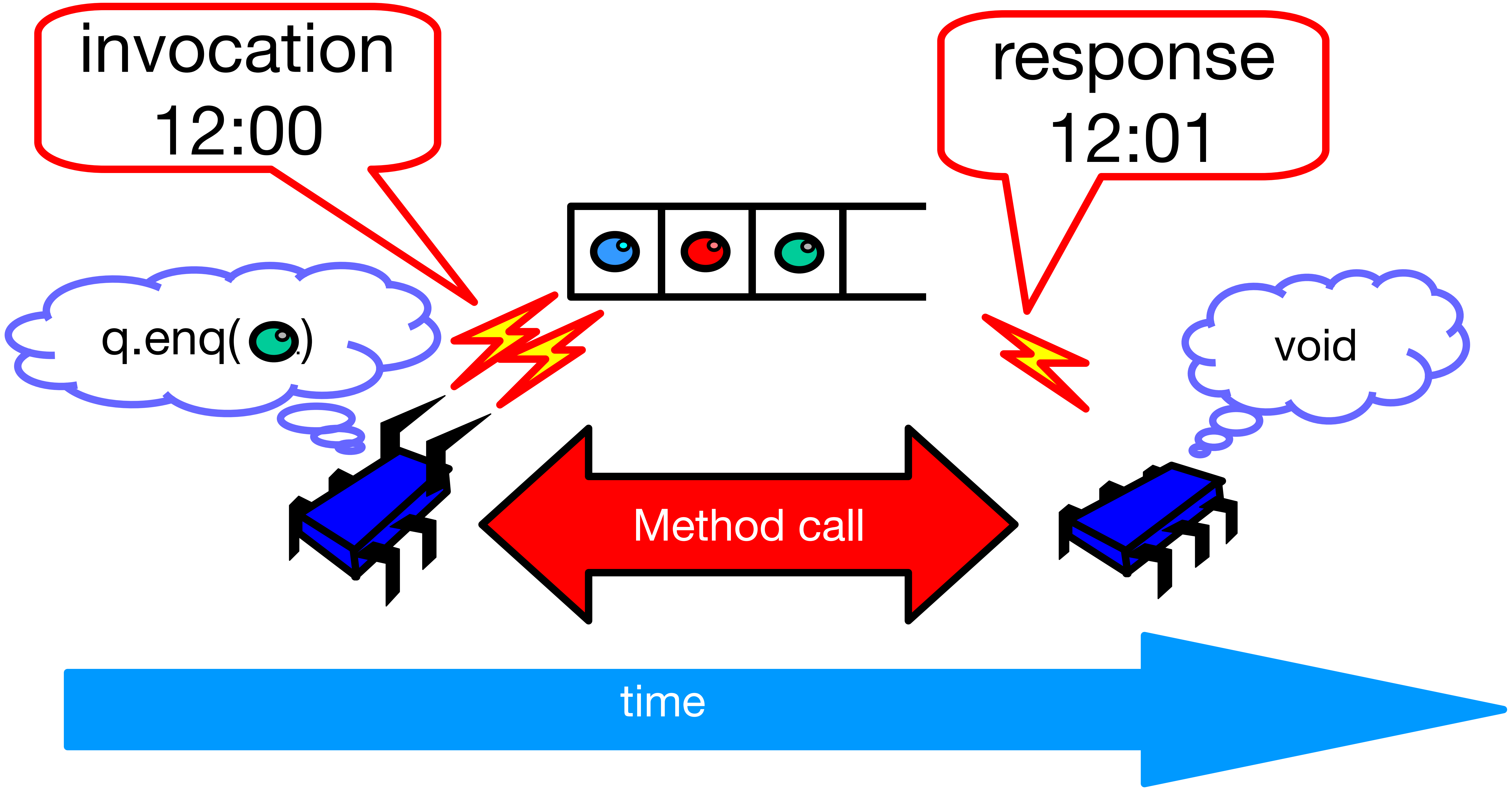
Concurrency in Java

CS 475, Fall 2019

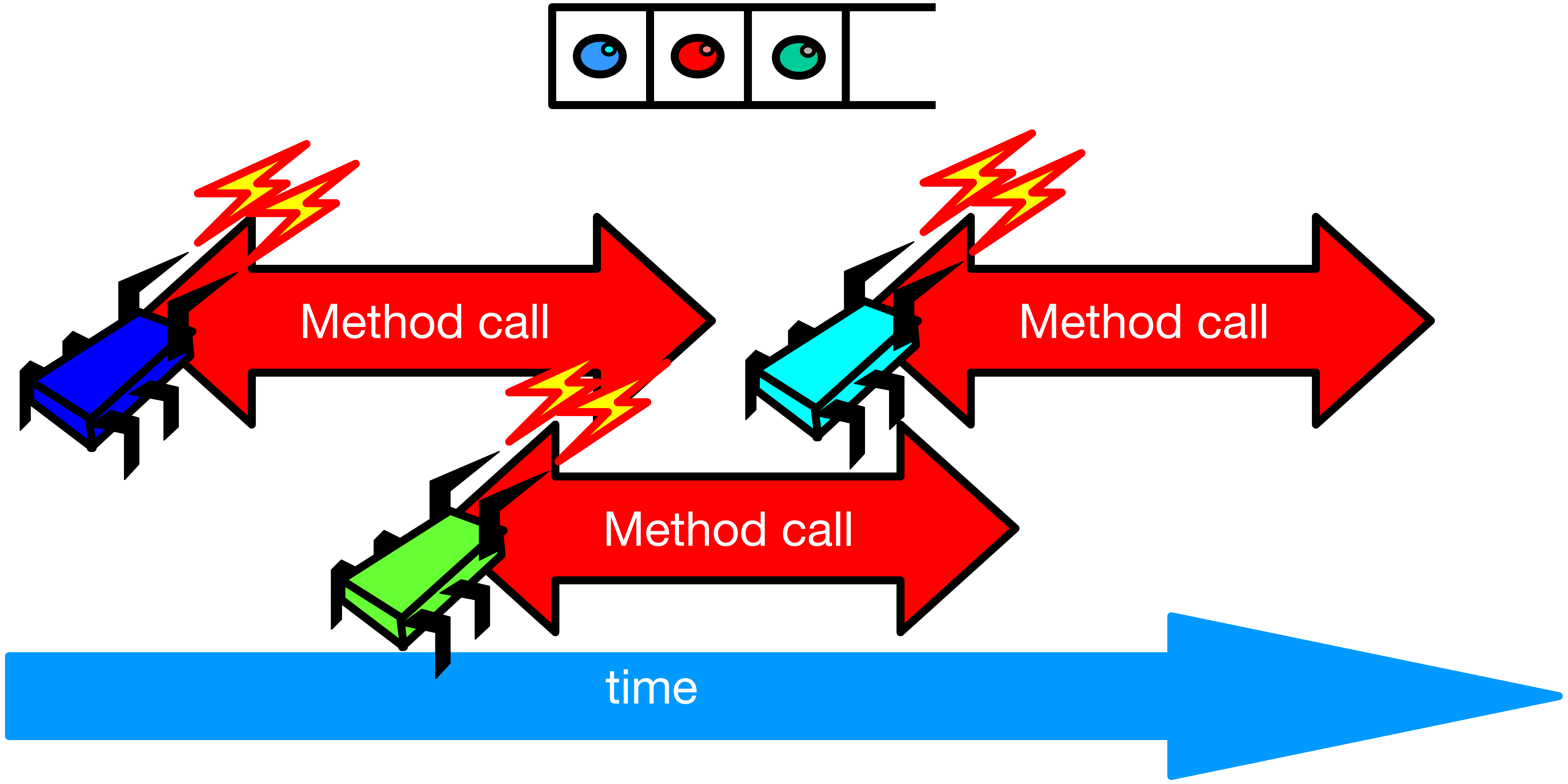
Concurrent & Distributed Systems

With material from Herlihy & Shavit, Art of Multiprocessor Programming

Methods Take Time

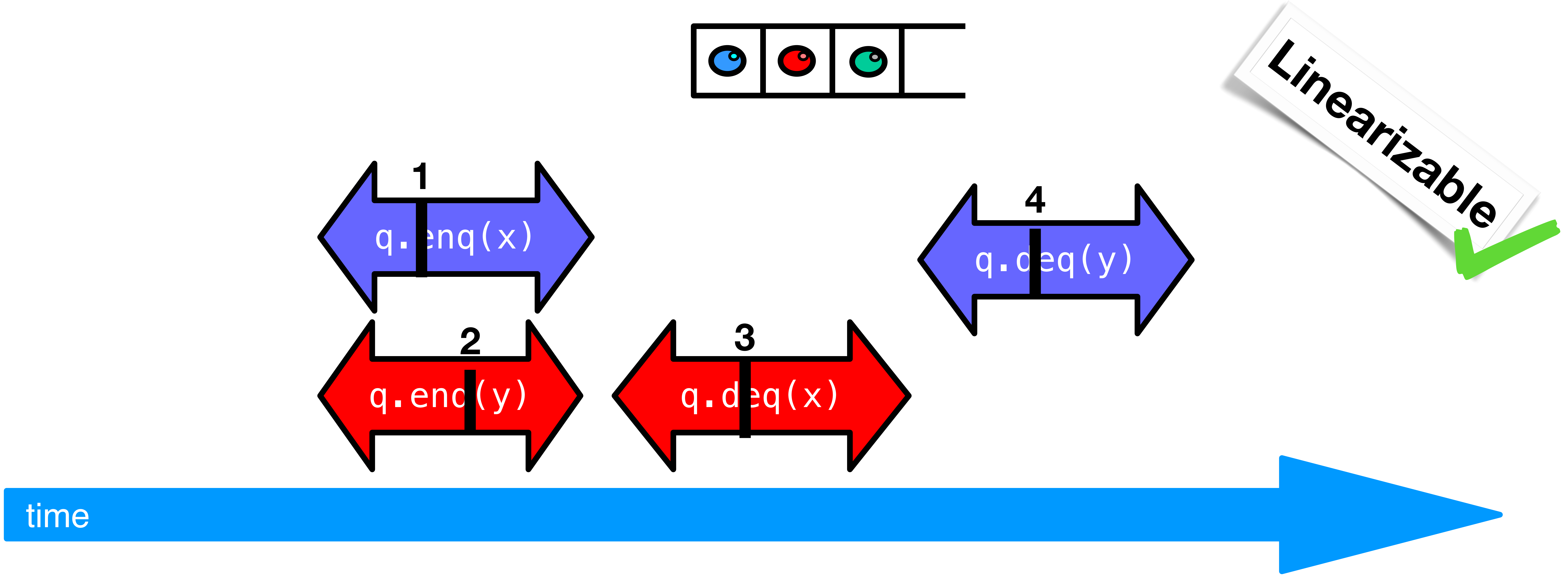


Concurrent Methods Take Overlapping Time



Example: Linearizable?

Reminder: Linearizable means: each method takes effect instantaneously, sometime in its observed time window



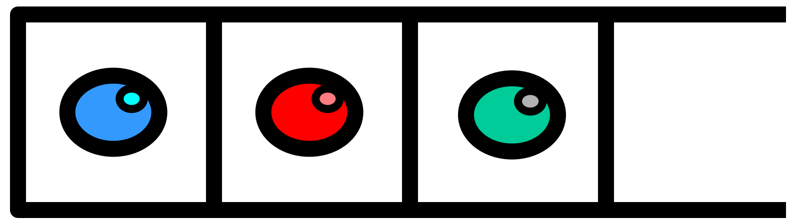
Today

- From our model of strict happens-before to… how programming languages really work
- Plus condition variables, monitors and semaphores
- Reading: H&S 3.8, 8.1-8.5
- Note: HW1 coming up: https://www.jonbell.net/gmu-cs-475-fall-2019/homework-1/

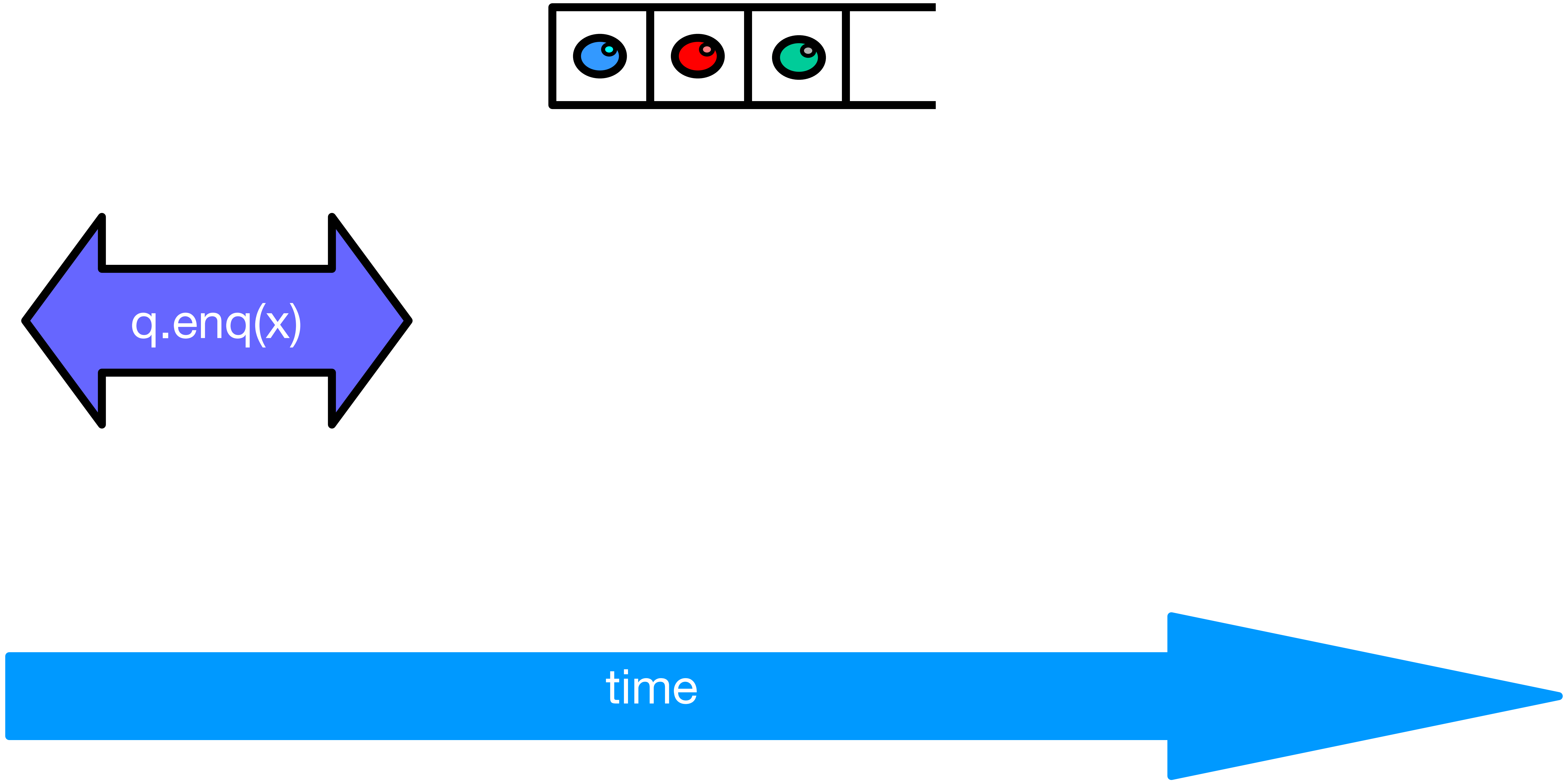
Alternative: Sequential Consistency

- No need to preserve real-time order
  - Cannot re-order operations done by the same thread
  - Can re-order operations done by different threads without affecting each individual threads' order
- Often used to describe multiprocessor memory architectures
- Formulation:
  - There is some total order of operations so that:
  - Each CPUs operations appear in order
  - All CPUs see results according to that order (read most recent writes)

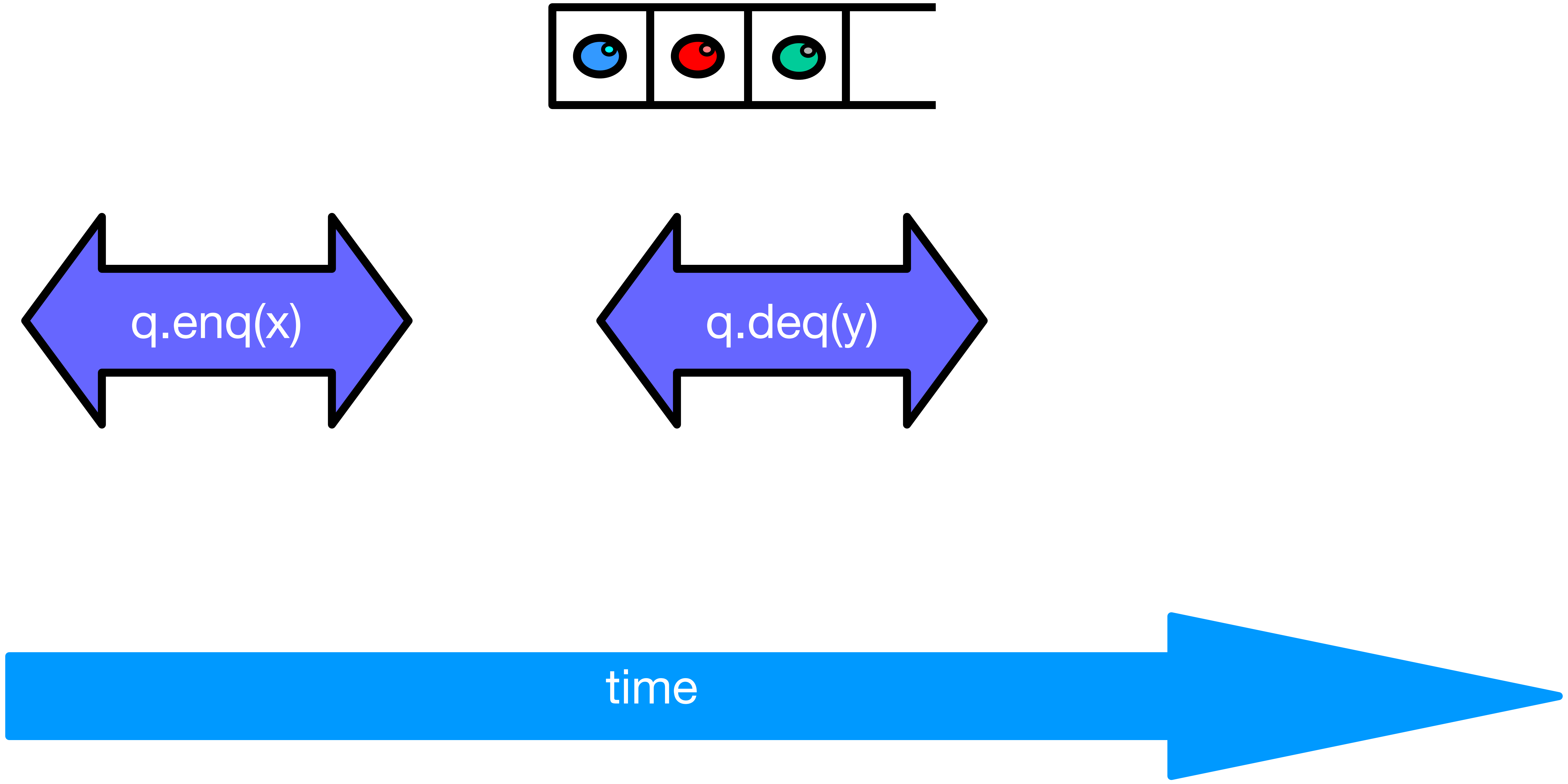
Example



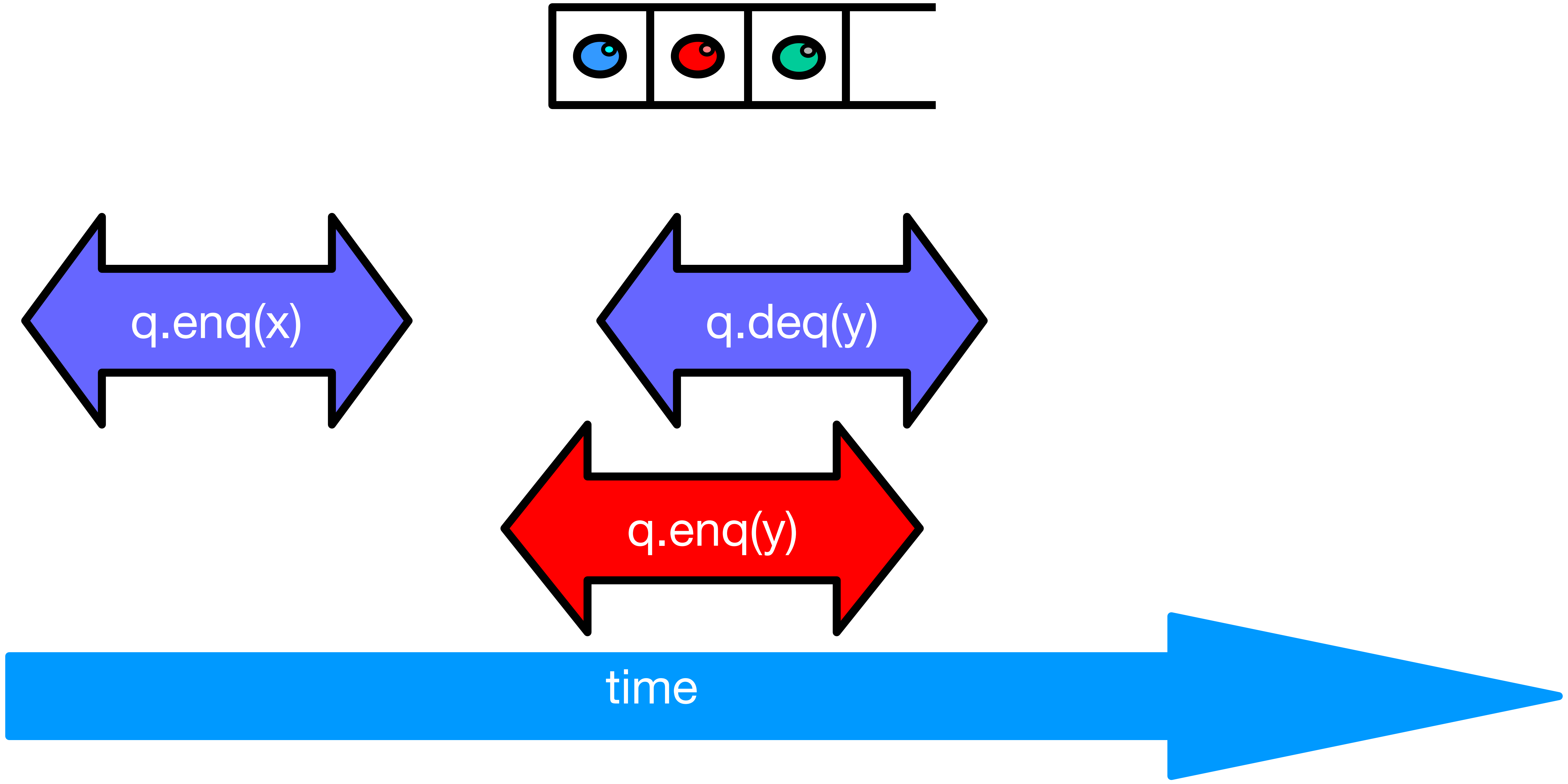
Example



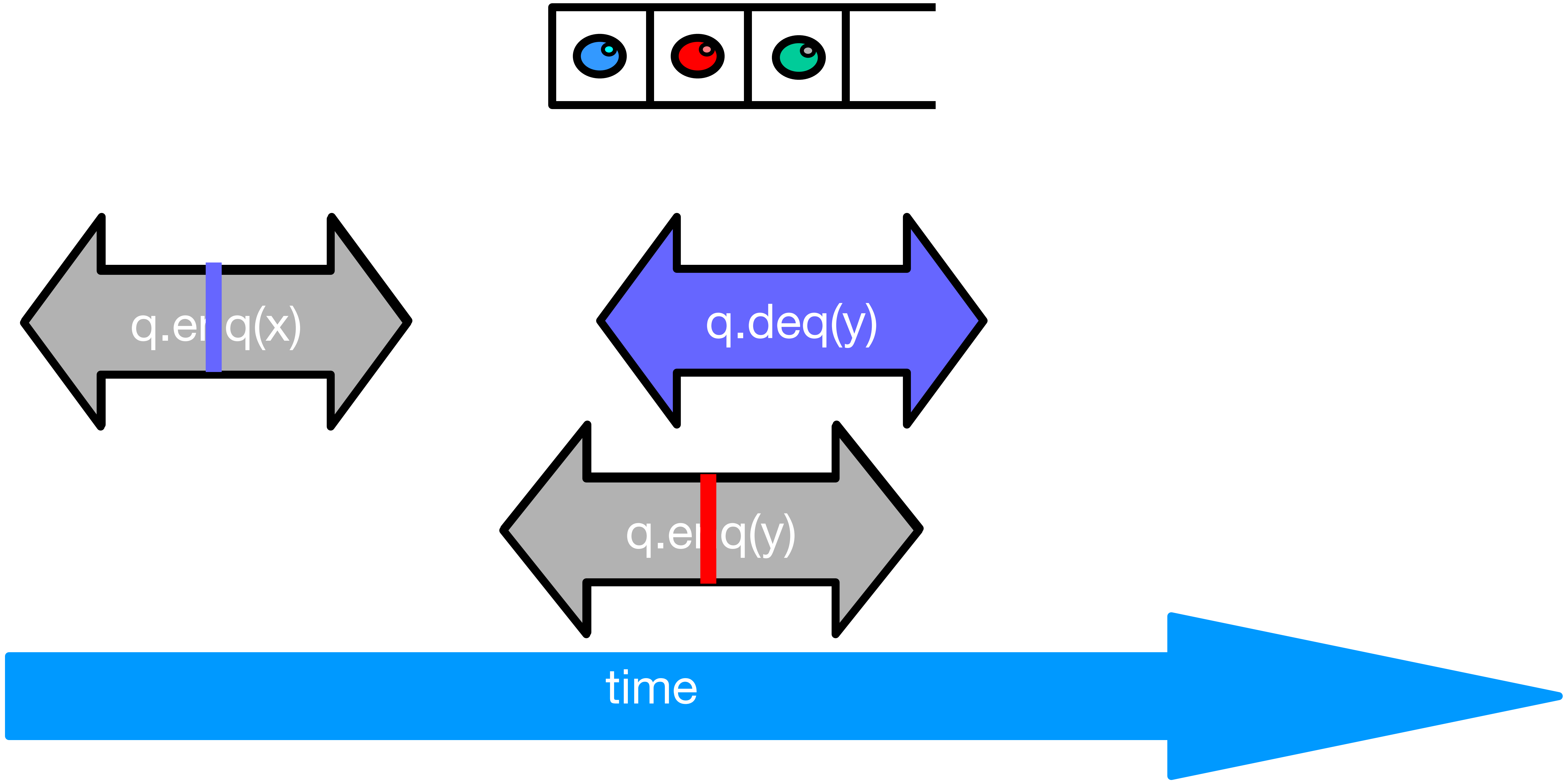
Example



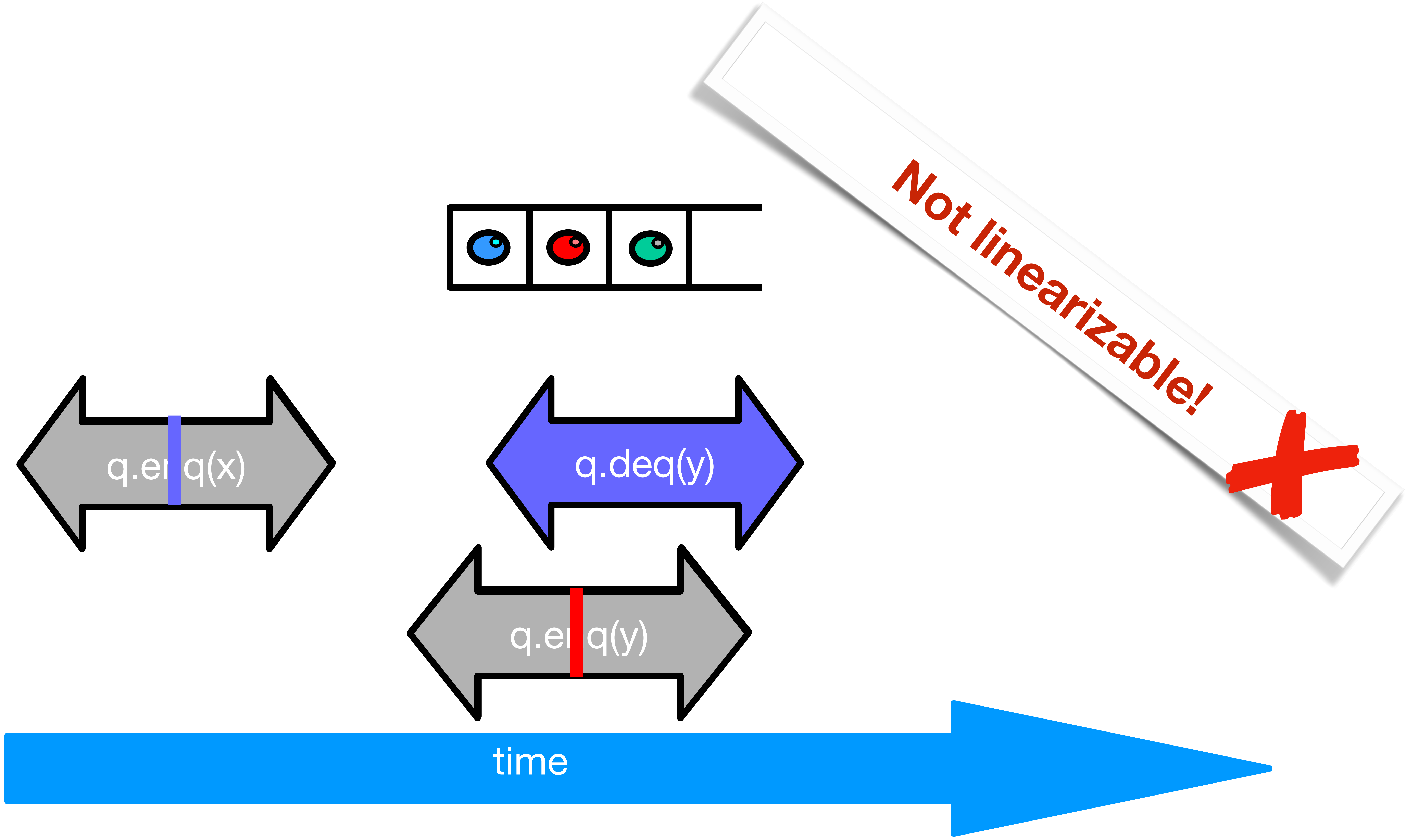
Example



Example

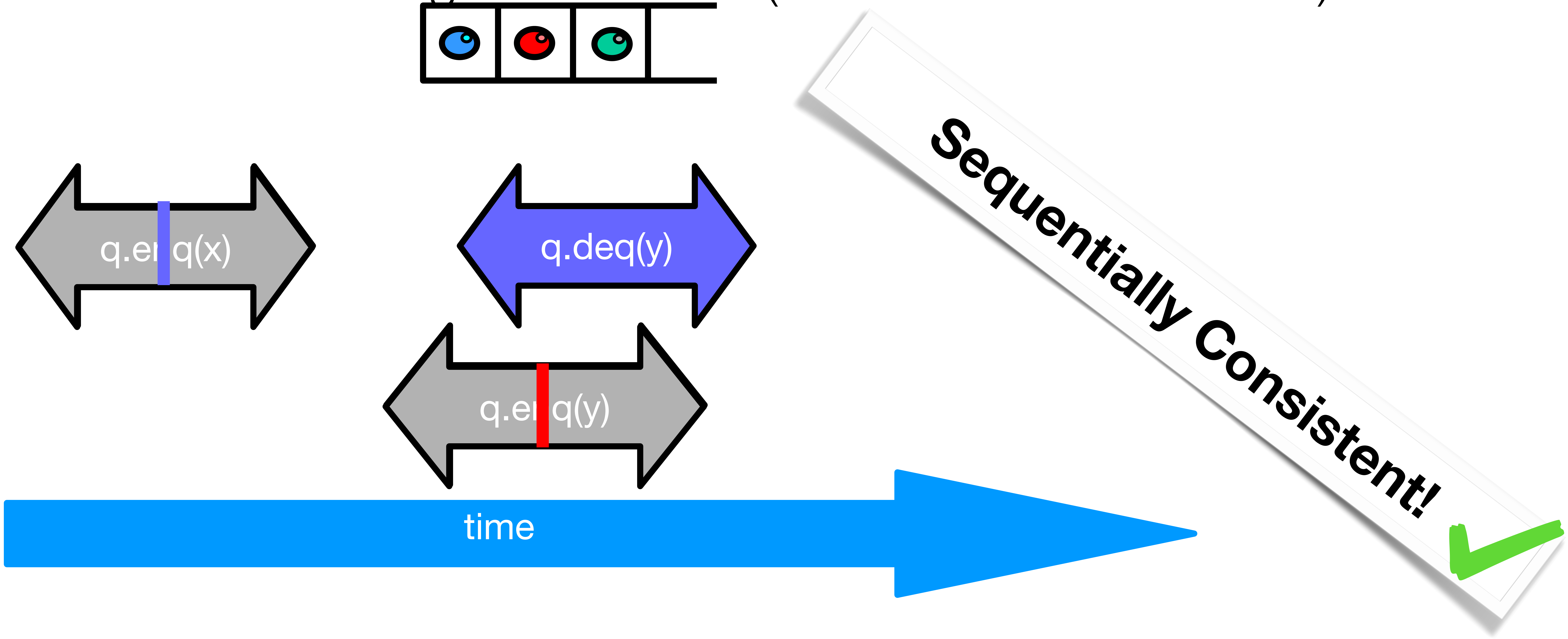


Example



Example

- Reminder, sequentially consistent if there is some total order of operations so that:
  - Each CPUs operations appear in order
  - All CPUs see results according to that order (read most recent writes)

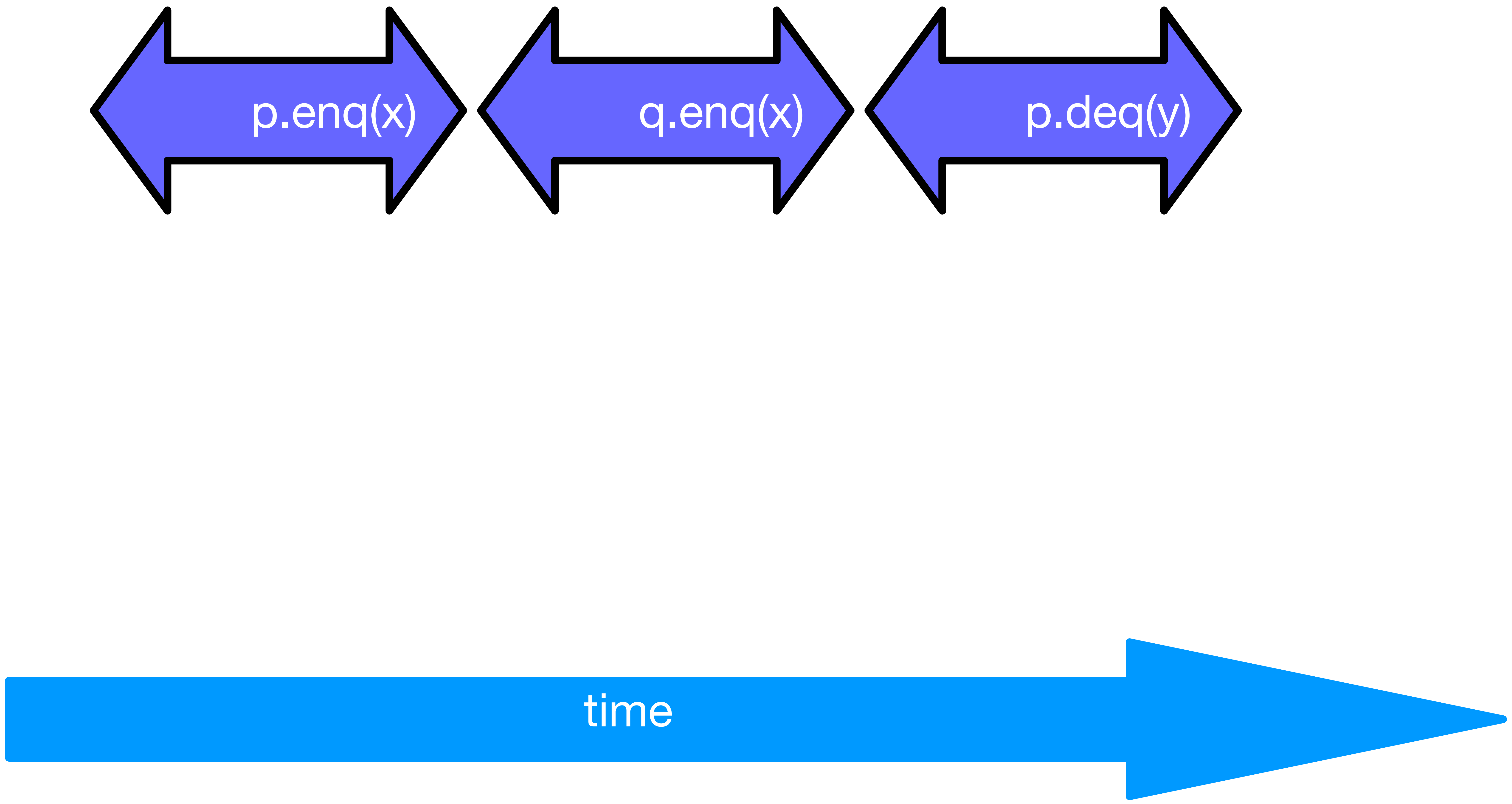


Theorem

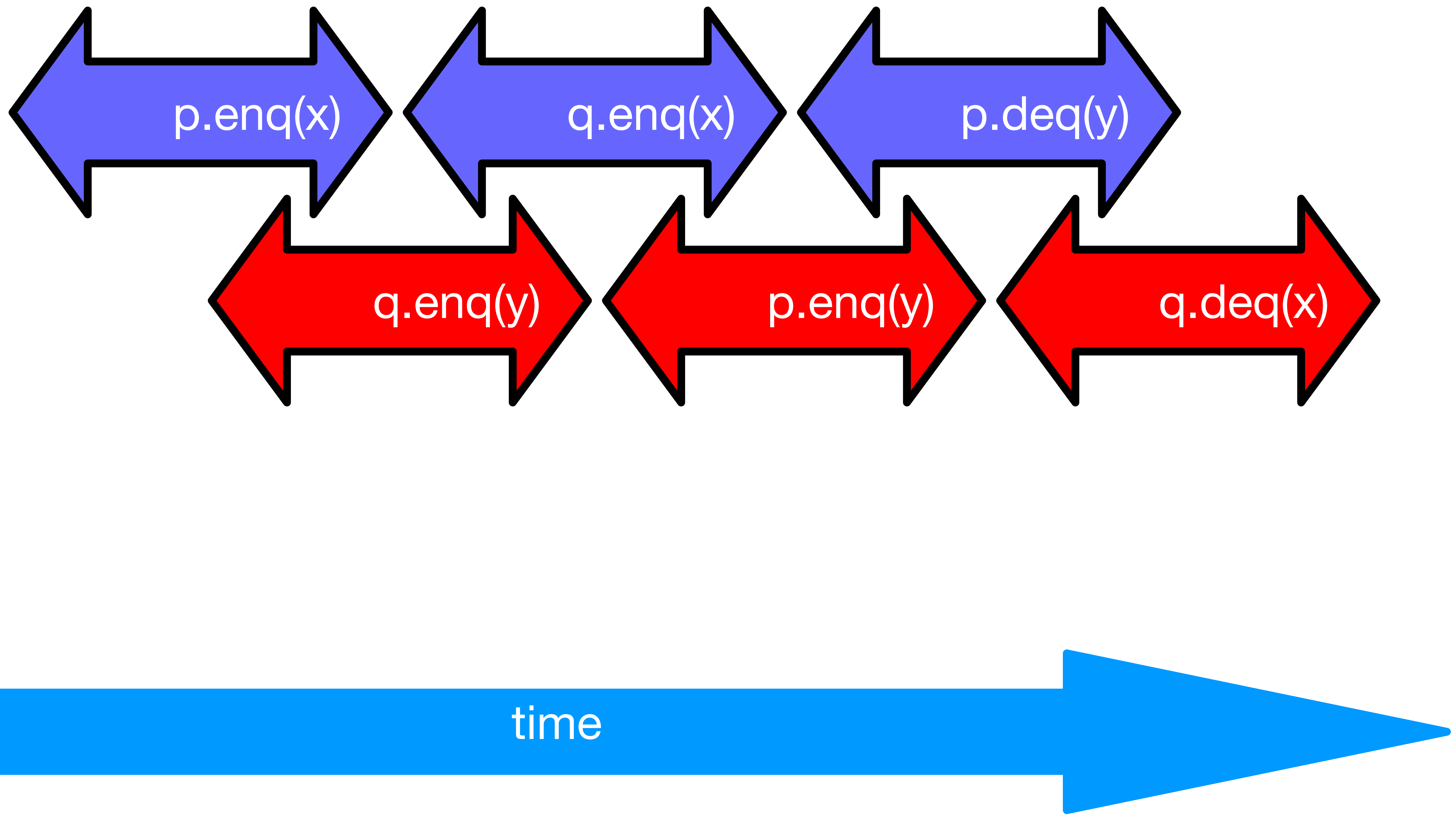
Sequential Consistency is not a local property

(and thus we lose composability…)

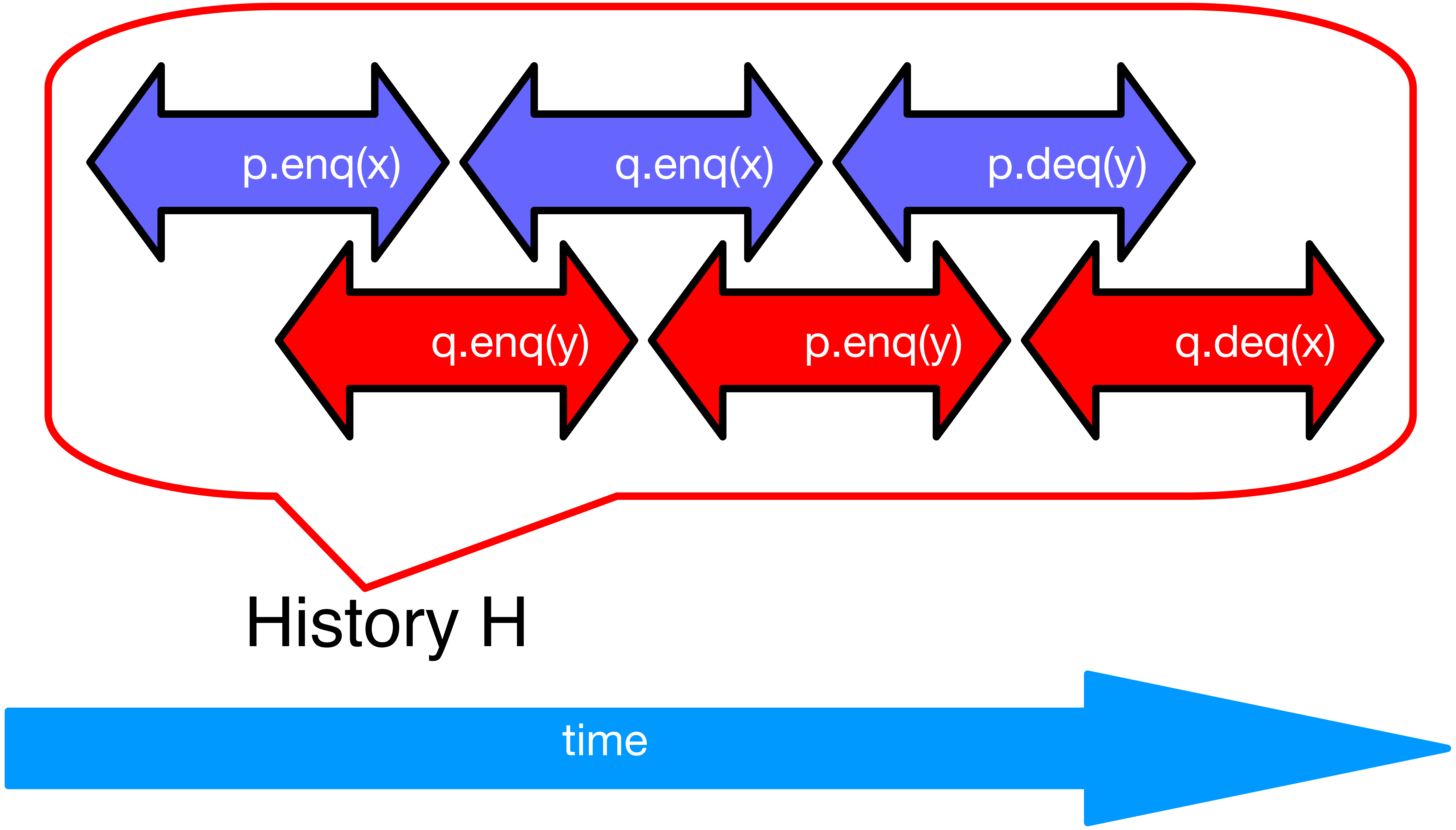
FIFO Queue Example



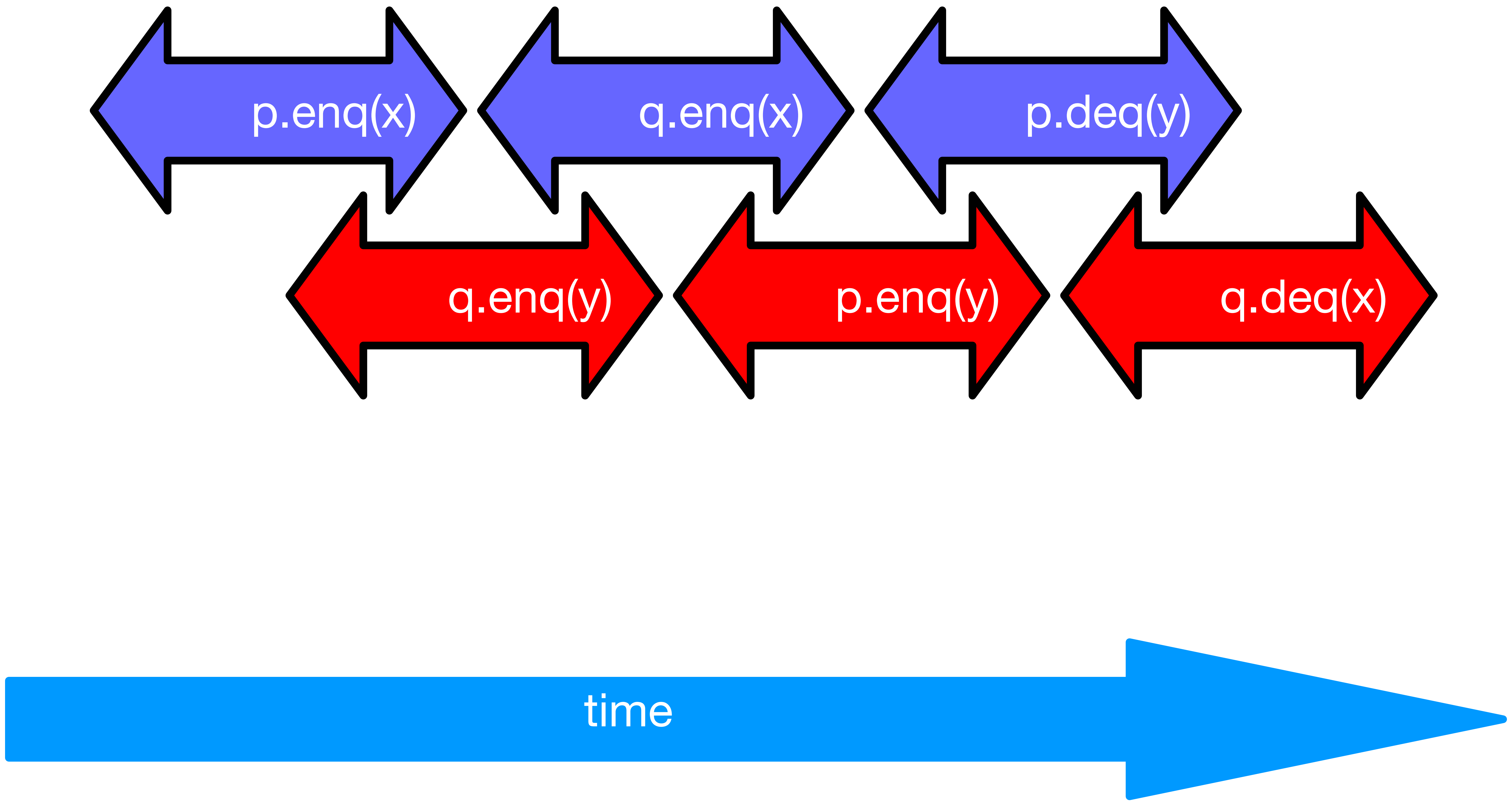
FIFO Queue Example



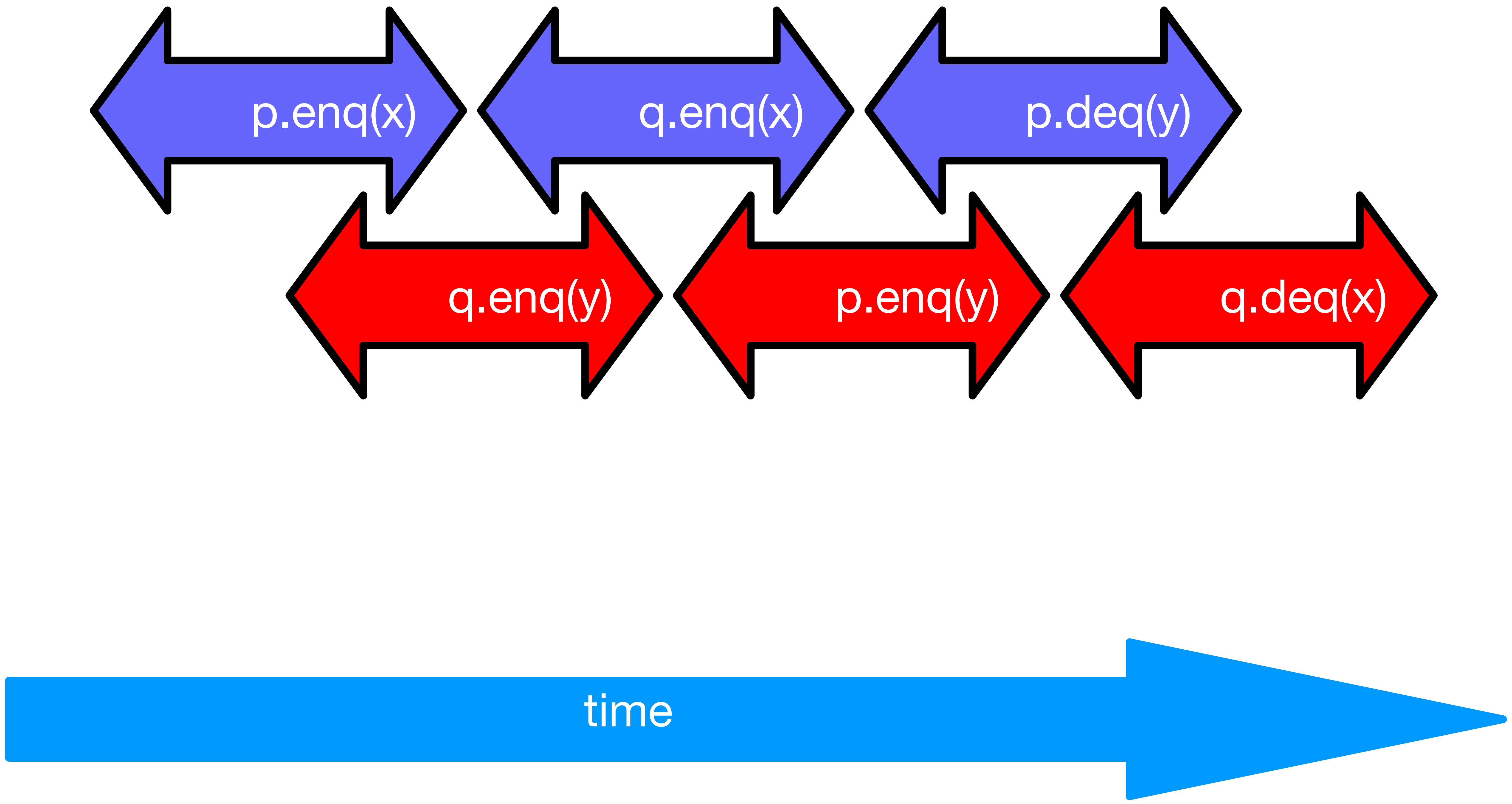
FIFO Queue Example



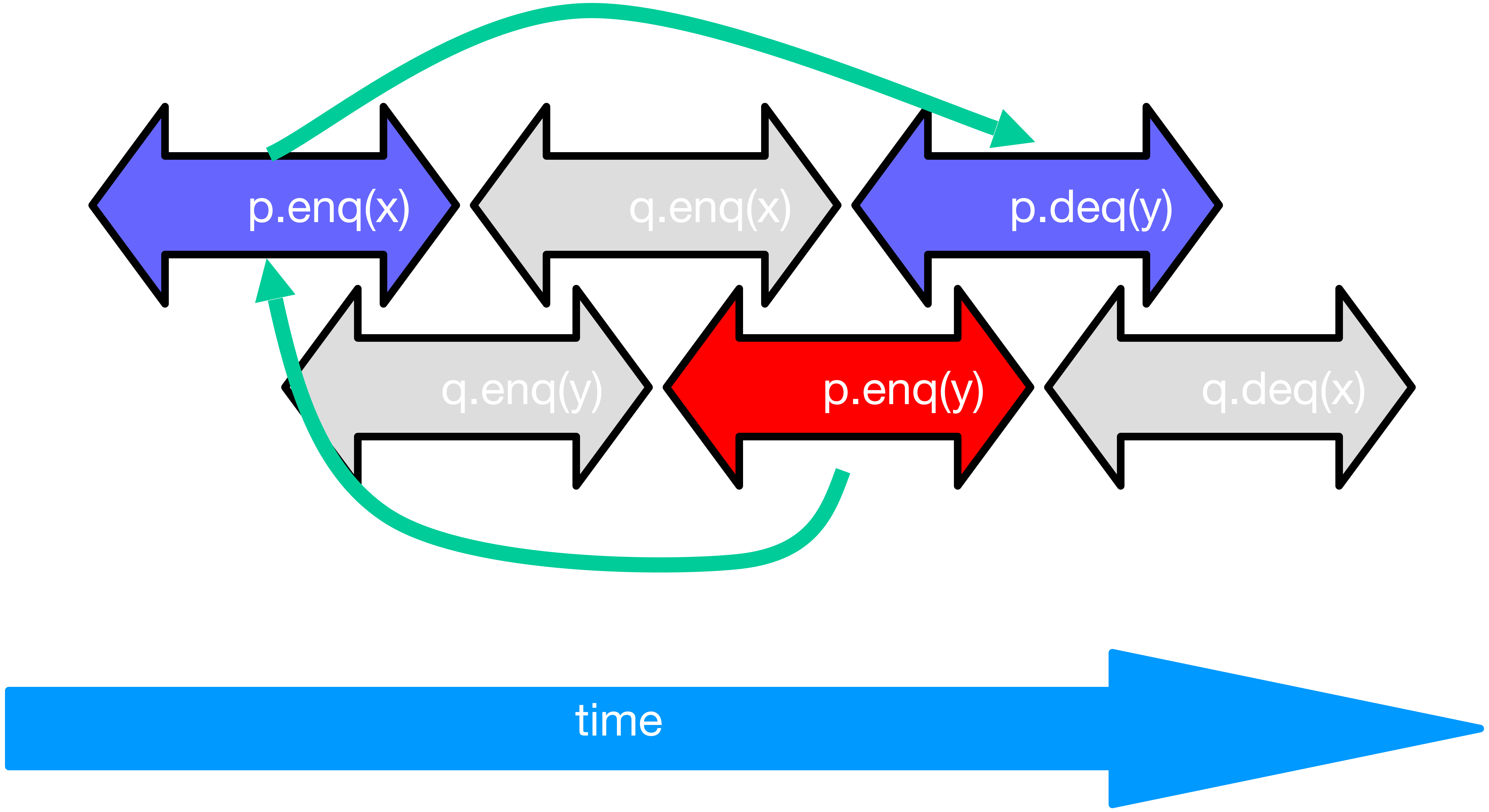
H|p Sequentially Consistent



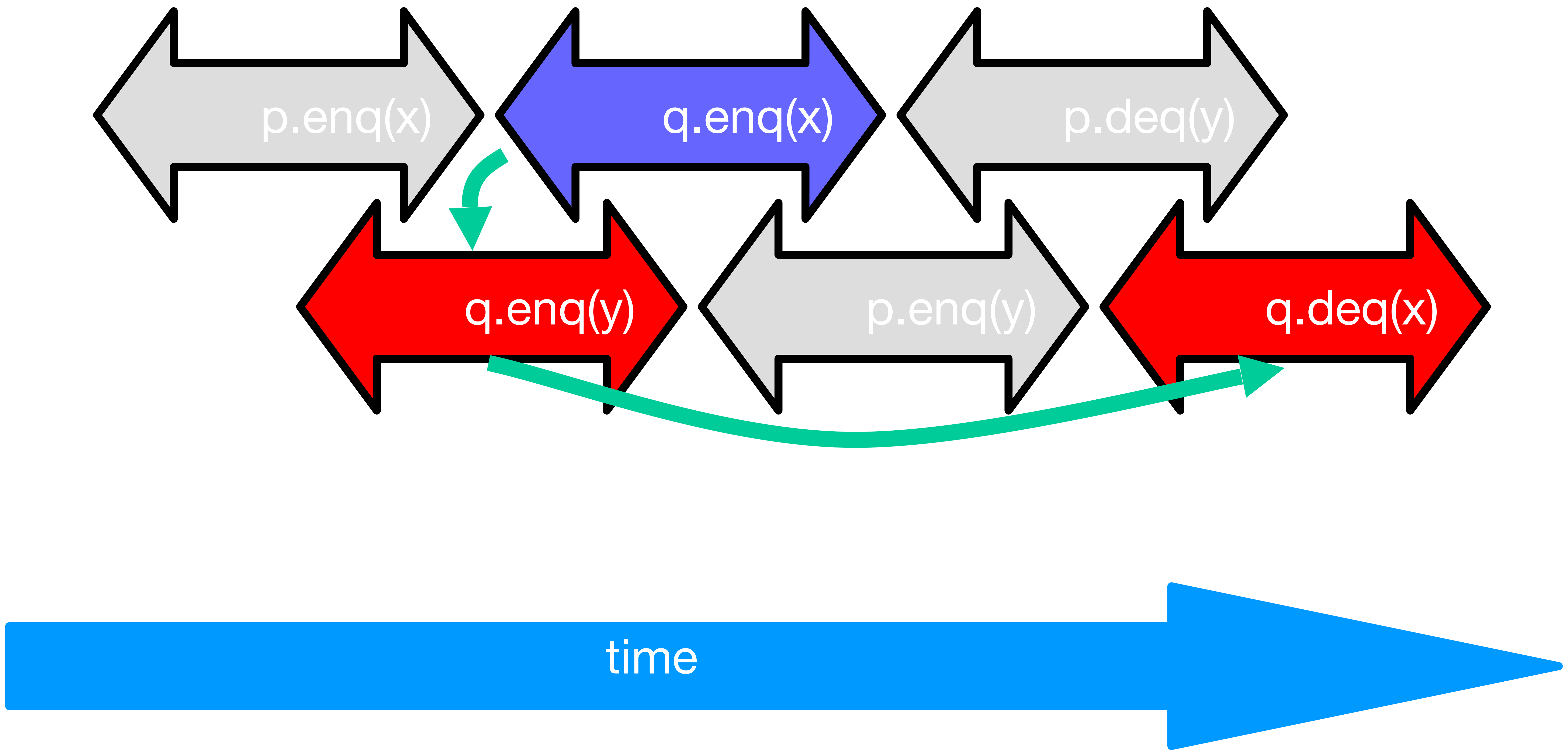
H|q Sequentially Consistent



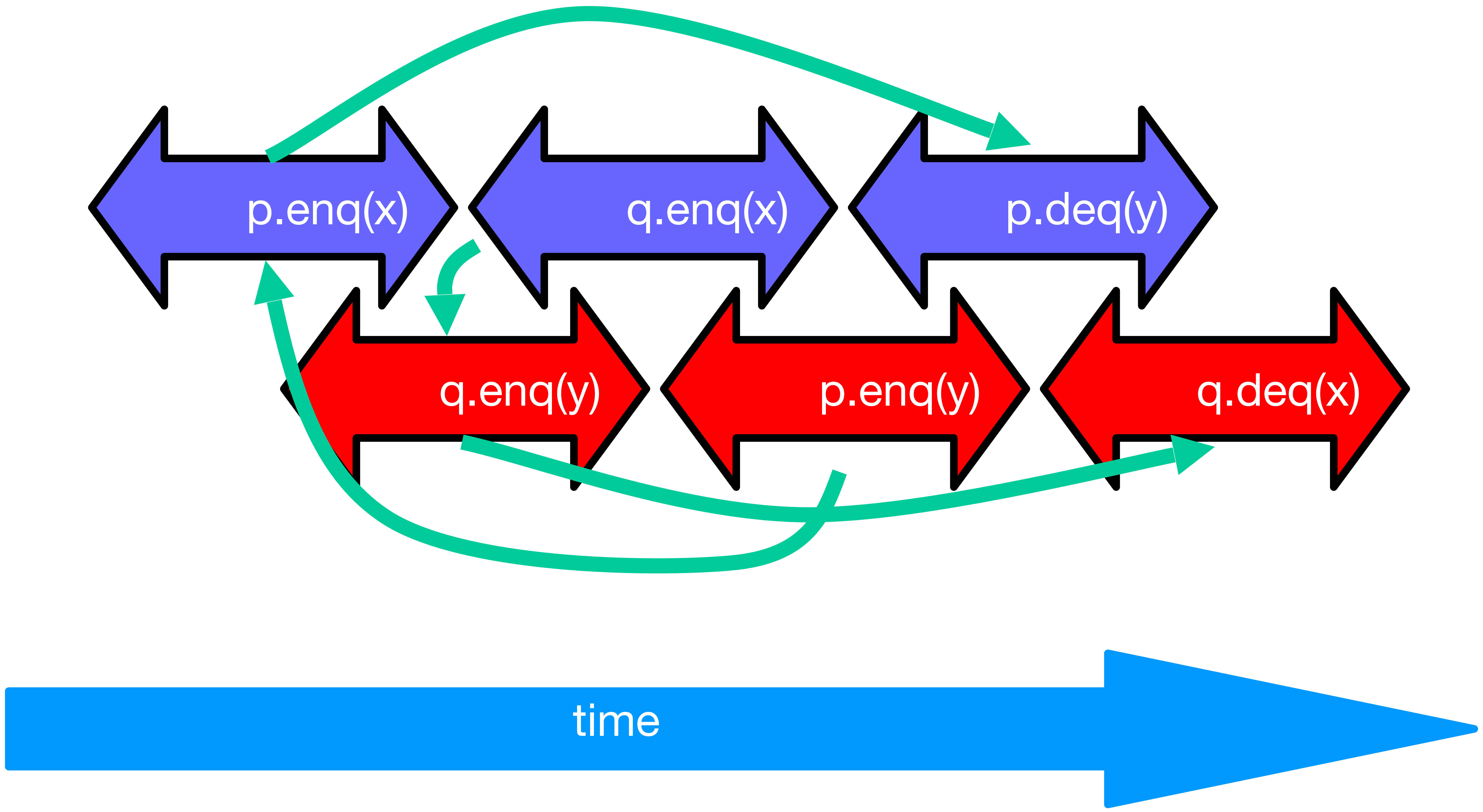
Ordering imposed by p



Ordering imposed by q

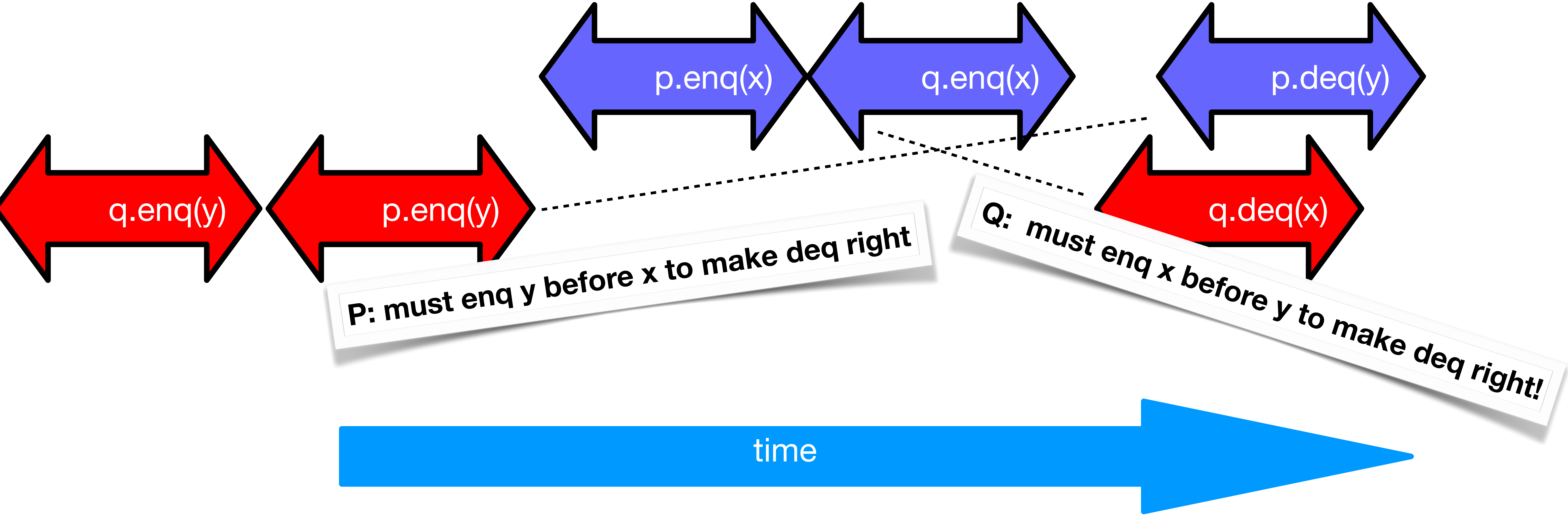


Ordering imposed by both



Sequentially Consistent Overall?

The only way to make this work is if these operations are reordered: but we can not reorder operations within a thread!



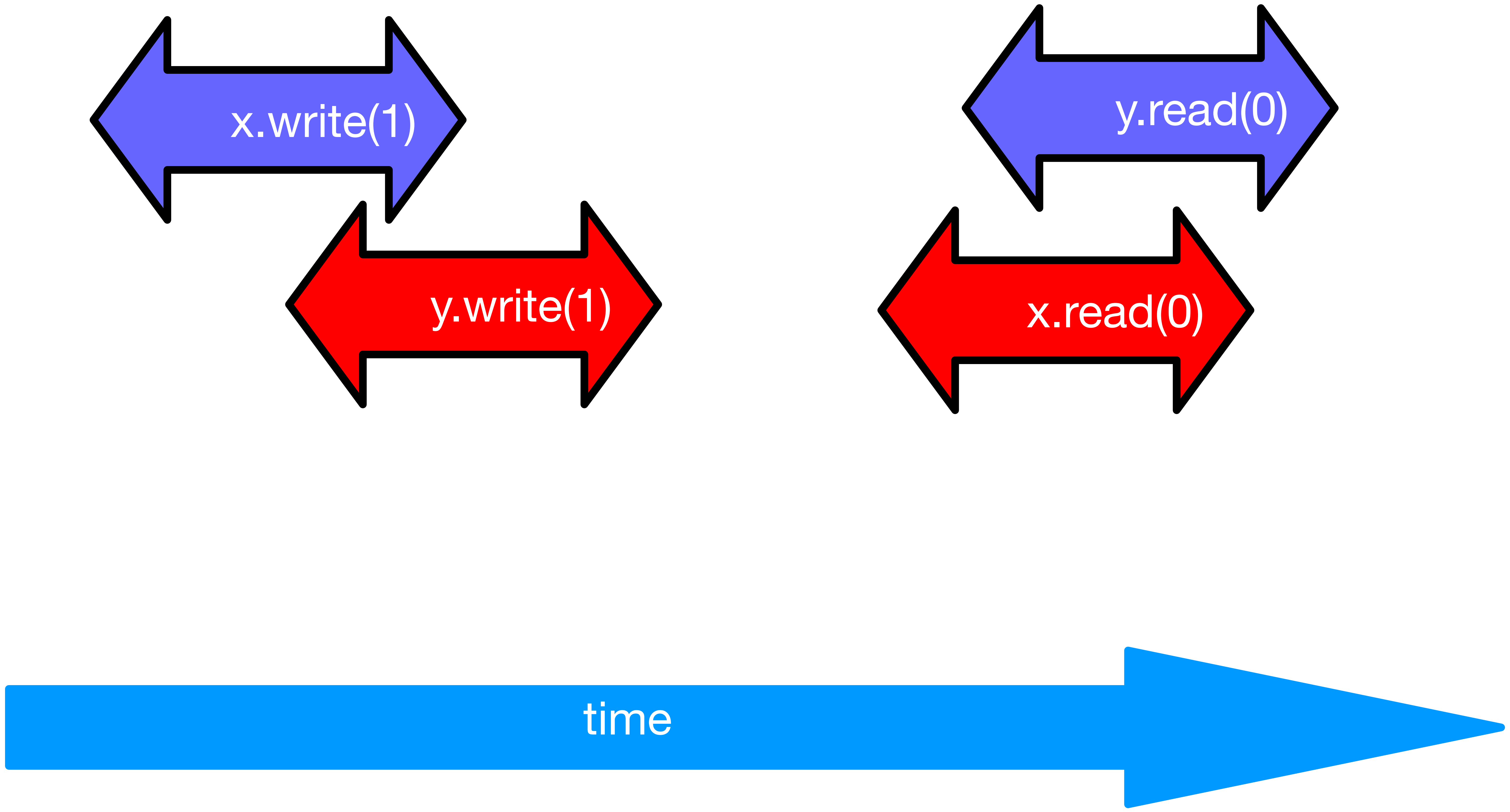
Sequential Consistency vs Linearizability

- Linearizability can be composed:
  - If p's execution and q's execution are both linearizable, then the combination must also be linearizable
- Sequential consistency can not be composed:
  - If p's execution and q's execution are both sequential, then the combination MAY also be sequential (but not guaranteed!)
- Why use sequential consistency?
  - Does not require global clock

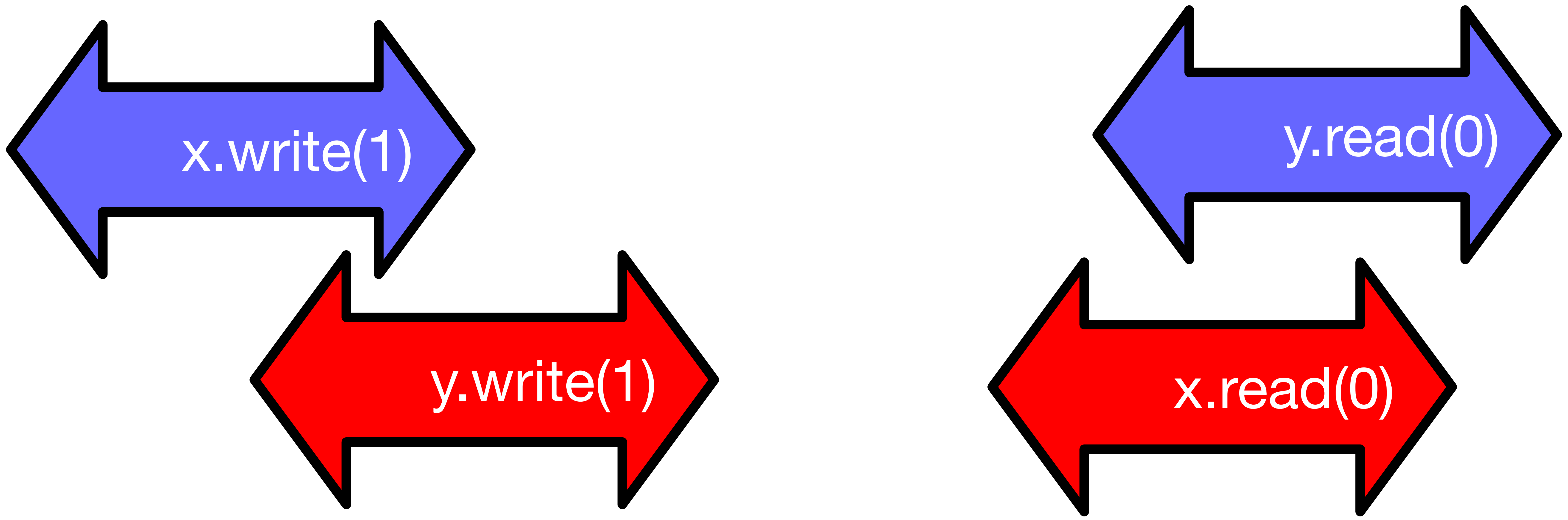
Sequential Consistency

- Even though it's easier to support than linearizability…
- Most hardware architectures don't support sequential consistency
- Because they think it's too strong
- Here's another story …

The Flag Example

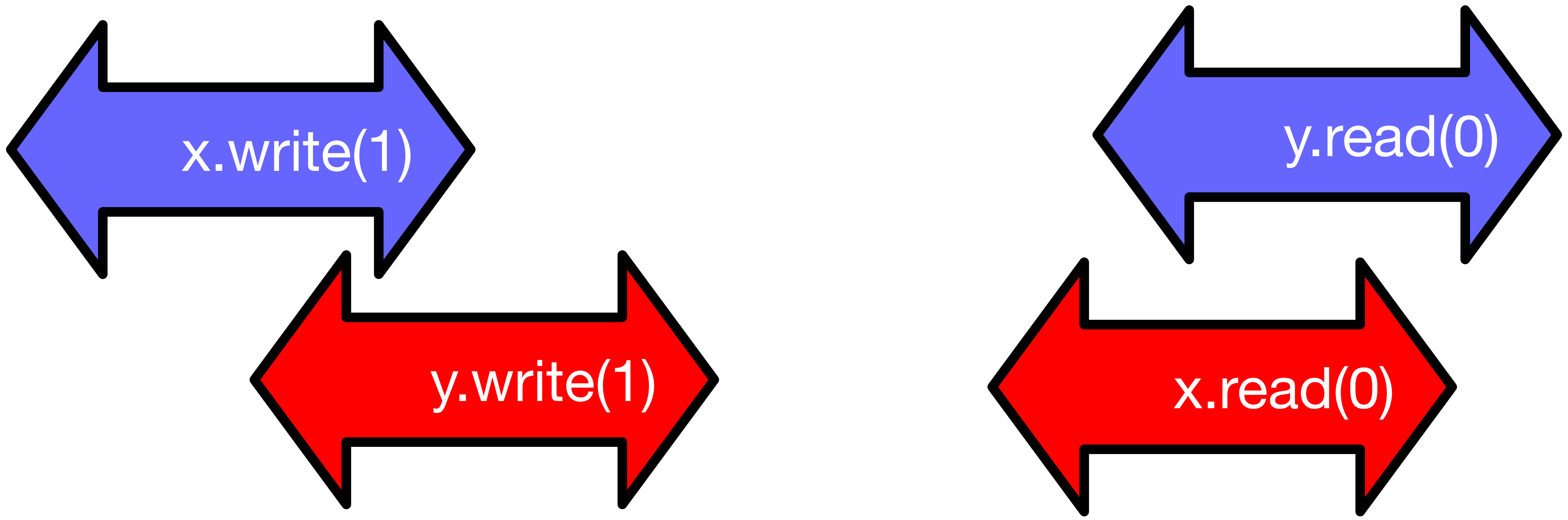


The Flag Example



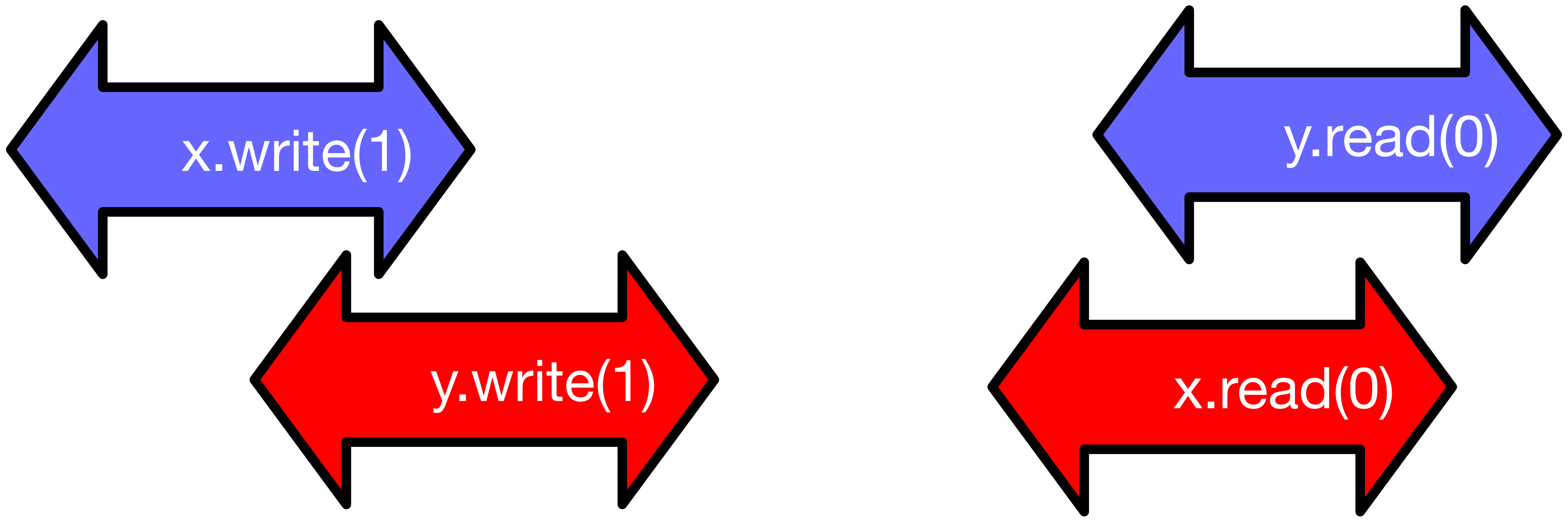
- Each thread's view is sequentially consistent
  - It went first

The Flag Example



- Entire history isn't sequentially consistent
  - Can't both go first

The Flag Example



- Is this behavior really so wrong?
  - We can argue either way …

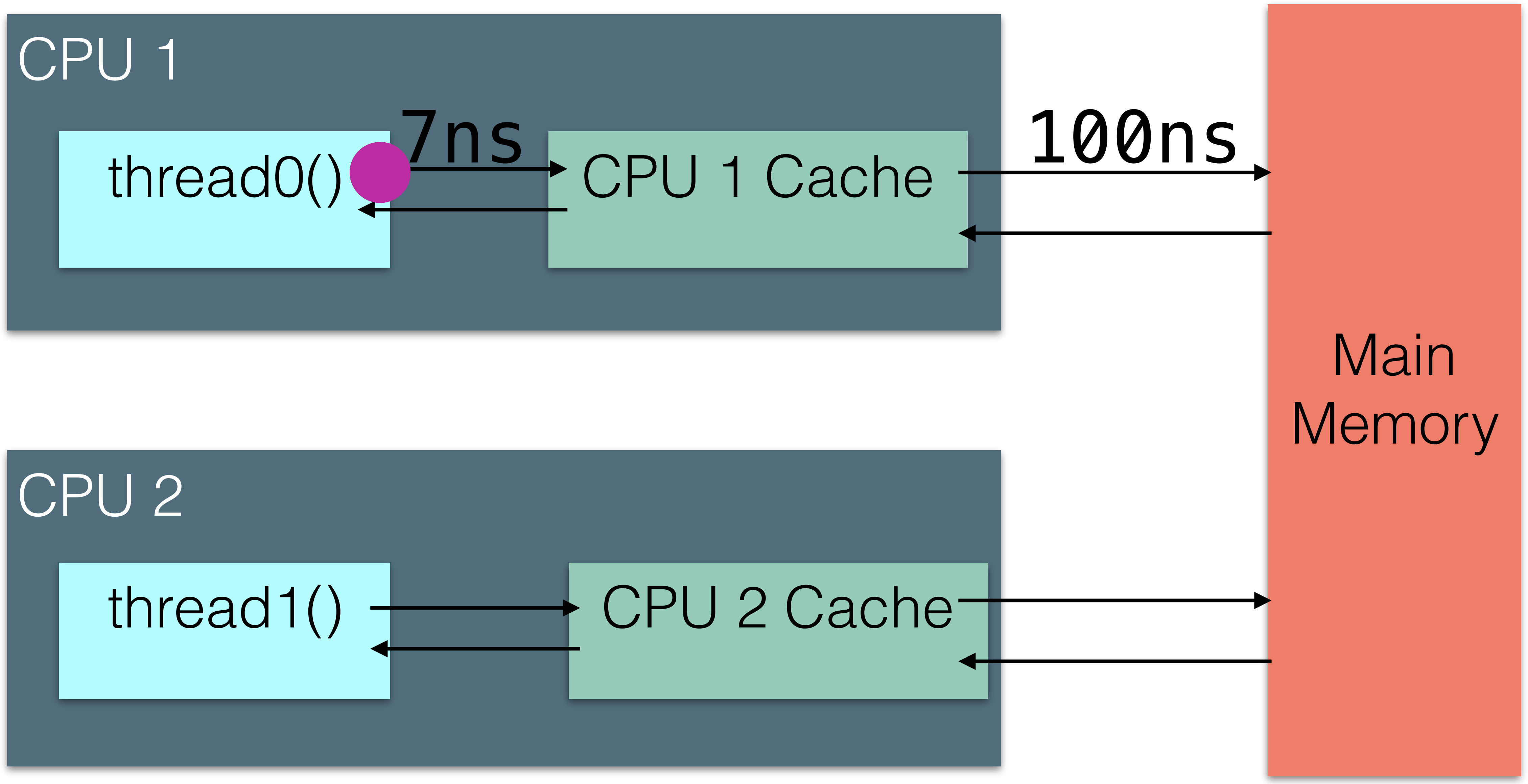
Opinion 1: It’s Wrong

- This pattern
  - Write mine, read yours
- Is exactly the flag principle
  - Beloved of Alice and Bob
  - Heart of mutual exclusion
    - We used this to implement our lock…
- It’s non-negotiable!

Opinion 2: But It Feels So Right …

- Many hardware architects think that sequential consistency is too strong
- Too expensive to implement in modern hardware
- OK if flag principle
  - violated by default
  - Honored by explicit request

Memory Operations are Slow



While Writing to Memory

- A processor can execute hundreds, or even thousands of instructions
- Why delay on every memory write?
- Instead, write back in parallel with rest of the program.

Revisionist History

- Flag violation history is actually OK
  - processors delay writing to memory
  - Until after reads have been issued.
- Otherwise unacceptable delay between read and write instructions.
- Who knew you wanted to share that variable?

Who knew you wanted to share the variable?

- Writing to memory = mailing a letter
- Vast majority of reads & writes
  - Not shared between CPUs
  - No need to idle waiting for post office
- If you want to make sure that there variable is shared
  - Announce it explicitly
  - Pay for it only when you need it
- Foreshadowing: Writing to network = mailing a letter to the moon

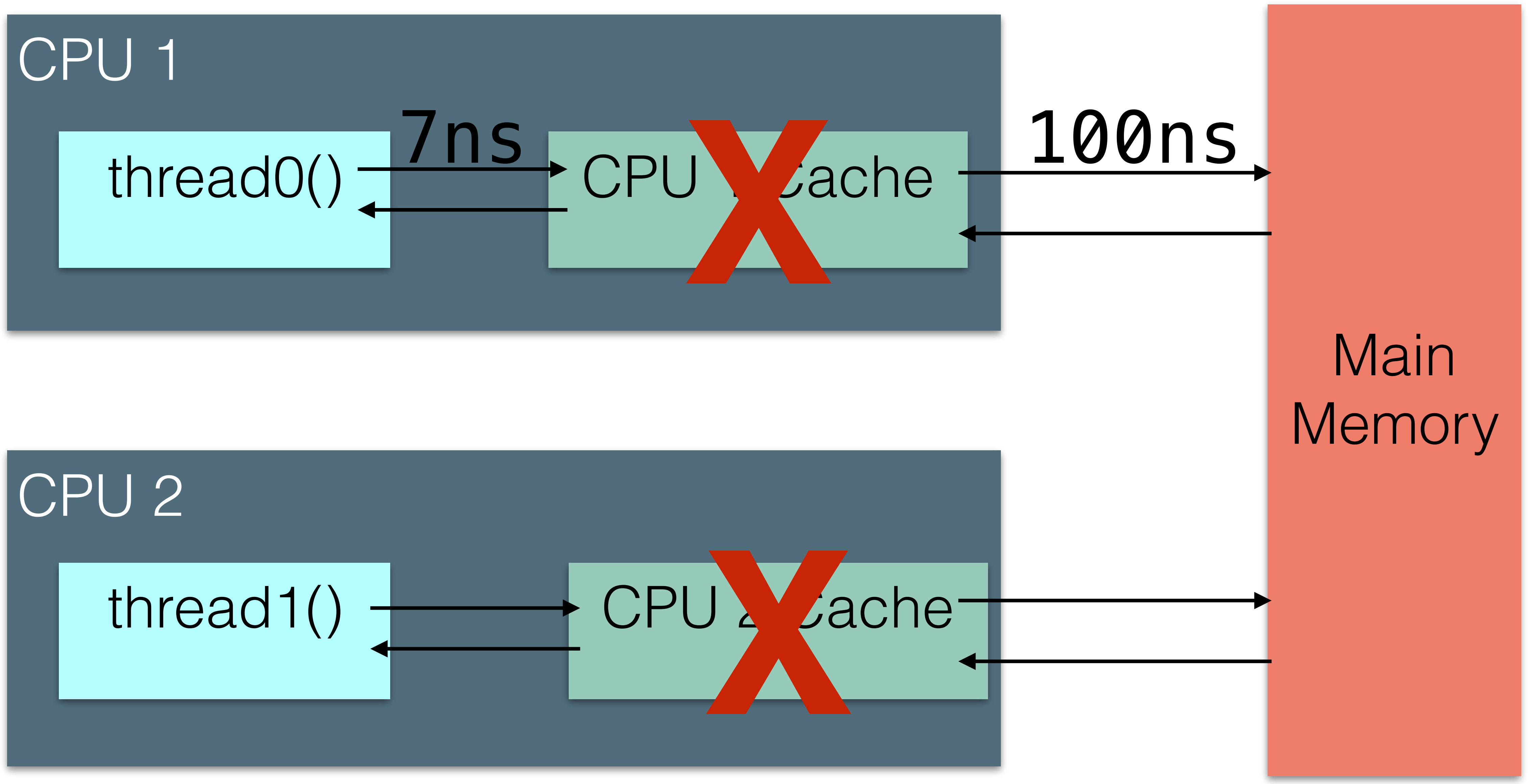
Explicitly Sharing Variables

- Memory barrier instruction
  - Flush unwritten caches
  - Bring caches up to date
- Compilers often do this for you
  - Entering and leaving critical sections
- Expensive

Volatile

- In Java, can ask compiler to keep a variable up-to-date with volatile keyword
- Also inhibits reordering, removing from loops, & other “optimizations”

Volatile Keyword



Linearizability, Sequential Consistency, Java, and Us

- What guarantees can we get, and how?
  - Different threads' access to the same variable is sequential -> volatile
  - Different threads' access to different variables is linear -> a lock around *every* read/write to those variables

Revisionist History

```
class Bouncer {
   public static final int DOWN = 0;
   public static final int RIGHT = 1;
   public static final int STOP = 2;
   private boolean goRight = false;
   private ThreadLocal<Integer> myIndex;
   private int last = -1;

   int visit() {
      int i = myIndex.get();
      last = i;
      if (goRight)
         return RIGHT;
      goRight = true;
      if (last == i)
         return STOP;
      else
         return DOWN;
   }
}
```

Without volatile, it would actually be possible for ALL threads to see STOP

Revisionist History

```
class Bouncer {
   public static final int DOWN = 0;
   public static final int RIGHT = 1;
   public static final int STOP = 2;
   private volatile boolean goRight = false;
   private ThreadLocal<Integer> myIndex;
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   int visit() {
      int i = myIndex.get();
      last = i;
      if (goRight)
         return RIGHT;
      goRight = true;
      if (last == i)
         return STOP;
      else
         return DOWN;
   }
}
```

Without volatile, it would actually be possible for ALL threads to see STOP

Synchronization beyond locks and flags

Return to the FIFO queue

- What if we want our lock based queue to be *bounded*
- Recall: what we did was use a lock around the enqueue and dequeue methods

```
mutex.lock()
try{
 queue.enq(x);
} finally{
 mutex.unlock();
}
```

- What happens if the queue is full?
  - Throw an exception?
  - Can't we make it wait until the queue has space?

Synchronized methods in Java

```
public synchronized static void increment()
{
    i = i + 1;
}
```

Result: Before entering `increment()`, thread gets a lock on the Class object of `increment()`

Synchronized methods in Java

```
public synchronized static void increment()
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Result: Before entering `increment()`, thread gets a lock on the Class object of `increment()`

```
public synchronized static void incrementOther()
{
    j = j + 1;
}
```

Result: Before entering `incrementOther()`, thread gets a lock on the Class object of `incrementOther()`

Problem?

Synchronized blocks in Java

- Can also use *any* object as that monitor

```
static Object someObject = new Object();
public static void increment()
{
    synchronized(someObject){
        i = i + 1;
    }
}
static Object someOtherObject = new Object();
public static void incrementOther()
{
    synchronized(someOtherObject){
        j = j + 1;
    }
}
```

Now, two different threads could call `increment()` and `incrementOther()` at the same time

wait and notify()

- Two mechanisms to enable coordination between multiple threads using the same monitor (target of synchronized)
- While holding a monitor on an object, a thread can **wait** on that monitor, which will temporarily release it, and put that thread to sleep
- Another thread can then acquire the monitor, and can **notify** a waiting thread to resume and re-acquire the monitor

wait and notify() example

Only one thread can be in put or take of the same queue

```
public class BlockingQueue<T> {

    private Queue<T> queue = new LinkedList<T>();
    private int capacity;

    public BlockingQueue(int capacity) {
        this.capacity = capacity;
    }

    public synchronized void put(T element) throws InterruptedException {
        while(queue.size() == capacity) {
            wait();
        }

        queue.add(element);
        notify(); // notifyAll() for multiple producer/consumer threads
    }

    public synchronized T take() throws InterruptedException {
        while(queue.isEmpty()) {
            wait();
        }

        T item = queue.remove();
        notify(); // notifyAll() for multiple producer/consumer threads
        return item;
    }
}
```

Java Lock API

- `Synchronized` gets messy: what happens when you need to synchronize many operations? What if we want more complicated locking?
- `ReentrantLock`: same semantics as synchronized, also supports `conditions`…

```
static ReentrantLock lock = new ReentrantLock();
public static void increment()
{
    lock.lock();
    try{
        i = i + 1;
    } finally{
        lock.unlock();
    }
}
```

Conditions

- When a thread is waiting for something to happen, it might want to release the lock and be notified when that thing has happened
  - Ex: while queue is full, release the lock to let someone else empty it
- This is what a *condition* does
- Key methods: *await*, *signal*

```
Condition condition = lock.newCondition();
lock.lock();
try{
   while(!property)
      condition.await();
}catch(InterruptedException e){
   //Application-dependent response, property may still be false
}
//at this point, property must be true and we have the lock again
```

```
condition.signal(); //wake up one thread await'ing
condition.signalAll(); //wake up all threads await'ing
```

Conditions

- An awakened thread must:
  - try to reclaim the lock;
  - when this has happened, retest the property it is waiting for;
  - if the property doesn't hold, release the lock by calling await().
- wrong: `if “boolean expression” condition.await()`
- correct: `while “boolean expression” condition.await()`

Monitors

- Java's **synchronized** keyword creates a *monitor*, which is both a lock and a condition variable
- Three relevant methods that have been there all along, and you may not have known what for:
  - object.notify();
  - object.notifyAll();
  - object.wait();

Non-mutual exclusion locks

- The strict mutual exclusion property of locks is often relaxed. Three examples are:
  - Readers-writers lock: Allows concurrent readers,
    while a writer disallows concurrent readers and writers.
  - Reentrant lock: Allows a thread to acquire the same lock multiple times, to avoid deadlock (we have mostly used reentrant locks)
  - Semaphore: Allows at most c concurrent threads in their critical section, for some given capacity c.

Readers and Writers Problem

- Commonly called a read-write lock: data can be read by an unlimited number of threads at a time, written by at most one
- If a thread wants to write, nobody else can be reading (Alice + Bob with the billboards)
- High level approach:
  - Build on top of mutual exclusion locks with condition variables

Readers and Writers Lock

```java
class ReadLock implements Lock{
   public void lock()
   {
      lock.lock();
      try{
         while(writer){
            condition.await();
         }
        readers++;
      } finally {
         lock.unlock();
      }
   }

   @Override
   public void unlock() {
      lock.lock();
      try{
         readers--;
         if(readers == 0)
            condition.signalAll();
      } finally{
         lock.unlock();
      }
   }
}
```

```java
class WriteLock implements Lock{
   public void lock(){
      lock.lock();
      try{
         while(readers > 0 || writer)
            condition.await();
         writer =true;

      } finally{
         lock.unlock();
      }
   }

   @Override
   public void unlock() {
      writer = false;
      condition.signalAll();
   }
}
```

Readers and Writers Lock

- Note: not fair - many readers can prevent a single writer from getting in
- A fair solution is outlined in the textbook

Where we go next

- How should we apply these different locking primitives?
- HW1 due on Weds