03 Concurrent Objects

CS 6868: Concurrent Programming

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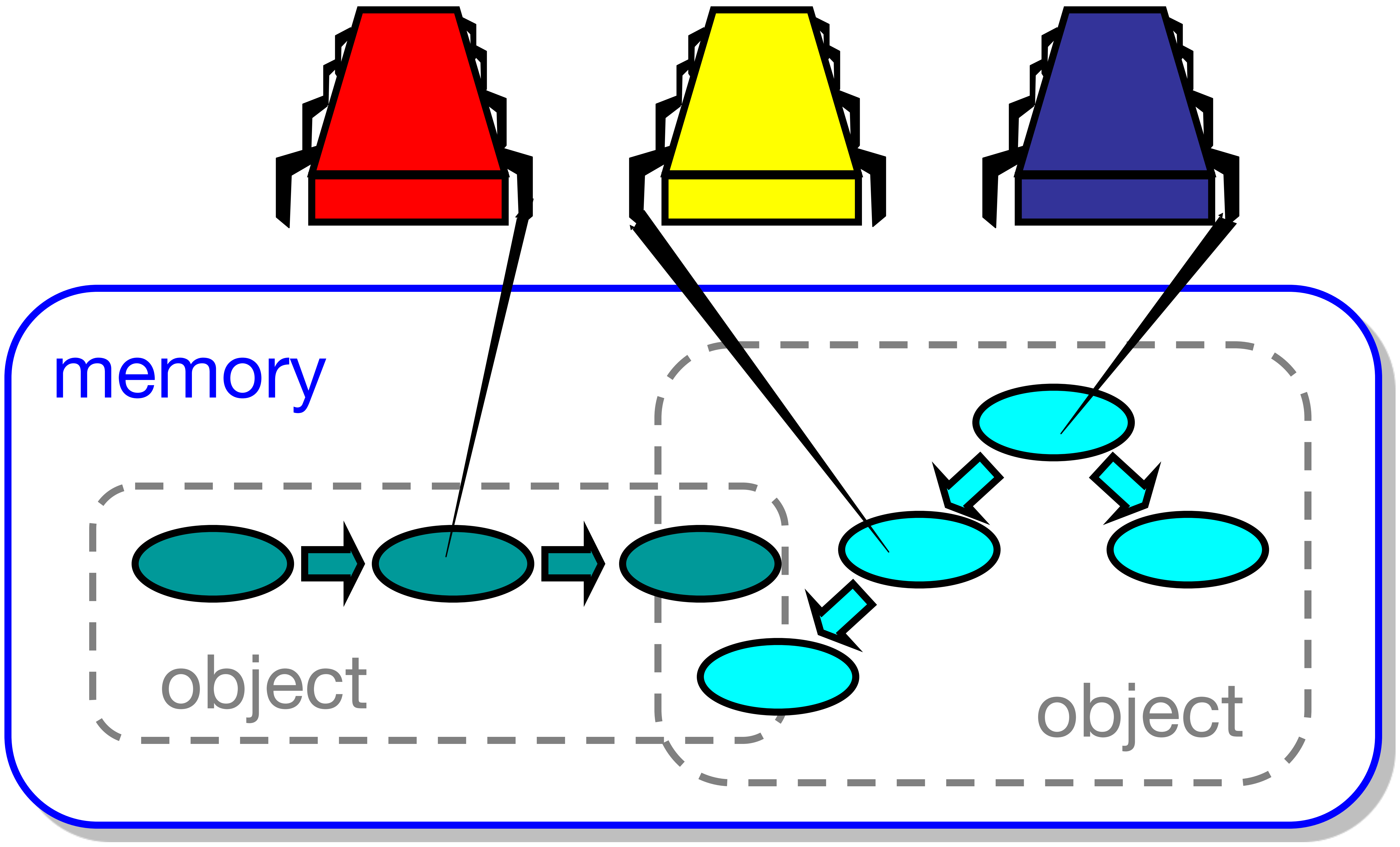
Concurrent Computation



Objectivism

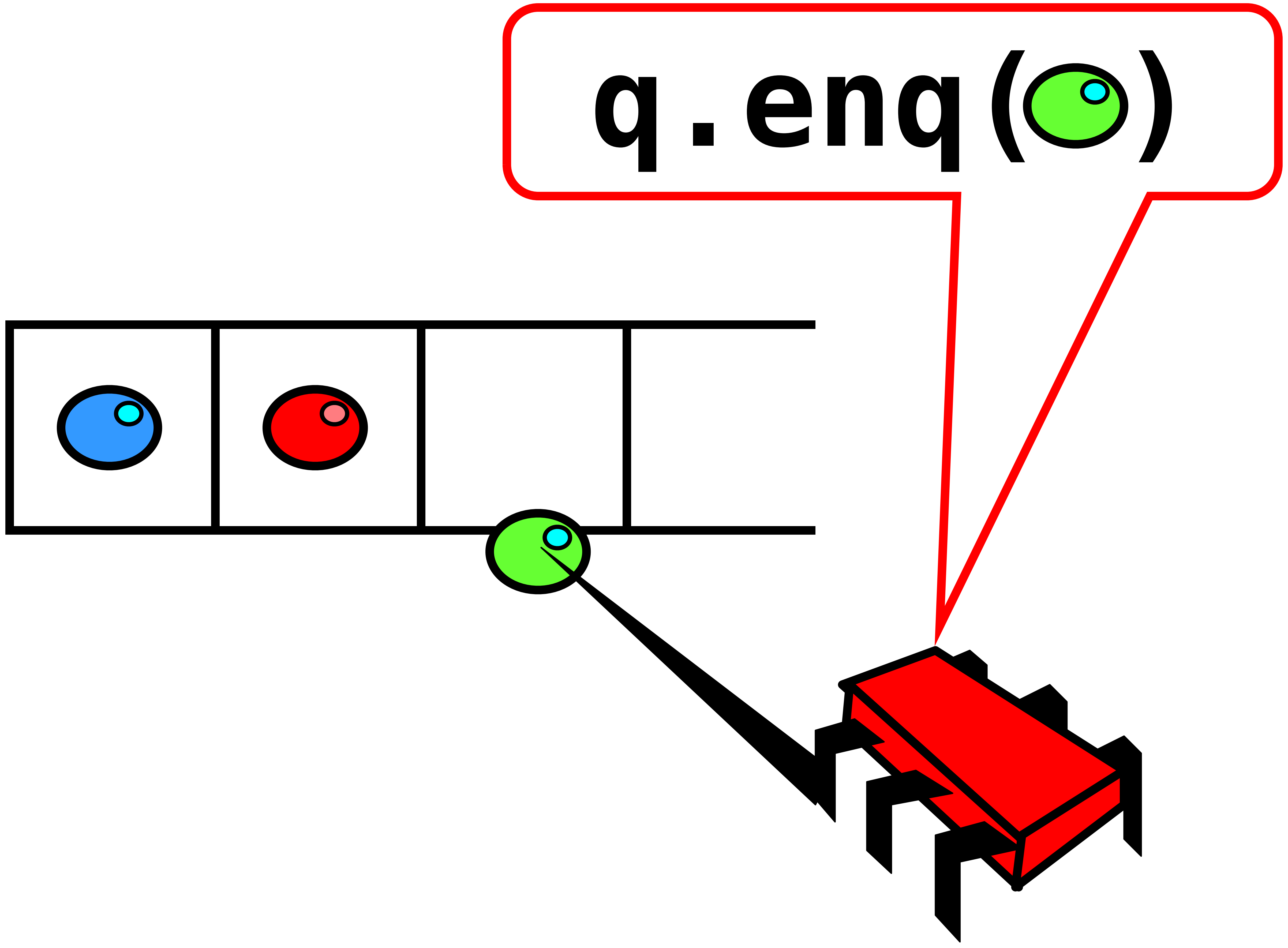
- What is a concurrent object?
  - How do we ***describe*** one?
  - How do we ***implement*** one?
  - How do we ***tell if we're right***?

Objectivism

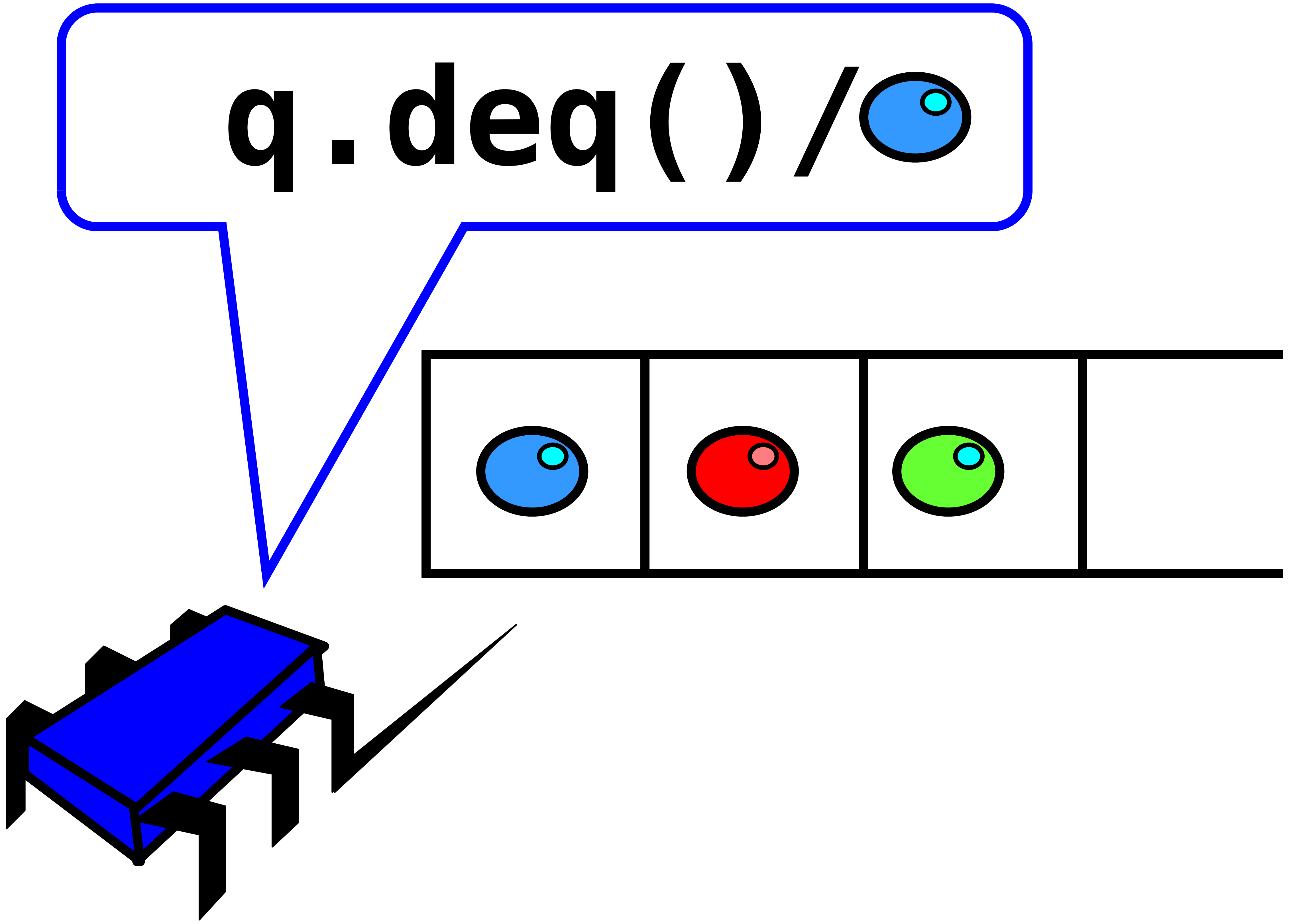
- What is a concurrent object?
  - How do we ***describe*** one?
  - ~~How do we ***implement*** one?~~
  - How do we ***tell if we're right***?

Concurrent Queues

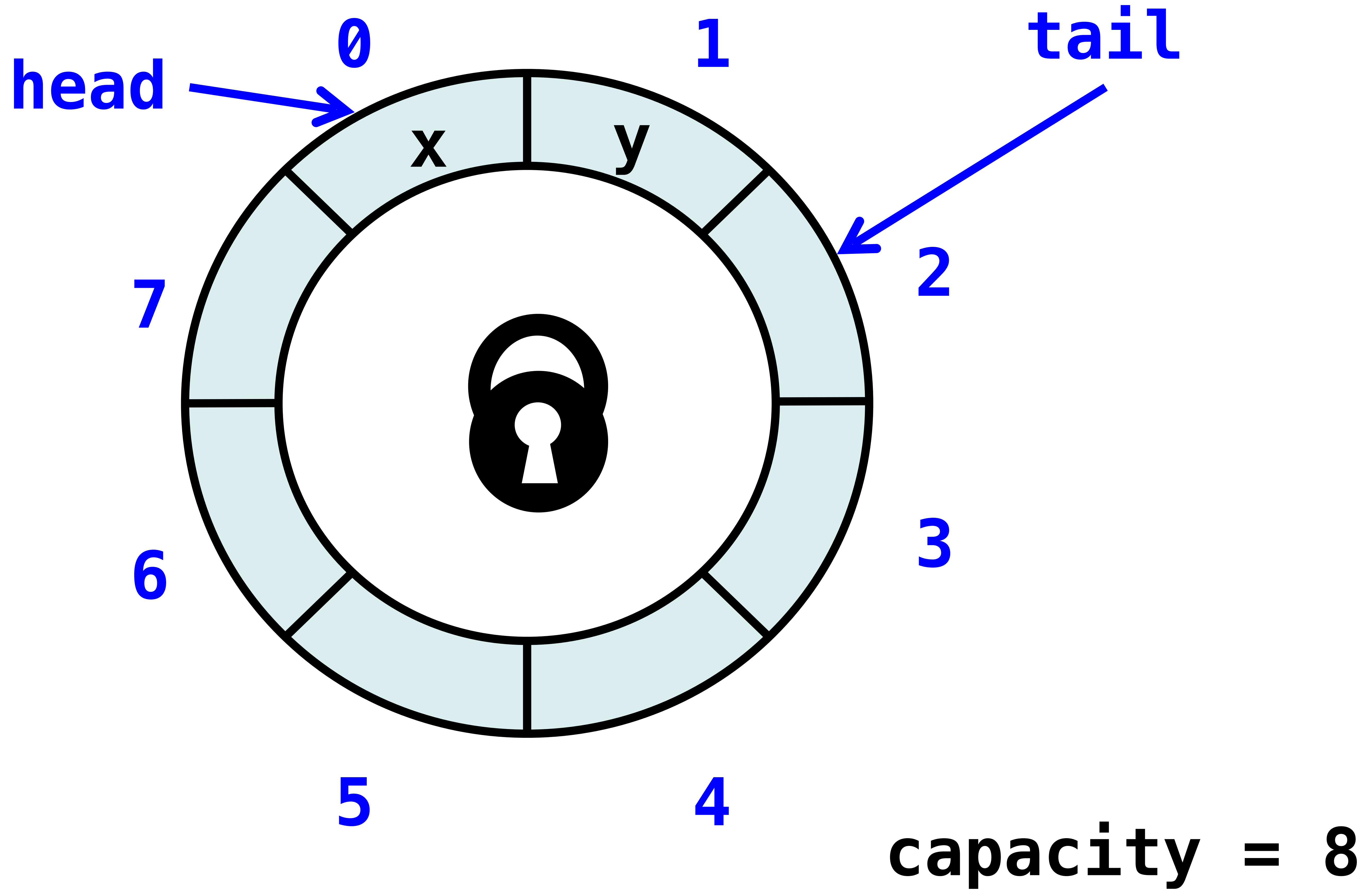
FIFO Queue — Enqeue method



FIFO Queue — Dequeue method



Lock-based Queue



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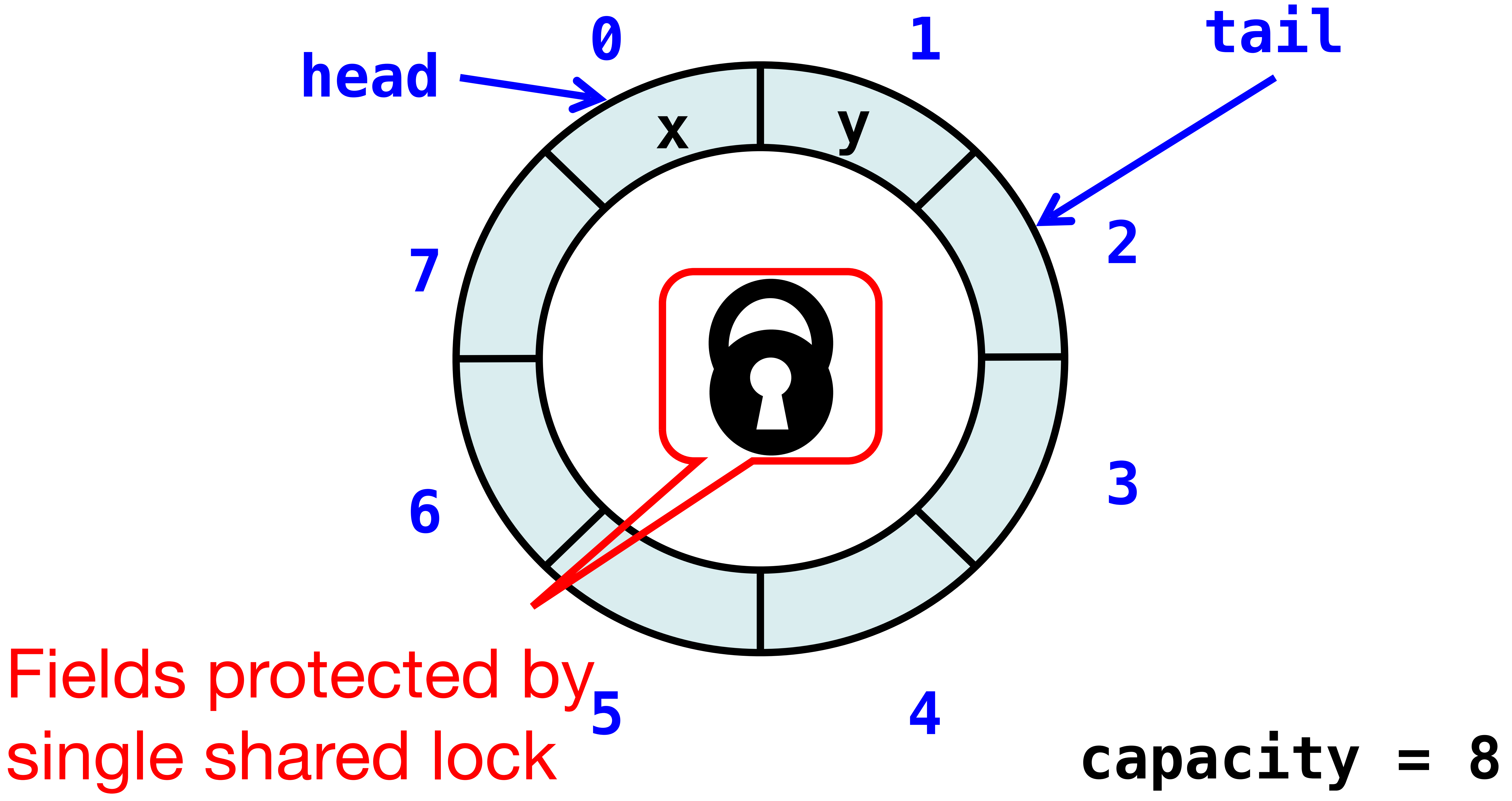
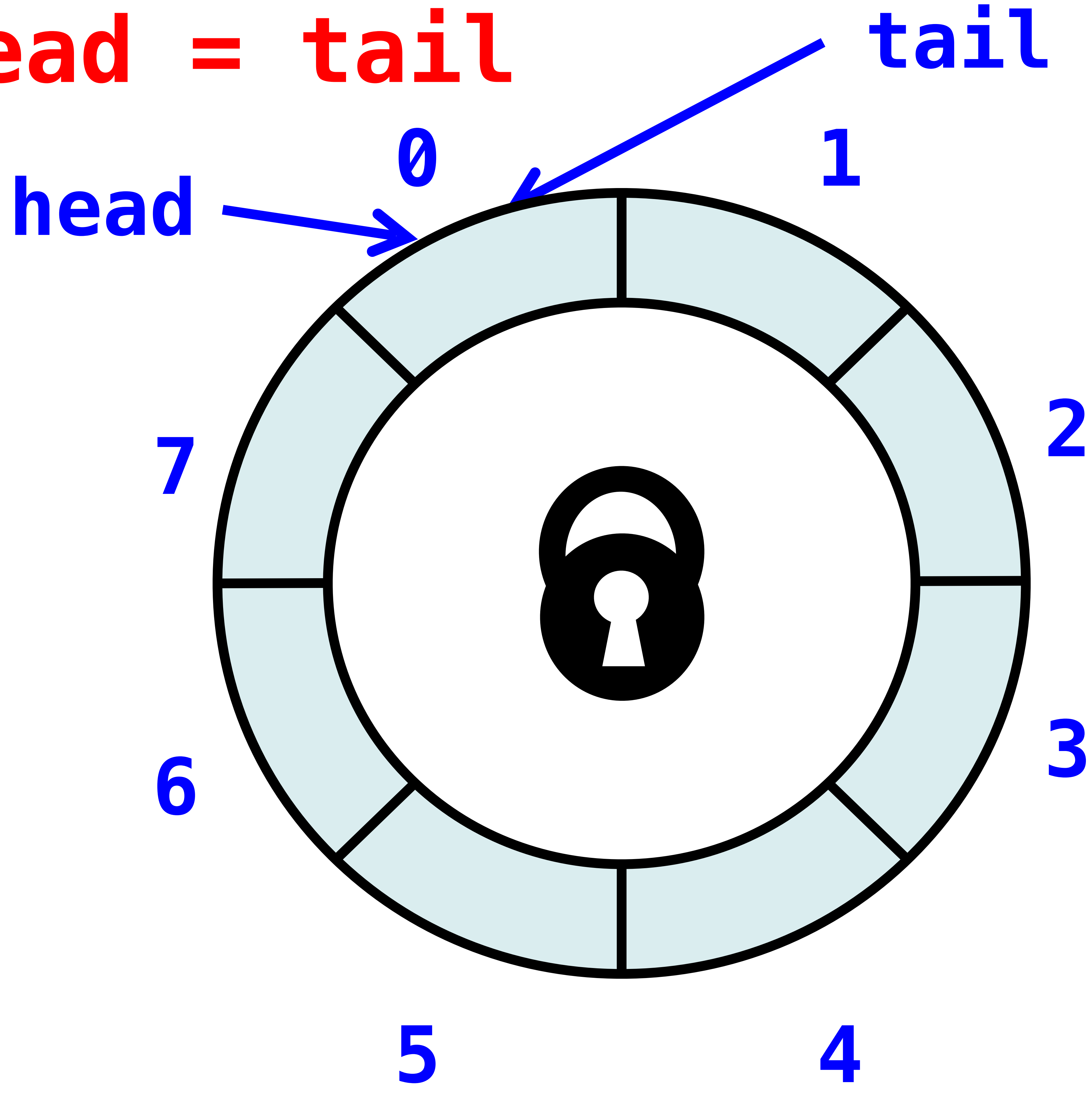


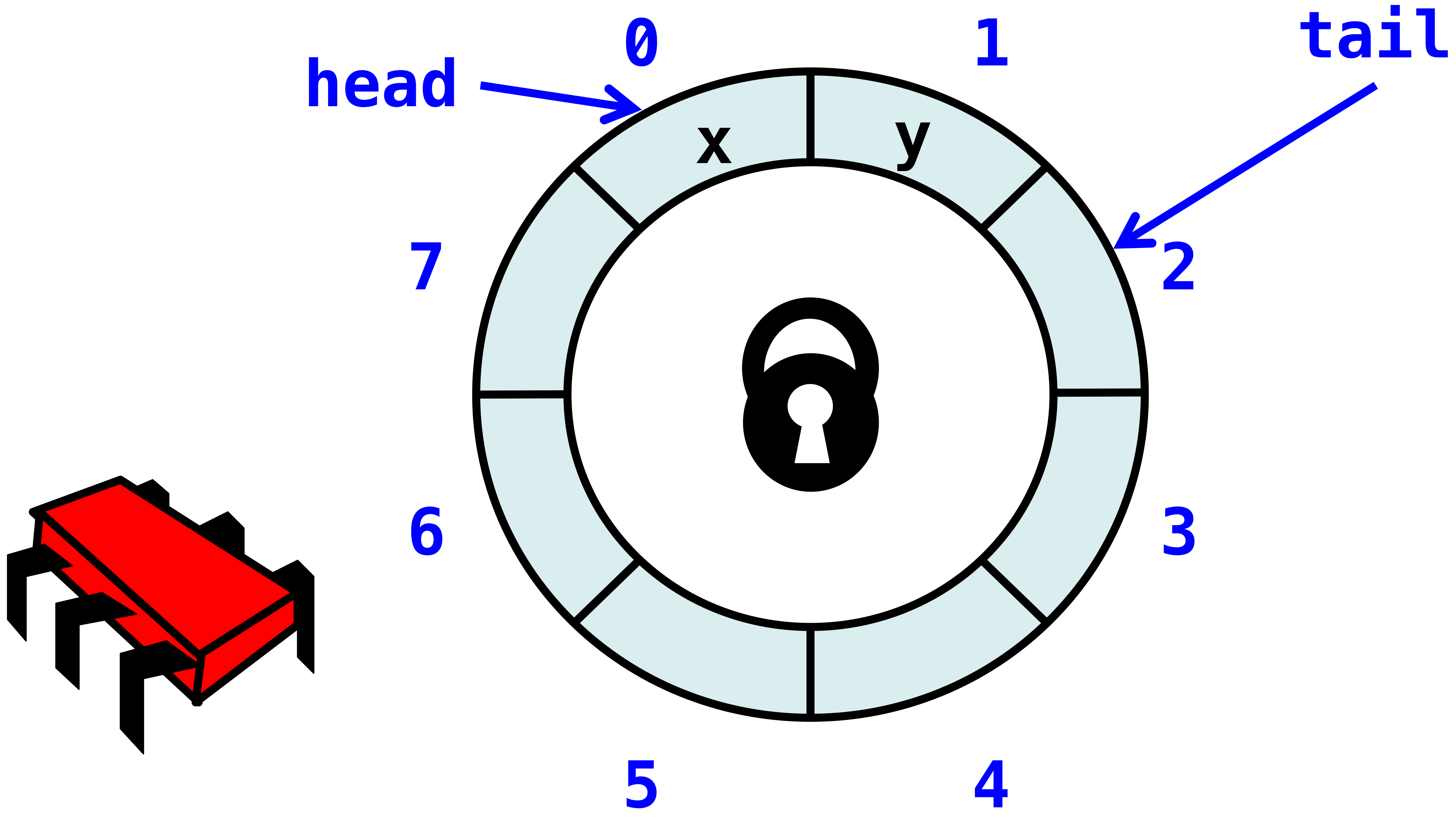
Lock-based Queue

```
exception Full
exception Empty

type 'a t = {
  items : 'a option array;
  capacity : int;
  mutable head : int;
  mutable tail : int;
  lock : Mutex.t;
}

let create capacity =
  {
    items = Array.make capacity None;
    capacity;
    head = 0;
    tail = 0;
    lock = Mutex.create ();
  }
```

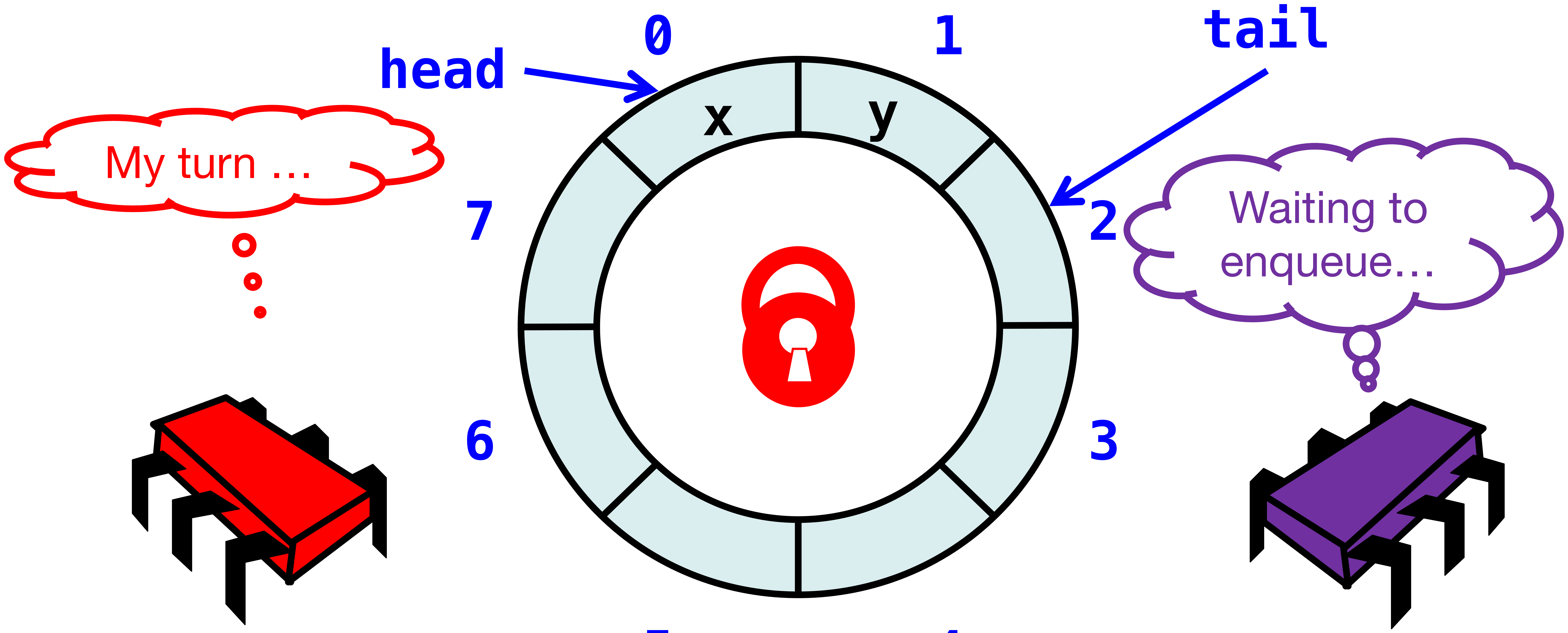
Initially: **head = tail**



Lock-based Queue — deq( ) operation



Acquire Lock

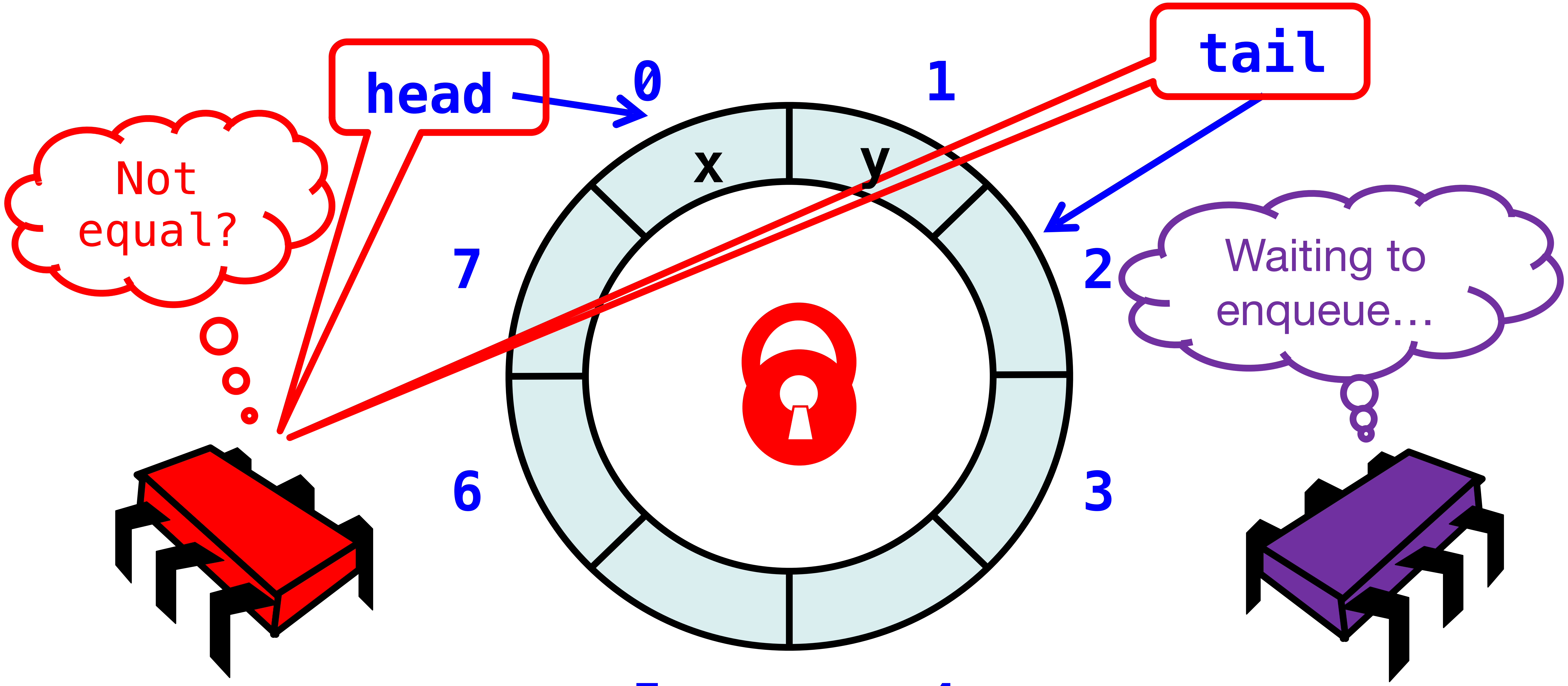


Acquire Lock

```
let deq q =
  Mutex.lock q.lock;
  try
    if q.tail = q.head then
      raise Empty;
    match q.items.(q.head mod q.capacity) with
    | None -> assert false
    | Some x ->
        q.head <- q.head + 1;
        Mutex.unlock q.lock;
        x
  with e ->
    Mutex.unlock q.lock;
    raise e
```

Acquire lock at method start

Check if non empty



Check if non empty

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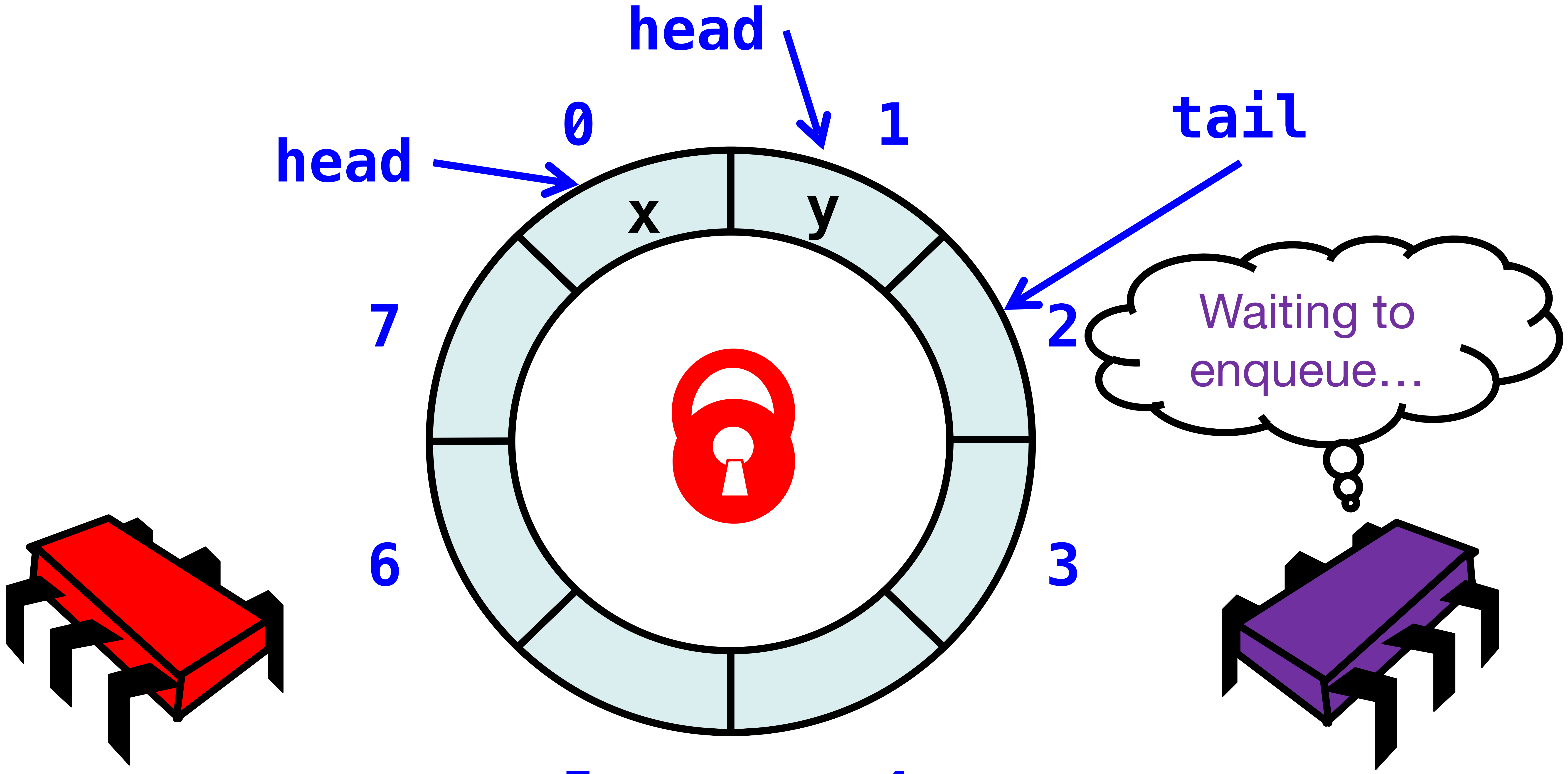
```

If queue empty throw exception

In case of exceptions, lock released here

Modify the queue



Modify the queue

```
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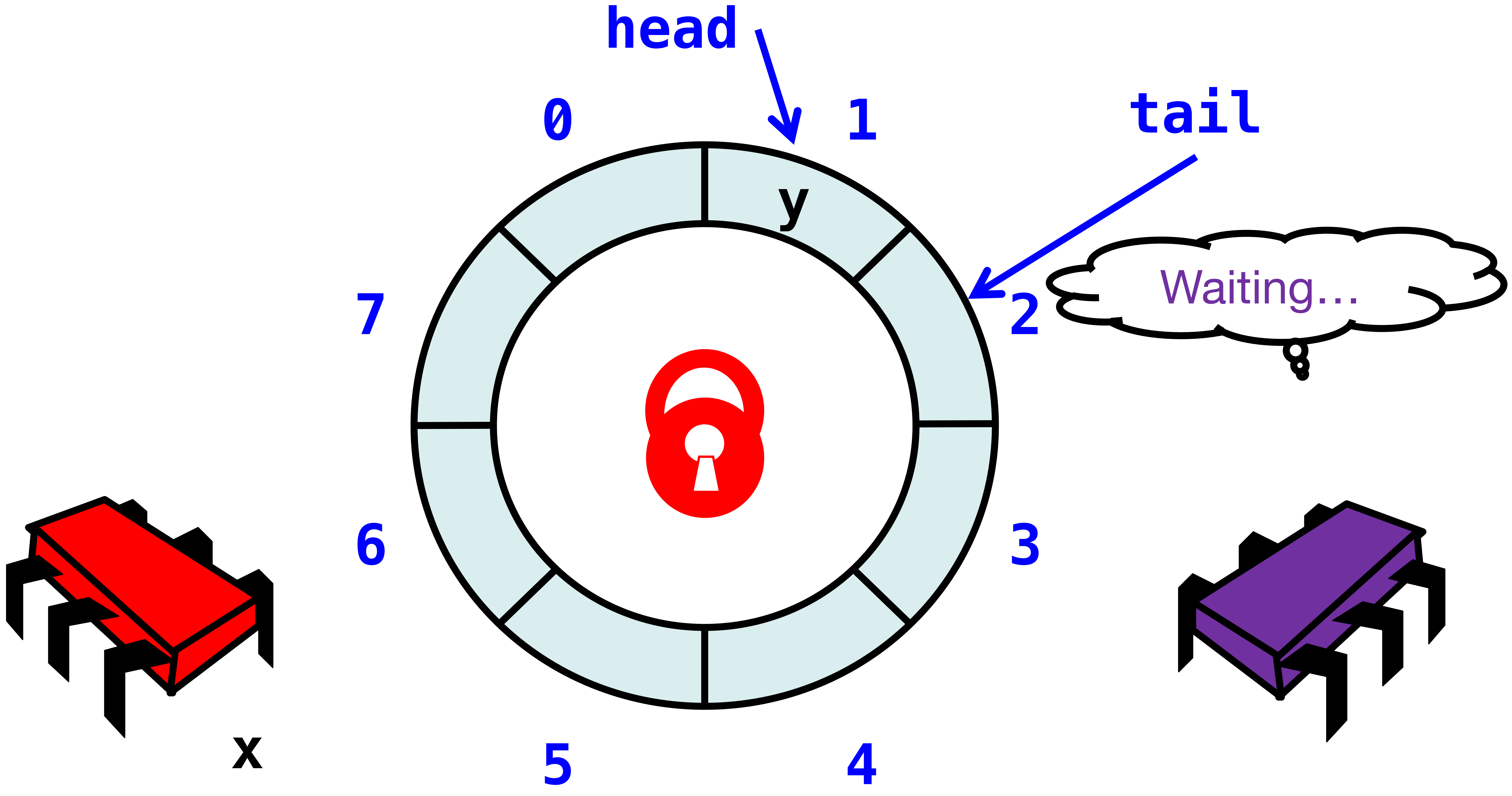
```

Queue not empty?
Remove item “x” and update head

Release the lock and return item



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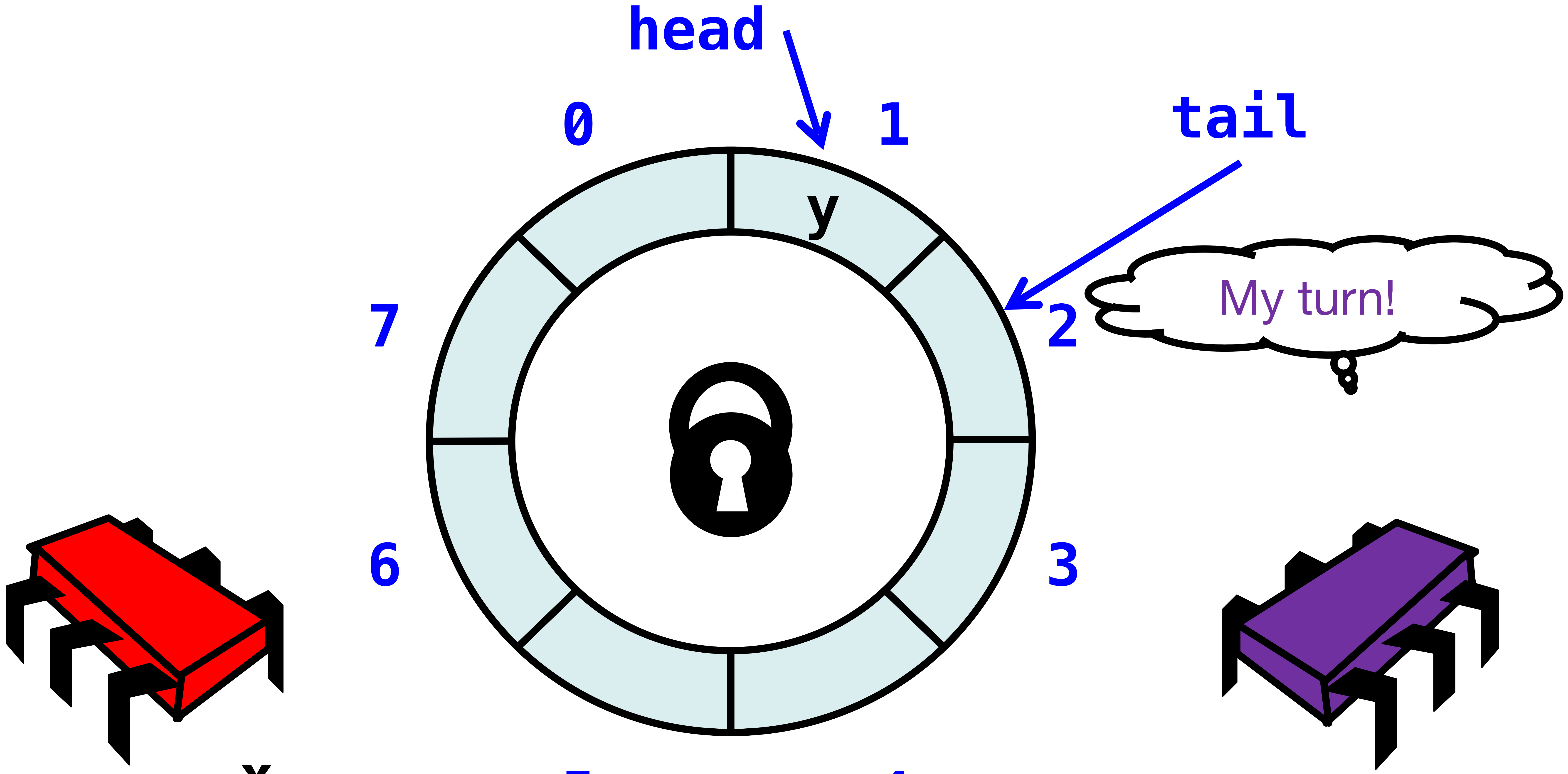

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```

Unlock and return item “x”

Implementation — deq()

```
let deq q =
  Mutex.lock q.lock;
  try
    if q.tail = q.head then
      raise Empty;
    match q.items.(q.head mod q.capacity) with
    | None -> assert false
    | Some x ->
        q.head <- q.head + 1;
        Mutex.unlock q.lock;
        x
  with e ->
    Mutex.unlock q.lock;
    raise e
```

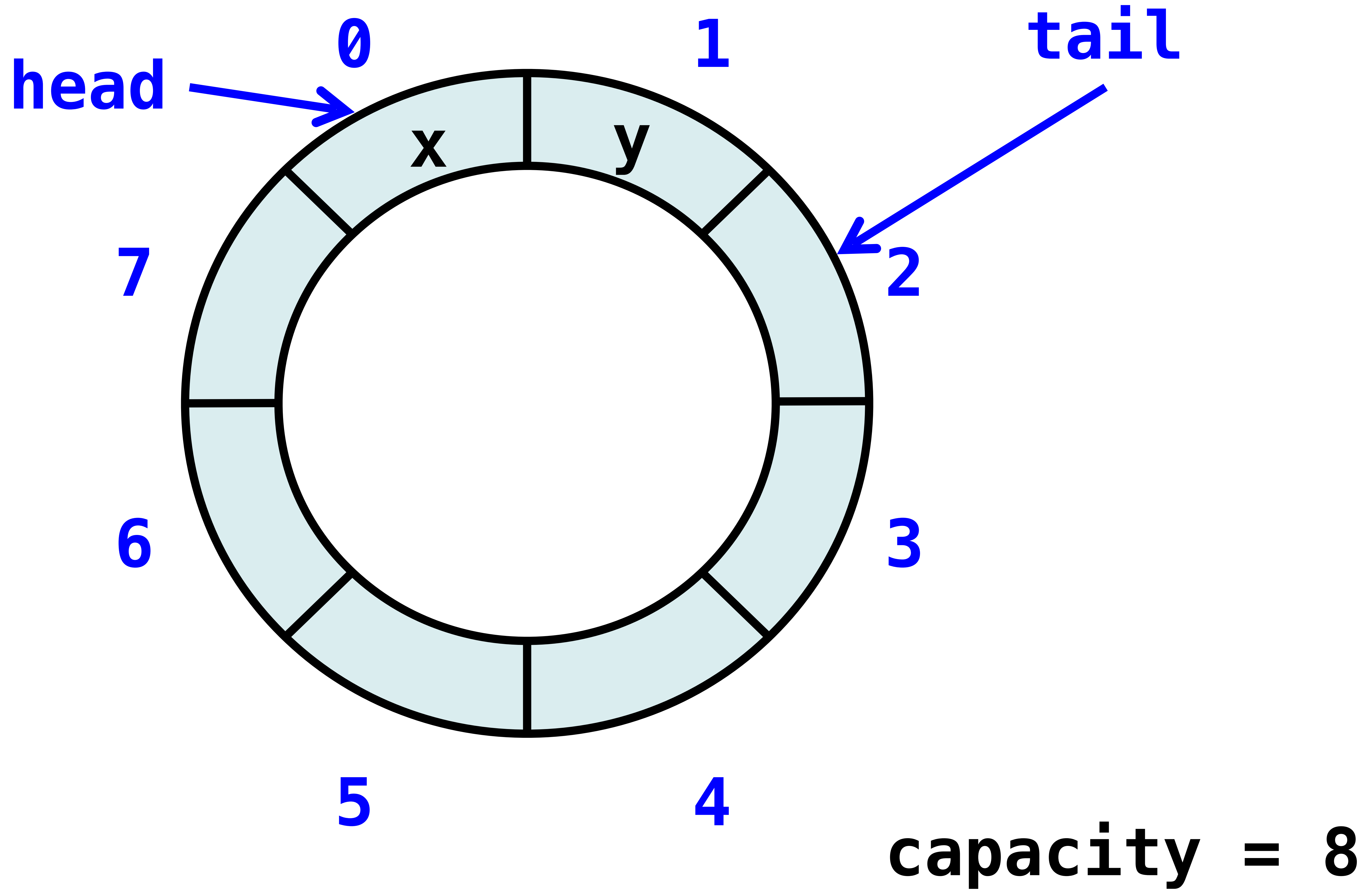
Should be correct because modifications are mutually exclusive…

Demo

Consider the following implementation

- The same thing without mutual exclusion
- For simplicity, only ***two*** threads
  - One thread enq only
  - The other deq only

Wait-free 2-thread queue



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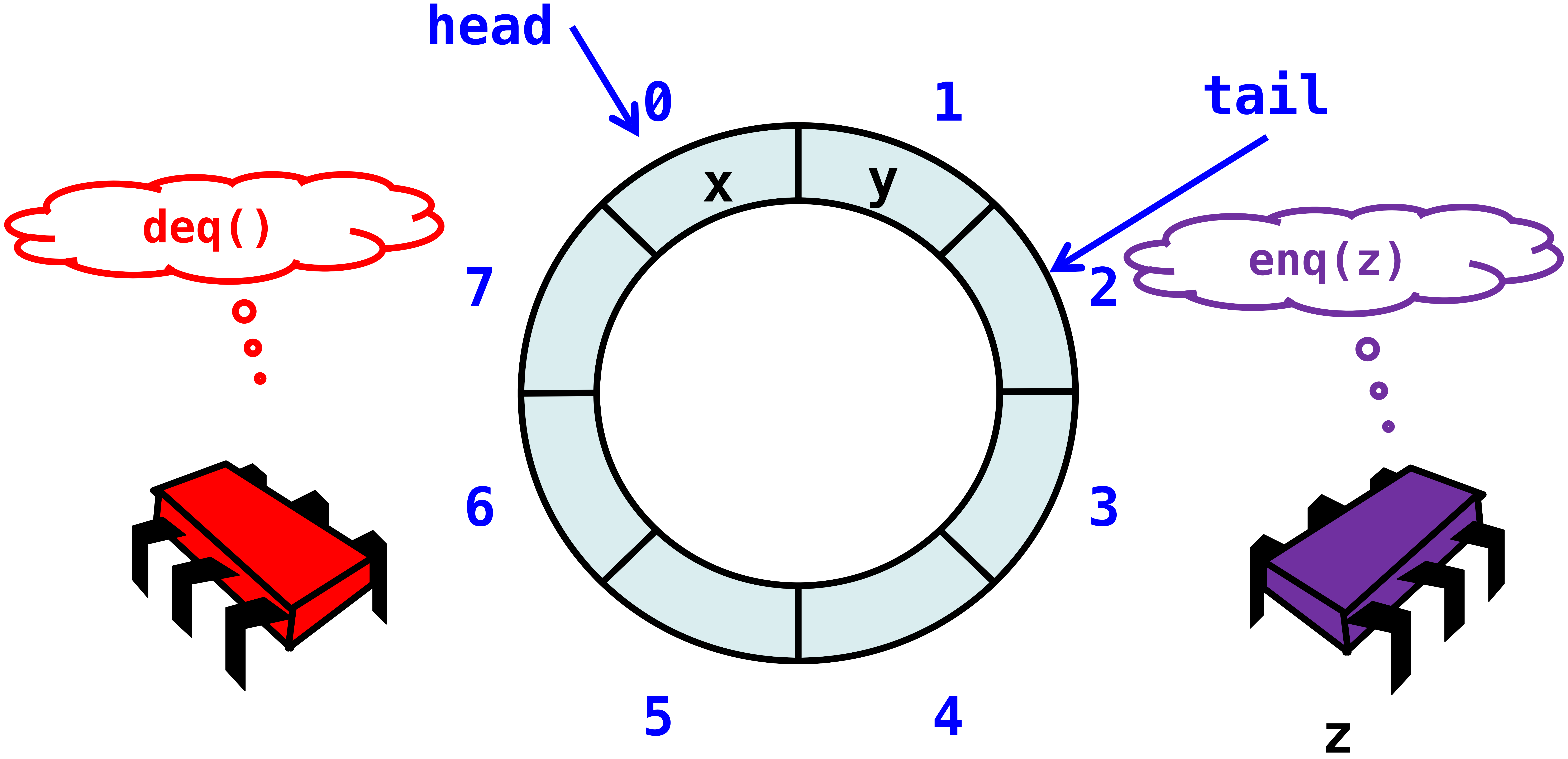
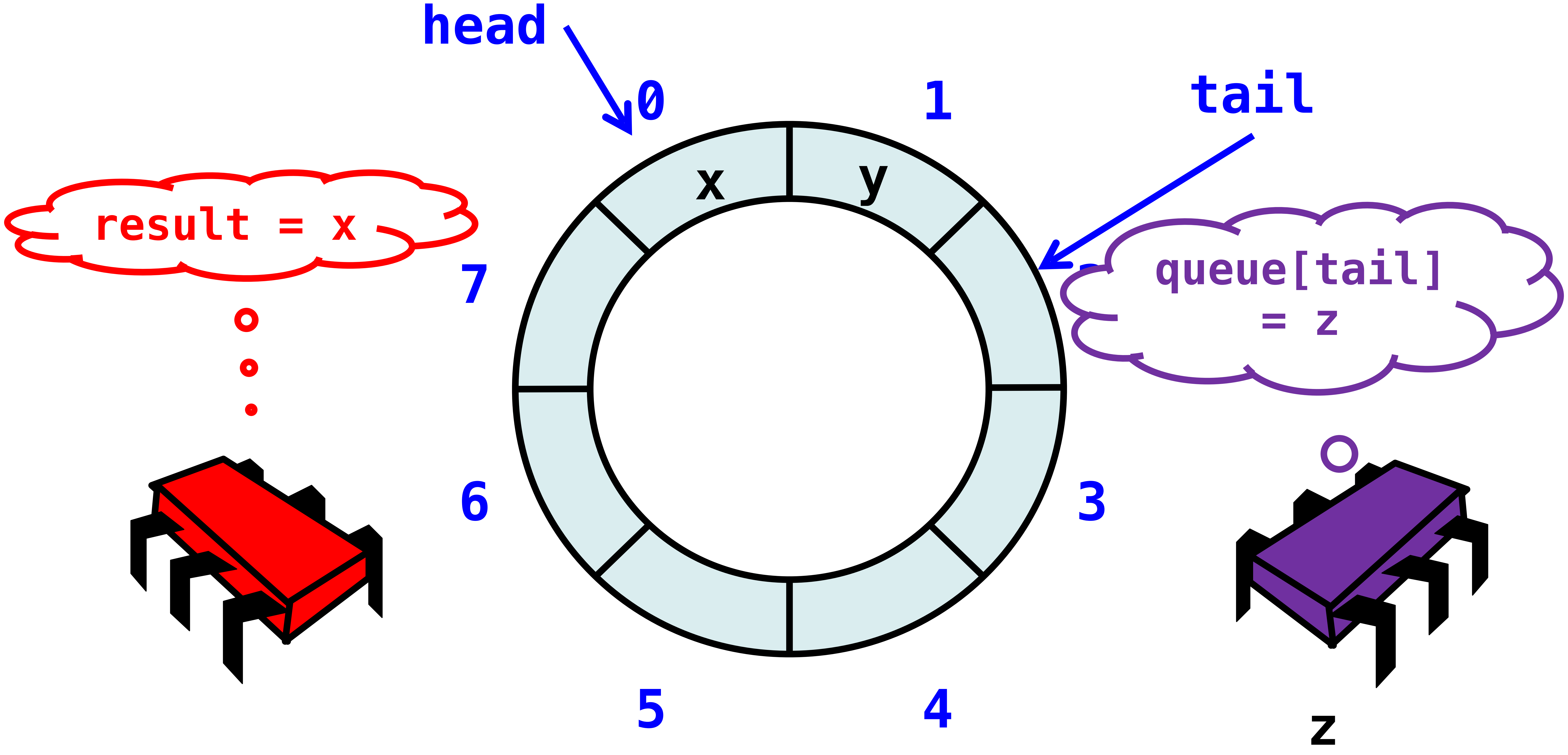


Wait-free 2-thread queue



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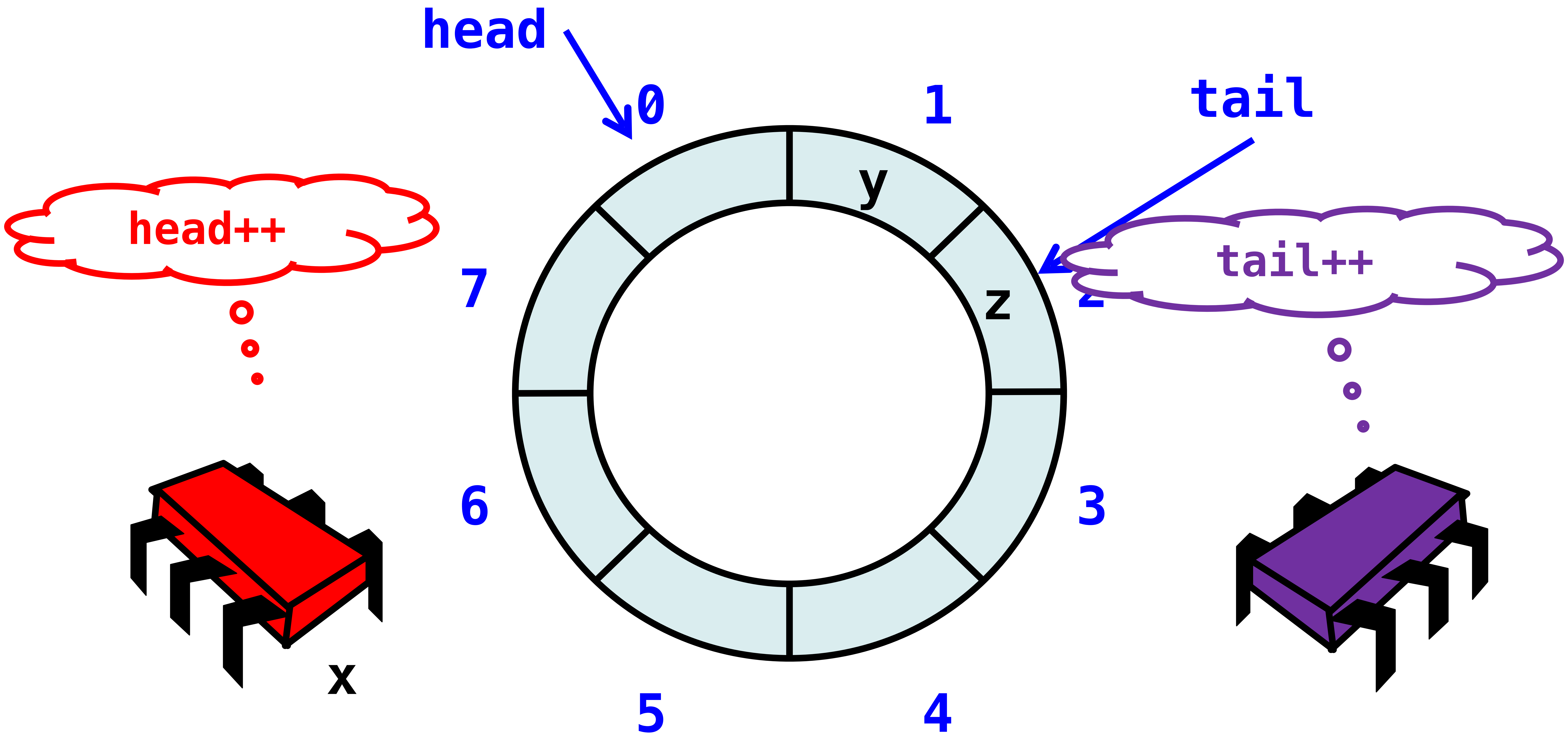


Wait-free 2-thread queue

No locks needed!

```
(** Enqueue – should be called by only ONE thread *)
let enq q x =
  (* Check if queue is full *)
  if q.tail - q.head = q.capacity then
    raise Full;
  (* Write to the array *)
  q.items.(q.tail mod q.capacity) <- Some x;
  (* Advance tail *)
  q.tail <- q.tail + 1
```

```
(** Dequeue – should be called by only ONE thread *)
let deq q =
  (* Check if queue is empty *)
  if q.tail = q.head then
    raise Empty;
  (* Read from the     rray *)
  match q.it           ead mod q.capacity) with
  | N                  lse  (* Should never happen *)
                         )
                 head + 1;
```

How do we define “correct” when modifications are not mutually exclusive?

Demo

Concurrency Specification

What *is* a concurrent queue?

- Need a way to ***specify*** a concurrent queue object
- Need a way to ***prove*** that an algorithm implements the object's specification
- Lets talk about object specifications …

Correctness and Progress

- In a concurrent setting, we need to specify both the ***safety*** and the ***liveness*** properties of an object
- Need a way to define
  - when an implementation is ***correct***
  - the conditions under which it guarantees ***progress***

Lets begin with correctness

Sequential Objects

- Each object has a ***state***
  - Usually given by a set of ***fields***
  - Queue example: sequence of items
- Each object has a set of ***methods***
  - Only way to manipulate state
  - Queue example: **enq** and **deq** methods

Sequential Specifications

- If (***precondition***)
  - the object is in such-and-such a state
  - before you call the method,
- Then (***postcondition***)
  - the method will return a particular value
  - or throw a particular exception.
- and (***postcondition, cont***)
  - the object will be in some other state
  - when the method returns,

Pre and Post Conditions for Dequeue

- Precondition:
  - Queue is ***non-empty***
- Postcondition:
  - Returns first item in queue
- Postcondition:
  - Removes first item in queue

- Precondition:
  - Queue is ***empty***
- Postcondition:
  - Raises `Empty` exception
- Postcondition:
  - Queue state is unchanged

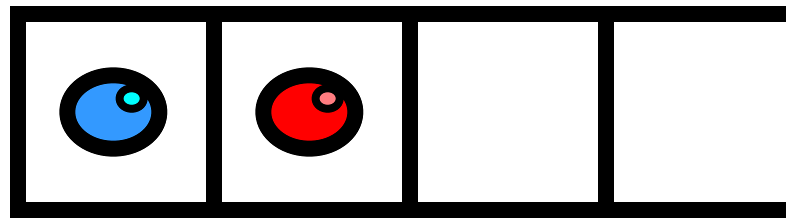
Why Sequential Specifications Totally Rock

- **Interactions among *methods* captured by side-effects on object state**
  - State meaningful between method calls
- ***Documentation* size is linear in the number of methods**
  - Each method described in isolation
- **Can add *new methods***
  - Without changing descriptions of old methods

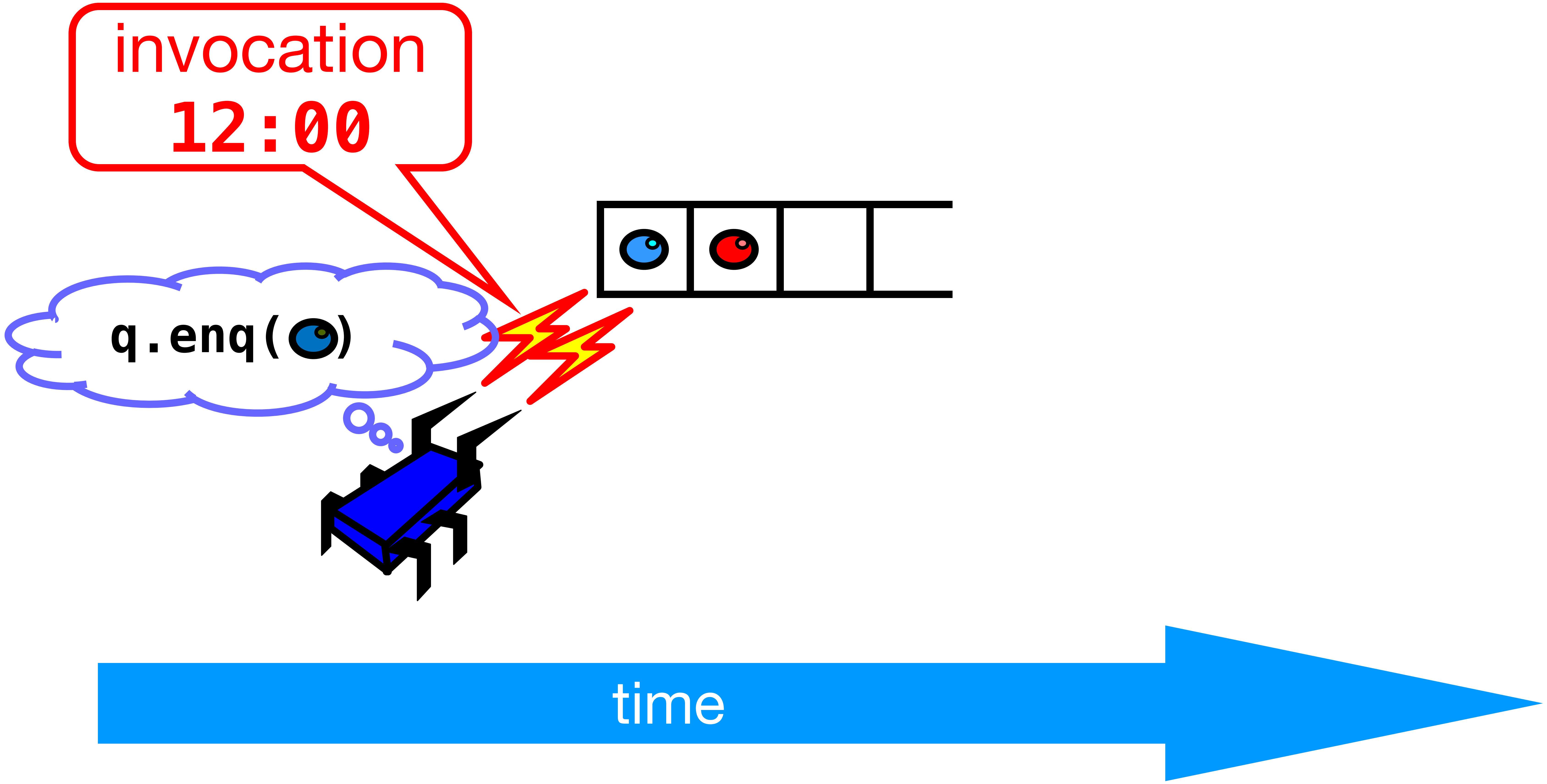
What about concurrent Specifications?

- Methods?
- Documentation?
- Adding new methods?

Methods take time



Methods take time



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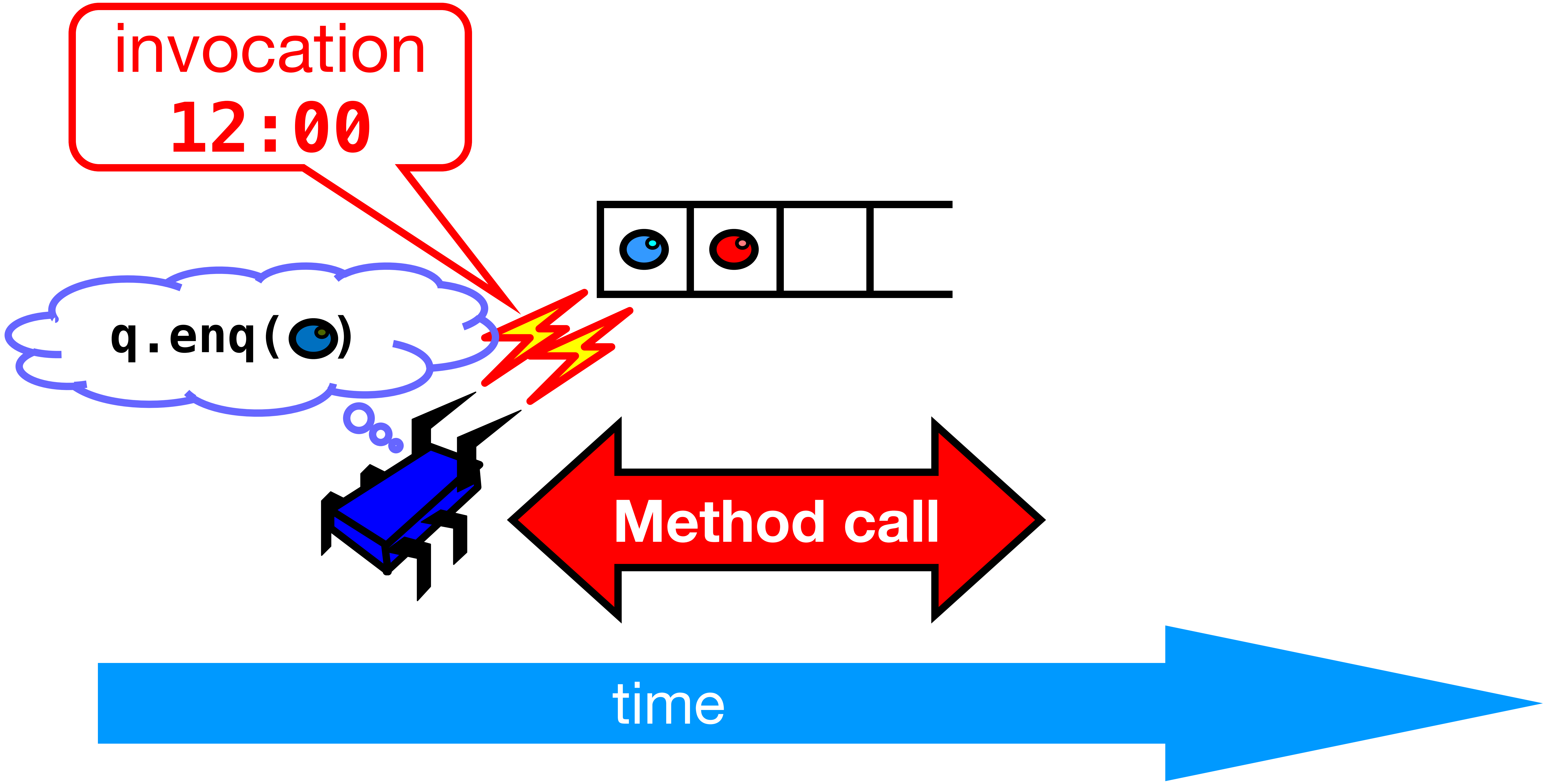

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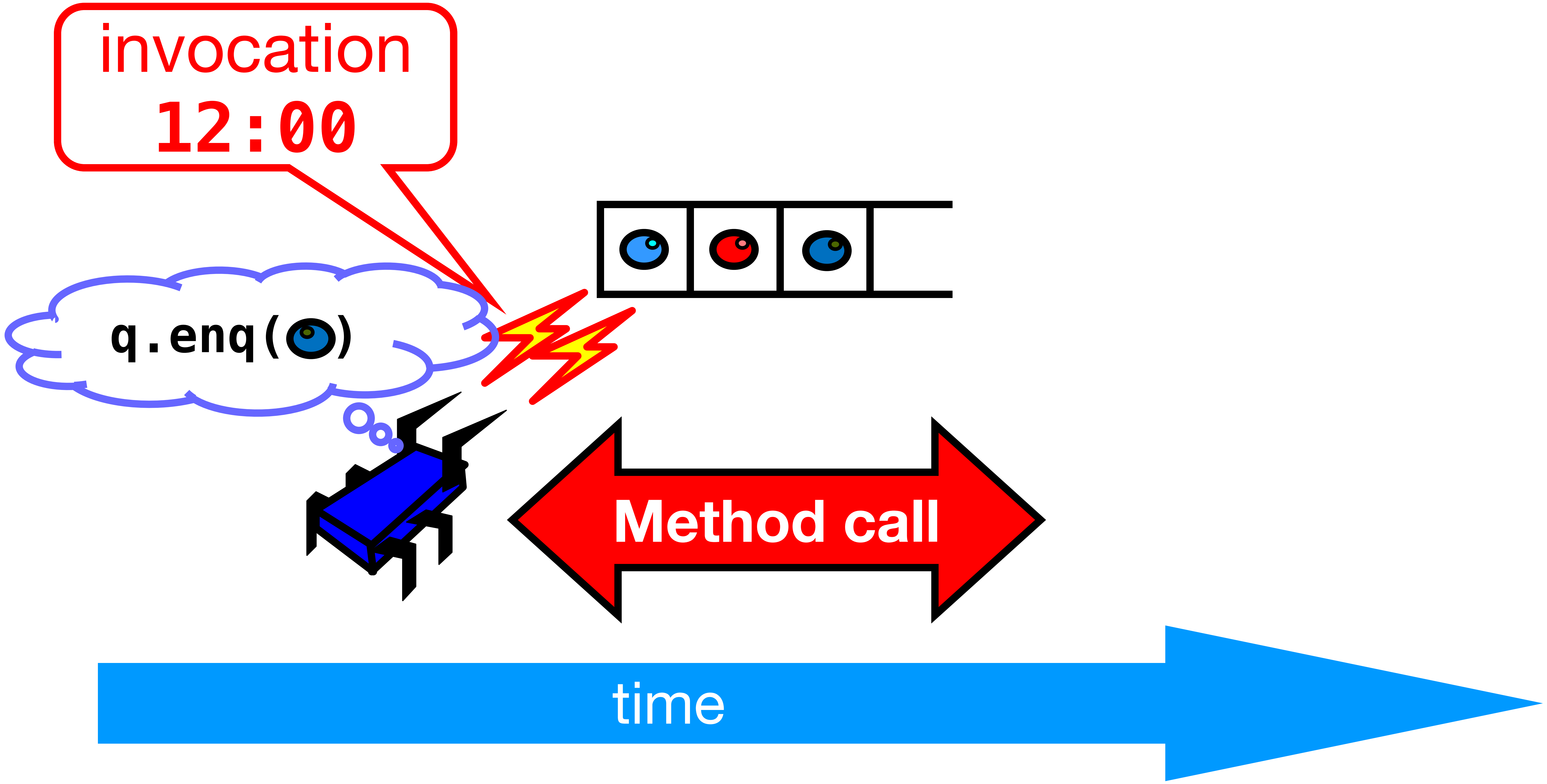
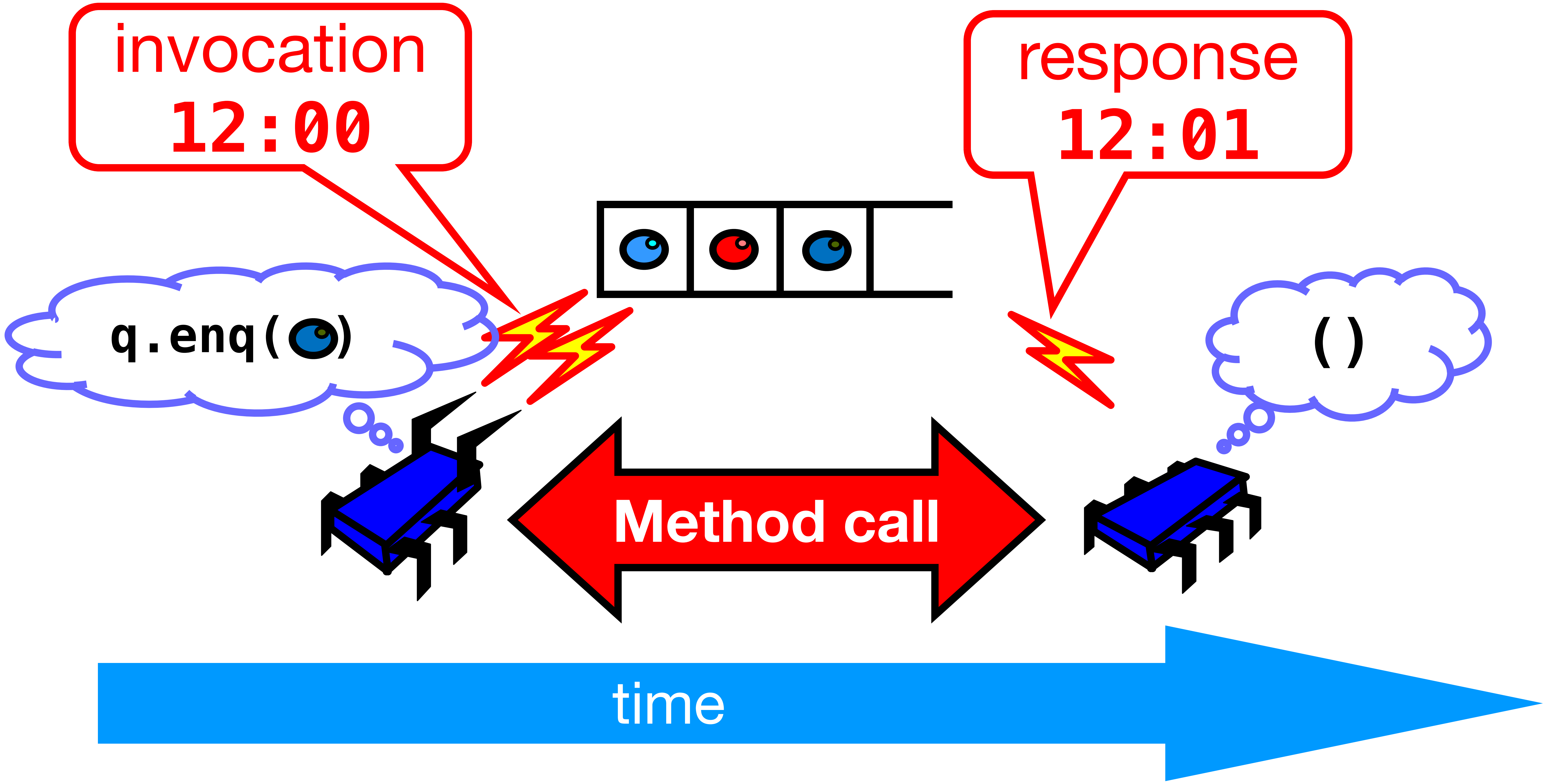


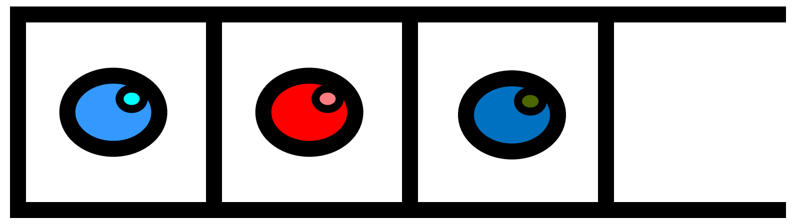
Methods take time



Sequential vs Concurrent

- Sequential
  - Methods take time? Who knew?
- Concurrent
  - Method call is not an ***event***
  - Method call is an ***interval***

Concurrent Methods Take Overlapping Time



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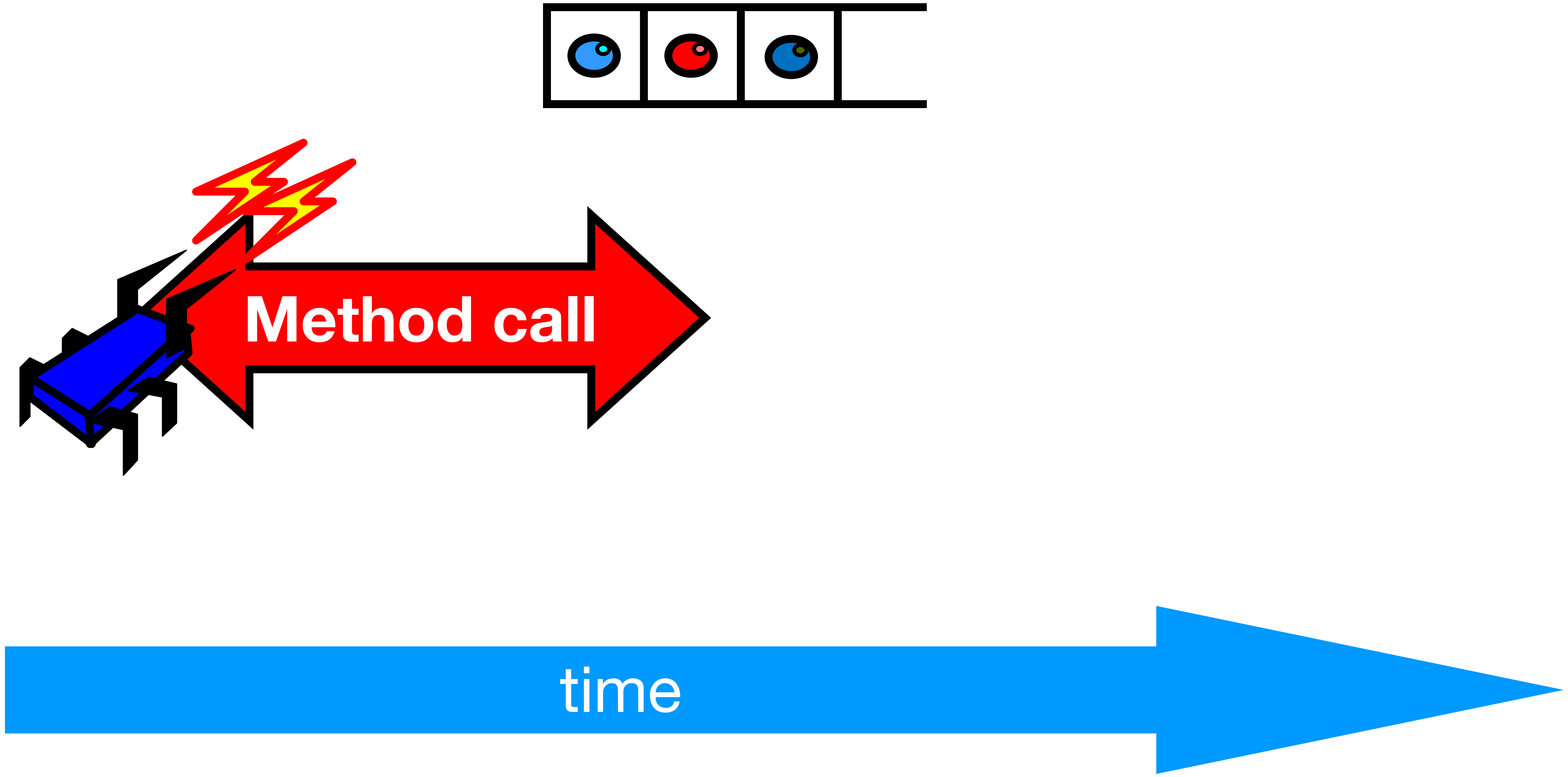

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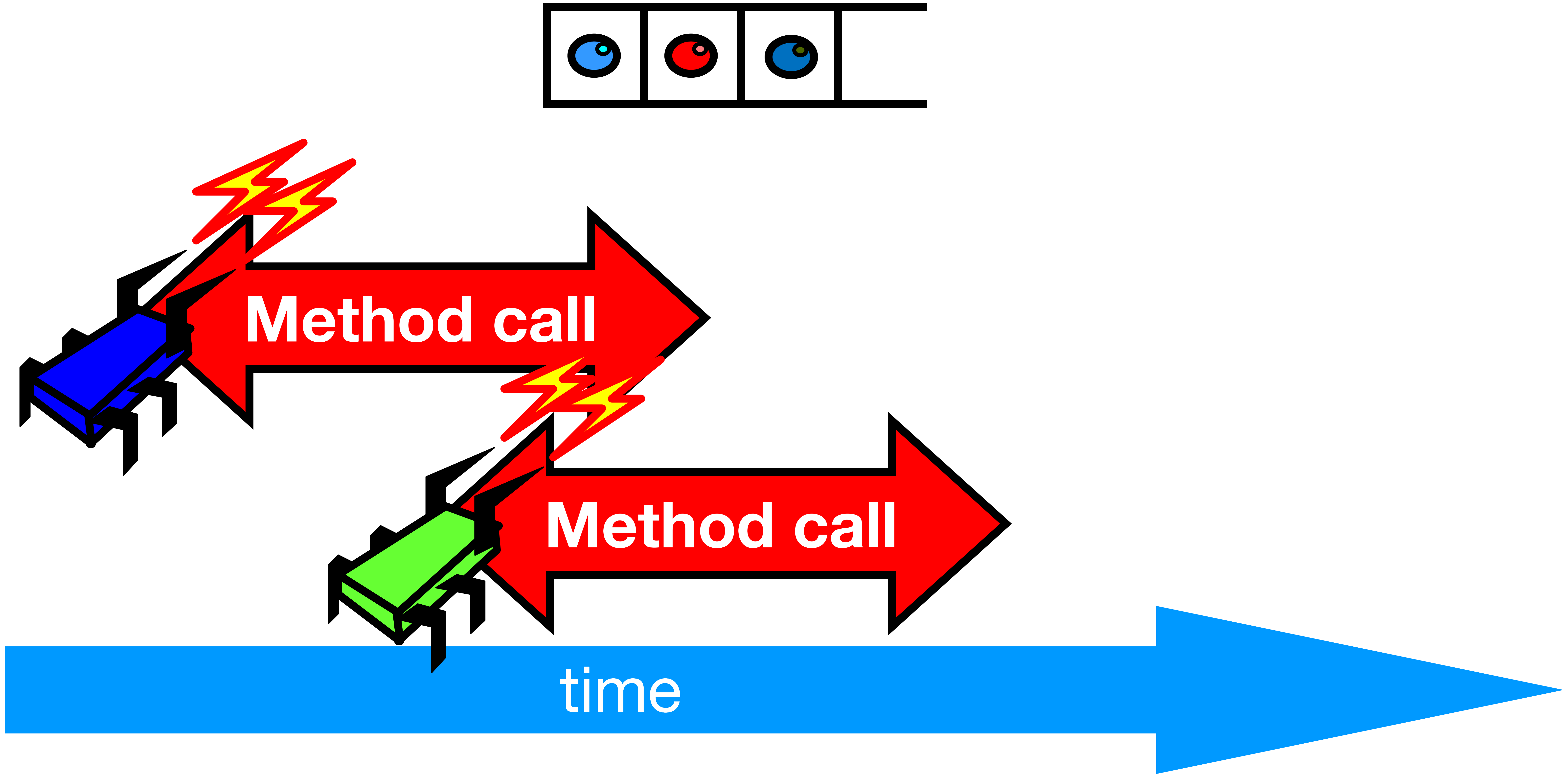

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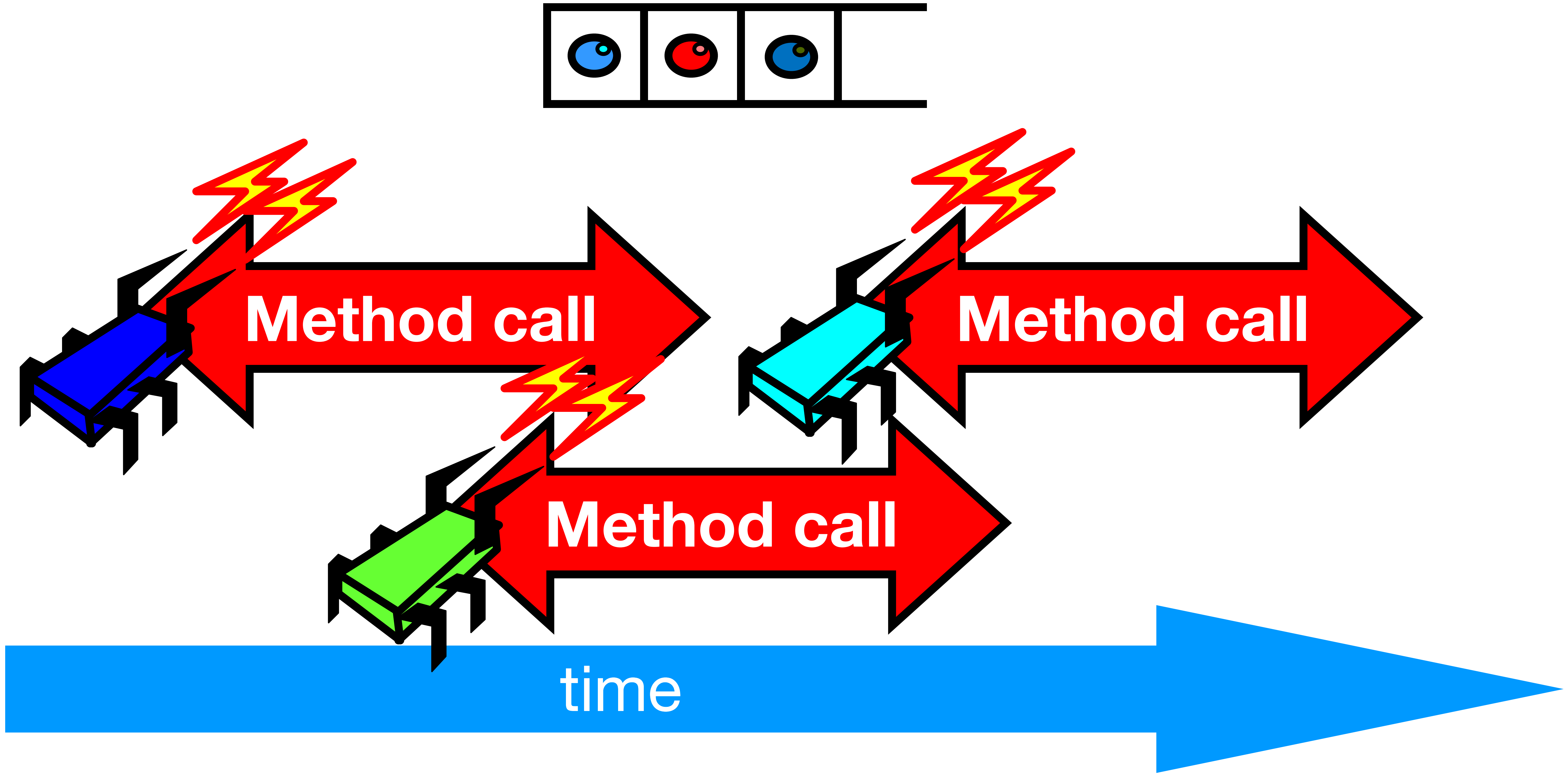


Sequential vs Concurrent

- Sequential
    - Object needs a meaningful state only ***between*** method calls
- Concurrent
    - Because method calls overlap, the object might ***never*** be between method calls

Sequential vs Concurrent

- Sequential:
  - Each method described in isolation
- Concurrent
  - Must characterize ***all*** possible interactions with concurrent calls
    - What if two **`enq()`** calls overlap?
    - Two **`deq()`** calls? **`enq()`** and **`deq()`**? …

Sequential vs Concurrent

- Sequential:
  - Can add new methods without affecting older methods
- Concurrent:
  - Everything can potentially interact with everything else

Sequential vs Concurrent

- Sequential:
  - Can add new methods without affecting older methods
- Concurrent:
  - Everything can potentially interact with everything else

Panic!

The Big Question

- What does it *mean* for a ***concurrent*** object to be correct?
  - What ***is*** a concurrent FIFO queue?
  - FIFO means ***strict temporal order***
  - Concurrent means ***ambiguous temporal order***

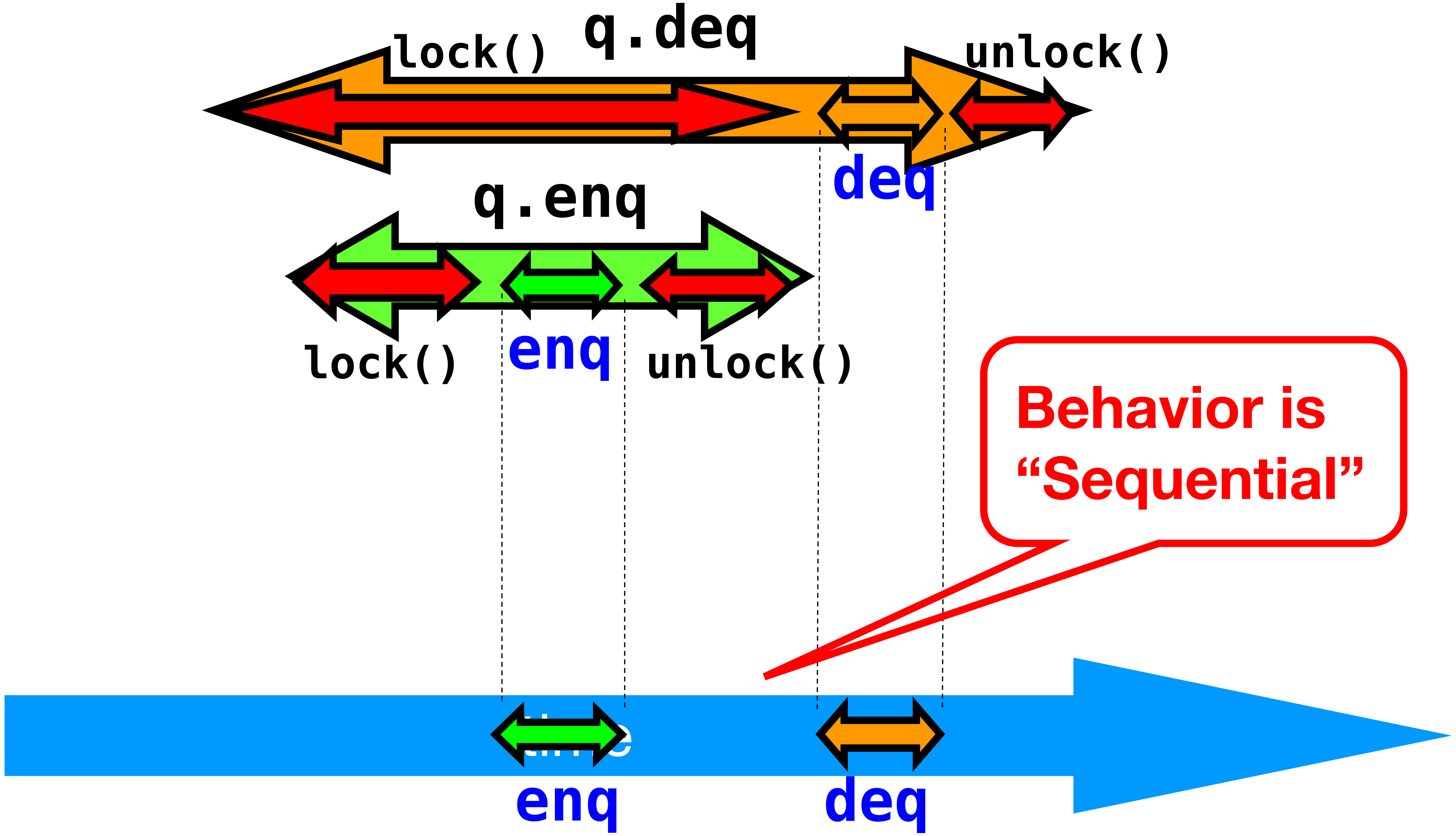
Intuitively

```
let deq q =
  Mutex.lock q.lock;
  try
    if q.tail = q.head then
      raise Empty;
    match q.items.(q.head mod q.capacity) with
    | None -> assert false
    | Some x ->
        q.head <- q.head + 1;
        Mutex.unlock q.lock;
        x
  with e ->
    Mutex.unlock q.lock;
    raise e
```

All queue modifications are mutually exclusive

Intuitively

Lets capture the idea of describing the concurrent via the sequential



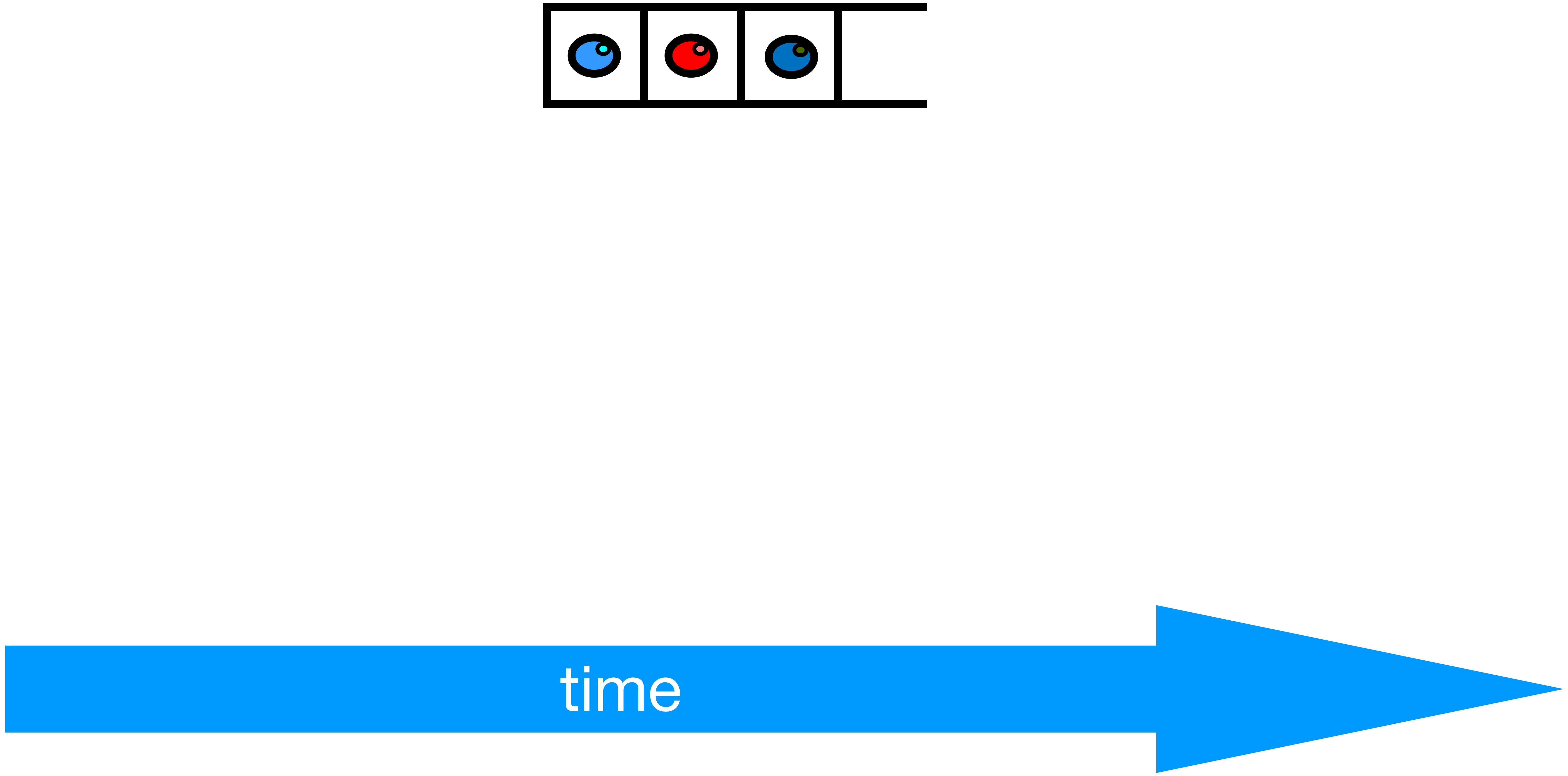
Linearizability

- Each method should
  - “take effect”
  - Instantaneously
  - Between ***invocation*** and ***response*** events
- Object is correct if this “sequentialised” behaviour is correct
- Any such concurrent object is
  - **Linearizable™**

Is it really about the object?

- Each method should
  - “take effect”
  - Instantaneously
  - Between ***invocation*** and ***response*** events
- Sounds like a property of *an execution…*
- A linearizable *object*
  - One of whose all possible executions are linearizable

Example



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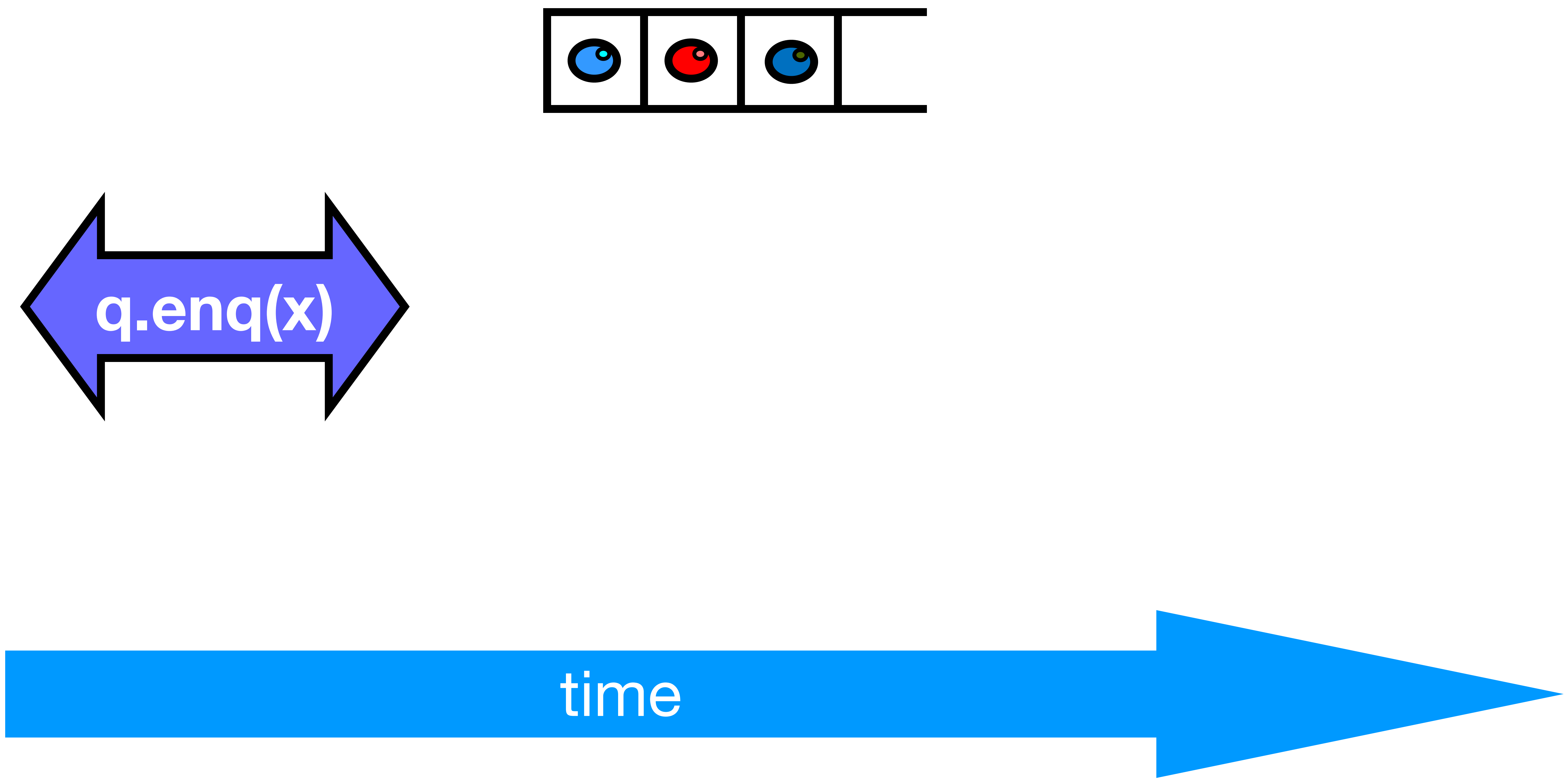

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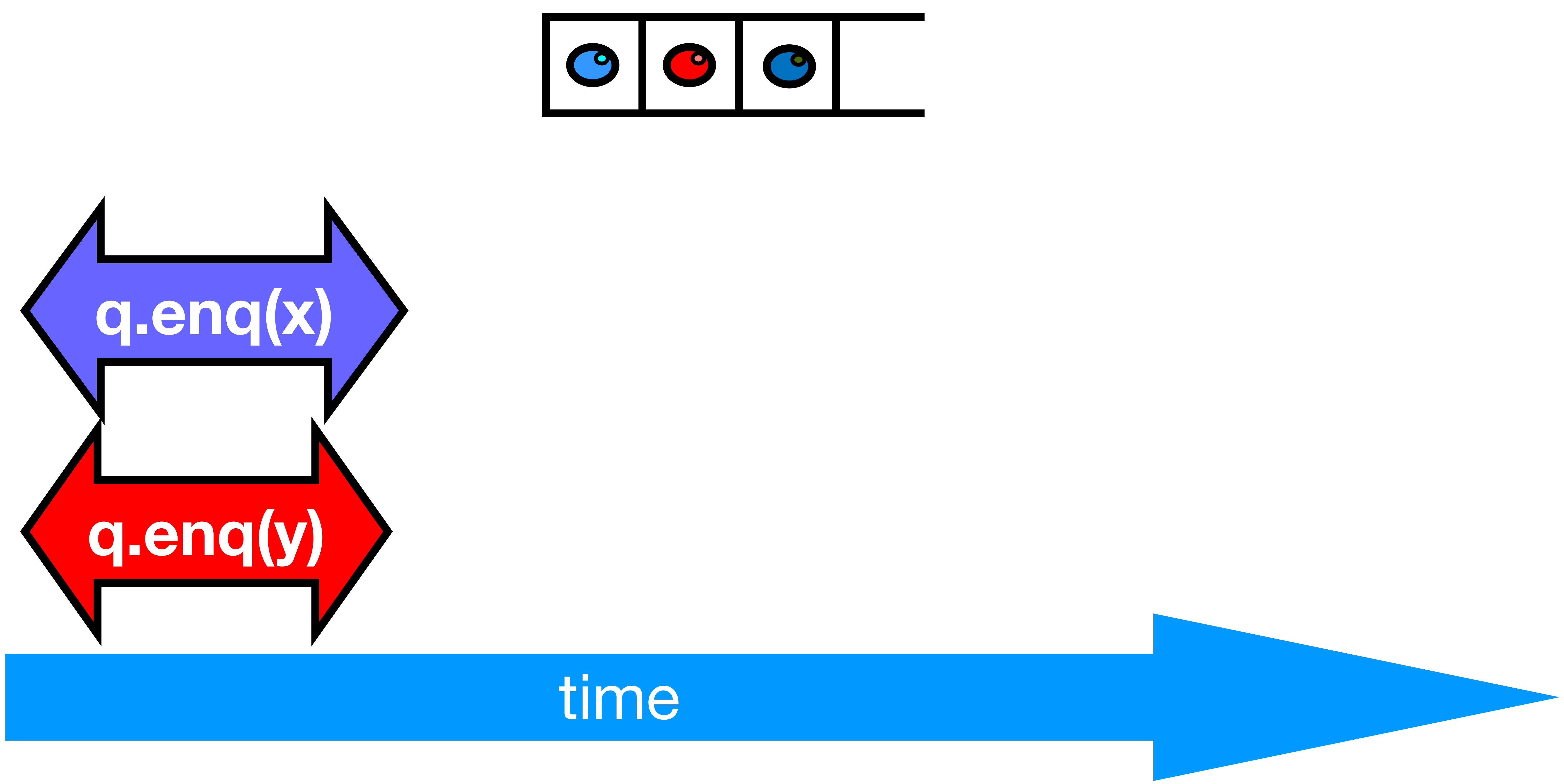

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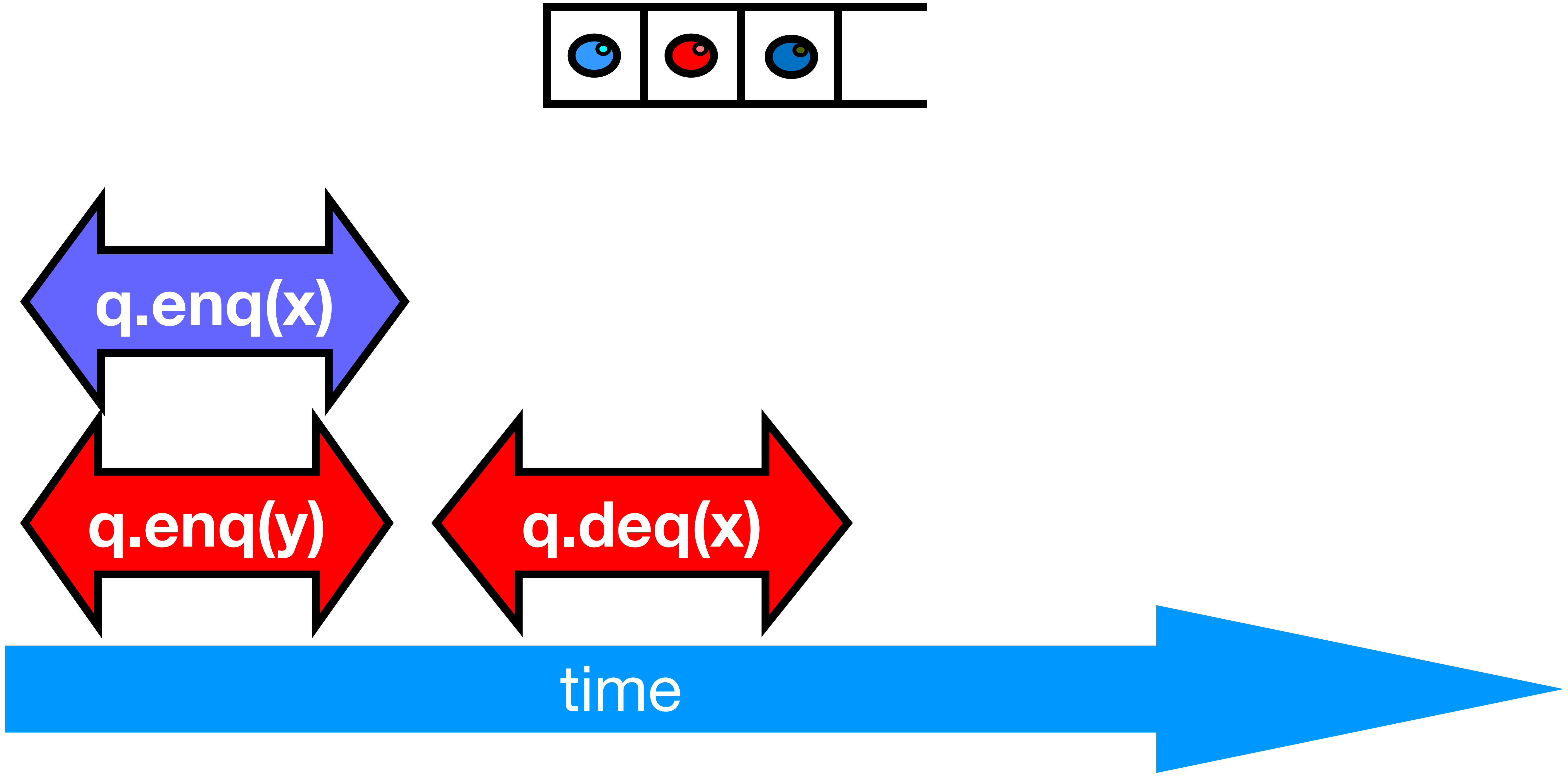

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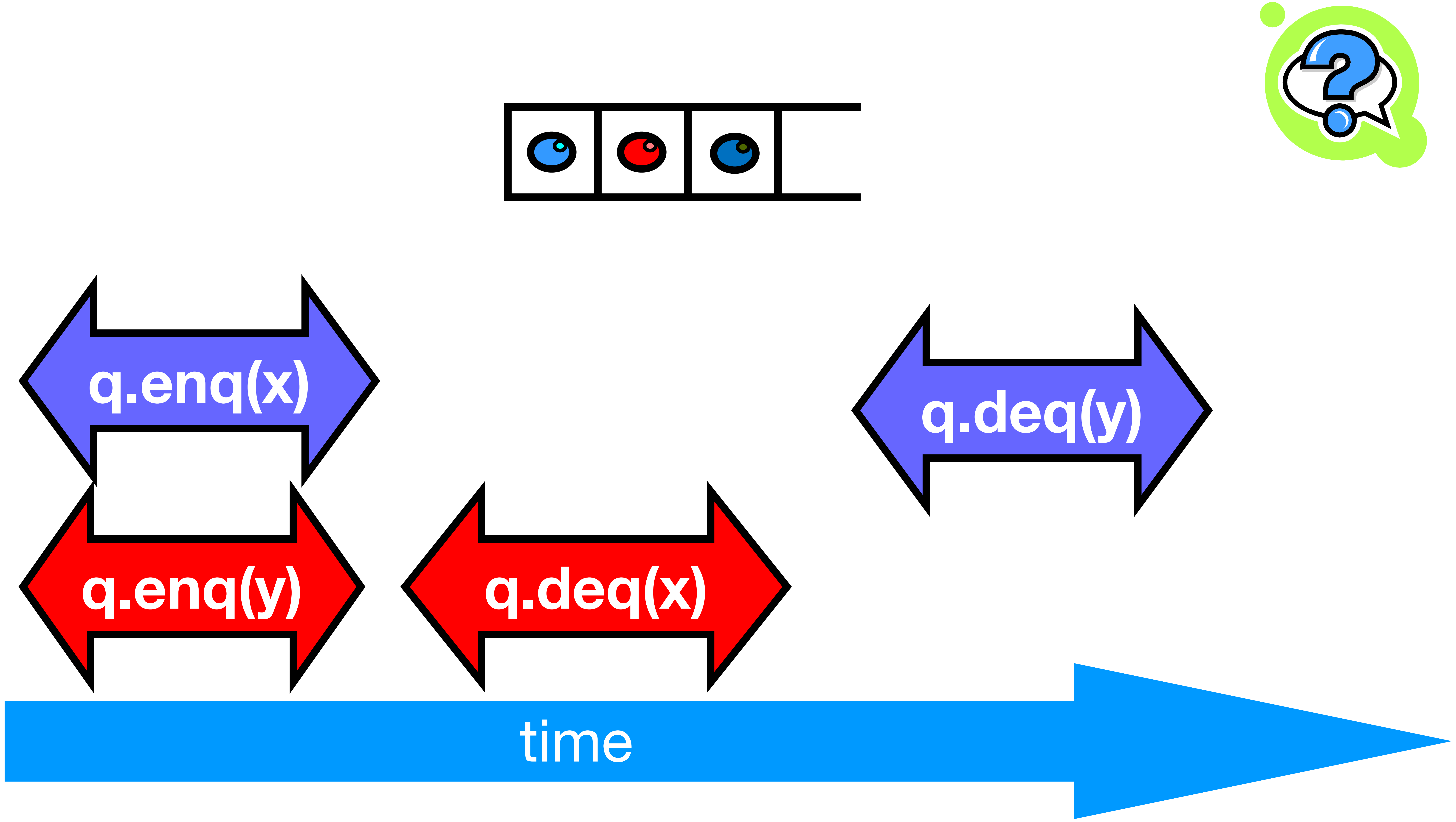

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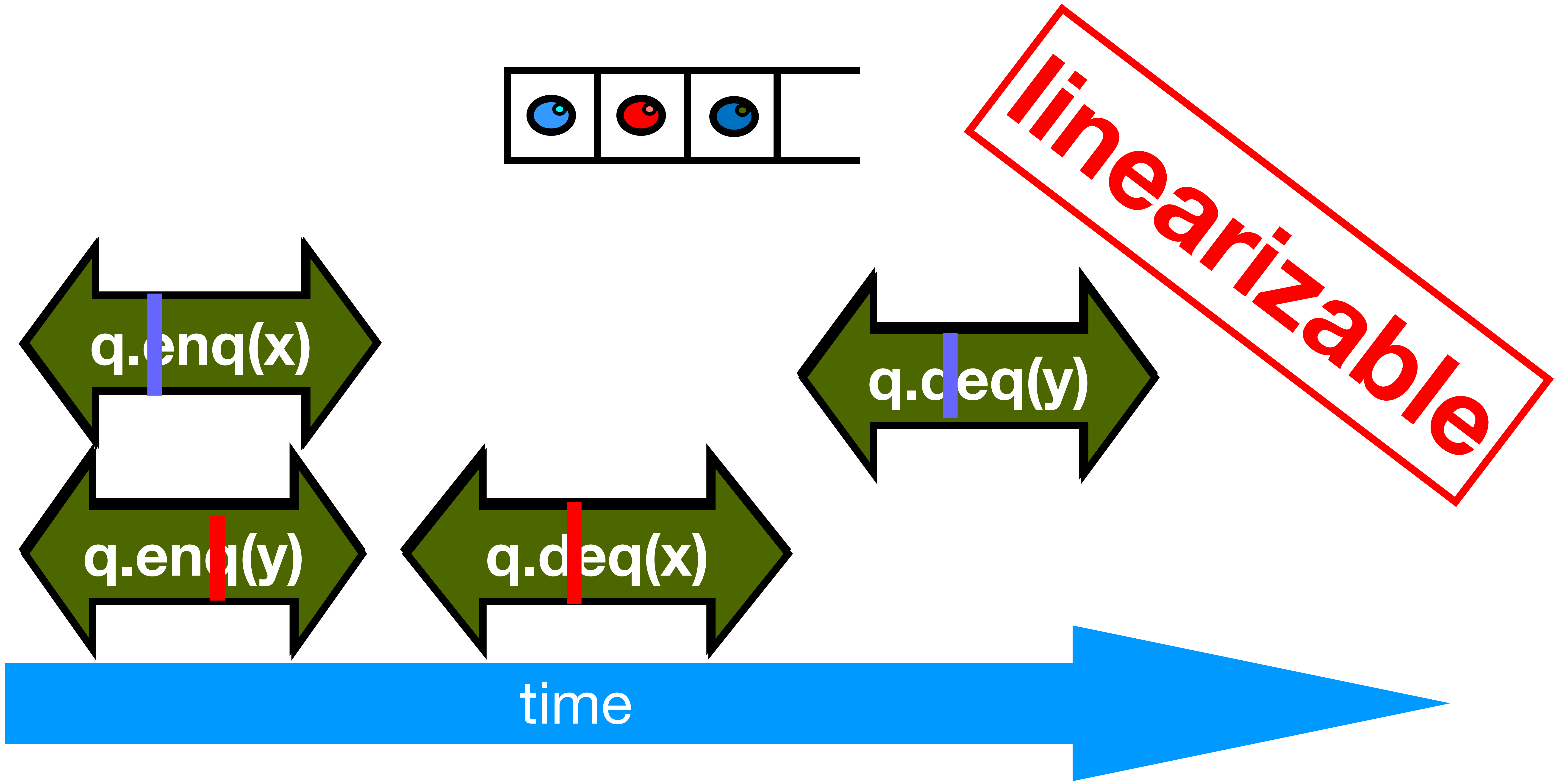

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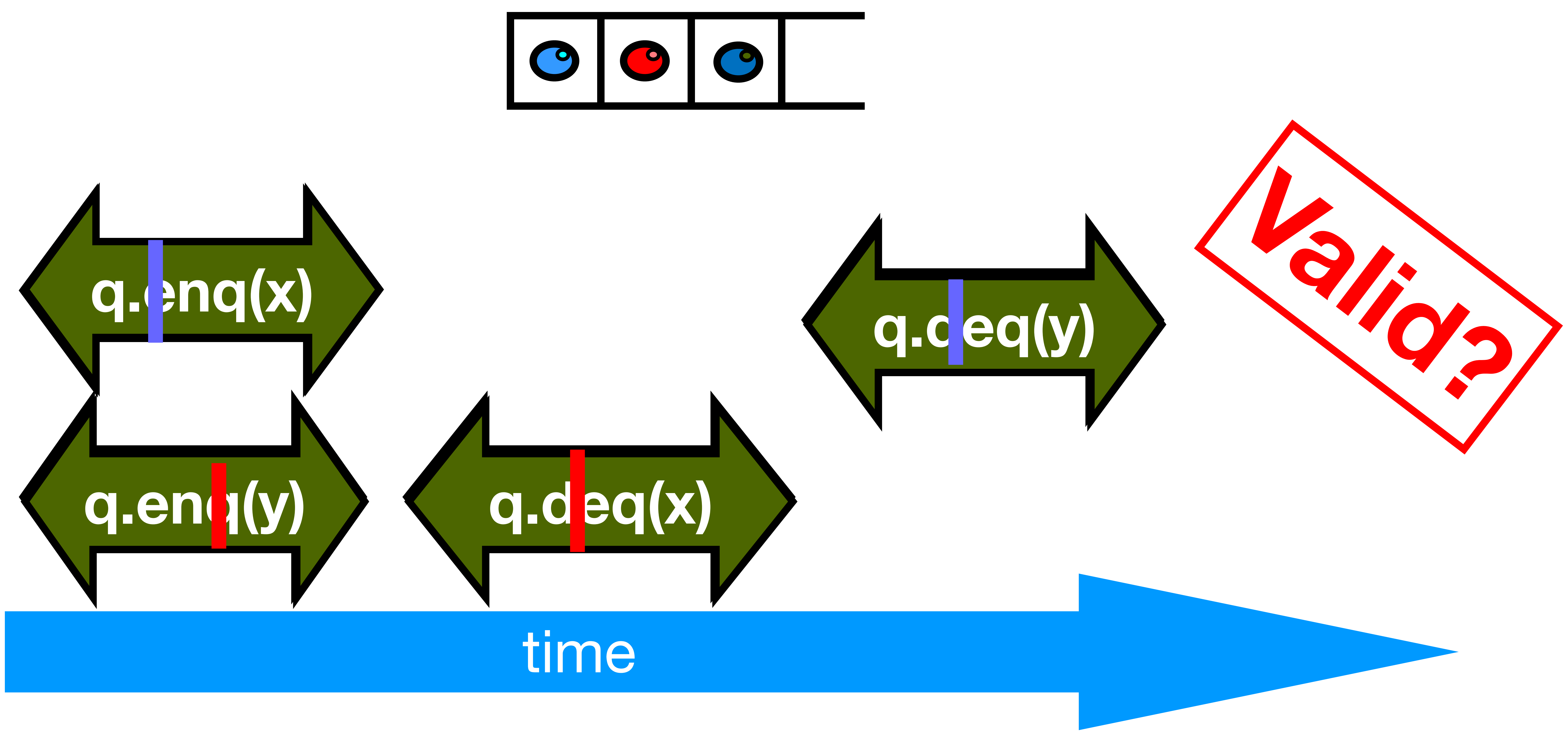

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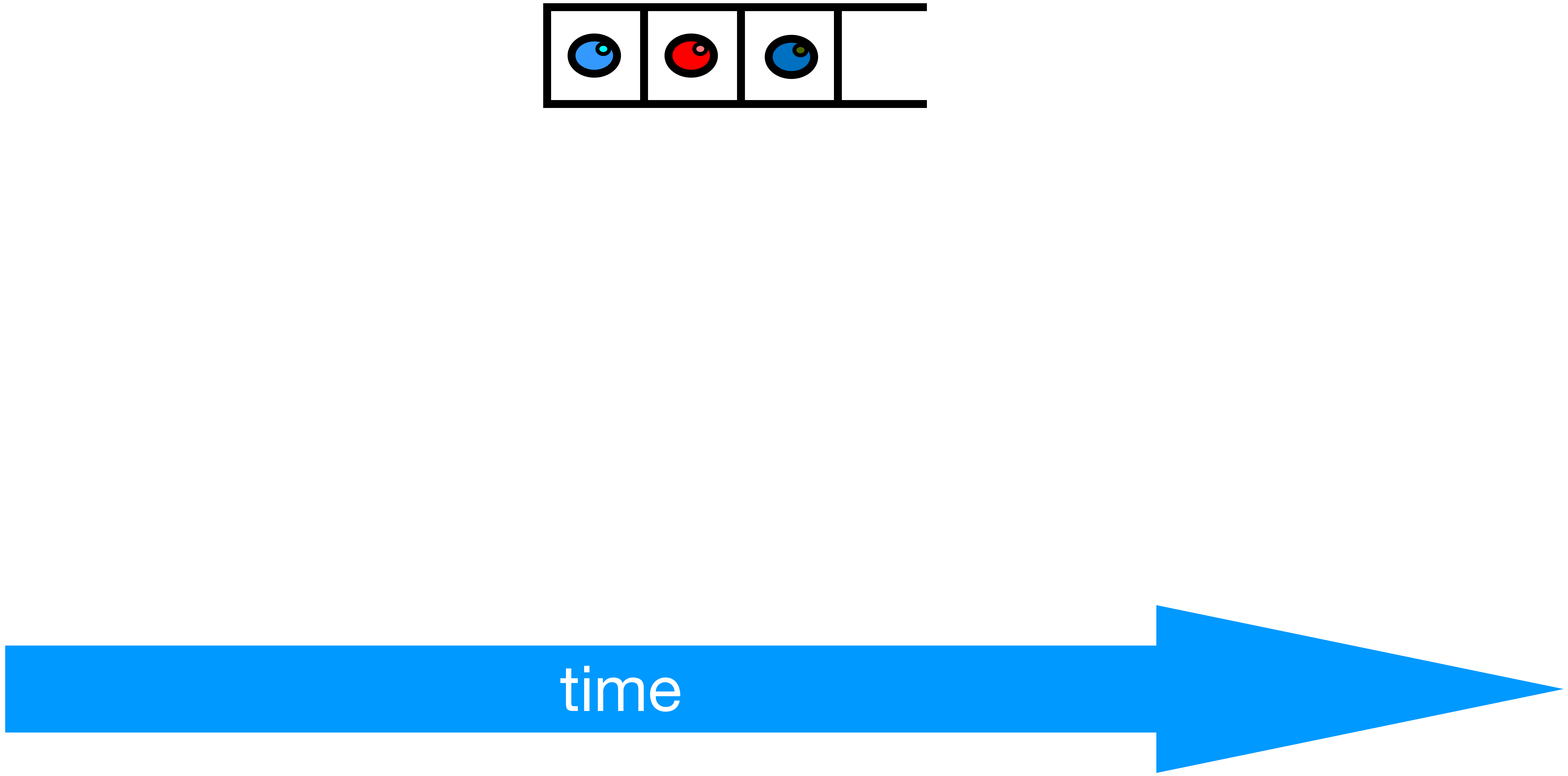

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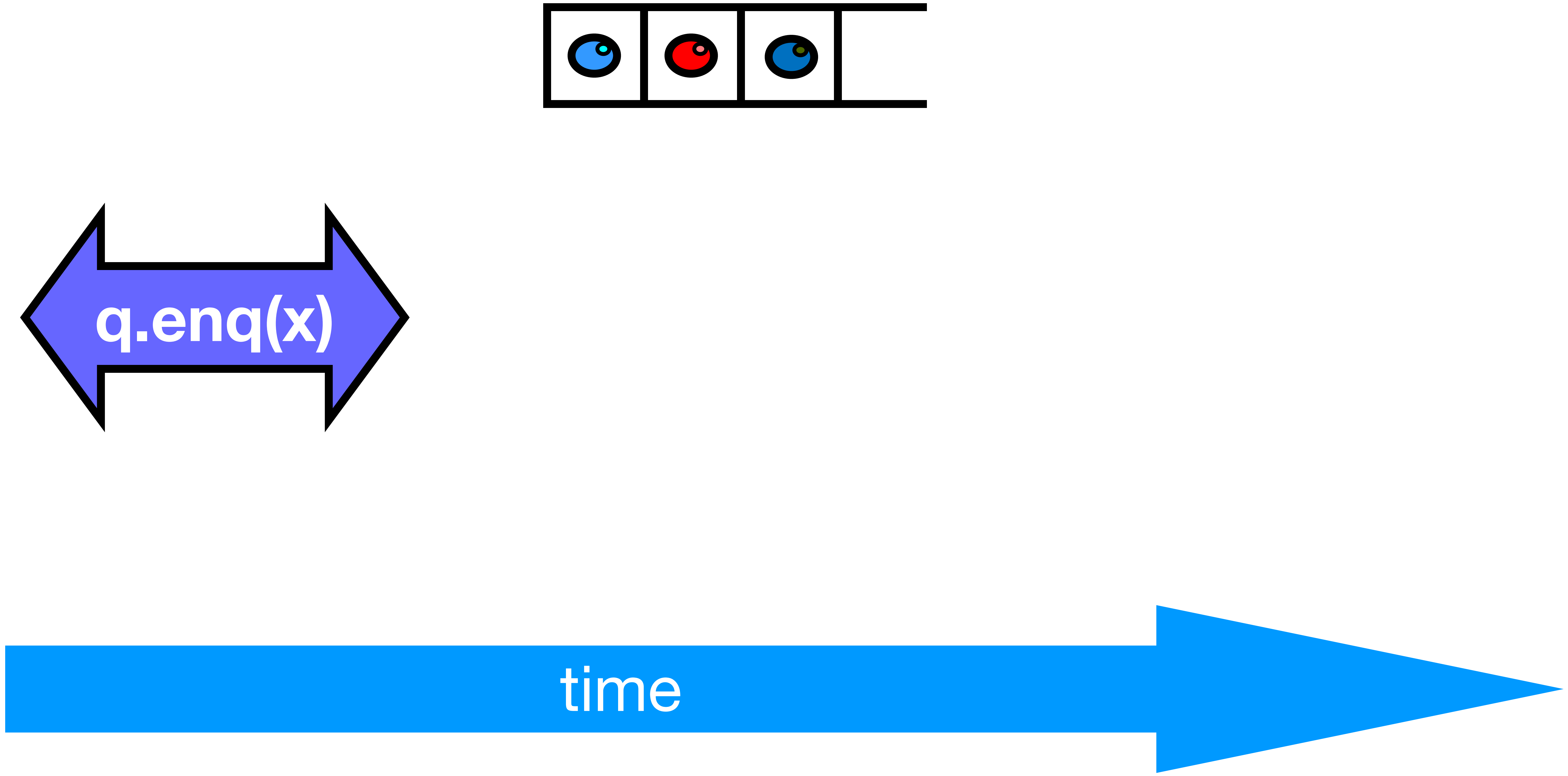

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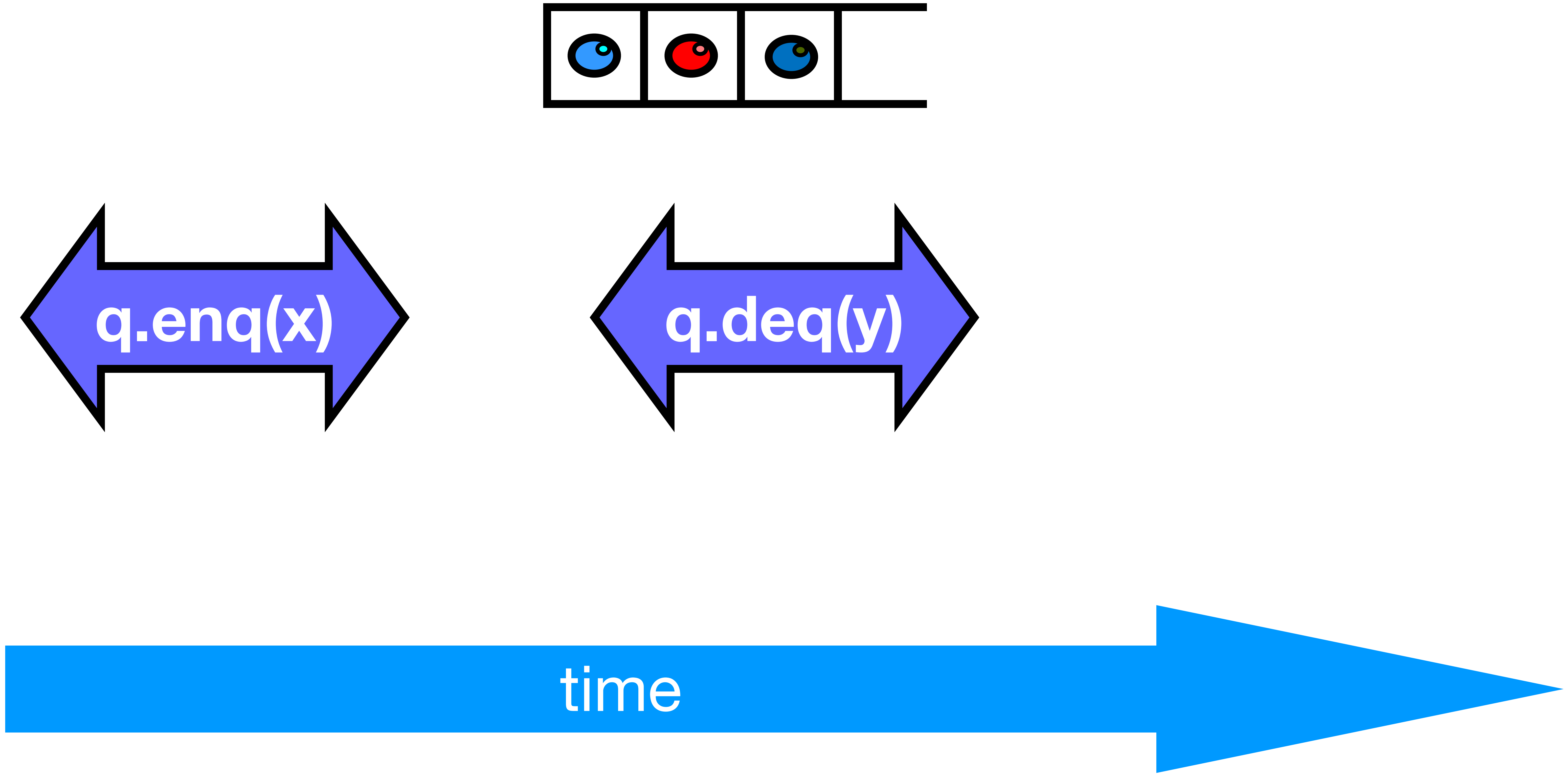

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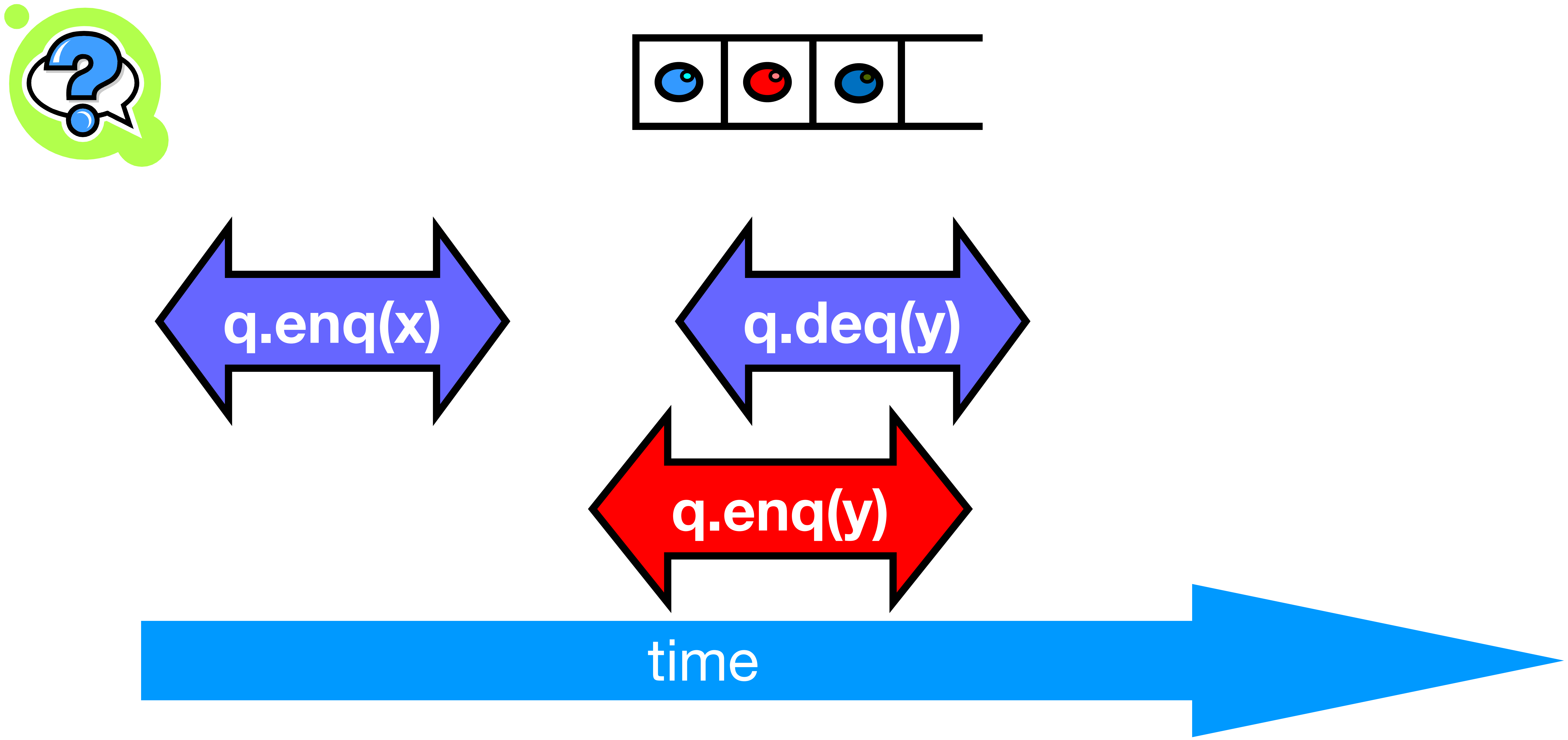

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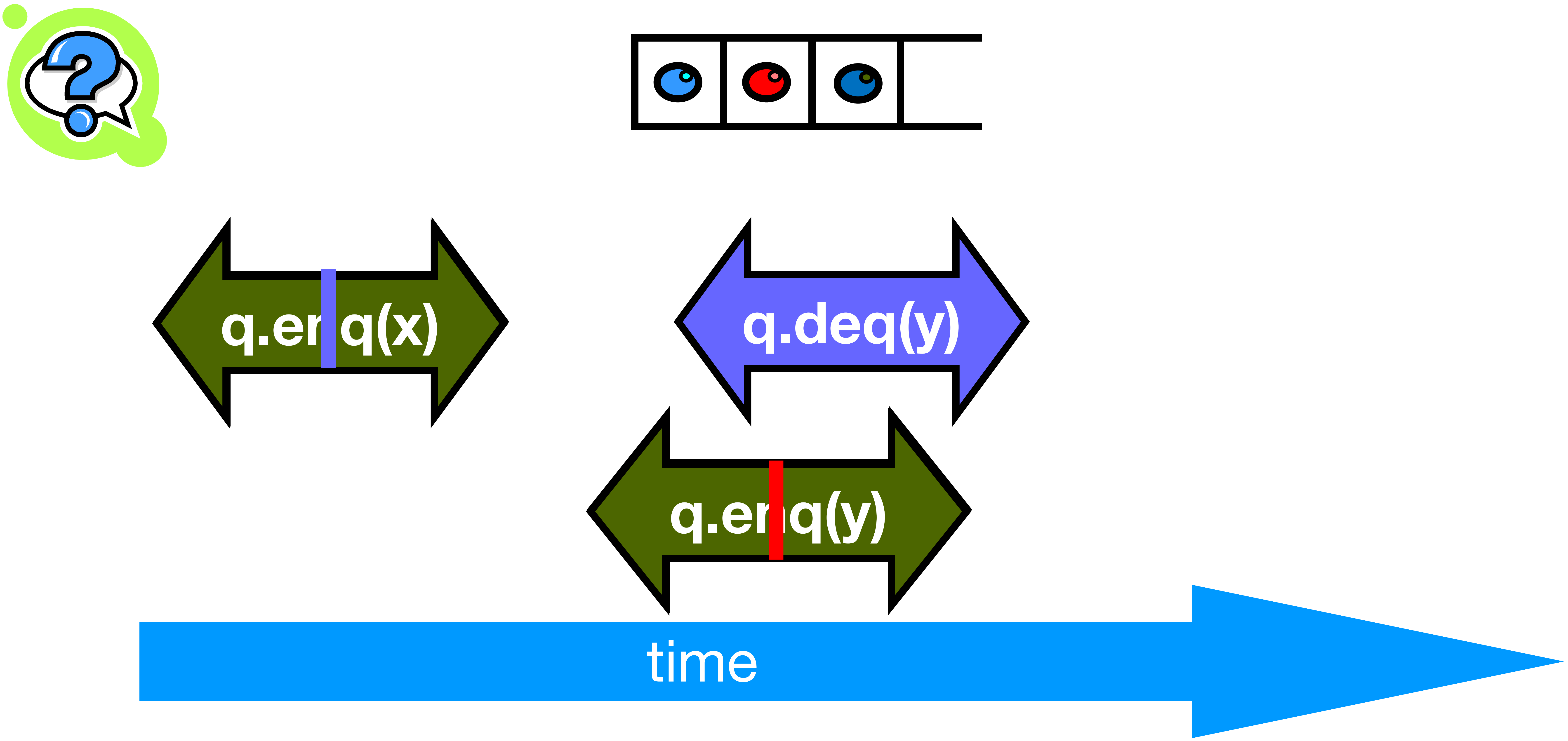

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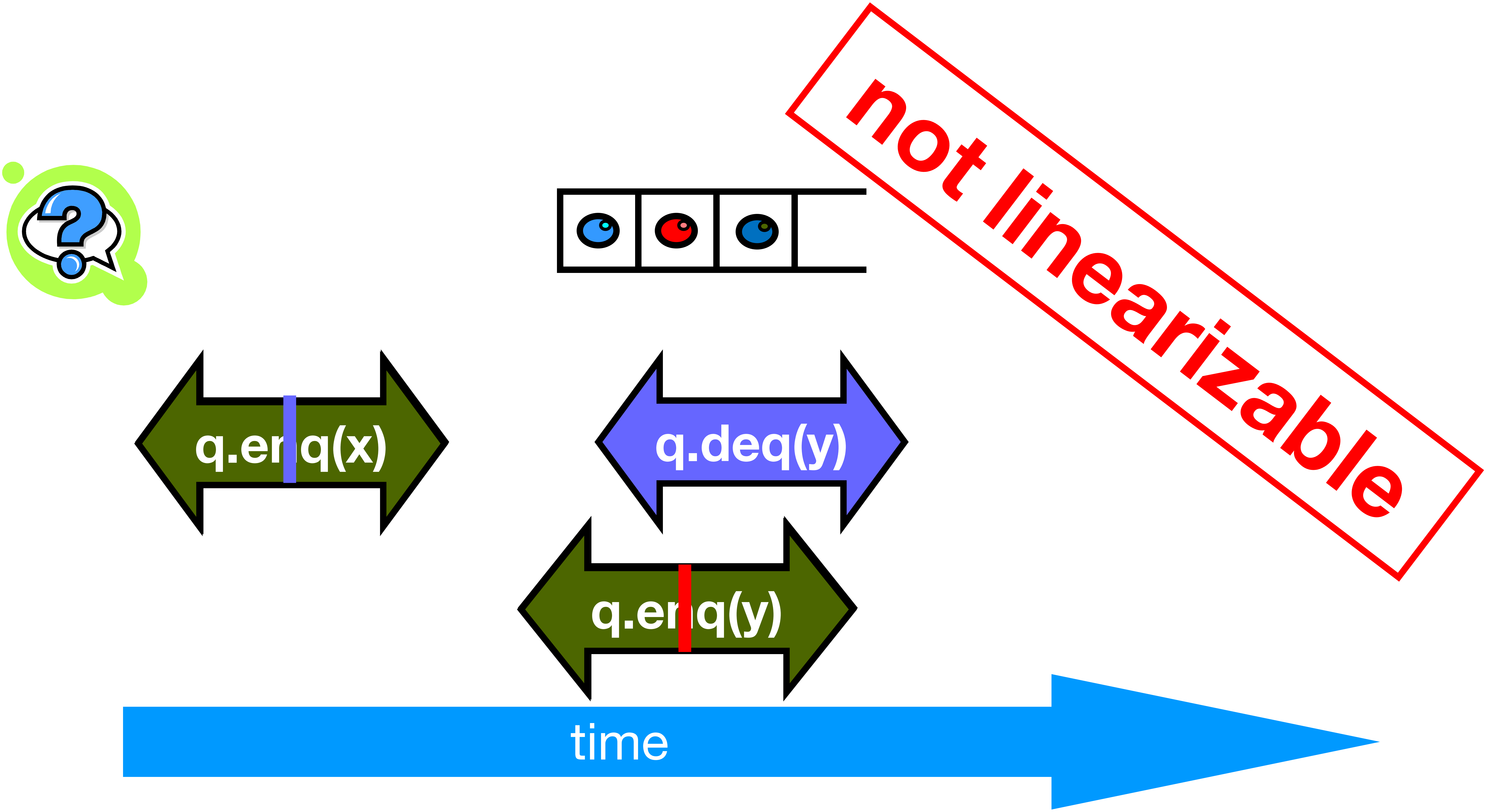

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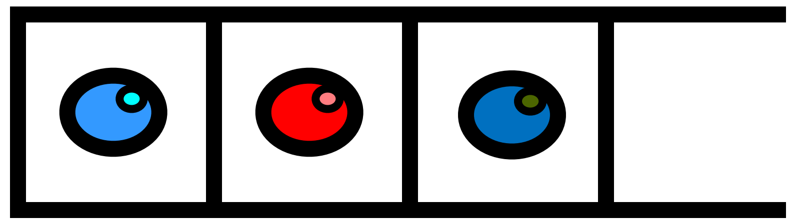

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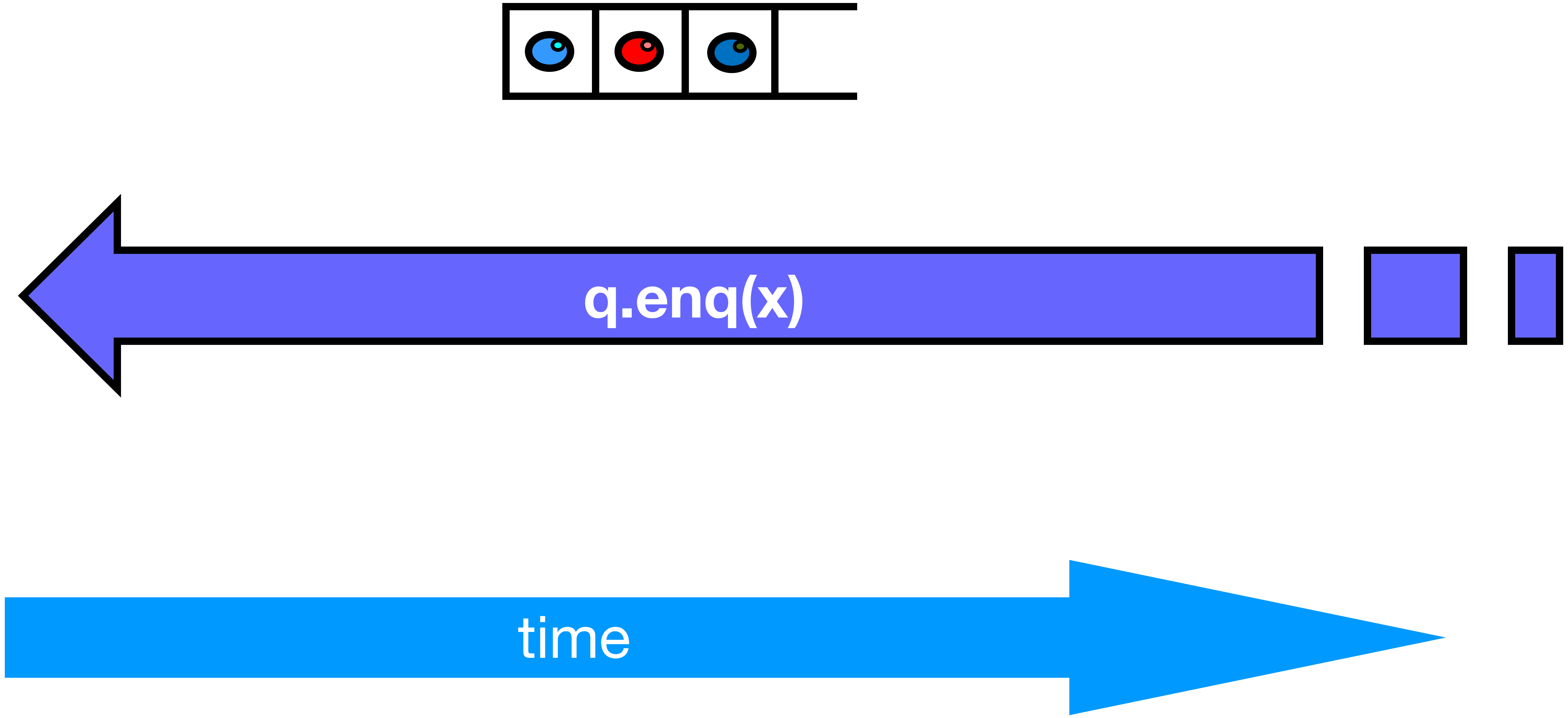

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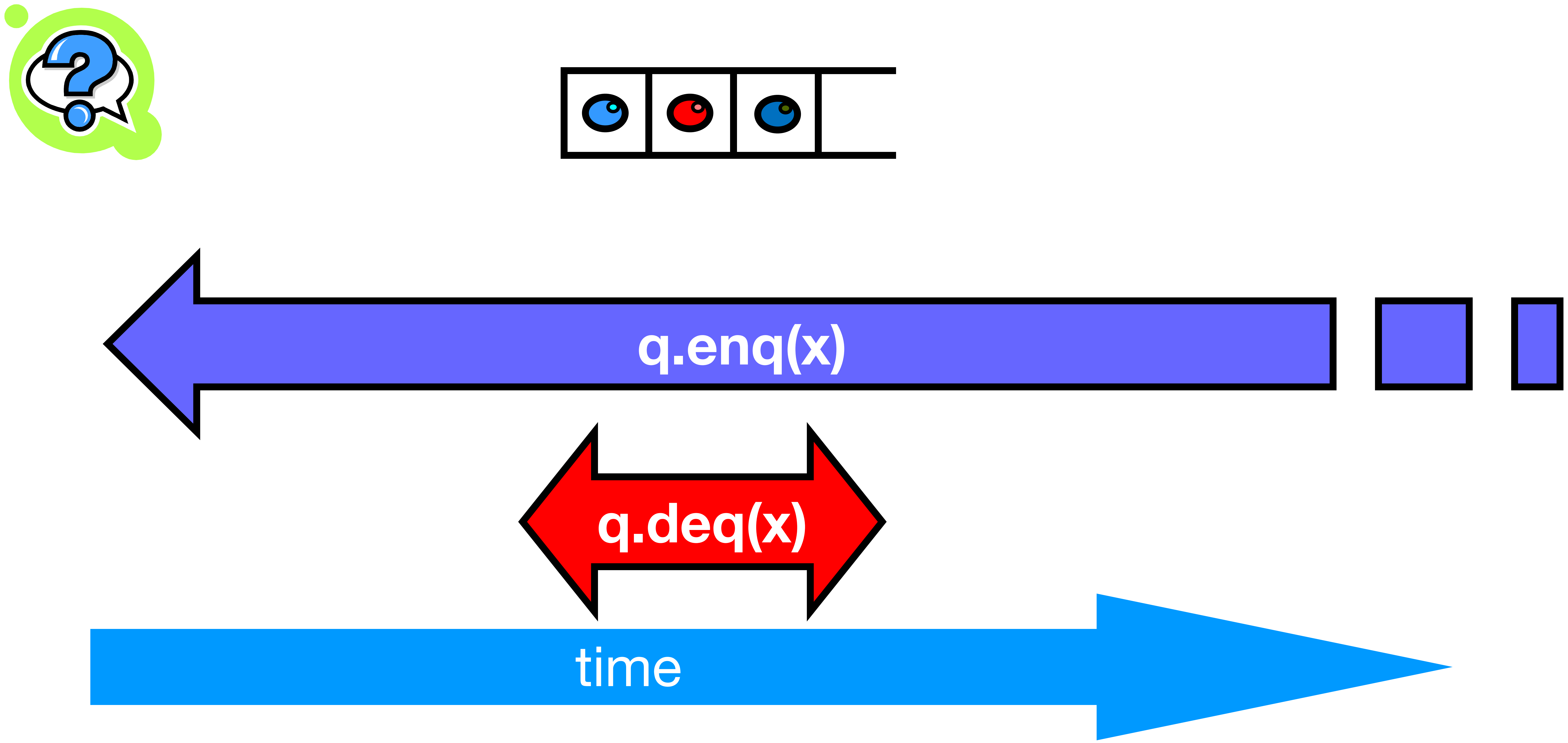

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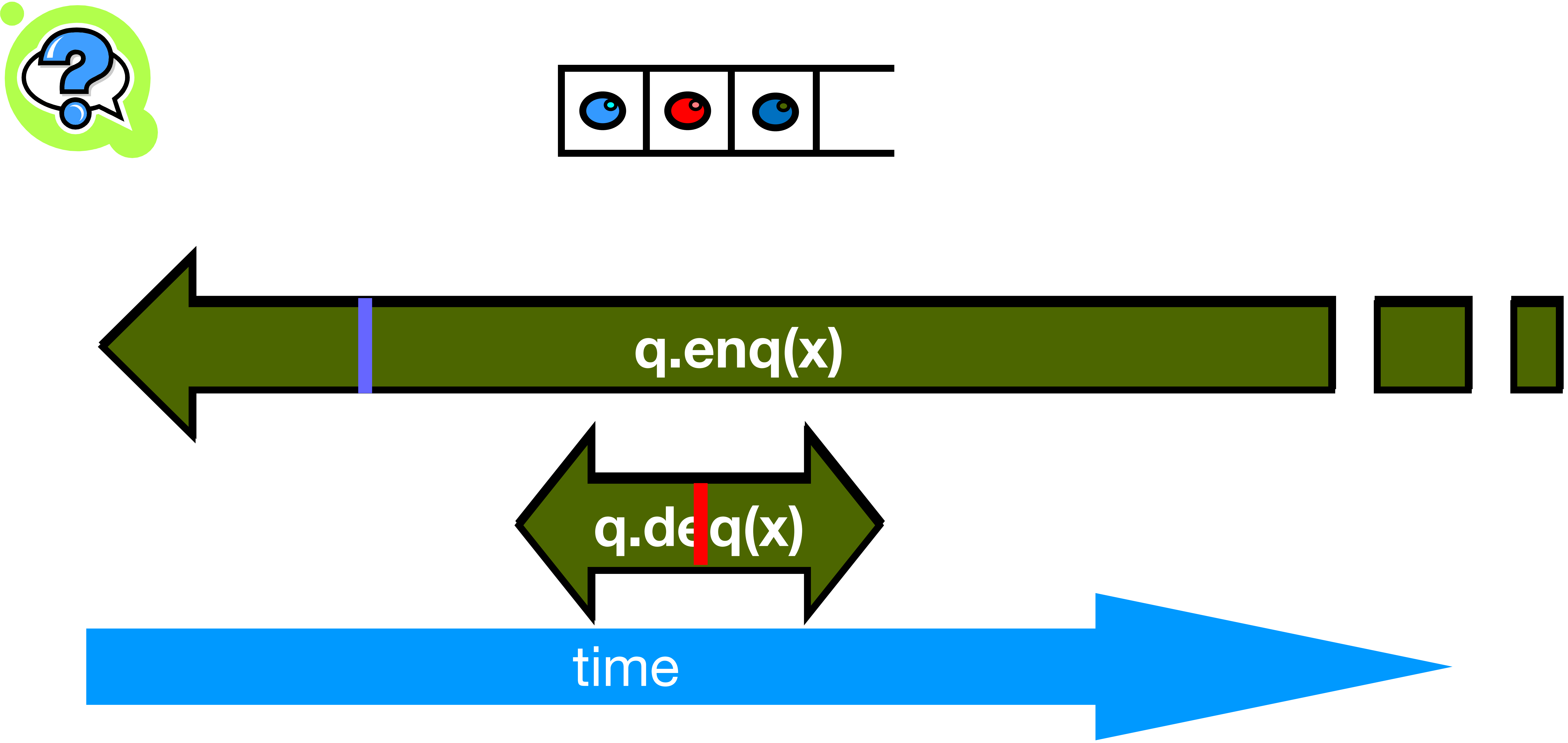

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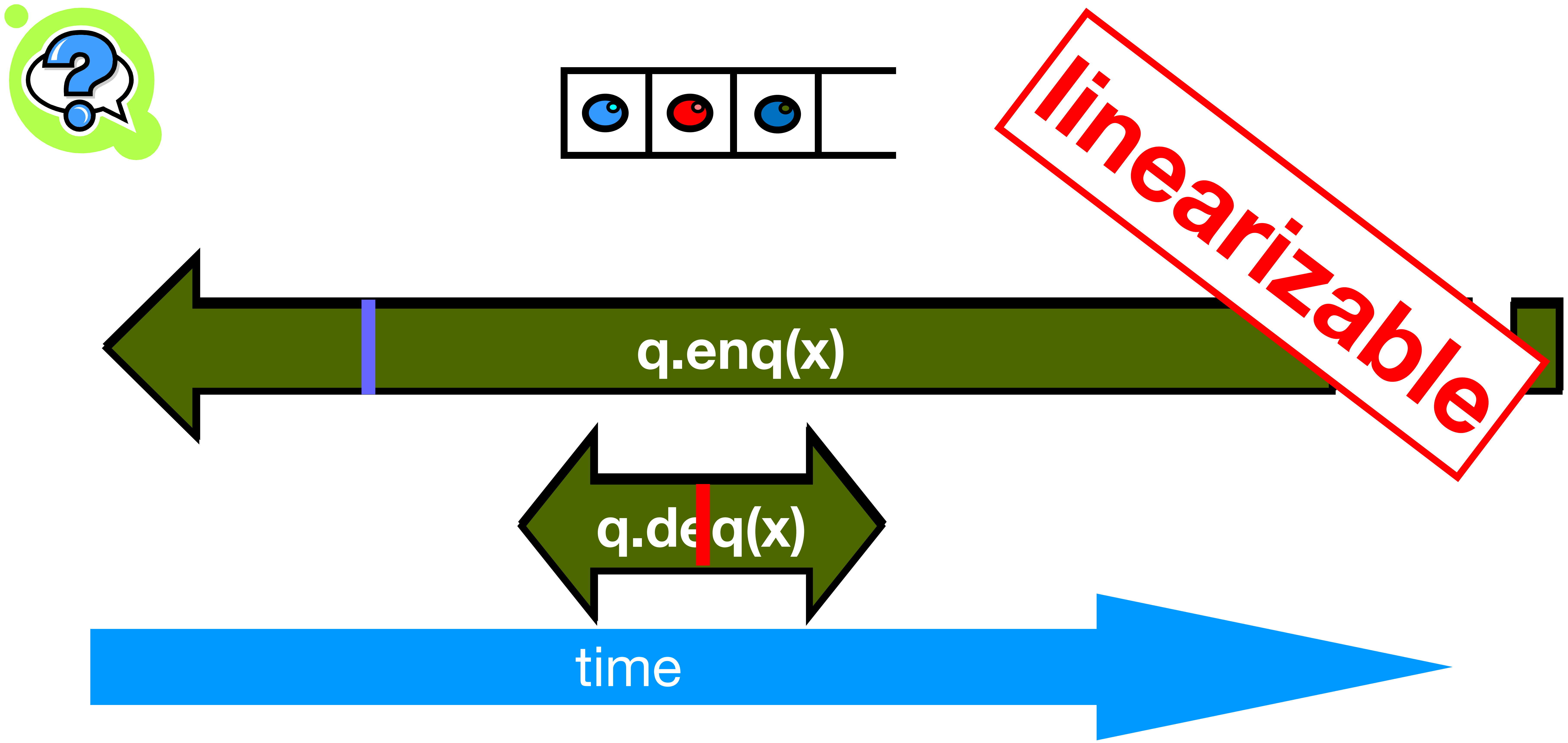

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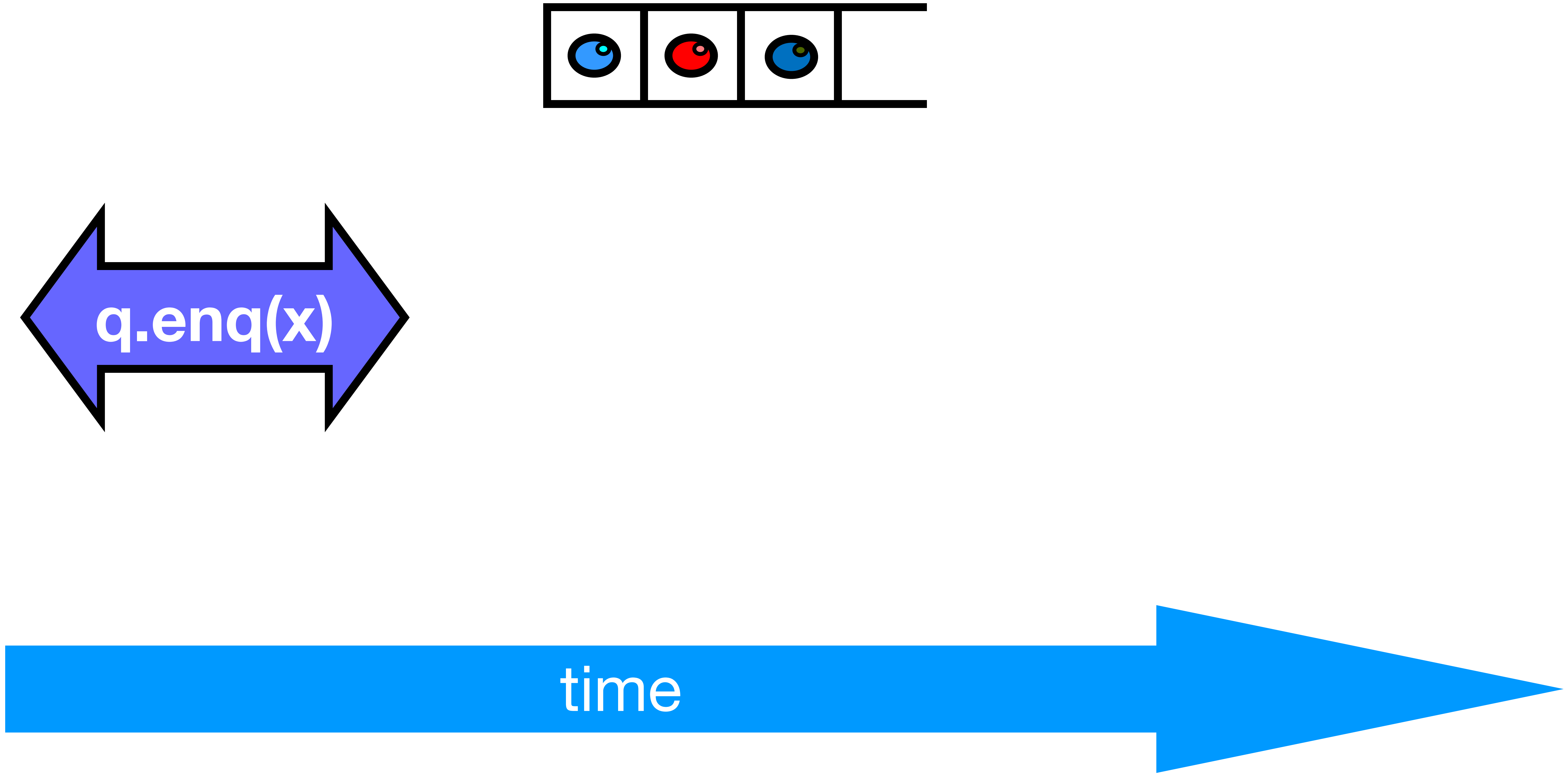

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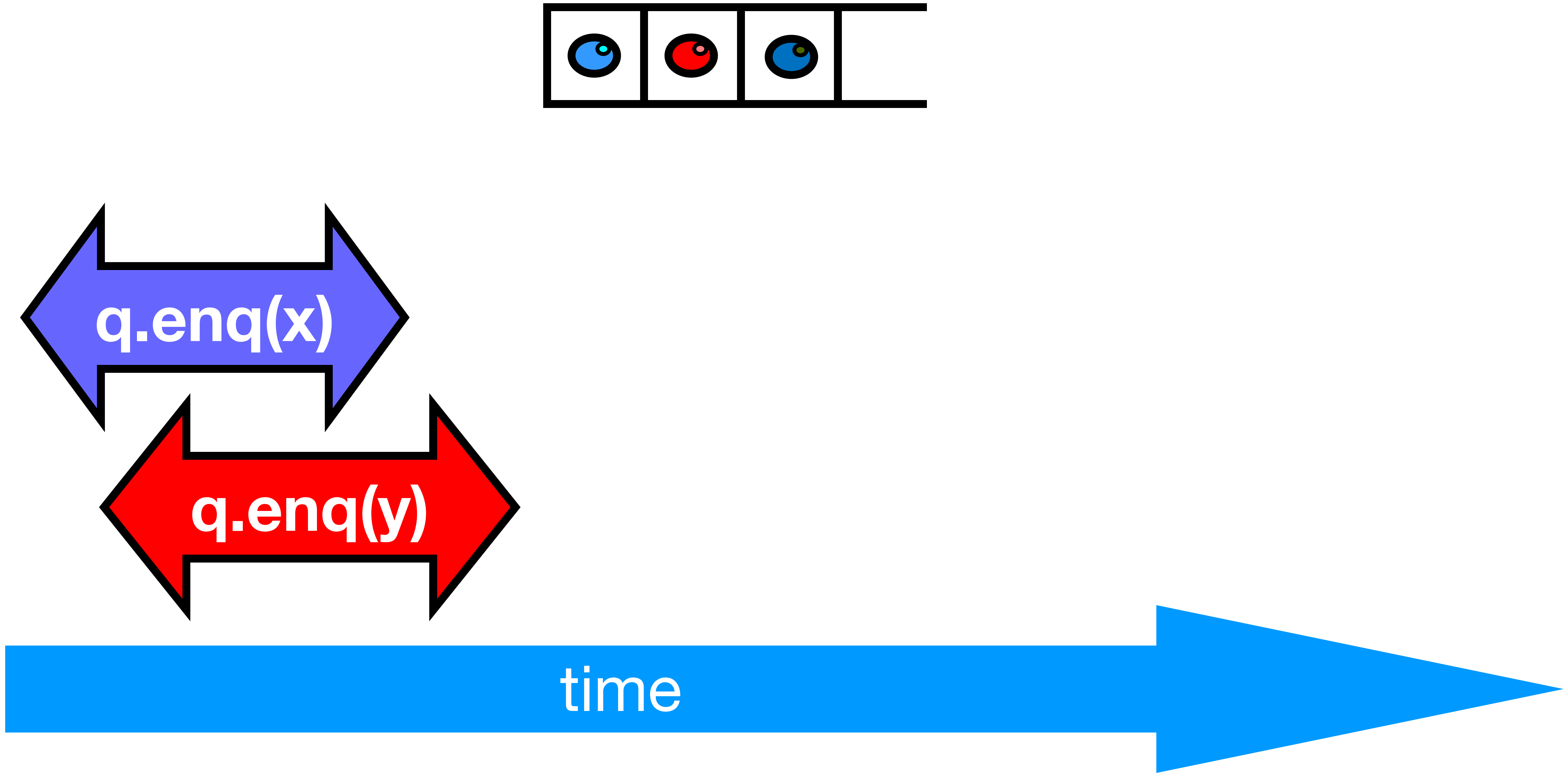

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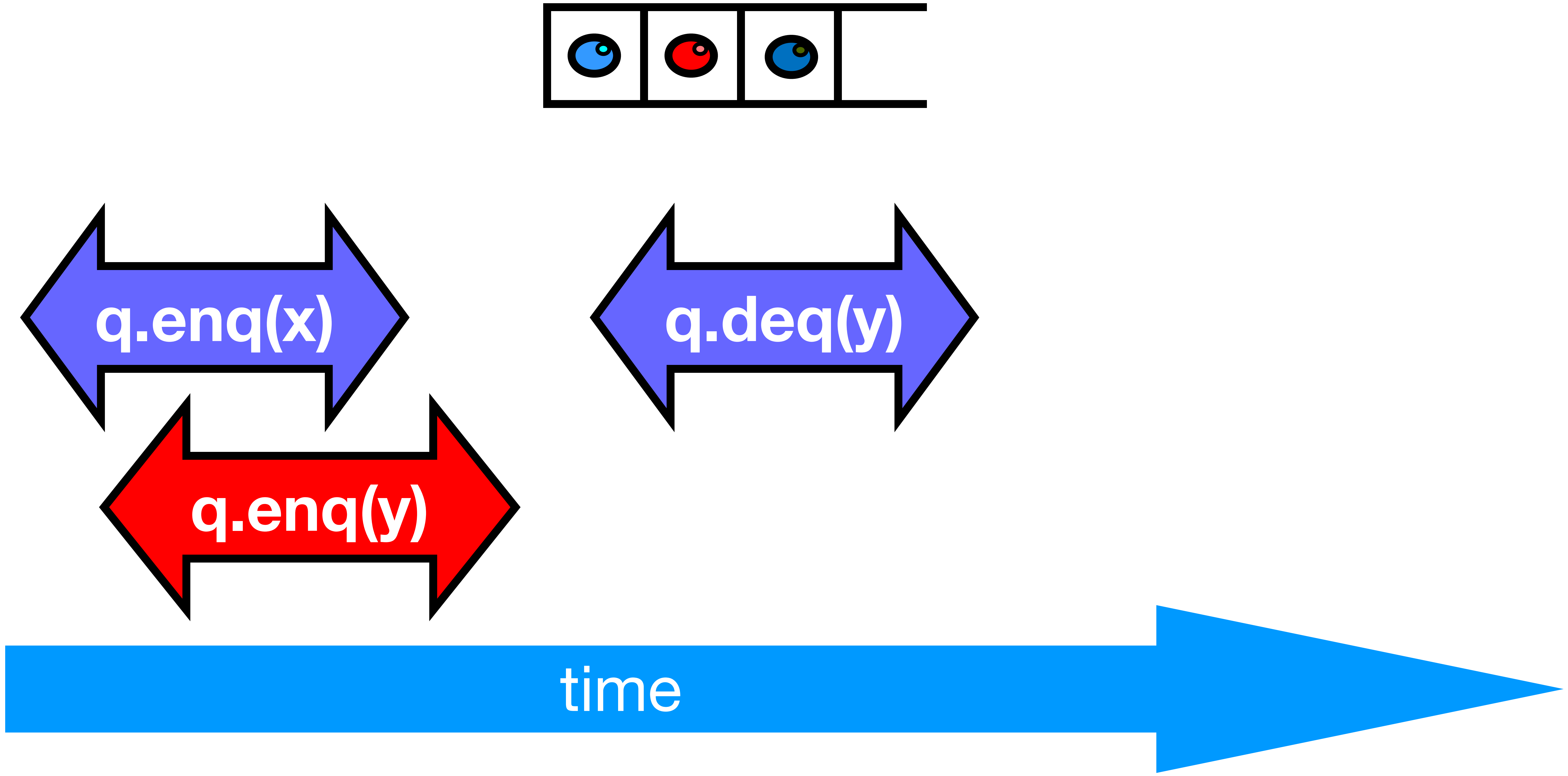

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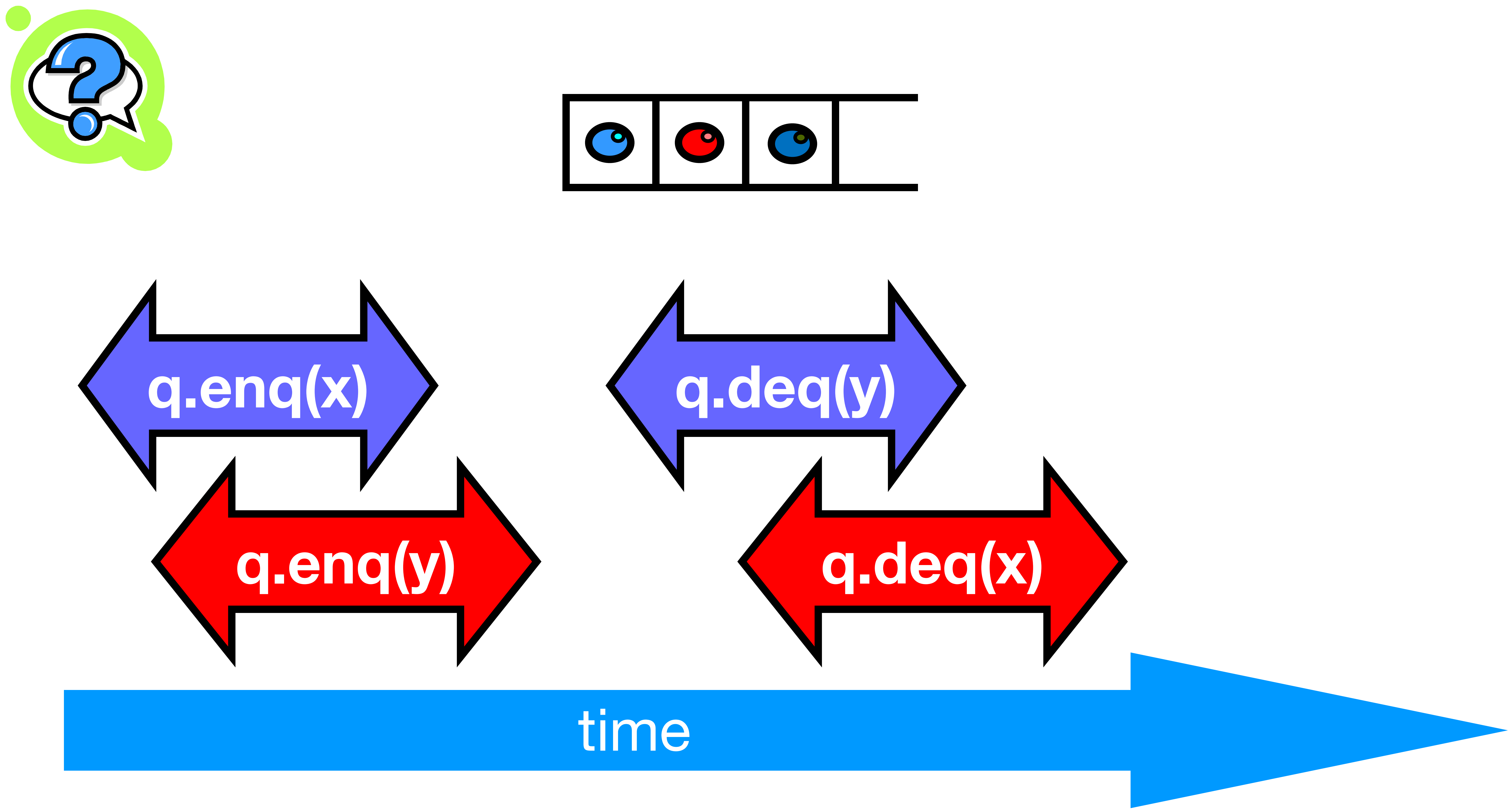

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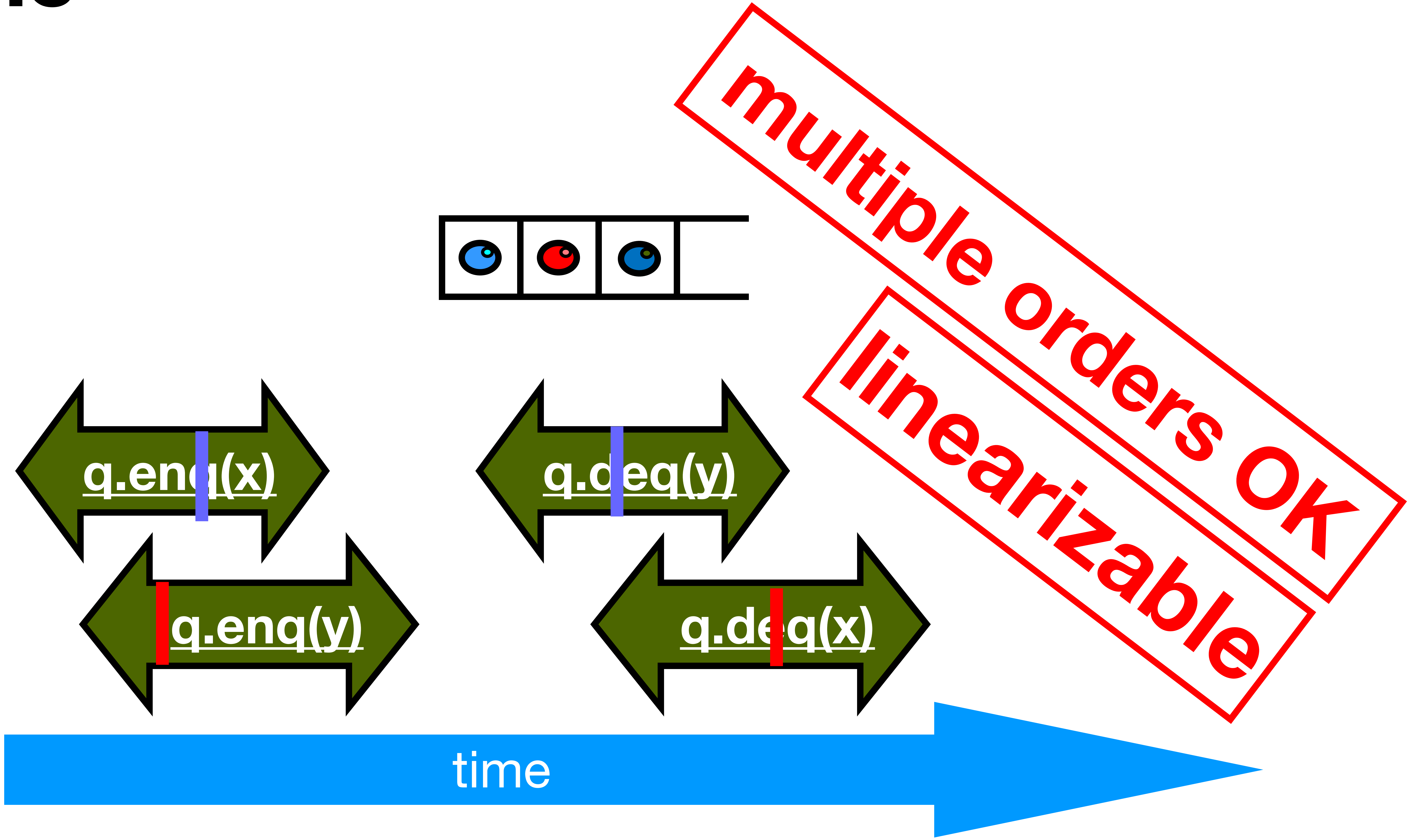
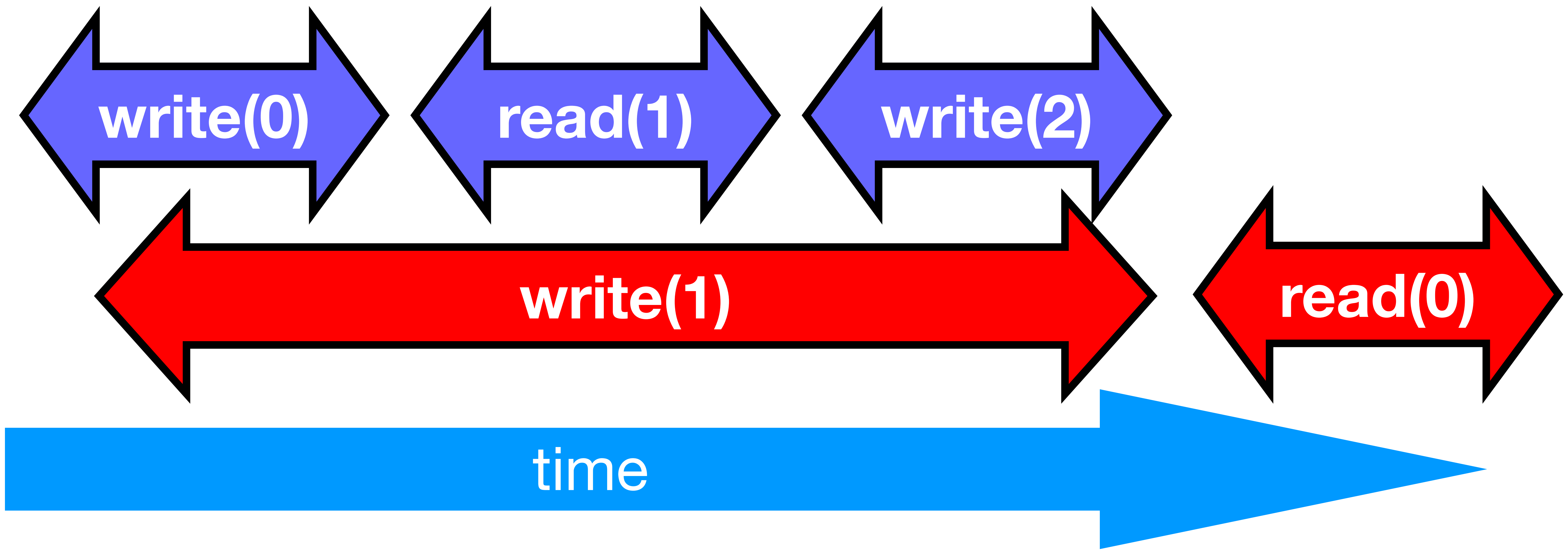
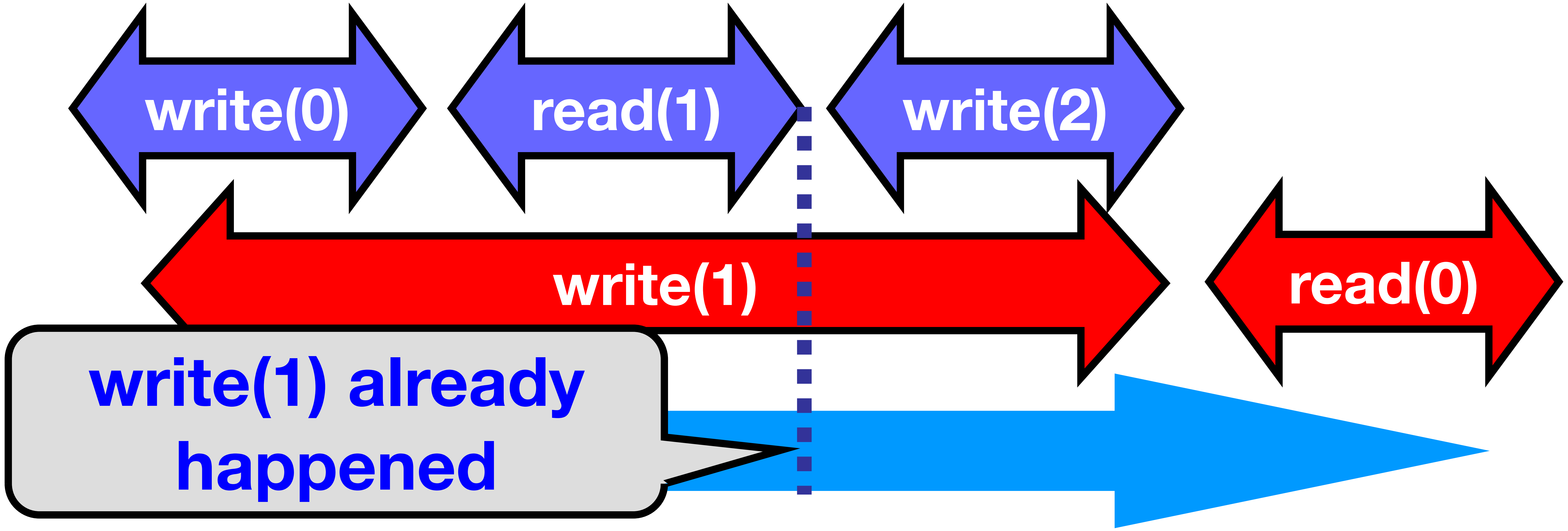


q.enq(x)
q.enq(y)
q.deq(y)
q.deq(x)
time
multiple orders OK
linearizable

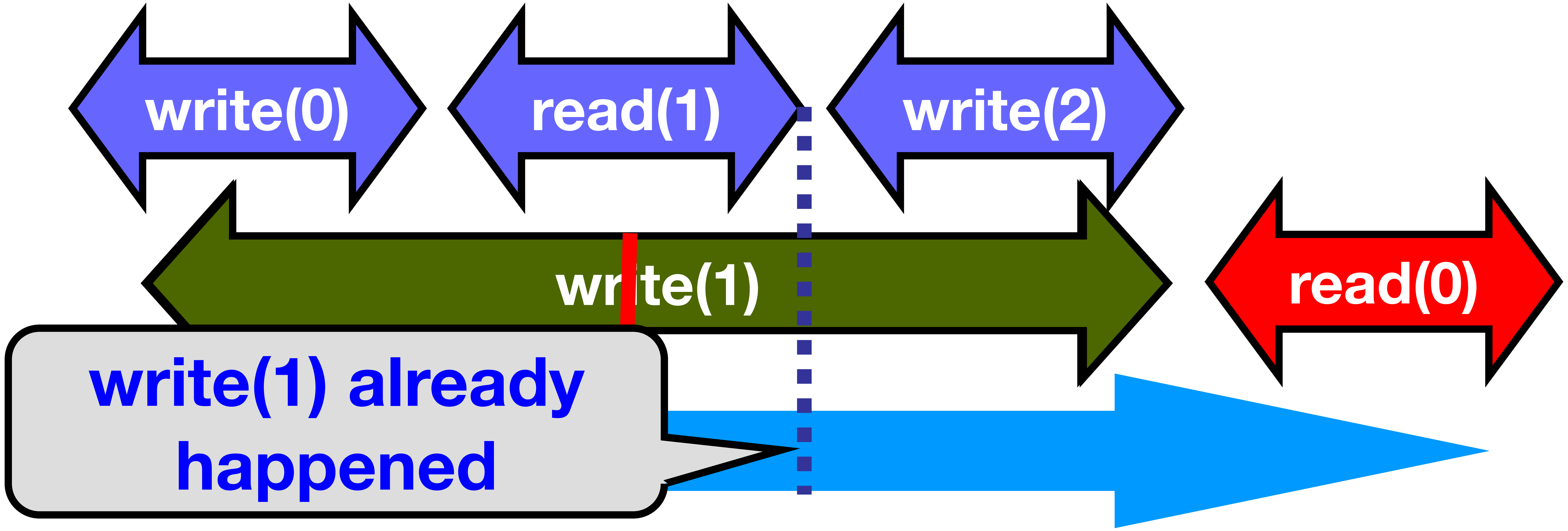
Read/Write Register Example



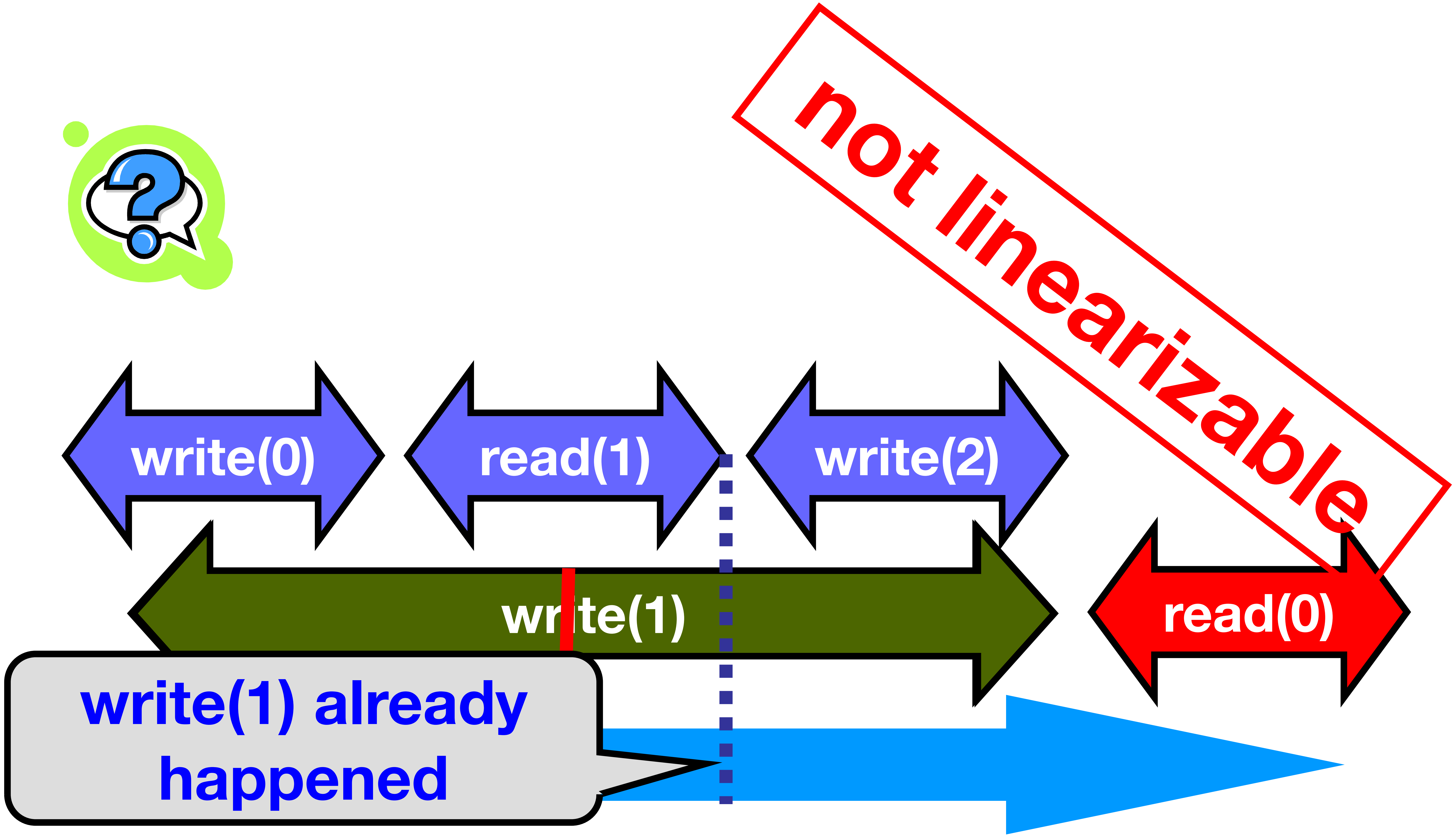
Read/Write Register Example



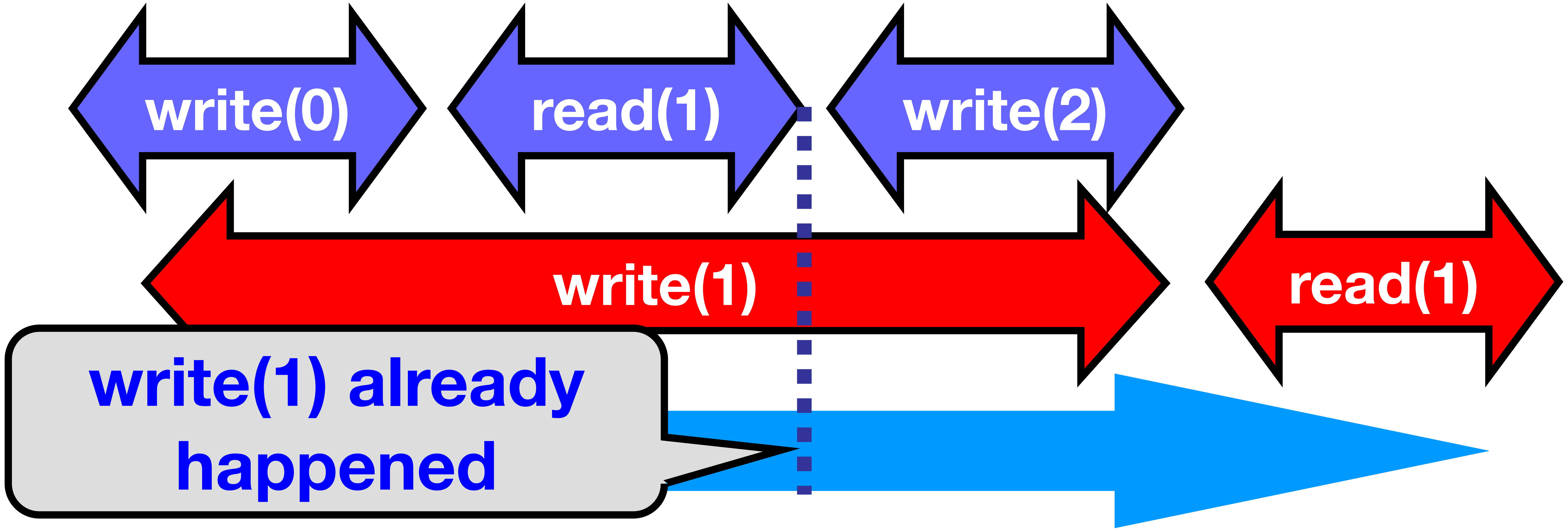
Read/Write Register Example



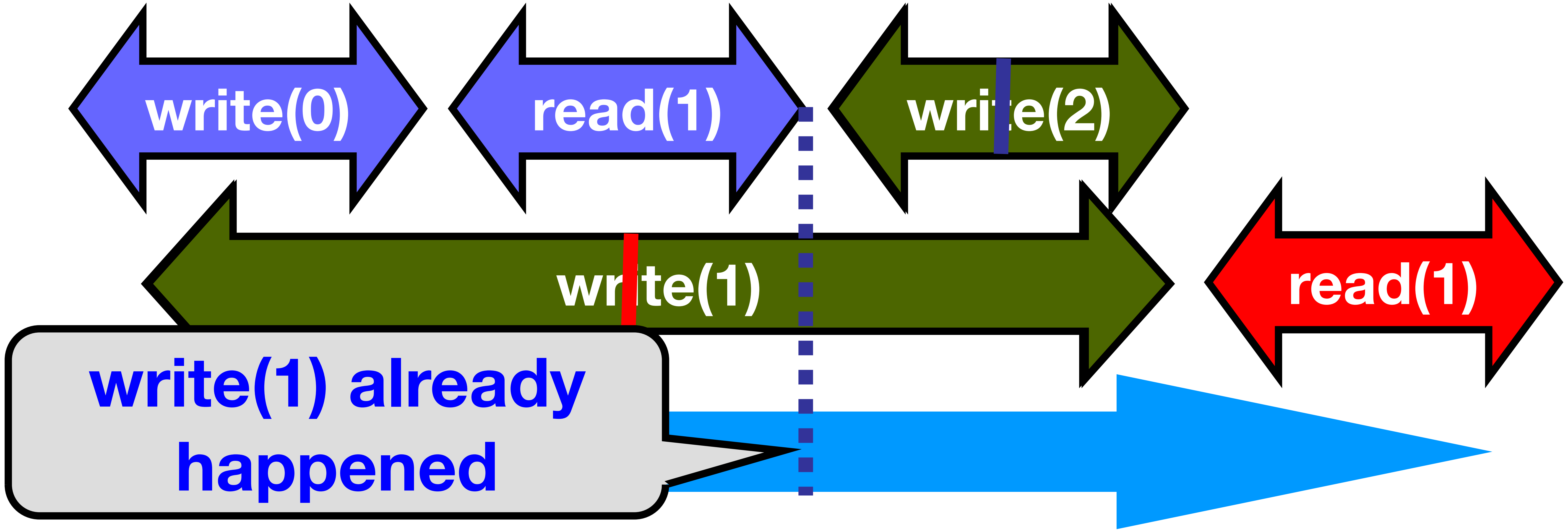
Read/Write Register Example



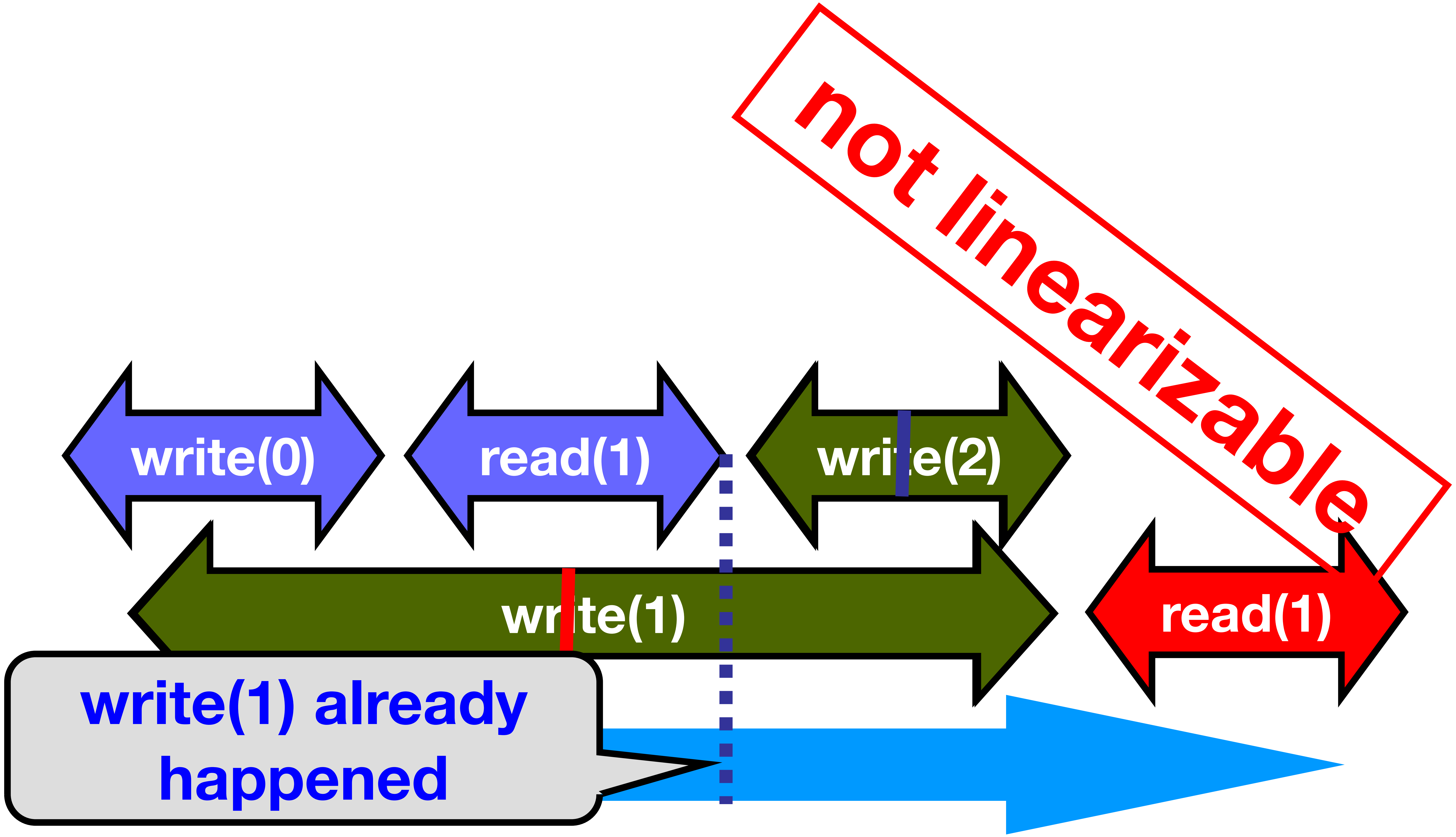
Read/Write Register Example



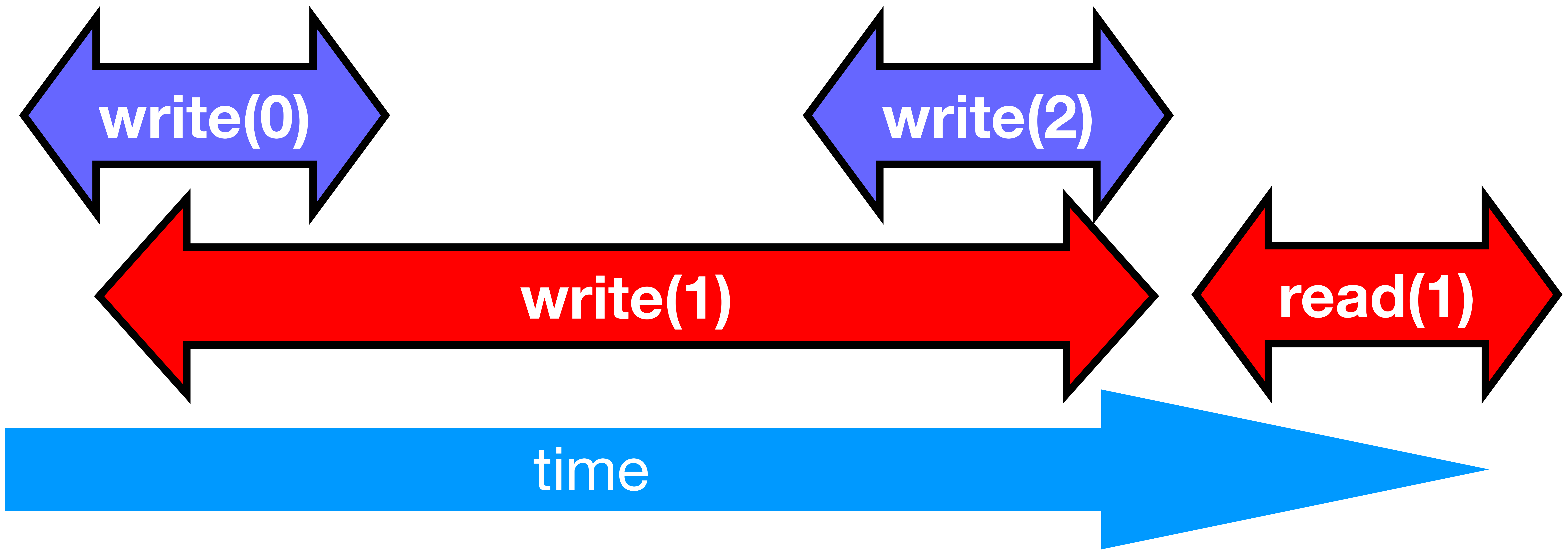
Read/Write Register Example



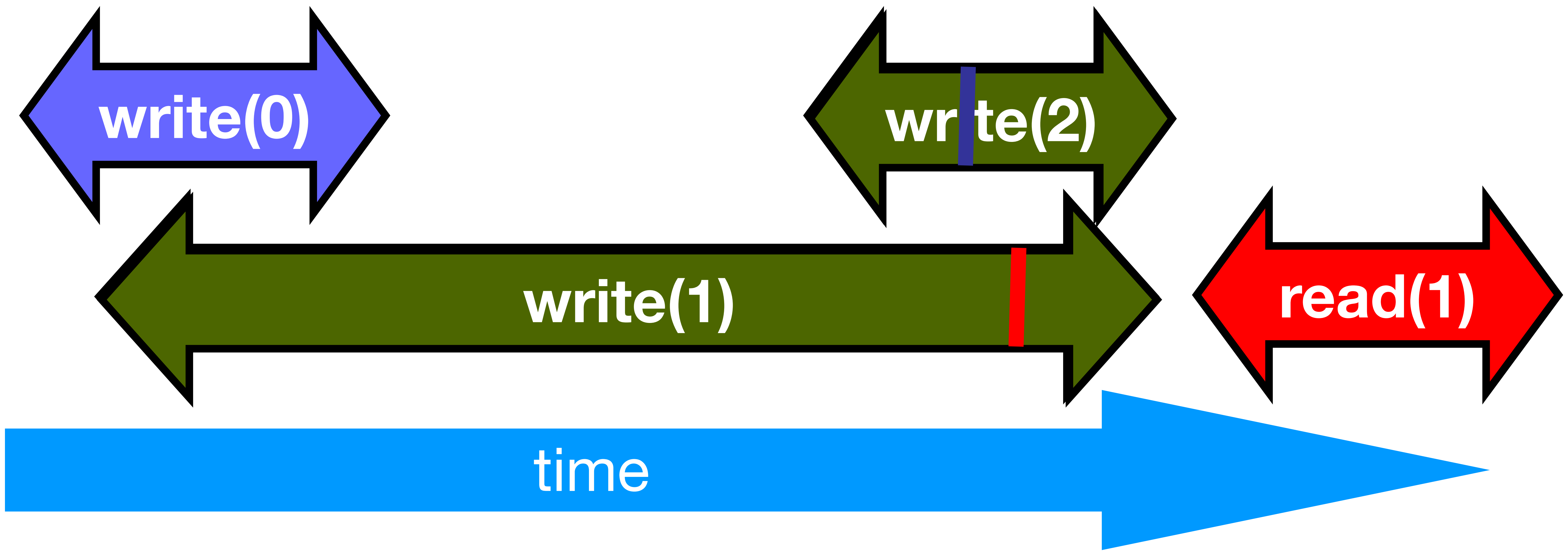
Read/Write Register Example



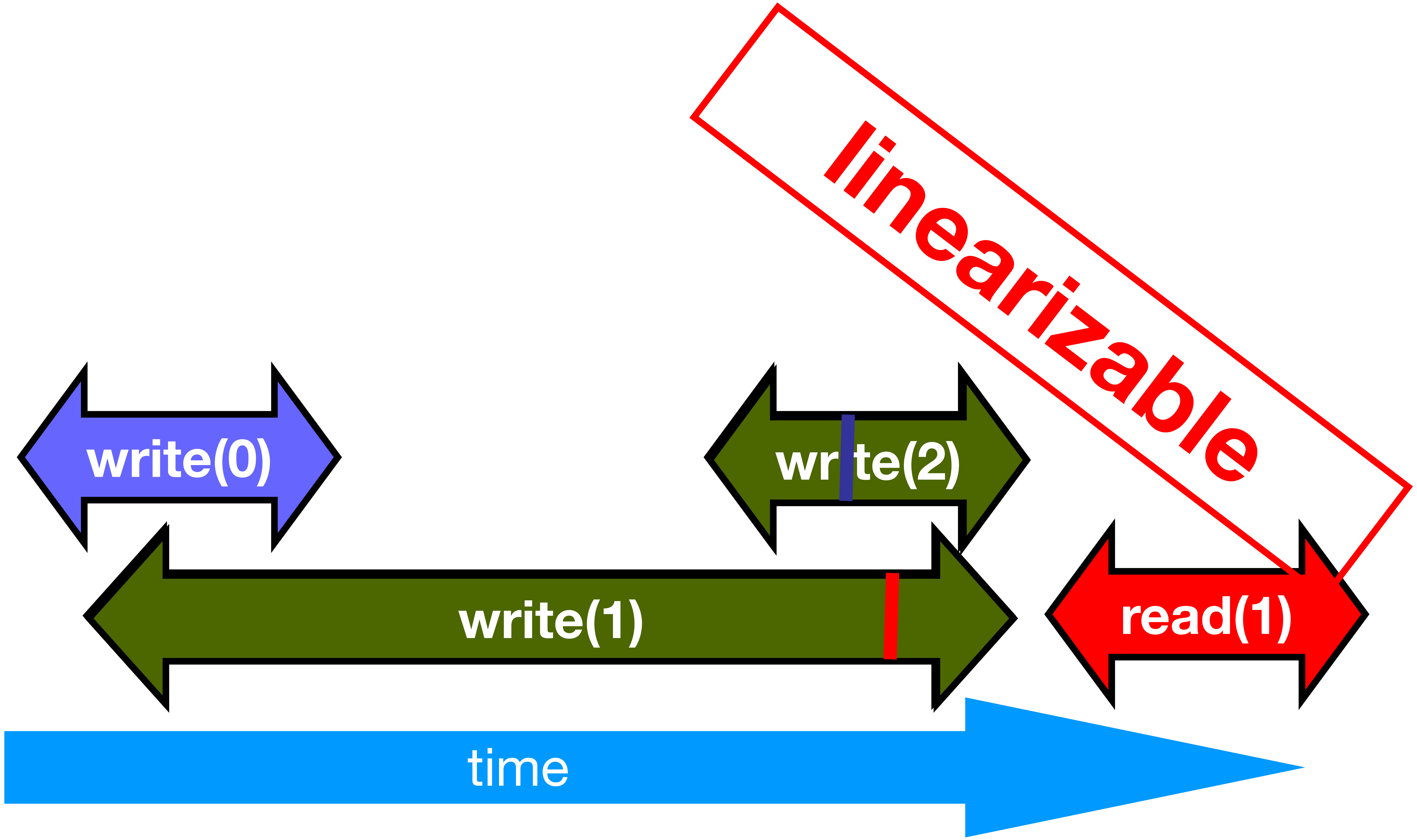
Read/Write Register Example



Read/Write Register Example



Read/Write Register Example



Talking About Executions

- Why?
  - Can’t we specify the linearization point of each operation without describing an execution?
- Not Always
  - In some cases, linearization point ***depends on the execution***

Formal Model of Executions

- Define precisely what we mean
  - Ambiguity is bad when intuition is weak
- Allow reasoning
  - Formal
  - But mostly informal
    - In the long run, actually, more important

Split Method Calls into Two Events

- Invocation
  - method name & args
  - **`q.enq(x)`**
- Response
  - result or exception
  - **`q.enq(x)`** returns **`void`**
  - **`q.deq()`** returns **`x`**
  - **`q.deq()`** throws **`empty`**

- Note that I'm following the convention of the book
  - Book uses OO
  - Code in this course uses FP
- Note that we're still reasoning using ***objectivism***
- For the current discussion, distinction doesn't matter
  - **`q.enq(x)`** is read as **`enq q x`** in code
  - Returns **`void`** is read as returns **`()`**
  - Throws **`empty`** is read as raises **`Empty`**

Invocation Notation

A q.enq(x)

Invocation Notation

$\boxed{A}$ q.enq(x)

thread

Invocation Notation

A q.enq(x)

thread

method

Invocation Notation

A q.enq(x)

thread

method

object

Invocation Notation

A q.enq(x)

thread

method

object

arguments

Response Notation

A q: void

Response Notation

$\boxed{A}$ q: void

thread

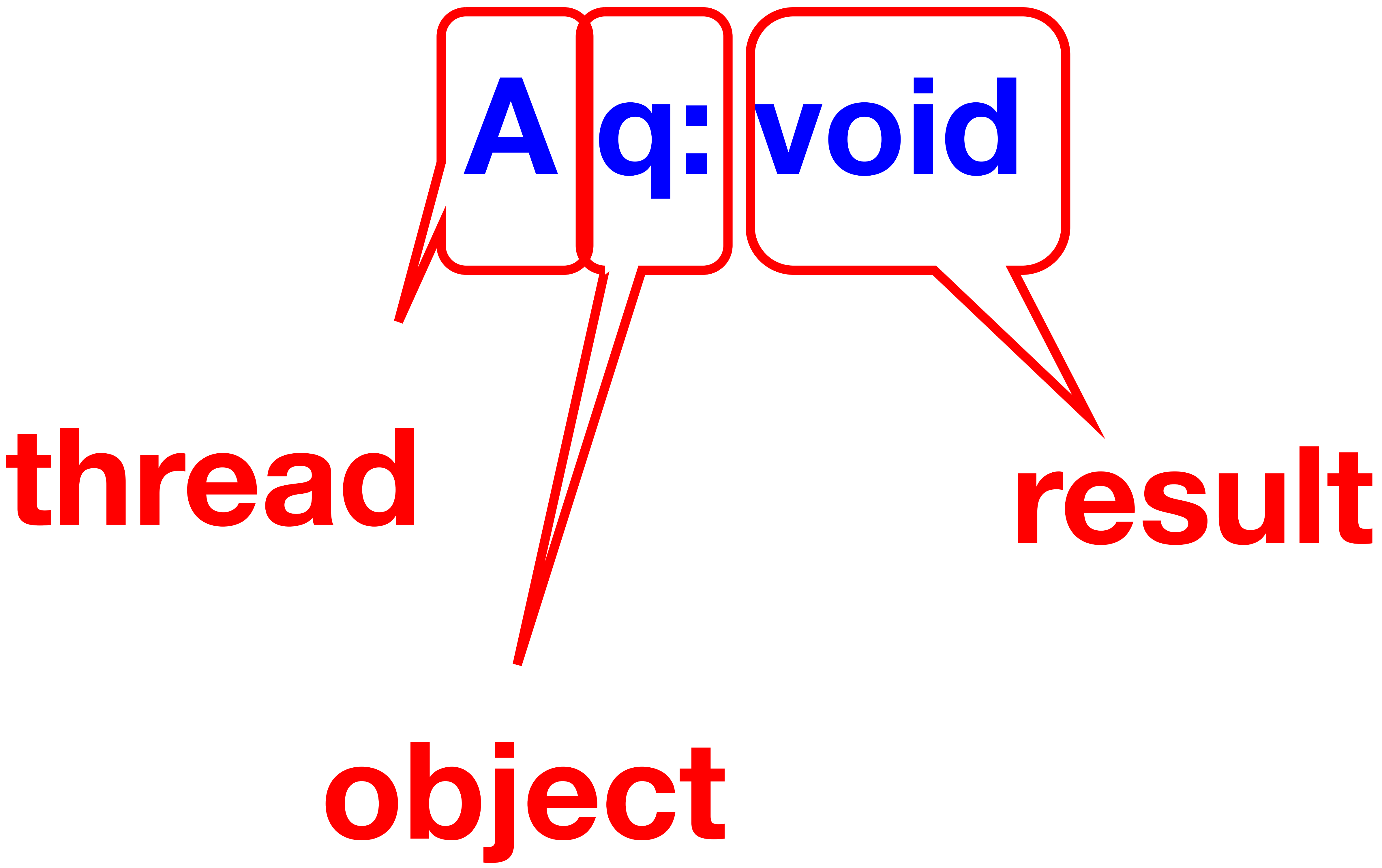
Response Notation

A q: void

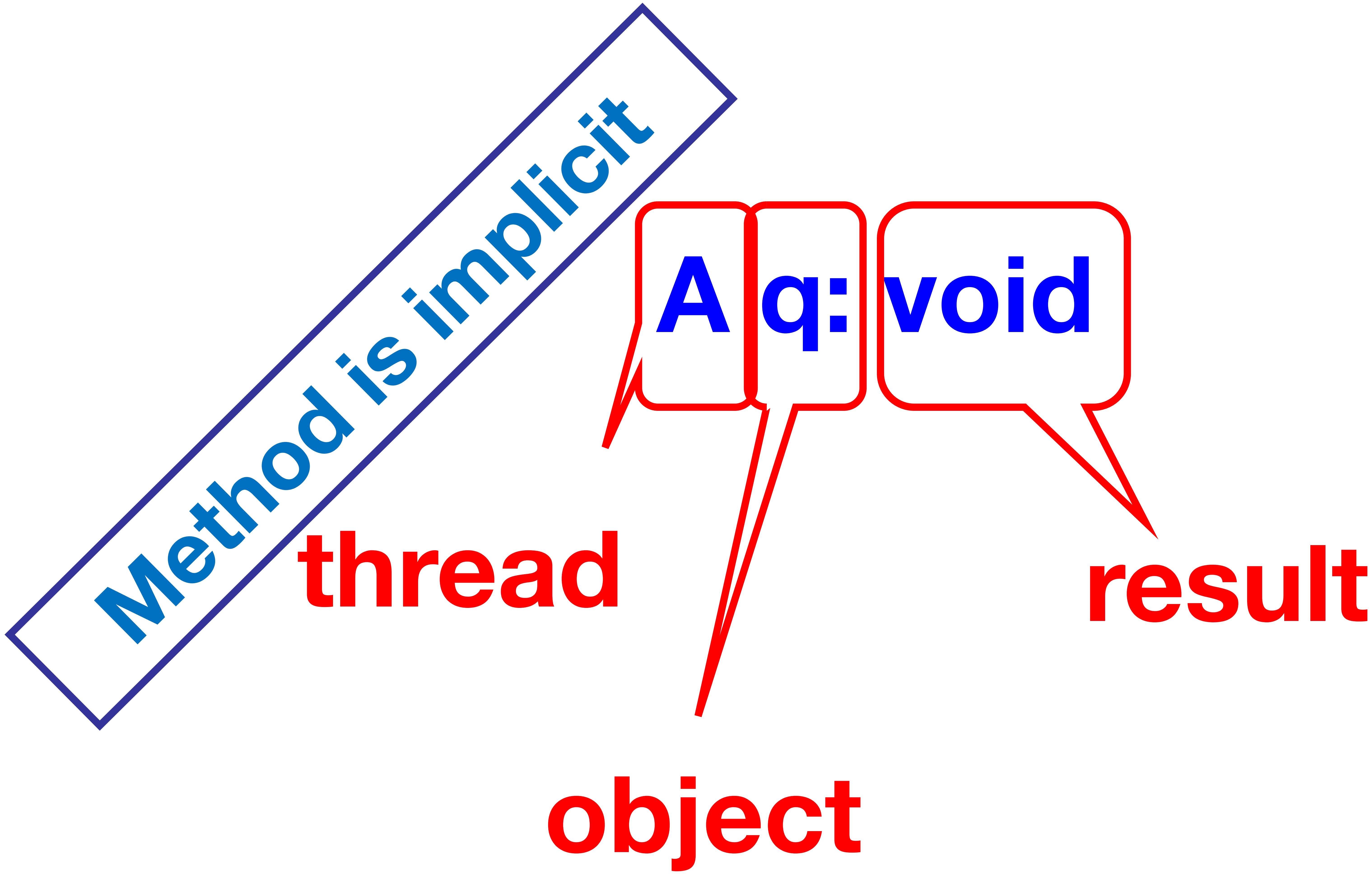
thread

result

Response Notation



Response Notation



Response Notation

Method is implicit

A q: empty()

thread

object

exception

History — Describing an execution

H =

```
A q.enq(3)
A q:void
A q.enq(5)
B p.enq(4)
B p:void
B q.deq()
B q:3
```

Sequence of invocations and responses

History — Describing an execution

- Invocation & response *match* if

Thread names agree

Object names agree

```
A q.enq(3)
A q:void
```

Method call

Object Projections

$H =$

```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
```

Object Projections

```
A q.enq(3)
A q:void
```

$H|q =$

```
B q.deq()
B q:3
```

Thread Projections

H =

```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
```

Thread Projections

$H|B =$

```
B p.enq(4)
B p:void
B q.deq()
B q:3
```

Complete Subhistory

H =

```
A q.enq(3)
A q:void
A q.enq(5)
B p.enq(4)
B p:void
B q.deq()
B q:3
```

An invocation is *pending* if it has no matching respnse

Complete Subhistory

H =

```
A q.enq(3)
A q:void
A q.enq(5)
B p.enq(4)
B p:void
B q.deq()
B q:3
```

May or may not have taken effect

Complete Subhistory

H =

```
A q.enq(3)
A q:void
A q.enq(5)
B p.enq(4)
B p:void
B q.deq()
B q:3
```

may discard
pending invocations

Complete Subhistory

```
A q.enq(3)
A q:void
```

Complete(H) =

```
B p.enq(4)
B p:void
B q.deq()
B q:3
```

Sequential Histories

```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
A q:enq(5)
```

Sequential Histories

```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
A q:enq(5)
```

match

Sequential Histories

```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
A q:enq(5)
```

match

match

Sequential Histories

```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
A q:enq(5)
```

match

match

match

Sequential Histories

```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
A q:enq(5)
```

match

match

match

Final pending invocation OK

Sequential Histories

```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
A q:enq(5)
```

match

match

match

Final pending invocation OK

Method calls of different threads do not interleave

Well-formed Histories

```
     A q.enq(3)
     B p.enq(4)
     B p:void
H=   B q.deq()
     A q:void
     B q:3
```

Well-formed Histories

Per-thread projections sequential

```
    A q.enq(3)
    B p.enq(4)
    B p:void
H=  B q.deq()
    A q:void
    B q:3
```

```
      B p.enq(4)
H|B=  B p:void
      B q.deq()
      B q:3
```

Well-formed Histories

Per-thread projections sequential

```
H=  A q.enq(3)
    B p.enq(4)
    B p:void
    B q.deq()
    A q:void
    B q:3
```

```
H|B= B p.enq(4)
     B p:void
     B q.deq()
     B q:3
```

```
H|A= A q.enq(3)
     A q:void
```

Equivalent Histories

Threads see the same thing in both

$$\left\{\begin{array}{l} H|A = G|A \\ H|B = G|B \end{array}\right.$$

H=

```
A q.enq(3)
B p.enq(4)
B p:void
B q.deq()
A q:void
B q:3
```

G=

```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
```

Sequential Specifications

- A sequential ***specification*** is some way of telling whether a
  - Single-thread, single-object history
  - Is ***legal***
- For example:
  - Pre and post-conditions
  - But plenty of other techniques exist …

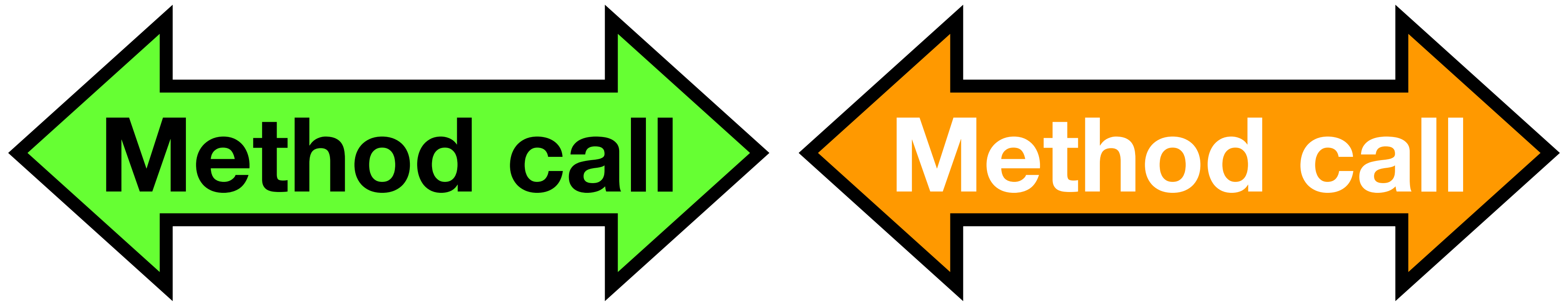
Legal Histories

- A sequential *(multi-object)* history H is *legal* if
  - For every object **x**
  - **H|x** is in the sequential spec for **x**

Precedence

```
A q.enq(3)
B p.enq(4)
B p.void
A q:void
B q.deq()
B q:3
```

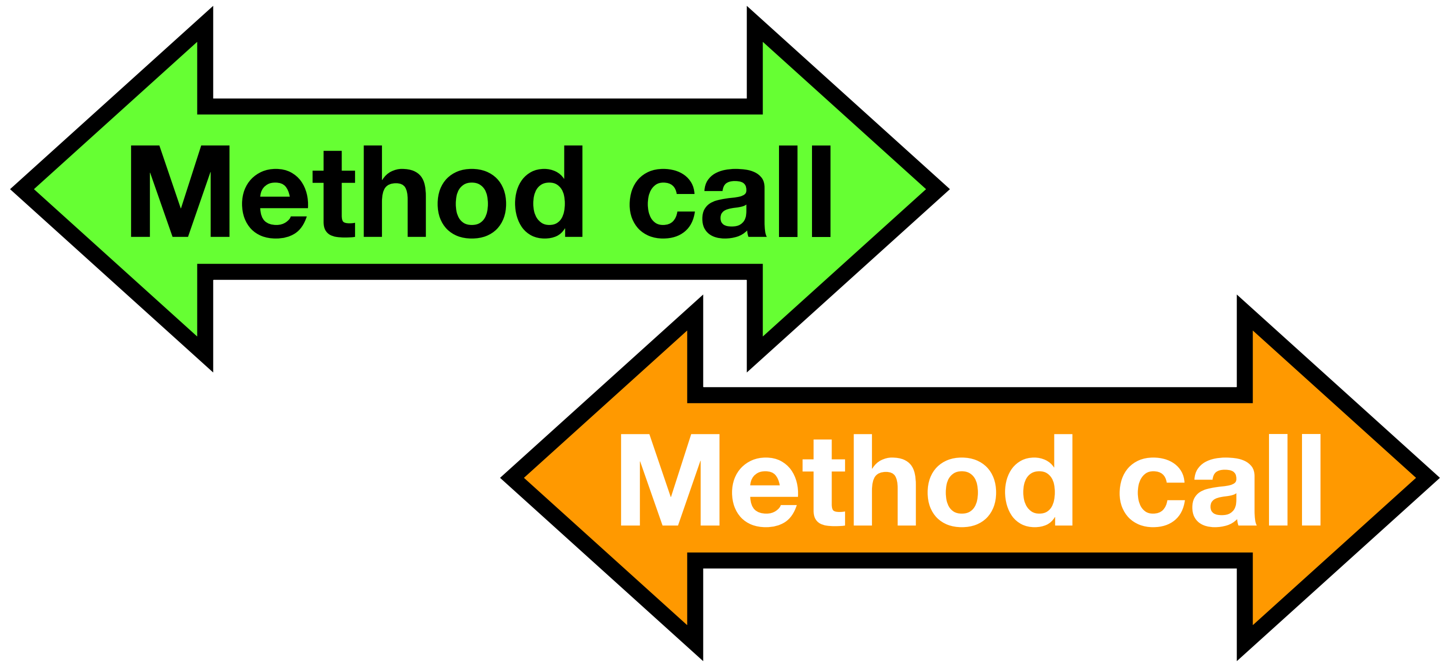
A method call precedes another if response event precedes invocation event



Non-Precedence

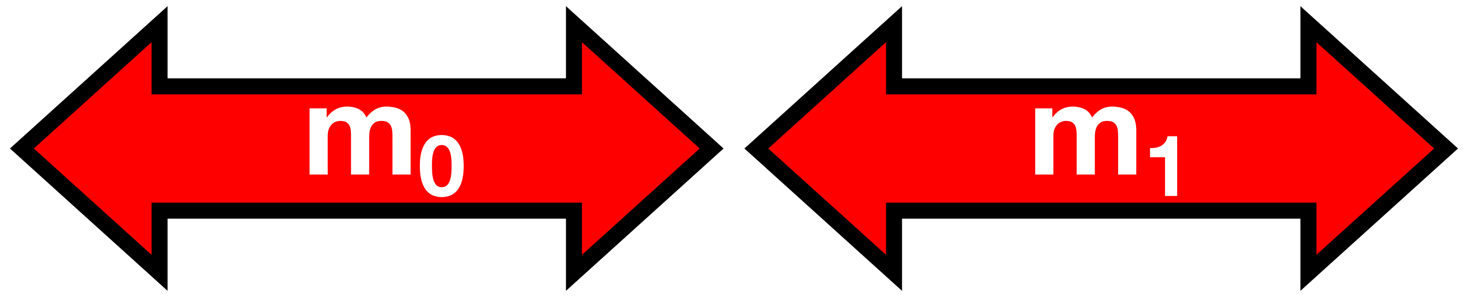
```
A q.enq(3)
B p.enq(4)
B p.void
B q.deq()
A q:void
B q:3
```

Some method calls **overlap** one another



Notation

- Given
  - History **H**
  - method executions $\mathbf{m_0}$ and $\mathbf{m_1}$ in **H**
- We say $\mathbf{m_0} \rightarrow_{\mathbf{H}} \mathbf{m_1}$, if
  - $\mathbf{m_0}$ precedes $\mathbf{m_1}$



- Relation $\mathbf{m_0} \rightarrow_{\mathbf{H}} \mathbf{m_1}$ is a
  - Partial order
  - Total order if **H** is sequential

Linearizability

- History H is ***linearizable*** if it can be extended to **G** by
  - Appending zero or more responses to pending invocations
  - Discarding other pending invocations
- So that G is equivalent to
  - Legal sequential history **S**
  - where $\rightarrow_G \subset \rightarrow_S$

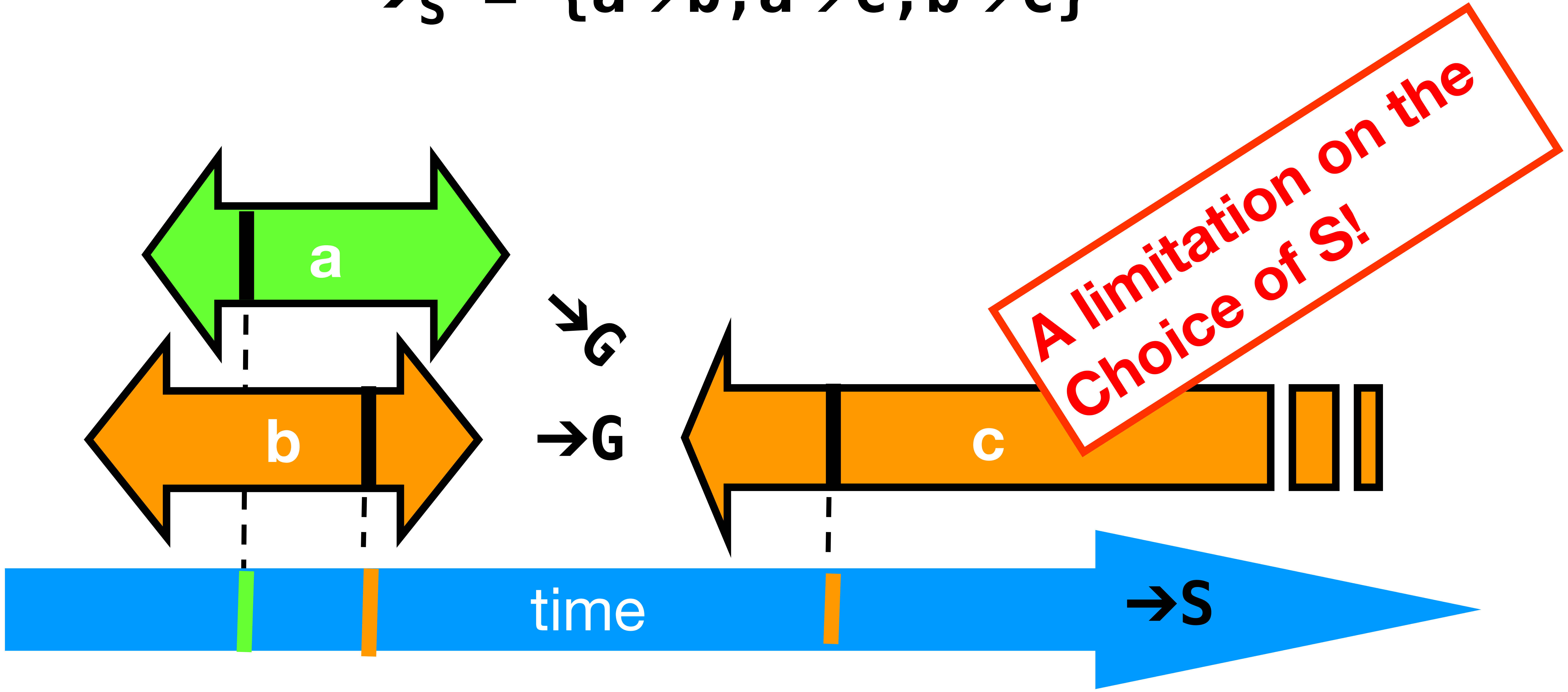
Remarks on Linearizability

- Some pending invocations
  - Took effect, so keep them
  - Discard the rest
- Condition $\rightarrow_{\mathbf{G}} \subset \rightarrow_{\mathbf{S}}$
  - Means that **S** respects "real-time order" of **G**

Ensuring $\rightarrow_G \subset \rightarrow_S$

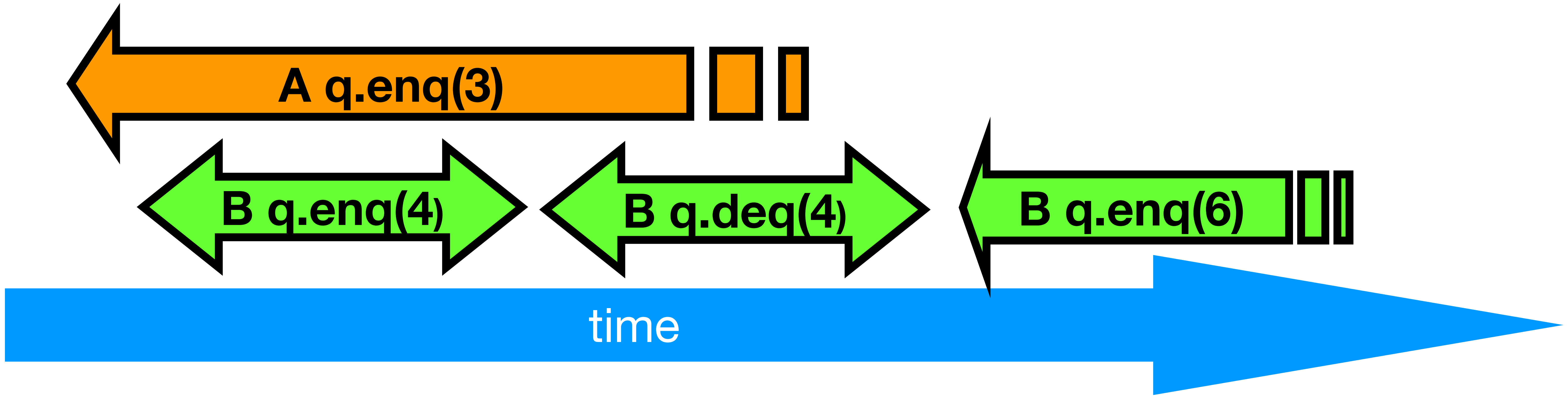
$\rightarrow_G$ = {a→c,b→c}

$\rightarrow_S$ = {a→b,a→c,b→c}



Example

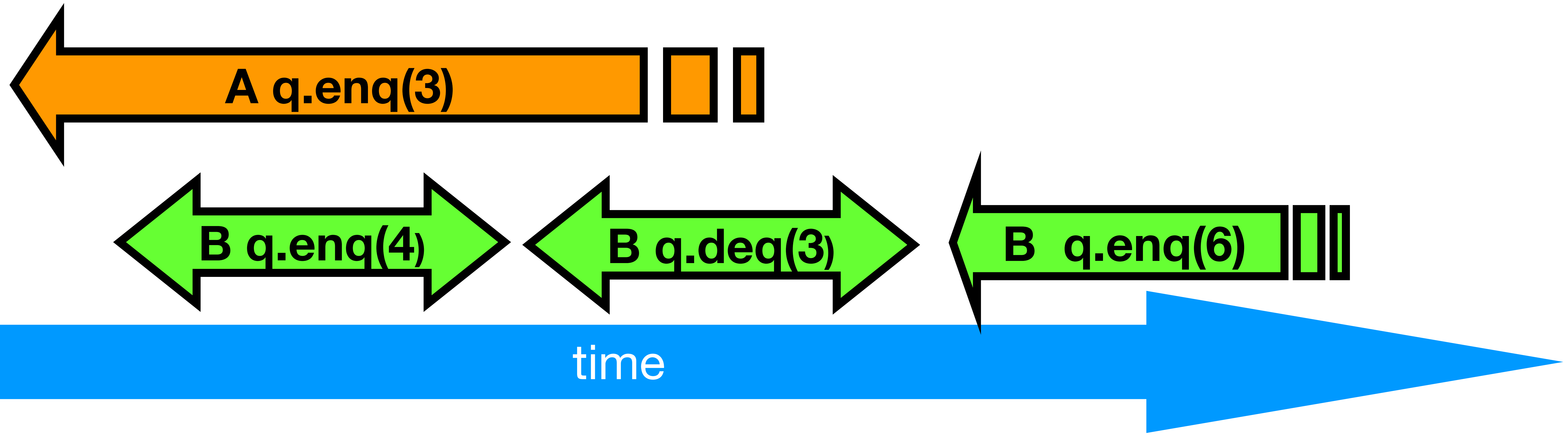
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
B q:enq(6)
```



Example

```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
B q:enq(6)
```

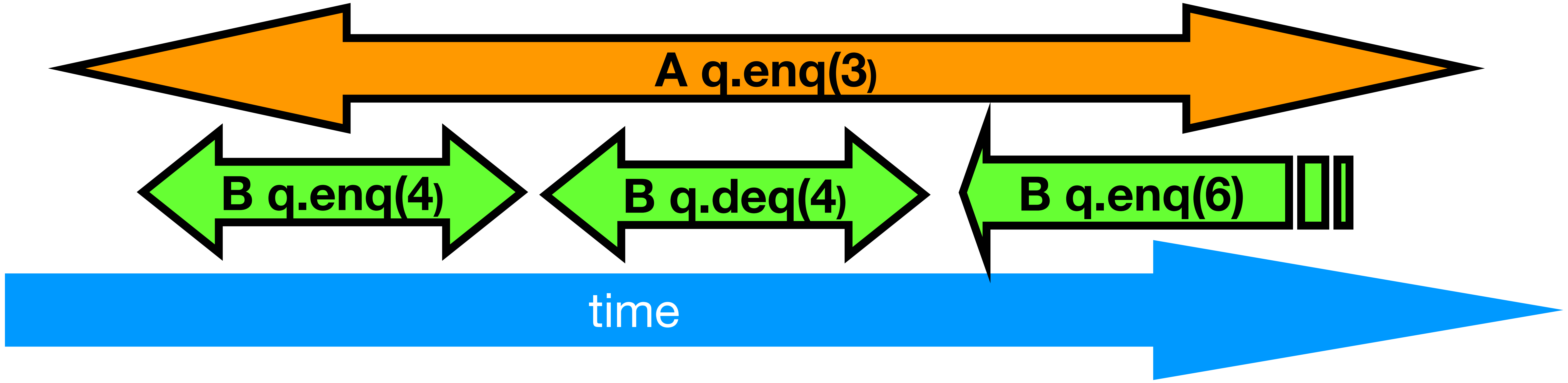
Complete this pending invocation



Example

```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
B q:enq(6)
A q:void
```

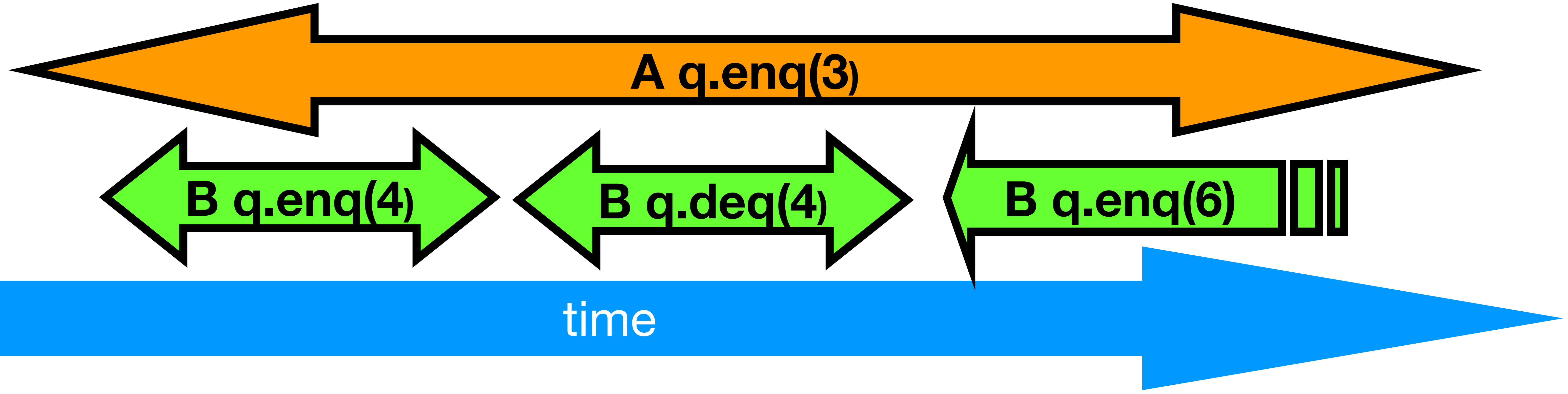
Complete this pending invocation



Example

discard this one

```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
B q:enq(6)
A q:void
```

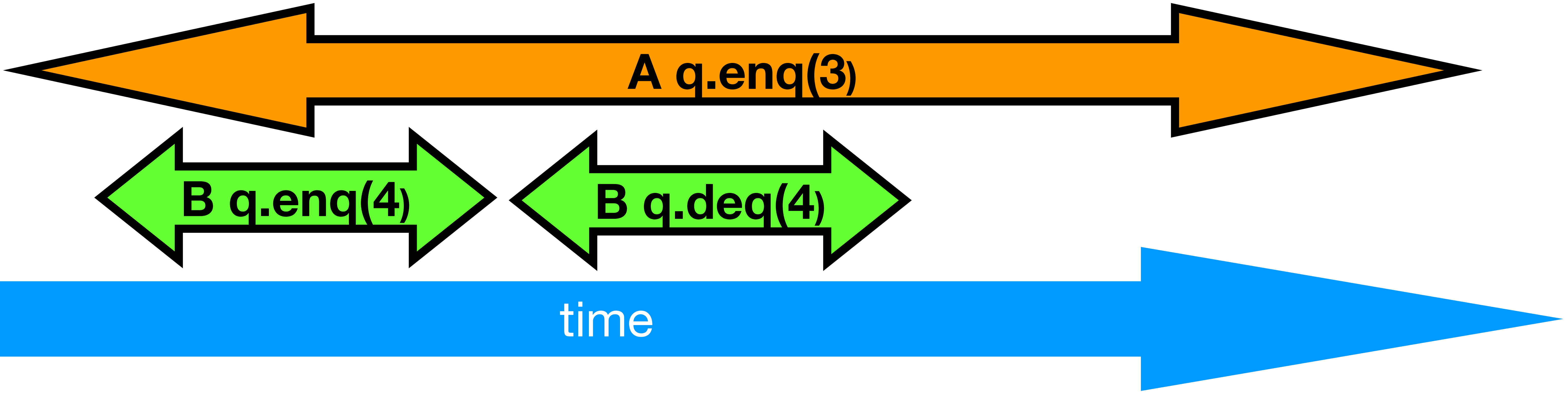


Example

discard this one

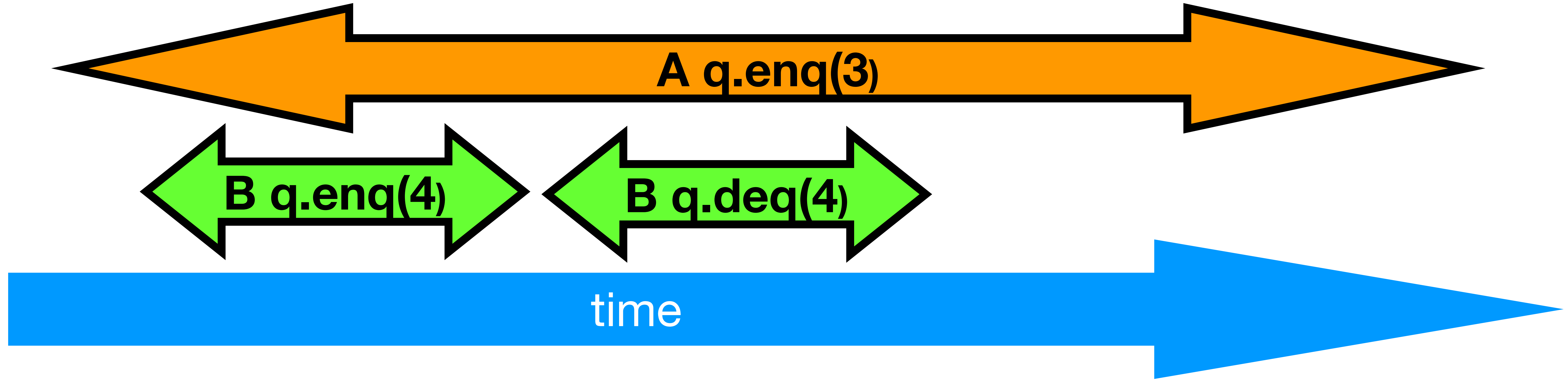
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4

A q:void
```



Example

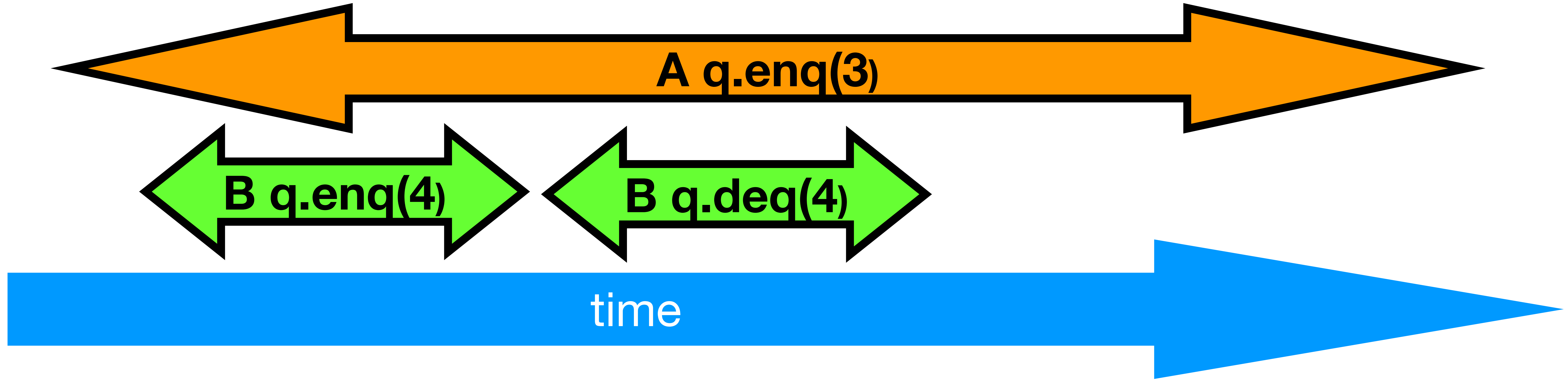
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
A q:void
```



Example

```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
A q:void
```

```
B q.enq(4)
B q:void
A q.enq(3)
A q:void
B q.deq()
B q:4
```

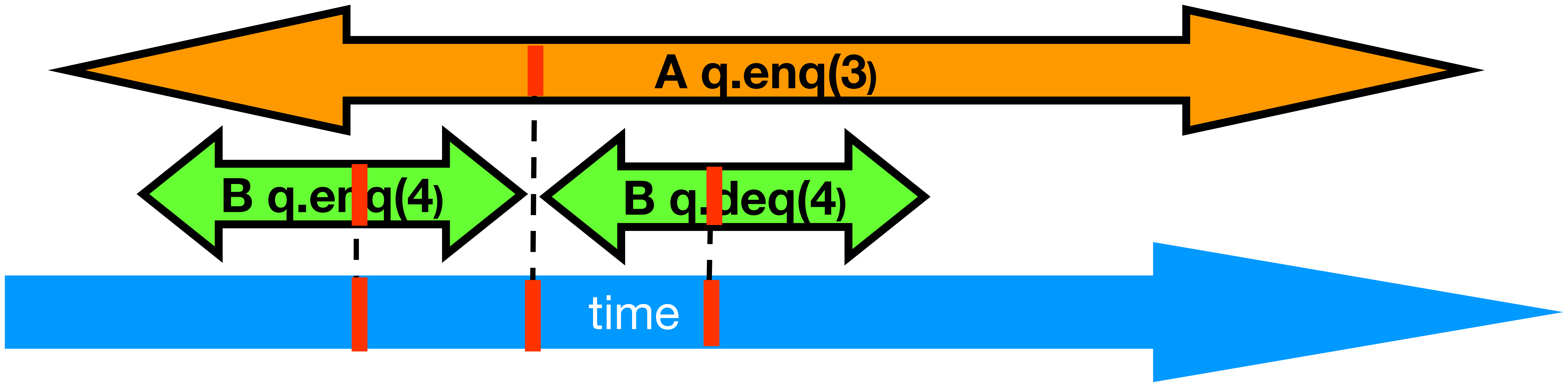


Example

```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
A q:void
```

Equivalent sequential history

```
B q.enq(4)
B q:void
A q.enq(3)
A q:void
B q.deq()
B q:4
```



Composability Theorem

- History H is linearizable if and only if
  - For every object x
  - H|x is linearizable
- We care about objects only!
  - (Materialism?)

Why does composability matter?

- Modularity
- Can prove linearizability of objects in isolation
- Can compose independently-implemented objects

Reasoning about Linearizability: Locking

```
let deq q =
  Mutex.lock q.lock;
  try
    if q.tail = q.head then
      raise Empty;
    match q.items.(q.head mod q.capacity) with
    | None -> assert false
    | Some x ->
        q.head <- q.head + 1;
        Mutex.unlock q.lock;
        x
  with e ->
    Mutex.unlock q.lock;
    raise e
```

Linearization points are when locks are released

More Reasoning — Wait-free

```
(** Enqueue - should be called by only ONE thread *)
let enq q x =
  (* Check if queue is full *)
  if q.tail - q.head = q.capacity then
    raise Full;
  (* Write to the array *)
  q.items.(q.tail mod q.capacity) <- Some x;
  (* Advance tail *)
  q.tail <- q.tail + 1
```

```
(** Dequeue - should be called by only ONE thread *)
let deq q =
  (* Check if queue is empty *)
  if q.tail = q.head then
    raise Empty;
  (* Read from the array *)
  match q.items.(q.head mod q.capacity) with
  | None -> assert false  (* Should never happen *)
  | Some x ->
      (* Advance head *)
      q.head <- q.head + 1;
      x
```

More Reasoning — Wait-free

```
(** Enqueue - should be called by only ONE thread
let enq q x =
  (* Check if queue is full *)
  if q.tail - q.head = q.capacity then
    raise Full;
  (* Write to the array *)
  q.items.(q.tail mod q.capacity)
  (* Advance tail *)
  q.tail <- q.tail + 1
```

```
ue - should be called by only ONE thread *)
=
eck if queue is empty *)
q.tail = q.head then
 raise Empty;
(* Read from the array *)
match q.items.(q.head mod q.capacity) with
| None -> assert false  (* Should never happen *)
| Some x ->
    (* Advance head *)
    q.head <- q.head + 1;
    x
```

Remember that there is only one enqueuer and only one dequeuer

Linearization order is order head and tail fields modified

Finding linearisation points

- Identify one atomic step where the method “happens”
  - Critical section
  - Machine instruction
- Doesn’t always work
  - Might need to define several different steps for a given method
  - We will see this phenomenon in future lectures

Linearizability: Summary

- Powerful specification tool for shared objects
- Allows us to capture the notion of objects being “atomic”
- Don’t leave home without it

Alternative: Sequential Consistency

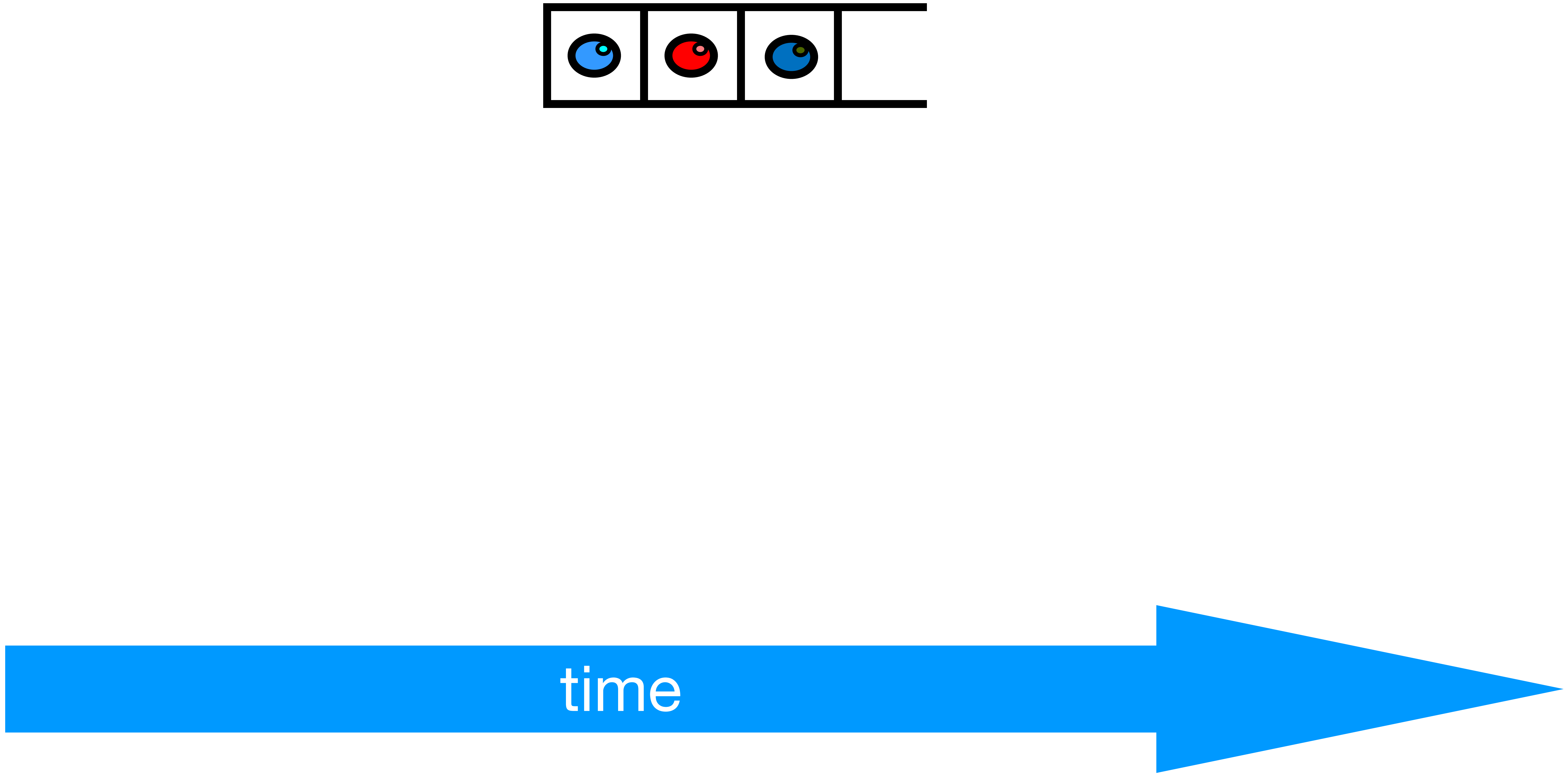
- History H is ***Sequentially Consistent*** if it can be extended to **G** by
  - Appending zero or more responses to pending invocations
  - Discarding other pending invocations
- So that G is equivalent to
  - Legal sequential history **S**
  - ~~where $\rightarrow_G \subset \rightarrow_S$~~

Differs from Linearizability

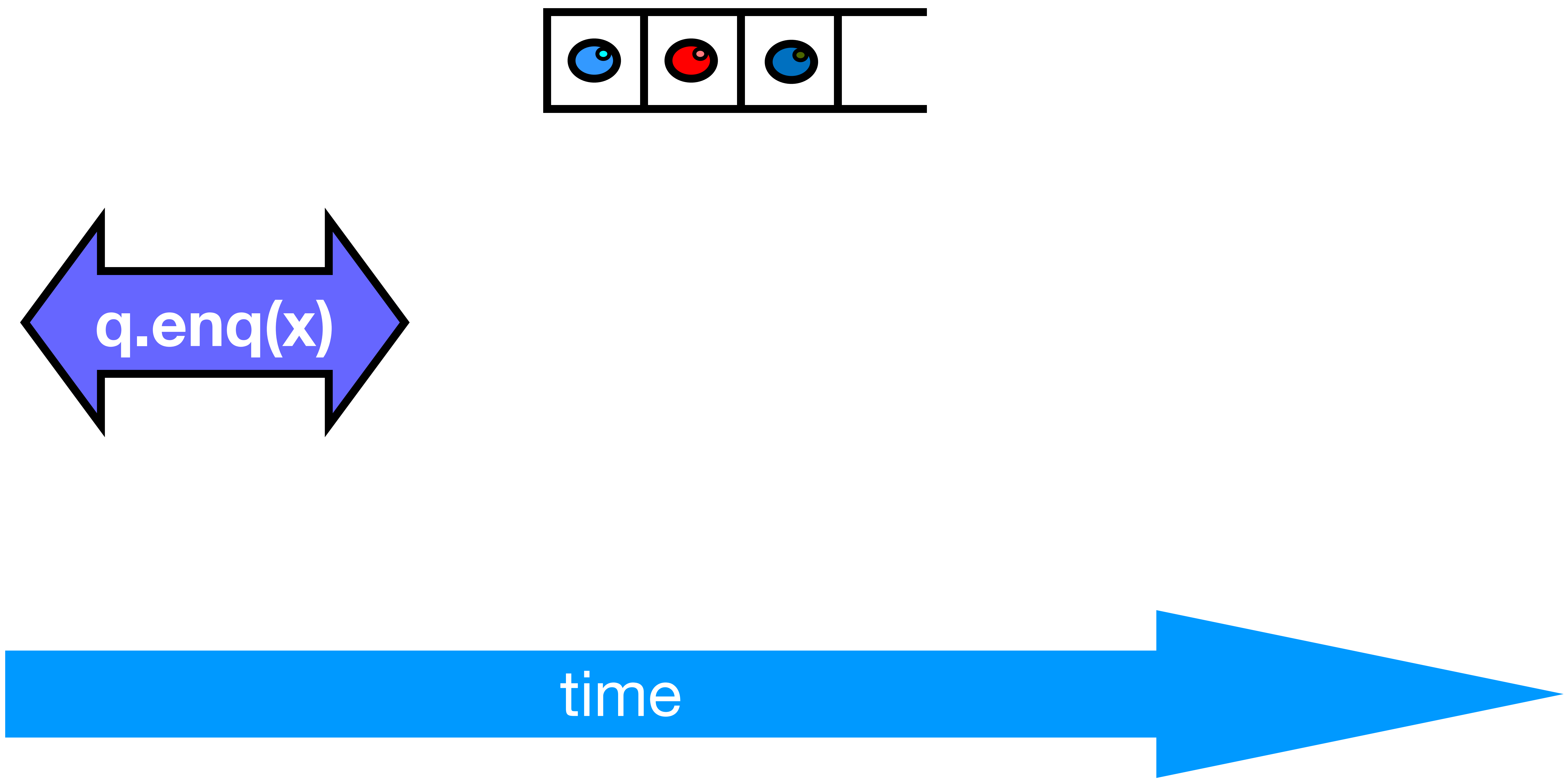
Sequential Consistency

- No need to preserve real-time order
  - ***Cannot*** re-order operations done by the same thread
  - ***Can*** re-order non-overlapping operations done by different threads
- Often used to describe multiprocessor memory architectures

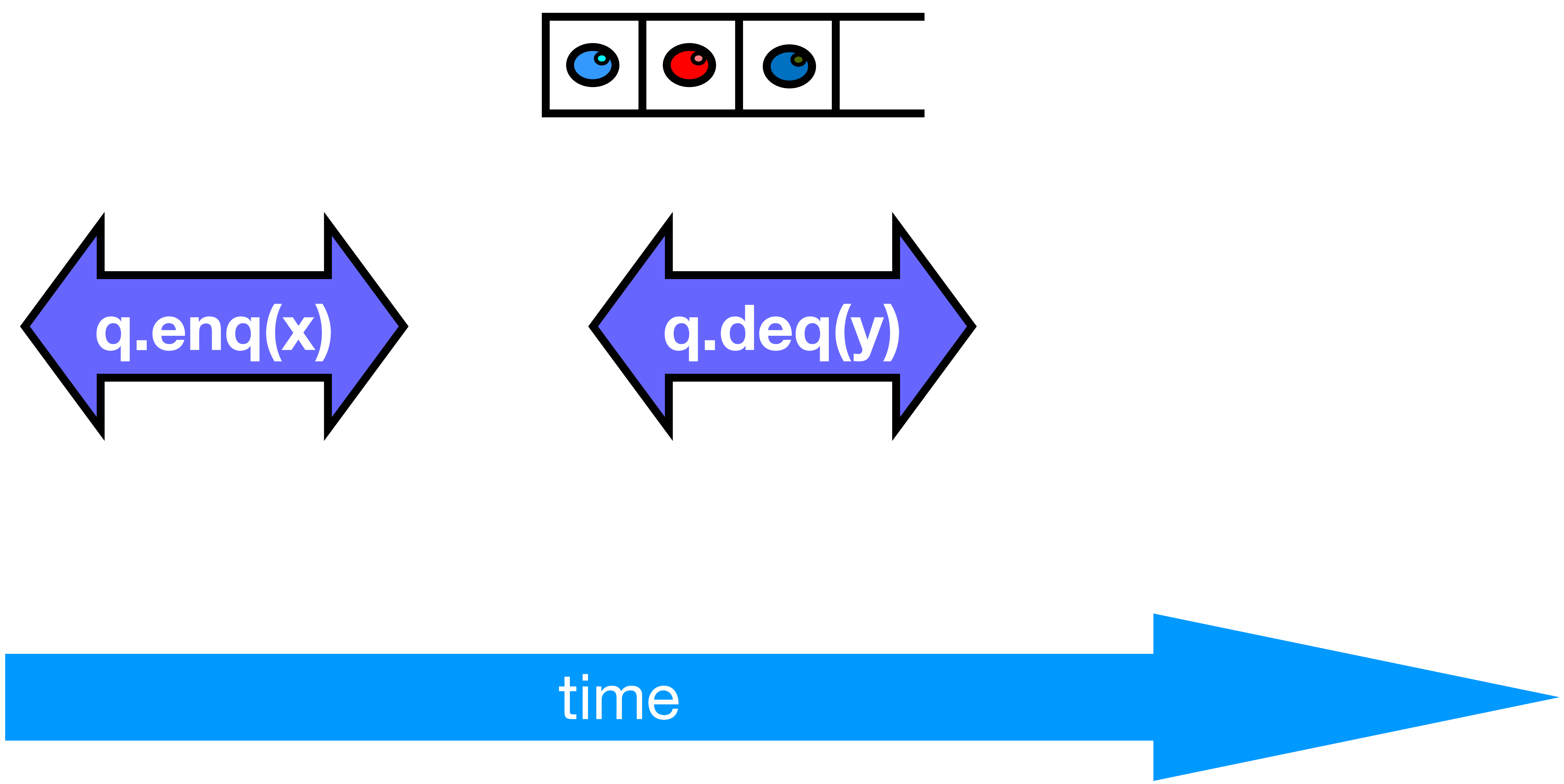
Example



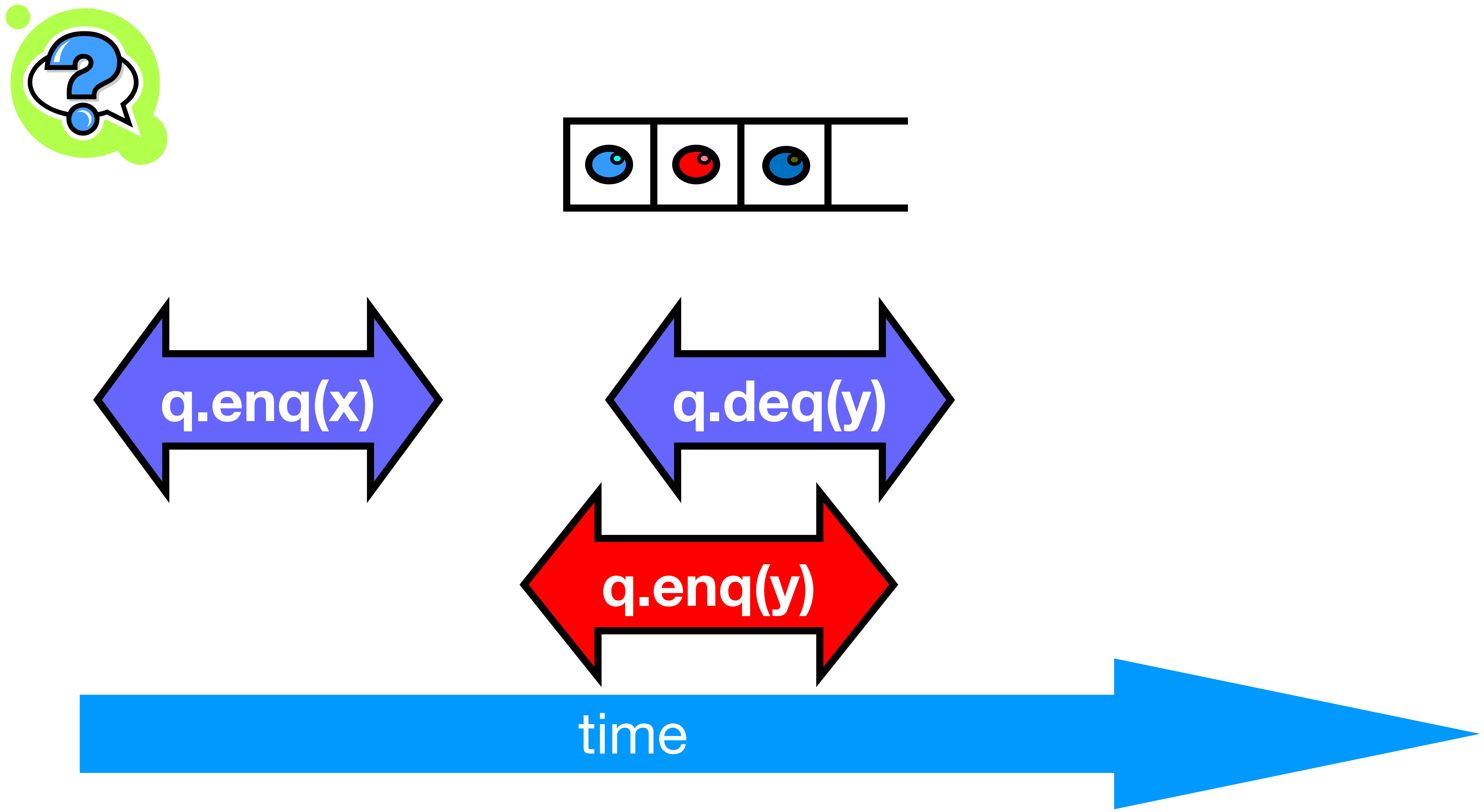
Example



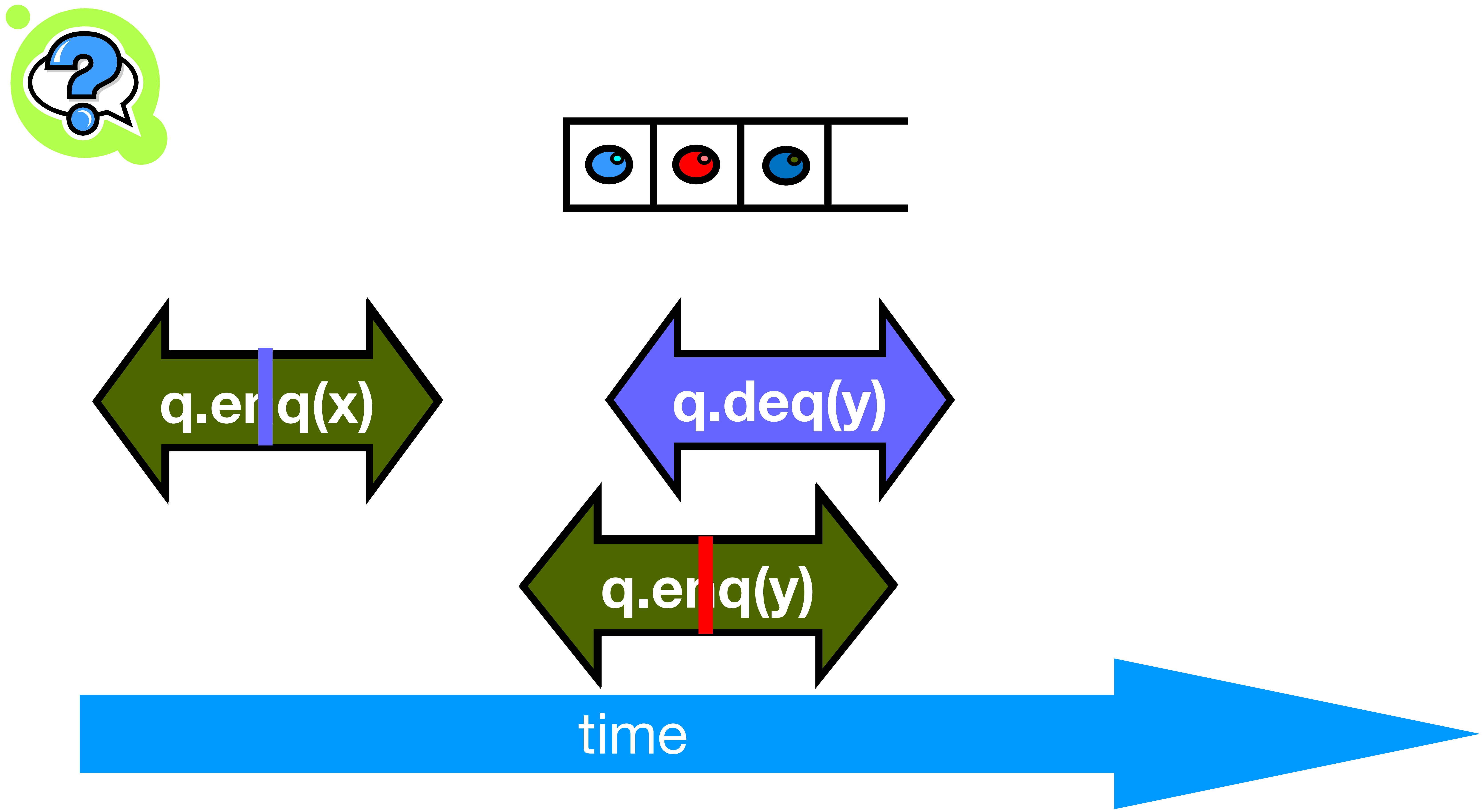
Example



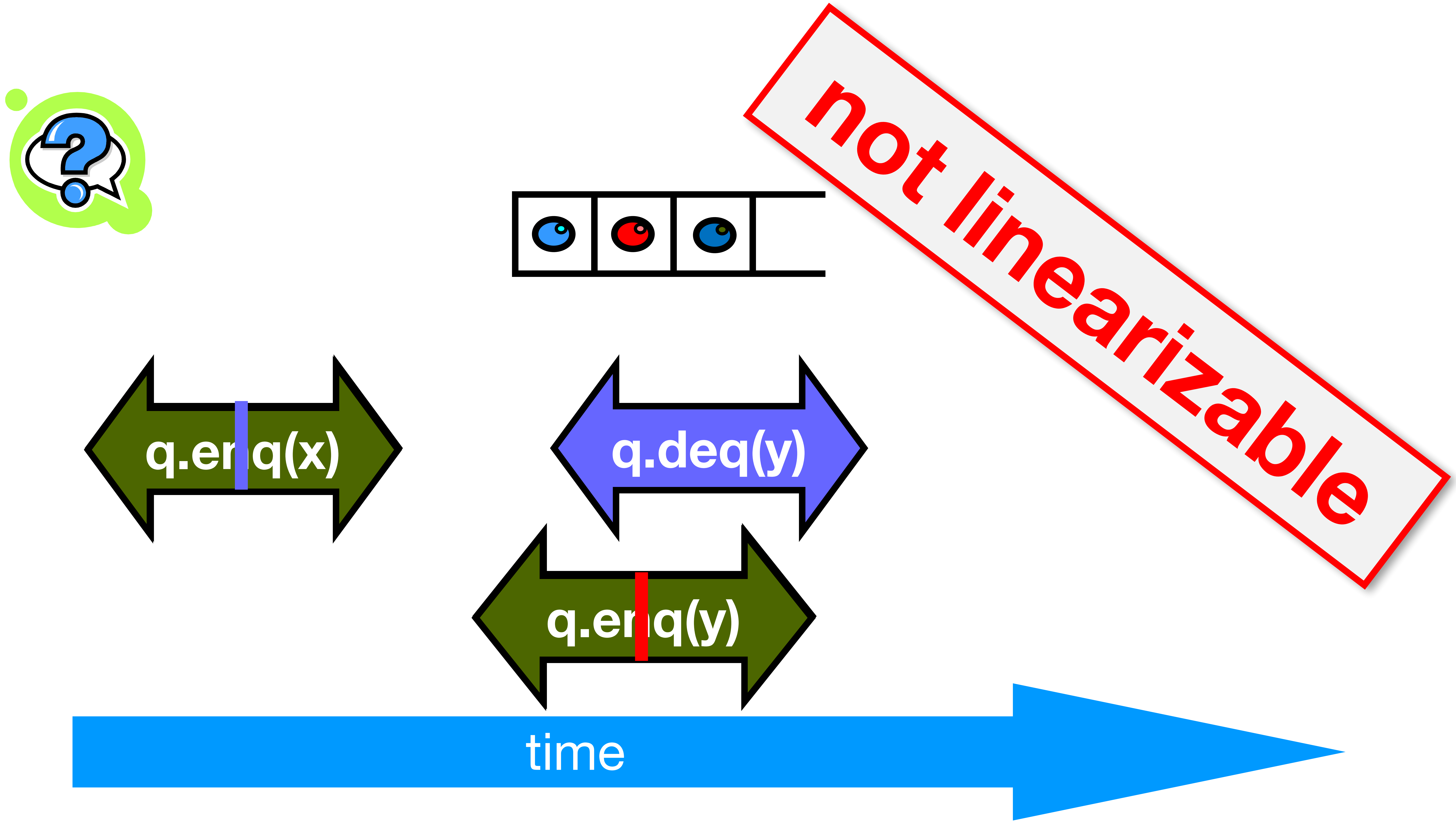
Example



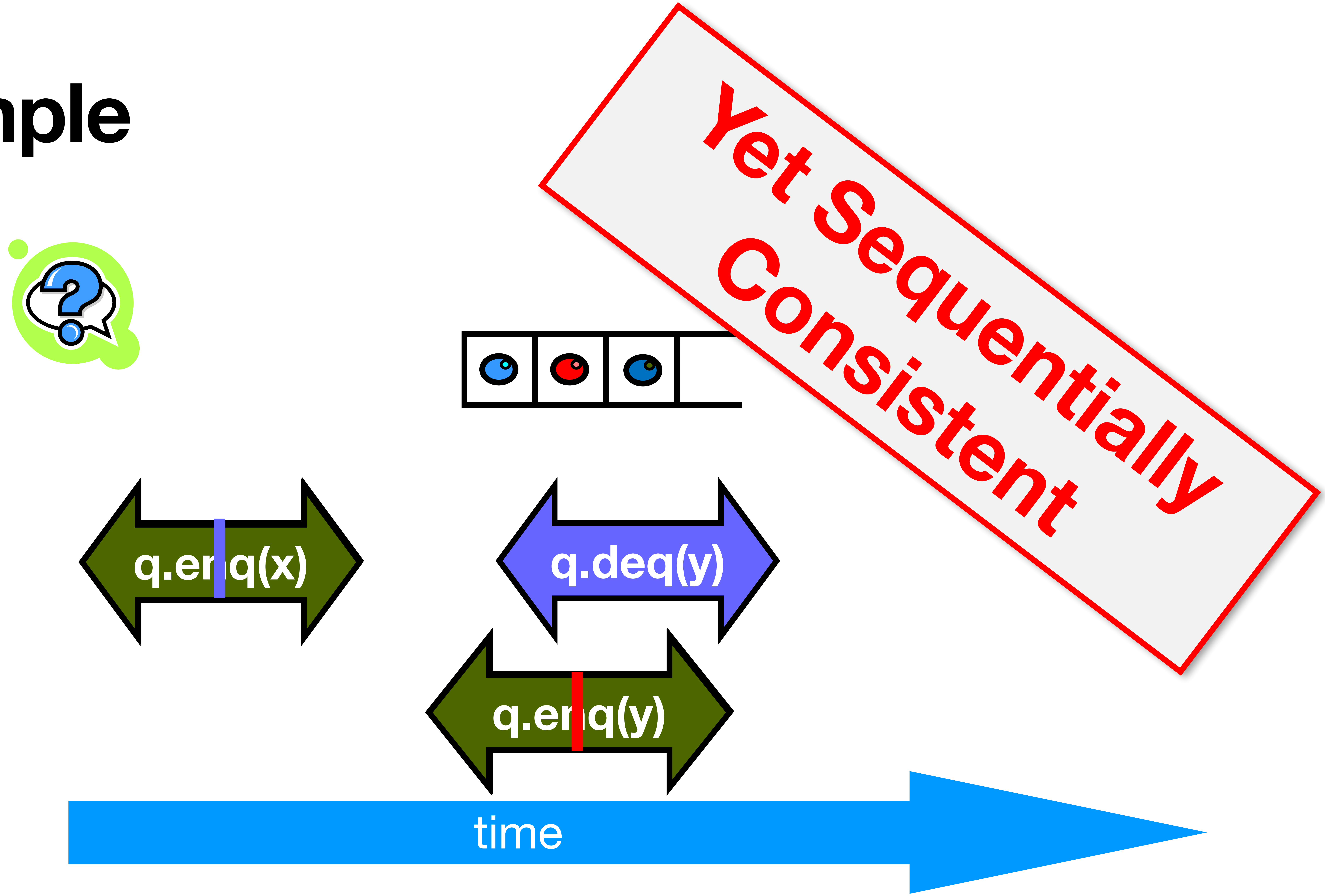
Example



Example



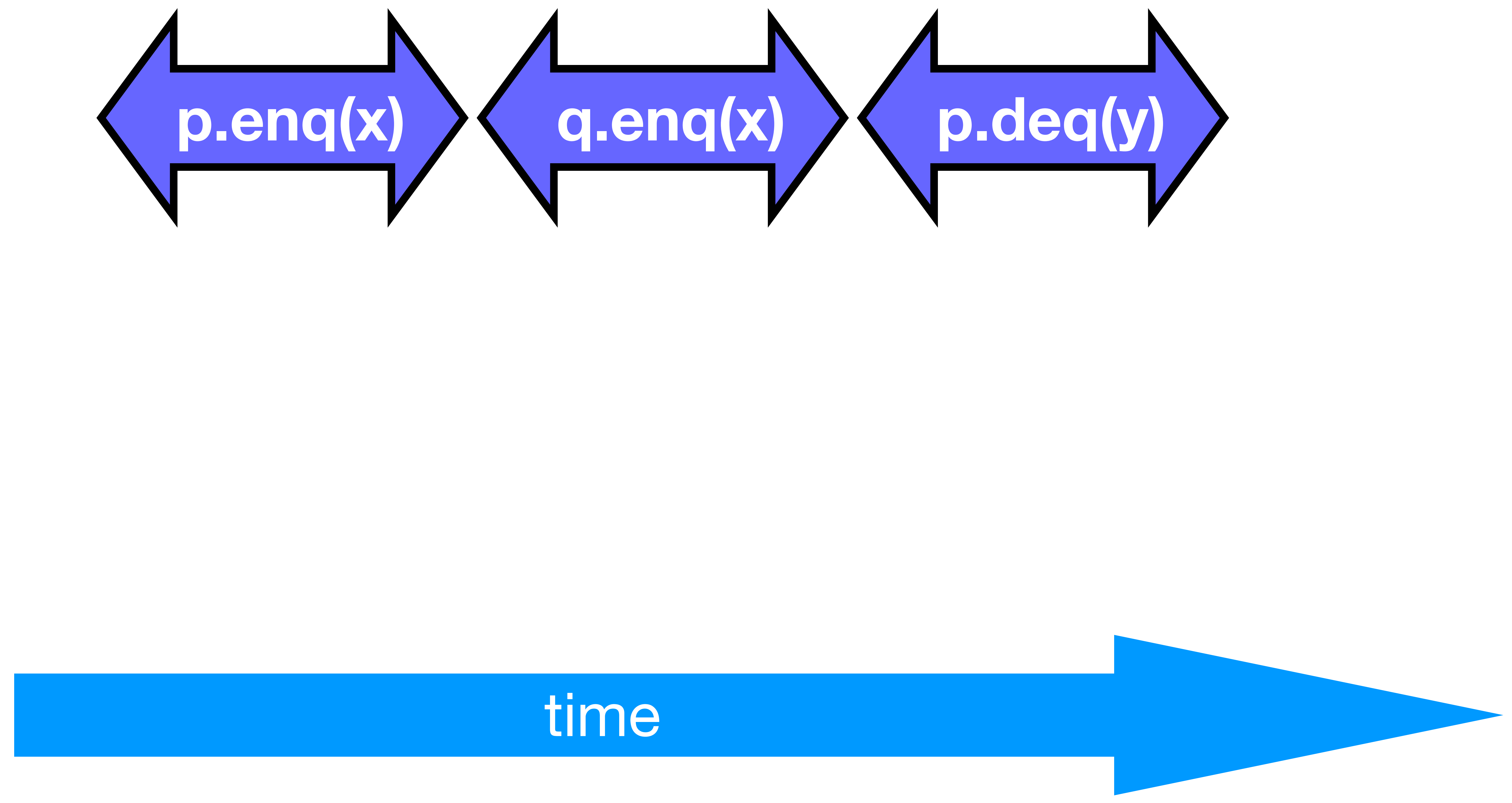
Example



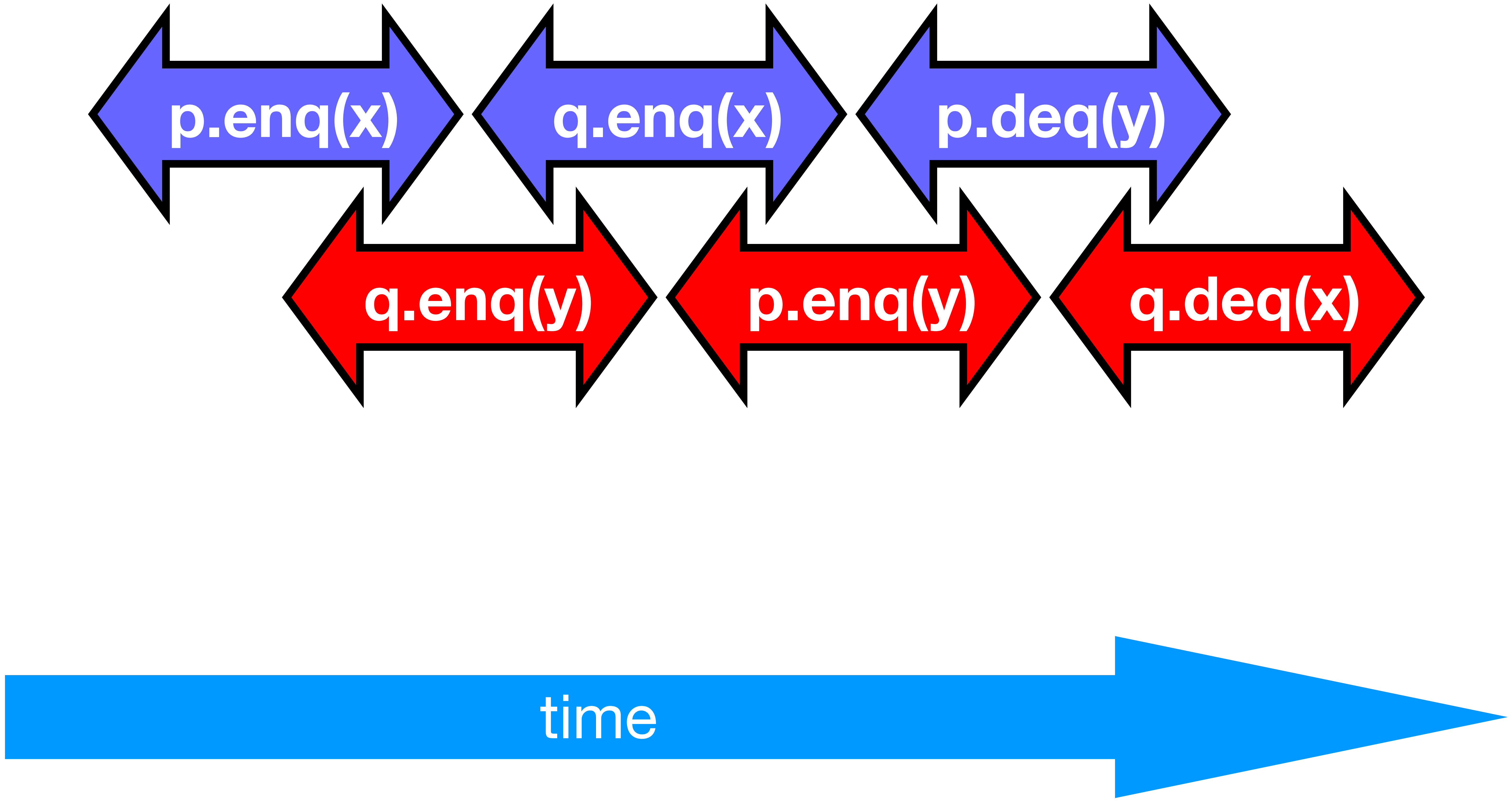
Theorem

Sequential Consistency is not Composable

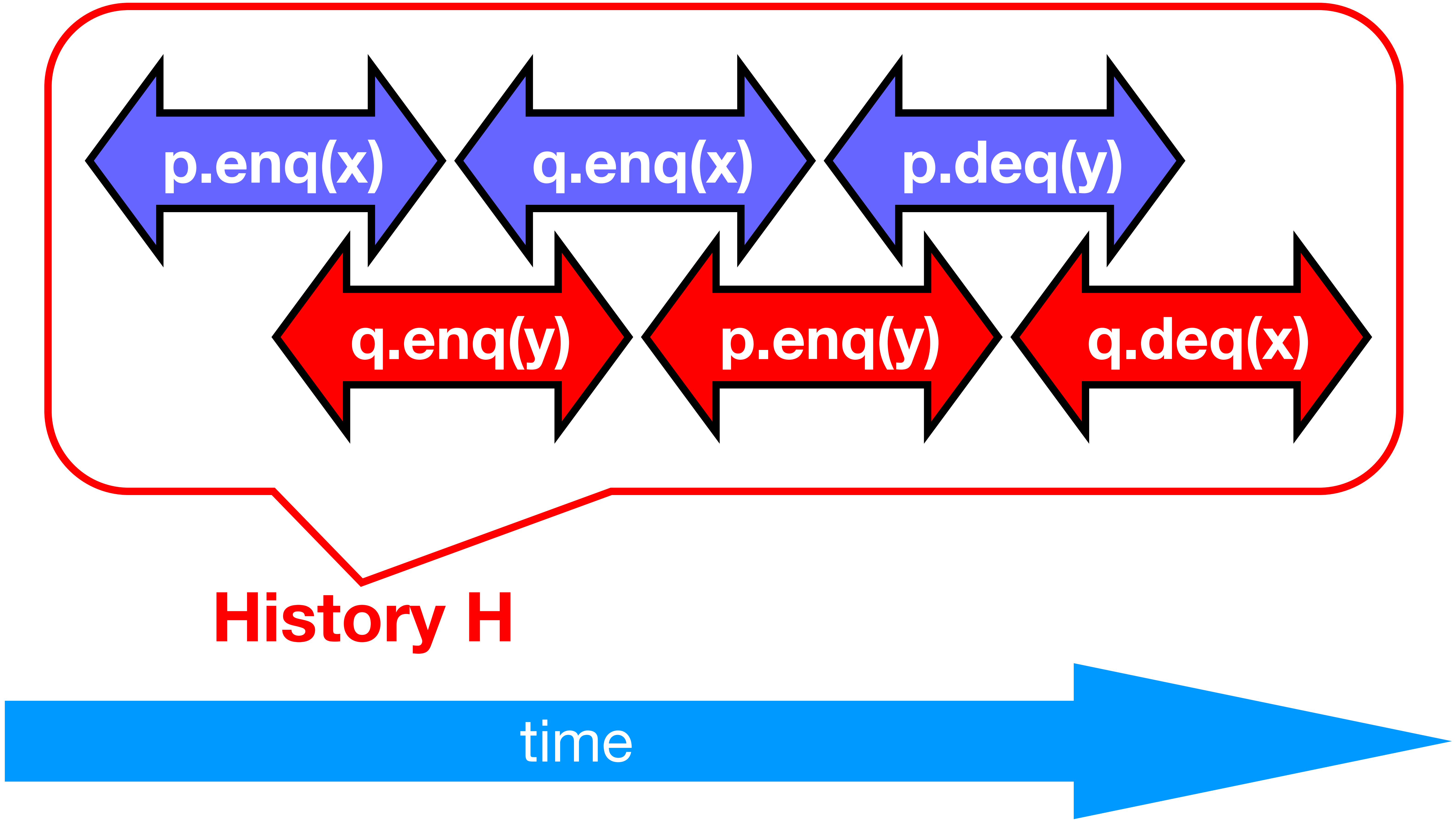
FIFO Queue Example



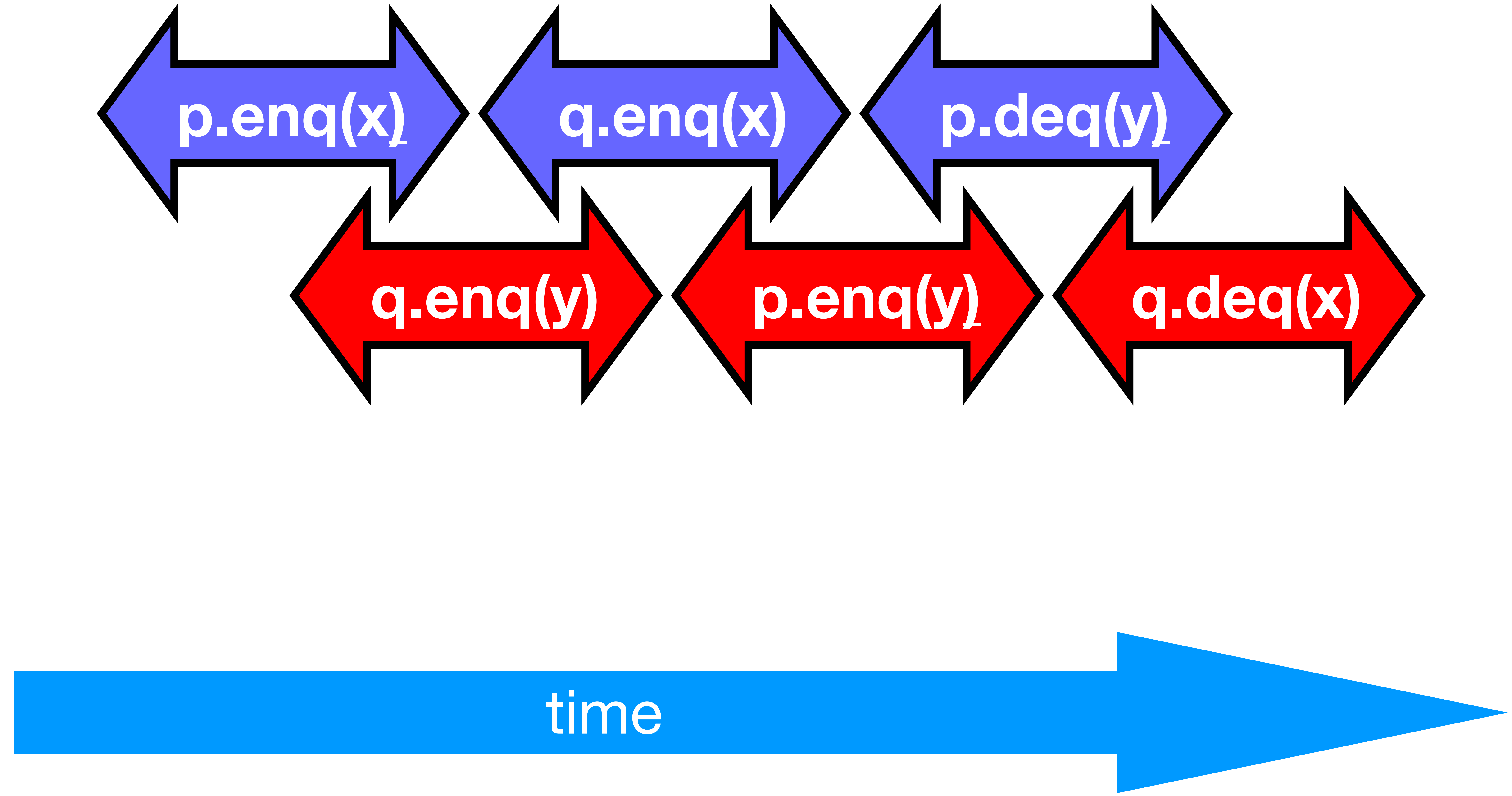
FIFO Queue Example



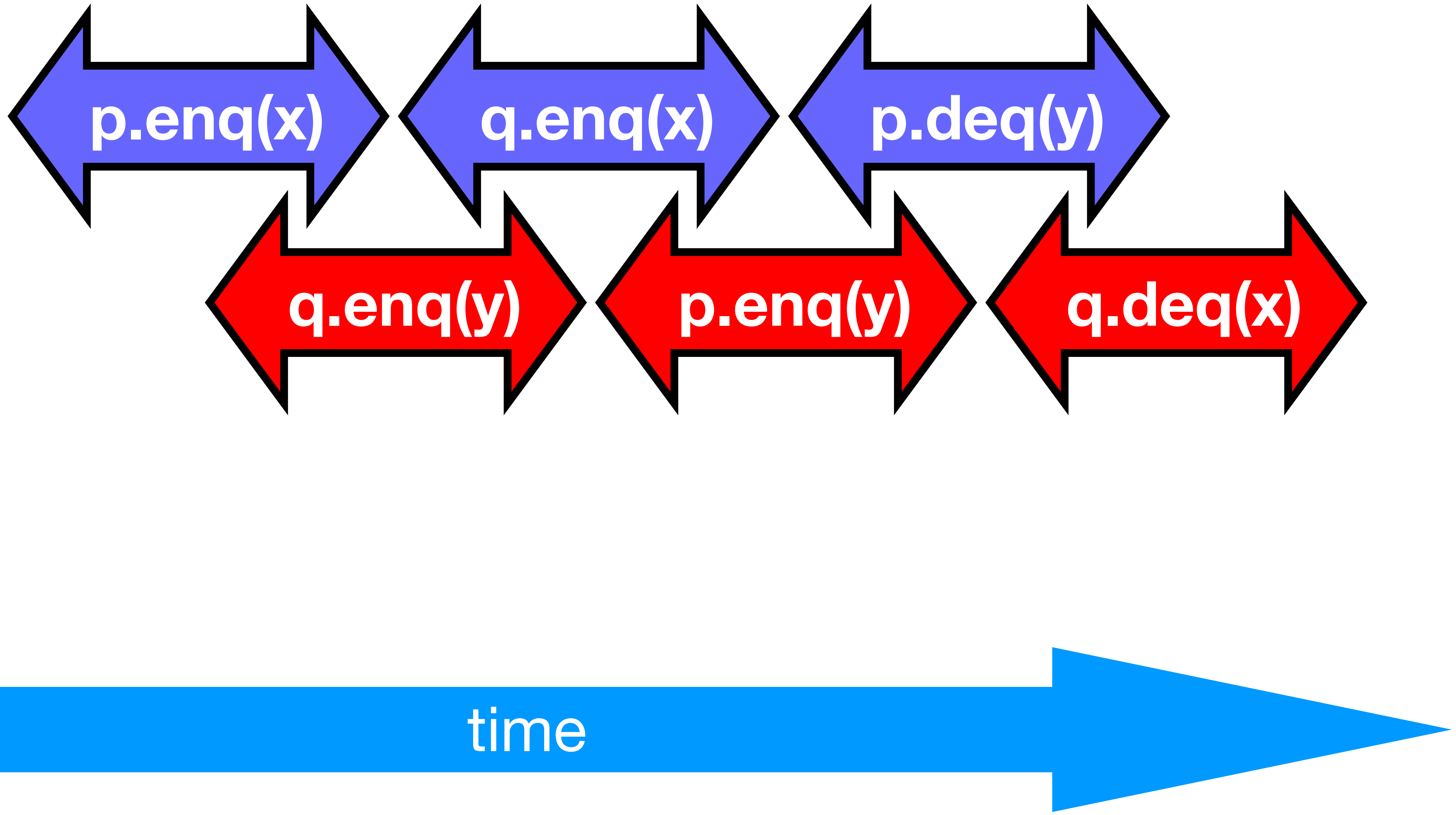
FIFO Queue Example



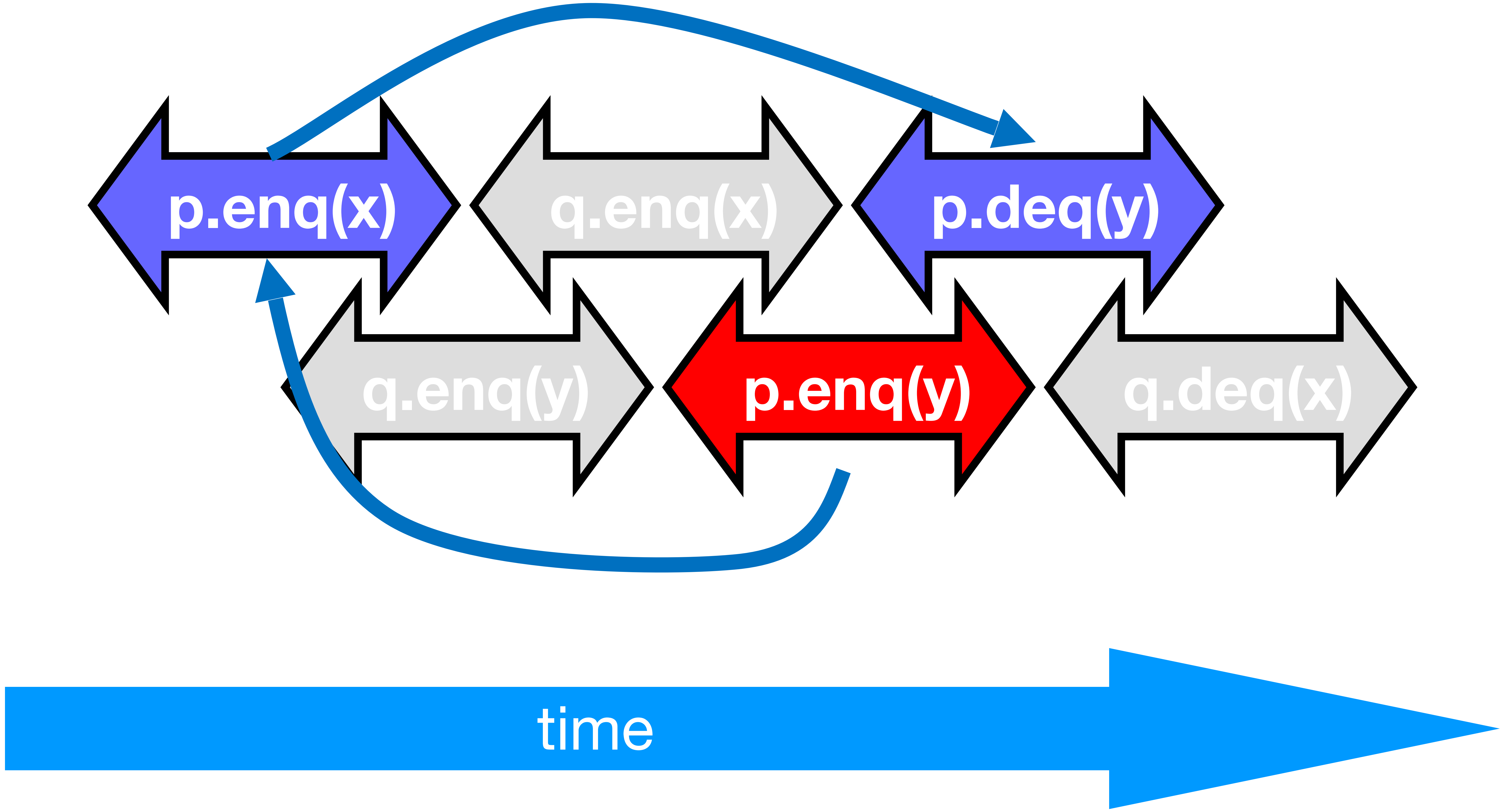
H|p Sequentially Consistent



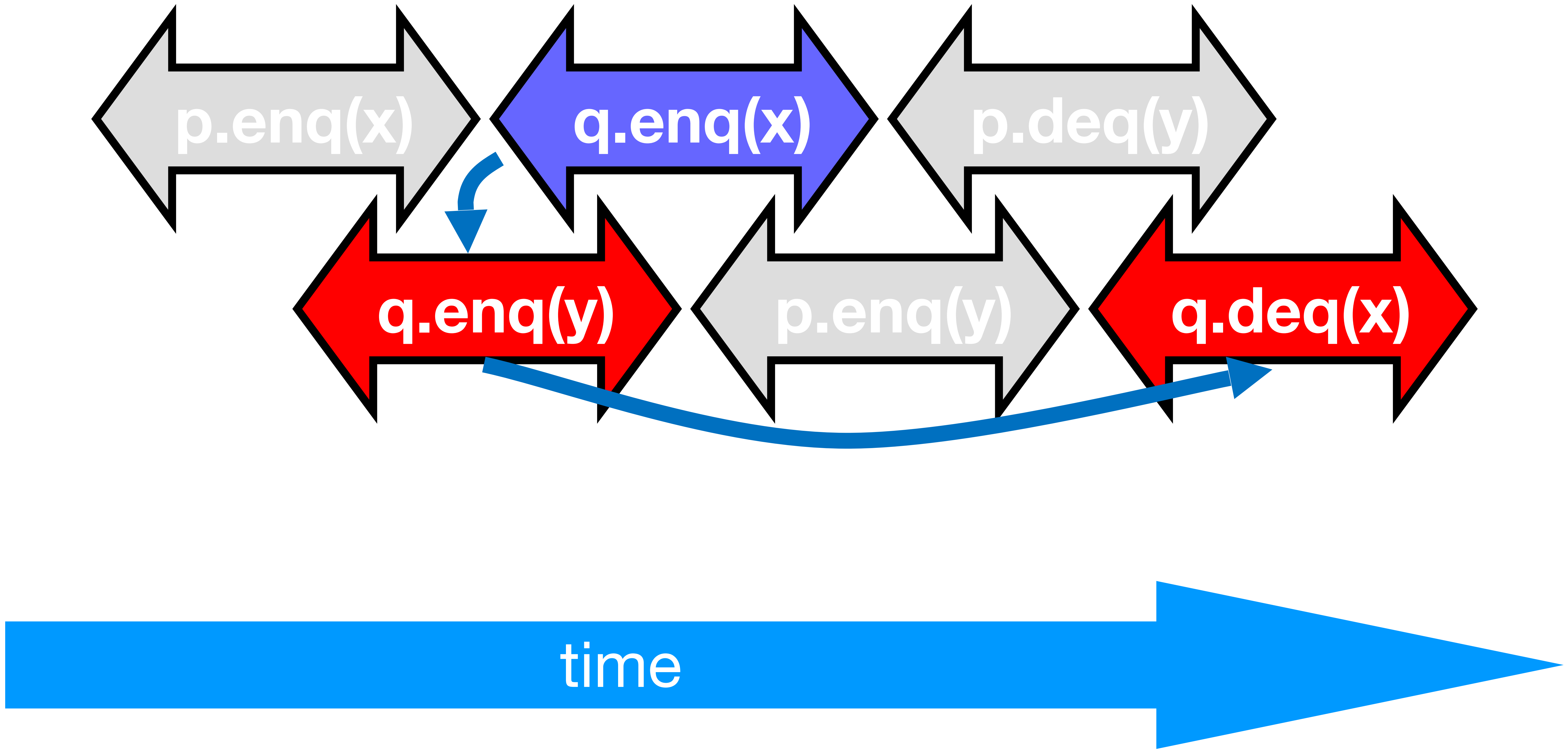
H|q Sequentially Consistent



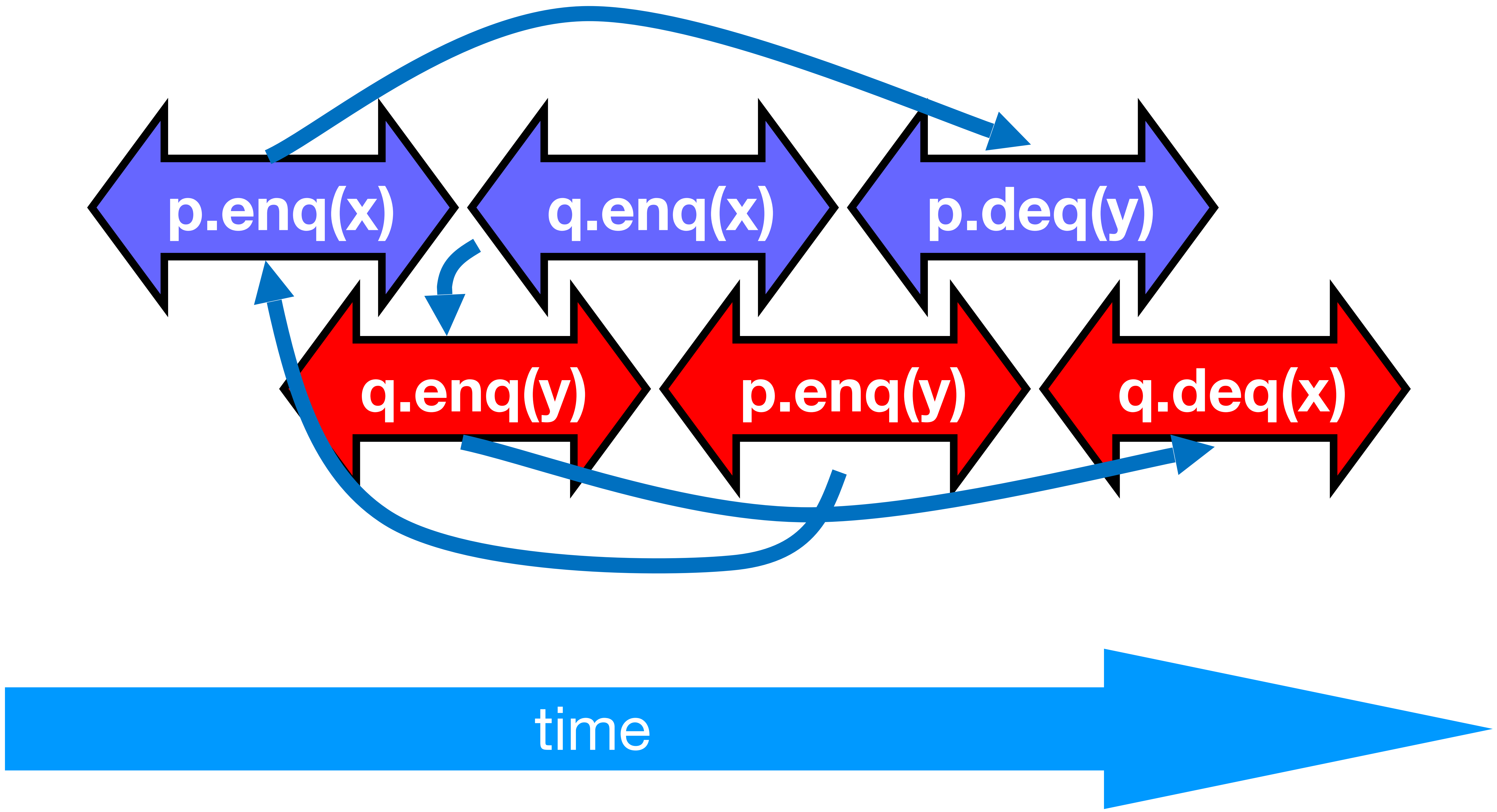
Ordering imposed by p



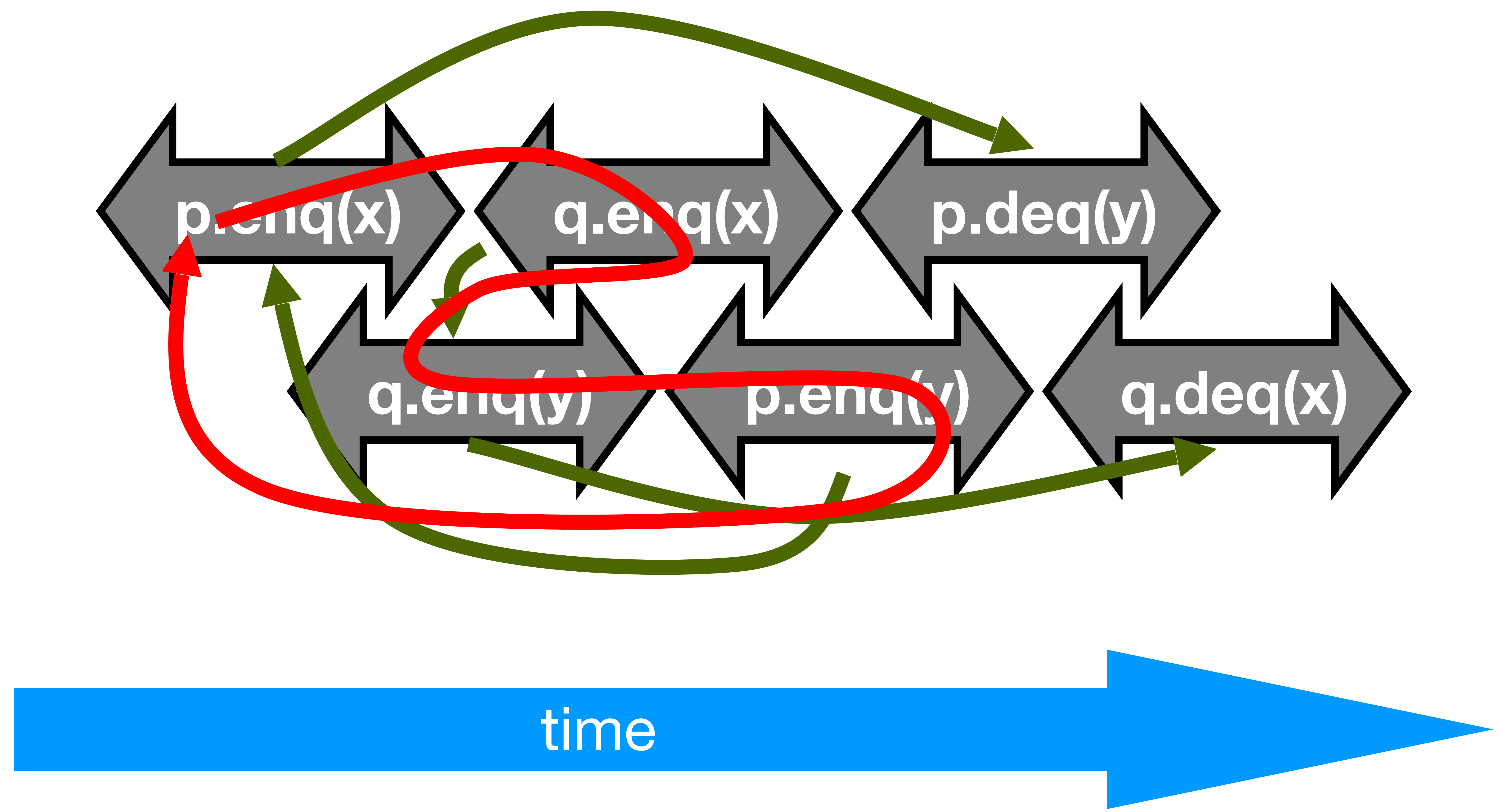
Ordering imposed by q



Ordering imposed by both



Combining orders



Concurrency Testing

- Linearizability and Sequential Consistency are good specifications for *testing* the correctness of concurrent data structures.
  - Any observed execution must match a sequential execution
  - Can be exploited for pragmatic testing
- See https://github.com/ocaml-multicore/multicoretests

qcheck-lin

- Checks for sequential consistency violations (despite what the name says)
- ***Every sequential consistency violation is a linearizability violation***
- Check that the observed result of a parallel implementation can be observed with a sequential run

Demo

qcheck-stm

- In ***qcheck-lin,*** what if the implementation is wrong for the sequential program itself?
  - We're only comparing equivalence.
  - Sequential run of a buggy implementation ≡ Parallel run of a buggy implementation
    - ***Is not useful!***
- qcheck-stm
  - Write a state-machine ***model*** of the concurrent object
  - Compare the sequential and parallel executions of the implementation against the state machine model
  - ***More work!***

Demo

Summary

- ***Linearizability***
  - The operation takes effect instantaneously between the invocation and the response
  - Uses sequential specification, locality implies composability
- ***Sequential Consistency***
  - Linearizability without real-time ordering
  - Not composable
  - Harder to work with
  - Useful to reason about hardware models (next lecture)
- We will use ***linearizability*** as our consistency condition for reasoning about objects

Progress

- We saw an implementation whose methods were lock-based (deadlock-free)
- We saw an implementation whose methods did not use locks (lock-free)
- How do they relate?

Progress Conditions

- ***Deadlock-free:*** <u>some</u> thread trying to acquire the lock eventually succeeds.
- ***Starvation-free:*** <u>every</u> thread trying to acquire the lock eventually succeeds.
- ***Lock-free:*** <u>some</u> thread calling a method eventually returns.
- ***Wait-free:*** <u>every</u> thread calling a method eventually returns.

	Non-Blocking	**Blocking**
Everyone makes progress	Wait-free	Starvation-free
Someone makes progress	Lock-free	Deadlock-free

We will look at linearizable blocking and non-blocking implementations of objects.