FACULDADE DE
CIÊNCIAS E TECNOLOGIA
DEPARTAMENTO DE INFORMÁTICA

Concurrent Objects

lectures 05 & 06 (2025-03-24)

Master in Computer Science and Engineering

— Concurrency and Parallelism / 2024-25 —

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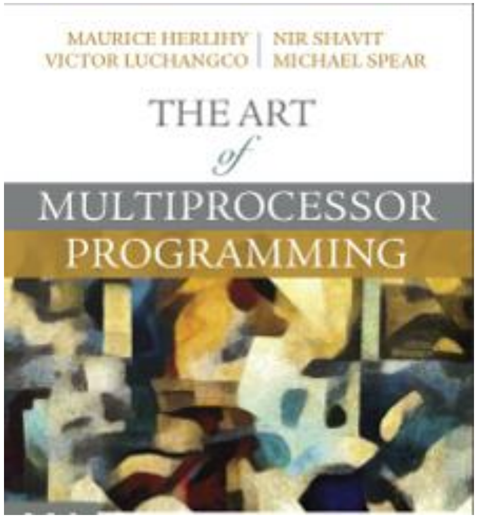
Based in slides the companion slides from “The Art of Multiprocessor Programming”

Outline

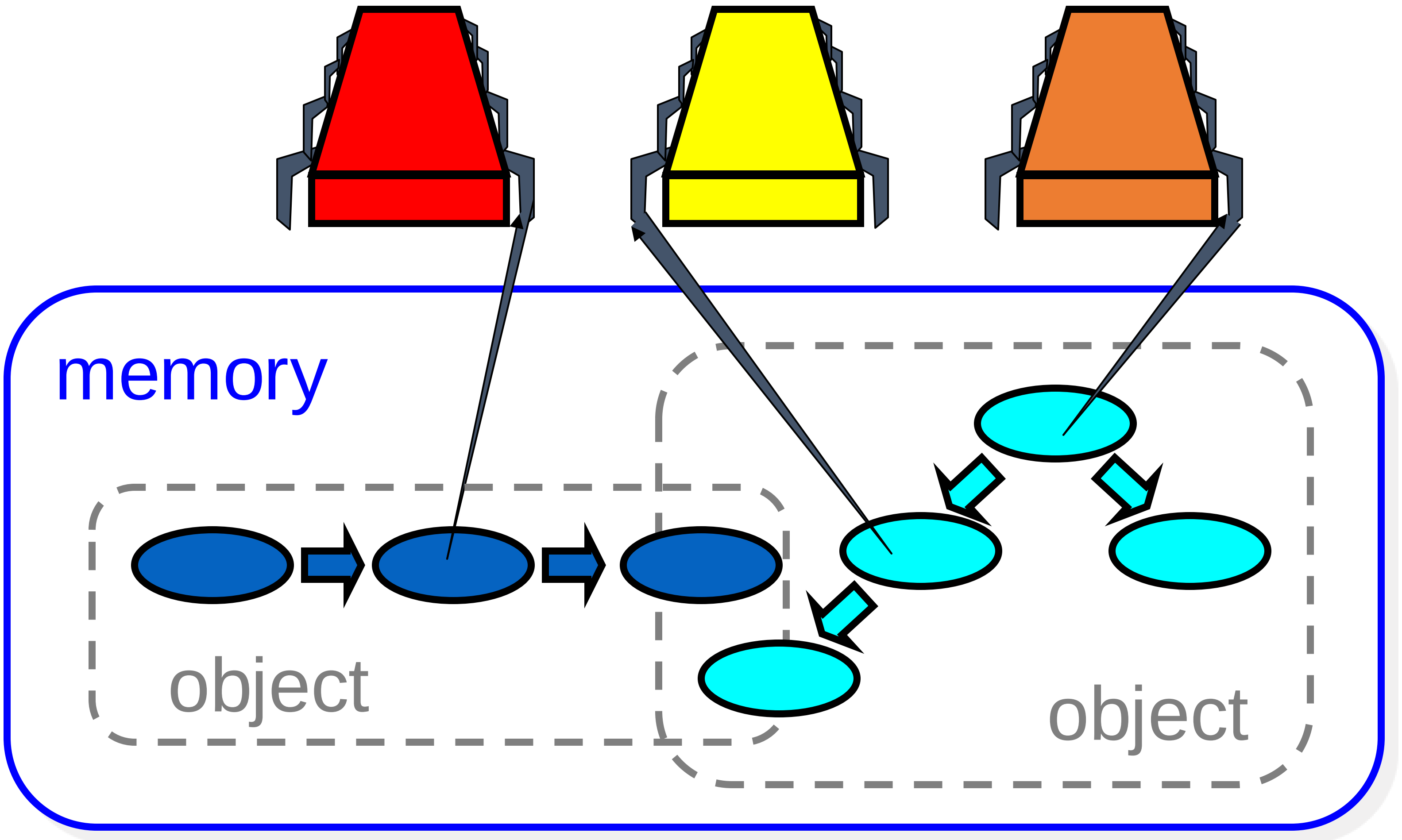
- Concurrent Objects
  - Correctness
  - Sequential Objects
  - Quiescent and Sequential Consistency
  - Linearizability
  - Progress Conditions



  - Bibliography:
    - **Chapters 3** of book

      Herlihy M., Shavit N., Luchangco V., Spear M.;
      The Art of Multiprocessor Programming;
      Morgan Kaufmann (2020); ISBN: 978-0-12-415950-1

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

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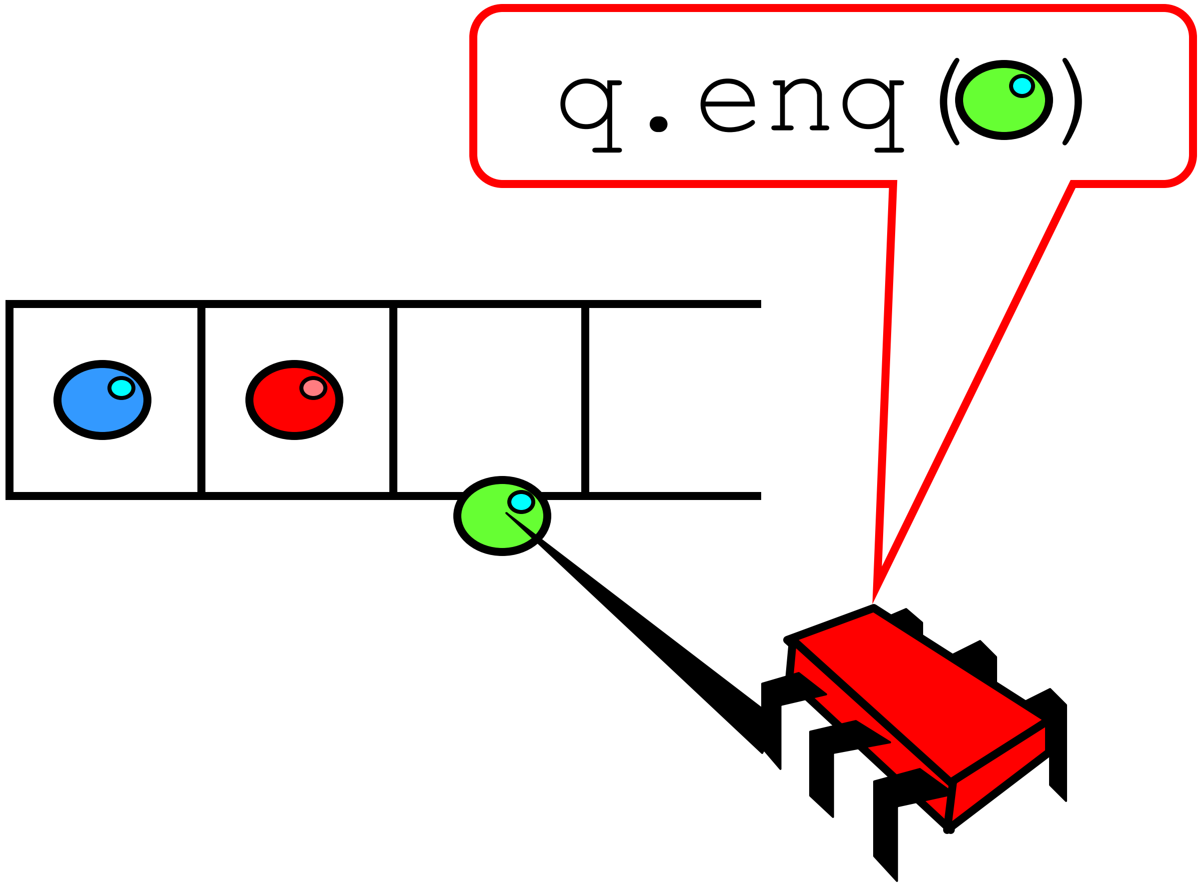
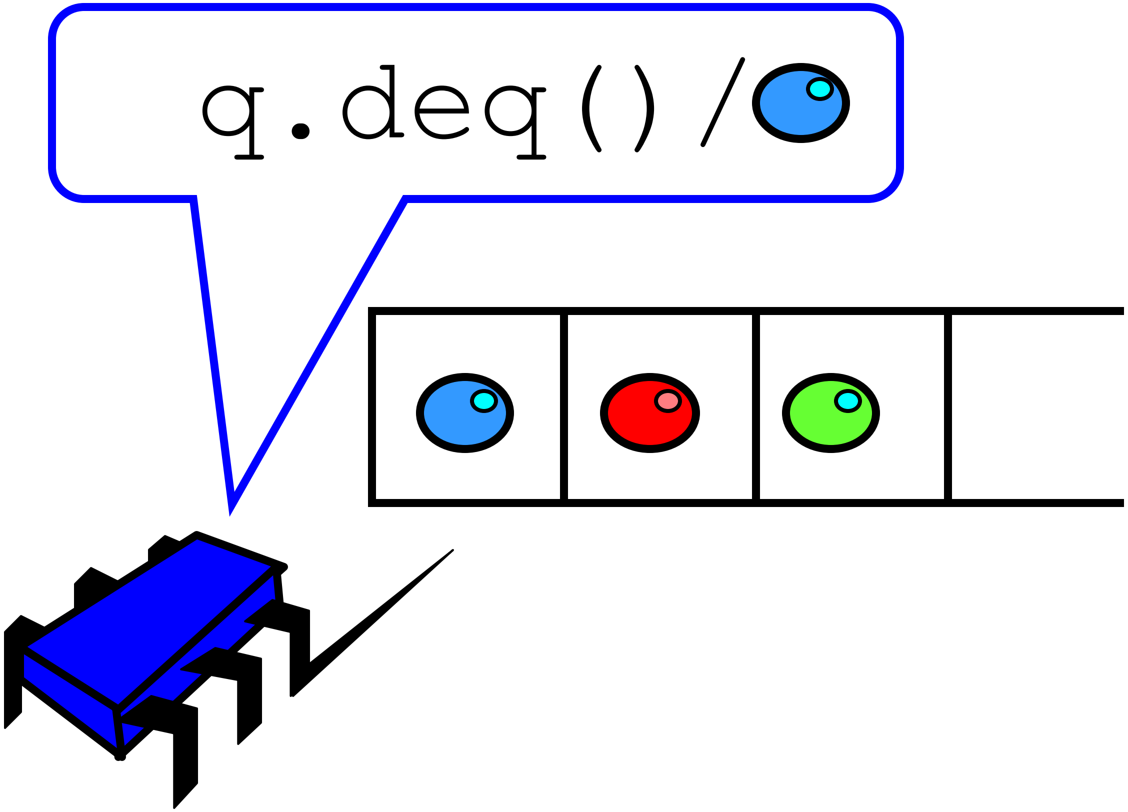
  - How do we **describe** one?
  - How do we **tell if we're right**?

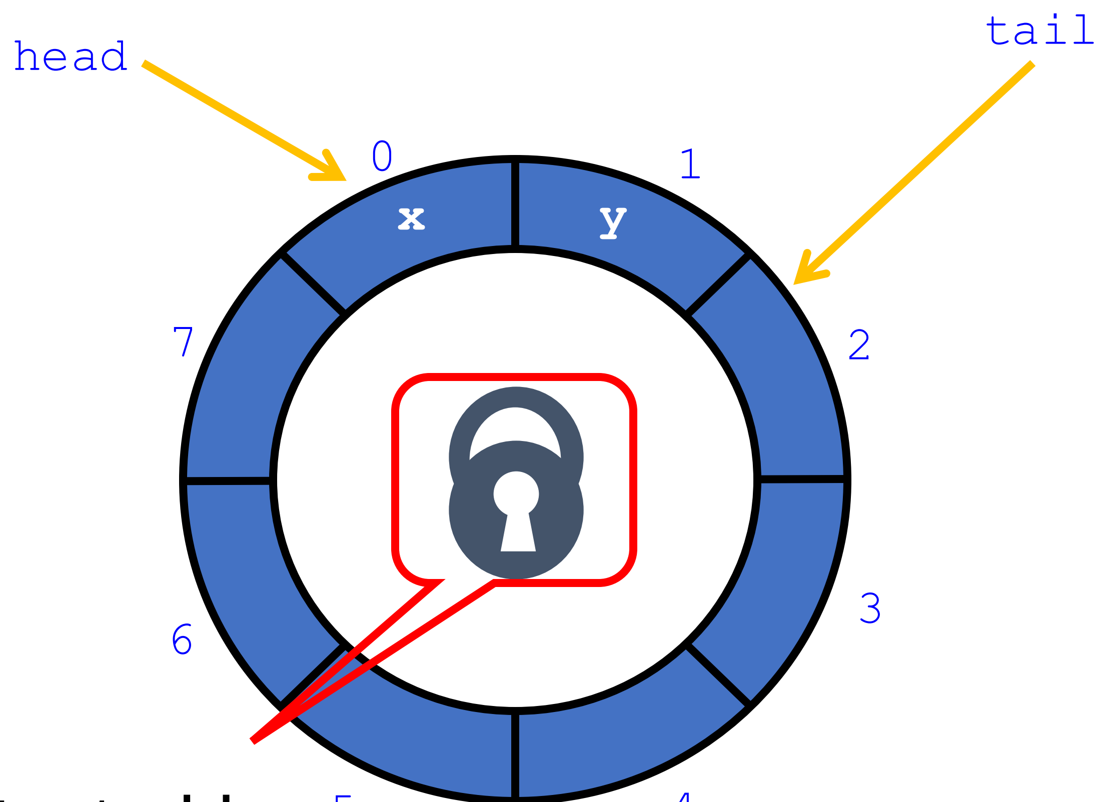
FIFO Queue: Enqueue Method



FIFO Queue: Dequeue Method



Lock-Based Queue



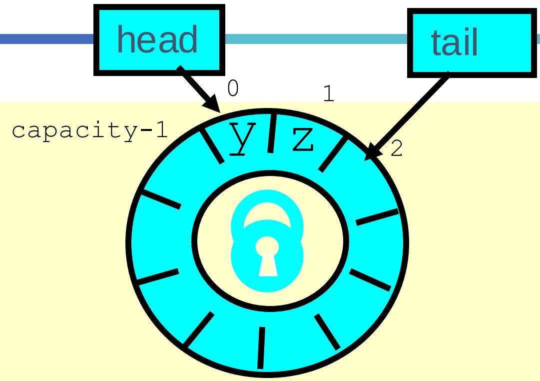
Fields protected by single shared lock

capacity = 8

A Lock-Based Queue

```
class LockBasedQueue<T> {
  int head, tail;
  T[] items;
  Lock lock;
  public LockBasedQueue(int capacity) {
    head = 0; tail = 0;
    lock = new ReentrantLock();
    items = (T[]) new Object[capacity];
}
```

A Lock-Based Queue

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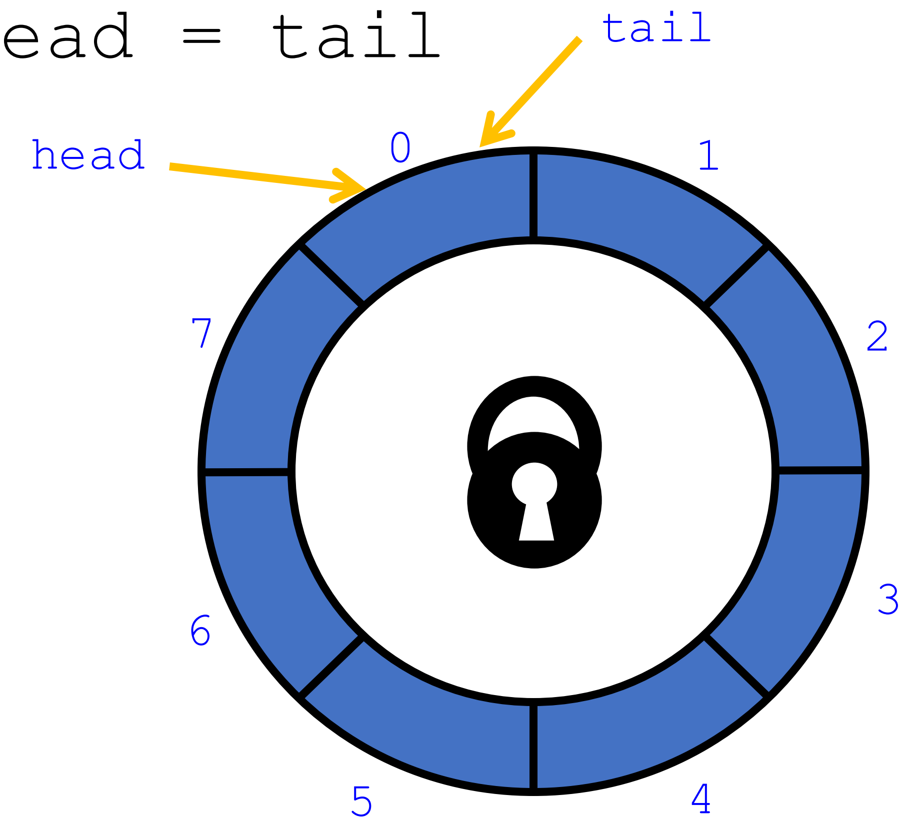
Fields protected by single shared lock

Lock-Based Queue

Initially: `head = tail`



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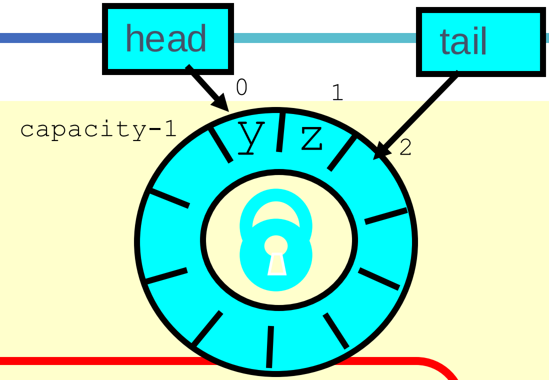


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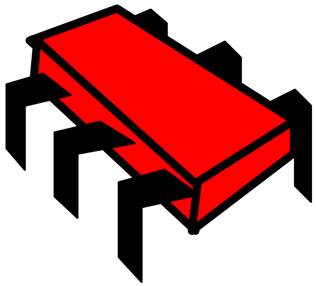
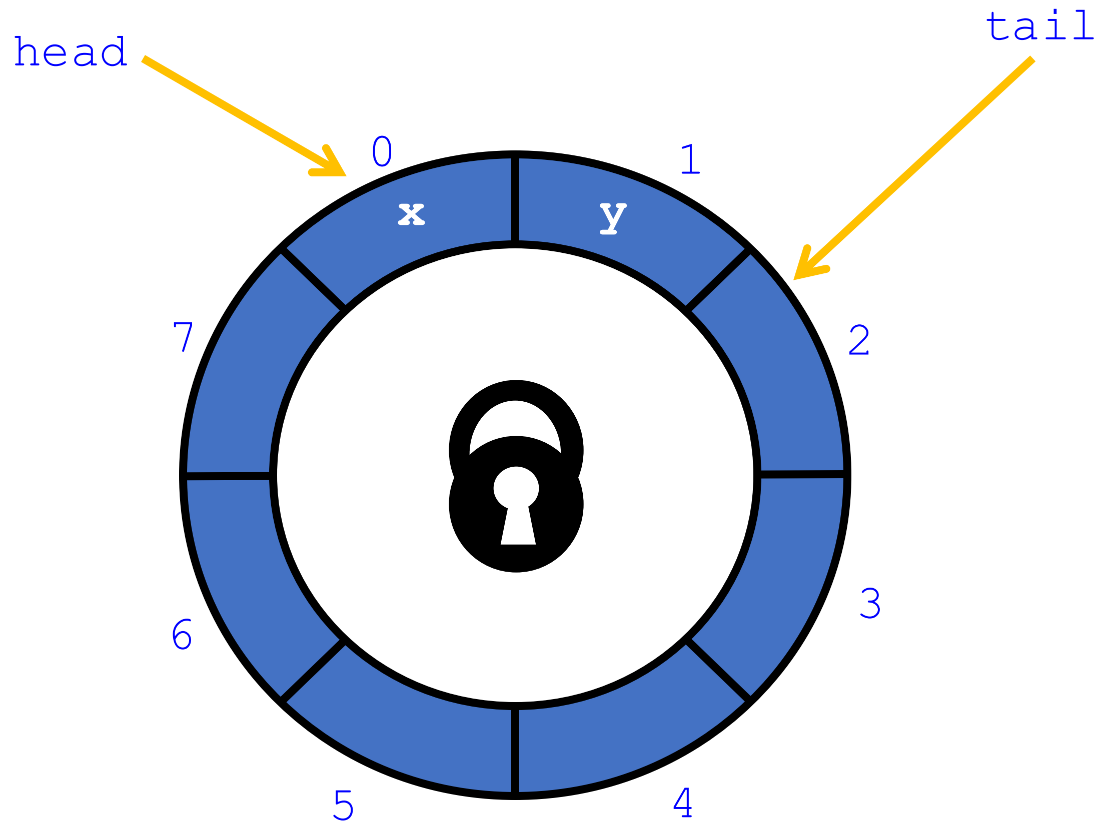
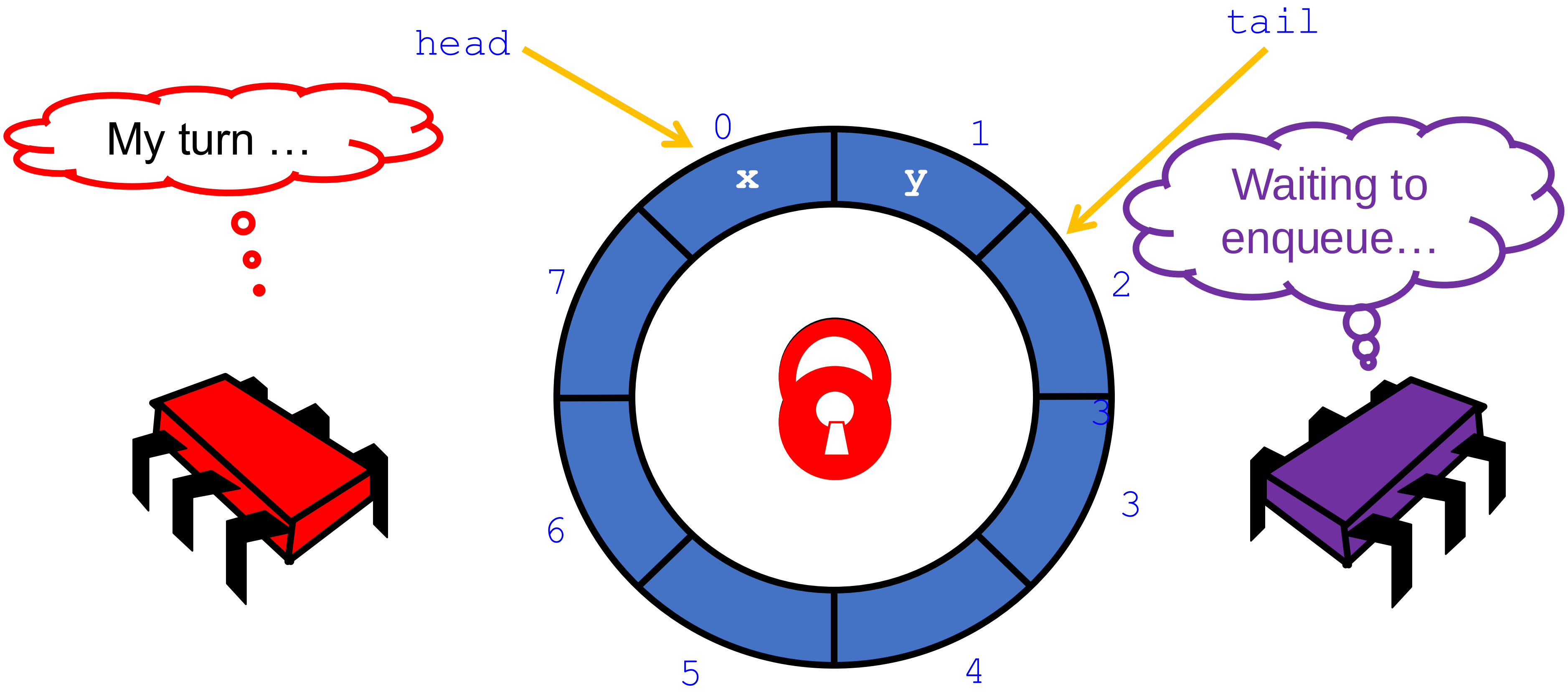
Lock-Based **`deq()`**





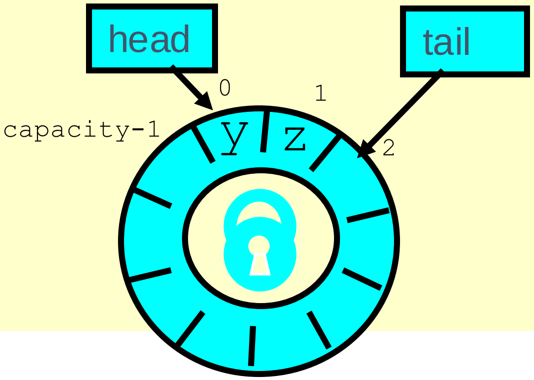
Acquire Lock



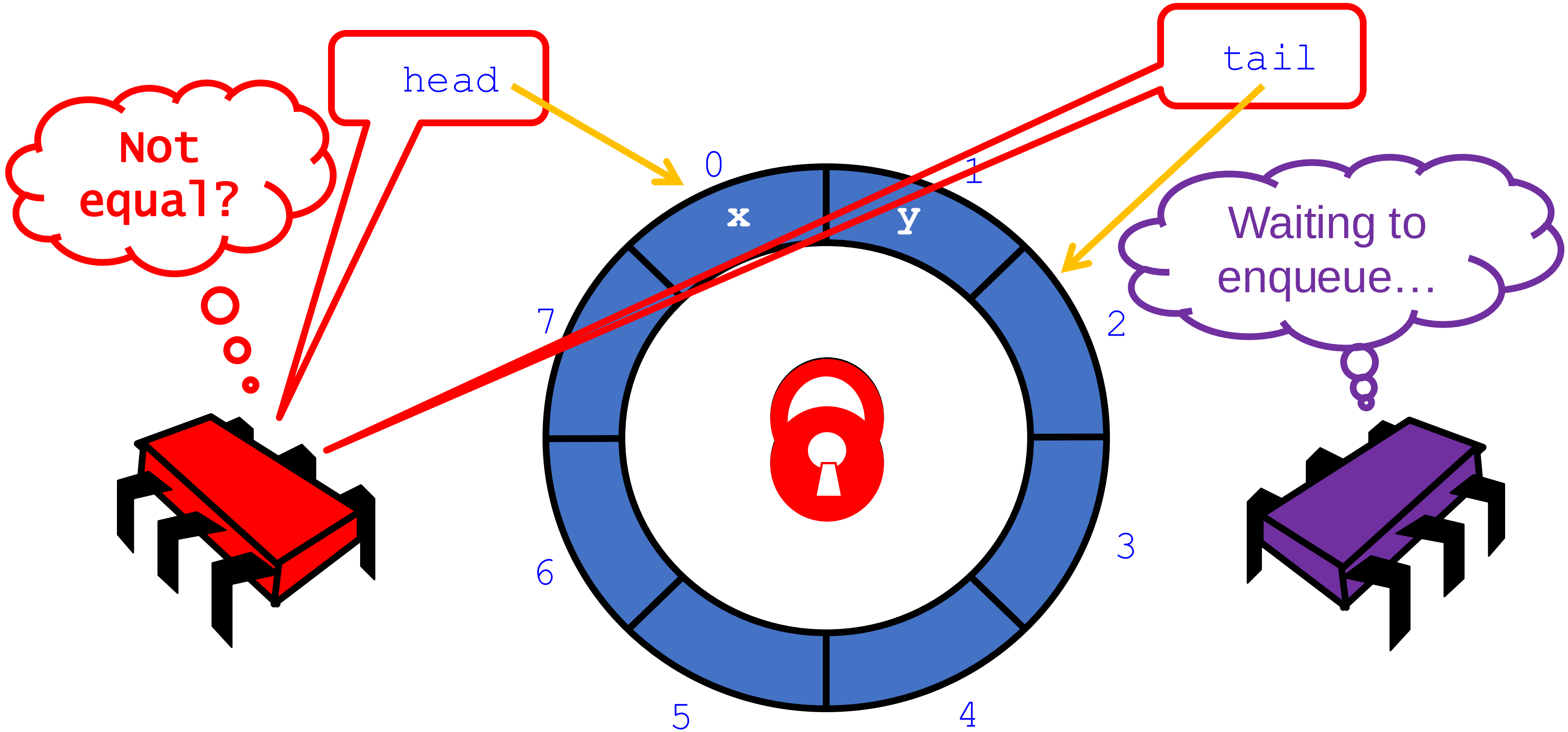
Implementation: **deq()**

```
public T deq() throws EmptyException {
  lock.lock();
  try {
    if (tail == head)
       throw new EmptyException();
    T x = items[head % items.length];
    head++;
    return x;
  } finally {
    lock.unlock();
  }
}
```

Acquire lock at method start



Check if Non-Empty



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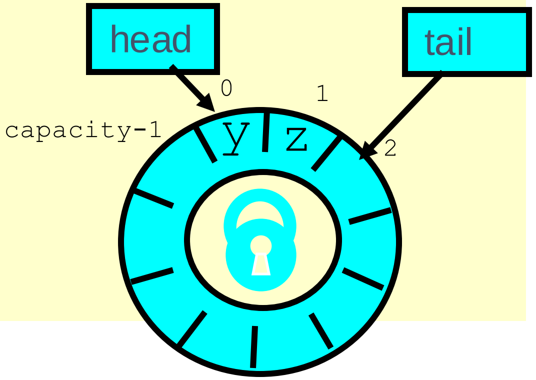
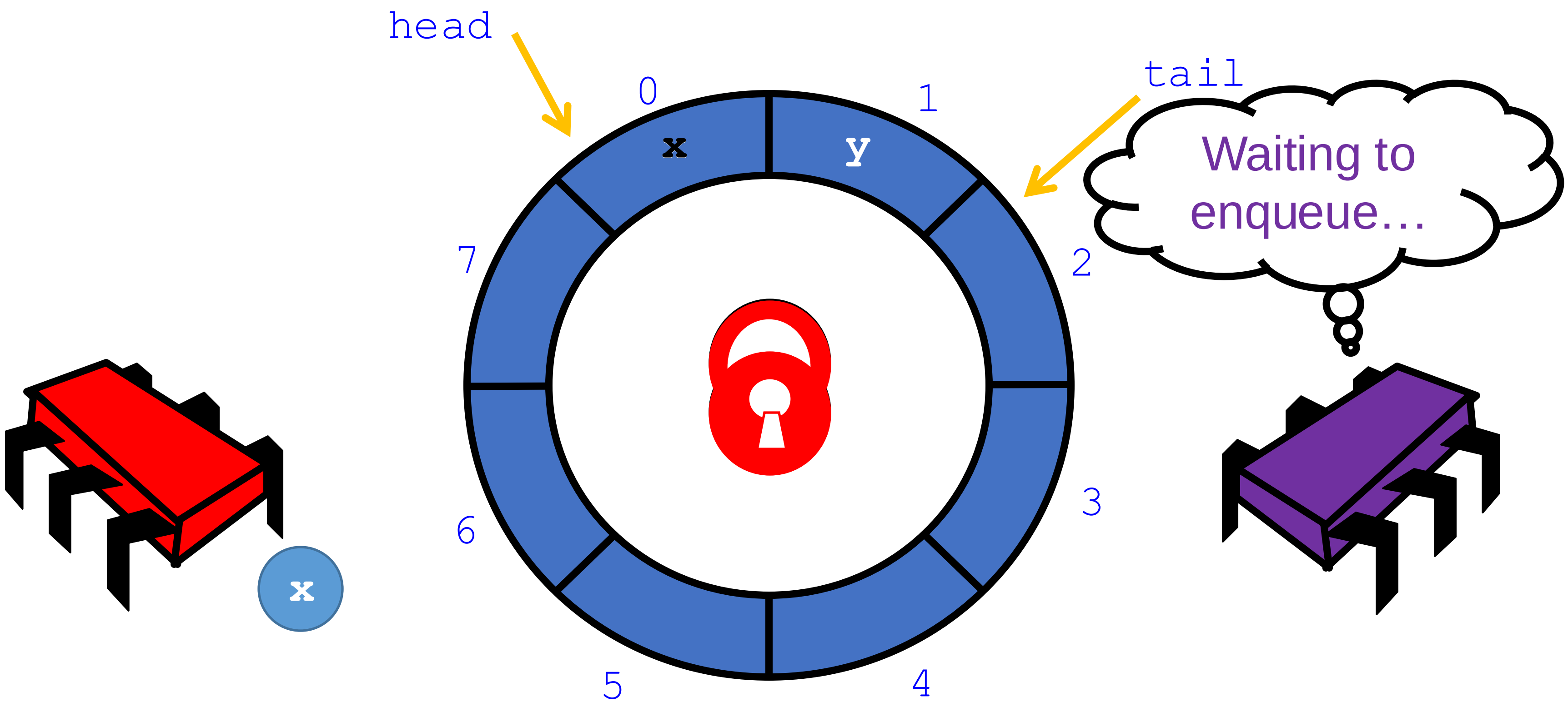
  }
}
```

If queue empty
throw exception



Modify the Queue



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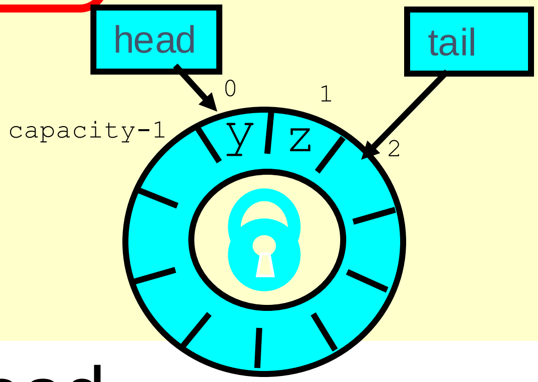
}
```

Queue not empty?

Remove item and update head



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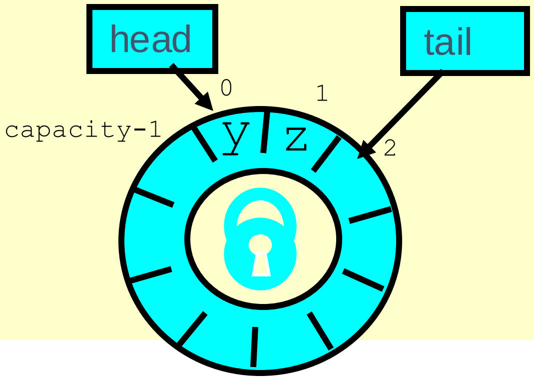
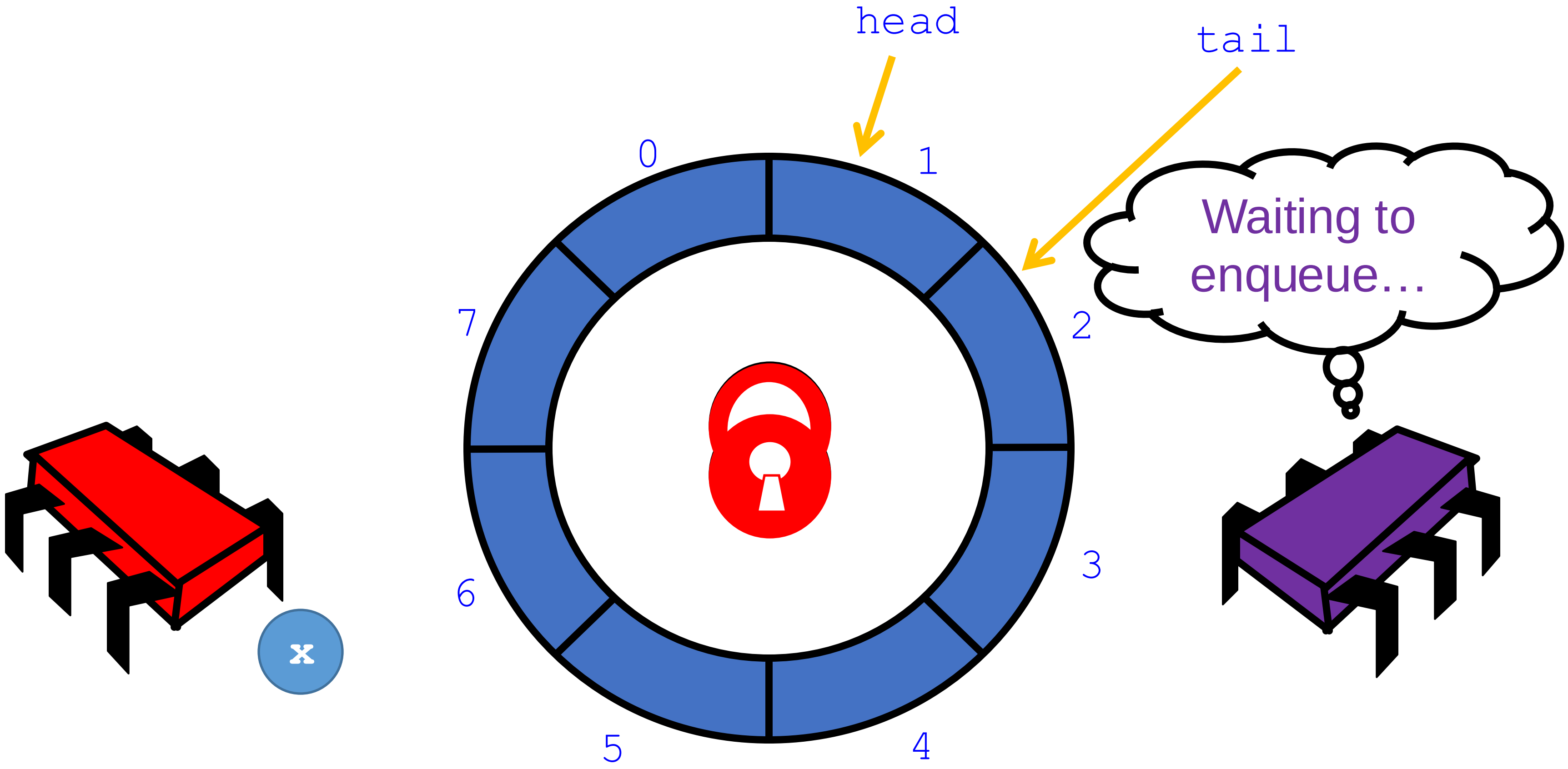
```

Return result



Release the Lock



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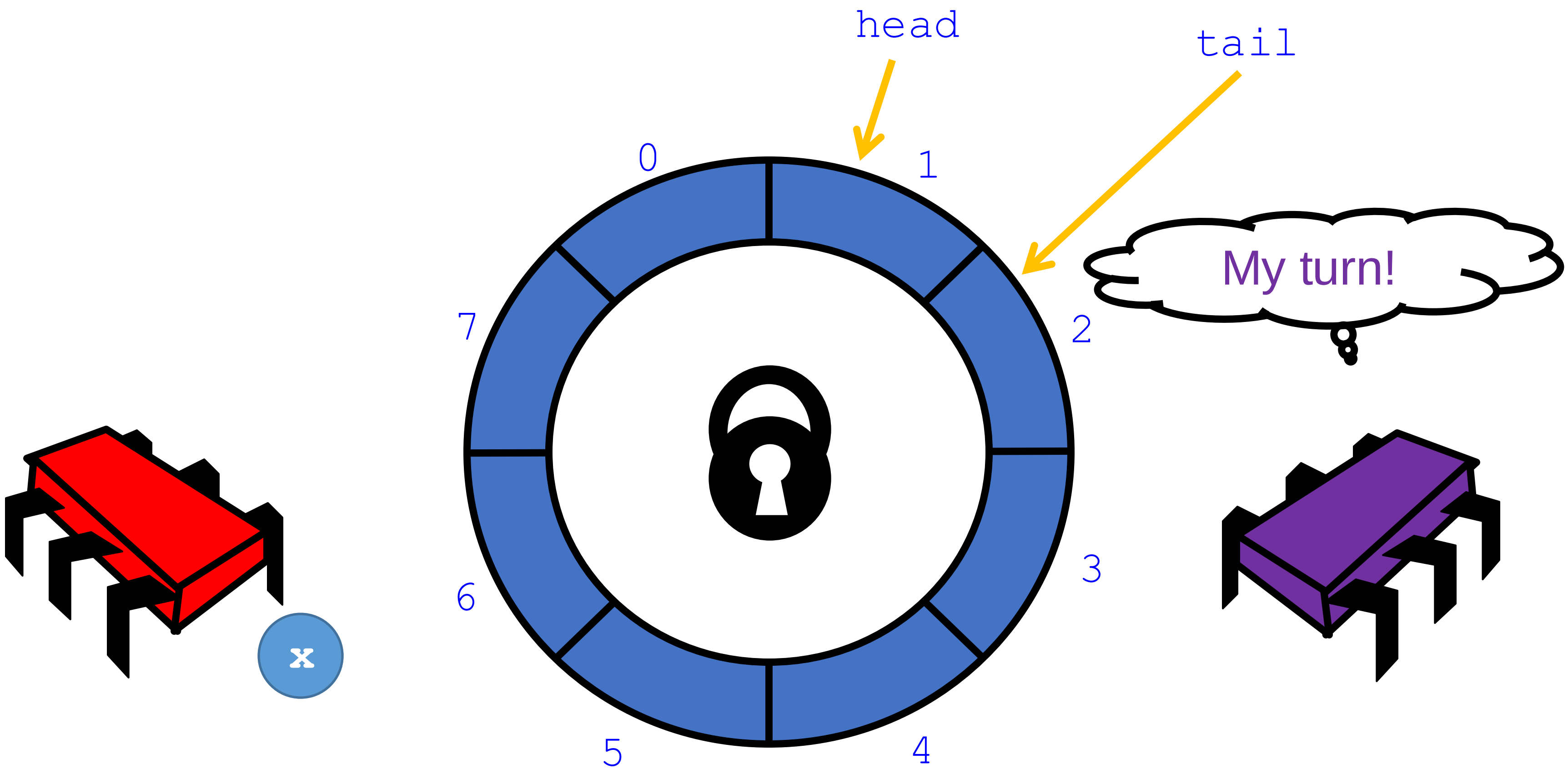

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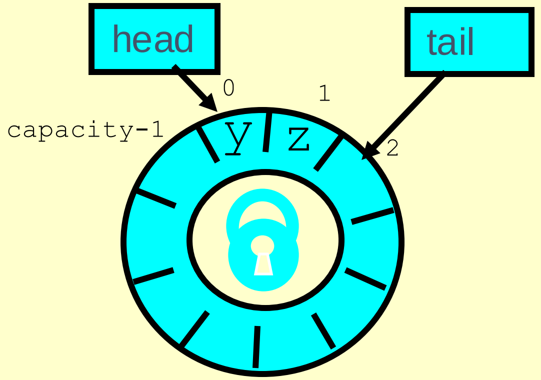
Release lock no matter what!



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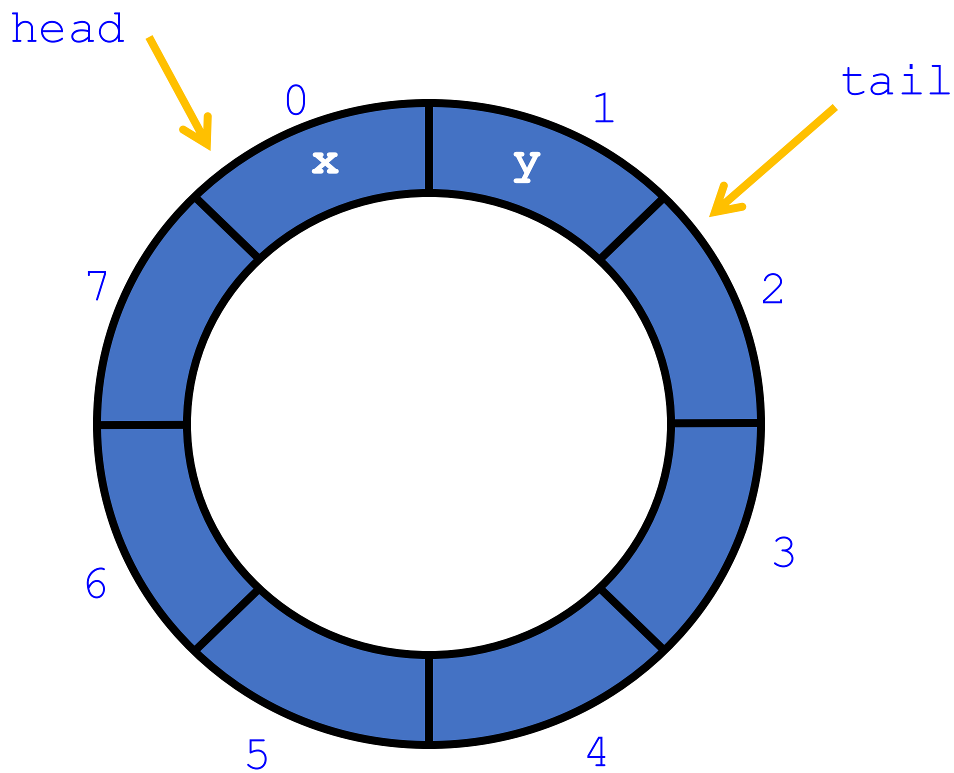
  }
}
```

Should be correct because modifications are mutually exclusive…

Now consider the following implementation

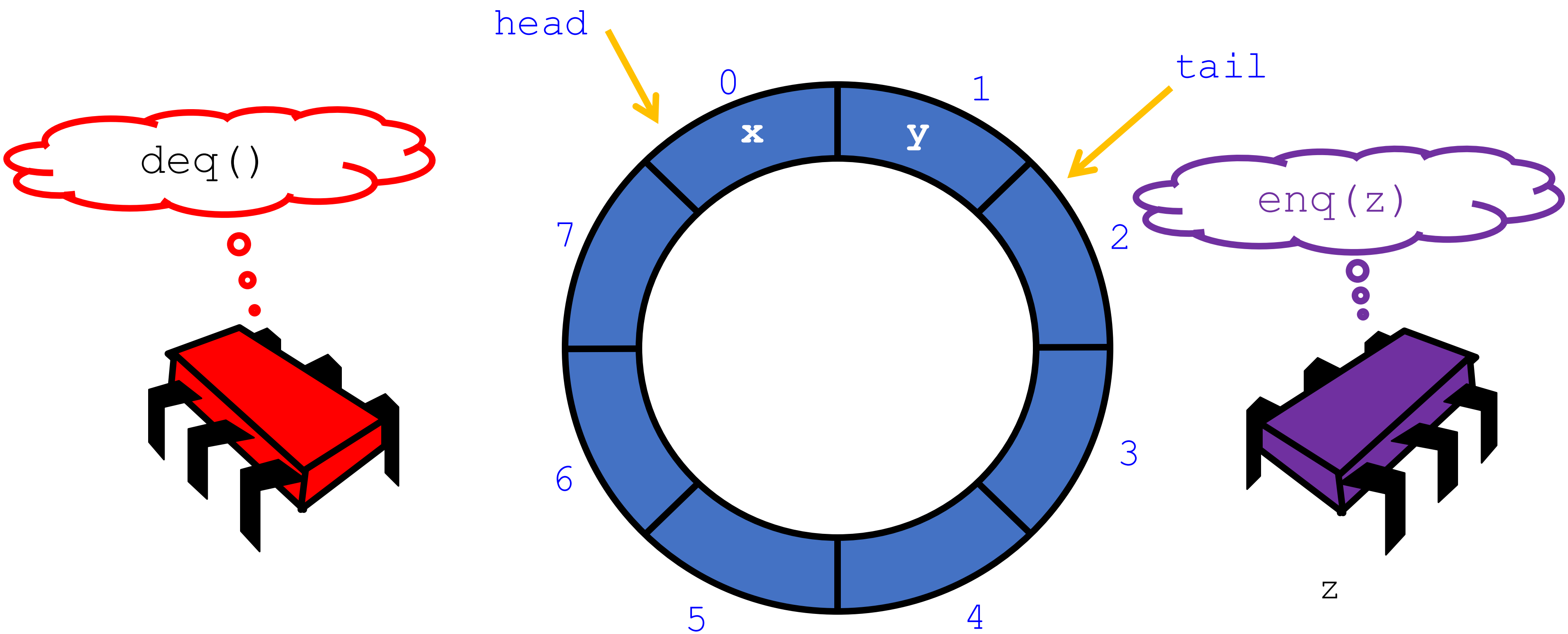
- The same thing without mutual exclusion
- For simplicity, only two threads
  - One thread enq only
  - The other deq only

Wait-free 2-Thread Queue



capacity = 8

Wait-free 2-Thread Queue



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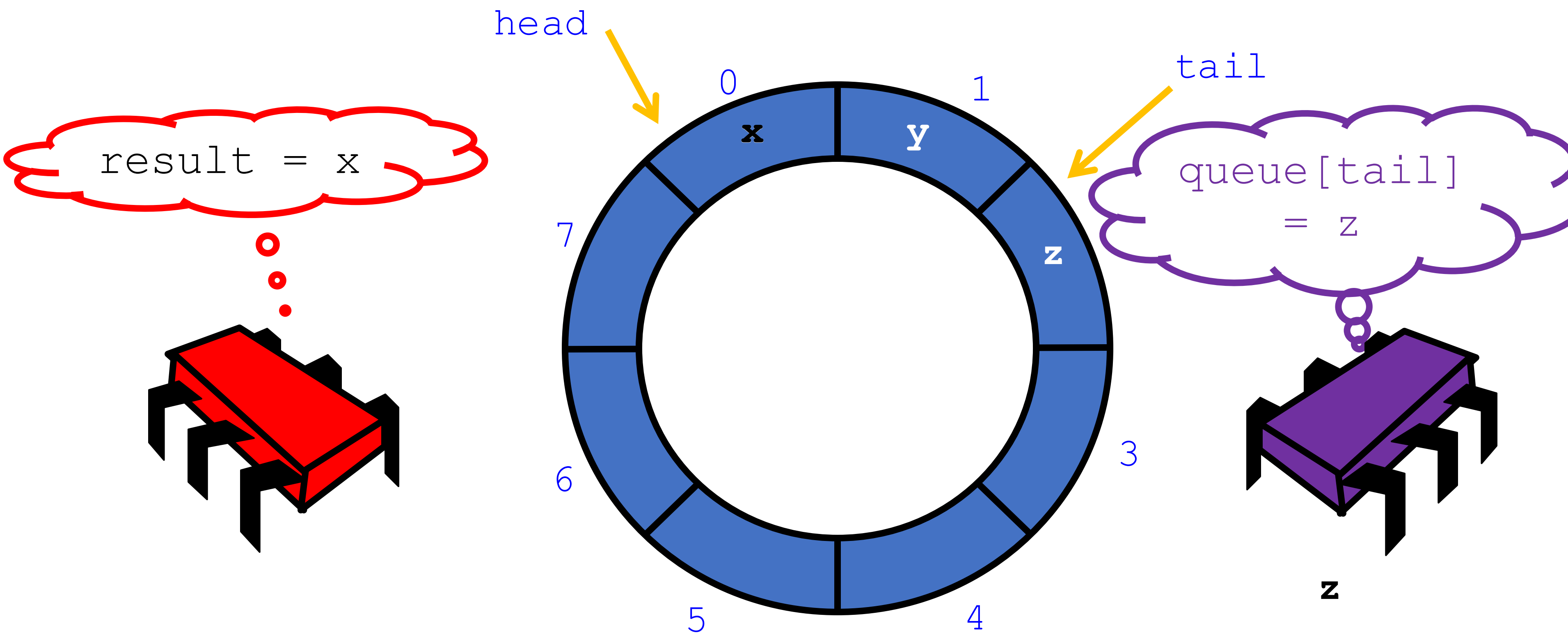
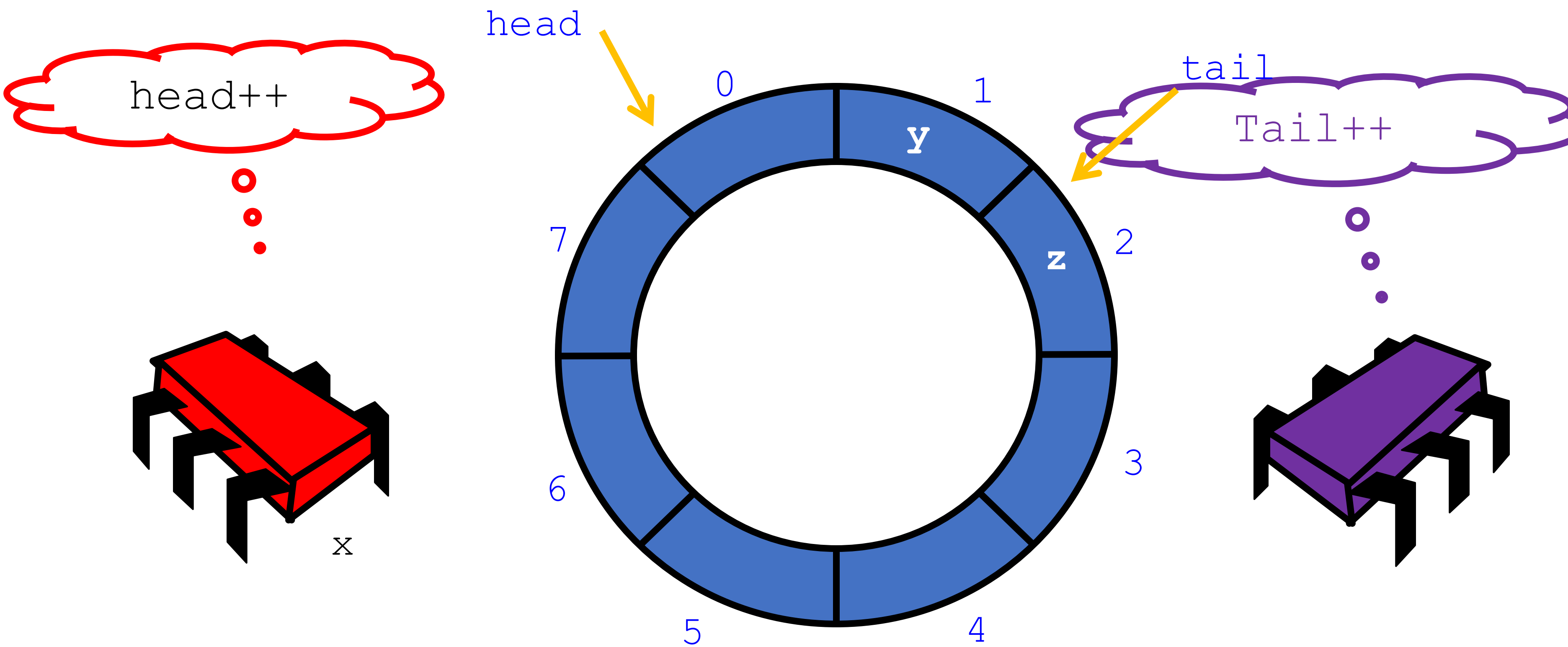
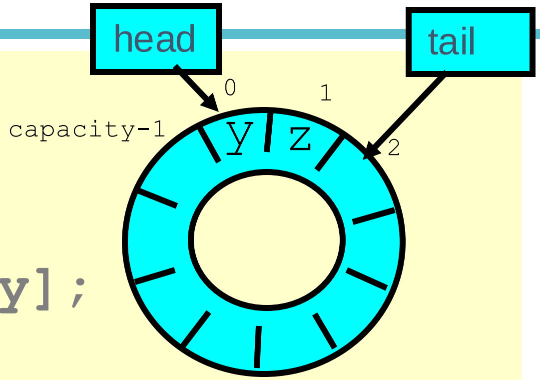


Wait-free 2-Thread Queue



Wait-free 2-Thread Queue



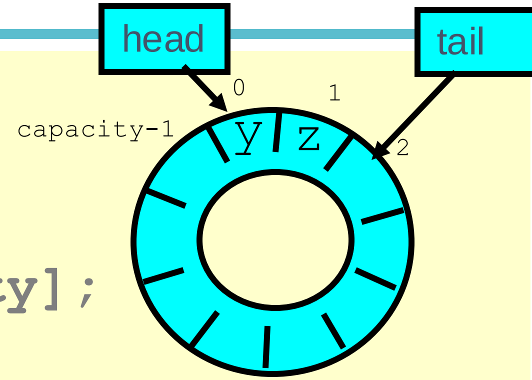

```
public class WaitFreeQueue {

  int head = 0, tail = 0;
  items = (T[]) new Object[capacity];

  public void enq(Item x) {
    if (tail-head == capacity) throw
         new FullException();
    items[tail % capacity] = x; tail++;
  }
  public Item deq() {
     if (tail == head) throw
         new EmptyException();
     Item item = items[head % capacity]; head++;
     return item;
}}
```

No lock needed?!

Wait-free 2-Thread Queue

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```

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

No lock needed?!

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
- Let's 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

Let's 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, con't)
  - the object will be in some other state
  - when the method returns,

Pre and PostConditions for Dequeue

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

- Precondition:
  - Queue is empty
- Postcondition:
  - Throws Empty exception
- Postcondition:
  - Queue state unchanged

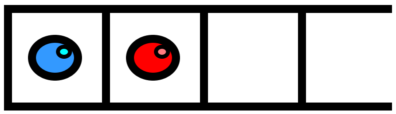
Why Sequential Specifications Totally Rock

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

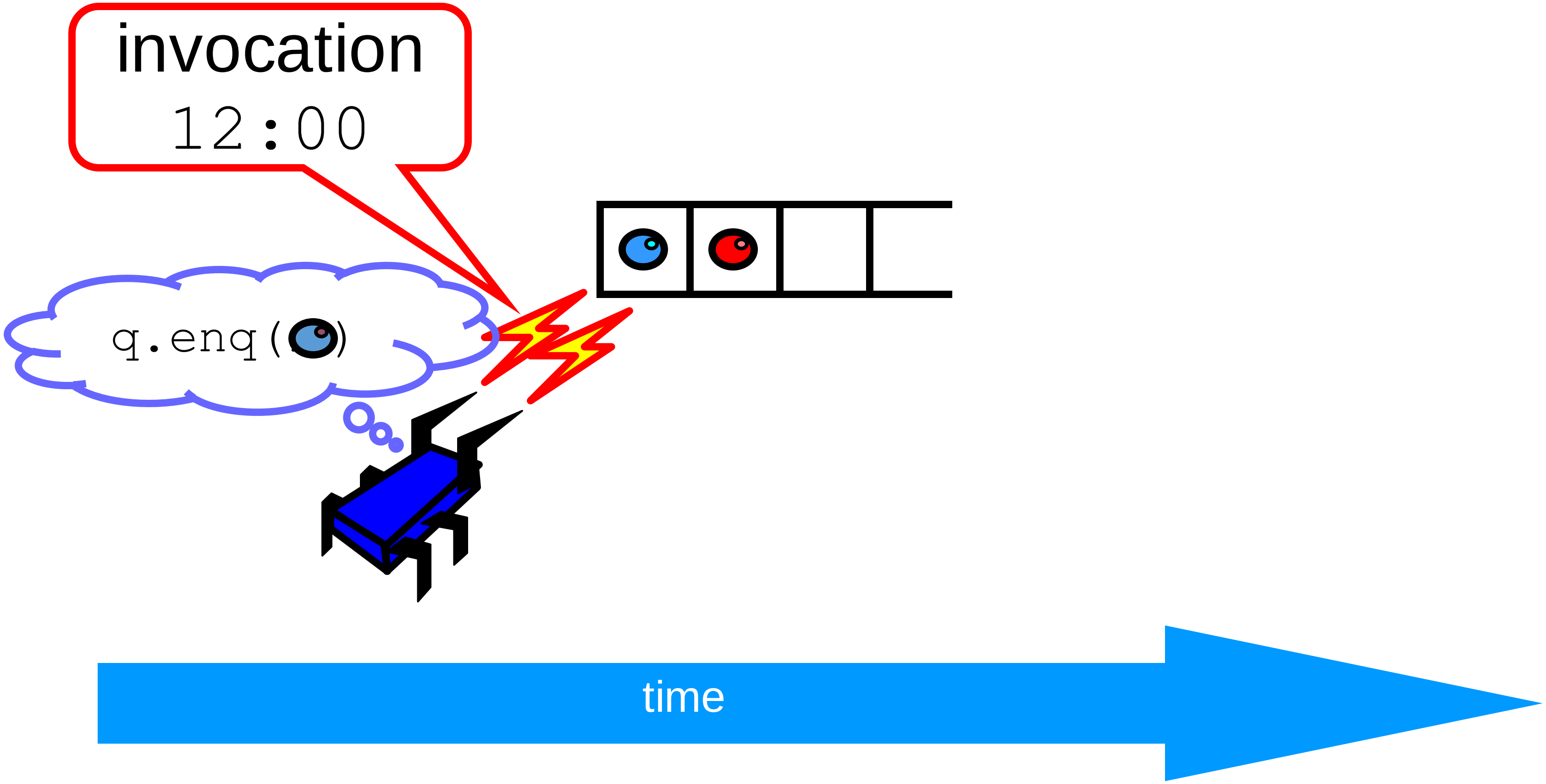
What About Concurrent Specifications ?

- Methods?
- Documentation?
- Adding new methods?

Methods Take Time



Methods Take Time



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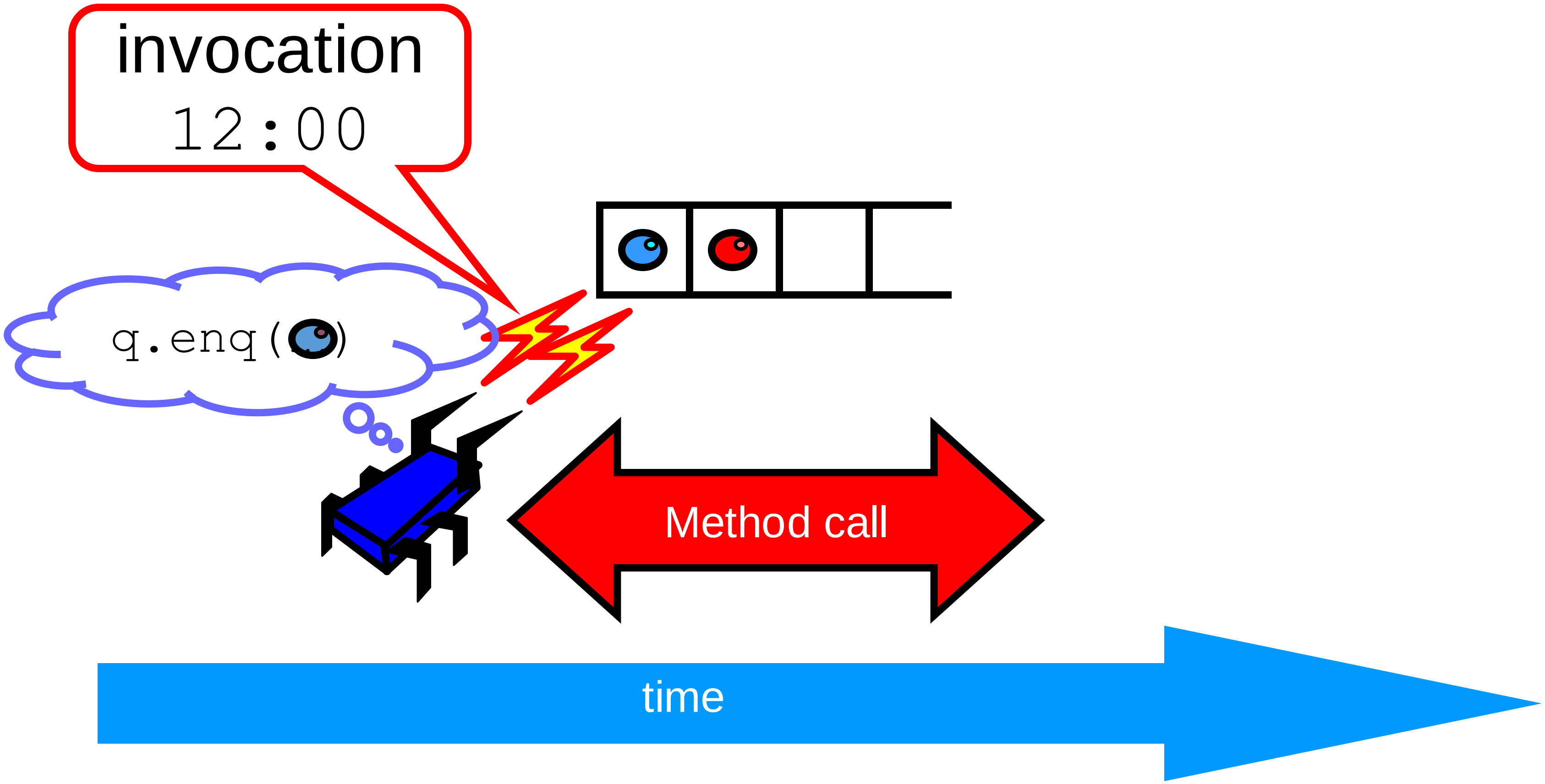

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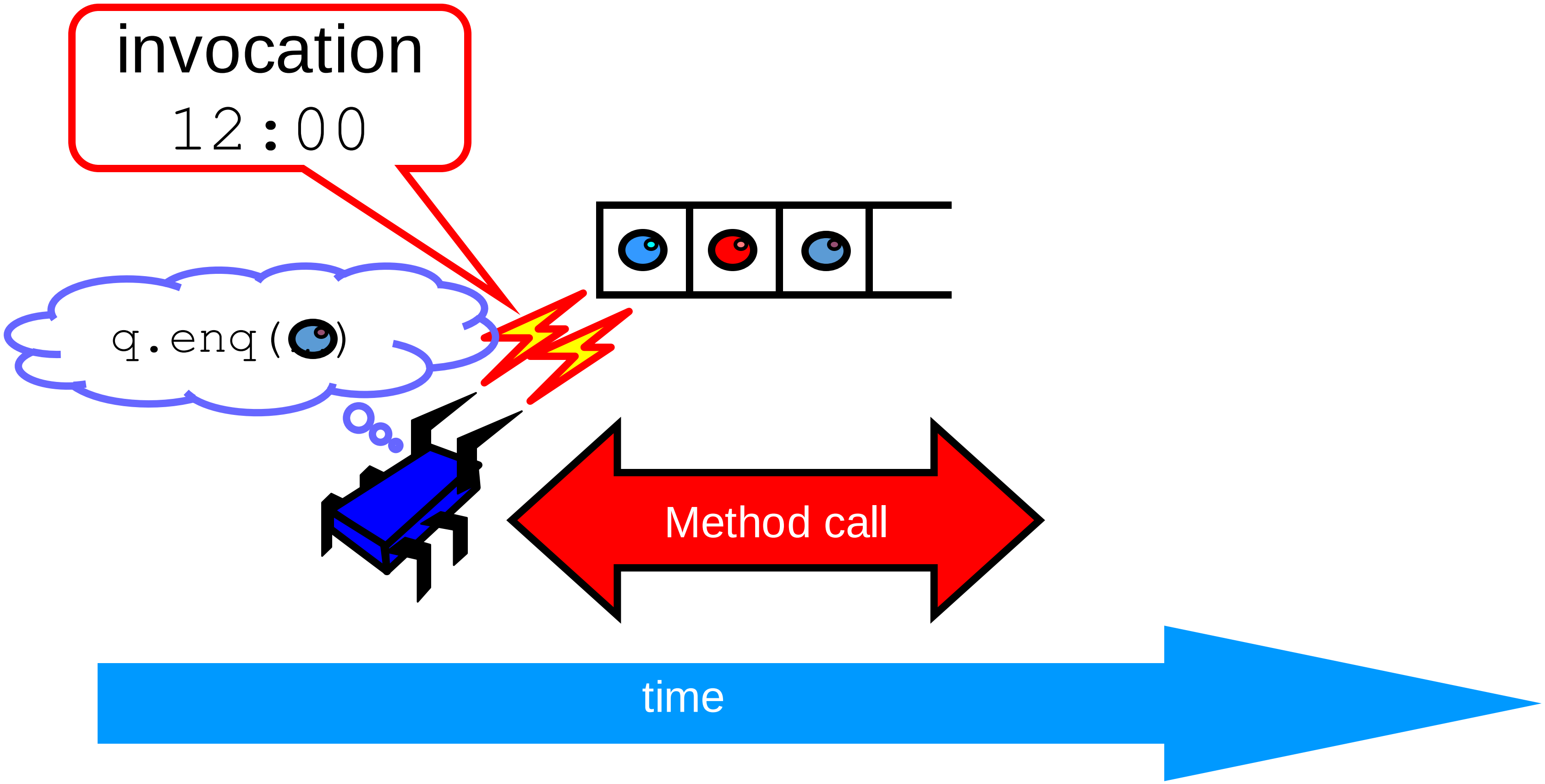

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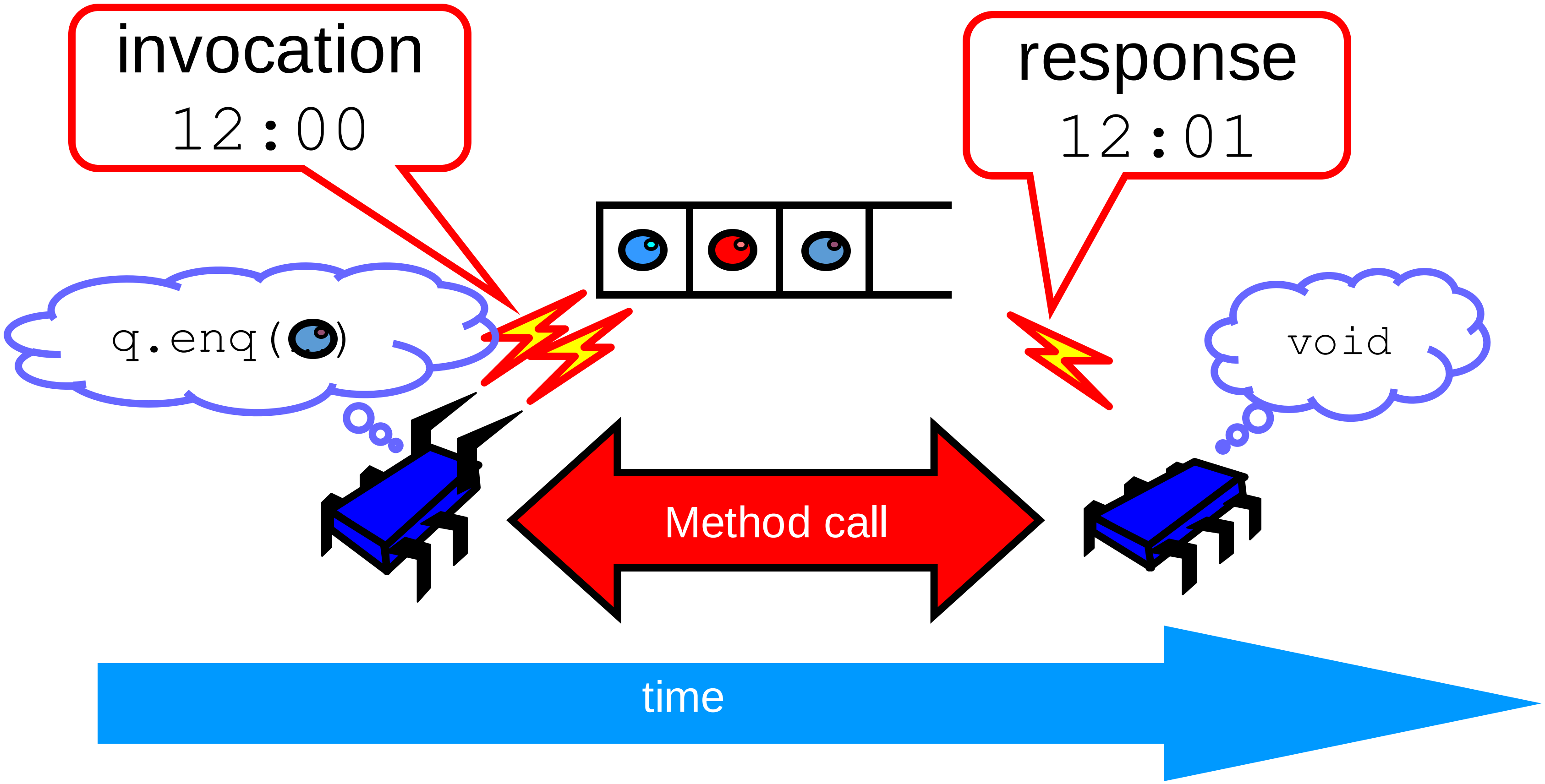
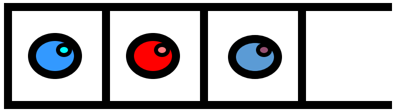


Sequential vs Concurrent

- 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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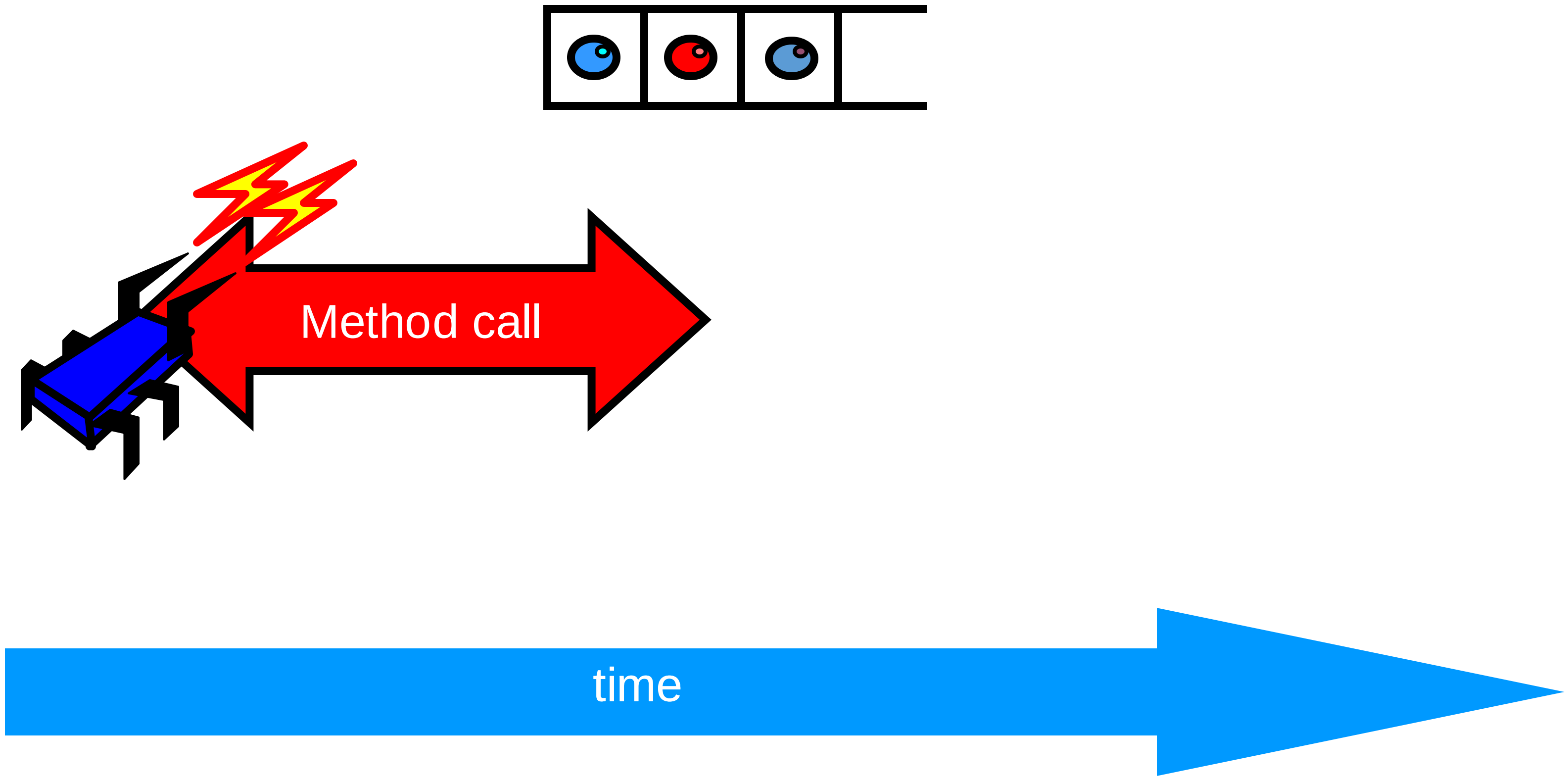

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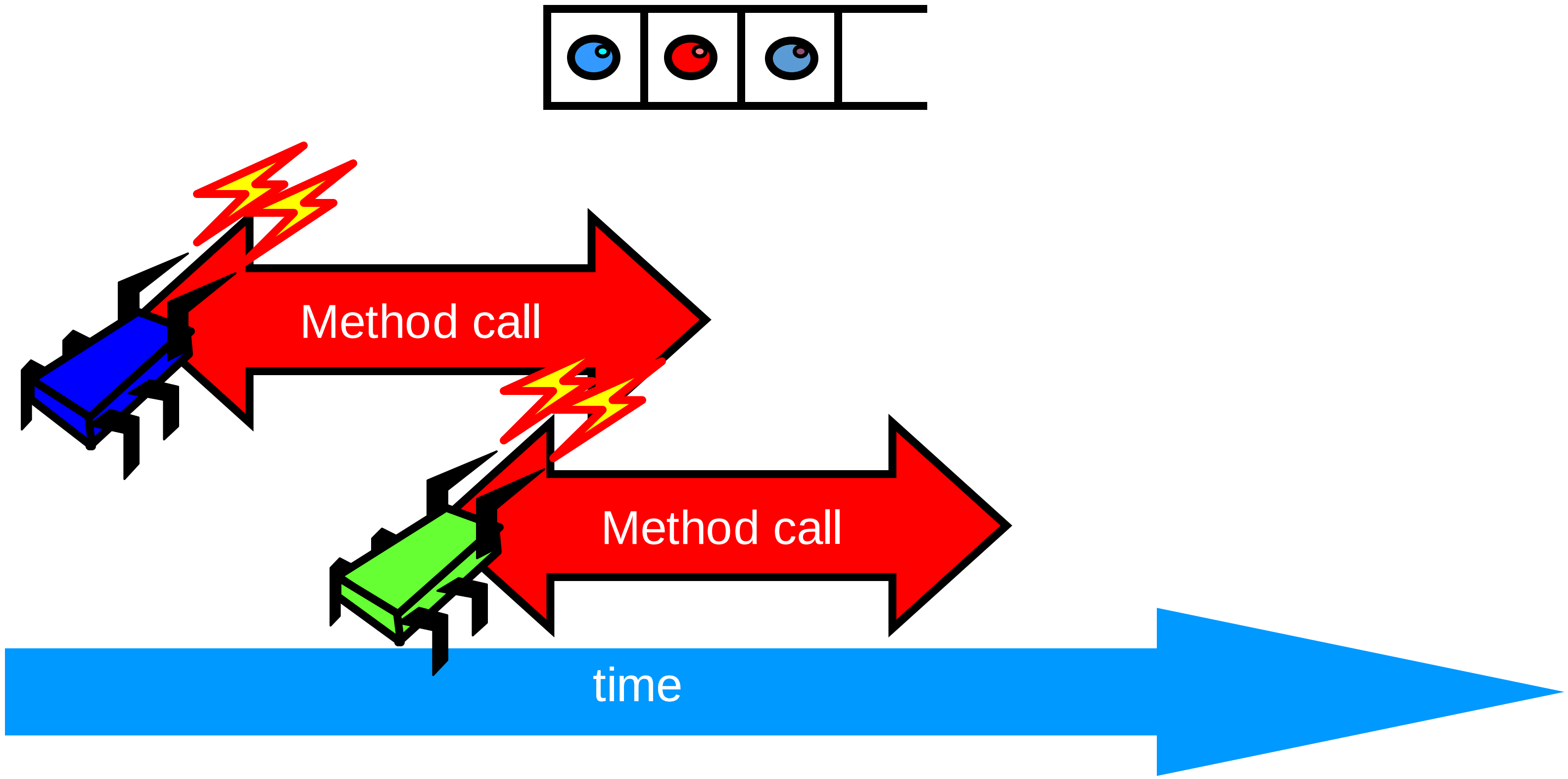

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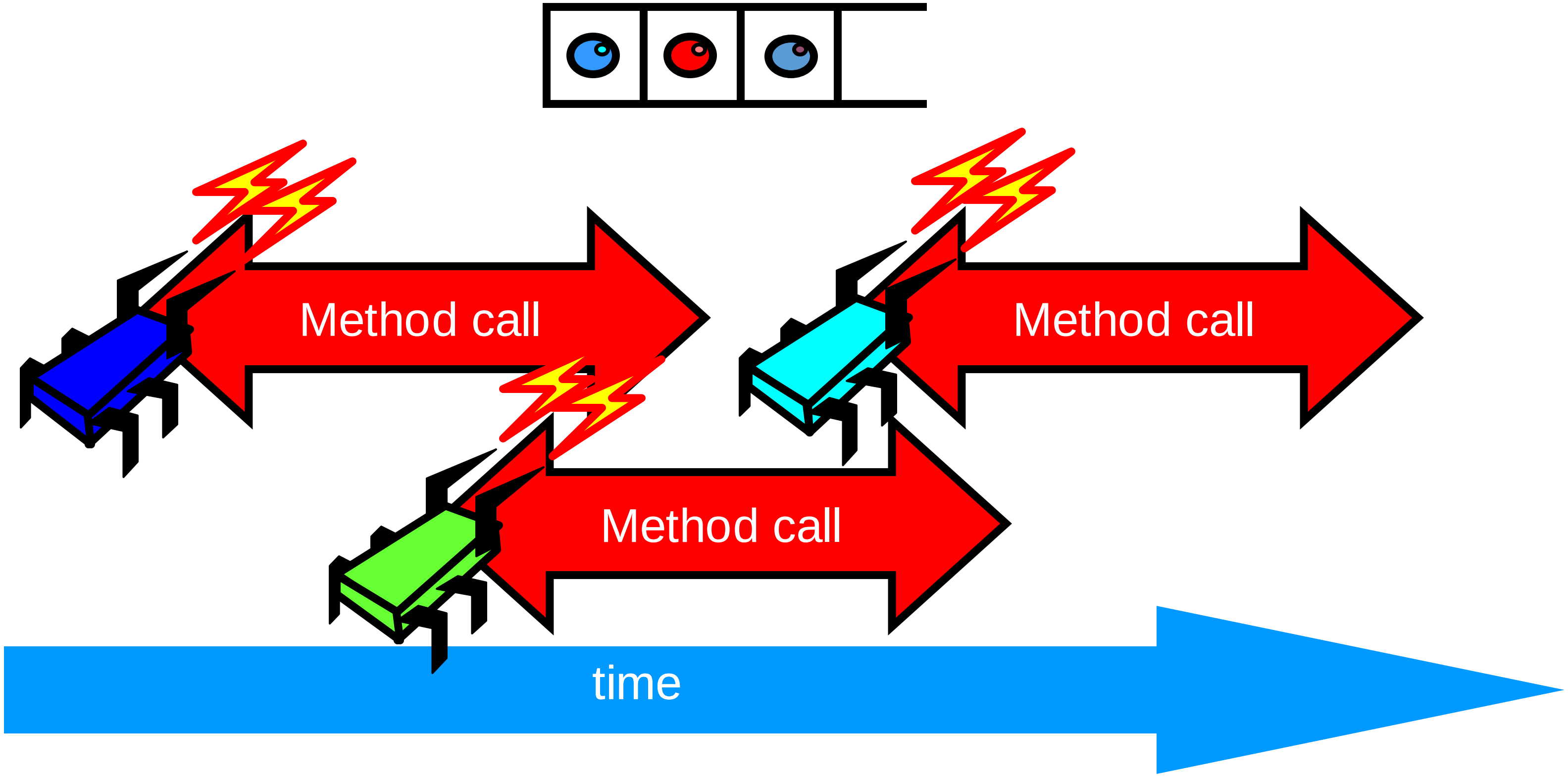

Sequential vs Concurrent: time

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

Sequential vs Concurrent: doc

- 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: add

- 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…

```java
public T deq() throws EmptyException {
  lock.lock();
  try {
    if (tail == head)
       throw new EmptyException();
    T x = items[head % items.length];
    head++;
    return x;
  } finally {
    lock.unlock();
  }
}
```

Intuitively…

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  } finally {
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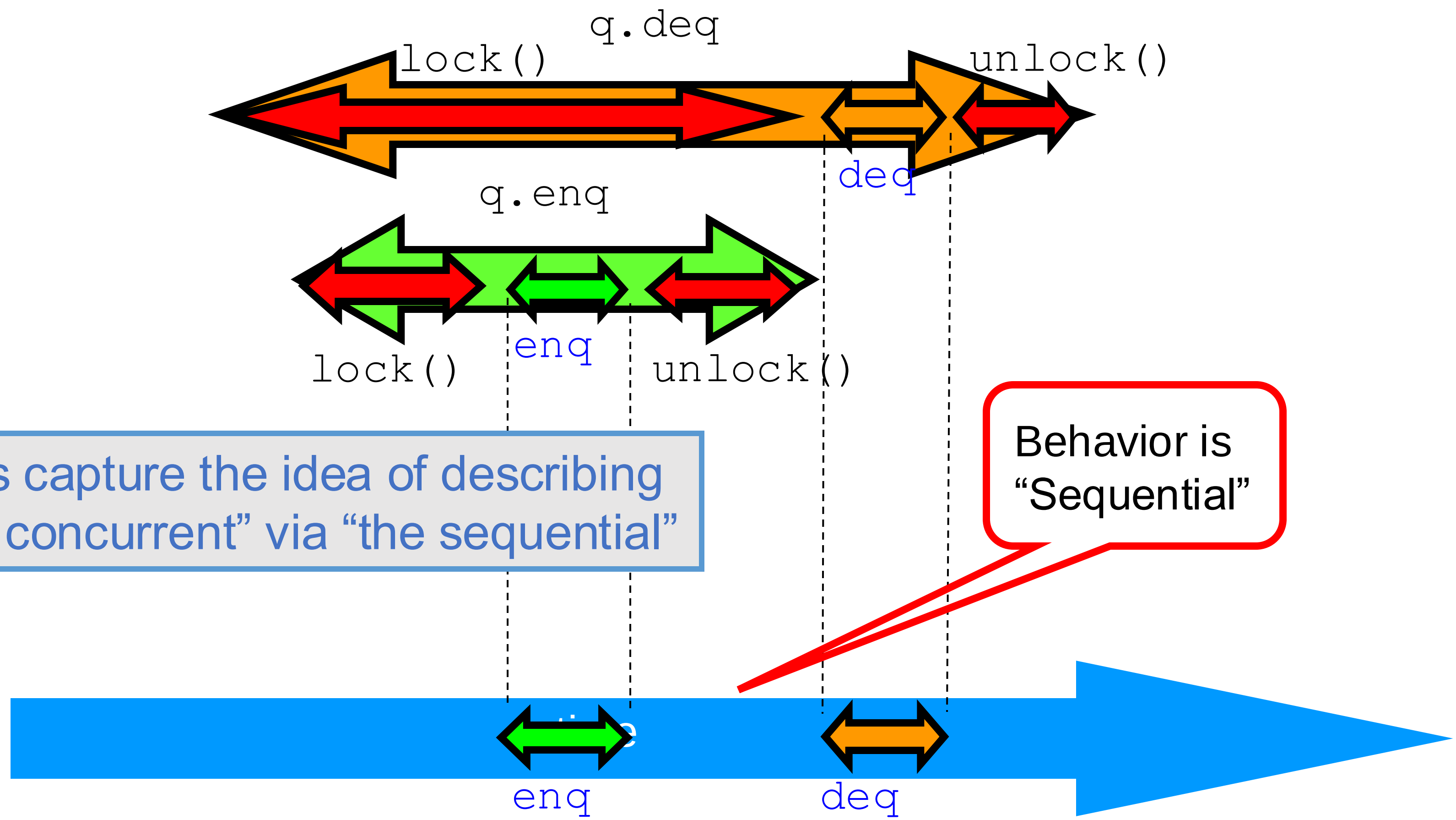
  }
}
```

All queue modifications are mutually exclusive

Intuitively



Let’s capture the idea of describing “the concurrent” via “the sequential”

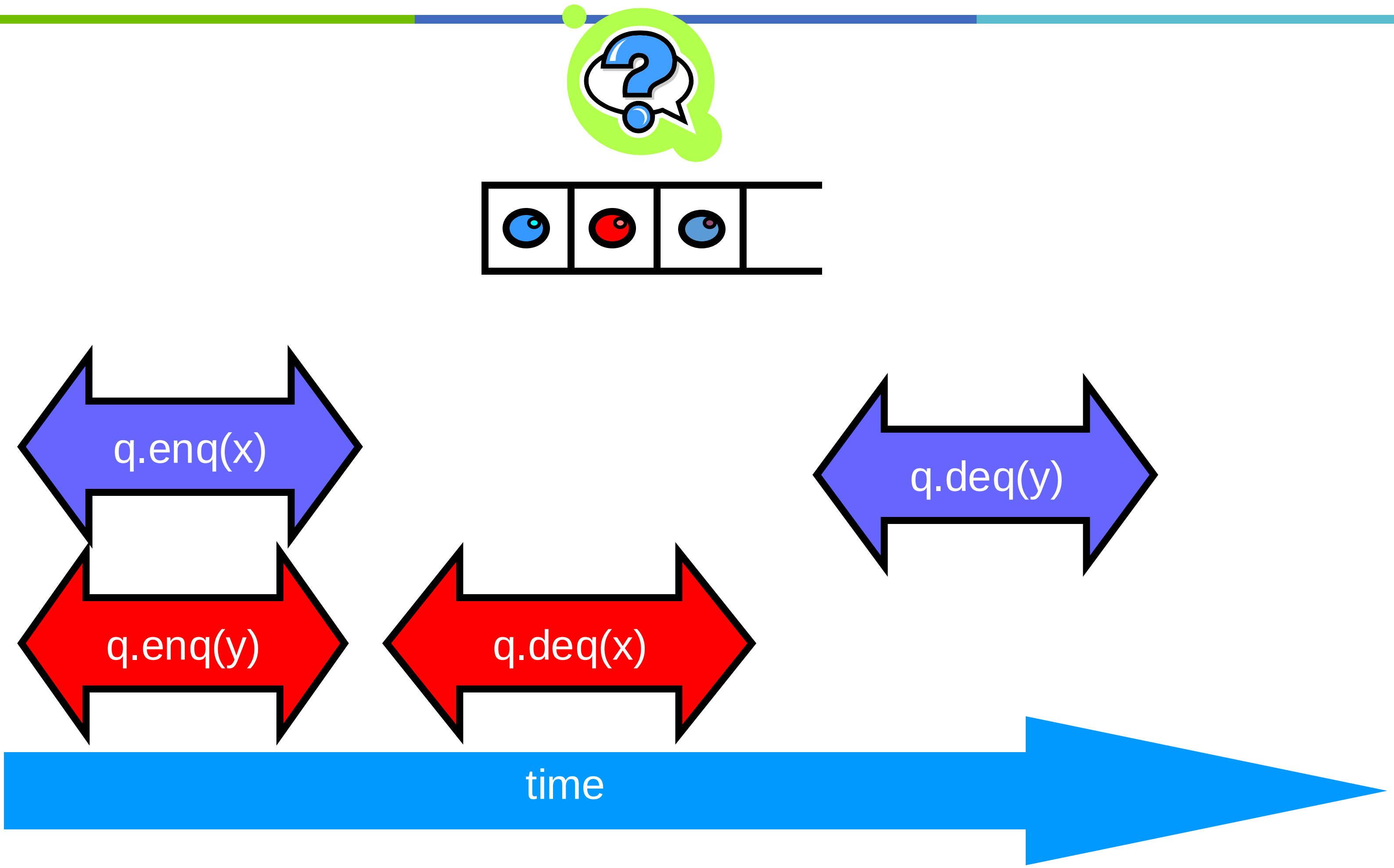
Linearizability

- Each method should
  - "Take effect"
  - Instantaneously
  - Between invocation and response events
- Object is correct if this "sequential" behavior 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…
  - Some methods may be linearizable, others don’t
- A linearizable object is…
  - *One whose methods are all linearizable*
  - *One whose all possible executions are linearizable*

Example



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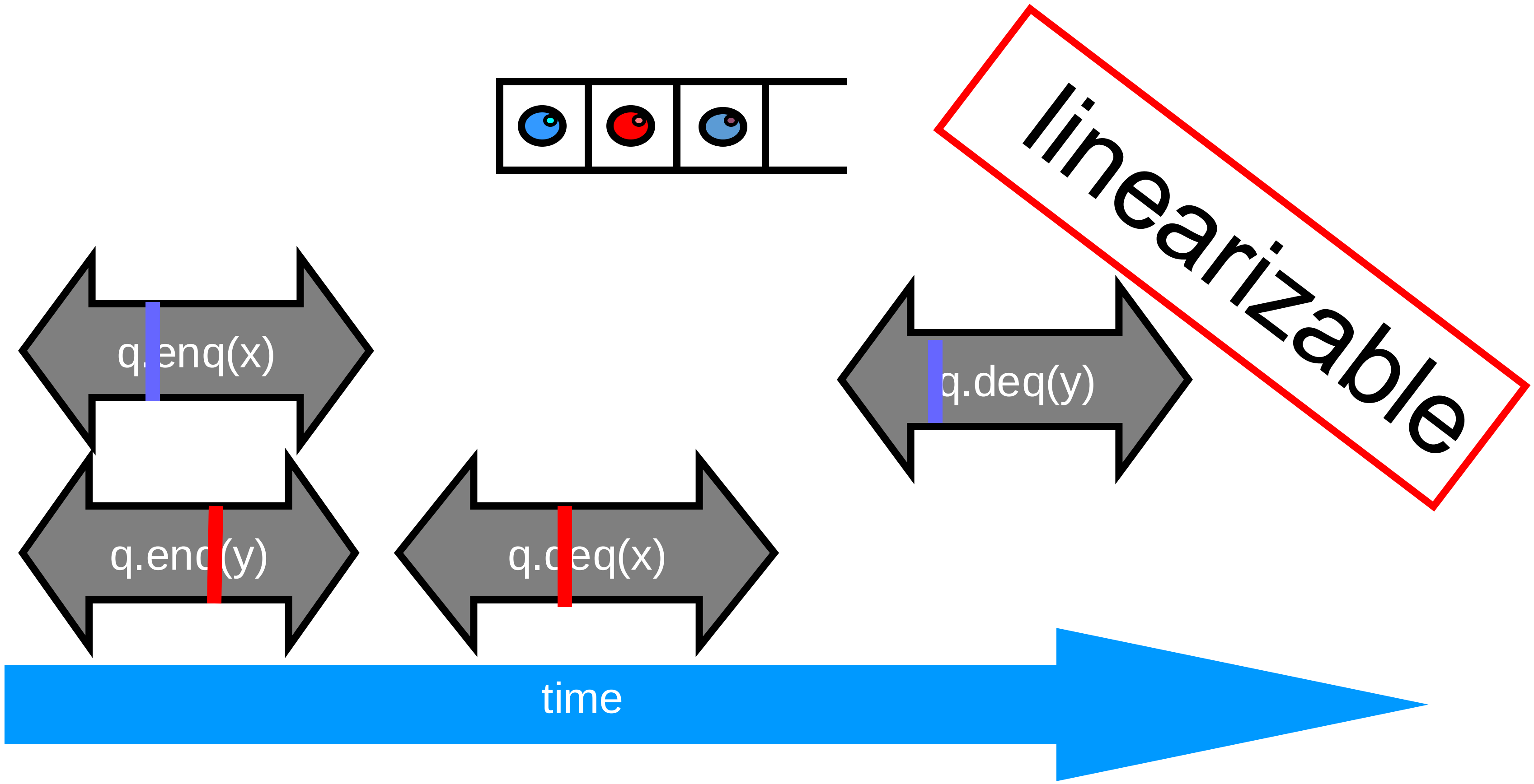

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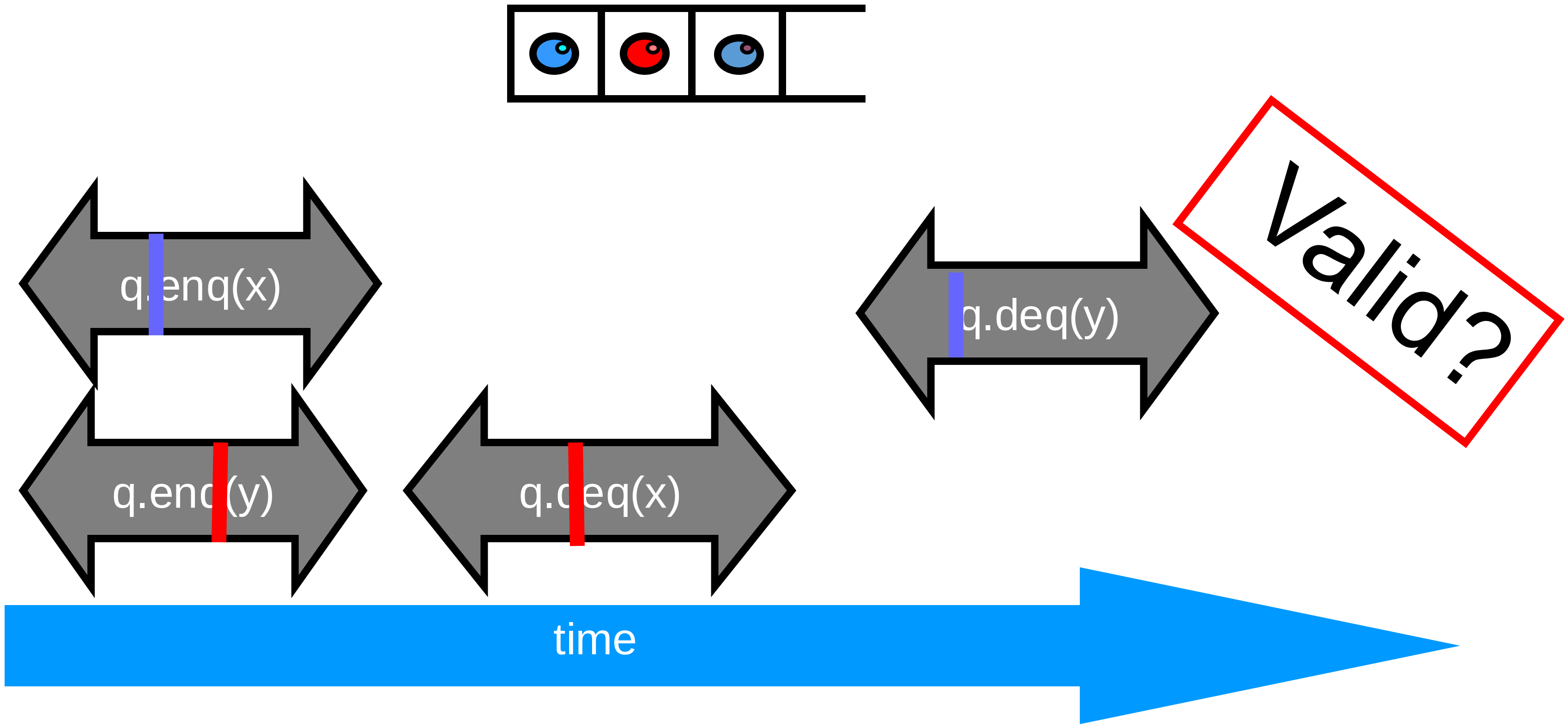

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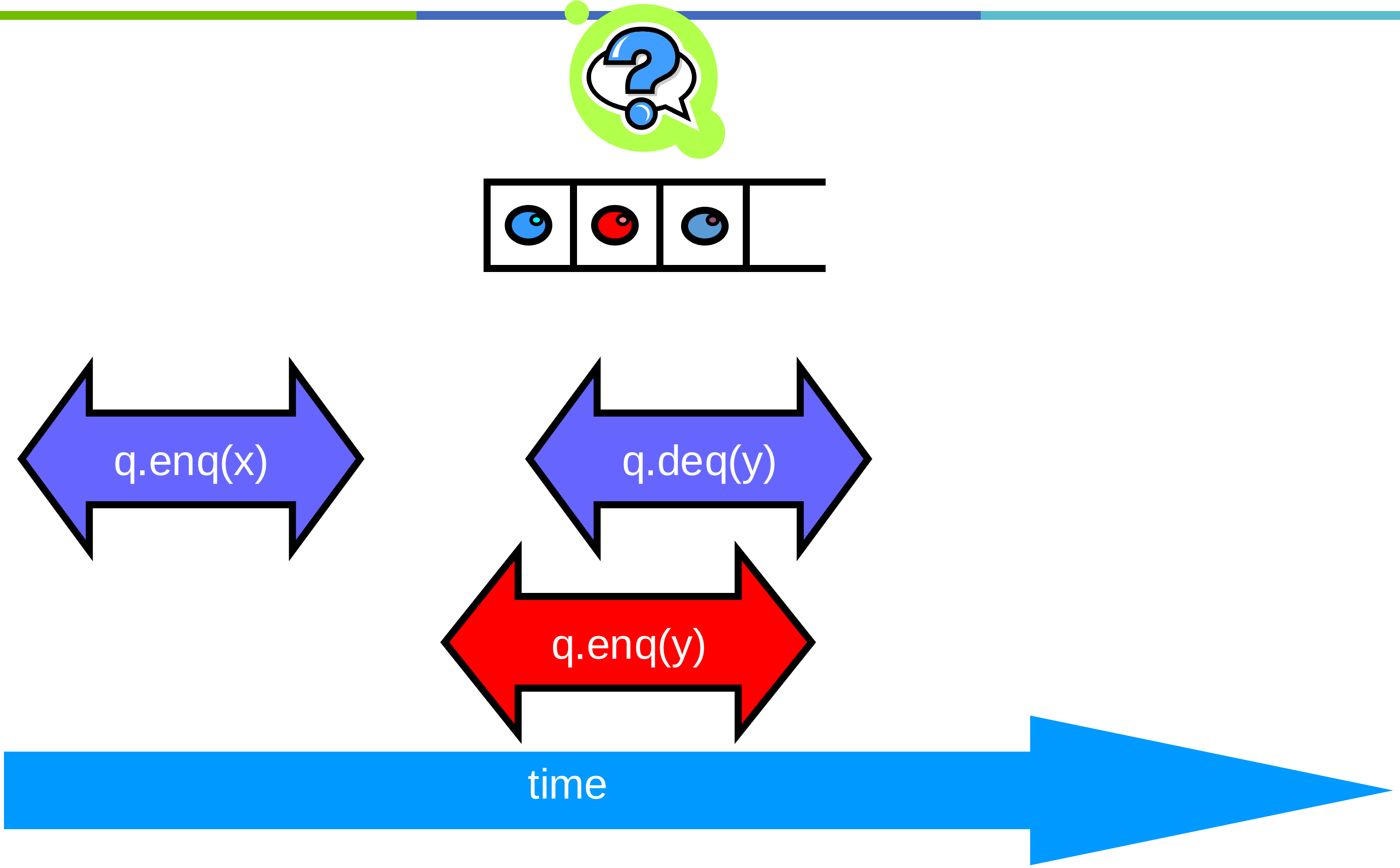

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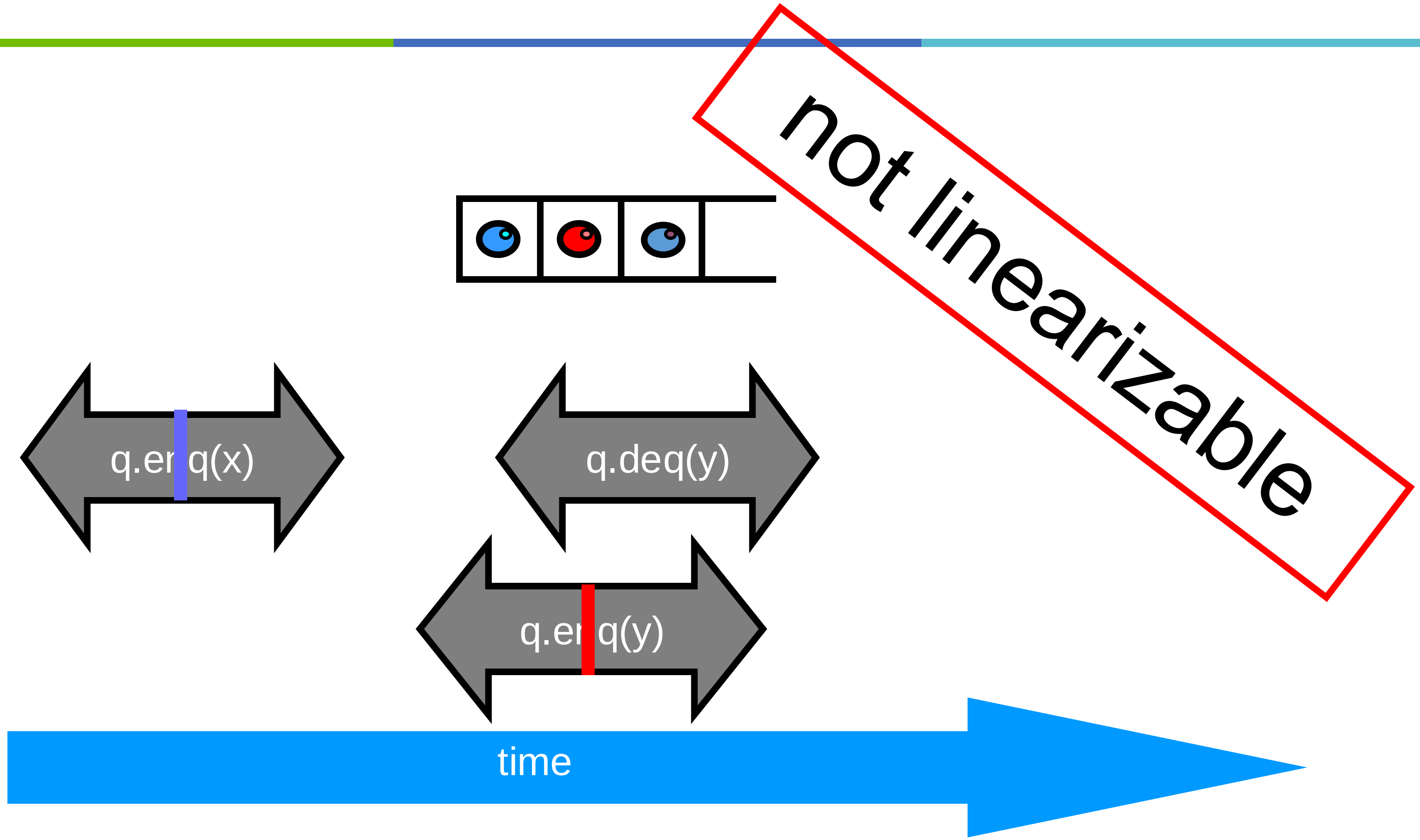

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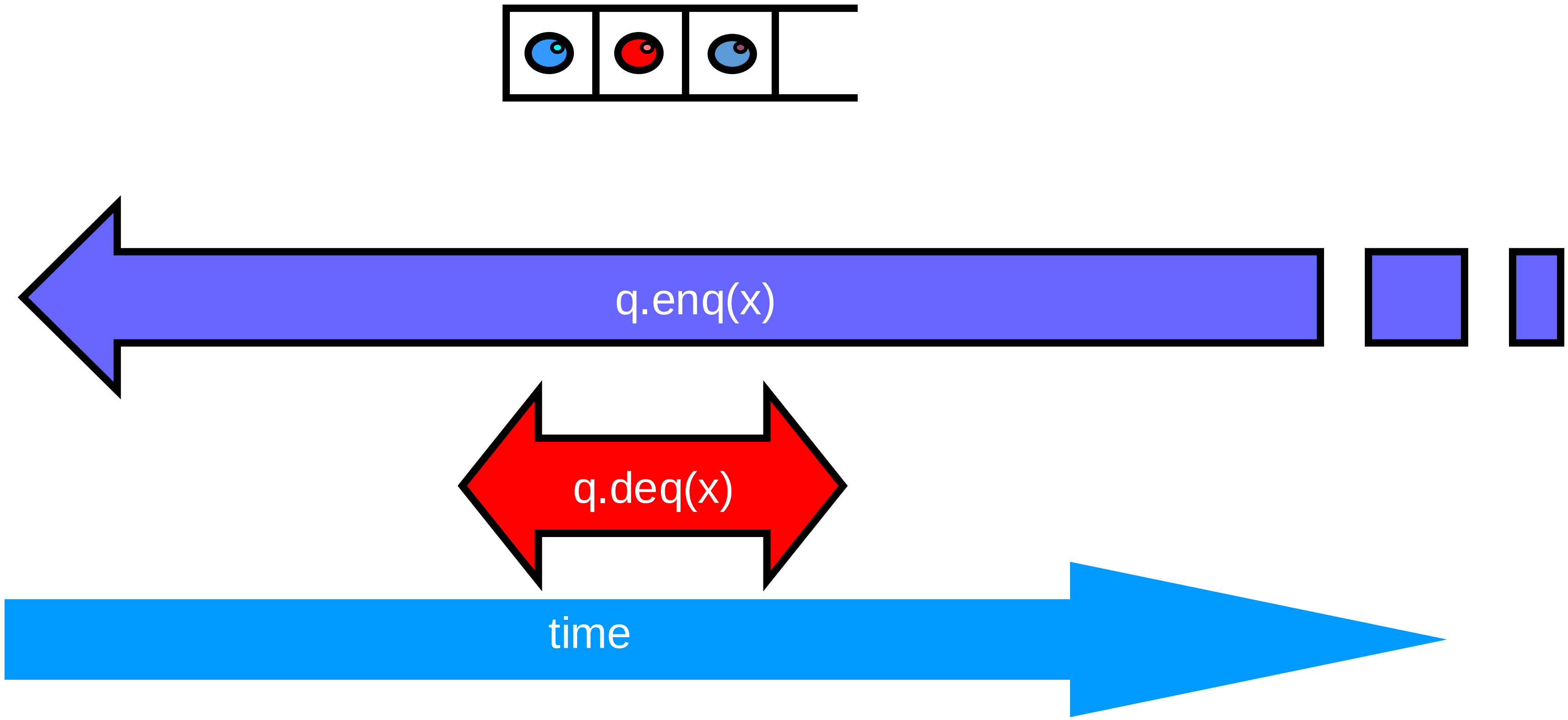

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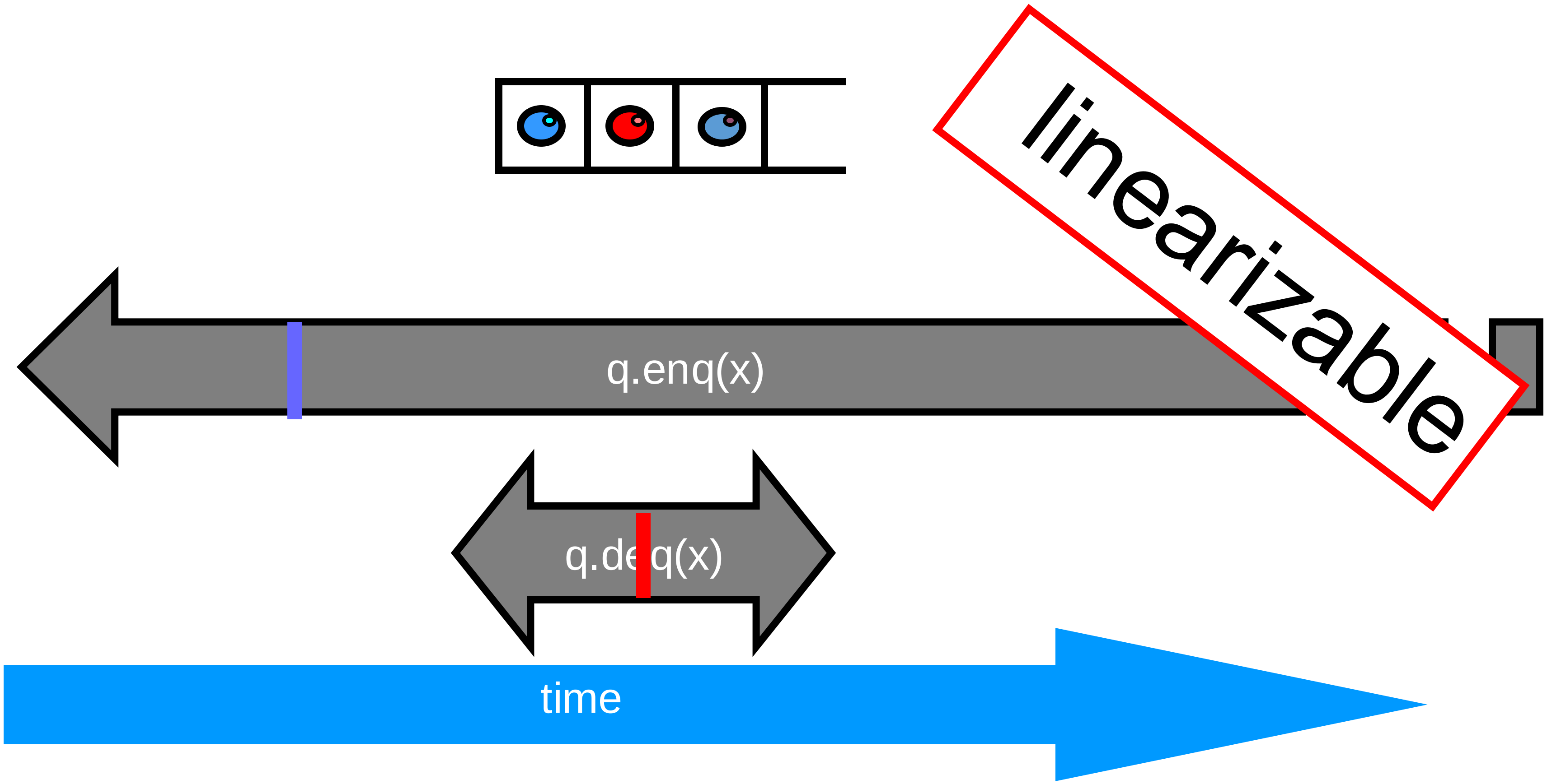

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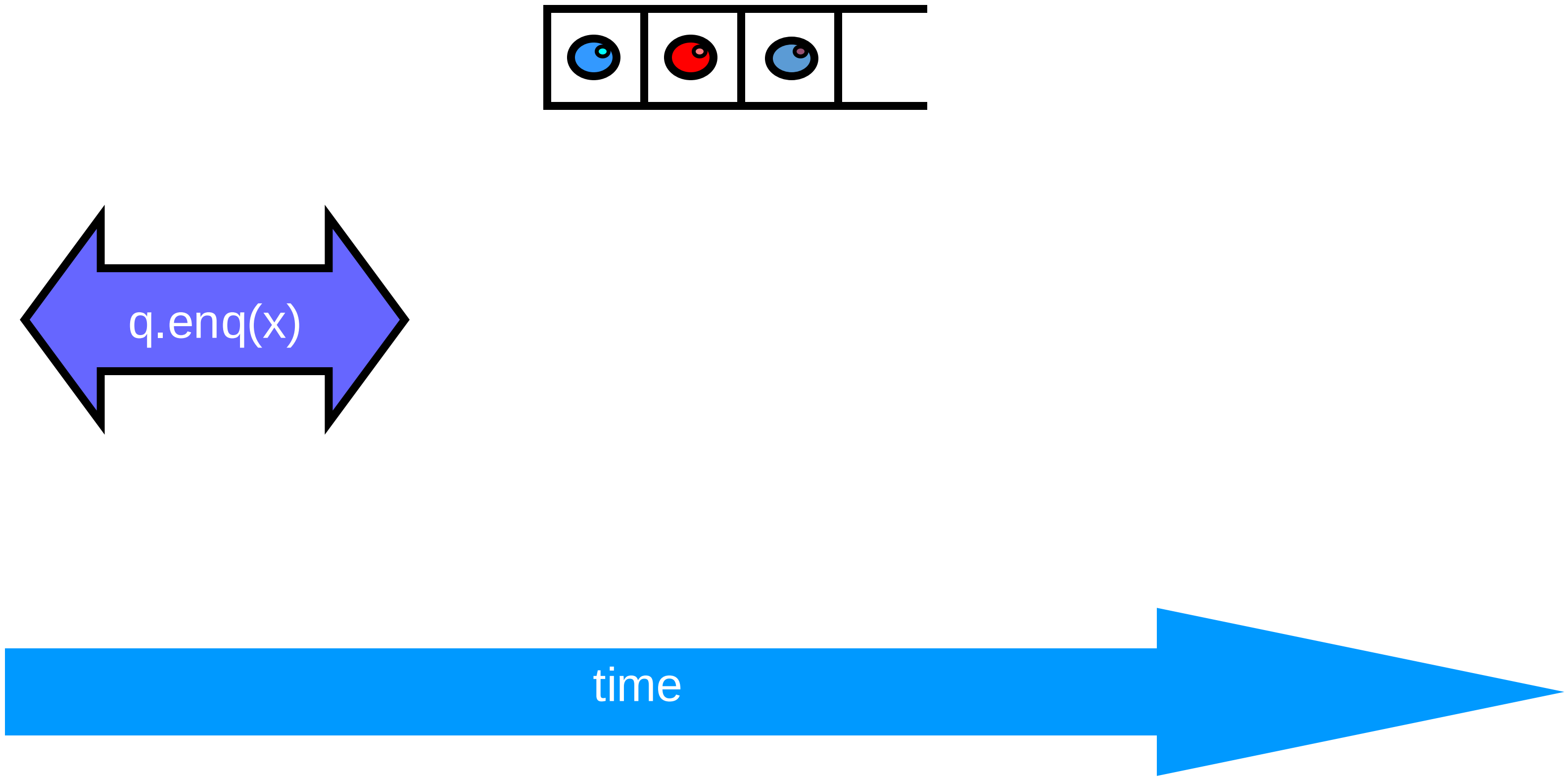

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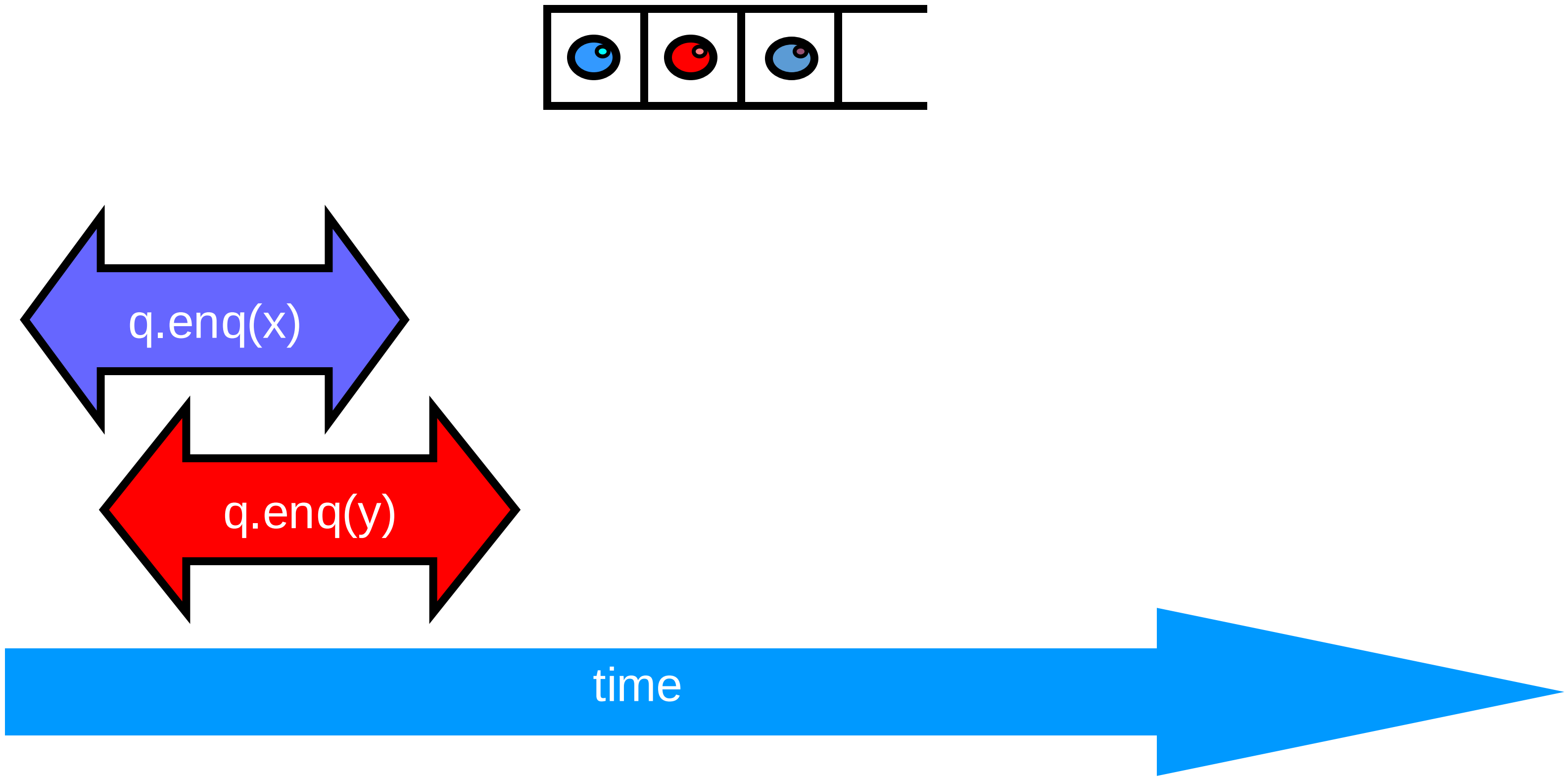

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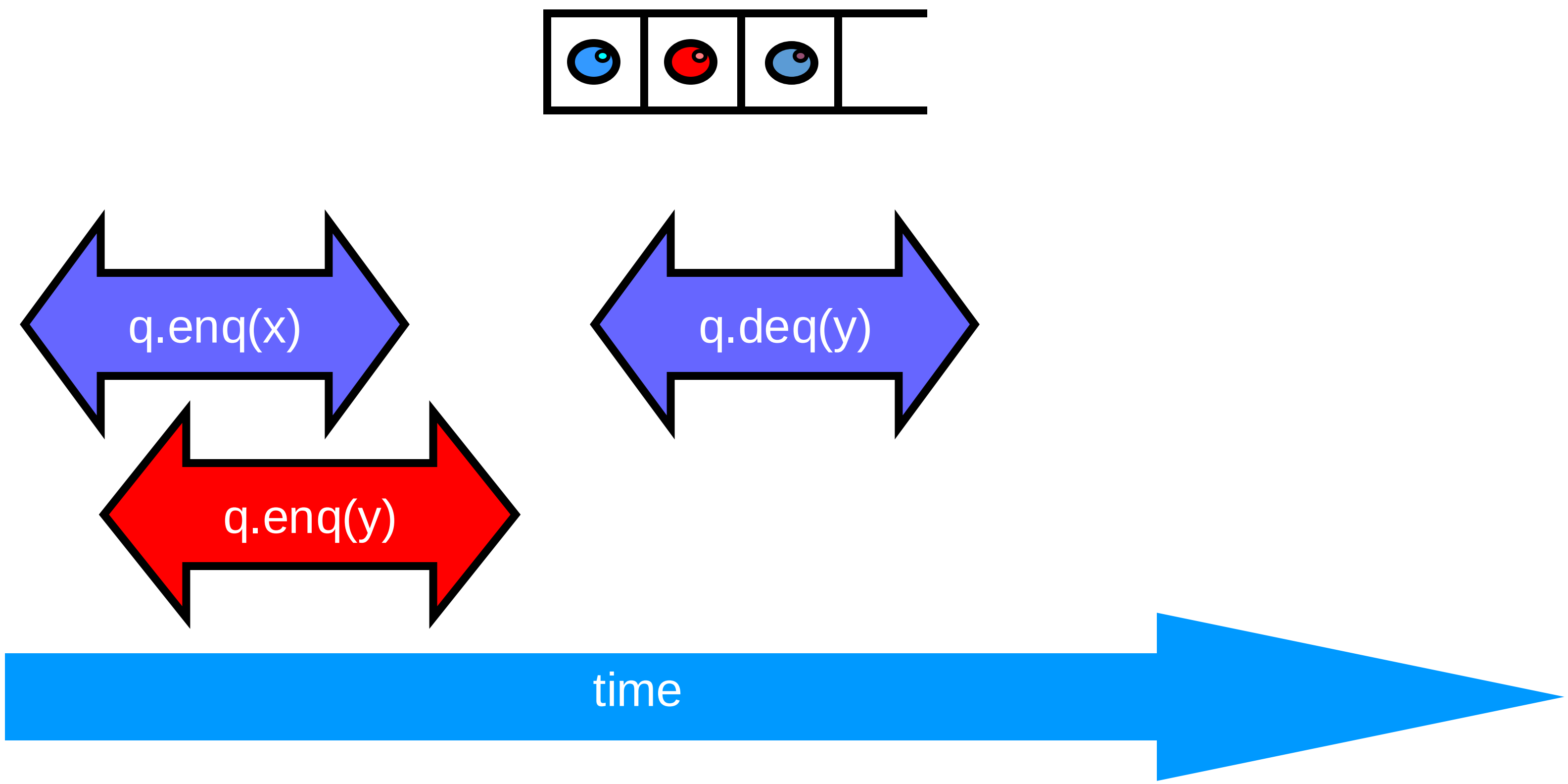

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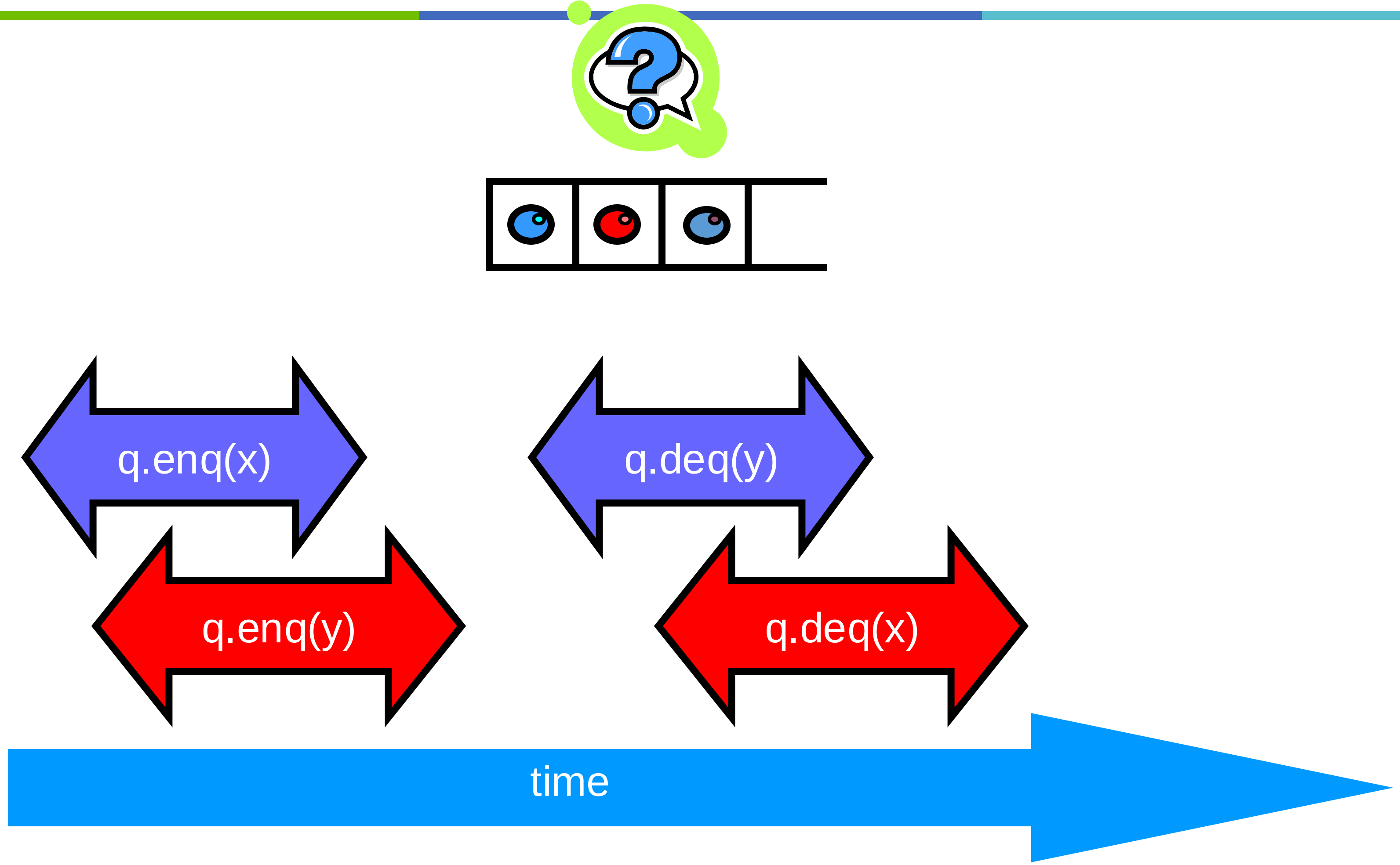

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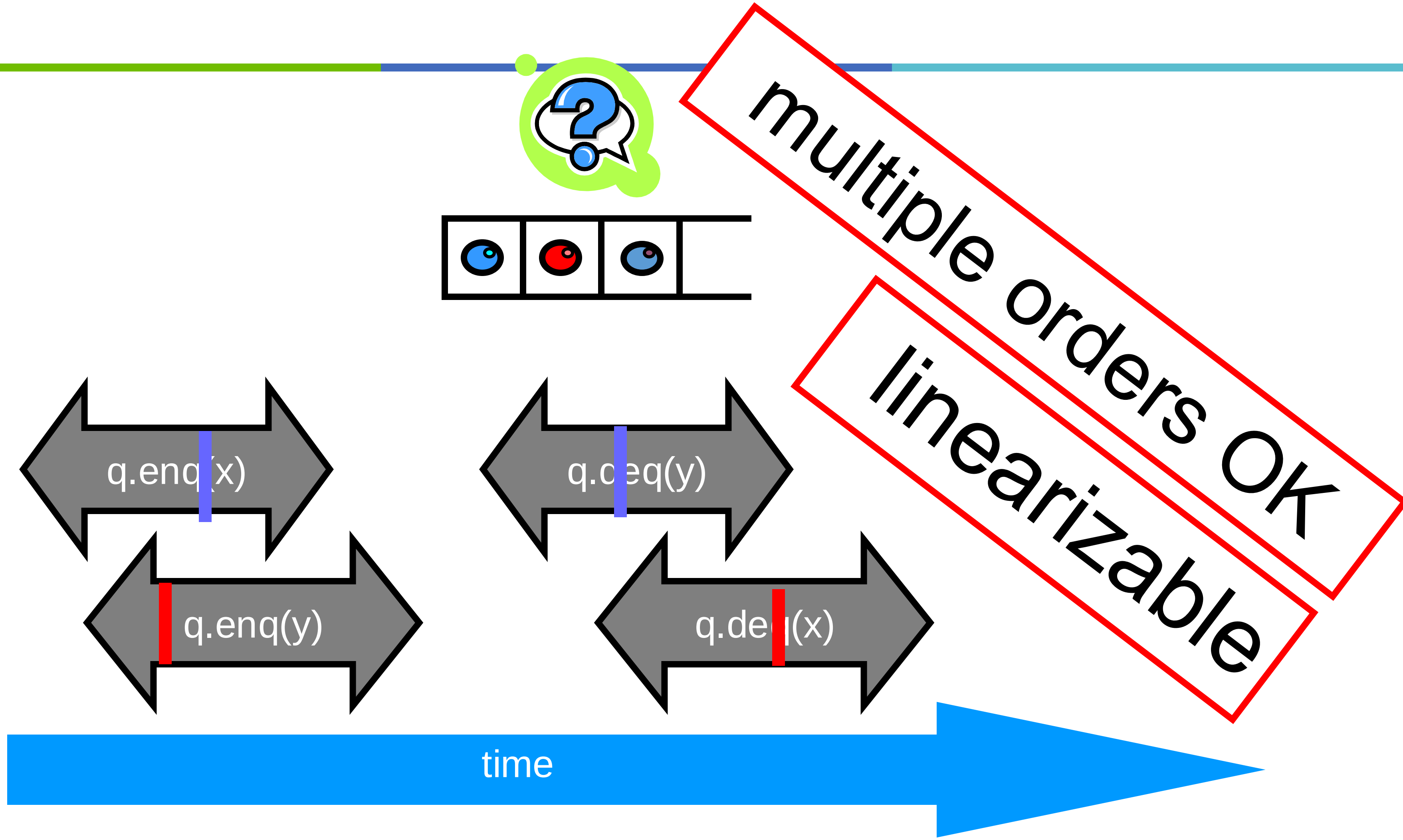
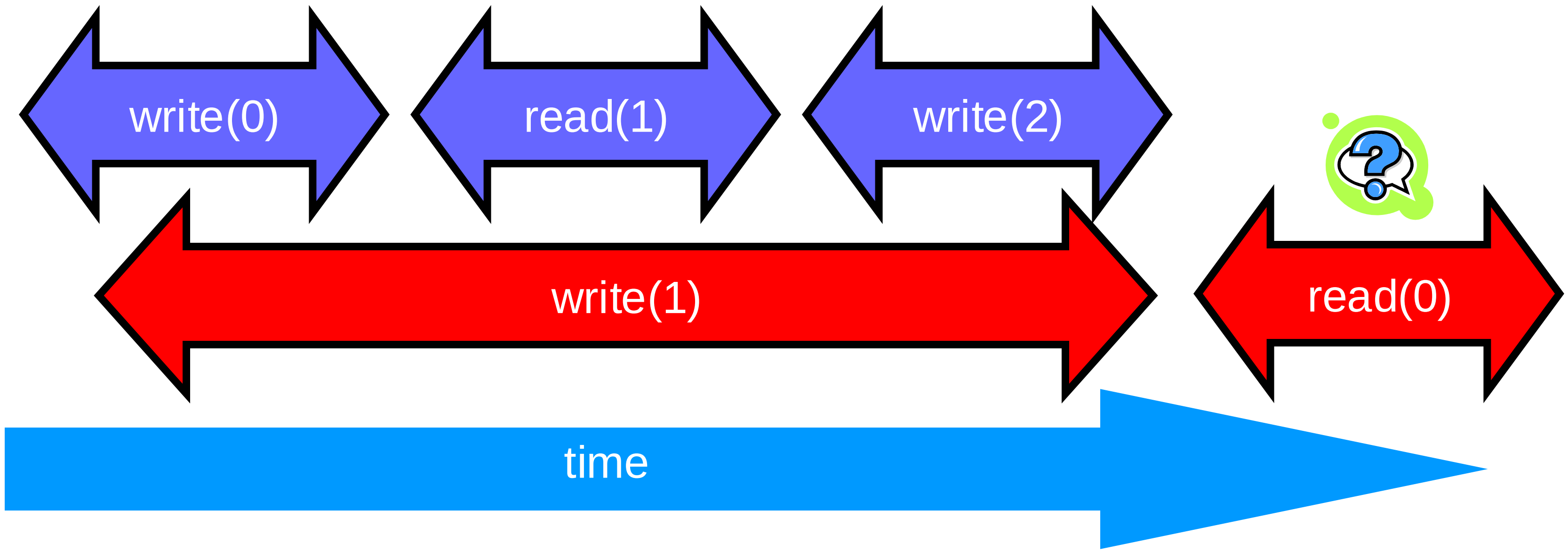
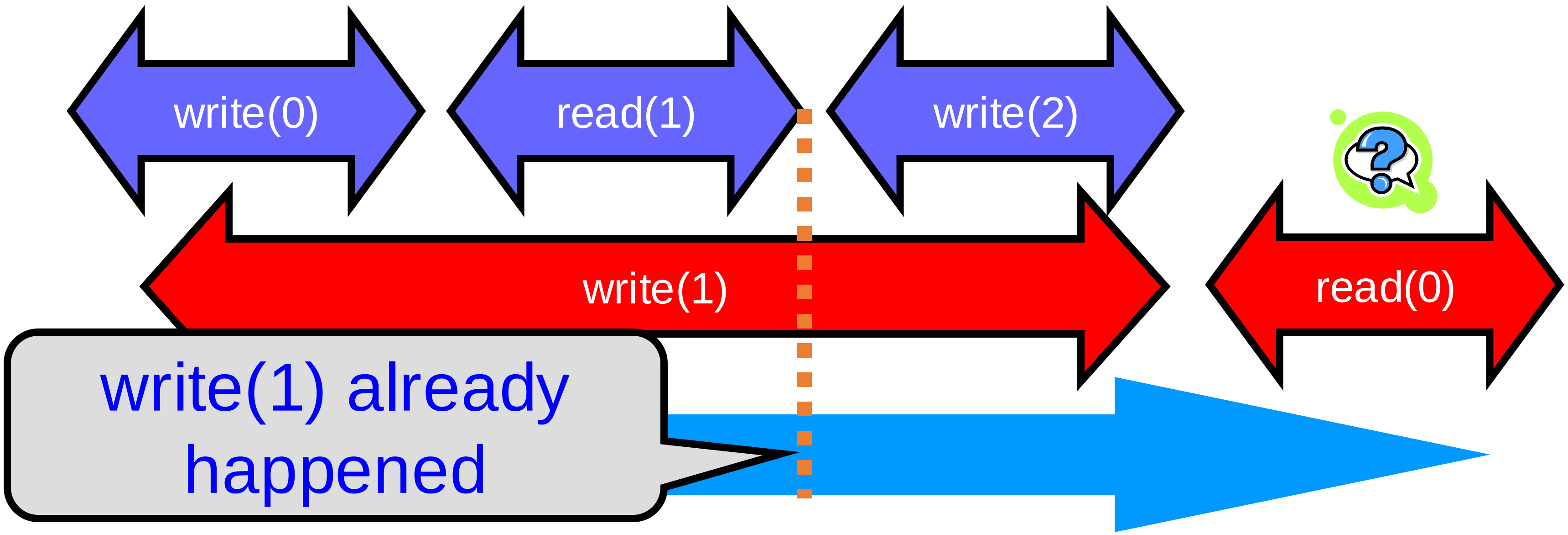


multiple orders OK
linearizable
q.enq(x)
q.deq(y)
q.enq(y)
q.deq(x)
time

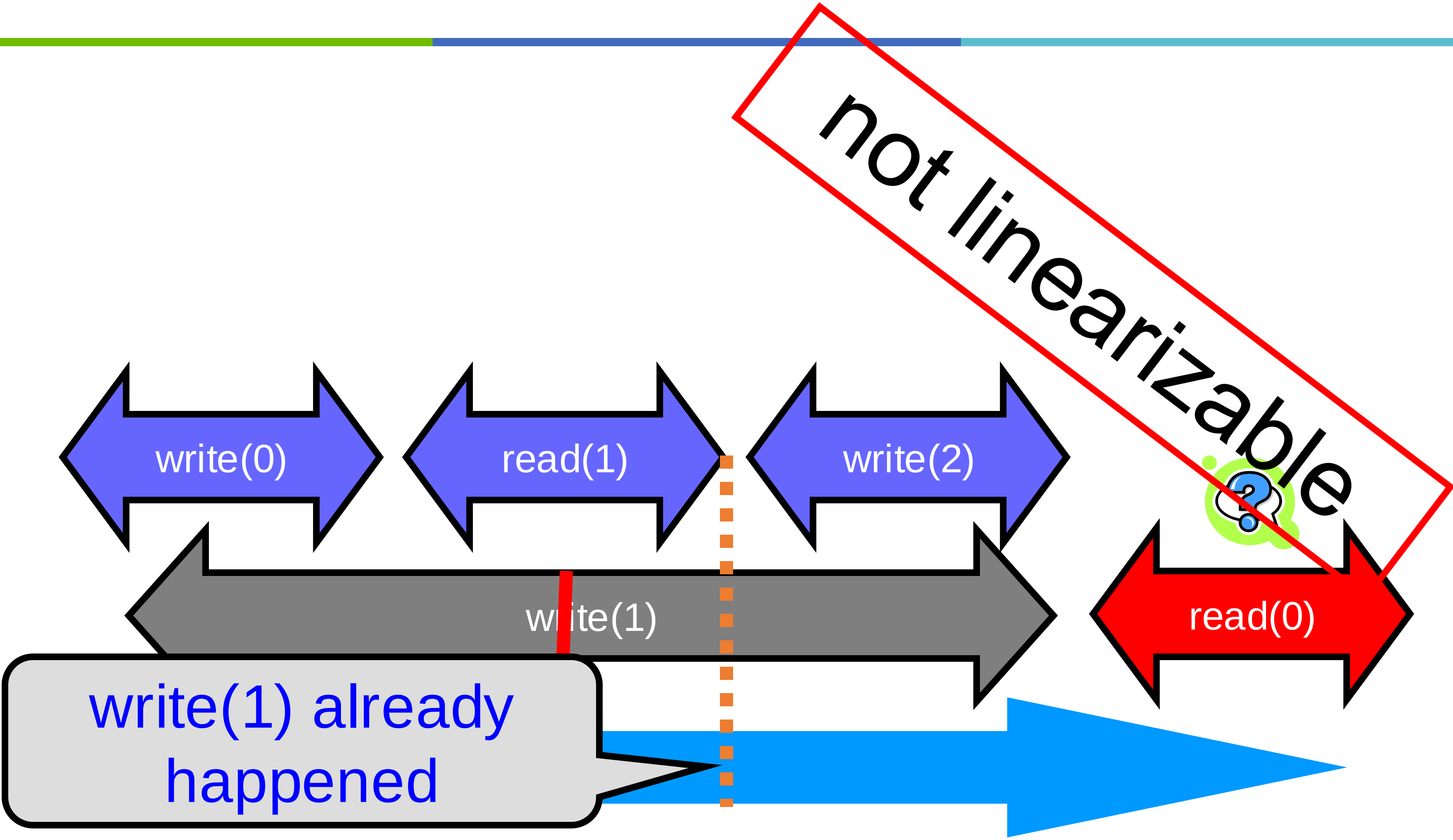
Read/Write Register Example



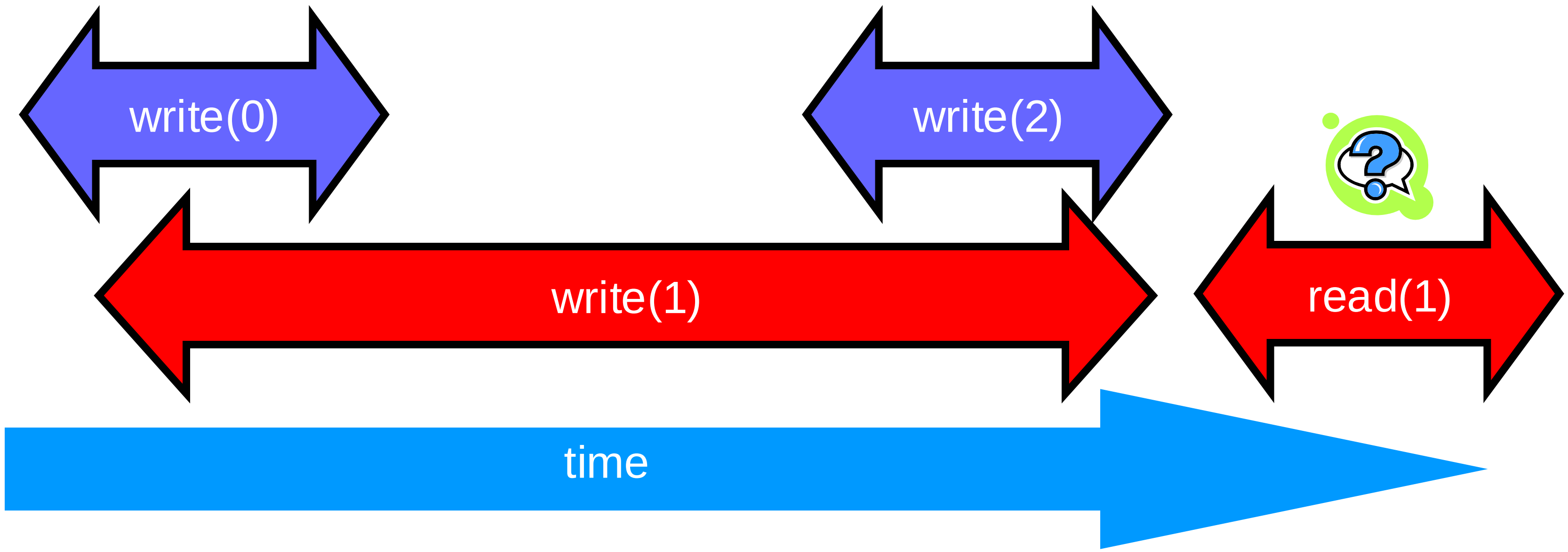
Read/Write Register Example



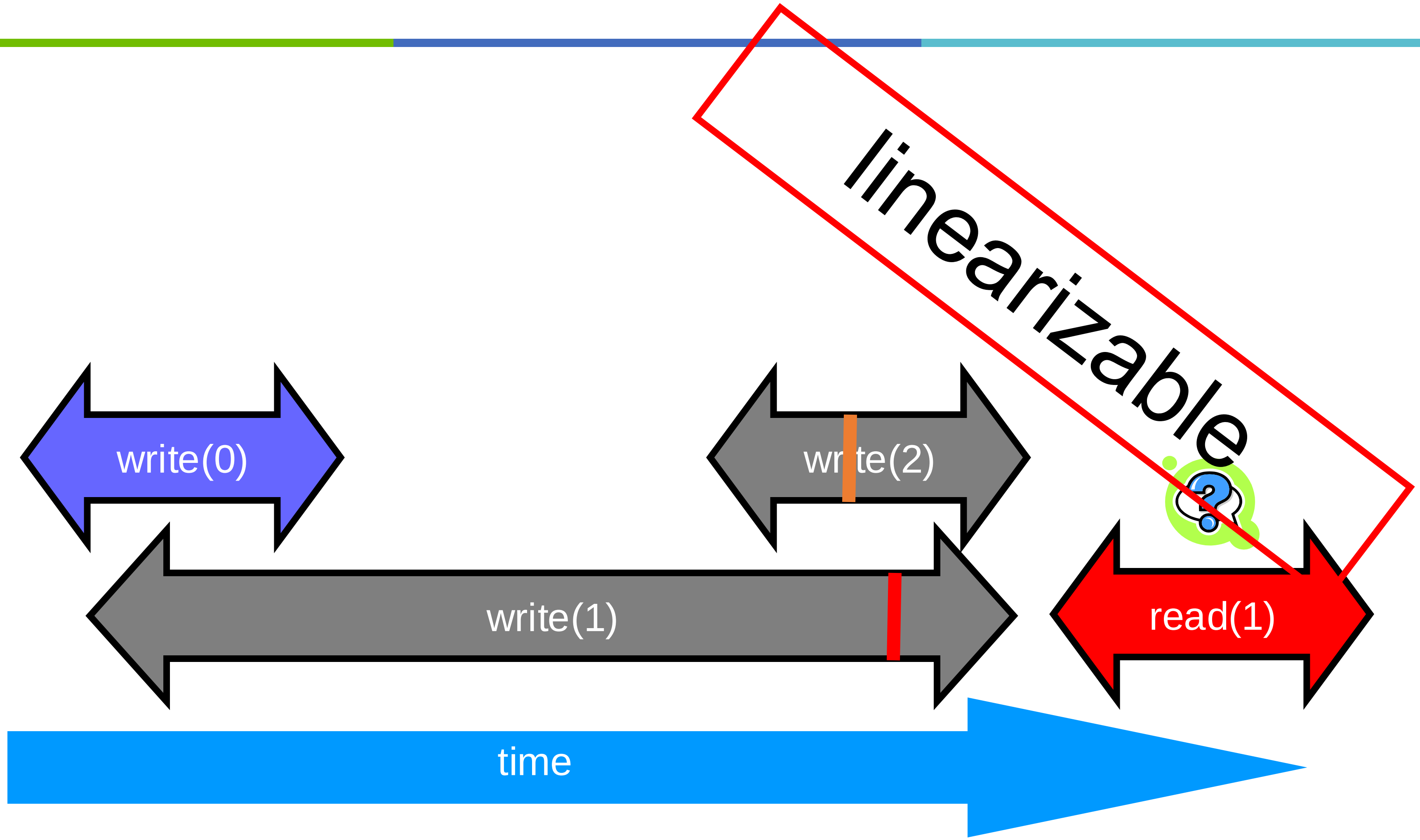
Read/Write Register Example



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 is equally (or even more) important
    - Why?!

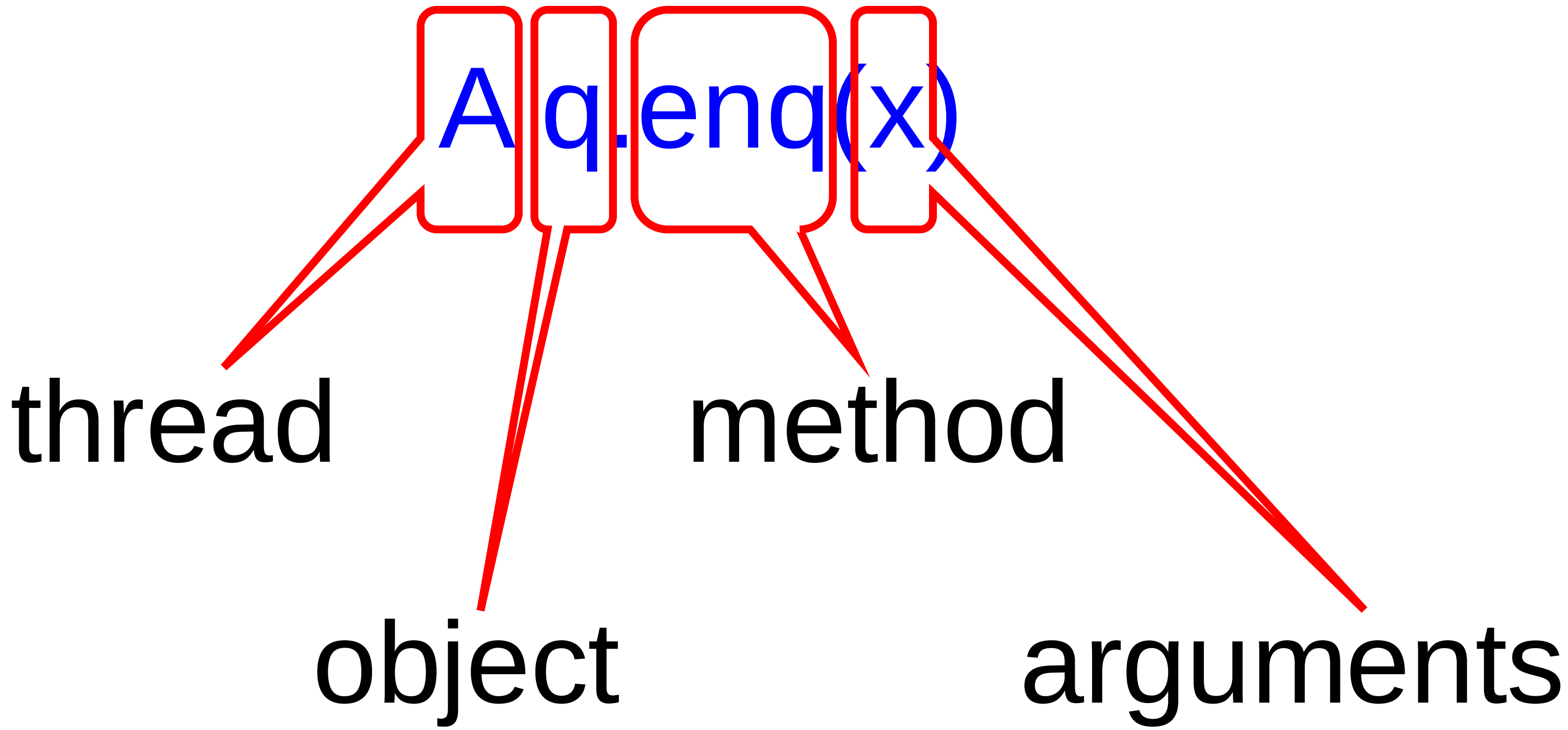
Split Method Calls into Two Events

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

Invocation Notation

A q.enq(x)

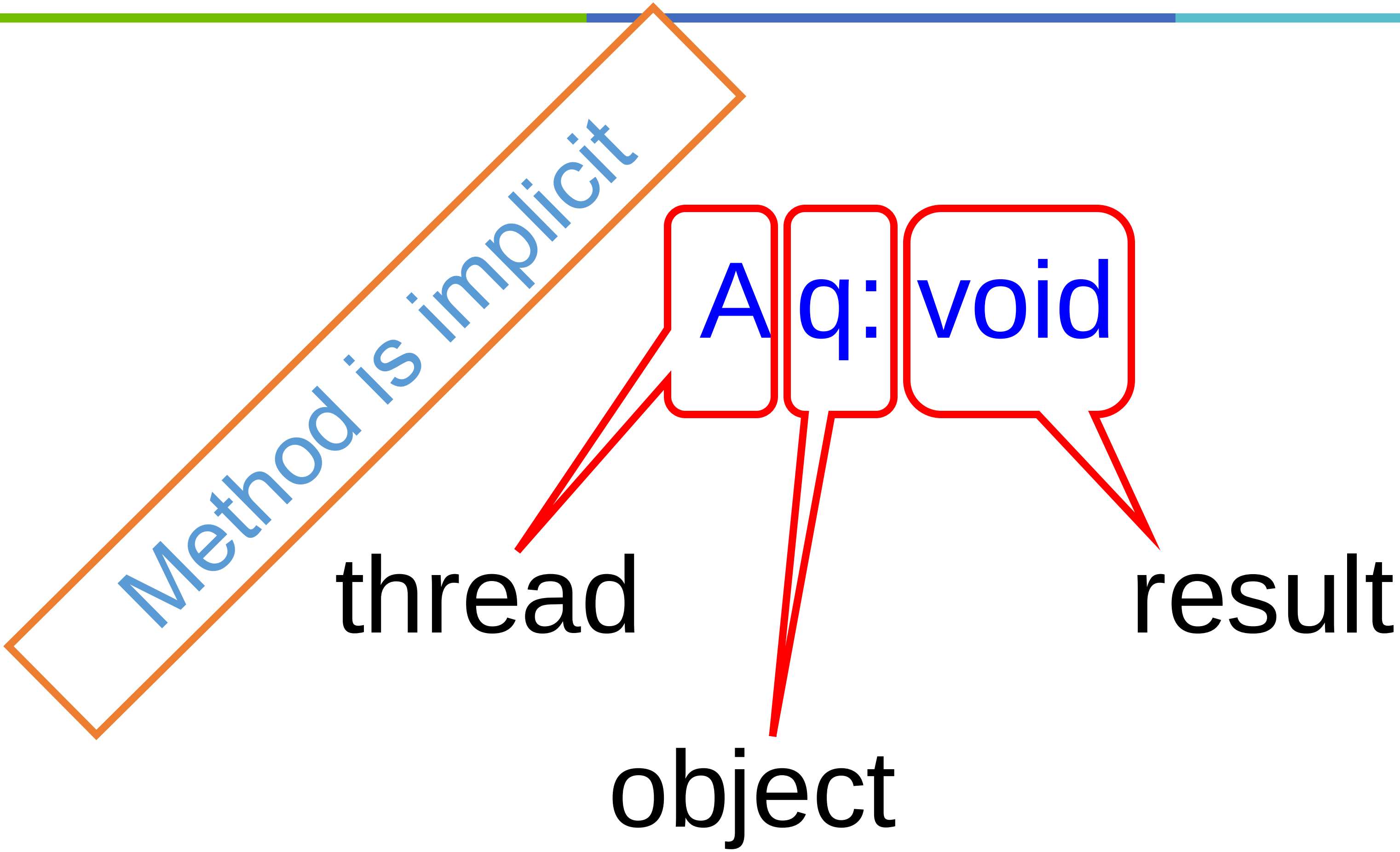
Invocation Notation



Response Notation

A q: void

Response Notation



Response Notation

Method is implicit

A q: empty()

thread

exception

object

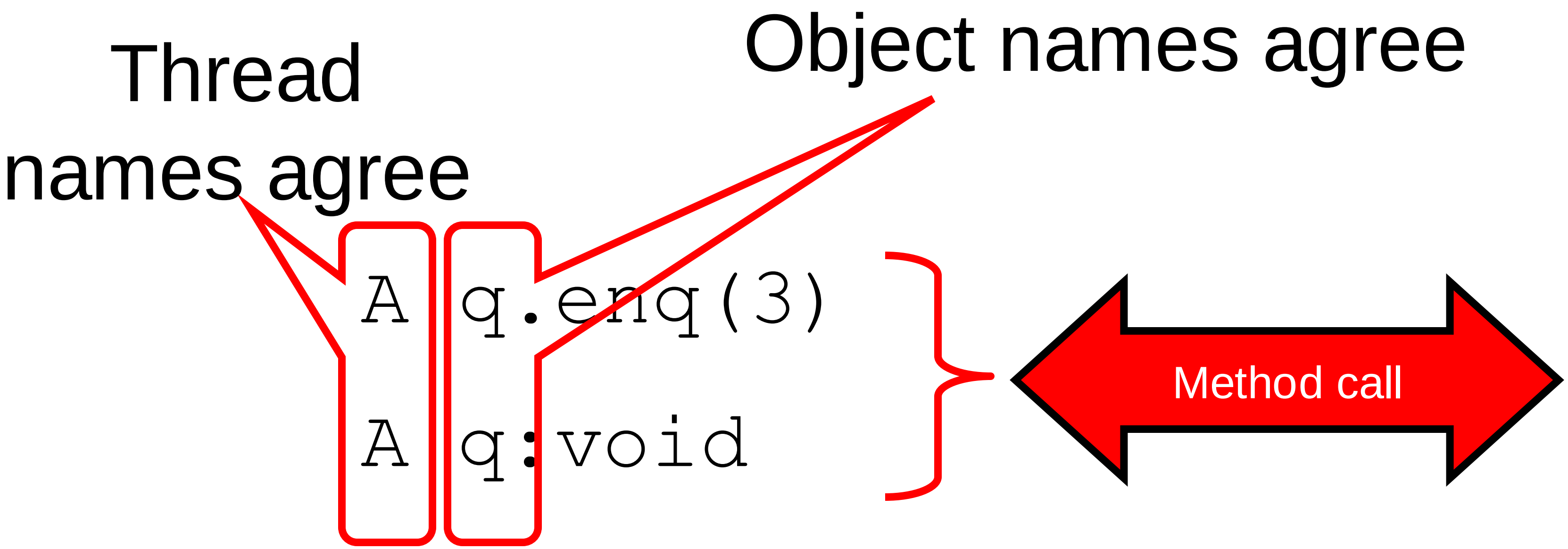
History - Describing an Execution

Sequence of invocations and responses

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

Definition

- Invocation & response *match* if



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

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

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

Complete Subhistory

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

May or may not have taken effect

Complete Subhistory

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

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

match

match

Final pending invocation OK

Method calls of different threads do not interleave

Well-Formed Histories

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

Well-Formed Histories

```
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
```

Per-thread projections are sequential

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

Equivalent Histories

Threads see the same thing in both projections

$$\begin{cases} H|A = G|A \\ H|B = G|B \end{cases}$$

H=

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

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

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

G=

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

```
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 …

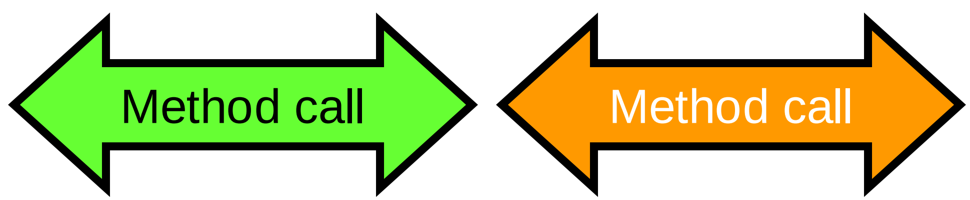
Legal Histories

- 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

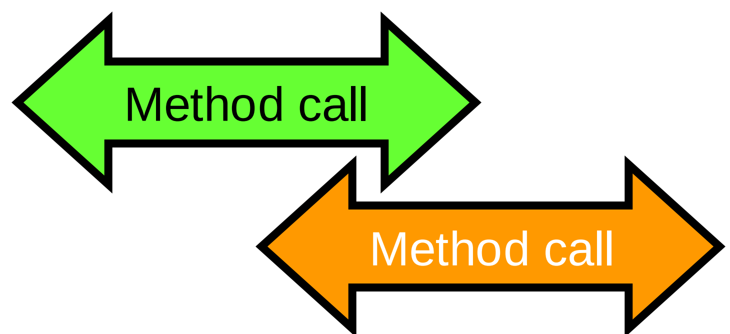


A q.enq() → B q.deq()

Non-Precedence

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

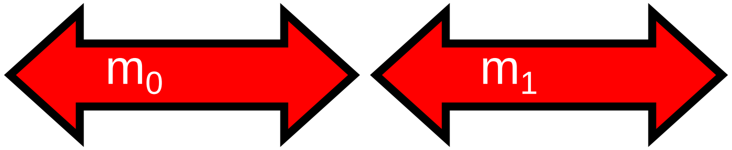
Some method calls overlap one another



A q.enq() $\nrightarrow$ B q.deq()

Notation

- Given
  - History **H**
  - method executions $\mathbf{m_0}$ and $\mathbf{m_1}$ in **H**
- We say $m_0 \rightarrow_H m_1$, if
  - $\mathbf{m_0}$ precedes $\mathbf{m_1}$
- Relation $\mathbf{m_0 \rightarrow_H m_1}$ 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 $\rightarrow_G \subset \rightarrow_S$

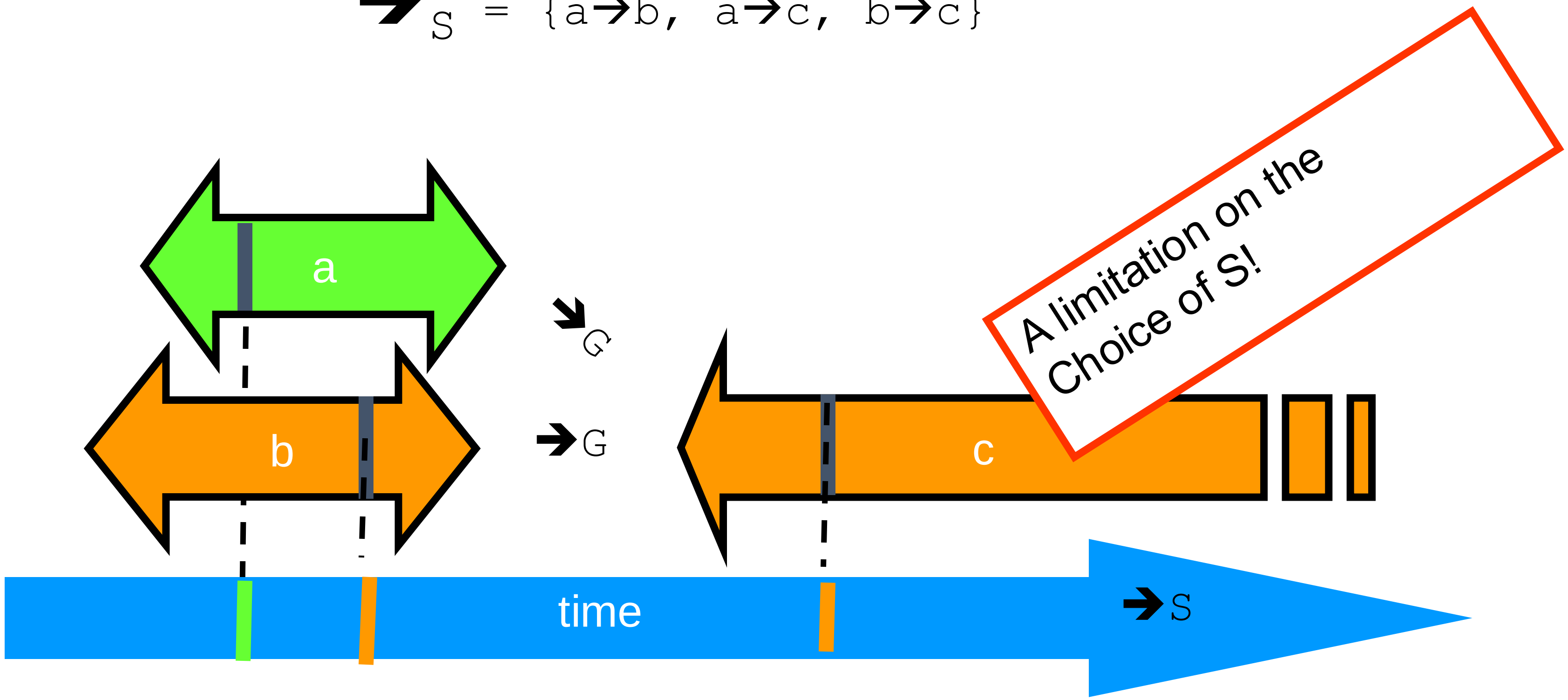
Remarks

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

Ensuring $\rightarrow_G \subset \rightarrow_S$

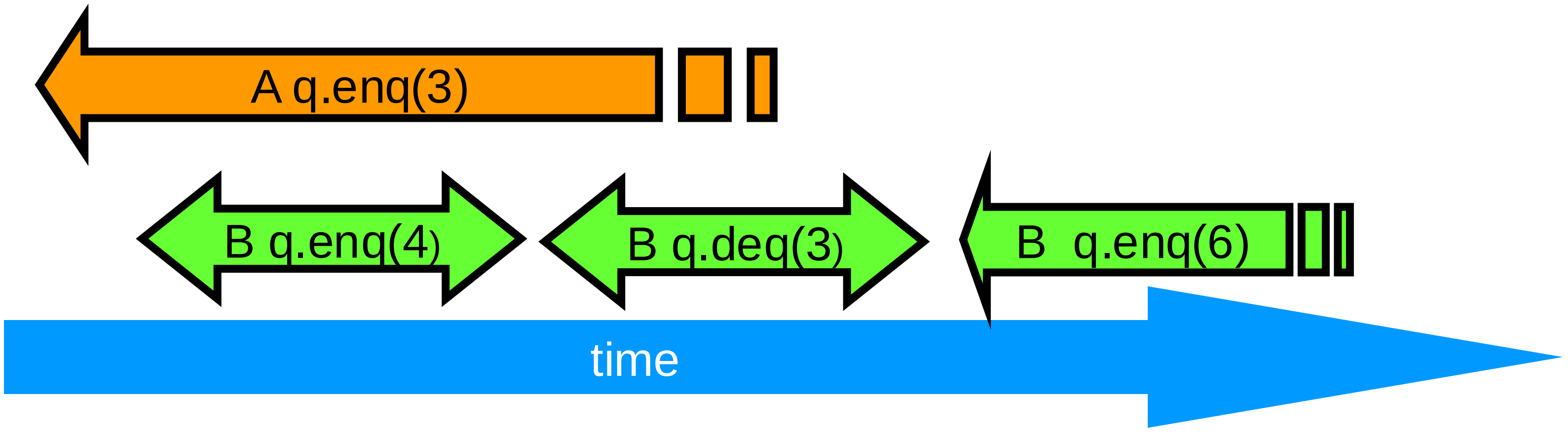
$\rightarrow_G$ = {a→c, b→c}

$\rightarrow_S$ = {a→b, a→c, b→c}



Example

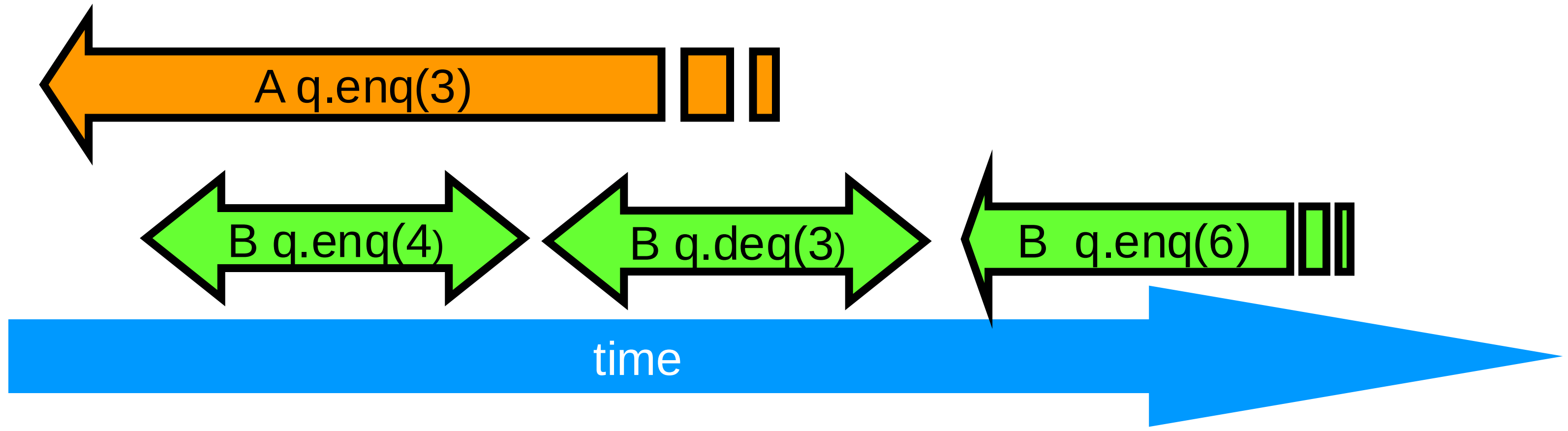
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
B q:enq(6)
```



Example

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

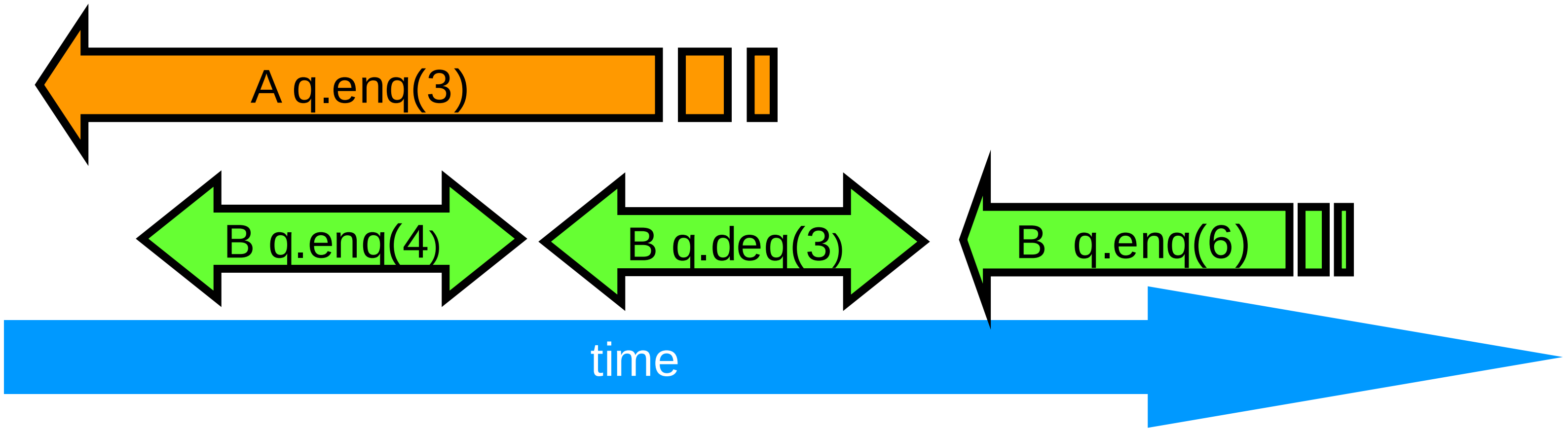
Complete this pending invocation



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
```

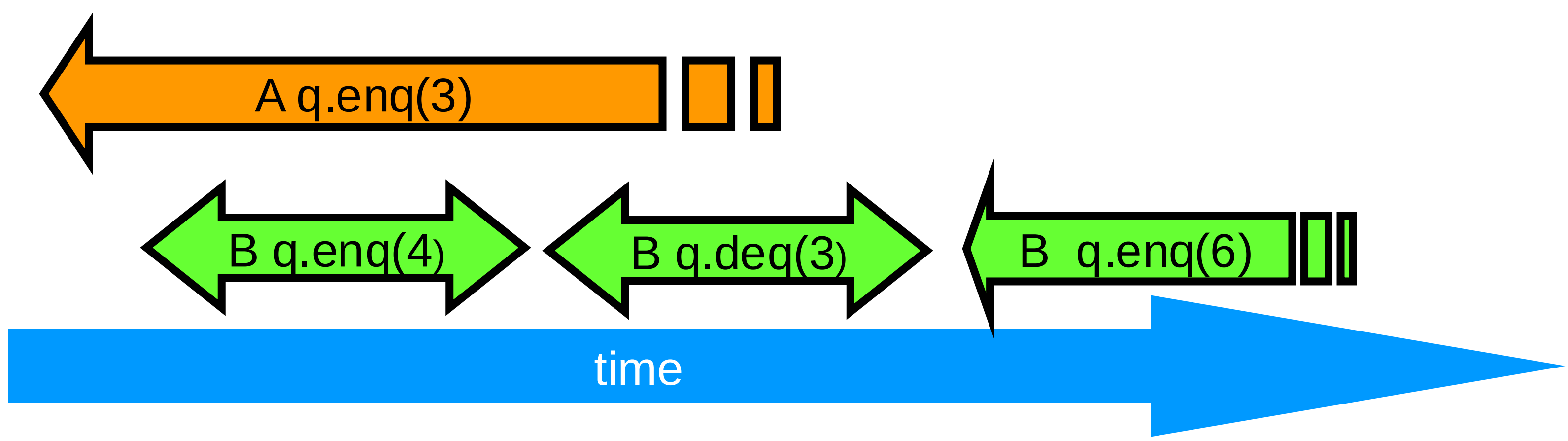
Complete this pending invocation



Example

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

discard this one

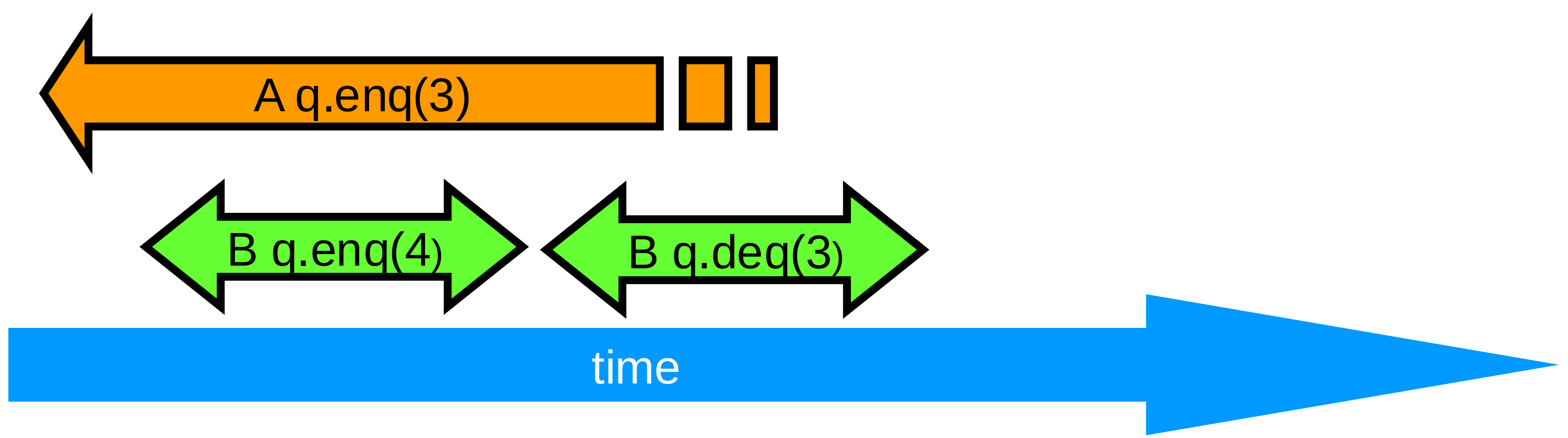


Example

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

discard this one

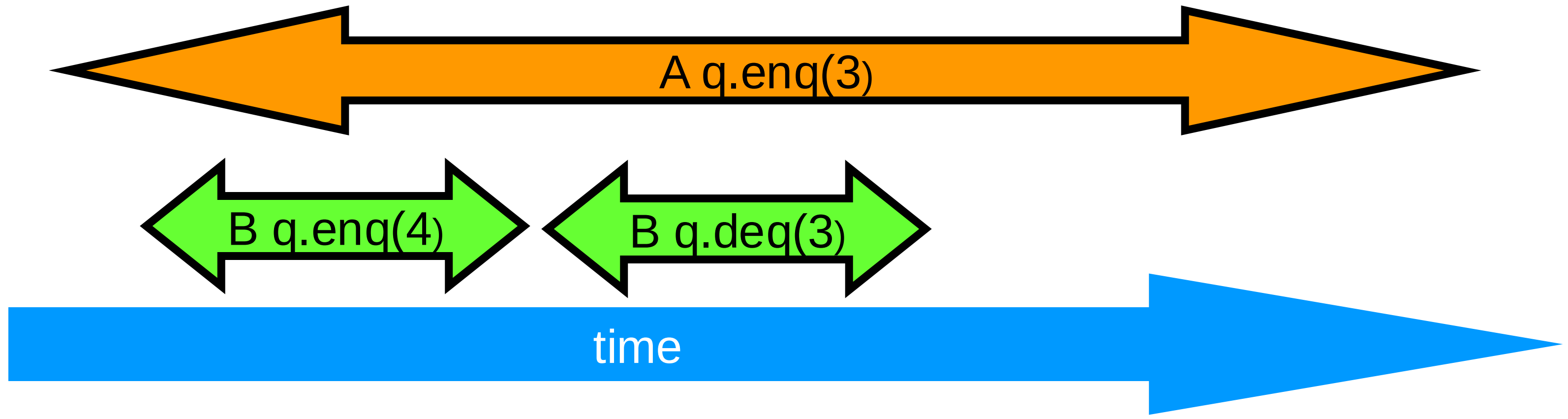
```
A q:void
```



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
```

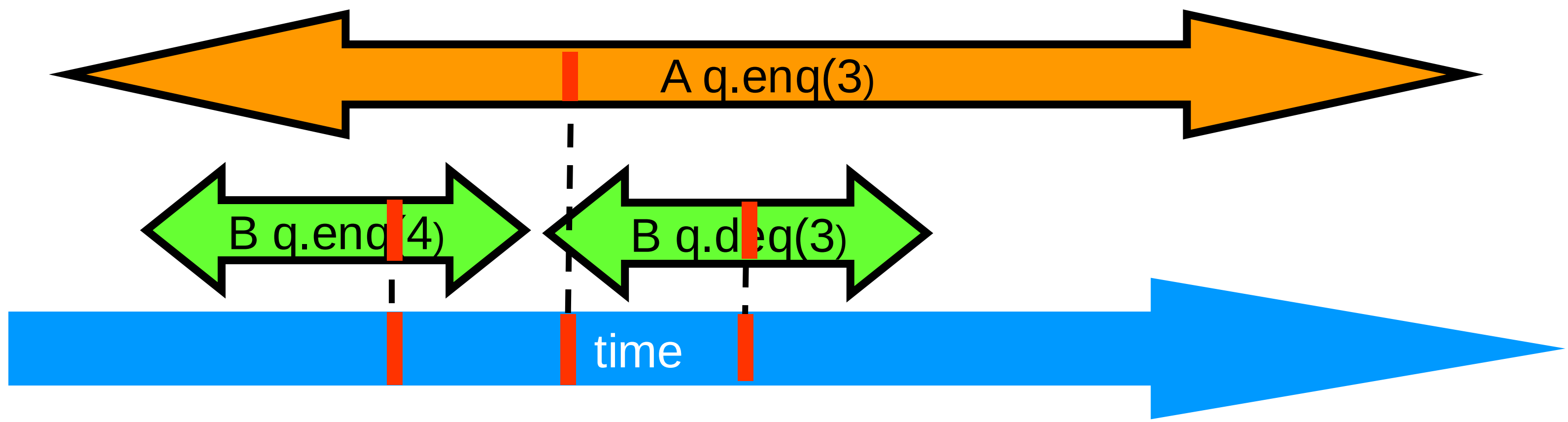


Example

```
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
```



Concurrency

- How much concurrency does linearizability allow?
- When must a method invocation block?

Concurrency

- Focus on ***total*** methods
  - Defined in every state
- Example:
  - `deq()` that throws `Empty` exception
  - Versus `deq()` that waits …
- Why?
  - Otherwise, blocking unrelated to synchronization

Concurrency

- Question: When does linearizability require a method invocation to block?
- Answer: never.
- Linearizability is *non-blocking*

Non-Blocking Theorem

If method invocation

```
A q.inv(…)
```

is pending in history H, then there exists a response

```
A q:res(…)
```

such that

```
H + A q:res(…)
```

is linearizable

Proof

- Pick linearization S of H
- If S already contains
  - Invocation `A q.inv(…)` and response,
  - Then we are done.
- Otherwise, pick a response such that
  - `S + A q.inv(…) + A q:res(…)`
  - Possible because object is ***total***

All methods are total

Methods are defined for
every object state

Composability Theorem

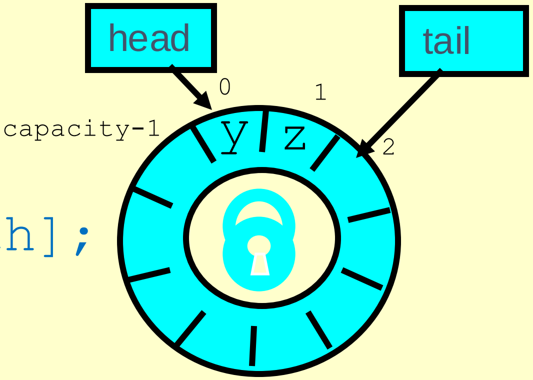
- History H is linearizable if and only if
  - For every object x
  - H | x is linearizable
- This means that linear histories are composable

Why Does Composability Matter?

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

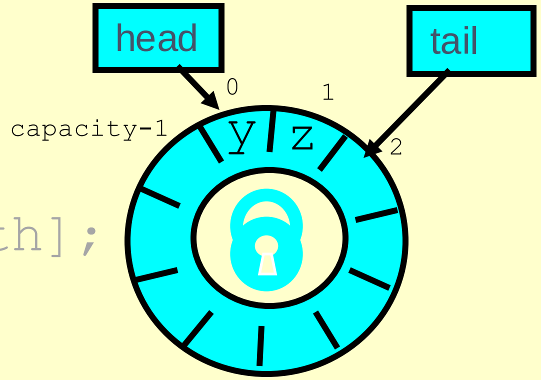
Reasoning About Linearizability: Locking

```
public T deq() throws EmptyException {
  lock.lock();
  try {
    if (tail == head)
       throw new EmptyException();
    T x = items[head % items.length];
    head++;
    return x;
  } finally {
    lock.unlock();
  }
}
```



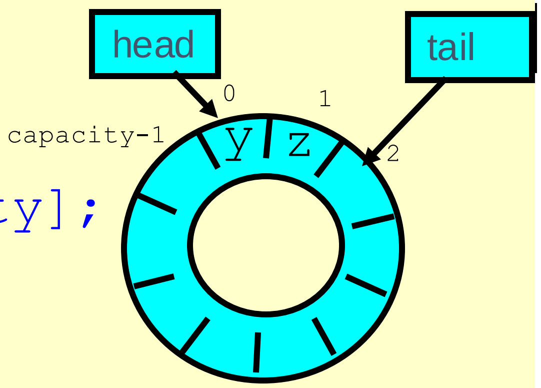
Reasoning About Linearizability: Locking

```
public T deq() throws EmptyException {
  lock.lock();
  try {
    if (tail == head)
       throw new EmptyException();
    T x = items[head % items.length];
    head++;
    return x;
  } finally {
    lock.unlock();
  }
}
```



Linearization points are when locks are released

More Reasoning: Wait-free




```
public class WaitFreeQueue {

  int head = 0, tail = 0;
  items = (T[]) new Object[capacity];

  public void enq(Item x) {
    if (tail-head == capacity) throw
         new FullException();
    items[tail % capacity] = x; tail++;
  }
  public Item deq() {
     if (tail == head) throw
         new EmptyException();
     Item item = items[head % capacity]; head++;
     return item;
}}
```

More Reasoning: Wait-free

Remember that there is only one enqueuer and only one dequeuer

Linearization order is when head and tail fields modified

```
public cla... FreeQueue {
  int ... =
  i... ew Ob
  ...d enq(Item x) {
    ...il-head == capacity) throw
        new FullException();
    ...tems[tail % capacity] = x;   tail++;
  }
  public Item deq() {
    if (tail == head) throw
        new EmptyException();
    Item item = items[head % capacity];   head++;
    return item;
}}
```

Strategy

- Identify one atomic step where method “happens”
  - Critical section
  - Machine instruction
- Doesn’t always work
  - Might need to define several different steps for a given method

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

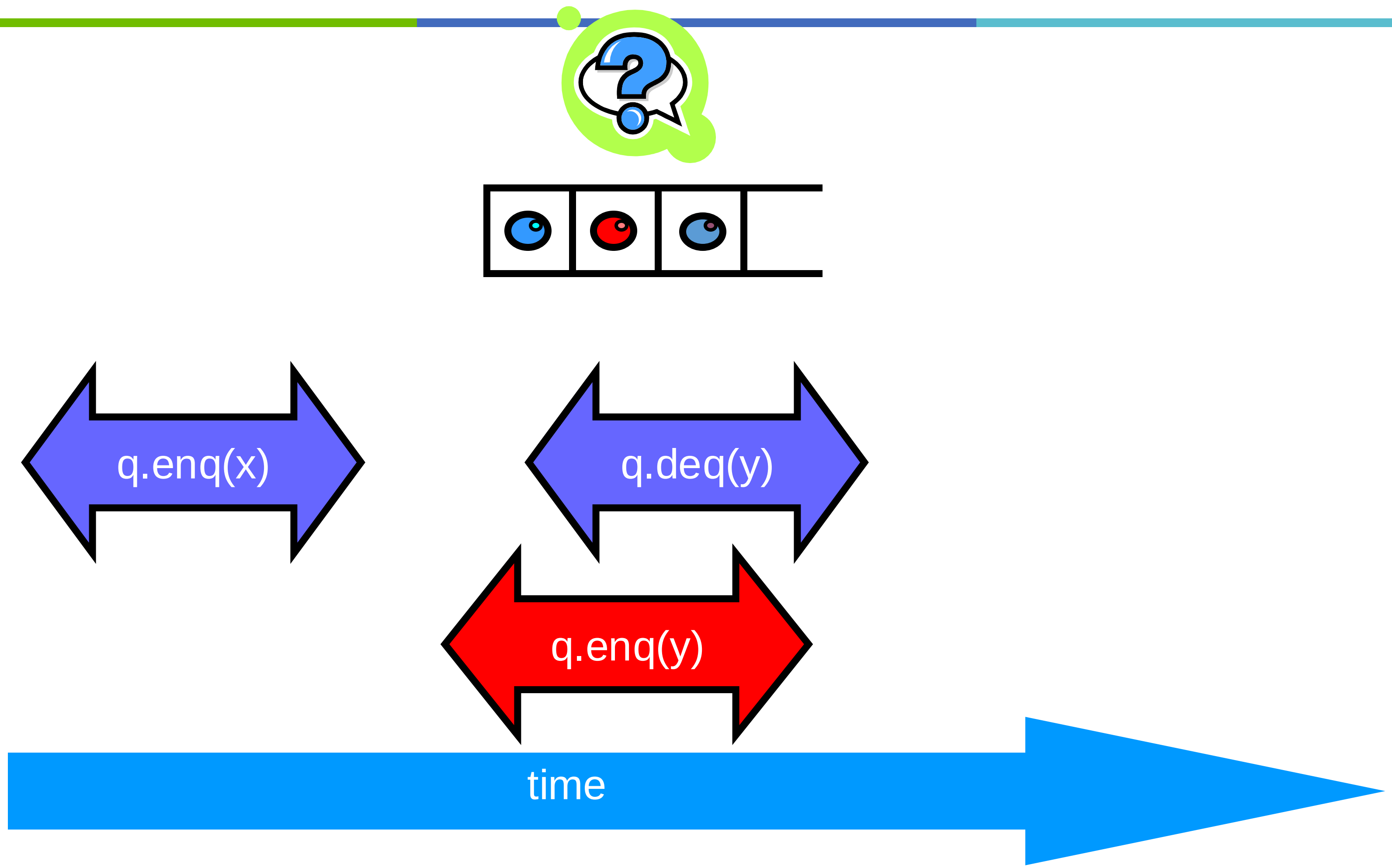
- History H is *Sequentially Consistent* if it can be extended to G by
  - Appending zero or more responses to pending invocations
  - Discarding other pending invocations
- So that G is equivalent to a
  - Legal sequential history S
  - ~~Where $\rightarrow_G \subset \rightarrow_S$~~

Differs from linearizability

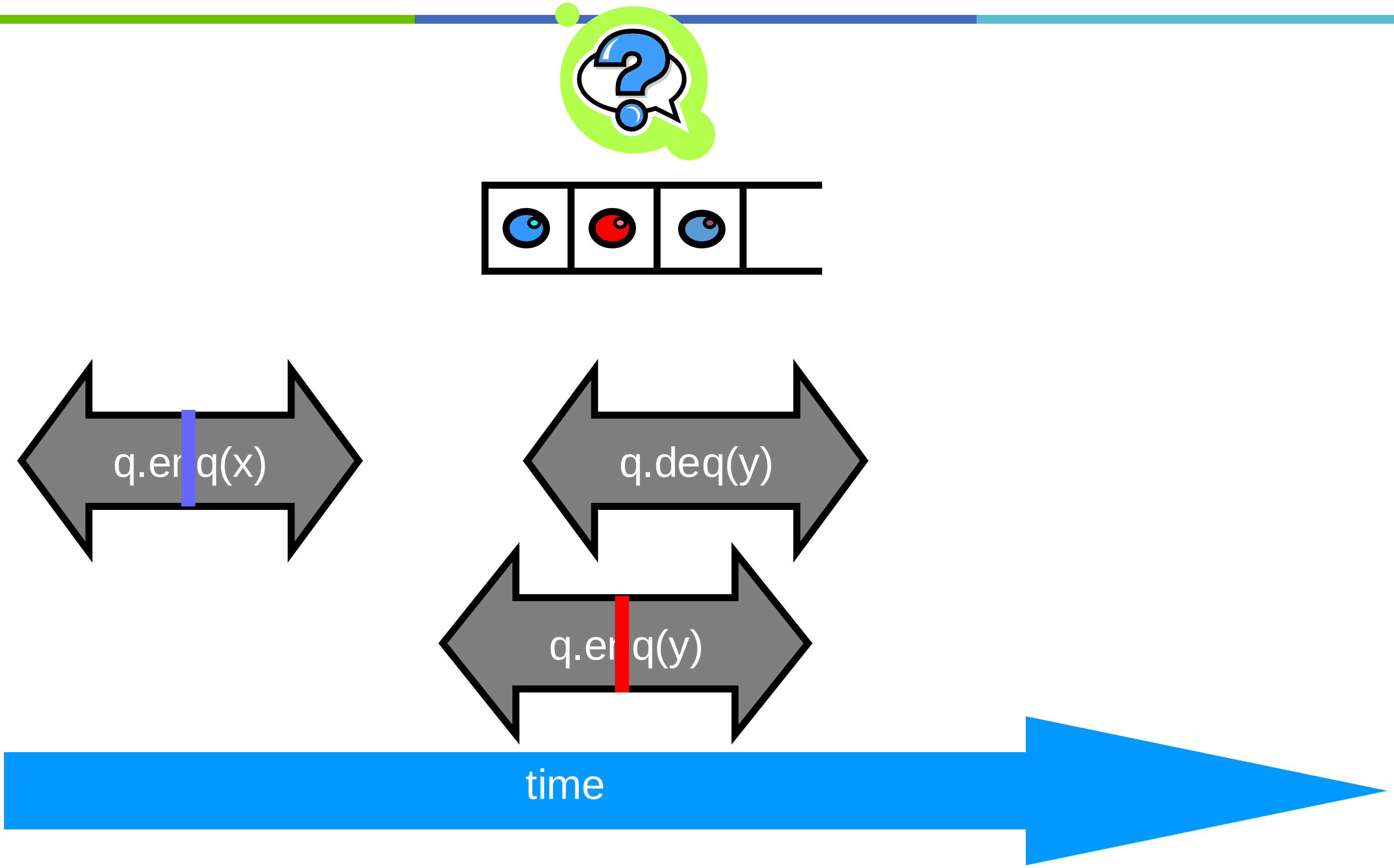
Sequential Consistency

- 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

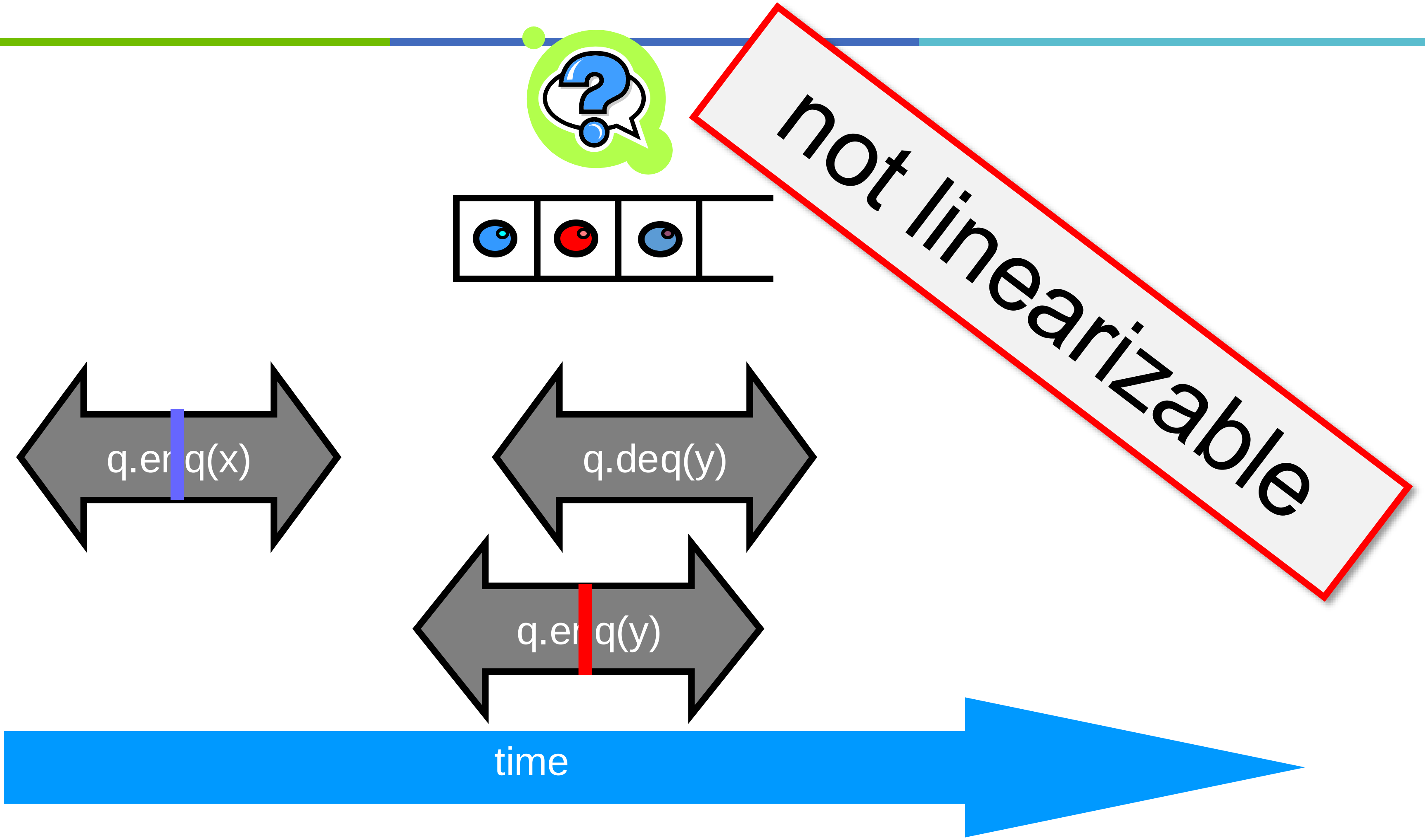
Example



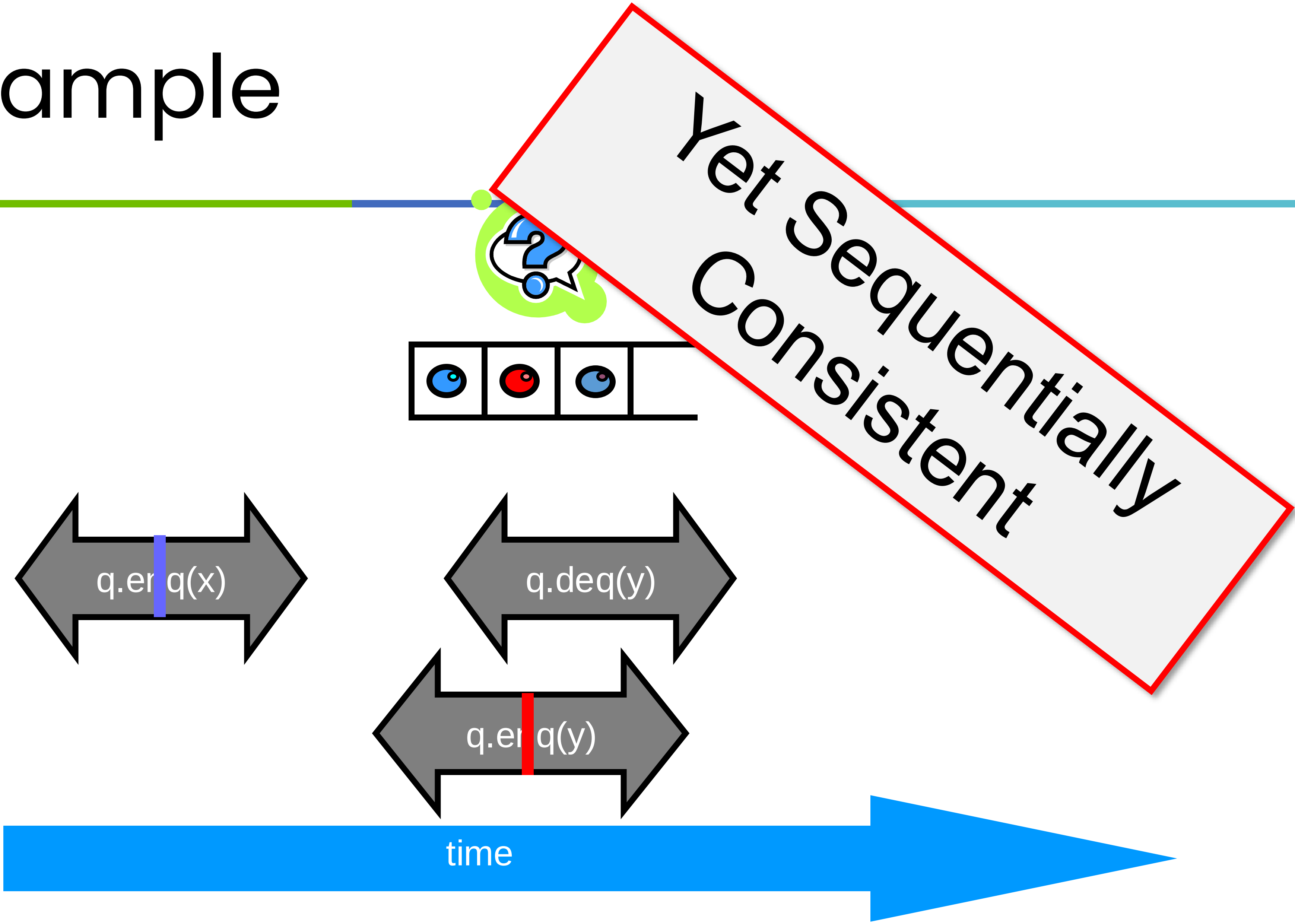
Example



Example



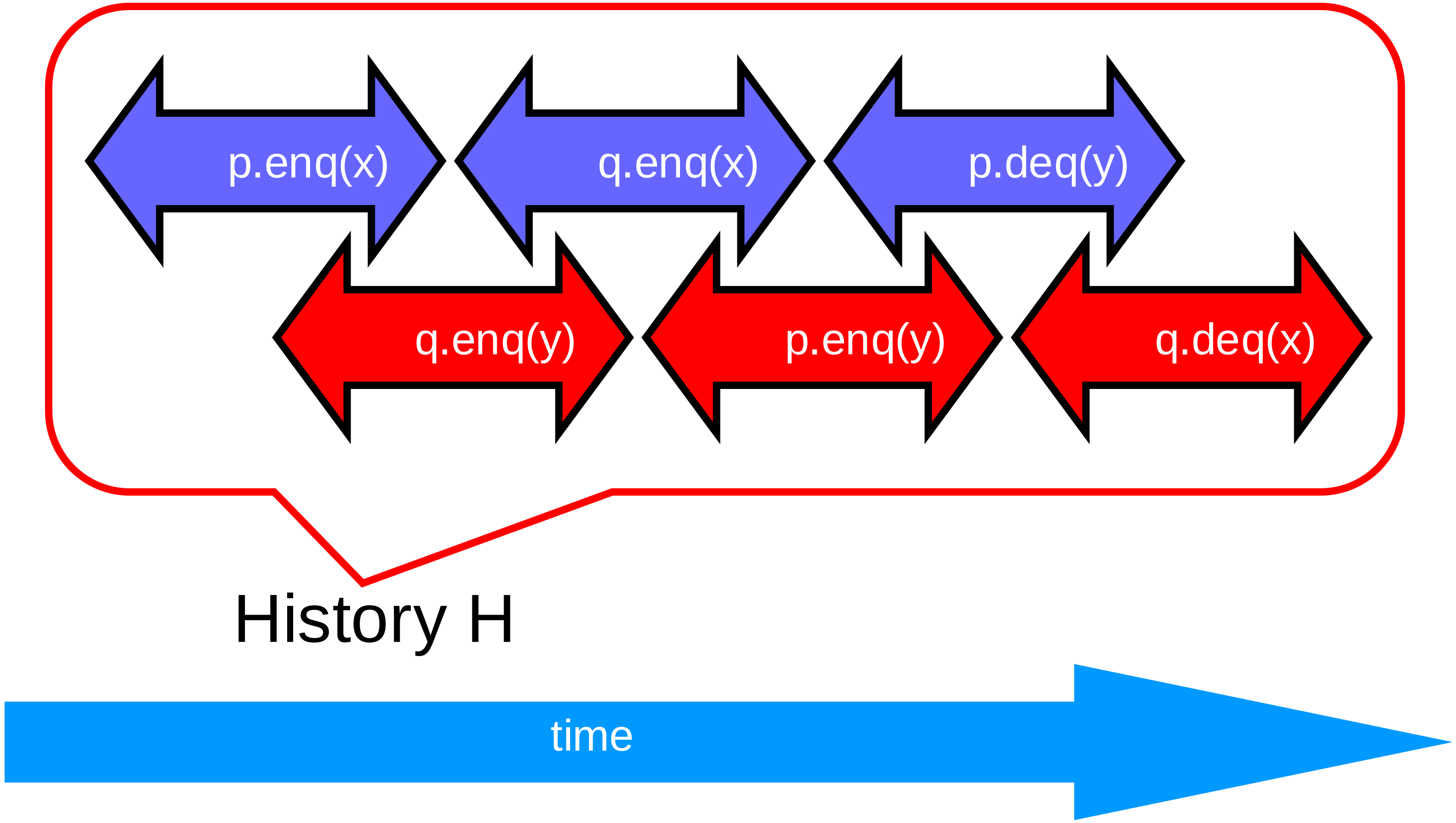
Example



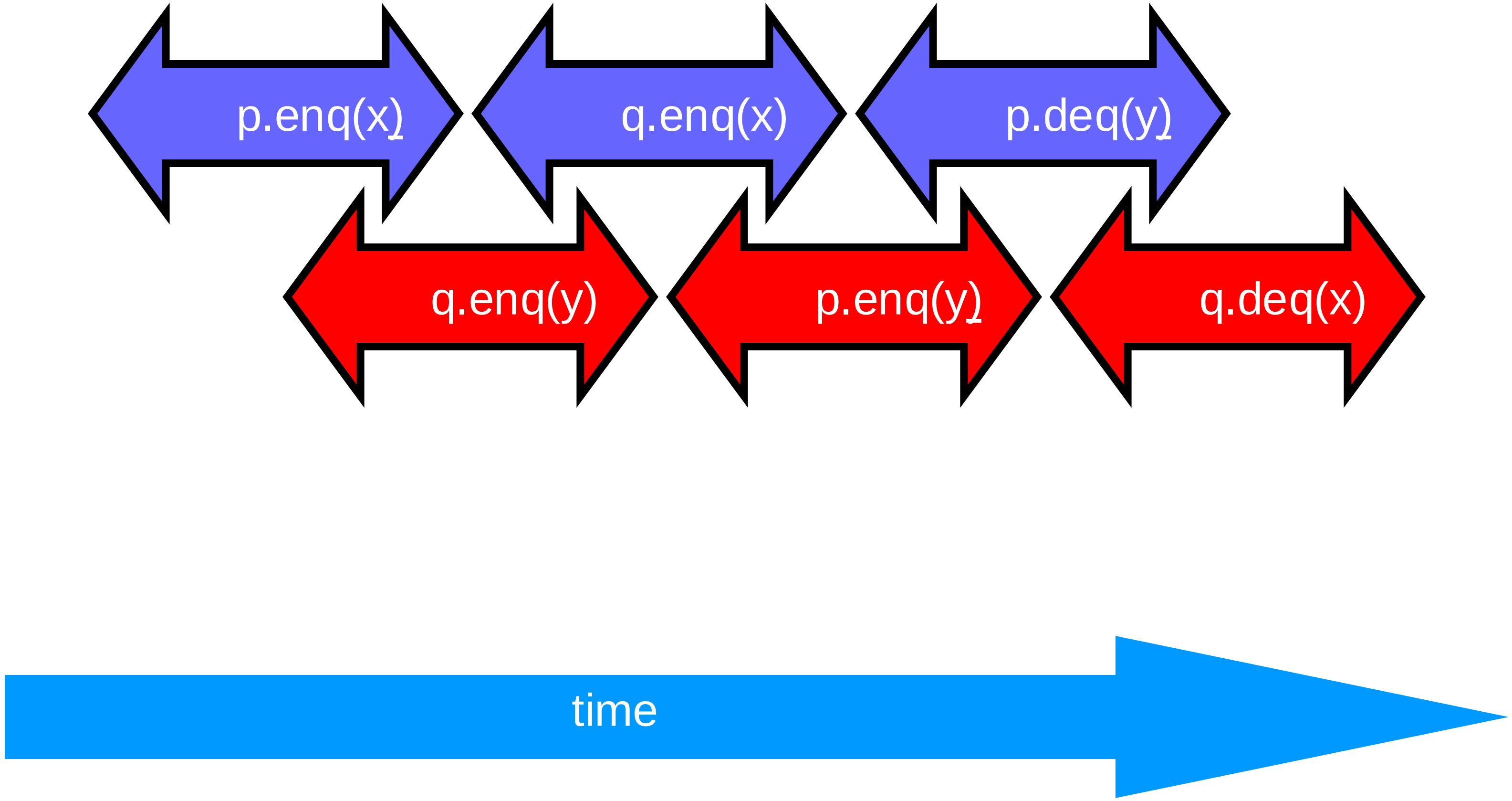
Theorem

Sequential Consistency is not composable

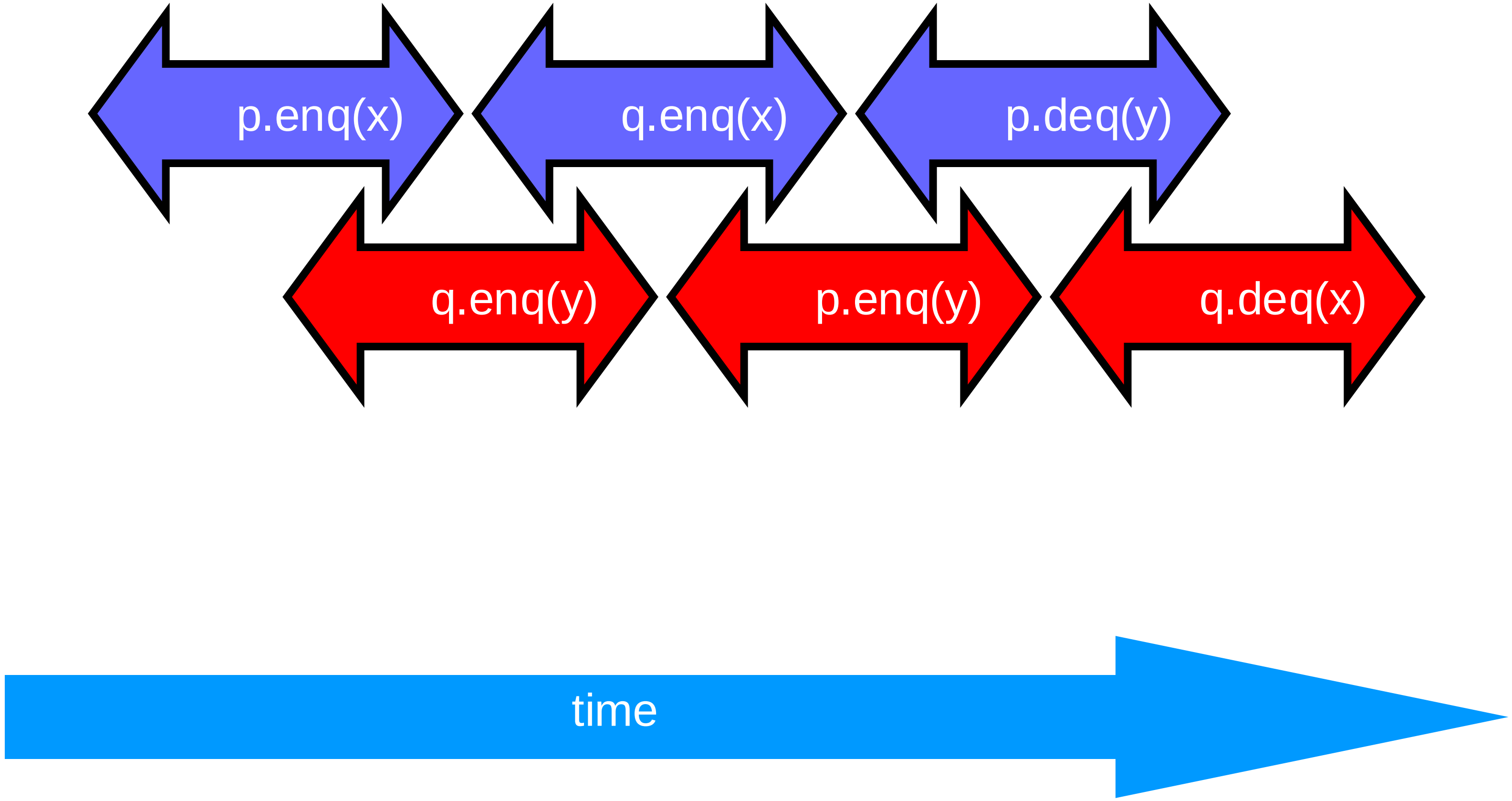
FIFO Queue Example



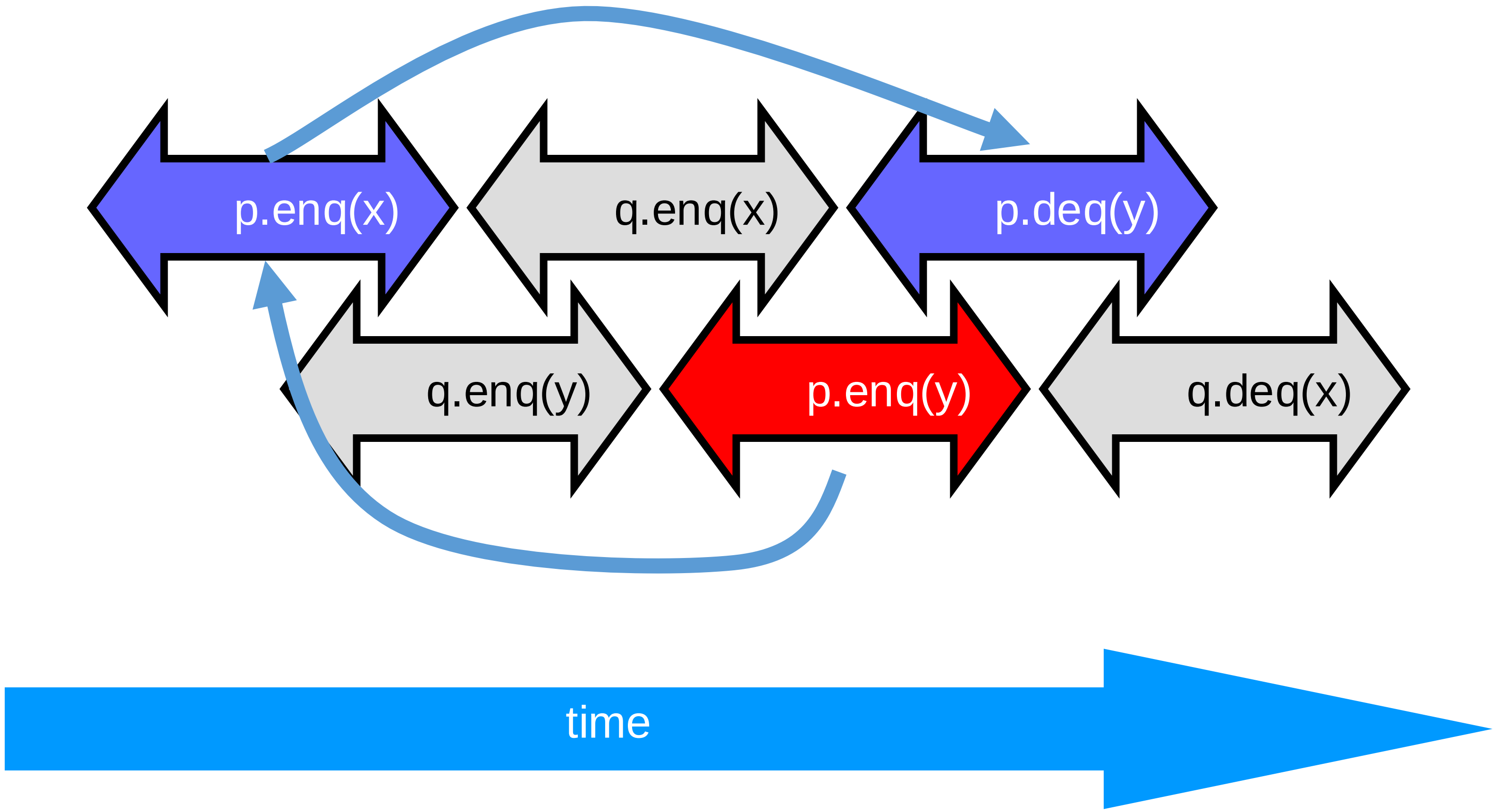
H|p Sequentially Consistent



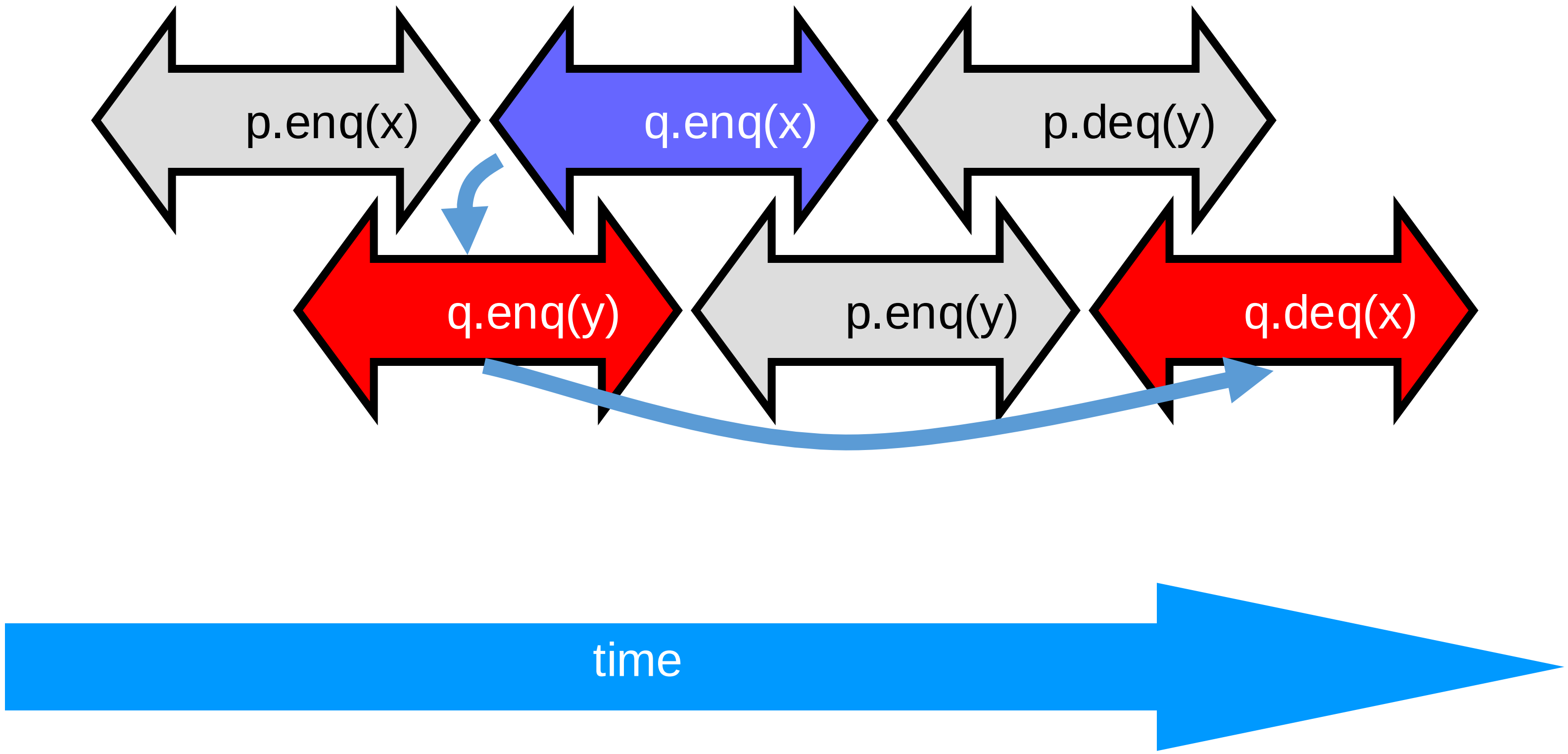
H|q Sequentially Consistent



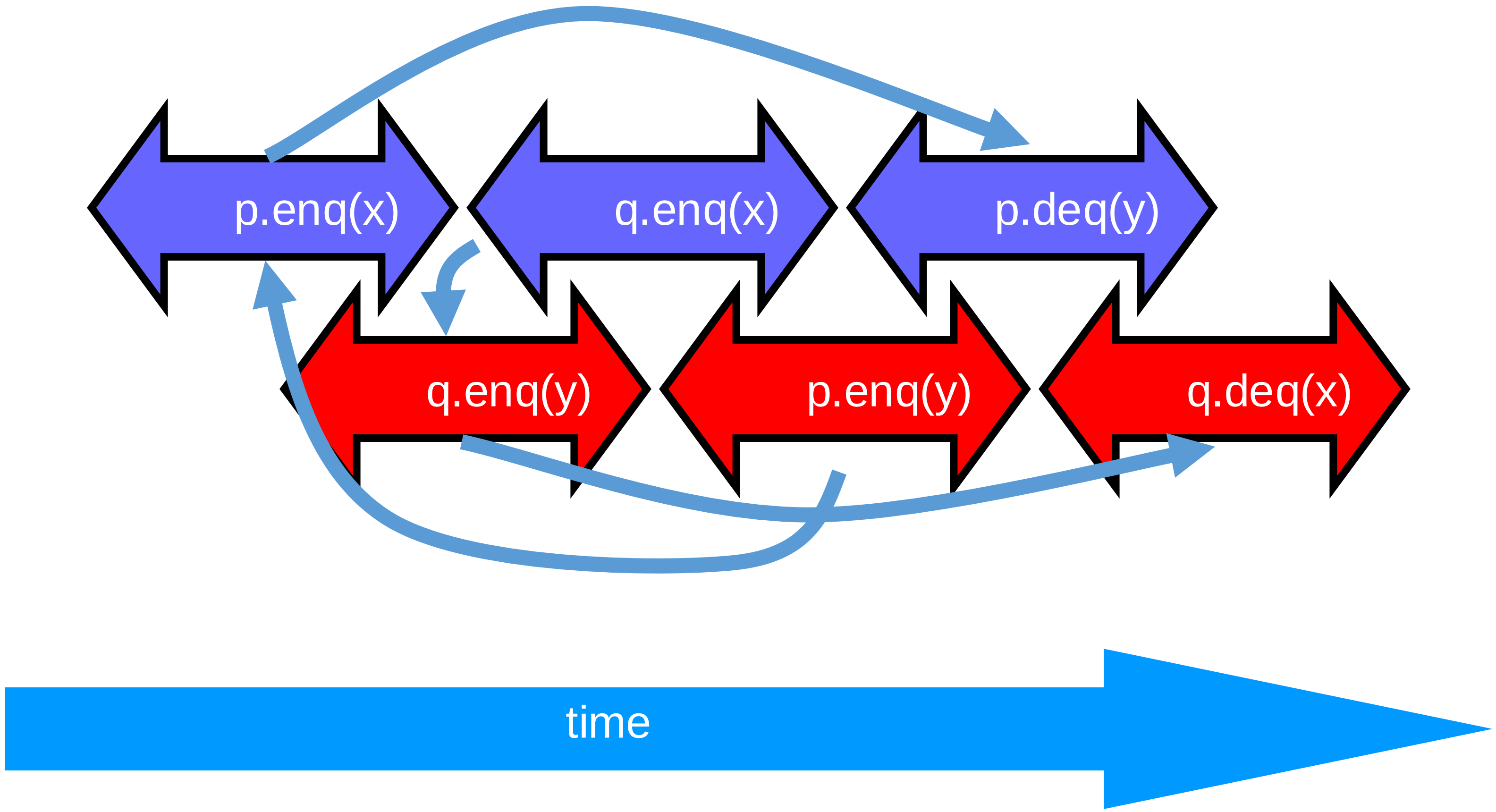
Ordering imposed by p



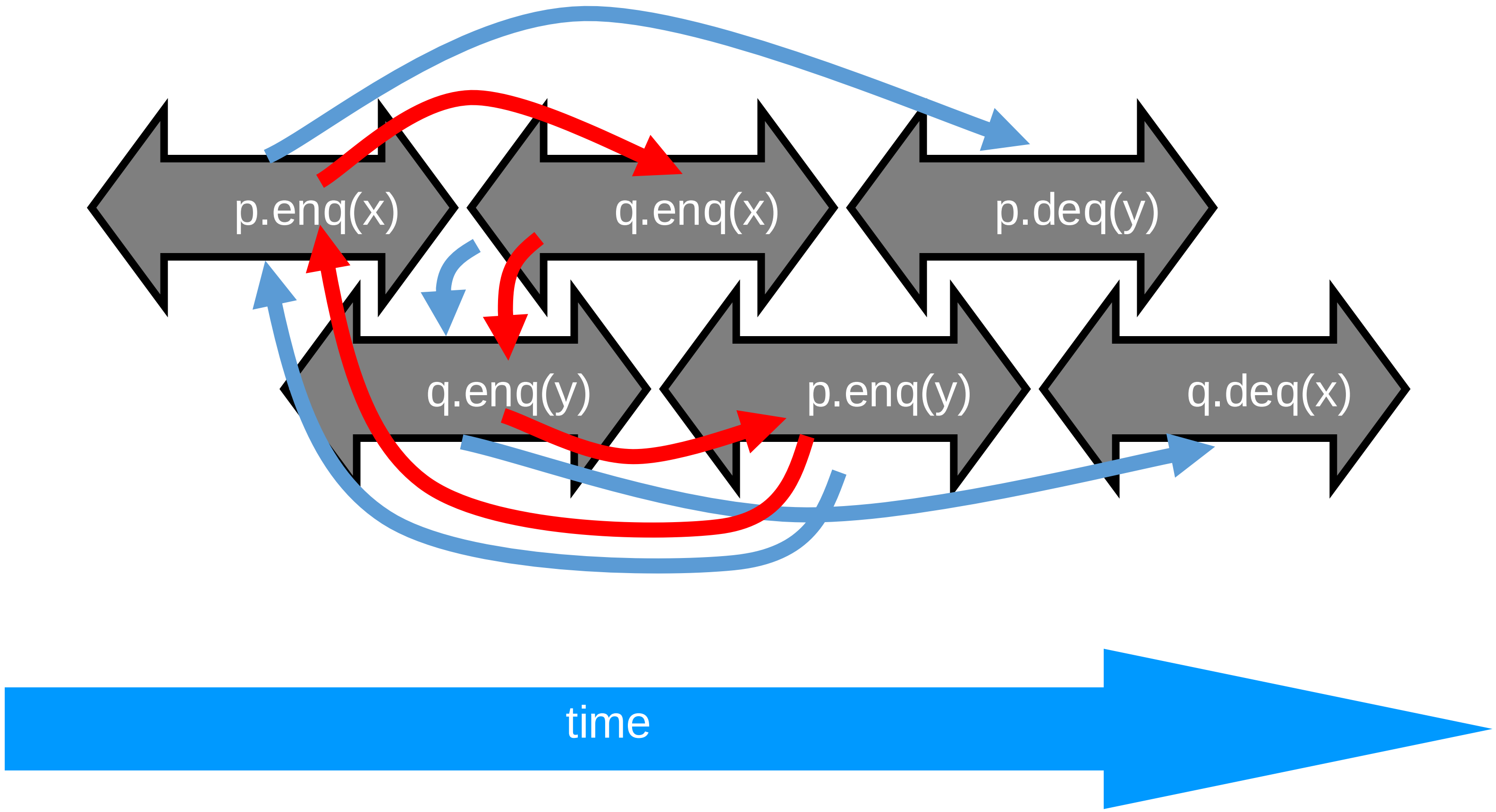
Ordering imposed by q



Ordering imposed by both



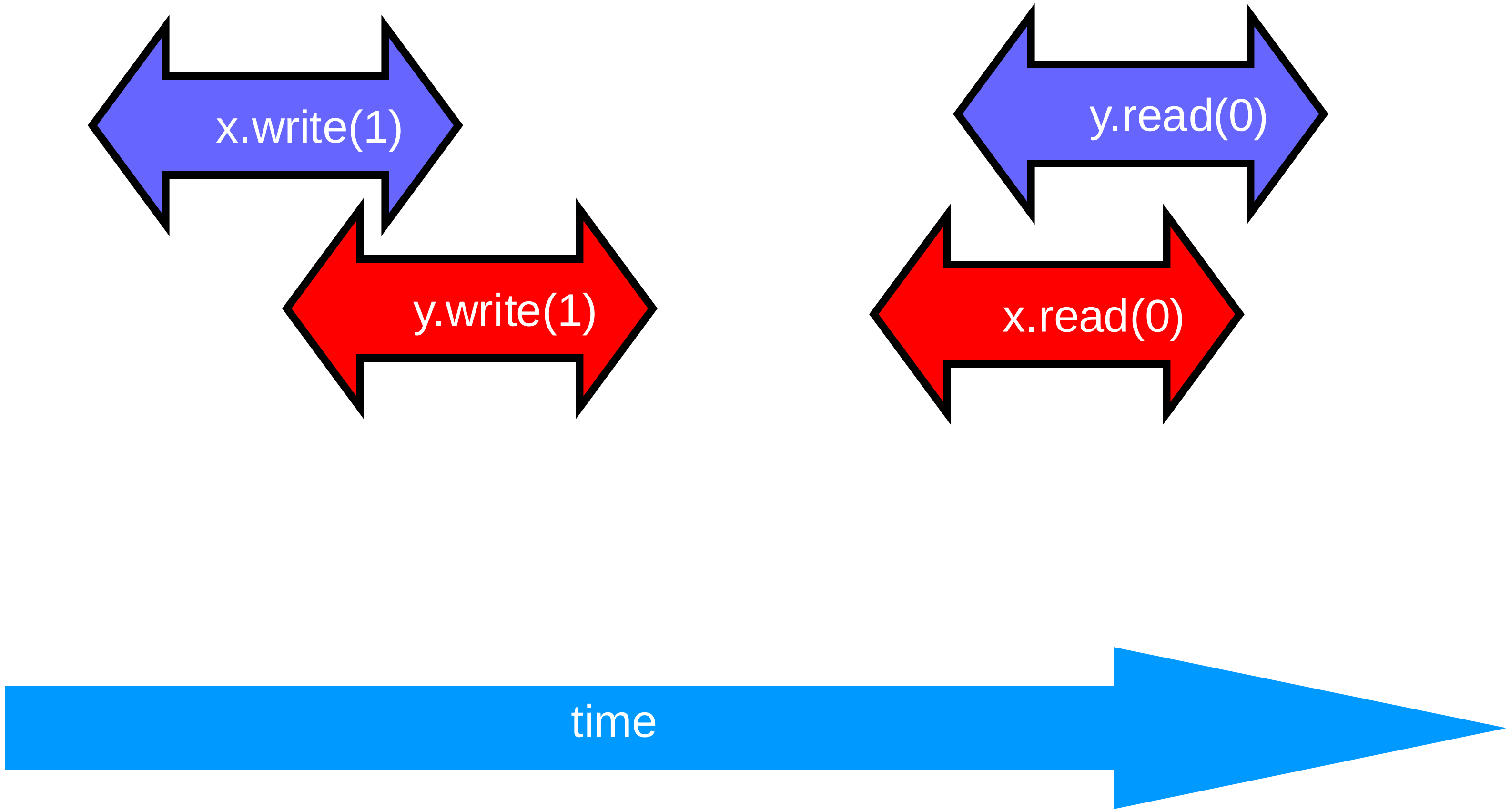
Combining orders



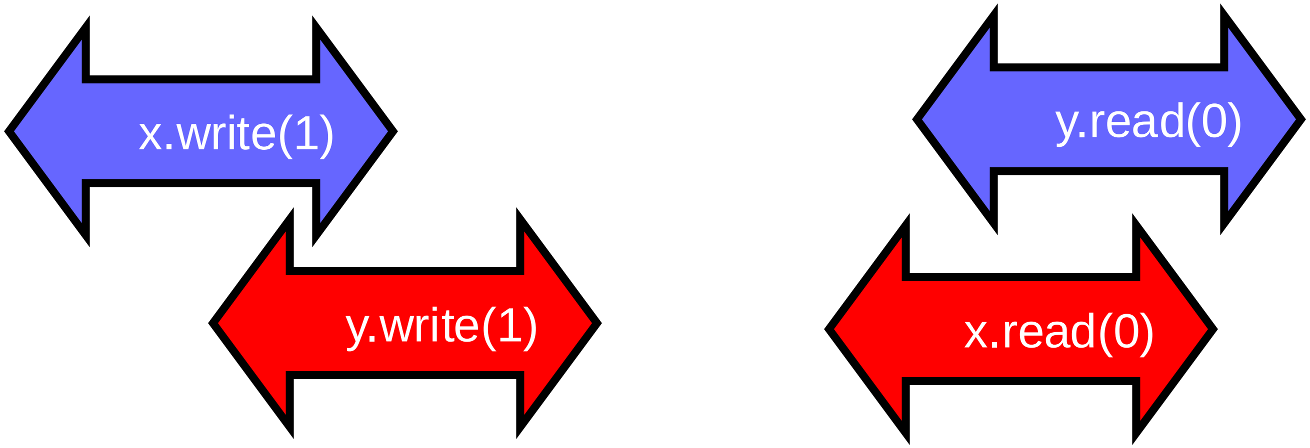
Fact

- Most hardware architectures don’t support sequential consistency
- Because they think it’s too strong
- Here’s another story…

The Flag Example

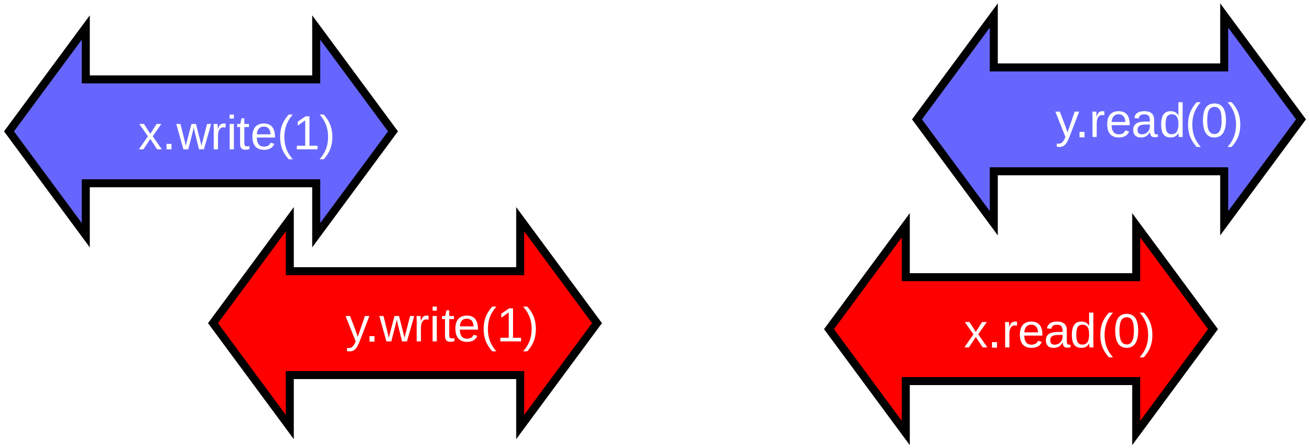


The Flag Example



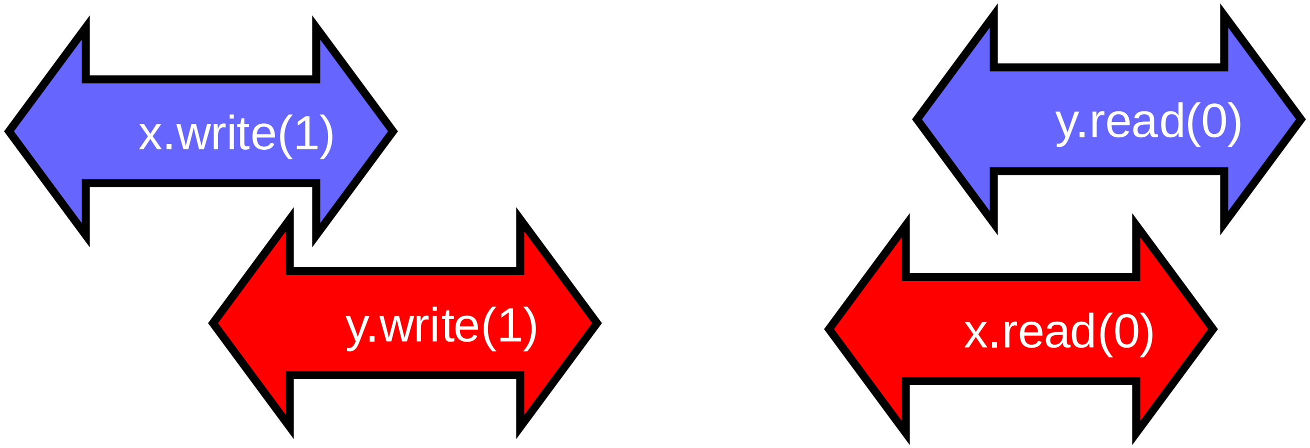
- Each thread's view is sequentially consistent
  - It went first

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: It's Wrong

- This pattern
  - Write mine, read yours
- Is exactly the flag principle
  - Beloved of Alice and Bob
  - Heart of mutual exclusion
    - Peterson
    - Bakery, etc.
- It's non-negotiable!

Peterson's Algorithm

```
public void lock() {
 flag[i] = true;
 victim  = i;
 while (flag[j] && victim == i) {};
}
public void unlock() {
 flag[i] = false;
}
```

Crux of Peterson Proof

(1) $\text{write}_B(\text{flag}[B]=\text{true}) \rightarrow$

(3) $\text{write}_B(\text{victim}=B) \rightarrow$

(2) $\text{write}_A(\text{victim}=A) \rightarrow \text{read}_A(\text{flag}[B])$
$\rightarrow \text{read}_A(\text{victim})$

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Crux of Peterson Proof

(1) $\boxed{\text{write}_B(\text{flag}[B]=\text{true})}$ ➔

(3) $\text{write}_B(\text{victim}=B)$ ➔

(2) $\text{write}_A(\text{victim}=A)$ ➔ $\boxed{\text{read}_A(\text{flag}[B])}$
➔ $\text{read}_A(\text{victim})$

Observation: proof relied on fact that if a location is stored, a later load by some thread will return this or a later stored value.

Opinion: 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

Hardware Consistency

Initially, a = b = 0.

Processor 0

```
mov 0, %ebx ;Init
mov 1, a    ;Store
mov b, %ebx ;Load
```

Processor 1

```
mov 0, %eax ;Init
mov 1, b    ;Store
mov a, %eax ;Load
```

- What are the final possible values of %eax and %ebx after both processors have executed?
- Sequential consistency implies that no execution ends with %eax = %ebx = 0

Hardware Consistency

- No modern-day processor implements sequential consistency
- Hardware actively reorders instructions
- Compilers may reorder instructions, too
- Why?
- Because most of performance is derived from a single thread’s unsynchronized execution of code

Instruction Reordering

Program Order

```
mov 1, a      ;Store
mov b, %ebx   ;Load
```

Execution Order

```
mov b, %ebx   ;Load
mov 1, a      ;Store
```

Q. Why might the hardware or compiler decide to reorder these instructions?

A. To obtain higher performance by covering load latency — *instruction-level parallelism*.

Instruction Reordering

Program Order

```
mov 1, a     ;Store
mov b, %ebx  ;Load
```

Execution Order

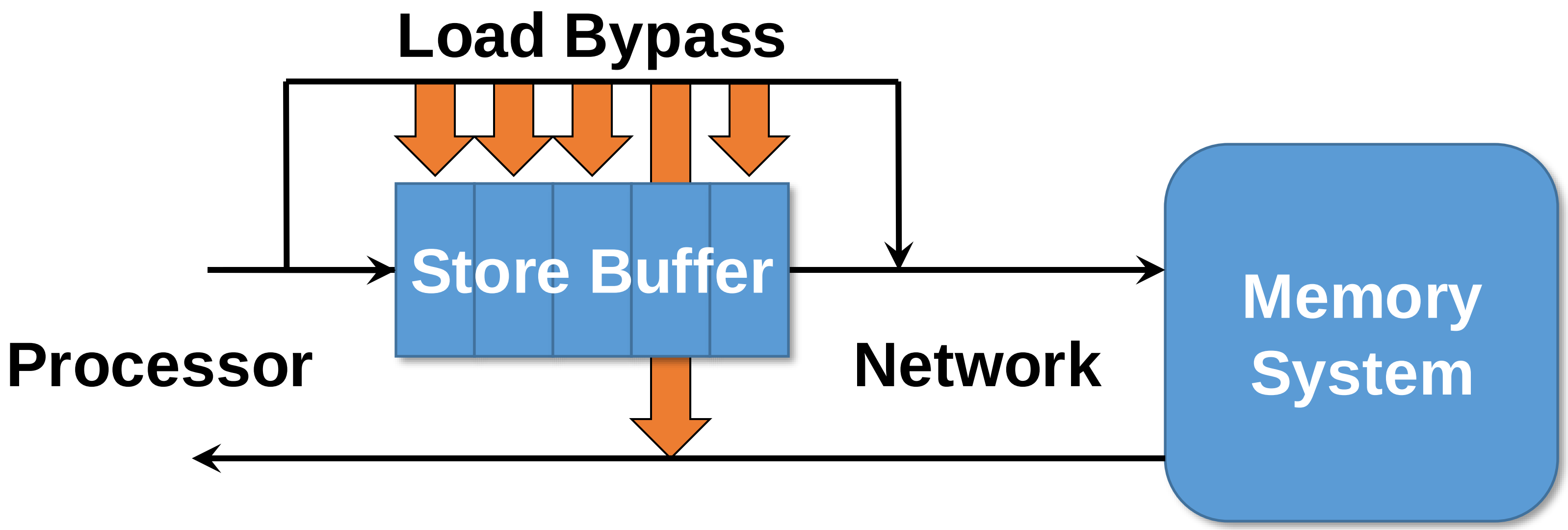
```
mov b, %ebx  ;Load
mov 1, a     ;Store
```

Q. When is it safe for the hardware or compiler to perform this reordering?

A. When a ≠ b

A'. And there's no concurrency

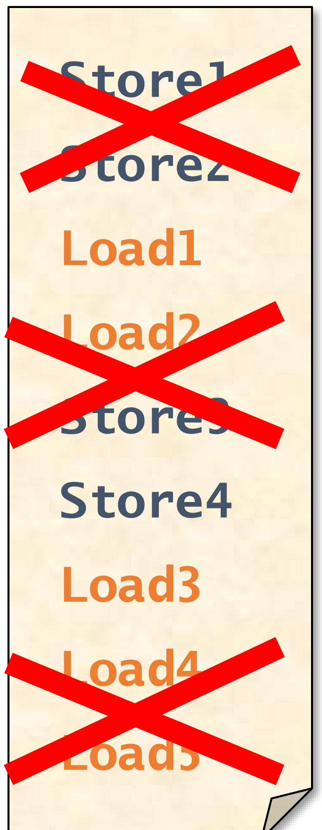
Hardware Reordering



- Processor can issue stores faster than the network can handle them ⇒ store buffer
- Loads take priority, bypassing the store buffer
- Except if a load address matches an address in the store buffer, the store buffer returns the result

X86: Memory Consistency

Thread's Code



1. Loads are *not* reordered with loads.
2. Stores are *not* reordered with stores.
3. Stores are *not* reordered with prior loads.
4. A load *may* be reordered with a prior store to a different location but *not* with a prior store to the same location.
5. Stores to the same location respect a global total order.

X86: Memory Consistency

Thread's Code

Store1
Store2
Load1
Load2
Store3
Store4
Load3
Load4
Load5

LOADS

OK!

1. Loads are *not* reordered with loads.
2. Stores are *not* reordered with stores.
3.
4. or with a prior store to the same location.
5. Stores to the same location respect a global total order.

Total Store Ordering (TSO)…weaker than sequential consistency

Memory Barriers (Fences)

- A *memory barrier* (or *memory fence*) is a hardware action that enforces an ordering constraint between the instructions before and after the fence.
- A memory barrier can be issued explicitly as an instruction (x86: mfence)
- The typical cost of a memory fence is comparable to that of an L2-cache access.

X86: Memory Consistency

Thread's Code

```
Store1
Store2
Load1
Load2
Store3
Store4
Barrier
Load3
Load4
```

1. Loads are *not* reordered with loads.
2. Stor
3. Stor
   load
4. A lo
   store to ... location but *not* with
   a prior store to the same location.
5. Stores to the same location respect a global total order.

Total Store Ordering + properly placed memory barriers = sequential consistency

Memory Barriers

- Explicit Synchronization
- Memory barrier will
  - Flush write buffer
  - Bring caches up to date
- Compilers often do this for you
  - Entering and leaving critical sections

Volatile Variables

- In Java (and C), can ask compiler to keep a variable up-to-date by declaring it volatile
- Adds a memory barrier after each store
- Inhibits reordering, removing from loops, & other "compiler optimizations"
- Will talk about it in detail in later lectures

Summary: Real-World

- Hardware weaker than sequential consistency
- Can get sequential consistency at a price
- Linearizability better fit for high-level software

Linearizability

- Linearizability
  - Operation takes effect instantaneously between invocation and response
  - Uses sequential specification, locality implies composablity

Summary: Correctness

- Sequential Consistency
  - Not composable
  - Harder to work with
  - Good way to think about hardware models
- We will use *linearizability* as our consistency condition in the remainder of this course unless stated otherwise

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

Progress Conditions

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

Summary

- Later in this course, will look at *linearizable blocking* and *non-blocking* implementations of objects

The END