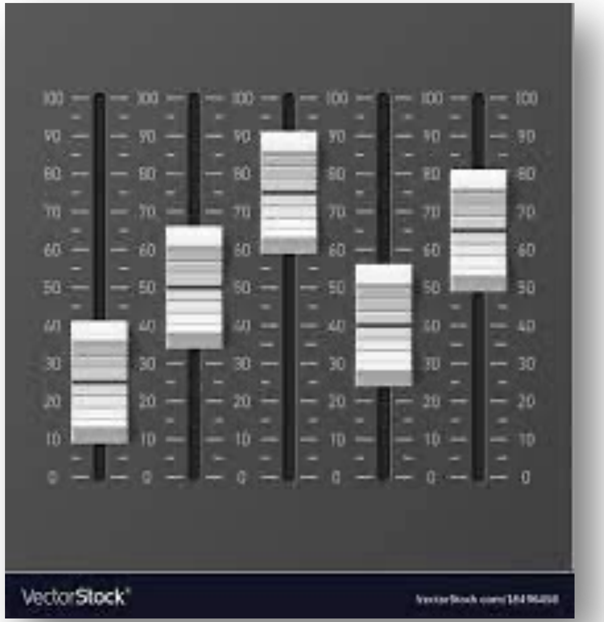
CSE113: Parallel Programming

Feb. 10, 2023

- **Topics**:
  - Concurrent data structure specifications
    - Sequential consistency
    - Breaking sequential consistency
    - Linearizability



Announcements

- Expect HW1 grades by Moday
  - Let us know if there are any issues ASAP
- Homework 2 was due, but you have until Monday
  - Please use office hours or piazza if you have questions
  - Remember, nights and weekends have no guarantees of responses.
- Homework 3 is scheduled for Monday release

Announcements

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

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

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:

```
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();
}
```

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;
};
```

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"

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();
}
```

The object is "thread safe"

```
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;
};
```

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

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

  private:
    atomic_int balance;
};
```

The object is "non-locking"

3 dimensions for concurrent objects

- **Correctness**:
  - How should concurrent objects behave (Specification)
- **Performance**:
  - How to make things fast fast fast!
- **Fairness**:
  - Under what conditions can concurrent objects deadlock

Sequential Consistency

- Our first specification

Lets think about a Queue

What is a queue?

We consider 2 API functions:

- enq(value v) - enqueues the value v
- deq() - returns the value at the front of the queue

```
Queue<int> q;
q.enq(6);
int t = q.deq();
```

```
Queue<int> q;
q.enq(6);
q.enq(7);
int t = q.deq();
```

```
Queue<int> q;
q.enq(6);
q.enq(7);
int t = q.deq();
int t1 = q.deq();
```

Lets think about a Queue

What is a queue?

We consider 2 API functions:

- enq(value v) - enqueues the value v
- deq() - returns the value at the front of the queue

```
Queue<int> q;
int t = q.deq();
```

Let’s say: *value of 0*

Lets think about a Queue

This is called a sequential specification:

The sequential specification is nice! We want to base our concurrent specification on the sequential specification

We will have to deal with the non-determinism of concurrency

Thinking about a concurrent queue

```
Queue<int> q;
q.enq(6);
q.enq(7);
int t = q.deq();
```

Thinking about a concurrent queue

Global variable:

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

Lets call our concurrent queue “CQueue”

Thread 0:

```
q.enq(6);
q.enq(7);
int t = q.deq();
```

Thinking about a concurrent queue

Global variable:

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

Thread 0:

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

Thread 1:

```
int t = q.deq();
```

what can be stored in t after this concurrent program?

Thinking about a concurrent queue

Global variable:

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

Thread 0:

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

Thread 1:

```
int t = q.deq();
```

what can be stored in t after this concurrent program?

Can t be 256?

Thinking about a concurrent queue

Global variable:

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

Thread 0:

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

Thread 1:

```
int t = q.deq();
```

what can be stored in t after this concurrent program?

Can t be 256? it should be one of {None, 6, 7}

Global variable:

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

Thread 0:

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

Construct a sequential timeline of API calls
Any sequence is valid:

Thread 1:

```
int t = q.deq();
```

Global variable:

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

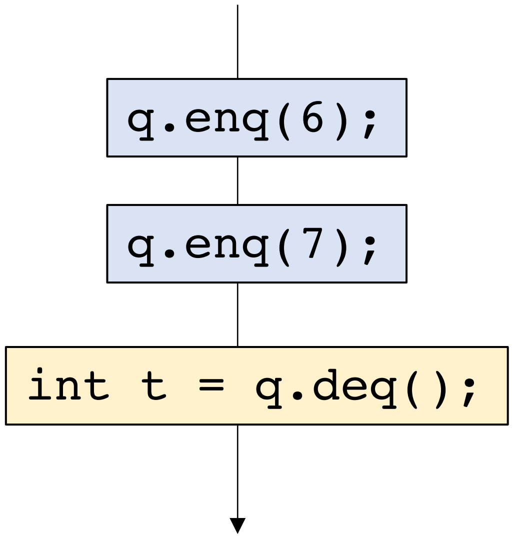
Thread 0:

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

Thread 1:

```
int t = q.deq();
```

Construct a sequential timeline of API calls
Any sequence is valid:



t is 6

Global variable:

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

Thread 0:

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

Thread 1:

```
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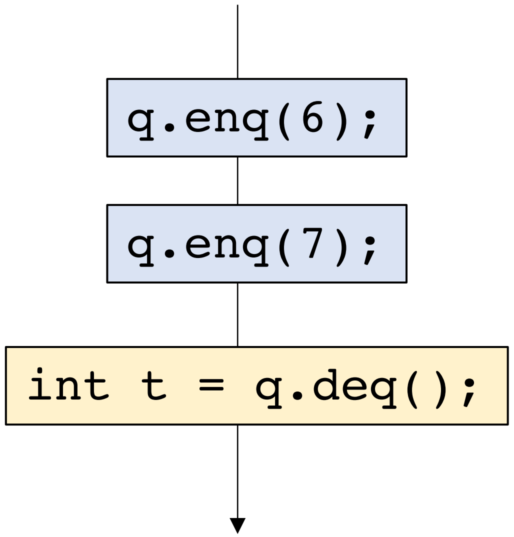
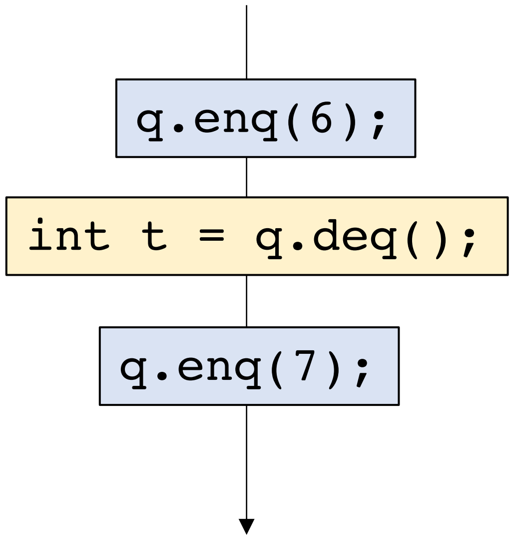


t is 6



t is 6

Global variable:

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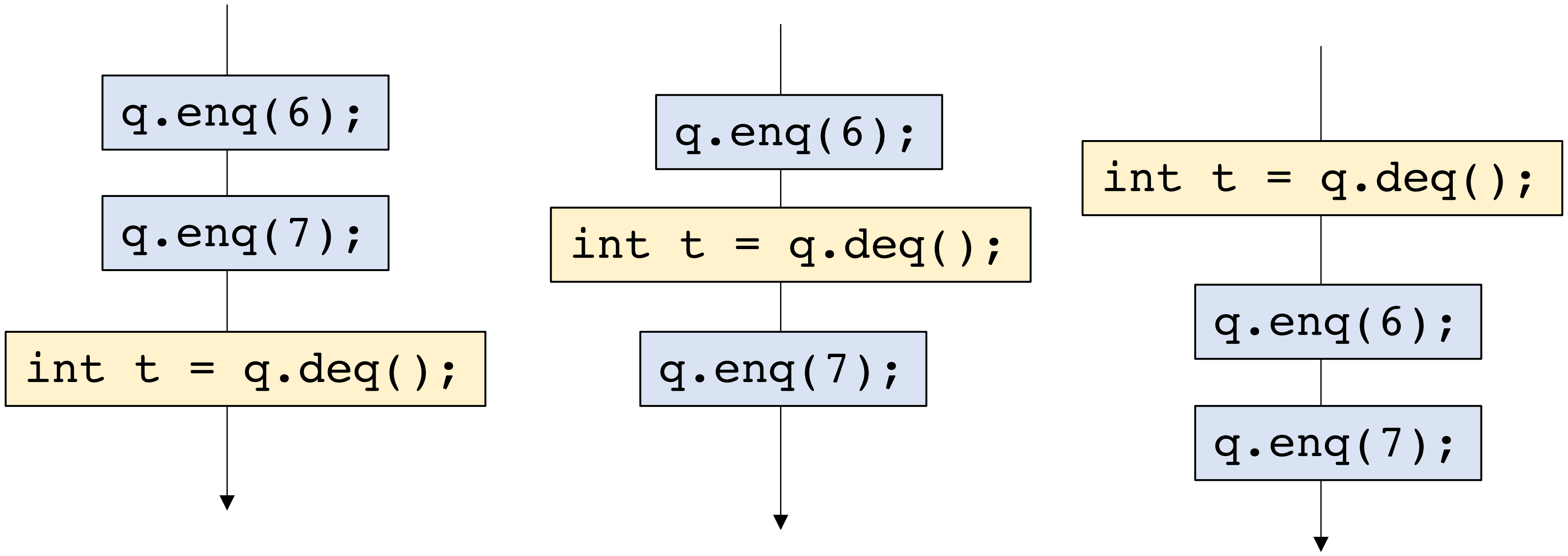


t is 6   t is 6   t is None

Global variable:

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

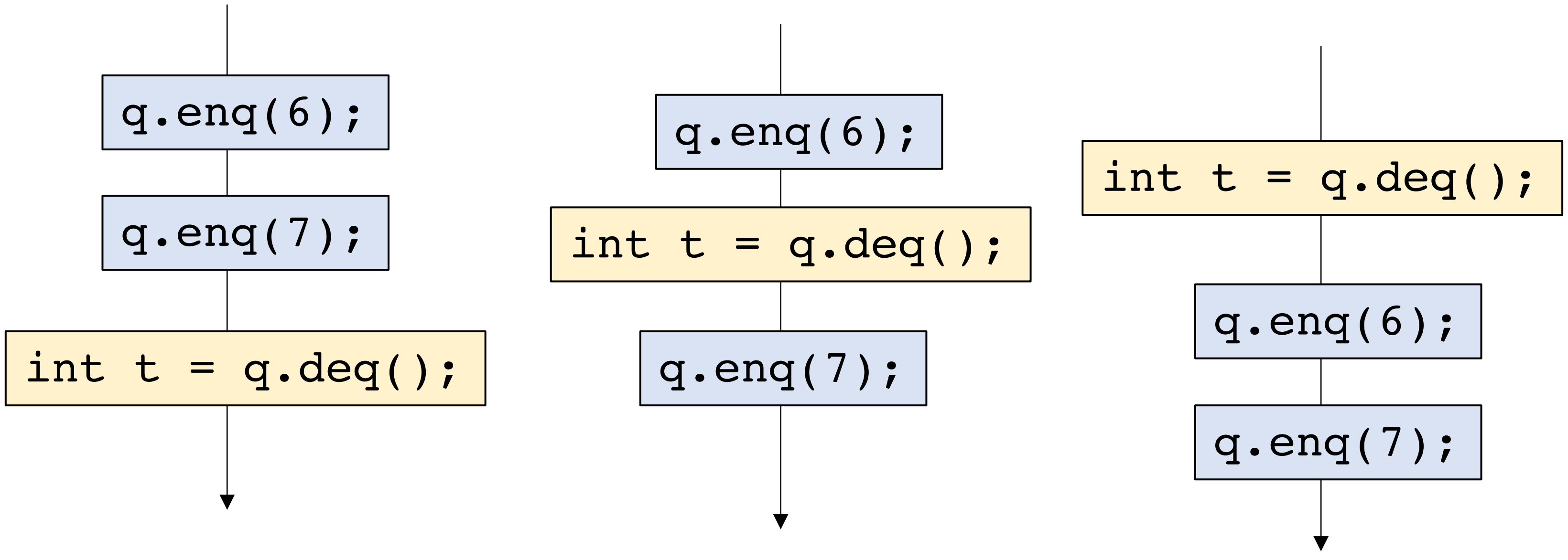
Thread 0:

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

Thread 1:

```
int t = q.deq();
```

Construct a sequential timeline of API calls
Any sequence is valid:



t is 6 | t is 6 | t is None

Can t ever be 7?

Global variable:

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

Thread 0:

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

Thread 1:

```
int t = q.deq();
```

Construct a sequential timeline of API calls
Any sequence is valid:

Can t ever be 7?

Global variable:

```
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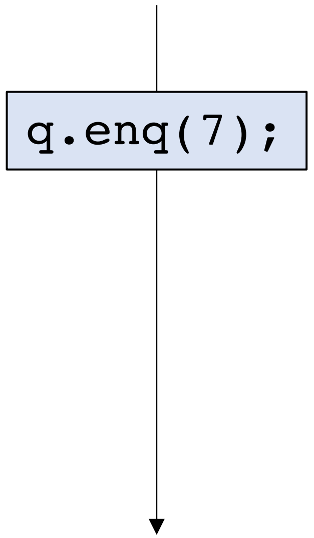
```

Construct a sequential timeline of API calls
Any sequence is valid:



Can t ever be 7?

Global variable:

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CQueue<int> q;
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Thread 0:

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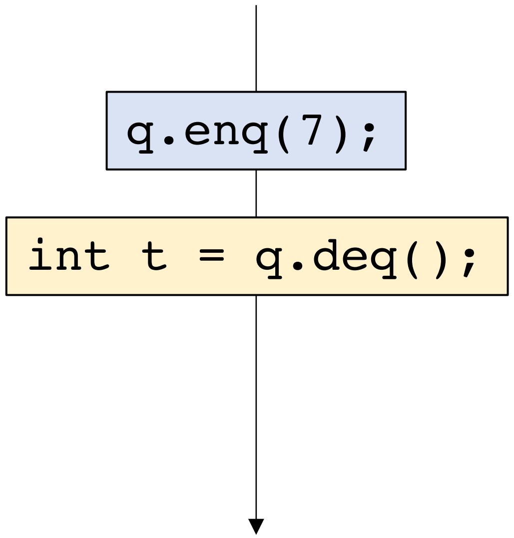
```
int t = q.deq();
```

Construct a sequential timeline of API calls
Any sequence is valid:



Can t ever be 7?

Global variable:

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

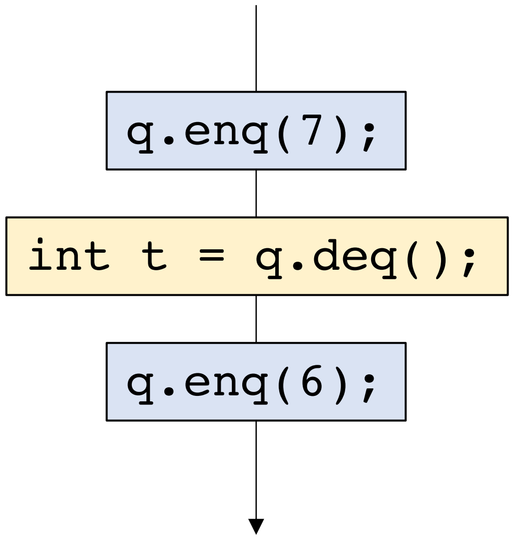
Thread 0:

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

Thread 1:

```
int t = q.deq();
```

Construct a sequential timeline of API calls
Any sequence is valid:



Can t ever be 7?

Global variable:

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

Thread 0:

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

Thread 1:

```
int t = q.deq();
```

Construct a sequential timeline of API calls
Any sequence is valid:

```
q.enq(7);
int t = q.deq();
q.enq(6);
```

The events of Thread 0 don't appear in the same order of the program!

This should not be allowed!

Can t ever be 7?

Sequential Consistency

- Valid executions correspond a sequentialization of object method calls

- The sequentialization must respect per-thread ”program order”, the order in which the object method calls occur in the thread

- Events across threads can interleave in any way possible

Sequential Consistency

- Valid executions correspond a sequentialization of object method calls

- The sequentialization must respect per-thread ”program order”, the order in which the object method calls occur in the thread

- Events across threads can interleave in any way possible

How many possible interleavings?
Combinatorics question:

if Thread 0 has N events
if Thread 1 has M events

$$\frac{(N+M)!}{N!\,M!}$$

Sequential Consistency

How many possible interleavings?
Combinatorics question:

if Thread 0 has N events
if Thread 1 has M events

$$\frac{(N+M)!}{N!\,M!}$$

Reminder that N and M are events, not instructions

Sequential Consistency

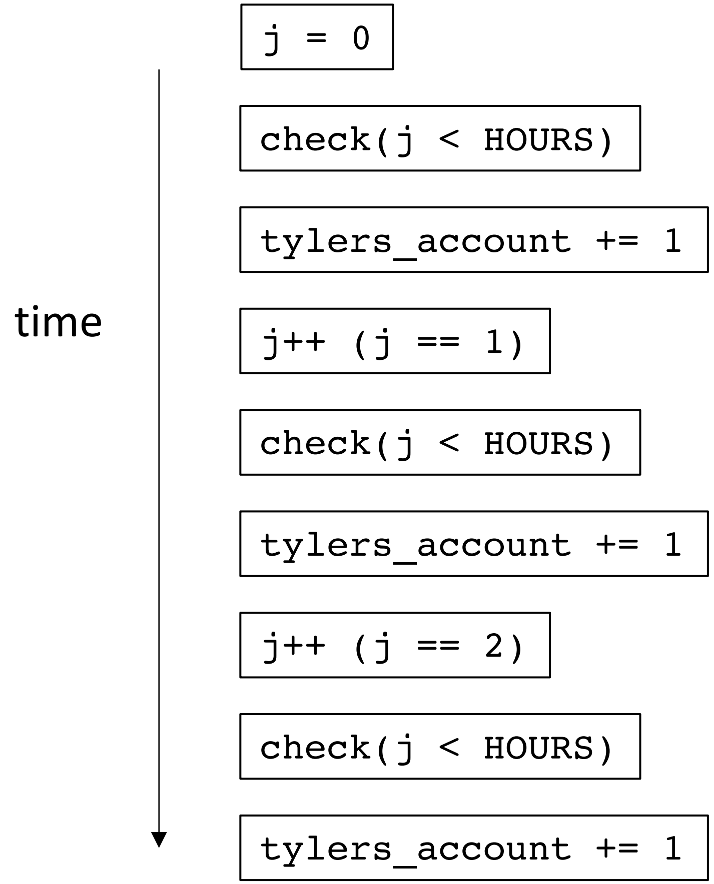
Tyler's employer

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

How many possible interleavings?
Combinatorics question:

if Thread 0 has N events
if Thread 1 has M events

$$\frac{(N+M)!}{N!\,M!}$$



Reminder that N and M are events, not instructions

If N and M execute 150 events each, there are more possible executions than particles in the observable universe!

Don’t think about all possible interleavings!

- Higher-level reasoning:
  - I get paid 100 times and buy 100 coffees, I should break even
  - If you enqueue 100 elements to a queue, you should be able to dequeue 100 elements
- Reason about a specific outcome
  - Find an interleaving that allows the outcome
  - Find a counter example

Reasoning about concurrent objects

To show that an outcome is possible, simply construct the sequential sequence

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:

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

Thread 0:

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

Thread 1:

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

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

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

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

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

Can t0 == 0 and t1 == 6?

Global variable:

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

Thread 0:

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

Thread 1:

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

```
int t0 = q.deq();
q.enq(6);
q.enq(7);
int t1 = q.deq();
```

Can t0 == 0 and t1 == 6?

Valid execution!

Are there others?

Global variable:

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

Lets do another!

Thread 0:

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

Thread 1:

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

Can t0 == 6 and t1 == 7?

Global variable:

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

Lets do another!

Thread 0:

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

Thread 1:

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

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

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

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

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

Can t0 == 6 and t1 == 7?

Global variable:

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

Thread 0:

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

Thread 1:

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

```
q.enq(6);
int t0 = q.deq();
q.enq(7);
int t1 = q.deq();
```

Found one! Are there others?

Can t0 == 6 and t1 == 7?

Reasoning about concurrent objects

To show that an outcome is possible, simply construct the sequential sequence

To show that an outcome is ***impossible*** show that there is no possible sequential sequence

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 == 7?

Global variable:

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

Thread 0:

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

Thread 1:

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

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

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

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

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

Can t0 == 0 and t1 == 7?

Global variable:

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

Thread 0:

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

Thread 1:

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

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

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

No place for this event to go!

Can t0 == 0 and t1 == 7?

One more example

Global variable:

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

Thread 0:

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

Thread 1:

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

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

Global variable:

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

Thread 0:

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

Thread 1:

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

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

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

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

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

Do we have our specification?

- Is sequential consistency a good enough specification for concurrent objects?

- It’s a good first step, but relative timing interacts strangely with absolute time.

- We will need something stronger.

Schedule

- **Problems with sequential consistency**

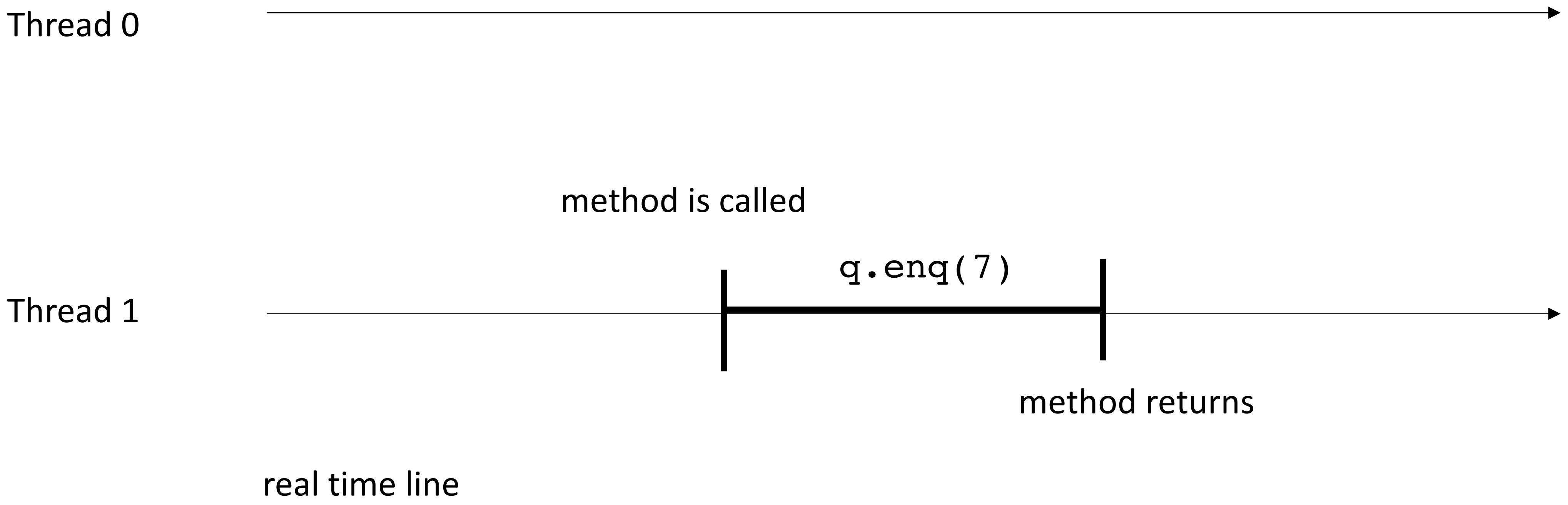
- Linearizability

- Specialized concurrent queues

Sequential consistency and real time

- Add in real time:

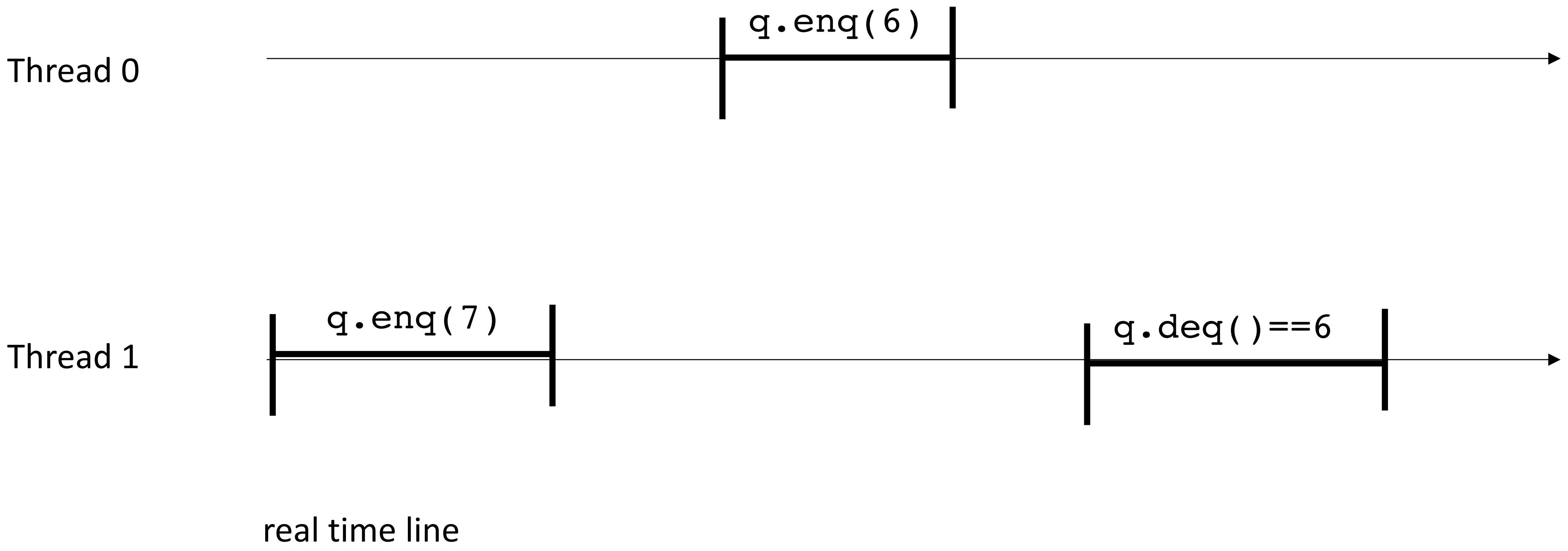
each method as a start, and end time stamp



Sequential consistency and real time

- Add in real time:

This timeline seems strange...

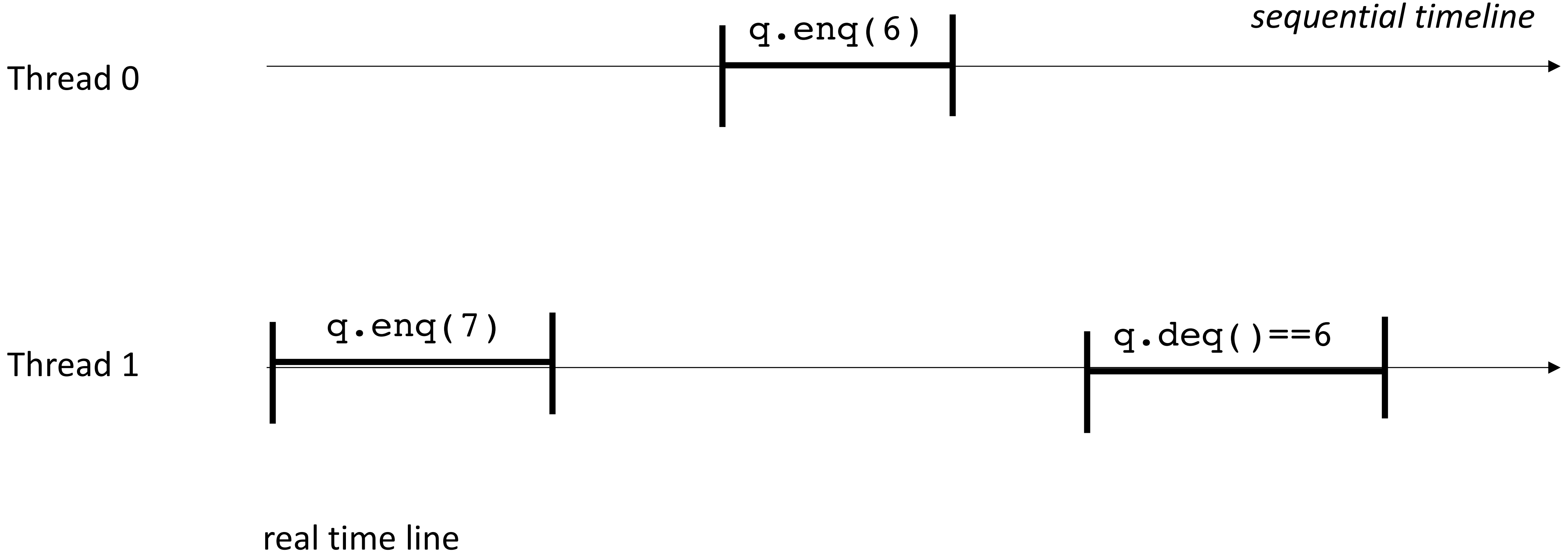


Sequential consistency and real time

- 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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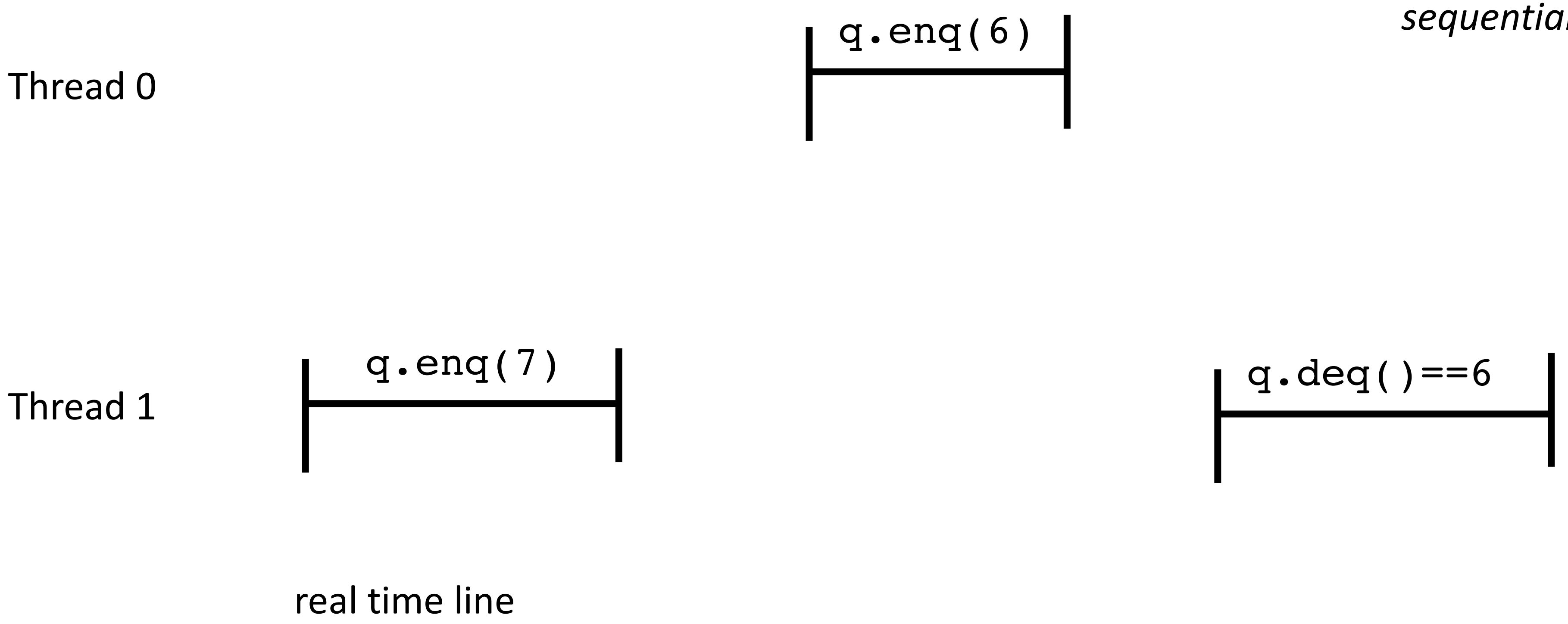


Sequential consistency and real time

- 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

`q.enq(6)`

Thread 0

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

Thread 1

real time line

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

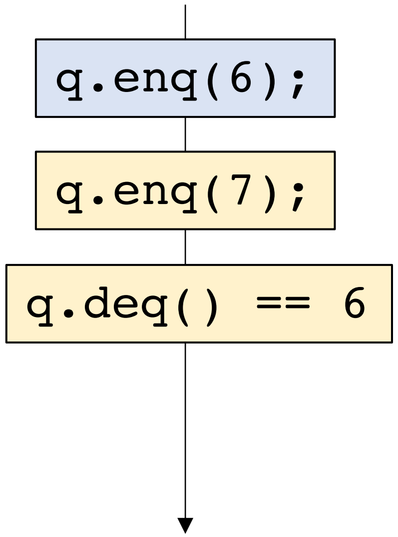
`q.enq(6)`

Thread 0

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

Thread 1

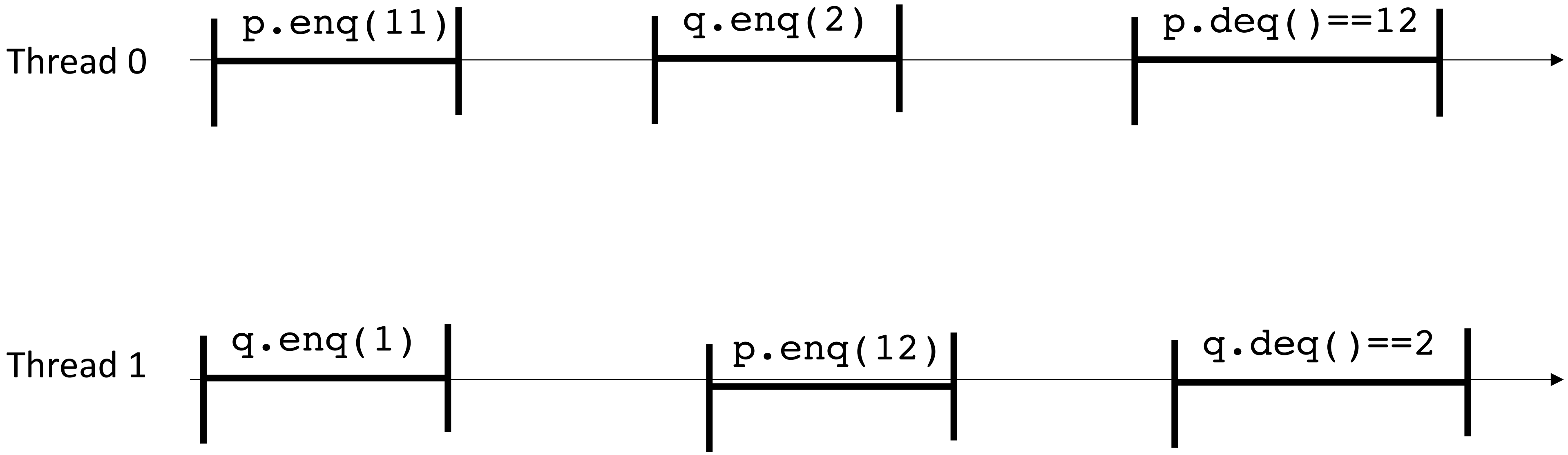
real time line



Sequential consistency and real time

- Add in real time:

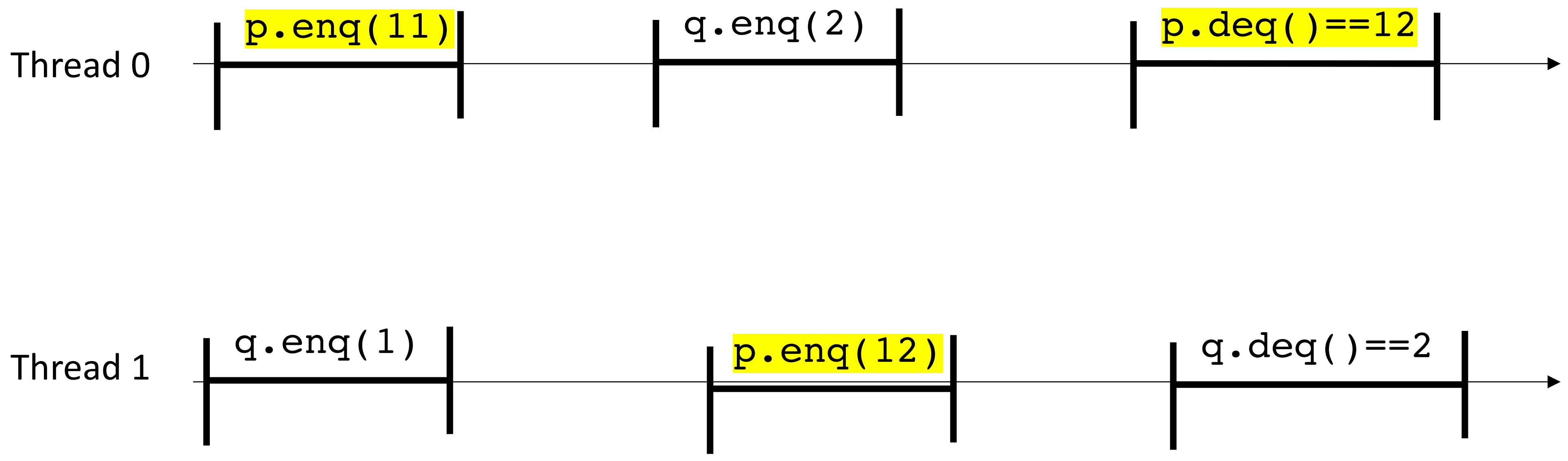
2 objects now: p and q



Sequential consistency and real time

- Add in real time:

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



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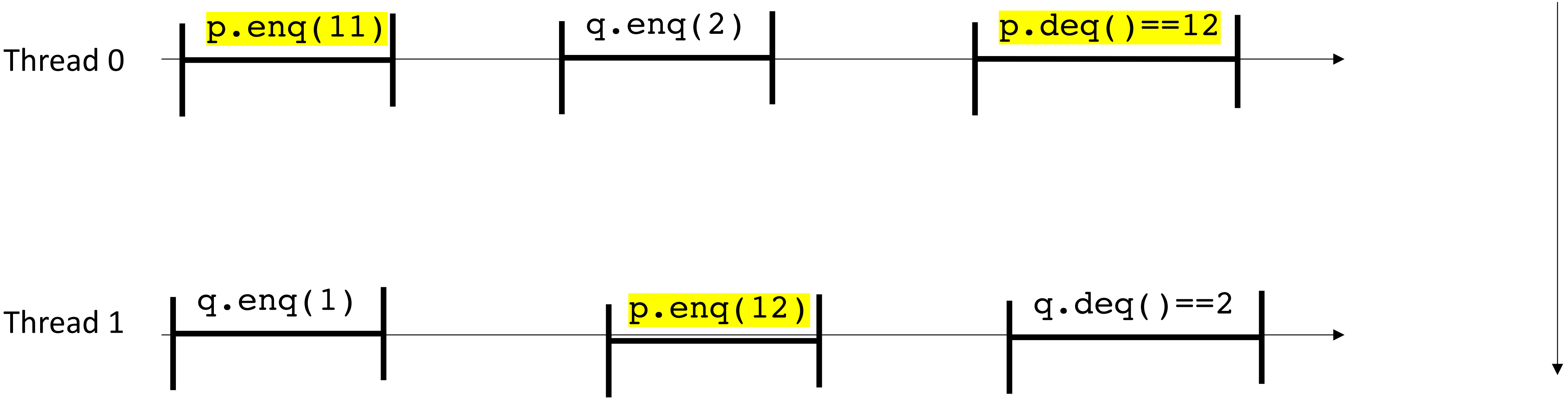

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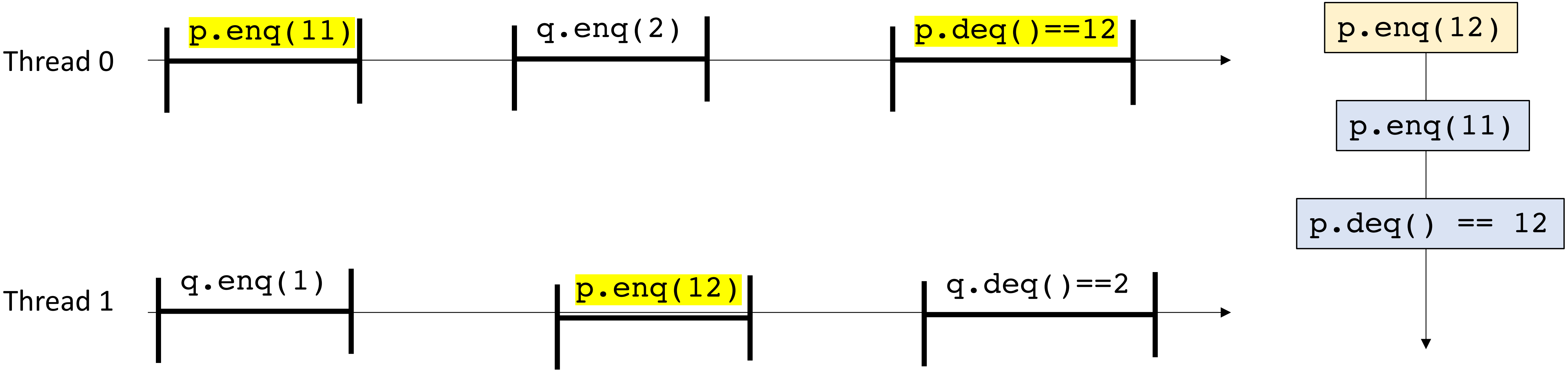

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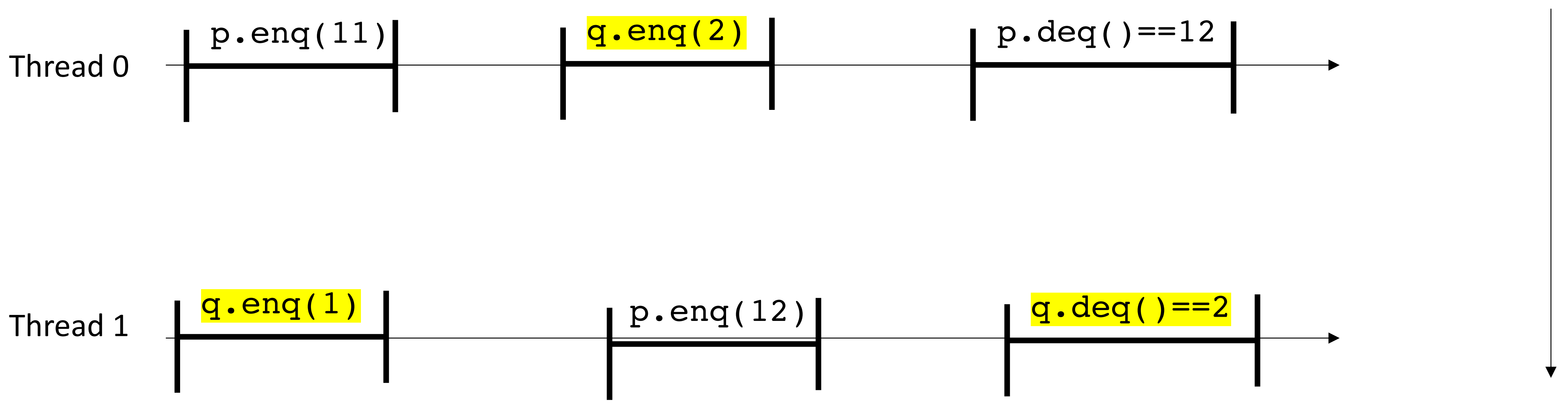

Sequential consistency and real time

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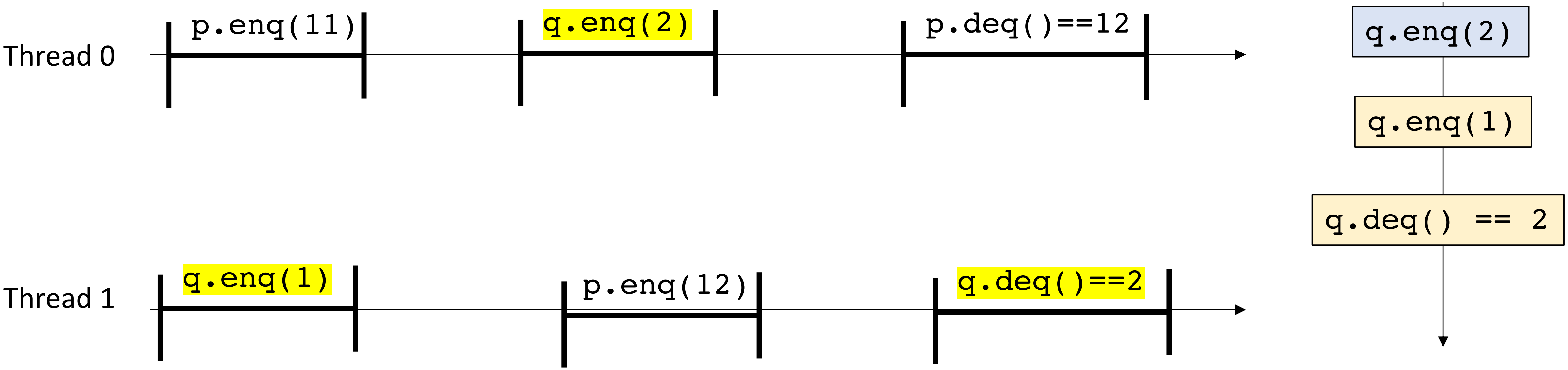
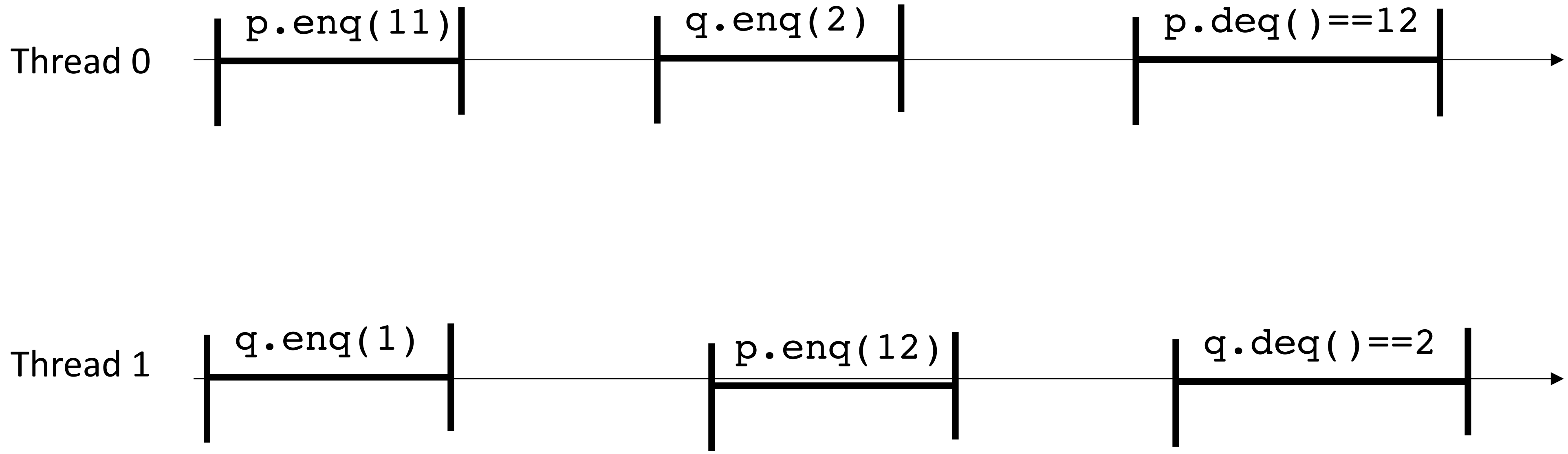
2 objects now: p and q
Consider each object in isolation



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:

```
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
```

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

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

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
```

```
q.enq(1);
p.enq(12);
p.enq(11);
q.enq(2);
p.deq()== 12;
```

```
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!

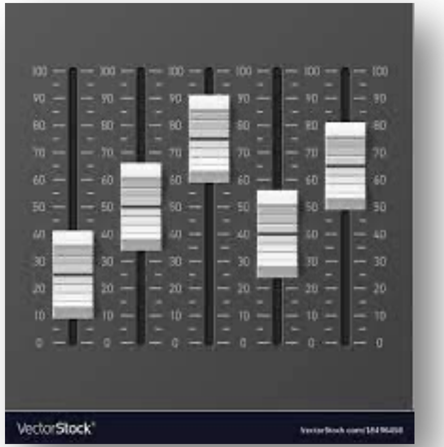
Schedule

- 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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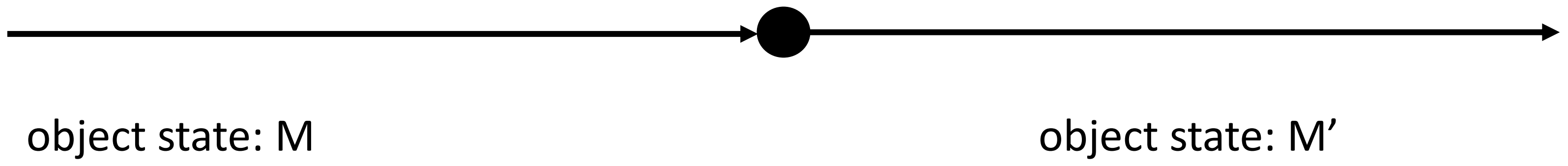

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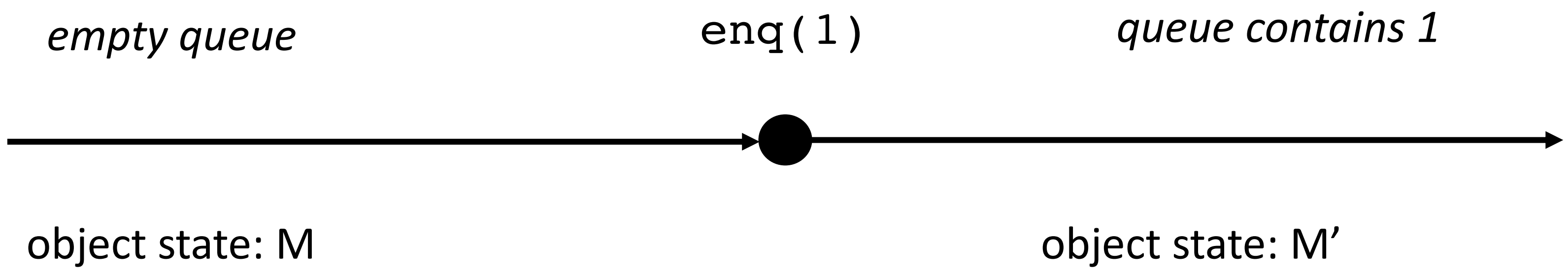

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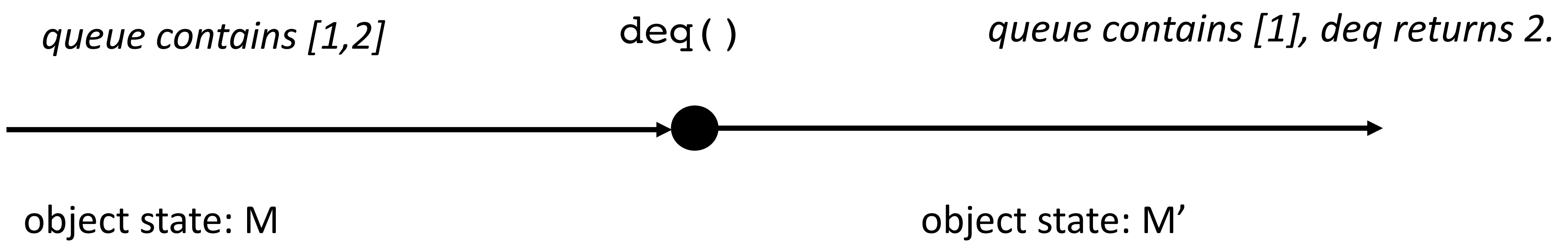

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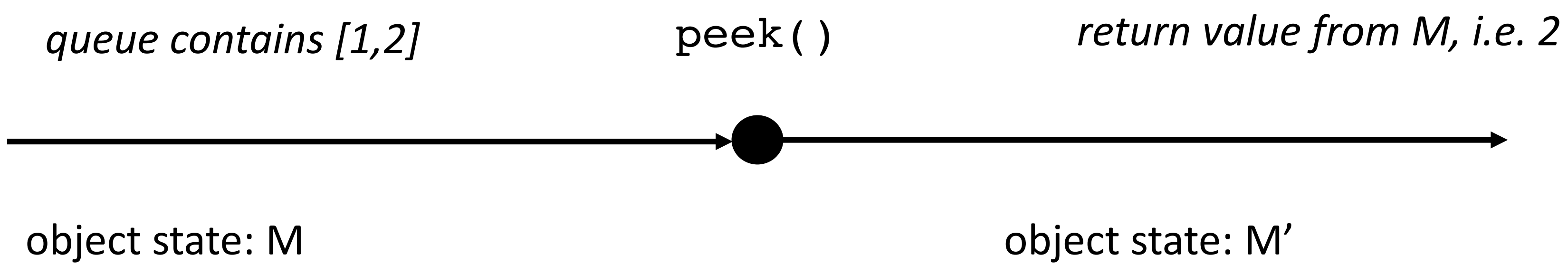
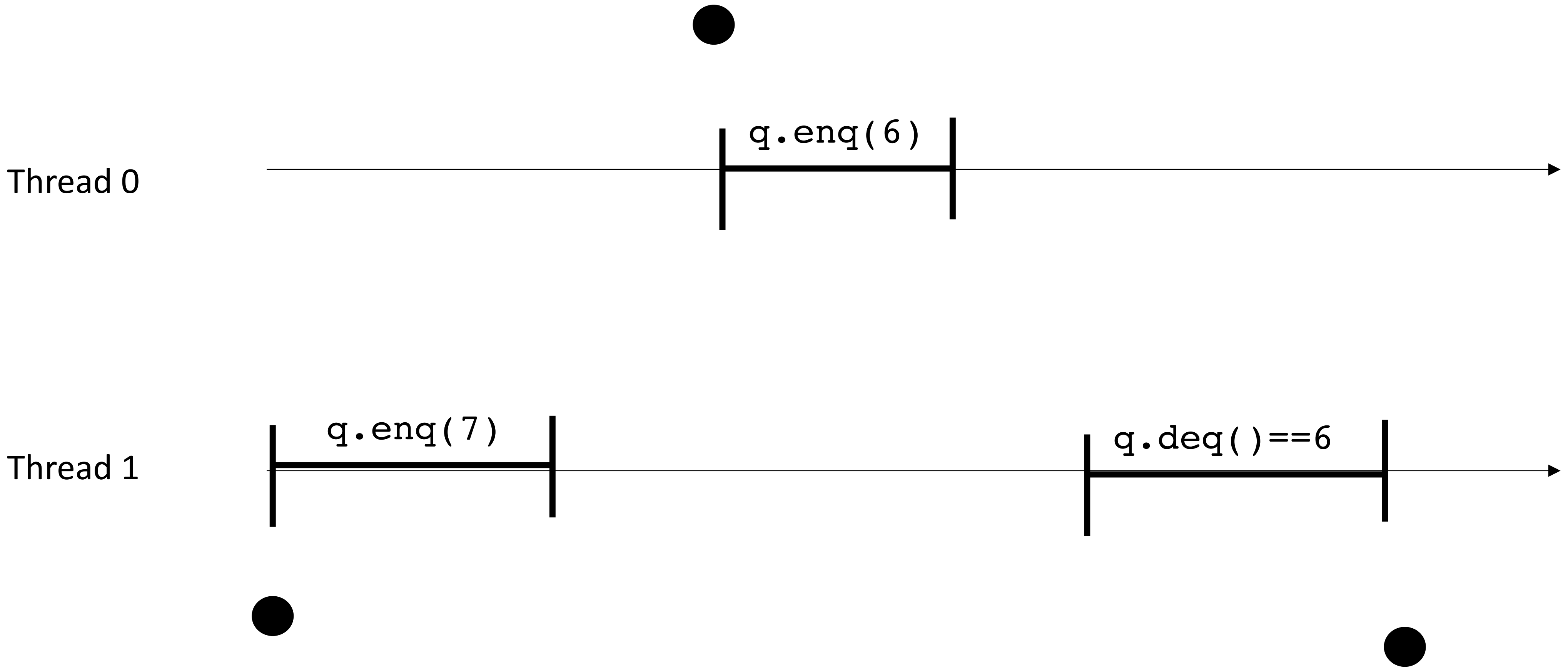


Linearizability

each command gets a linearization point.

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



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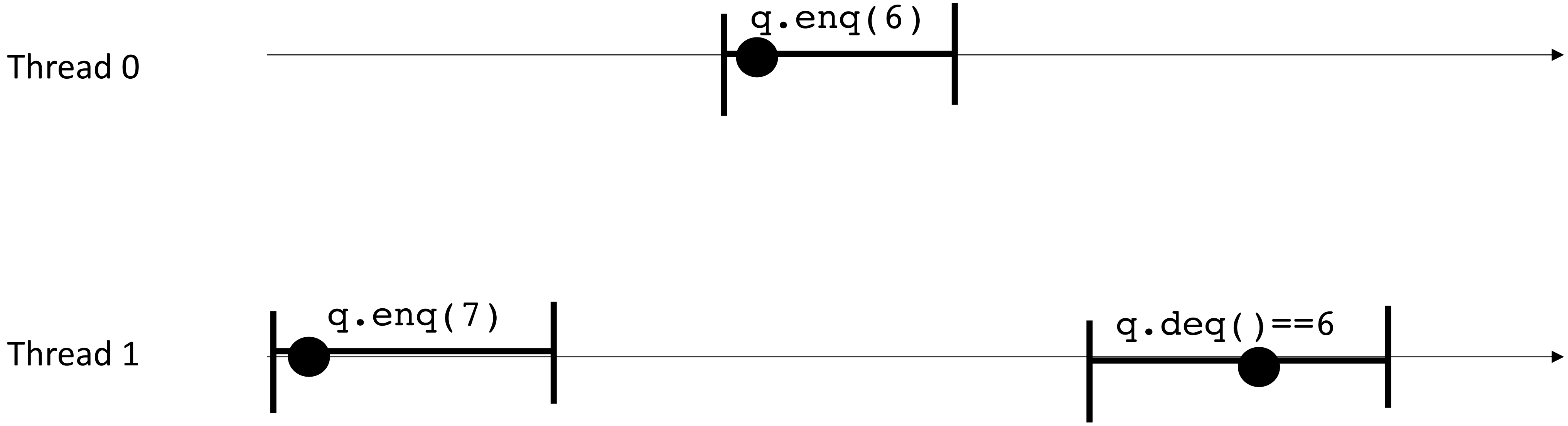

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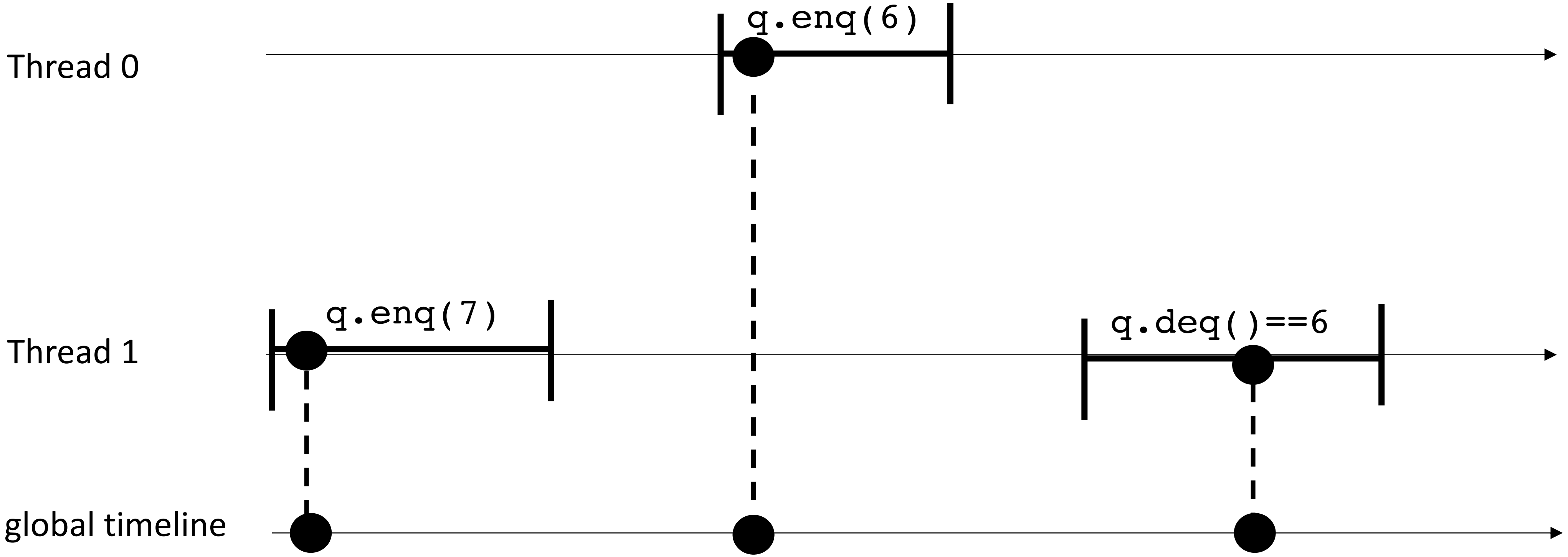
Project the linearization points to a global timeline



reason sequentially!

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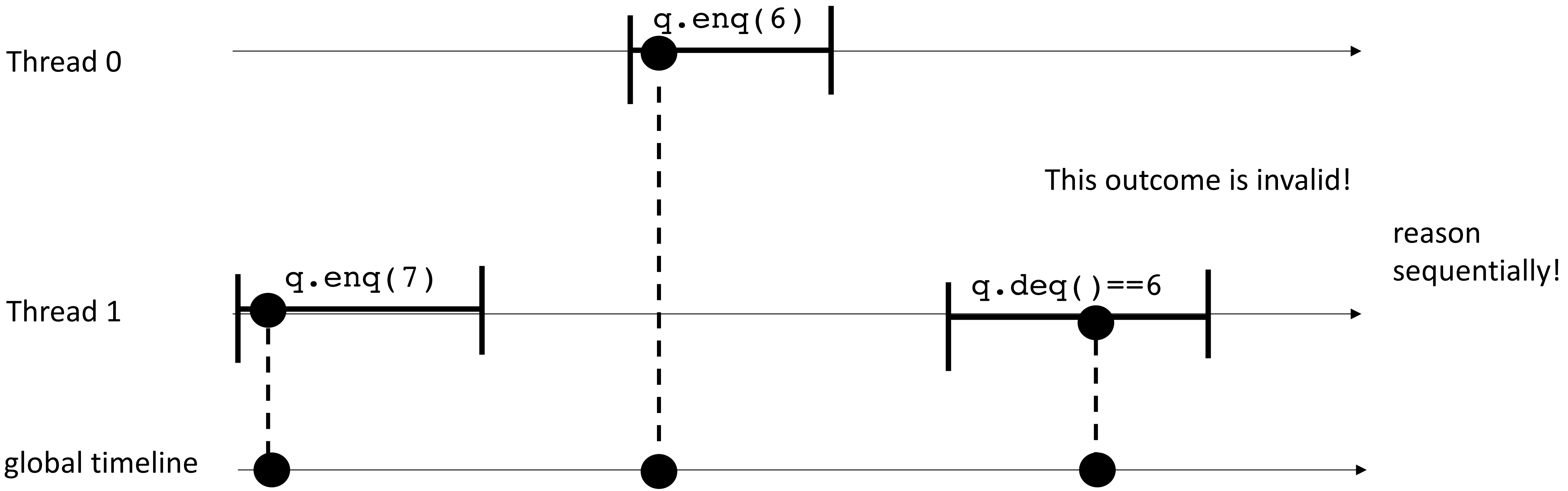
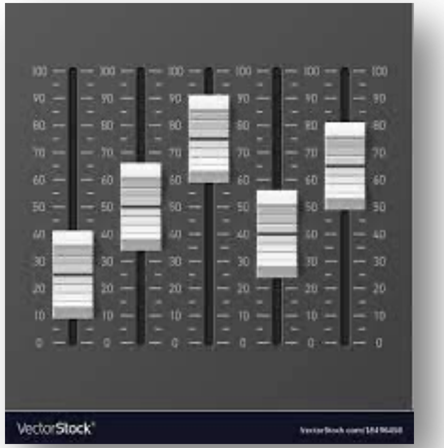


Linearizability



each command gets a linearization point.

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

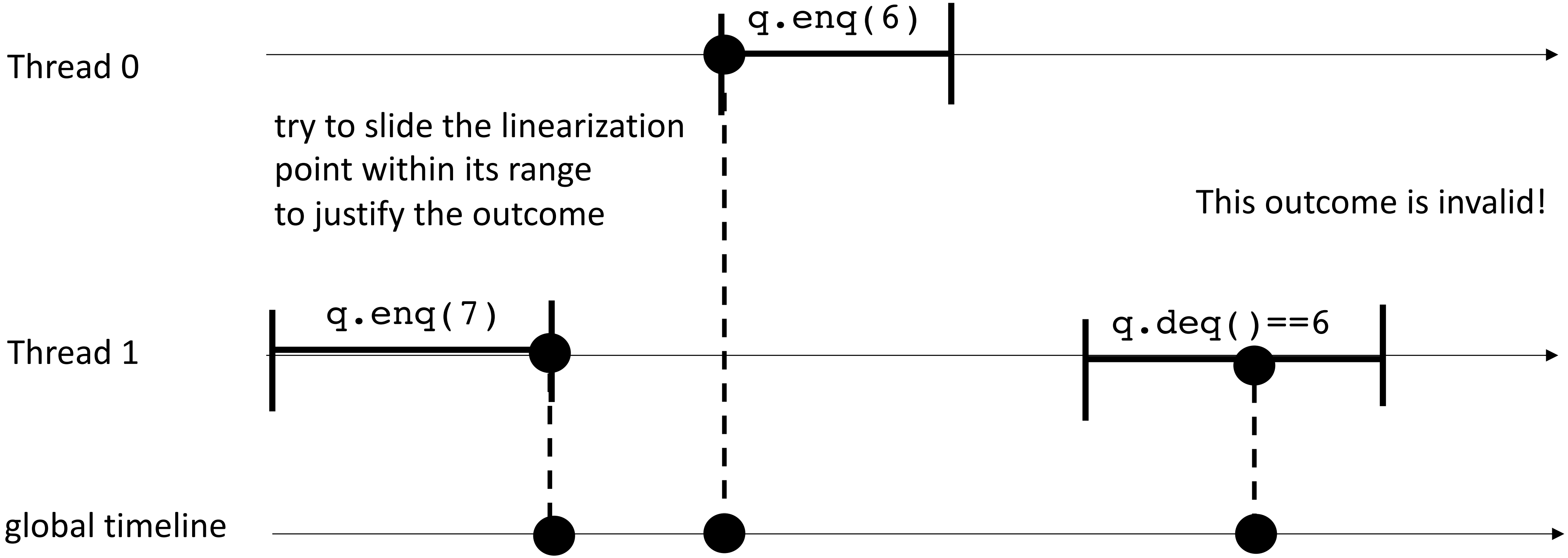
Project the linearization points to a global timeline

slider game!

try to slide the linearization
point within its range
to justify the outcome

This outcome is invalid!

reason sequentially!



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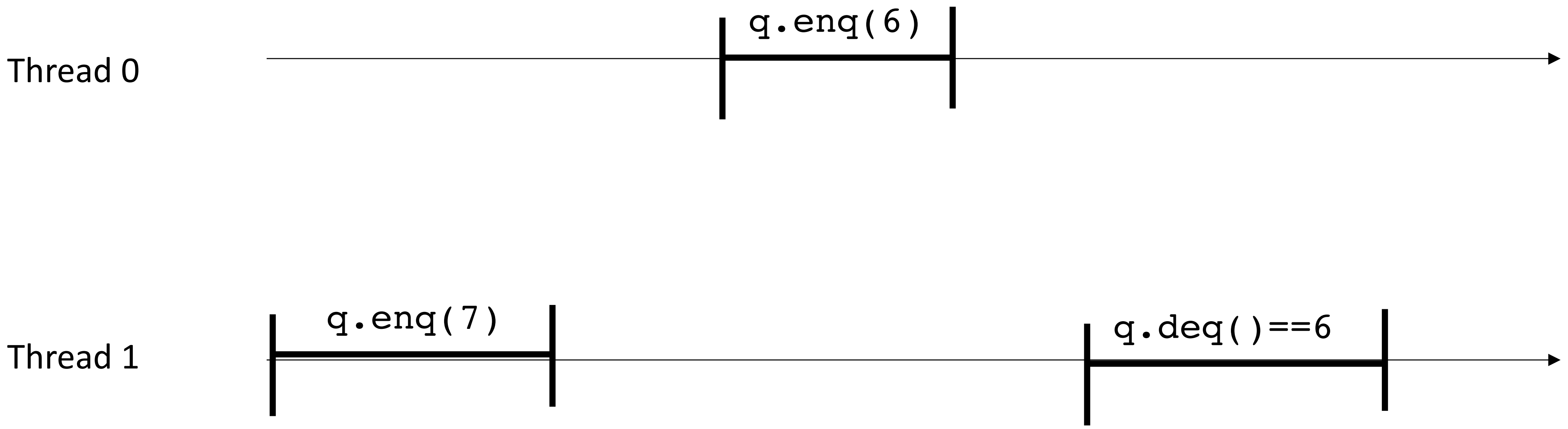

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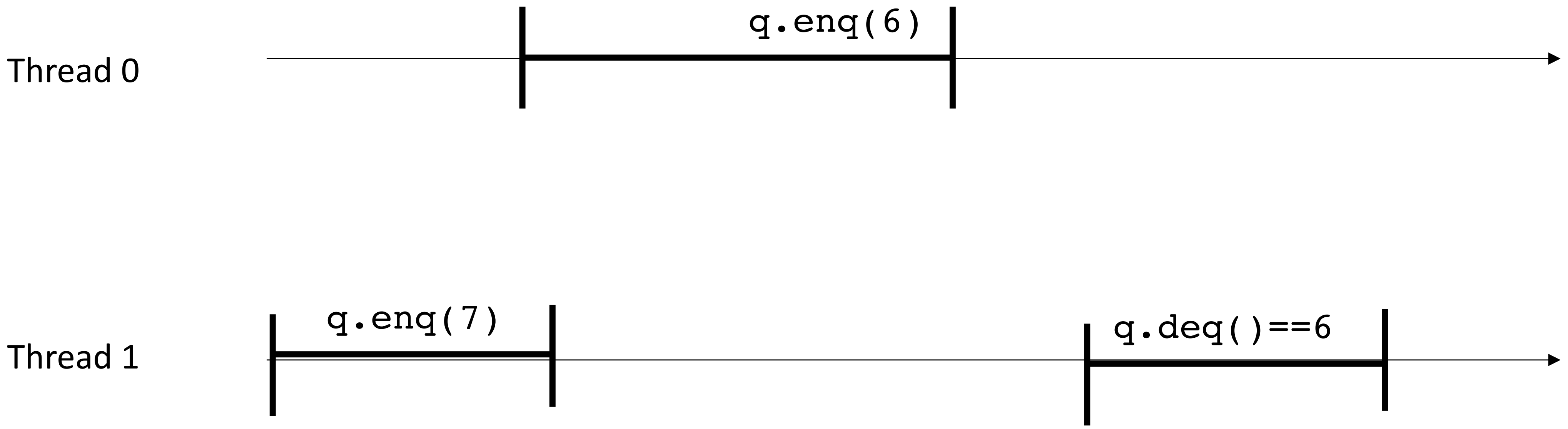

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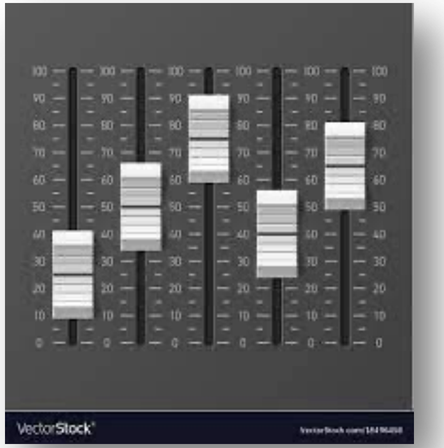
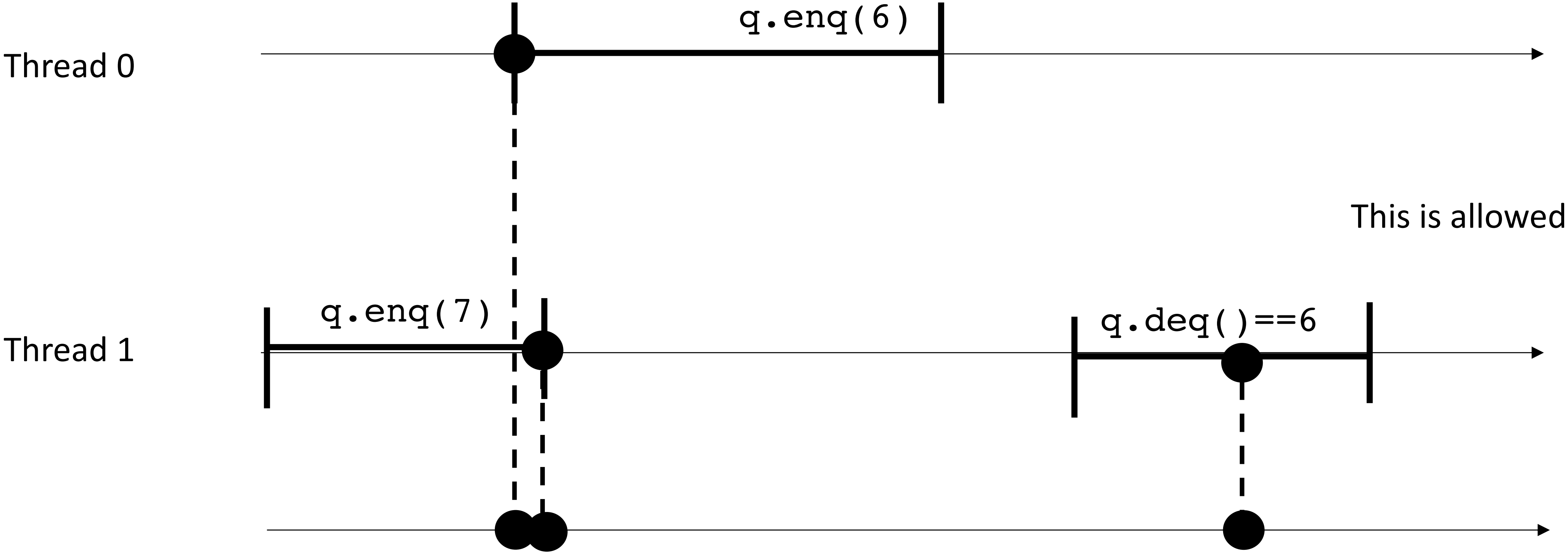
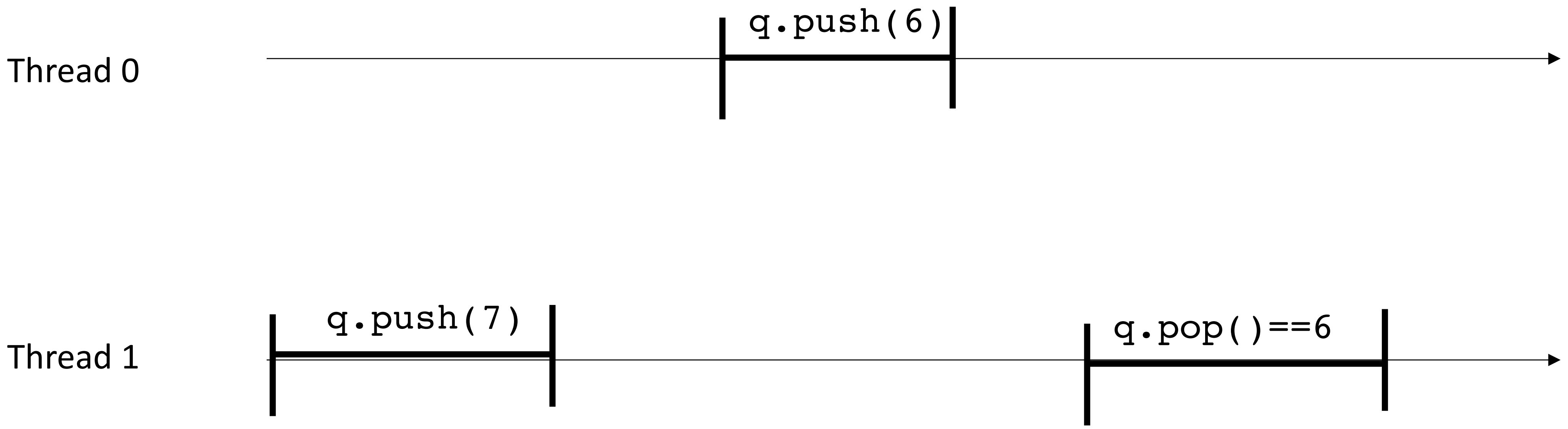




This is allowed now!

Linearizability



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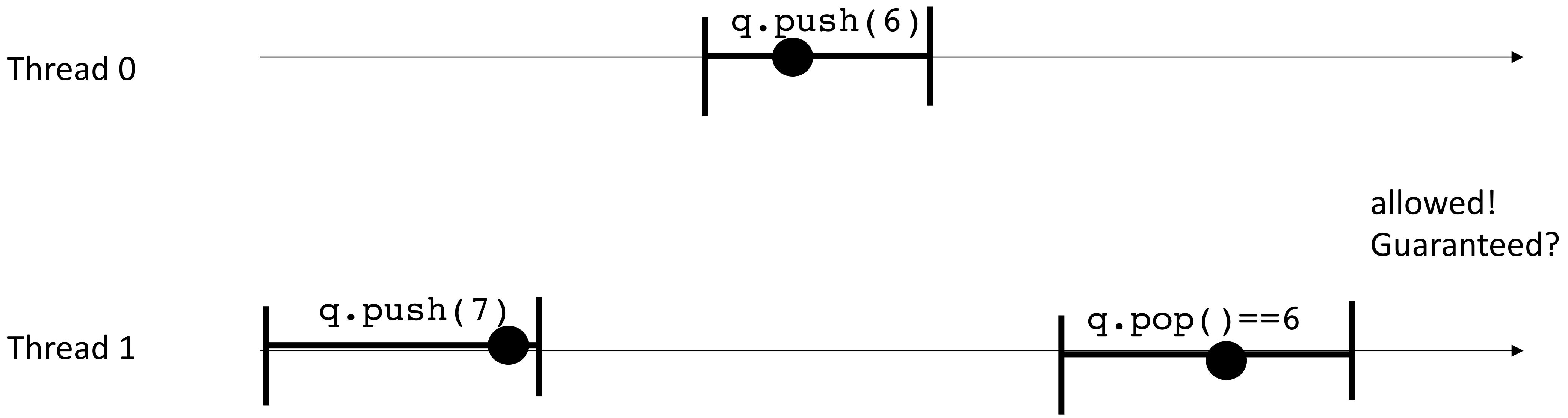

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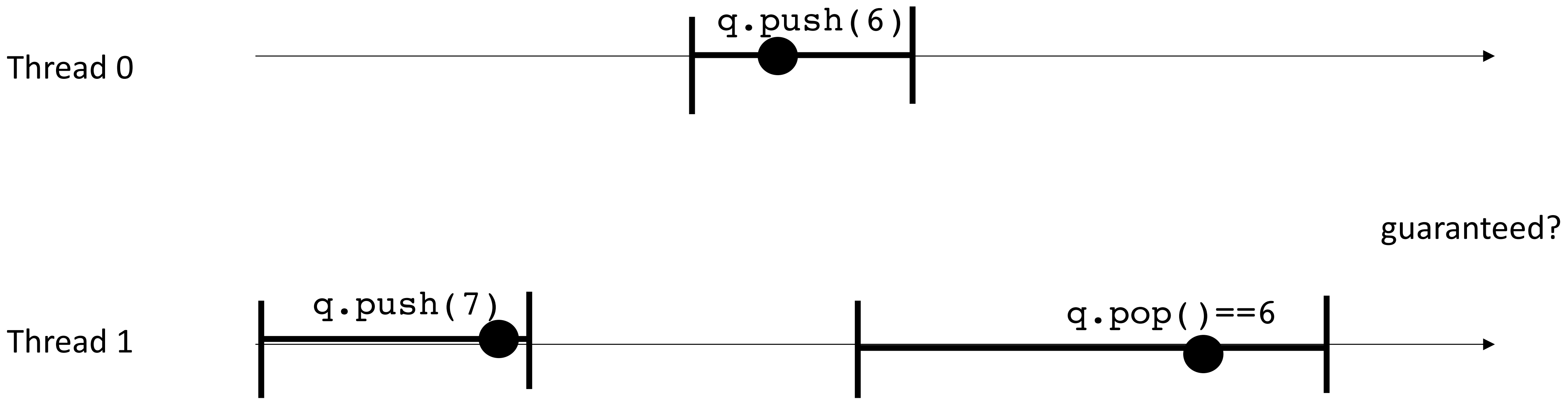

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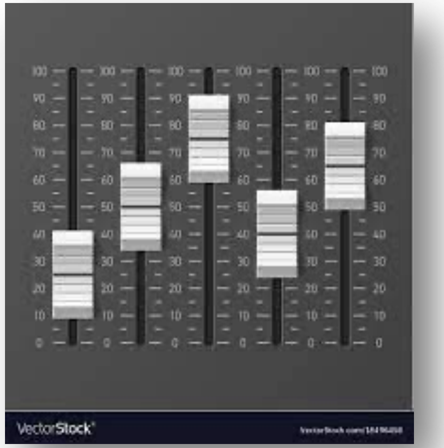
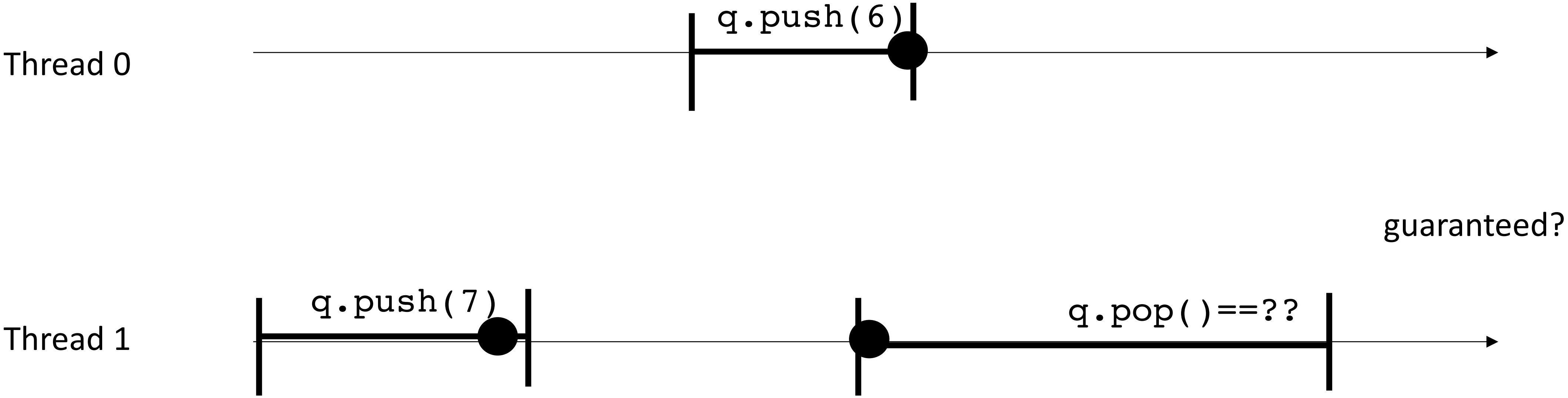




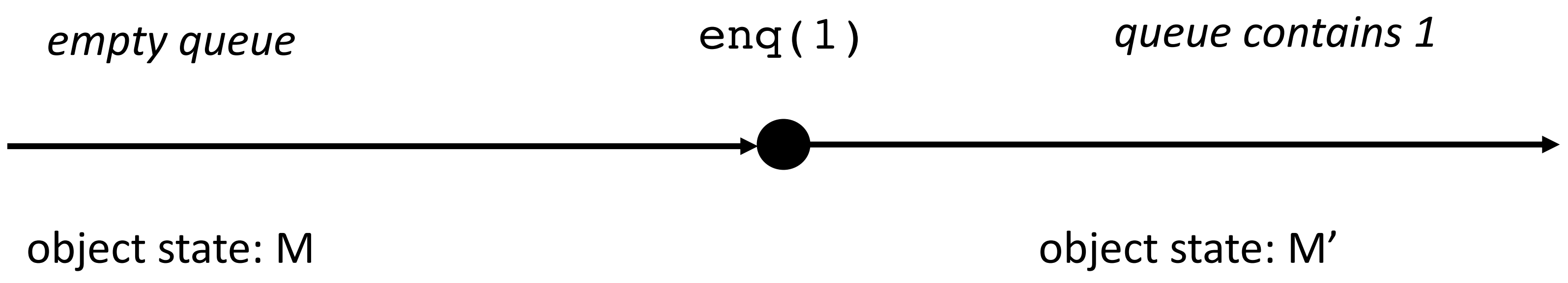
Linearizability

- 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.

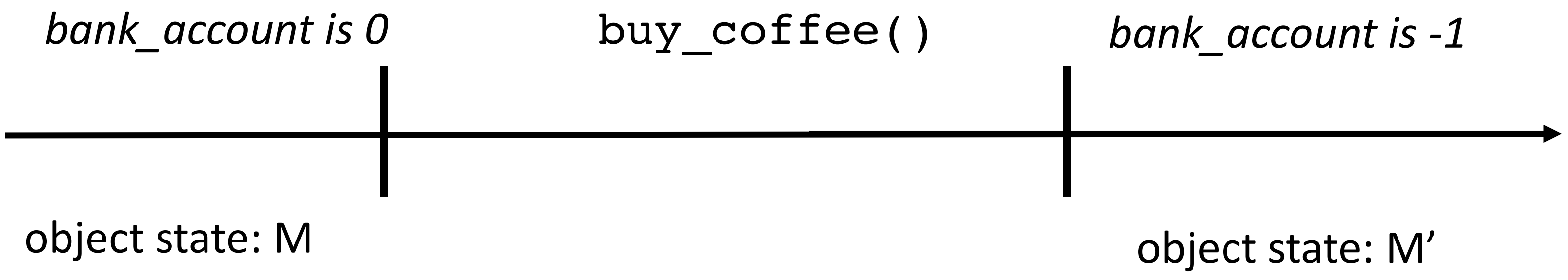
Linearizability

- 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();
    }

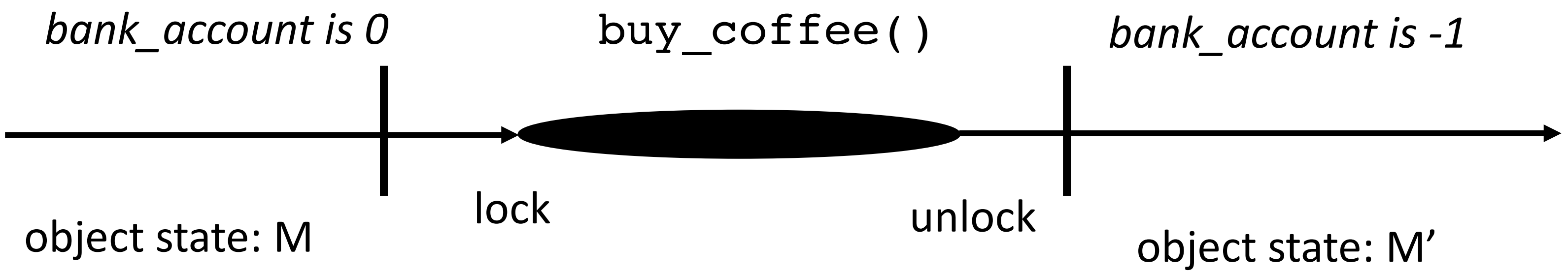
    void get_paid() {
      m.lock();
      balance += 1;
      m.unlock();
    }

  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

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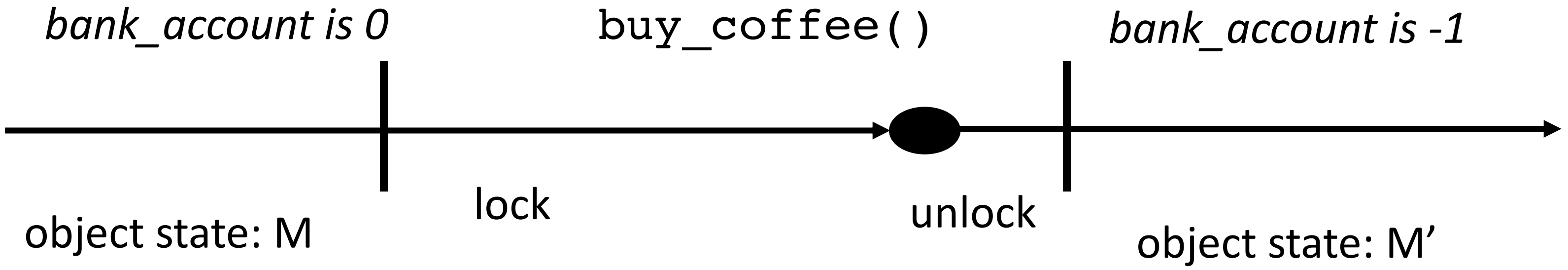
lets say released.

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      m.unlock();
    }

  private:
    int balance;
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};
```

Linearizability

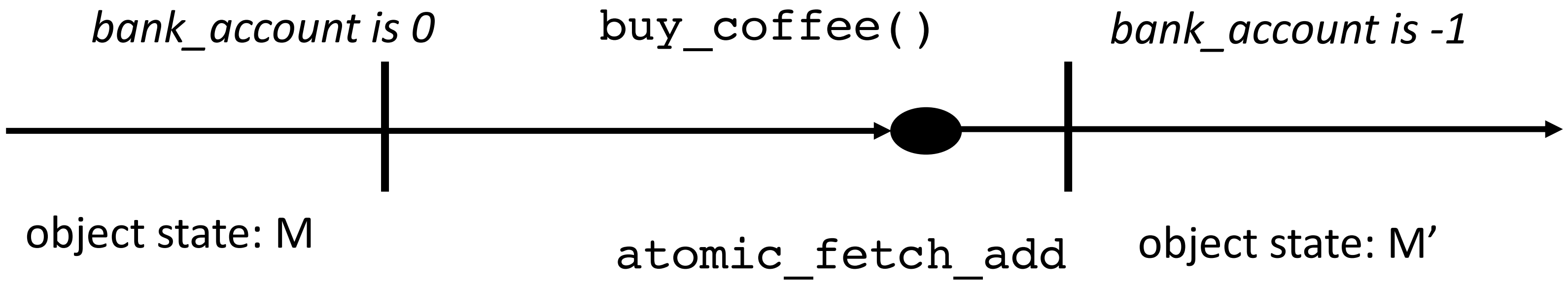
- Our lock-free bank account is linearizable:
  - The atomic operation is the linearizable point

```
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;
};
```



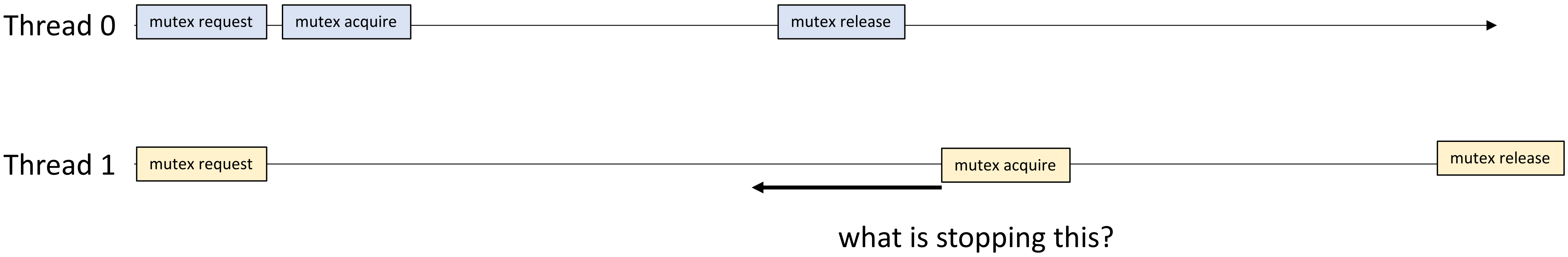
Lecture schedule

- Linearizablity
- **Progress Properties**
- Implementing a set

Progress properties

- Going back to specifications:

Recall the mutex

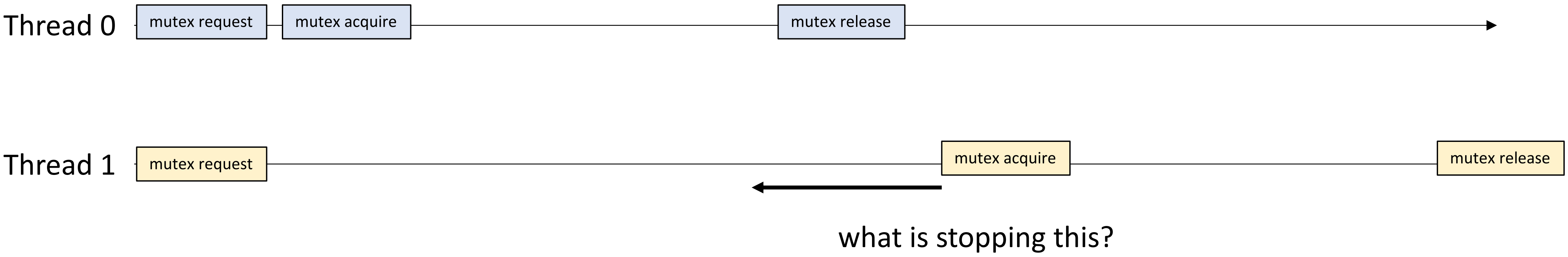


Progress properties

- 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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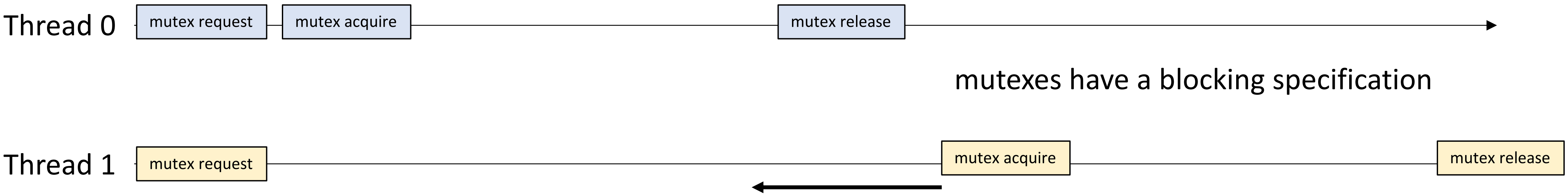

what is stopping this?

Progress properties

- Going back to specifications:

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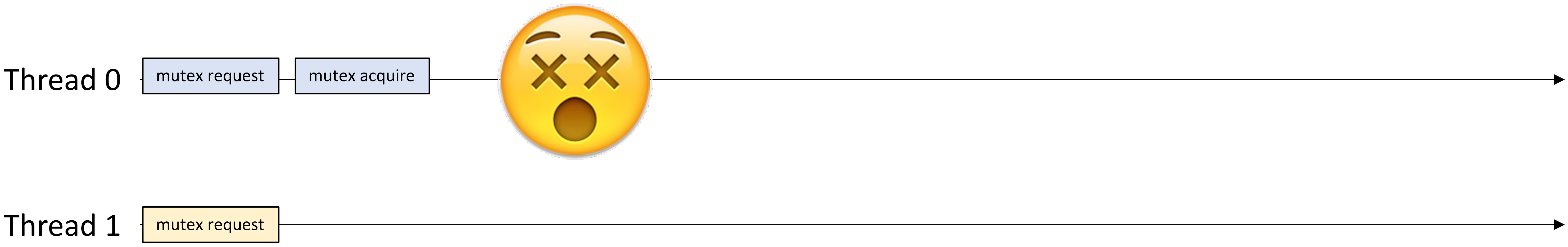
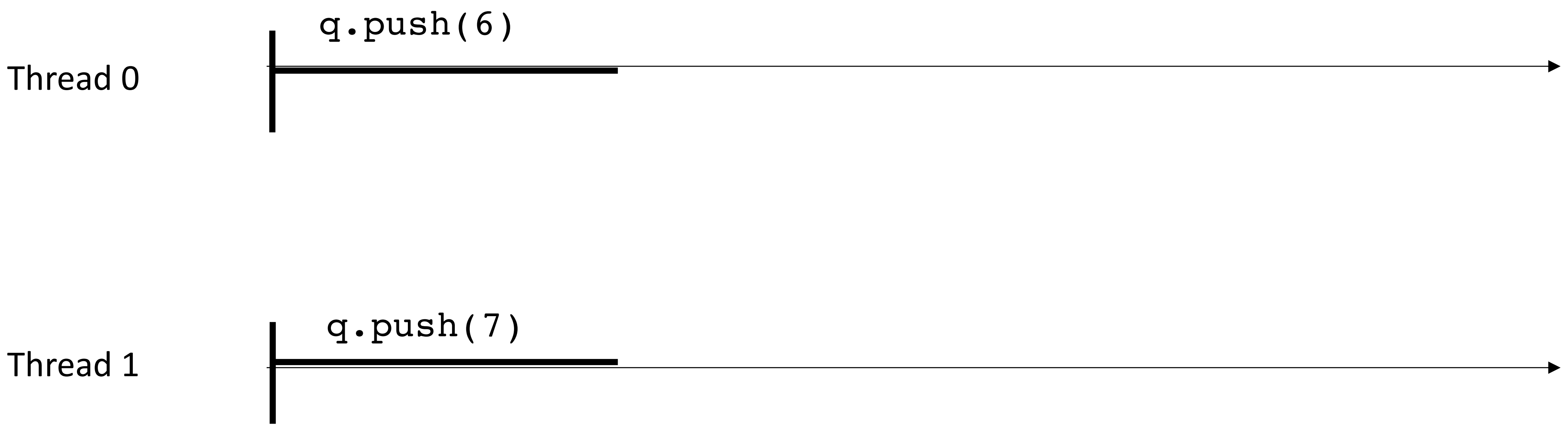
Recall the mutex



What now?!

Linearizability

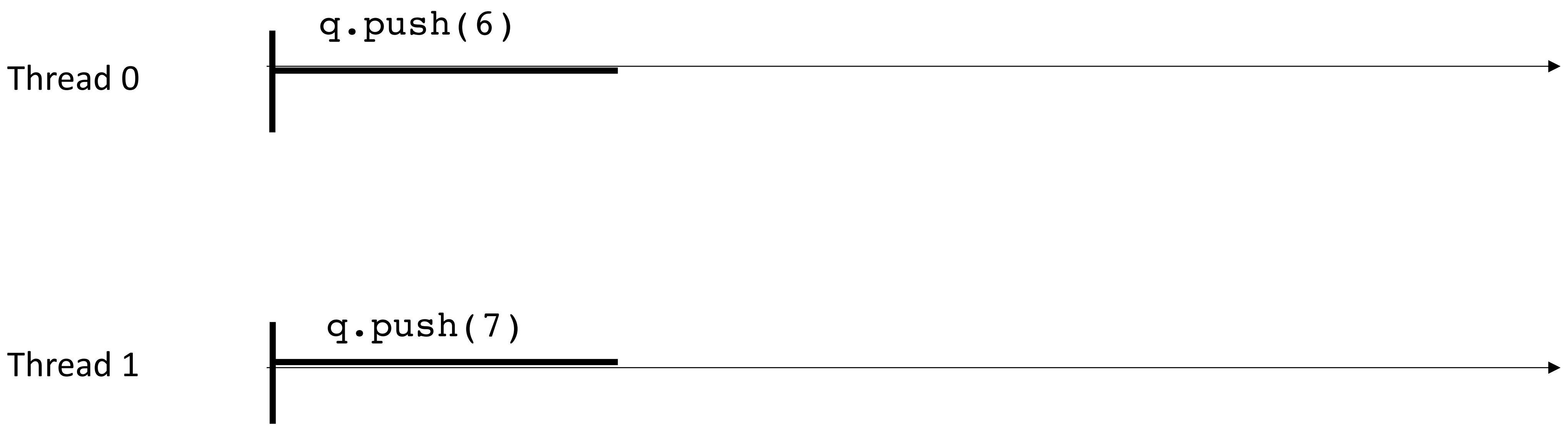
Two unfinished commands.



Linearizability

Two unfinished commands.

Linearizability does not dictate that one needs to wait for another



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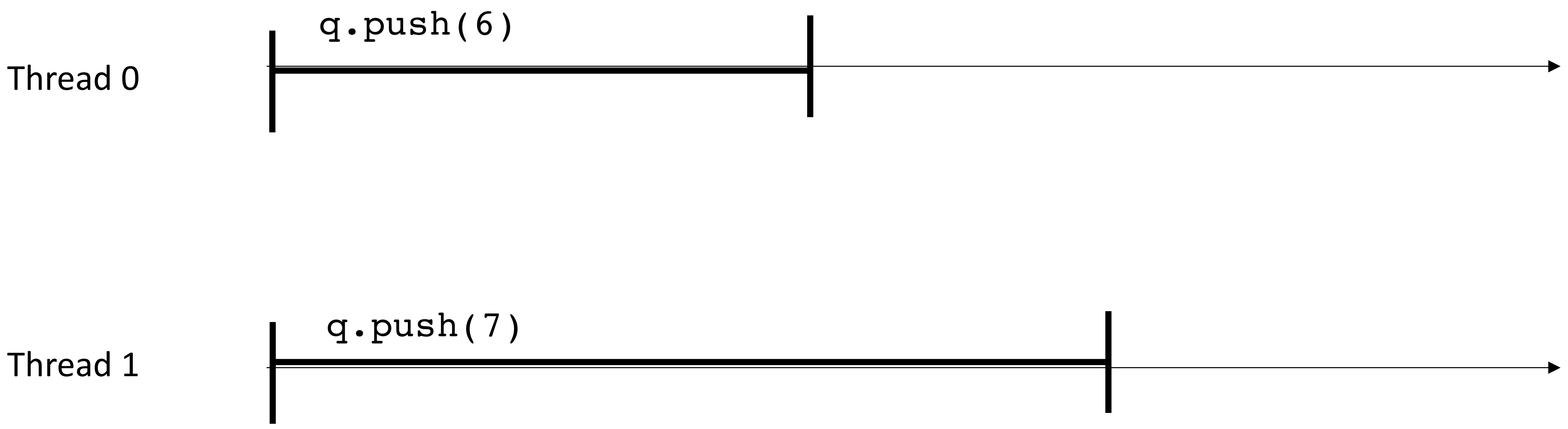

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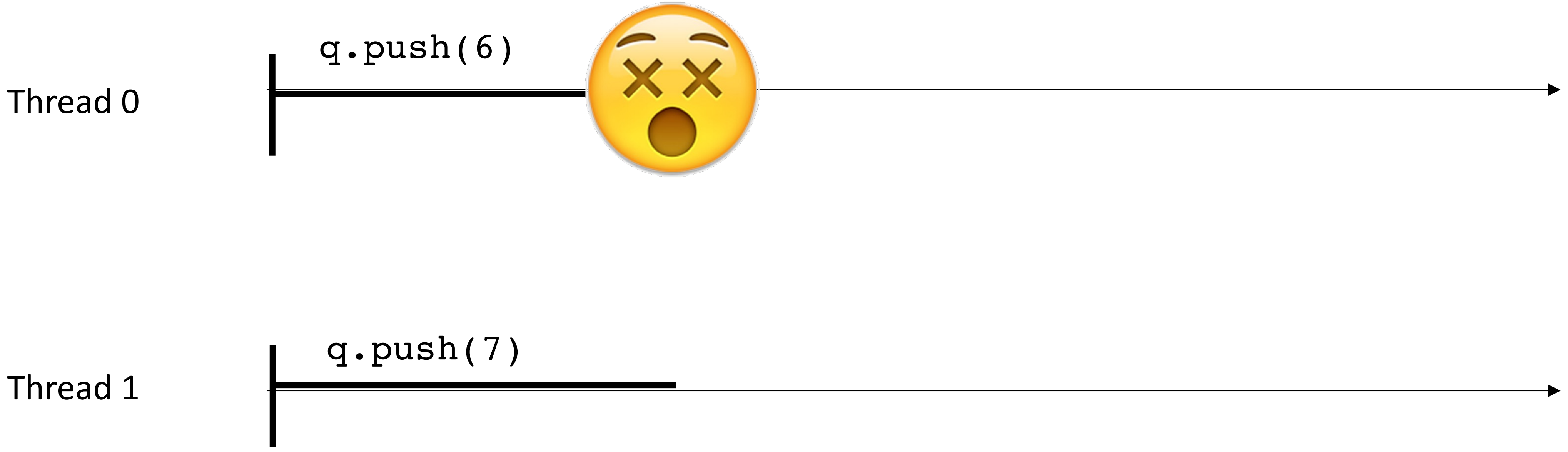

for mutexes, the specification required that the system hang.

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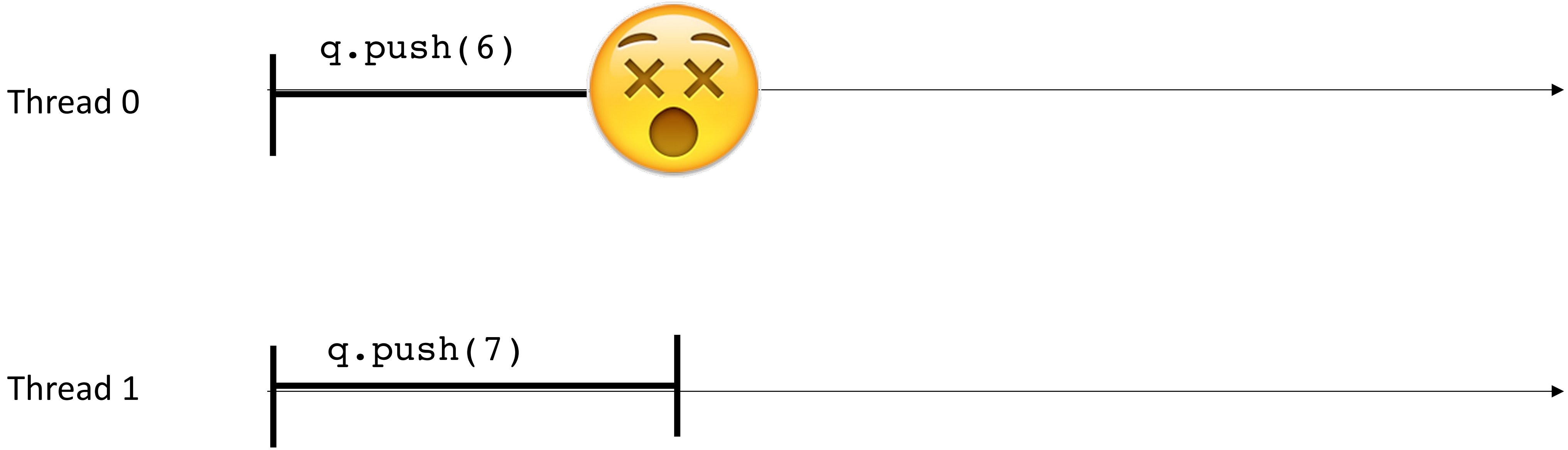
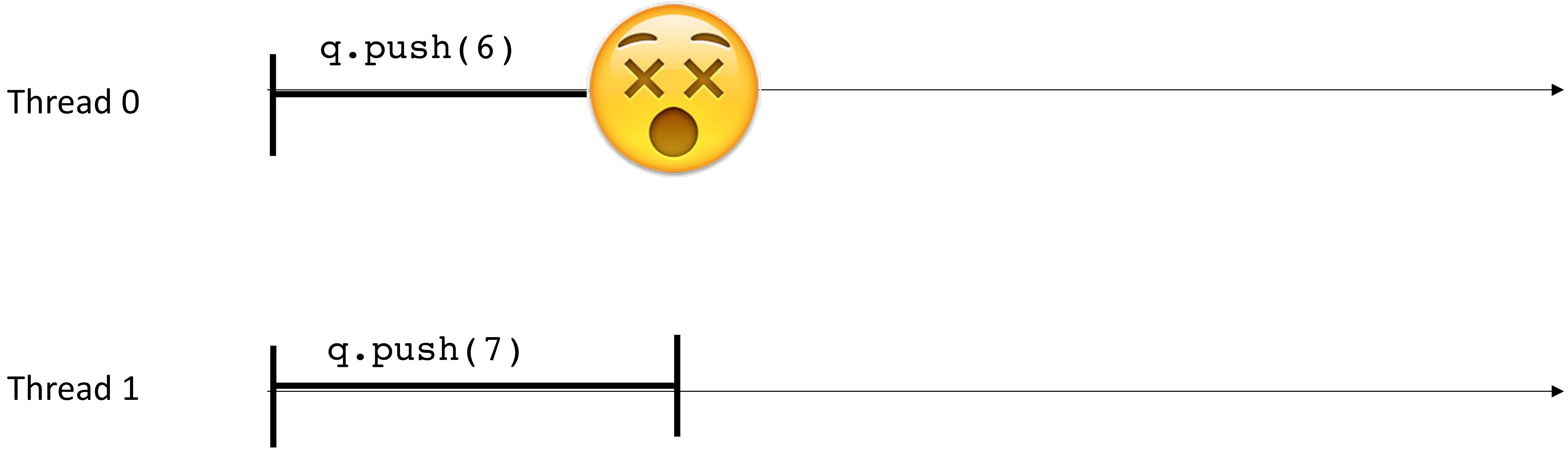


for mutexes, the specification required that the system hang.
no such specification here.

Linearizability

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



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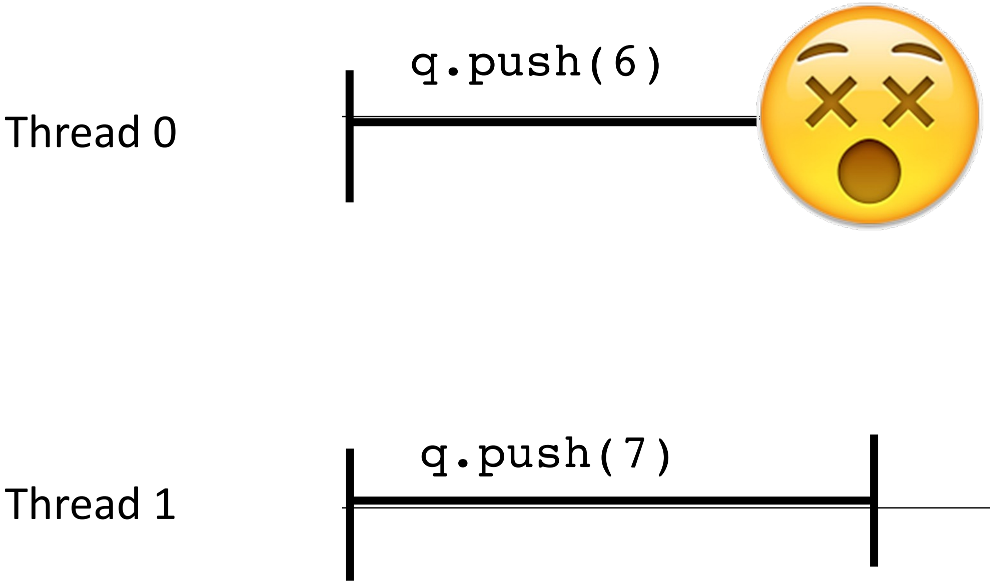

This is a specification property, not an implementation property! You can implement your concurrent objects with locks and have a “blocking implementation”.

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

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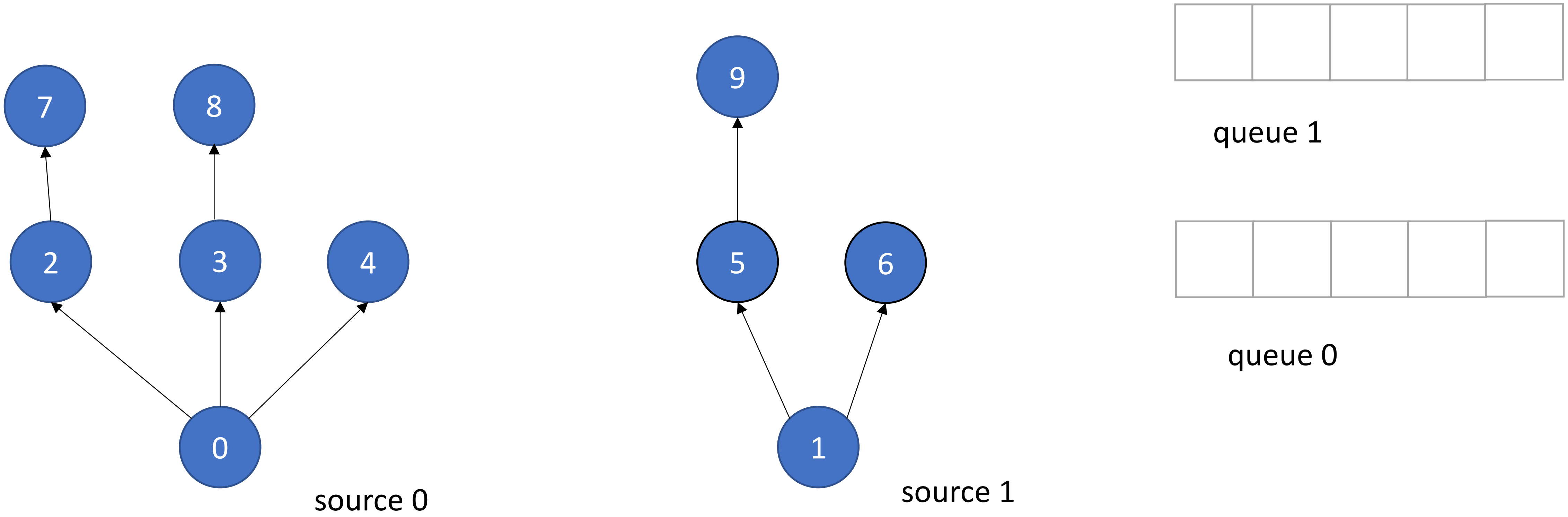

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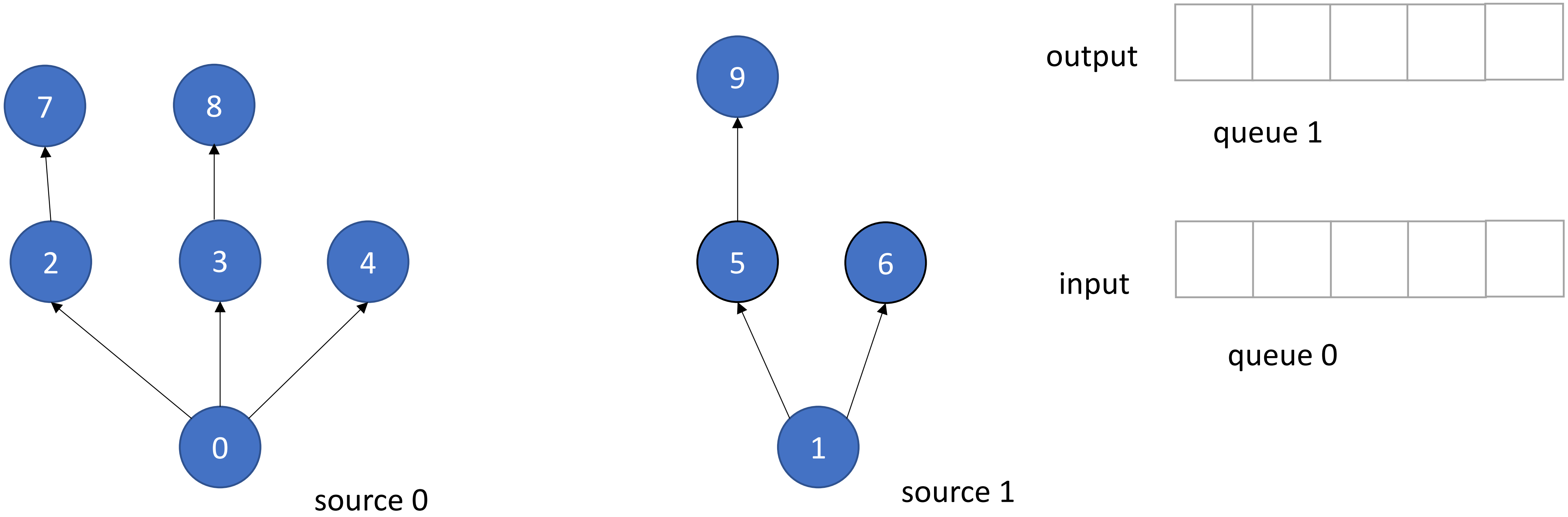

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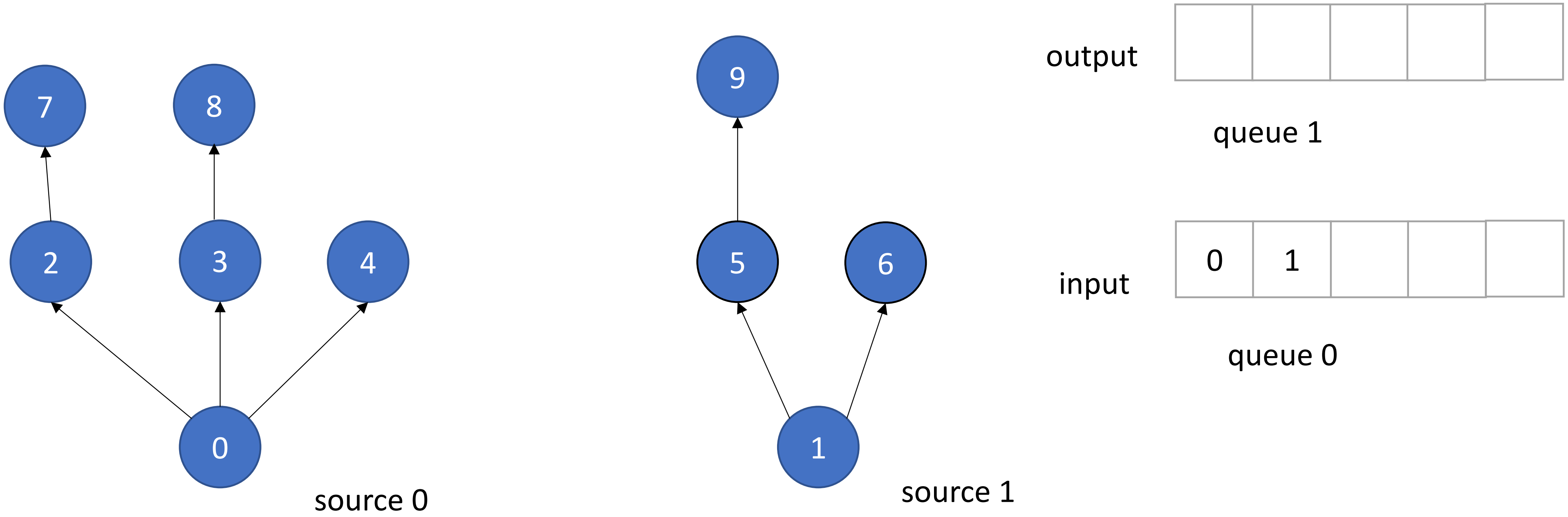

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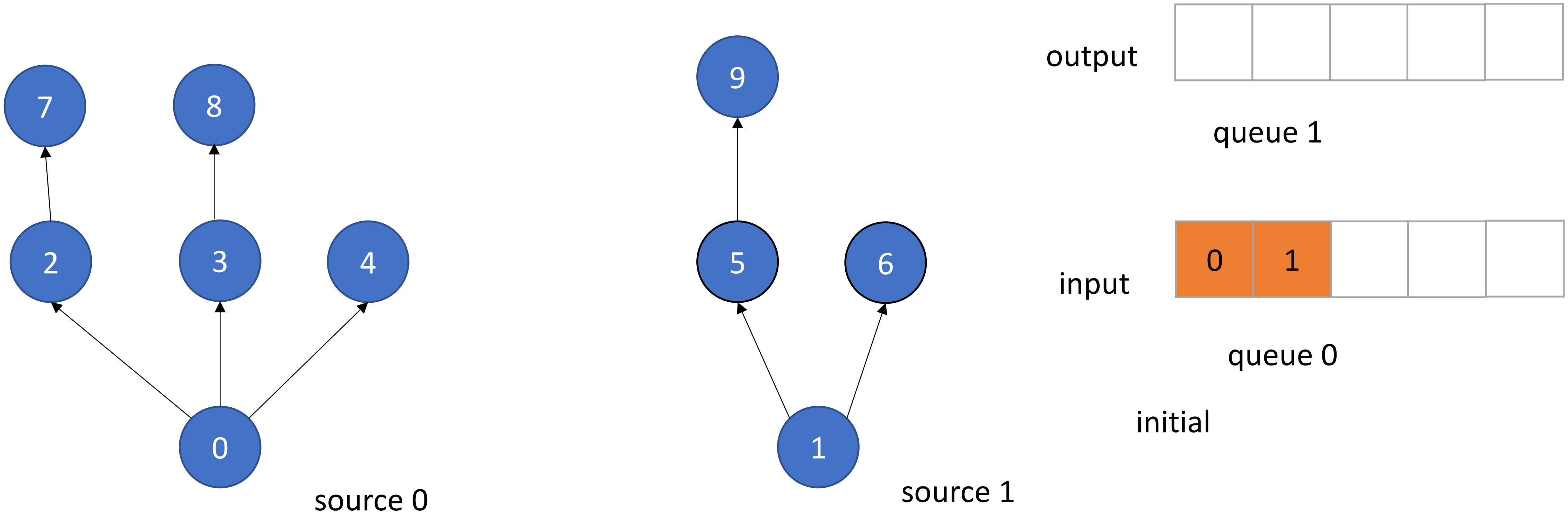

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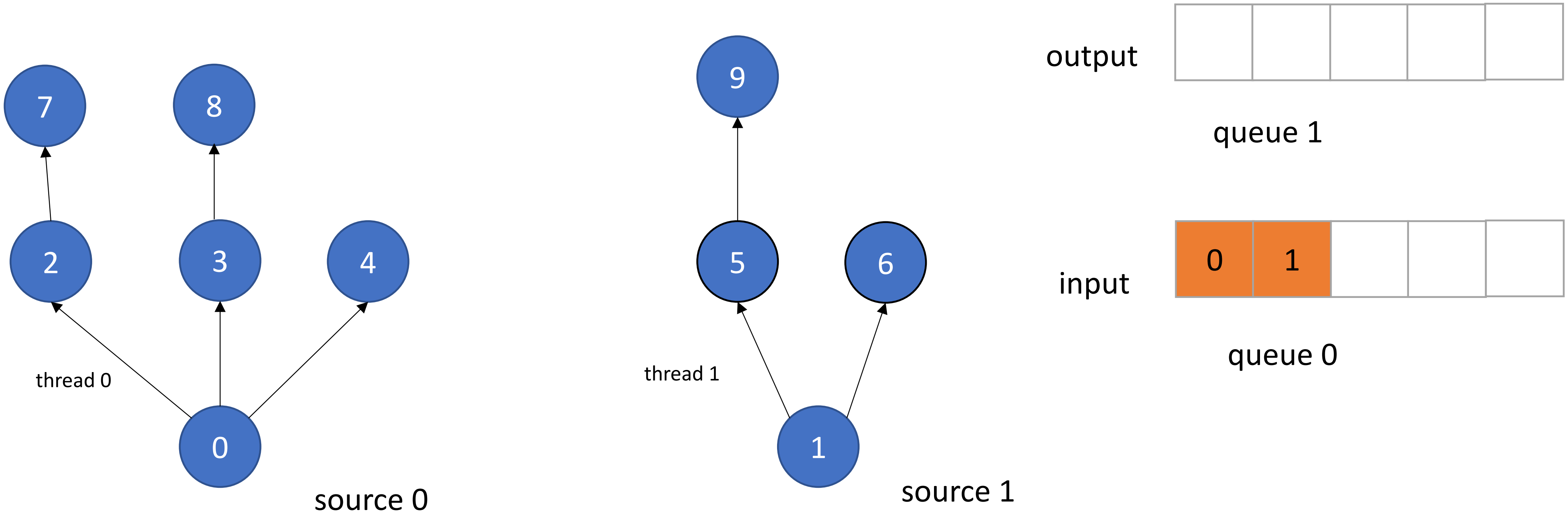

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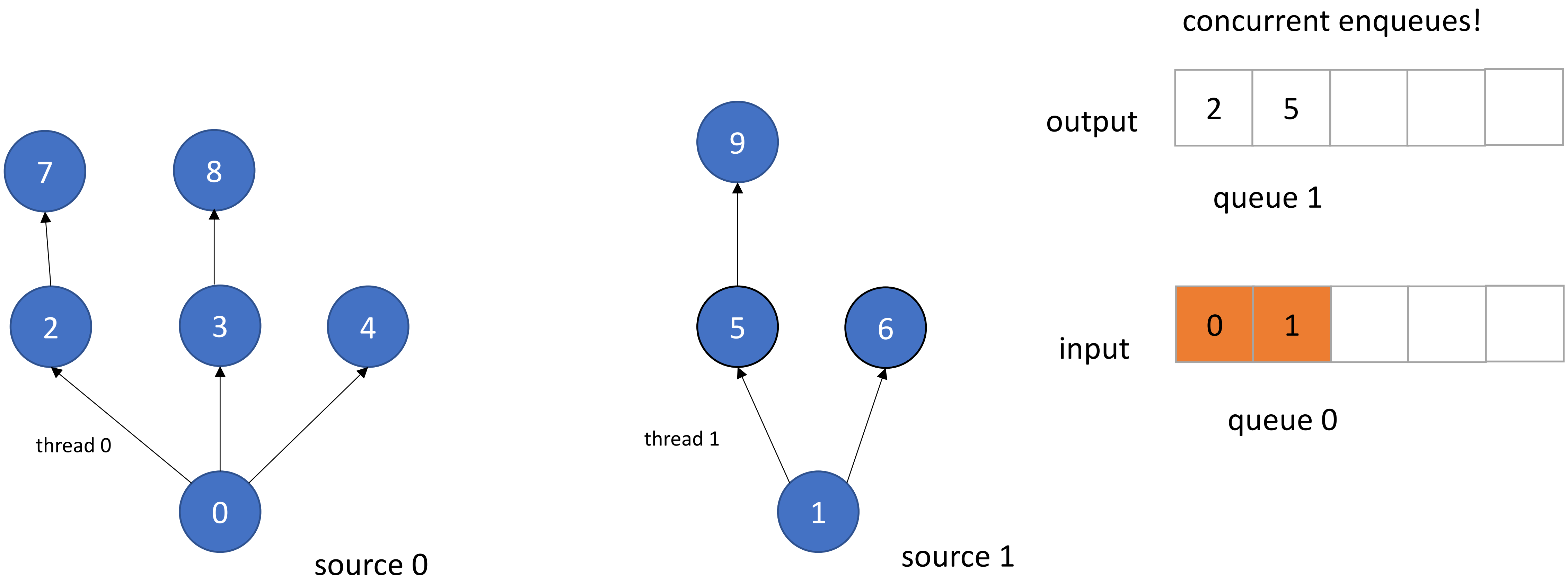

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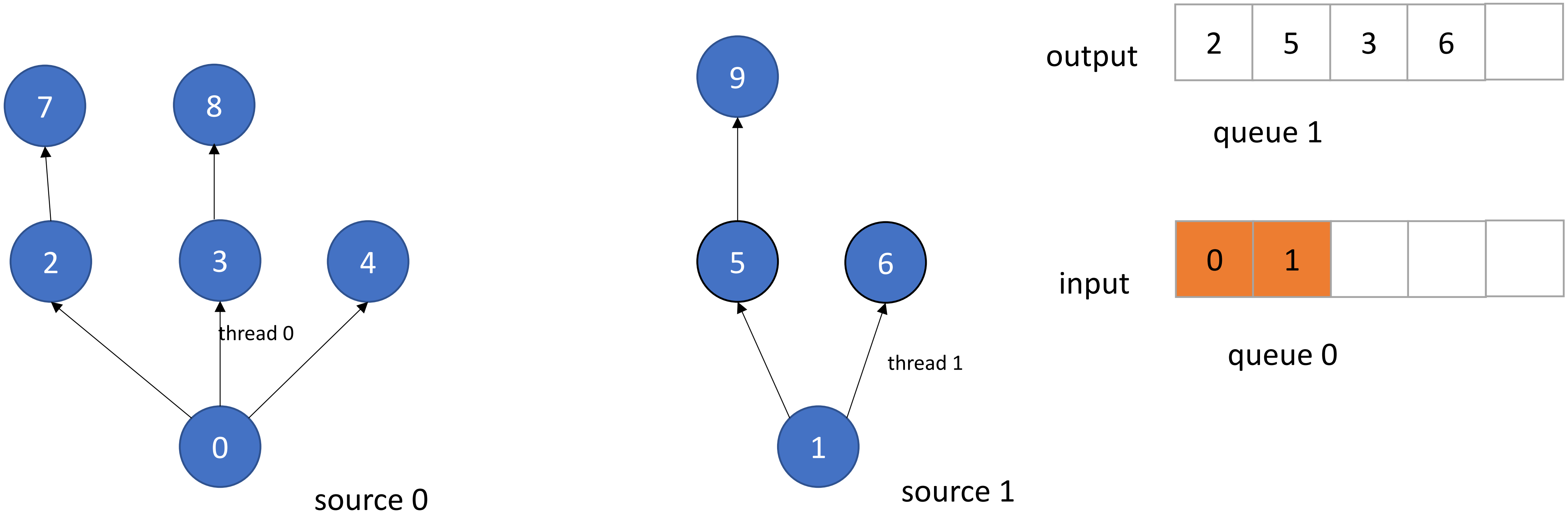

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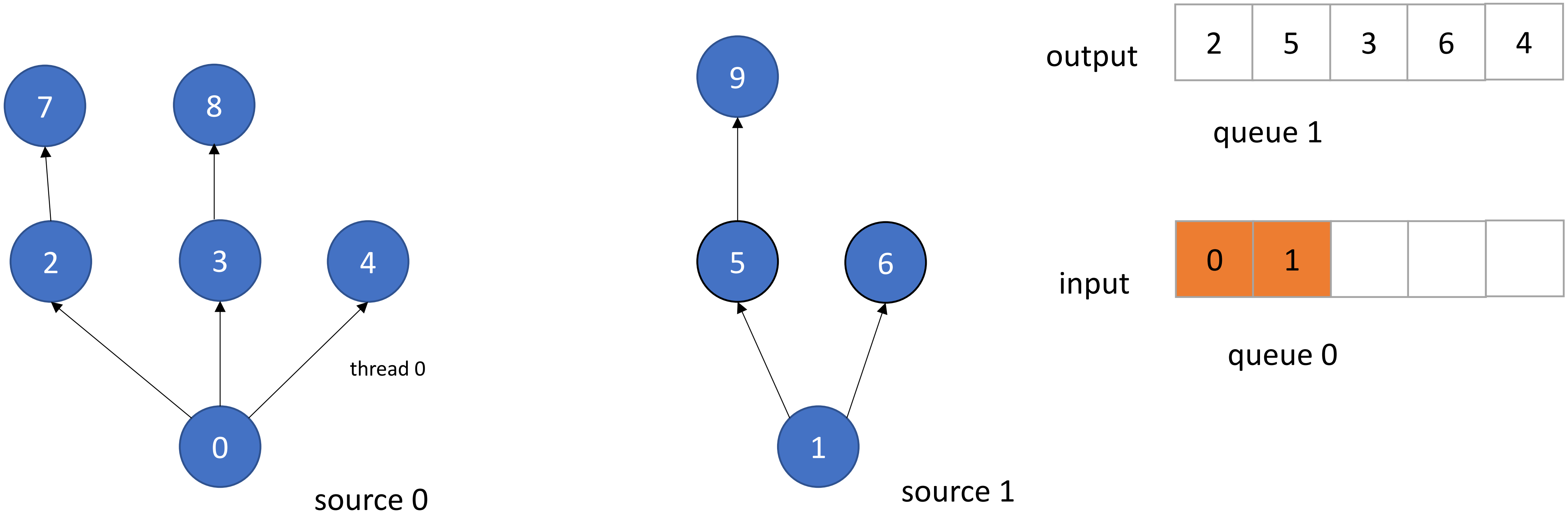

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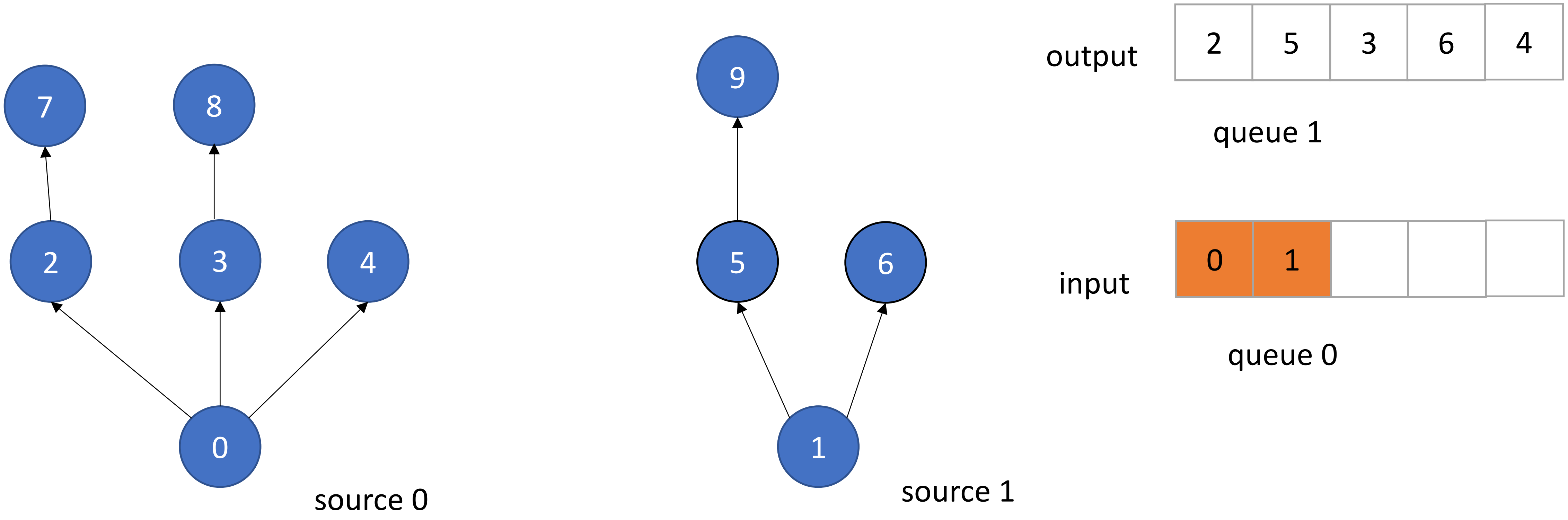

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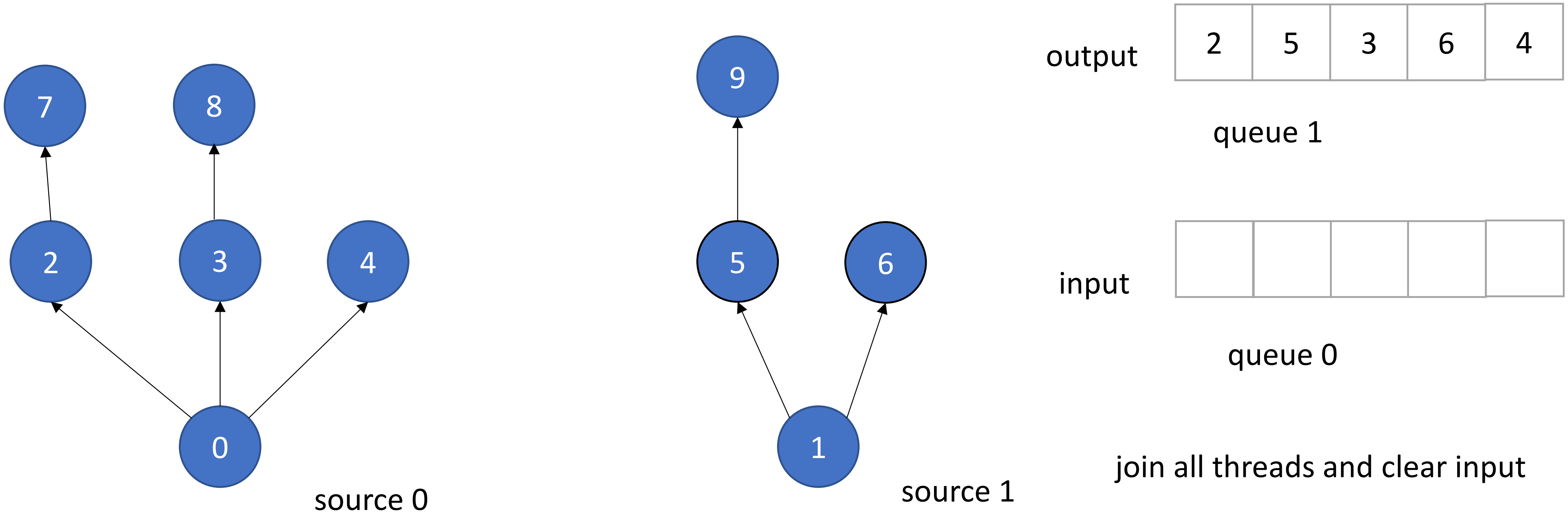

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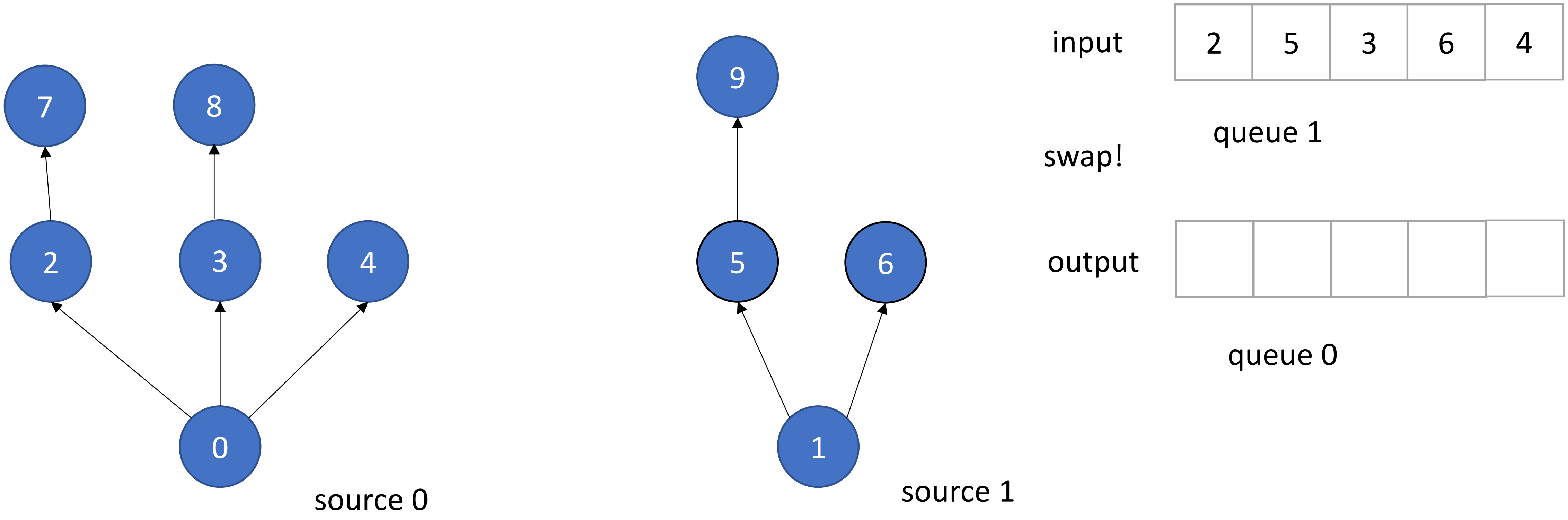

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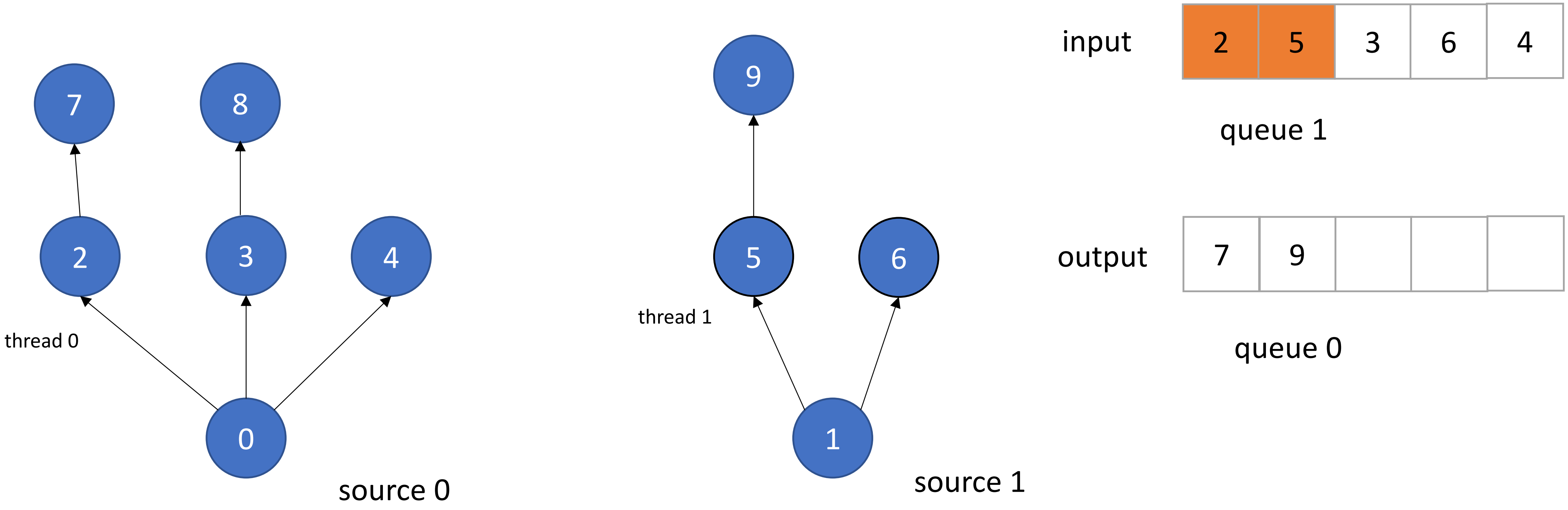
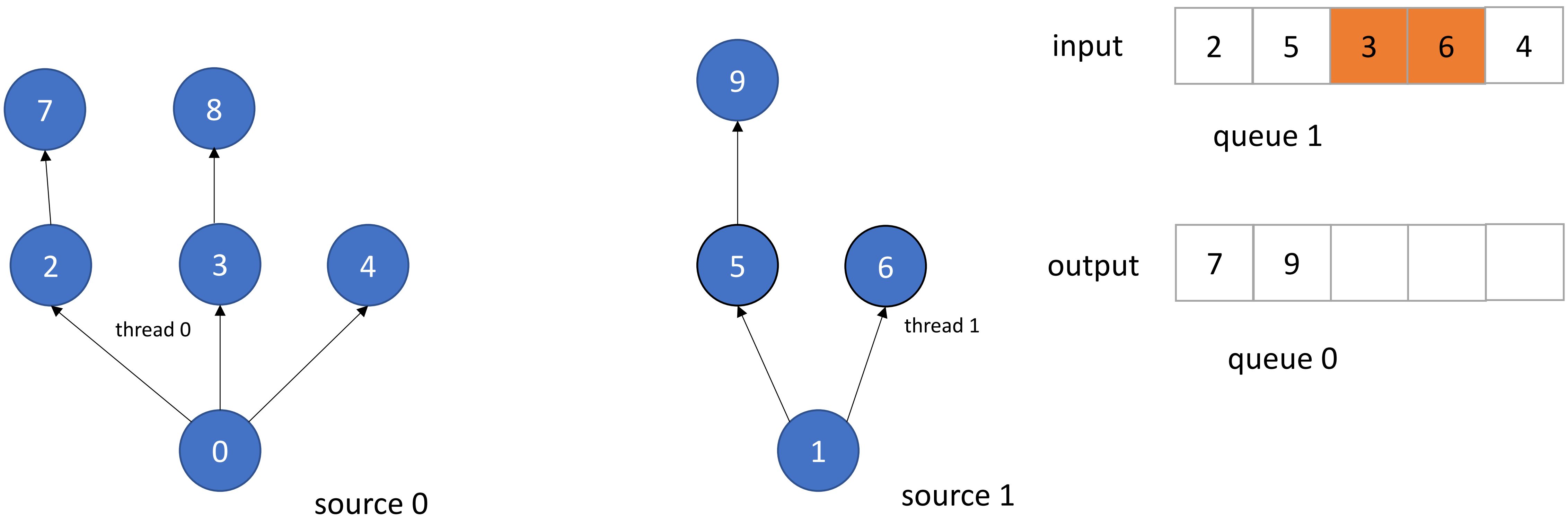


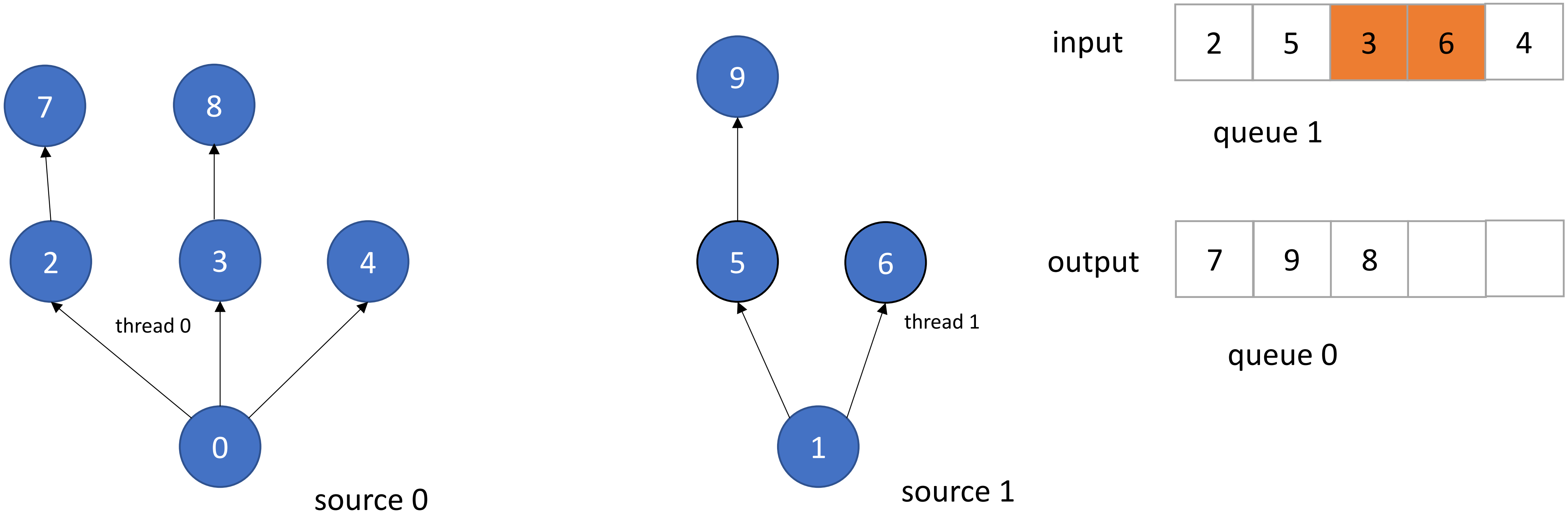
Input/Output Queues

- Example: Information flow in graph applications:



Input/Output Queues

- Example: Information flow in graph applications:



Input/Output Queues

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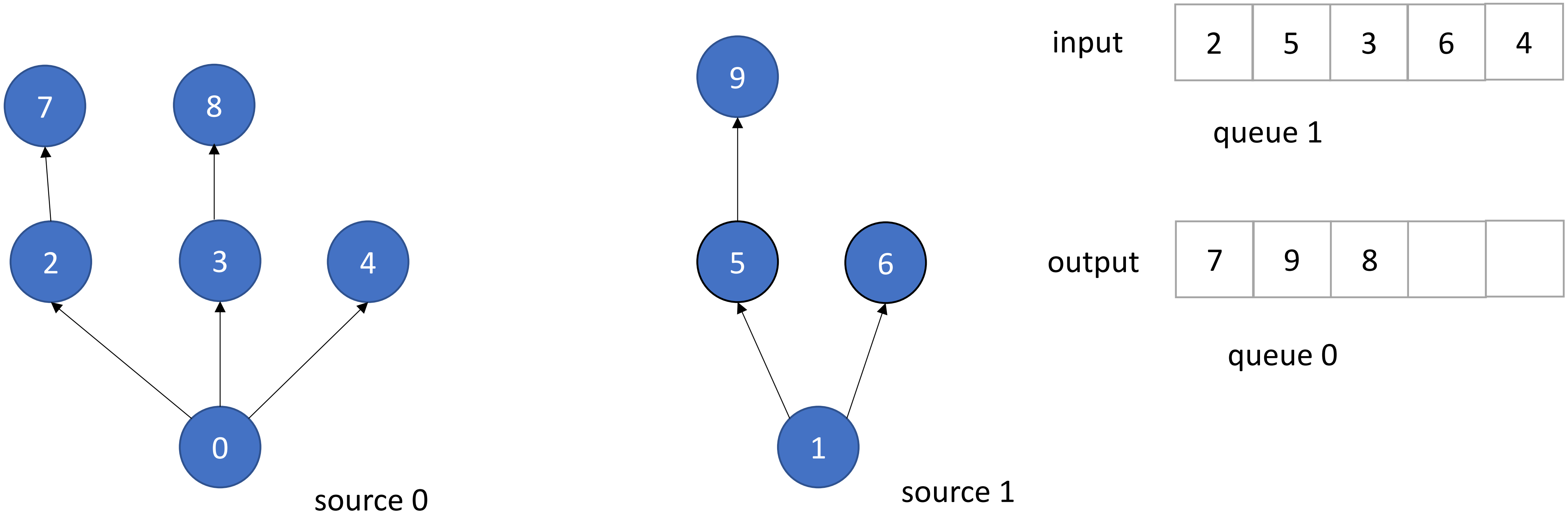
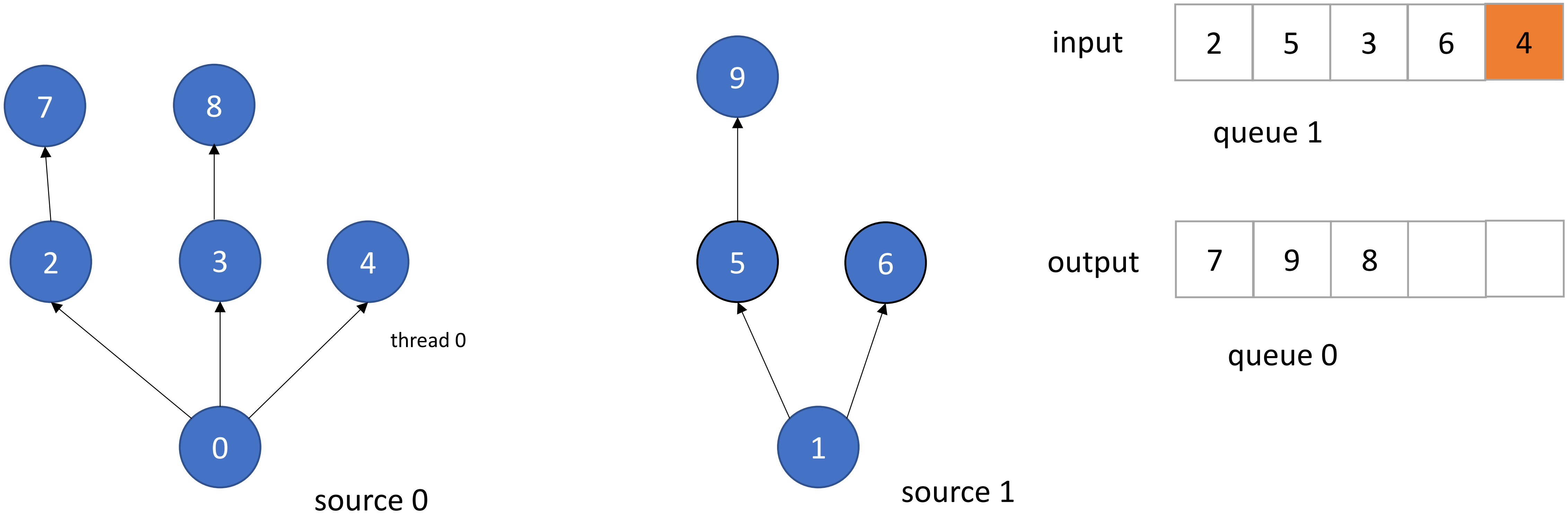


Input/Output Queues

- Example: Information flow in graph applications:



Input/Output Queues

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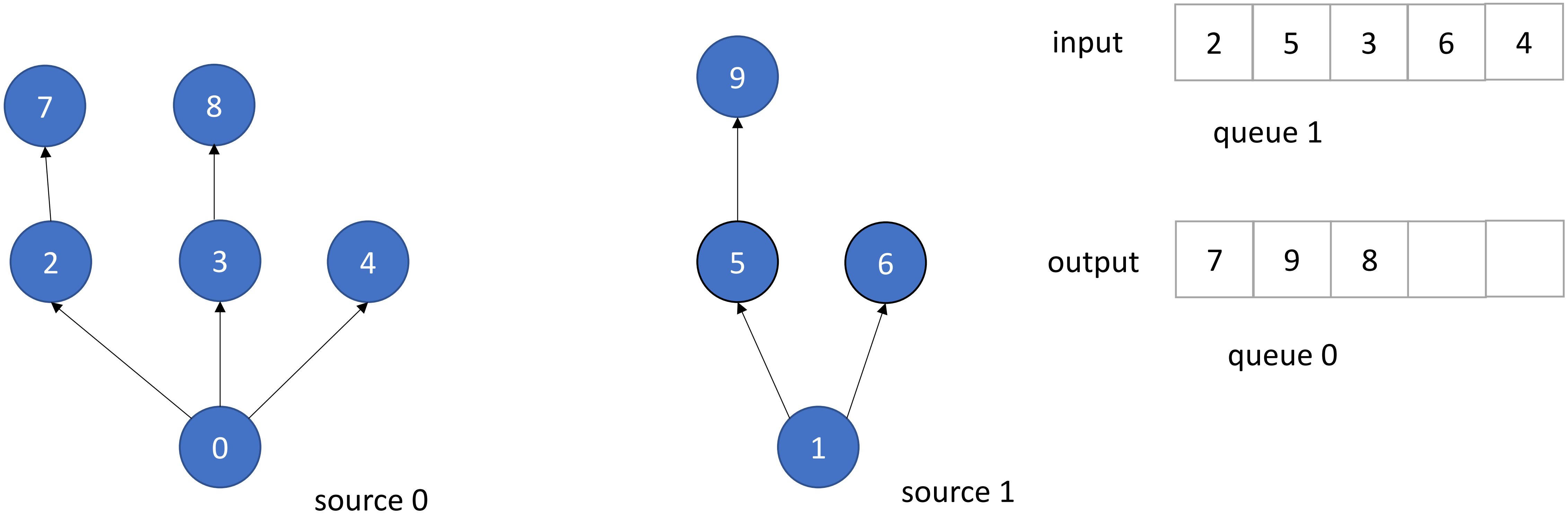
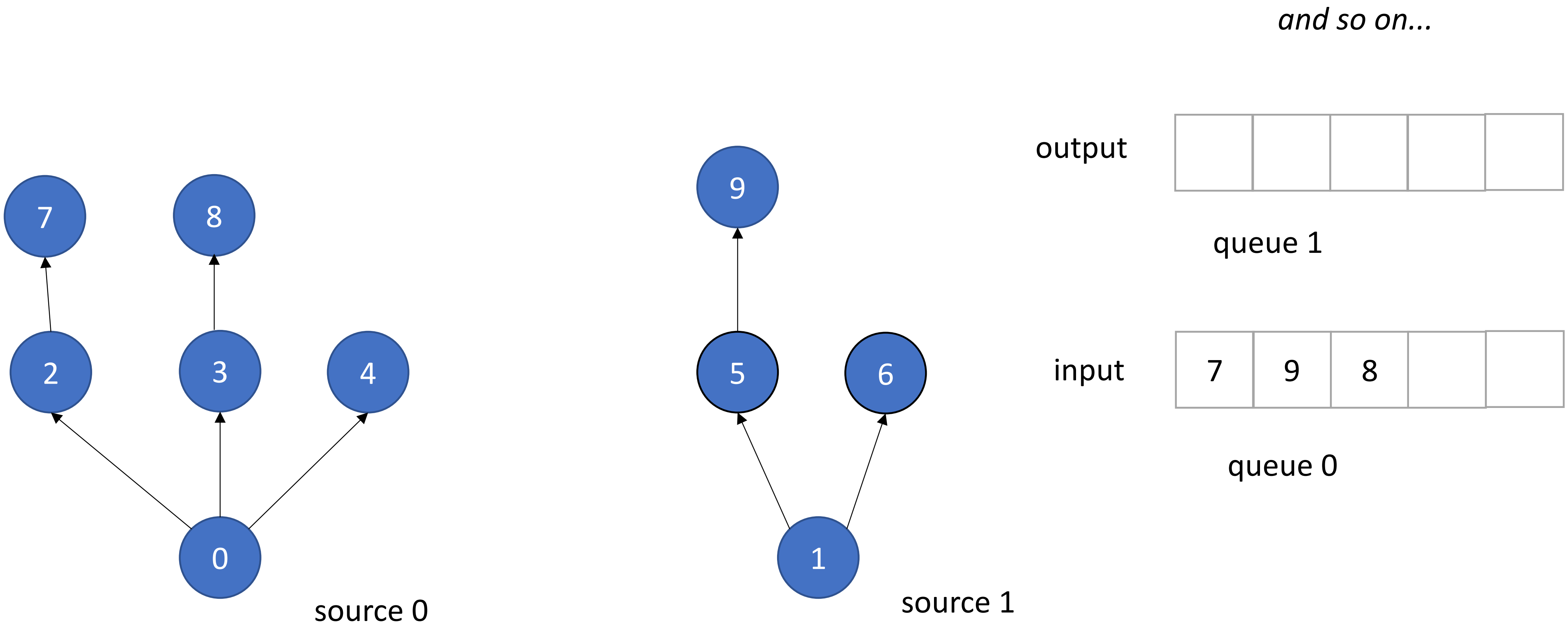


Input/Output Queues

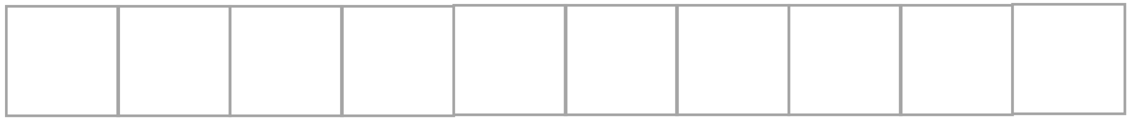
- Example: Information flow in graph applications:



Implementation

Implementation

Allocate a contiguous array

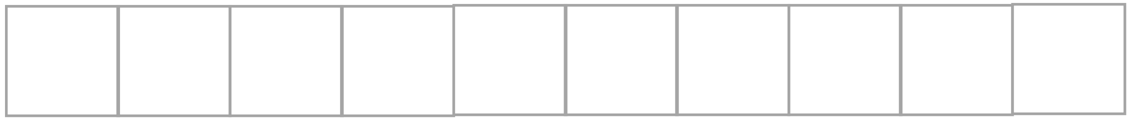


Pros:
?

Cons:
?

Implementation

Allocate a contiguous array



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

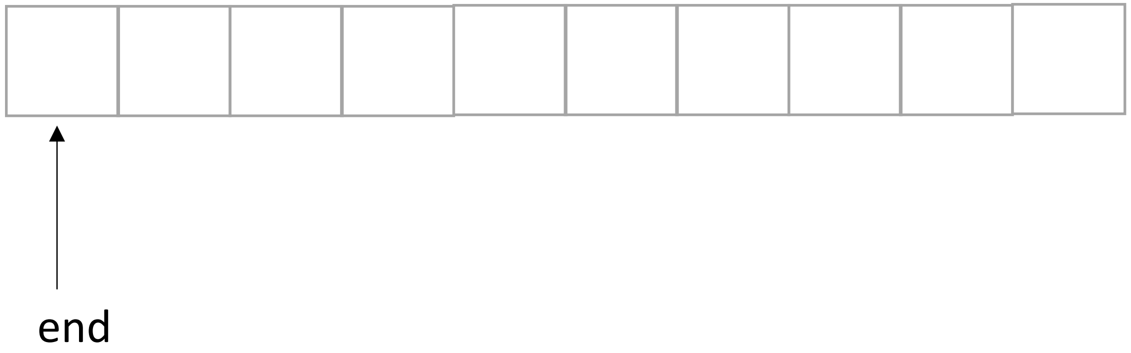
Cons:
- need to reason about overflow!

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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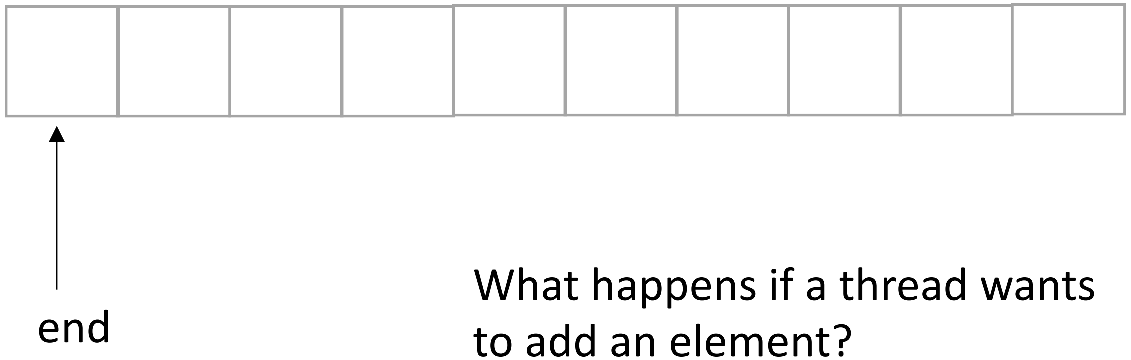
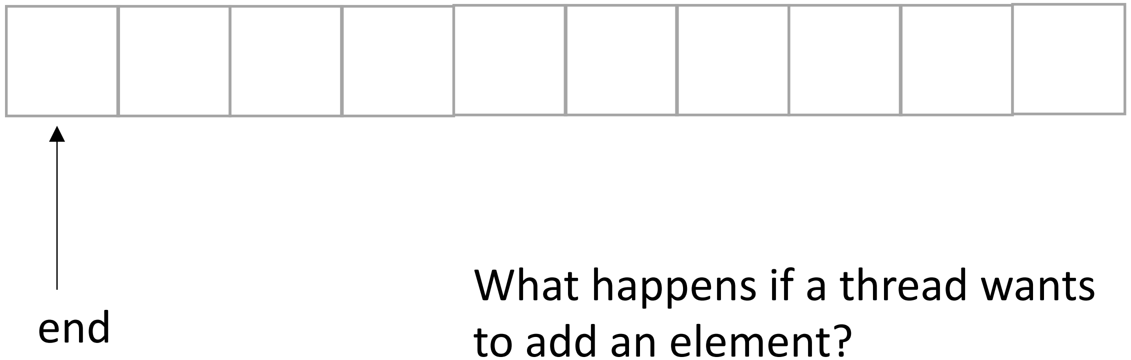


What happens if a thread wants to add an element?

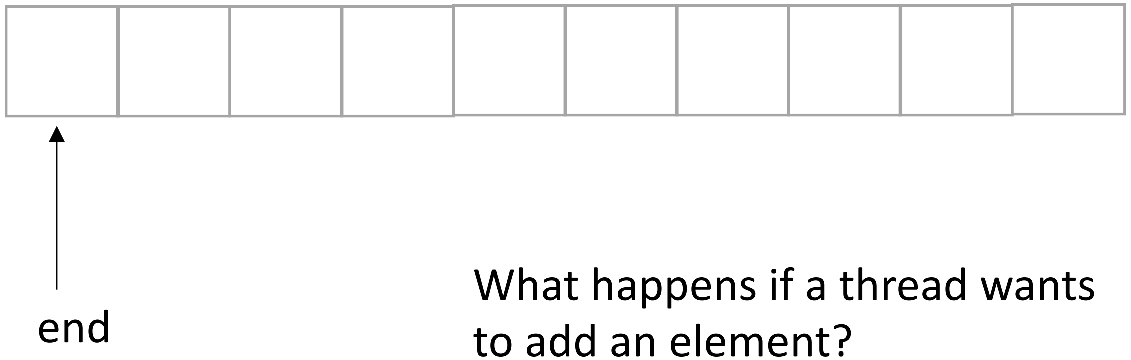
Implementation



What happens if a thread wants to add an element?

Think sequentially:

Implementation

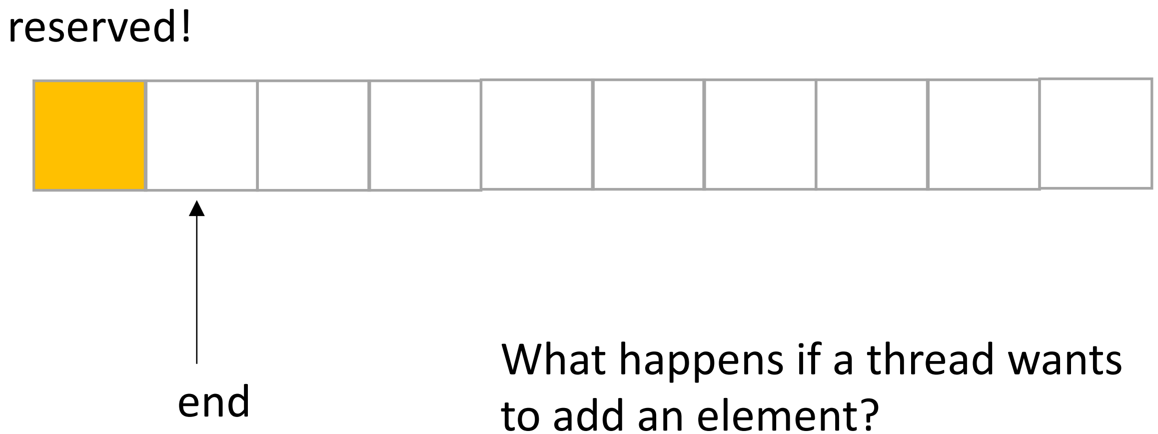


What happens if a thread wants to add an element?

Think sequentially:

*reserve a space - increment end

Implementation



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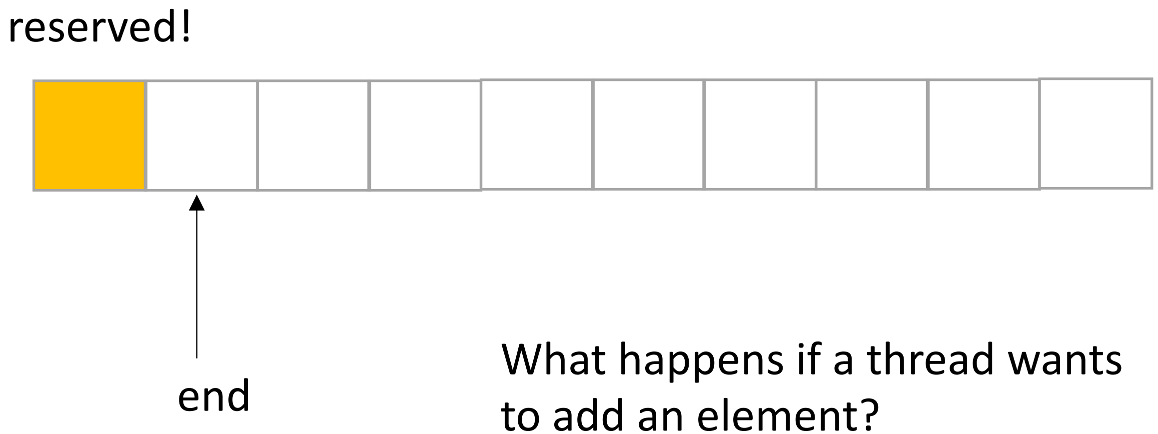

What happens if a thread wants to add an element?

Think sequentially:
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* add the element

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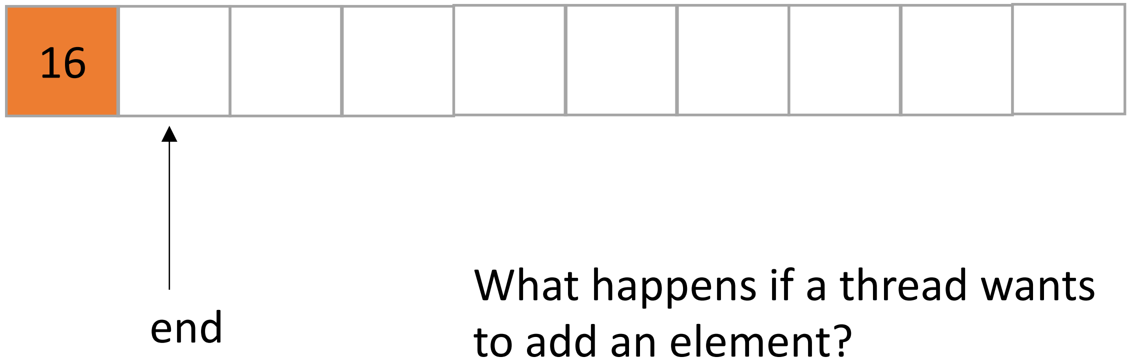

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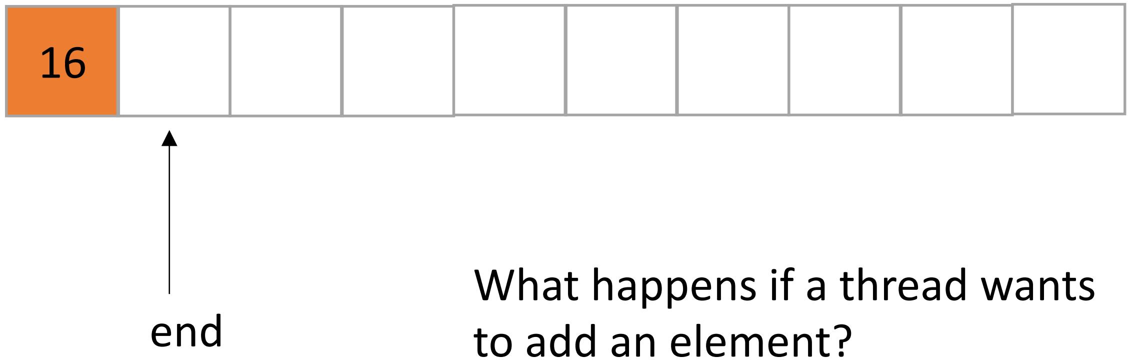
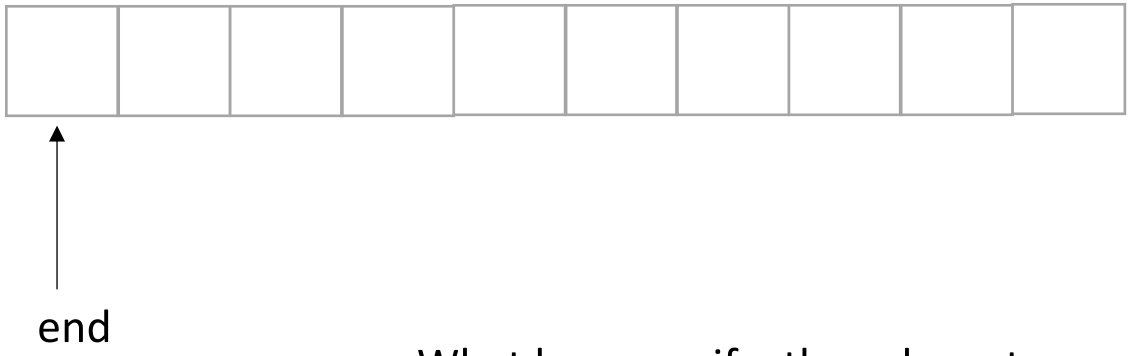


What happens if a thread wants to add an element?

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

done!

Implementation

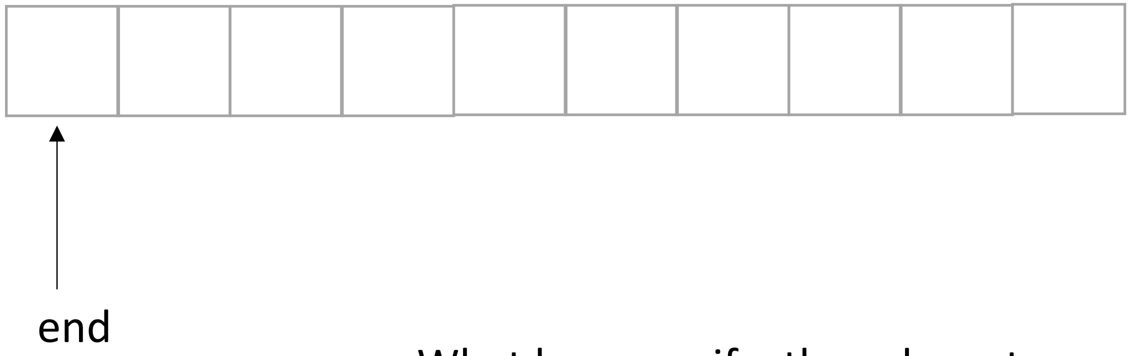


What happens if a thread wants to add an element?

Think concurrently:

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

Implementation

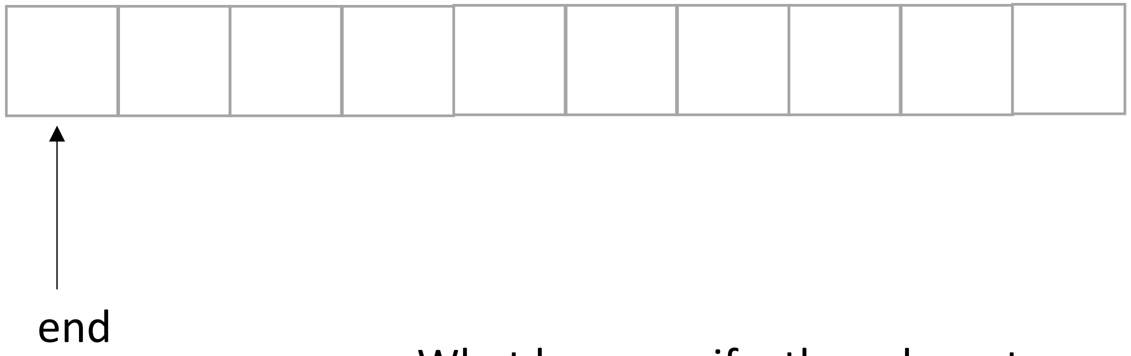


What happens if a thread wants to add an element?

Think concurrently:

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

Implementation



<u>Thread 0:</u>
enq(6);

<u>Thread 1:</u>
enq(7);

What happens if a thread wants to add an element?

Think concurrently:

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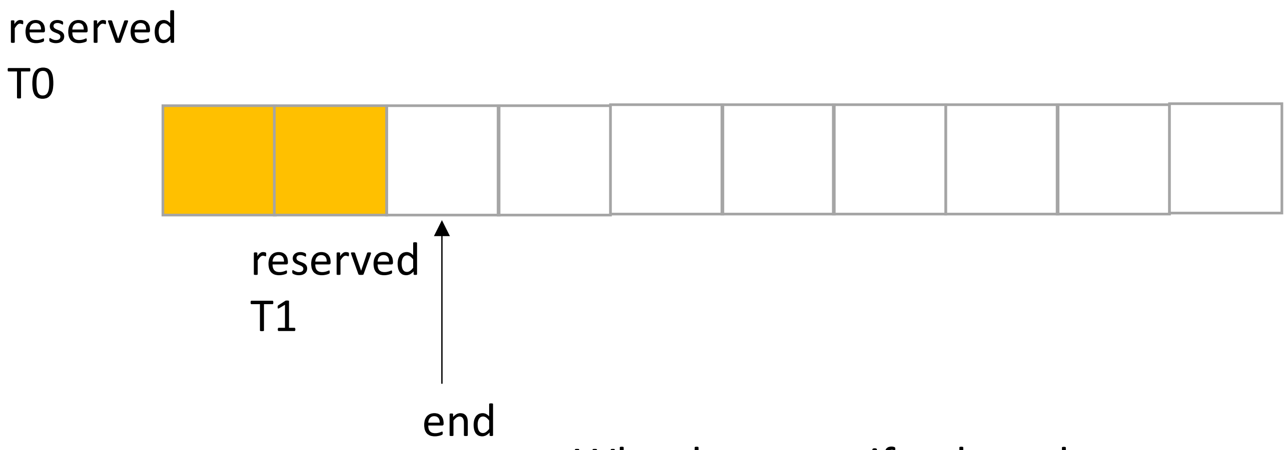
Implementation



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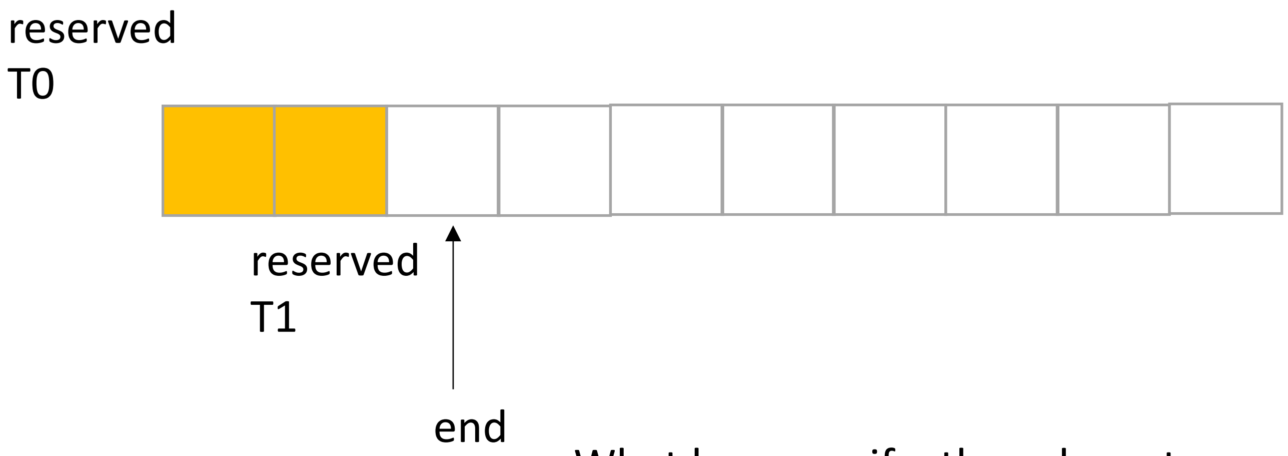
Implementation

does it matter which order threads add their data?



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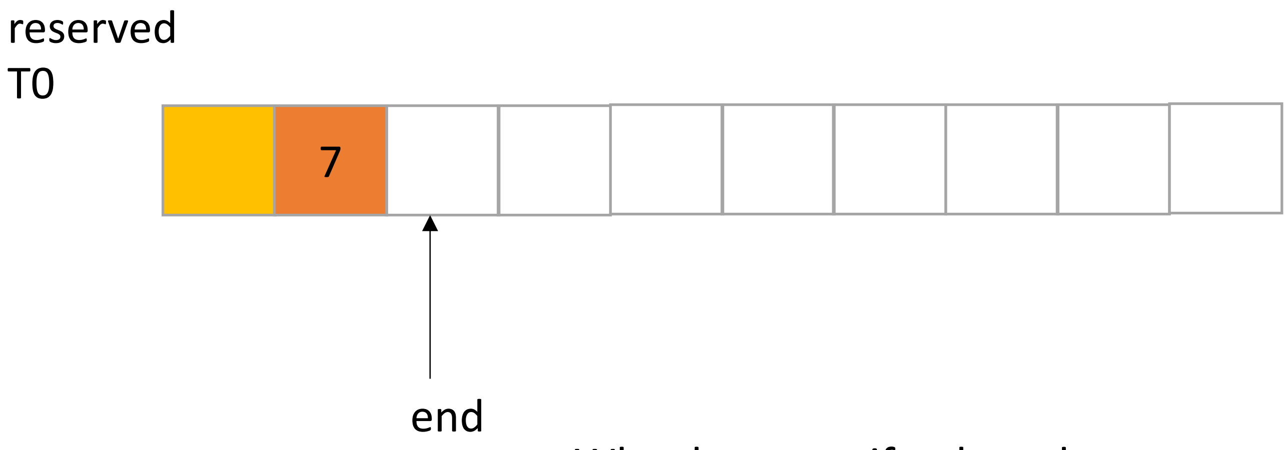


What happens if a thread wants to add an element?

Think concurrently:

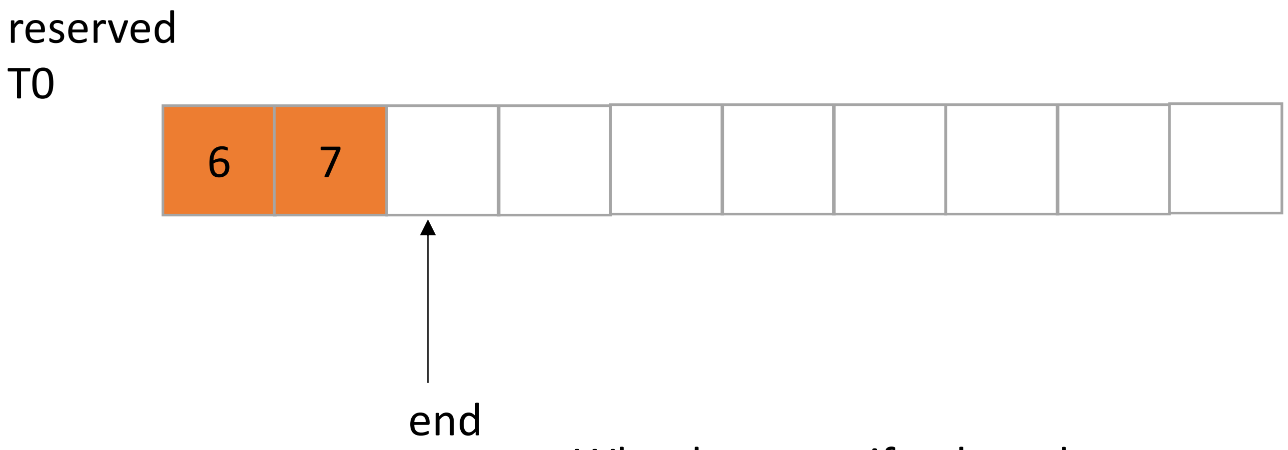
```
reserved_index = atomic_fetch_add(&end, 1);
```

<u>Thread 0:</u>
enq(6);

<u>Thread 1:</u>
enq(7);

Implementation

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



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What happens if a thread wants to add an element?

Think concurrently:

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

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

  public:
    InputOutputQueue() {
        end = 0;
     }

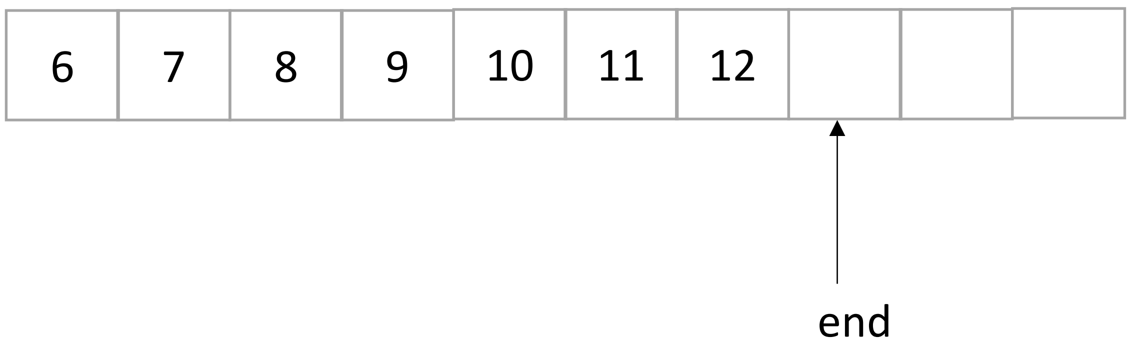
     void enq(int x) {
        int reserved_index = atomic_fetch_add(&end, 1);
        list[reserved_index] = x;
     }

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

How to protect against overflows?

What about Input?

- Now we only do deqs



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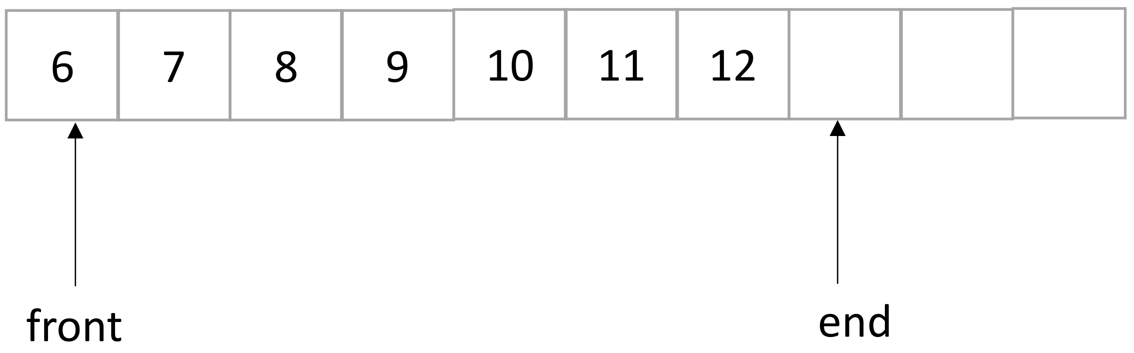

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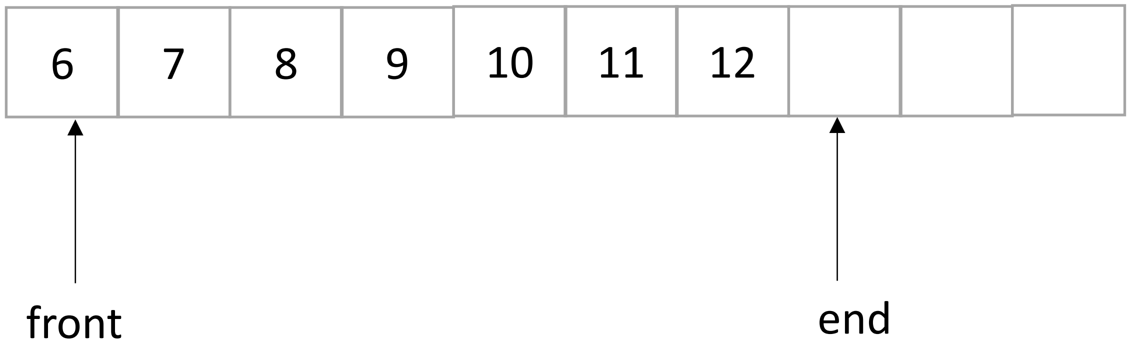


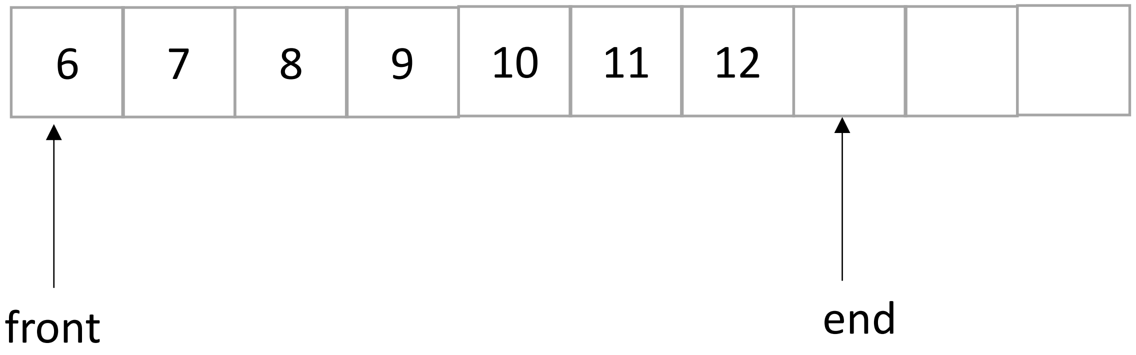
What happens if a thread wants to add an element?

Think concurrently:

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

What about Input?

- Now we only do deqs



<u>Thread 0:</u>
deq();

<u>Thread 1:</u>
deq();

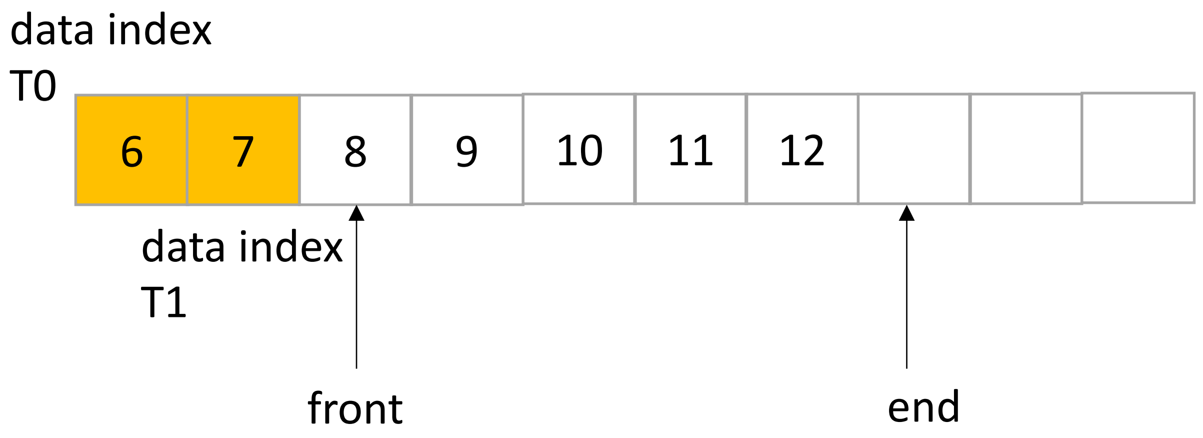
What happens if a thread wants to add an element?

Think concurrently:

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

What about Input?

- Now we only do deqs



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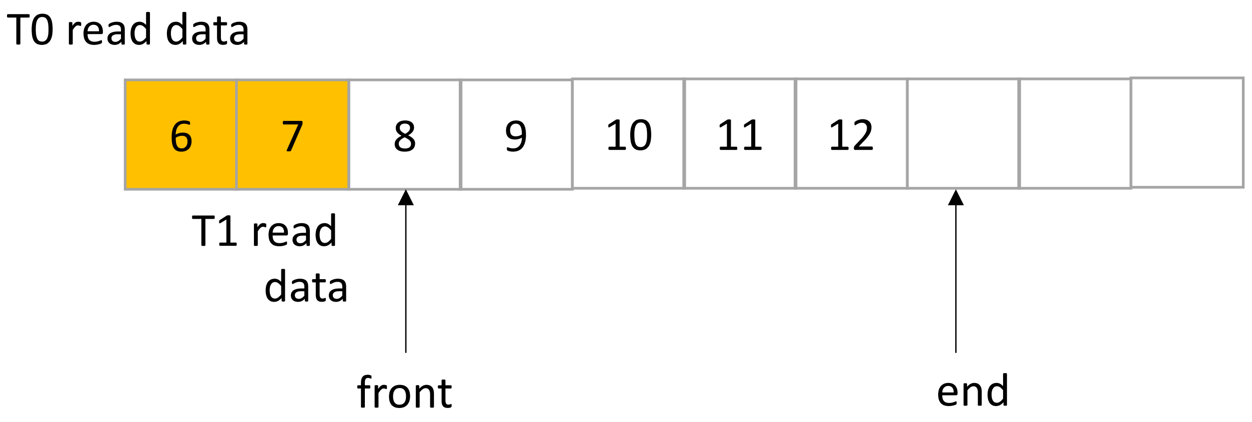

<u>Thread 0:</u>
deq(); // reads 6

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deq(); // reads 7

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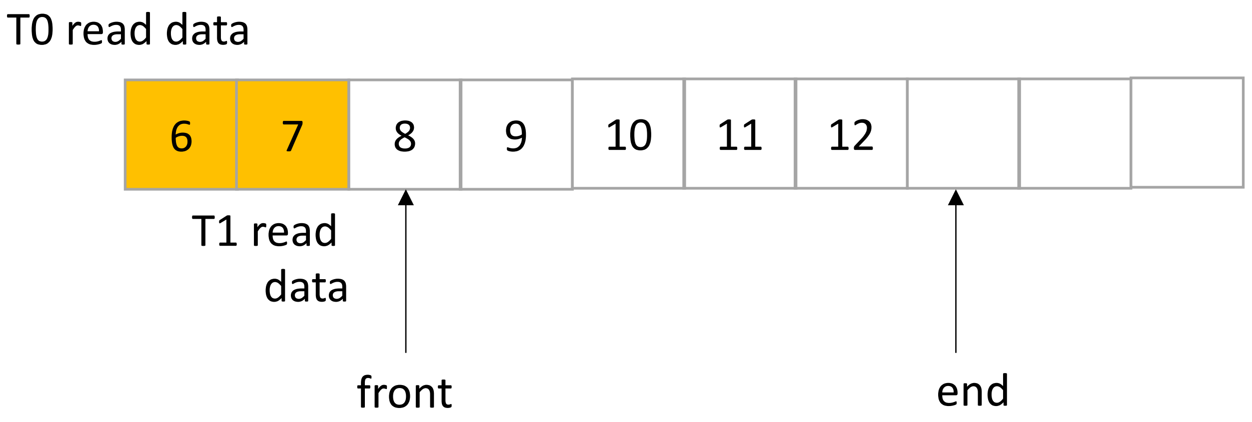
What about Input?

- Now we only do deqs



How to implement a stack?

<u>Thread 0:</u>
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    InputOutputQueue() {
        front = end = 0;
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     void enq(int x) {
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        list[reserved_index] = x;
     }

     void deq() {
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       return list[reserved_index];
     }

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

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How about size?

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```

how about size?

how do we reset?

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how do we reset?
Reset front and end

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 }
```

how about size?

how do we reset?
Reset front and end

does the list need
to be atomic?

See you on Monday!

- Get HW 2 submitted!