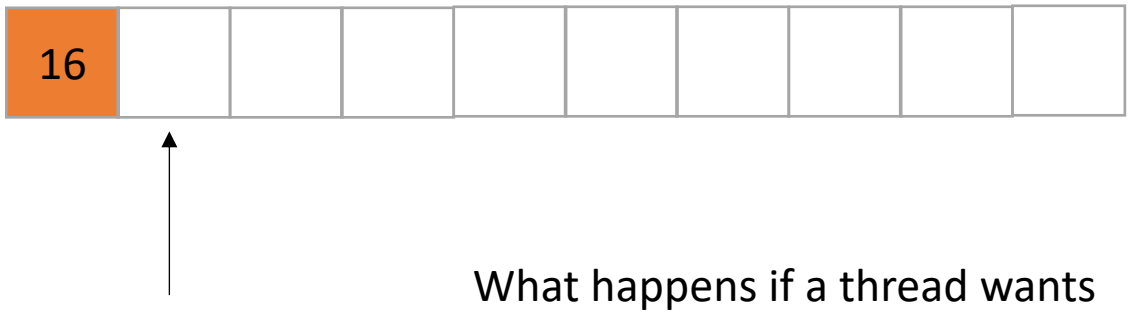
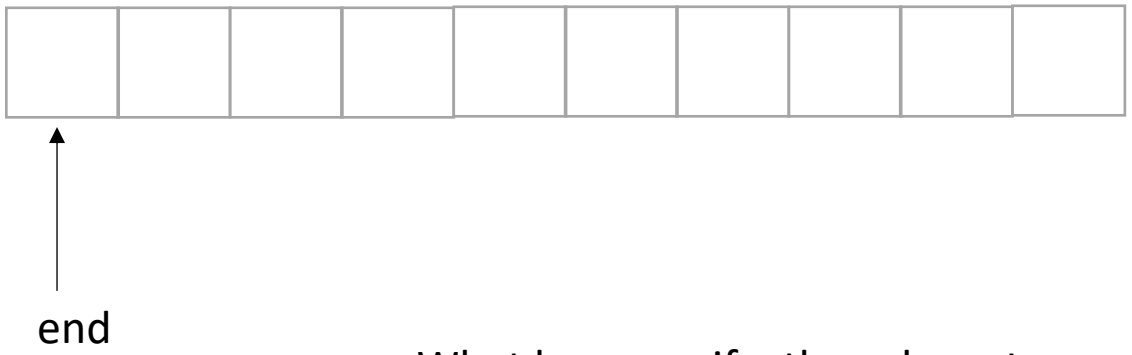


What happens if a thread wants to add an element?

Think sequentially:
* reserve a space - increment end
* add the element

done!

Implementation

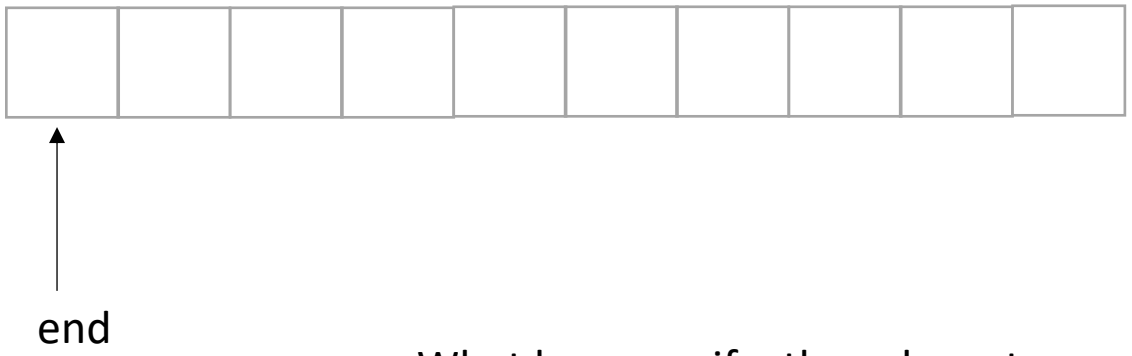


What happens if a thread wants
to add an element?

Think concurrently:

Two threads cannot reserve the same space!
We've seen this before

Implementation

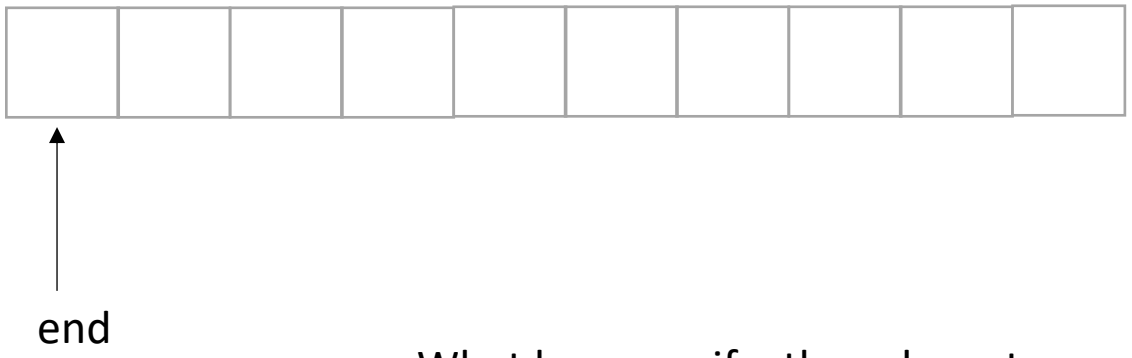


What happens if a thread wants to add an element?

Think concurrently:

```
reserved_index = atomic_fetch_add(&end, 1);
```

Implementation



Thread 0:
enq(6);

Thread 1:
enq(7);

What happens if a thread wants to add an element?

Think concurrently:

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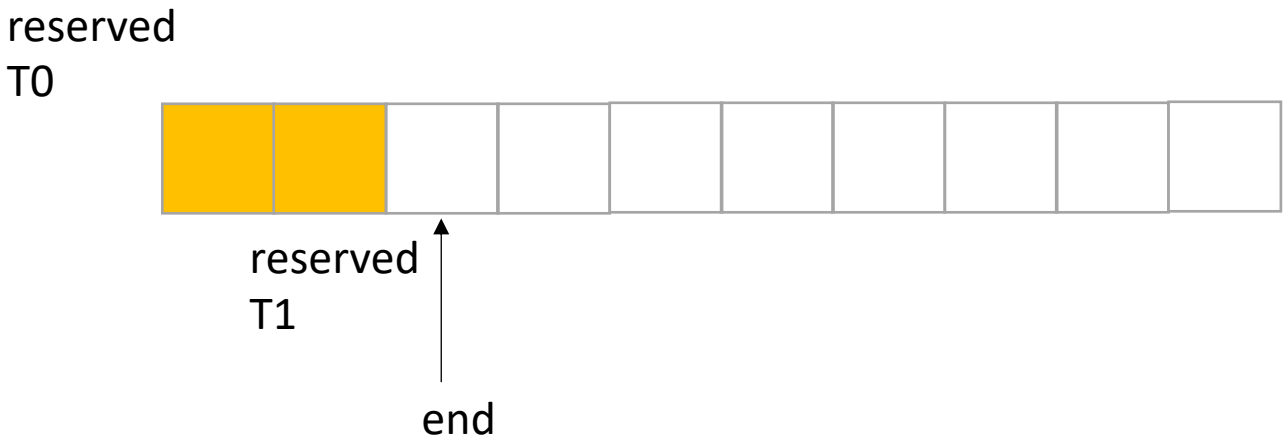
Implementation



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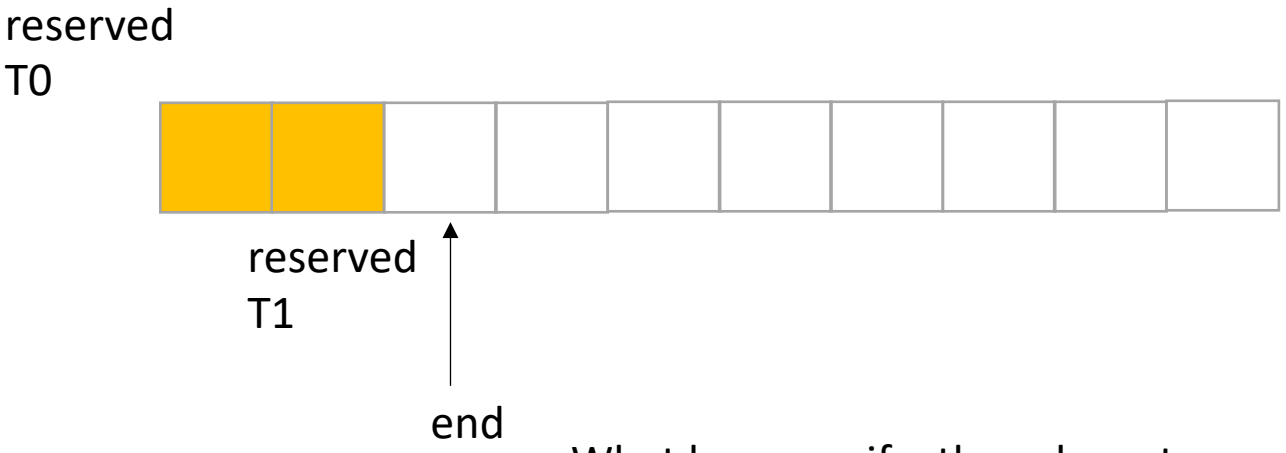
Implementation

does it matter which order threads add their data?



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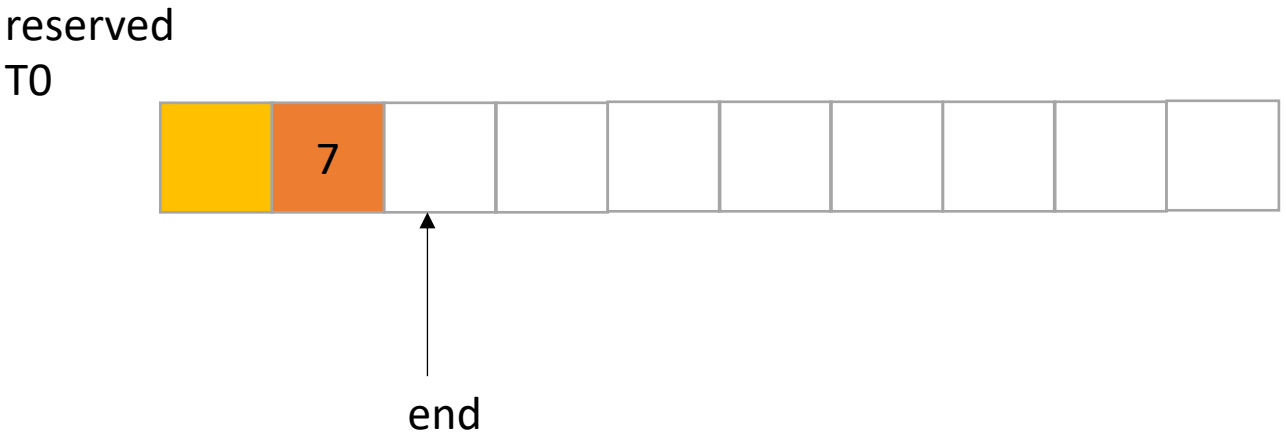

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What happens if a thread wants to add an element?

Think concurrently:

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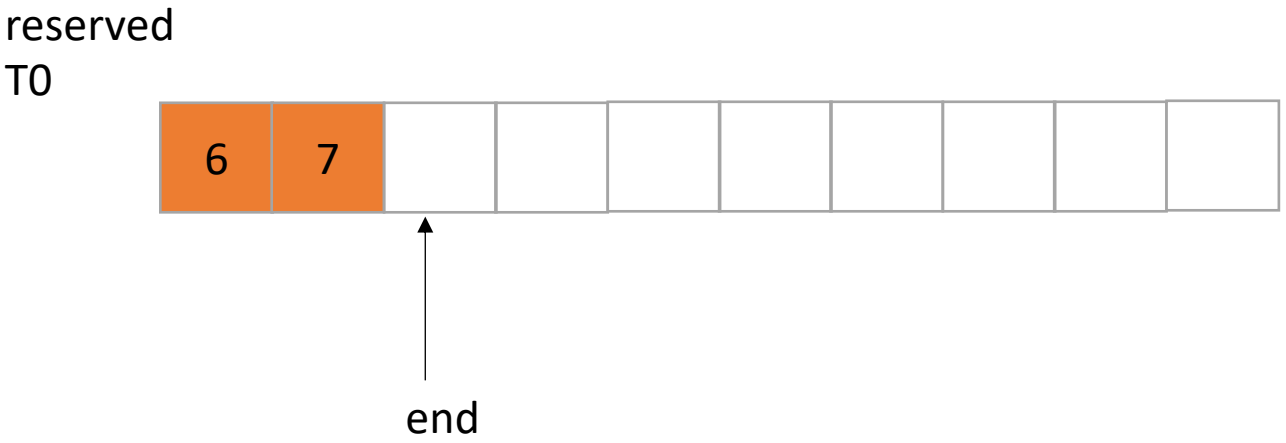
```

Implementation

does it matter which order threads add their data? No! Because there are no deqs!



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```
class InputOutputQueue {
  private:
    atomic_int end;
    int list[SIZE];

  public:
    InputOutputQueue() {
        end = 0;
     }

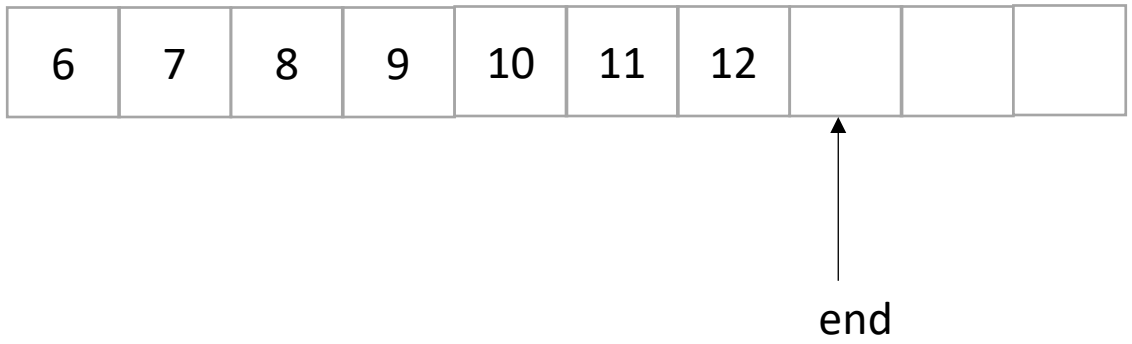
     void enq(int x) {
        int reserved_index = atomic_fetch_add(&end, 1);
        list[reserved_index] = x;
     }

     int size() {
        return end.load();
     }
 }
```

How to protect against overflows?

What about Input?

- Now we only do deqs



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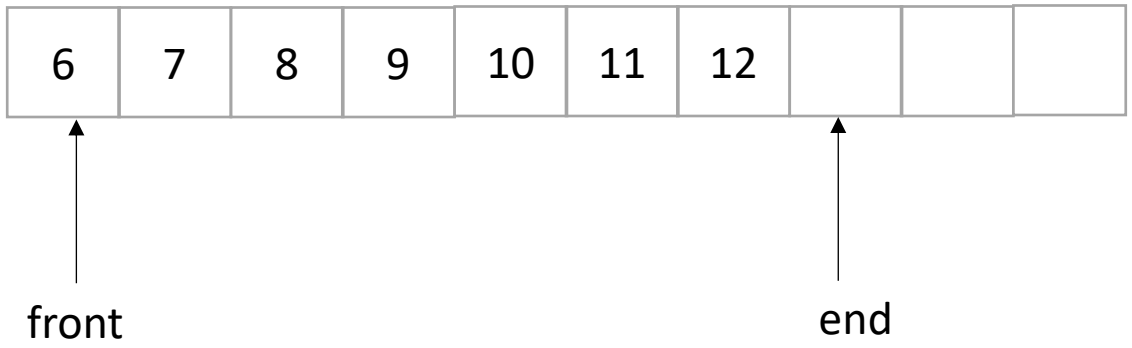

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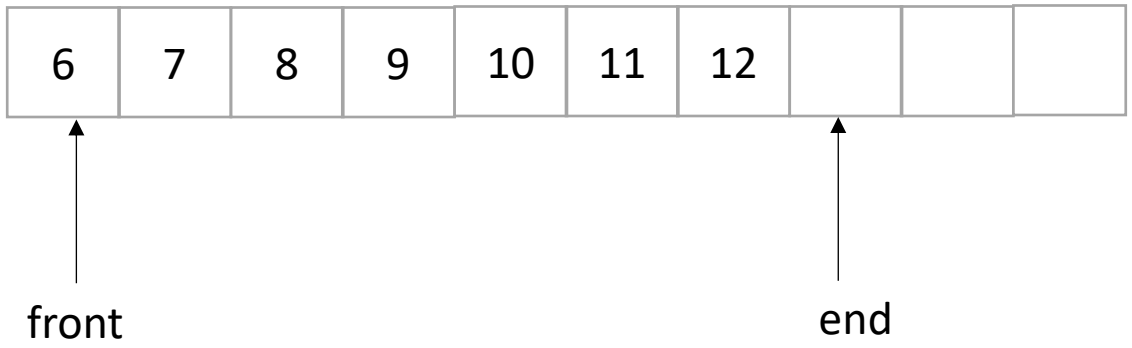


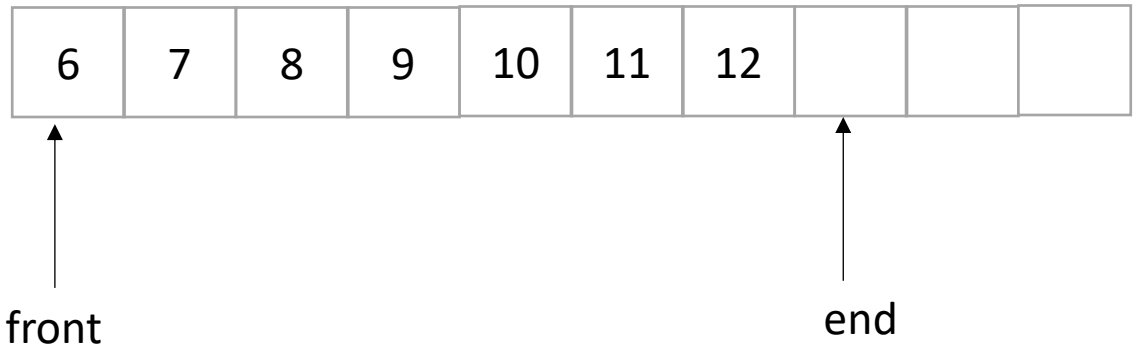
What happens if a thread wants to add an element?

Think concurrently:

```
data_index = atomic_fetch_add(&front, 1);
```

What about Input?

- Now we only do deqs



Thread 0:
deq();

Thread 1:
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What happens if a thread wants to add an element?

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What about Input?

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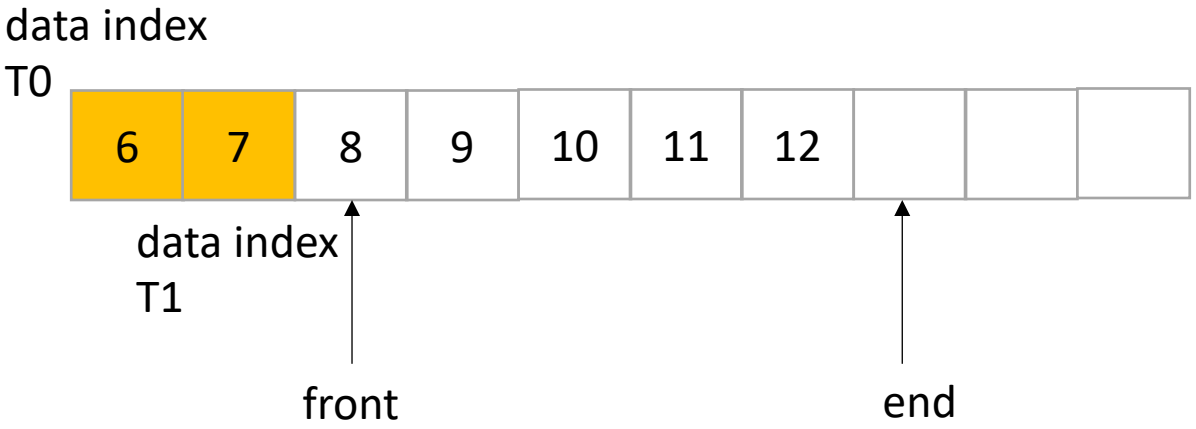

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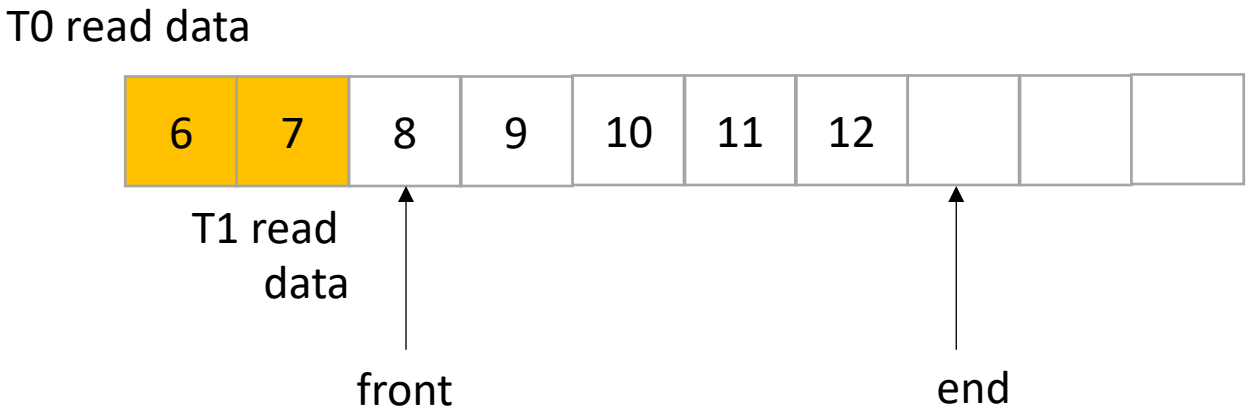

Thread 0:
deq(); // reads 6

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deq(); // reads 7

What happens if a thread wants to add an element?

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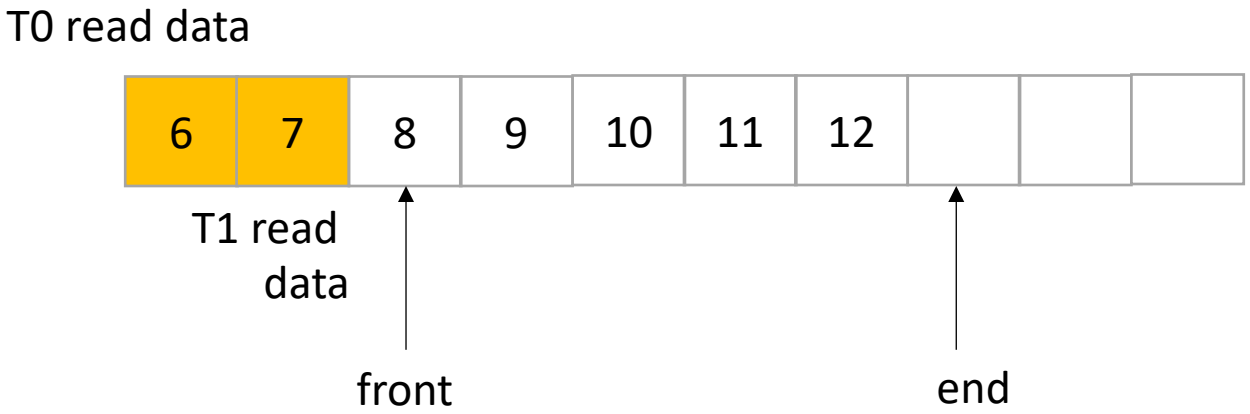

How to implement a stack?

Thread 0:
deq(); // reads 6

Thread 1:
deq(); // reads 7

What happens if a thread wants to add an element?

Think concurrently:

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```
class InputOutputQueue {
  private:
    atomic_int front;
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    int list[SIZE];

  public:
    InputOutputQueue() {
        front = end = 0;
     }

     void enq(int x) {
        int reserved_index = atomic_fetch_add(&end, 1);
        list[reserved_index] = x;
     }

     void deq() {
       int reserved_index = atomic_fetch_add(&front, 1);
       return list[reserved_index];
     }

     int size() {
        return ??;
     }
 }
```

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 }
```

How about size?

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        return end.load() - front.load();
     }
 }
```

how about size?

how do we reset?

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how about size?

how do we reset?
Reset front and end

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     int size() {
        return end.load() - front.load();
     }
 }
```

how about size?

how do we reset?
Reset front and end

does the list need
to be atomic?

See you on Friday!

- Work on HW 2!
  - Let us know if you need help! Piazza, office hours, etc.

- My office hours are tomorrow
  - They are hybrid (remote or in-person)
  - E2 - 233 (no nameplate still)
  - Sign-up sheet is still the format