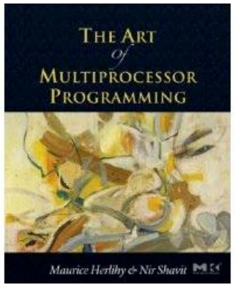
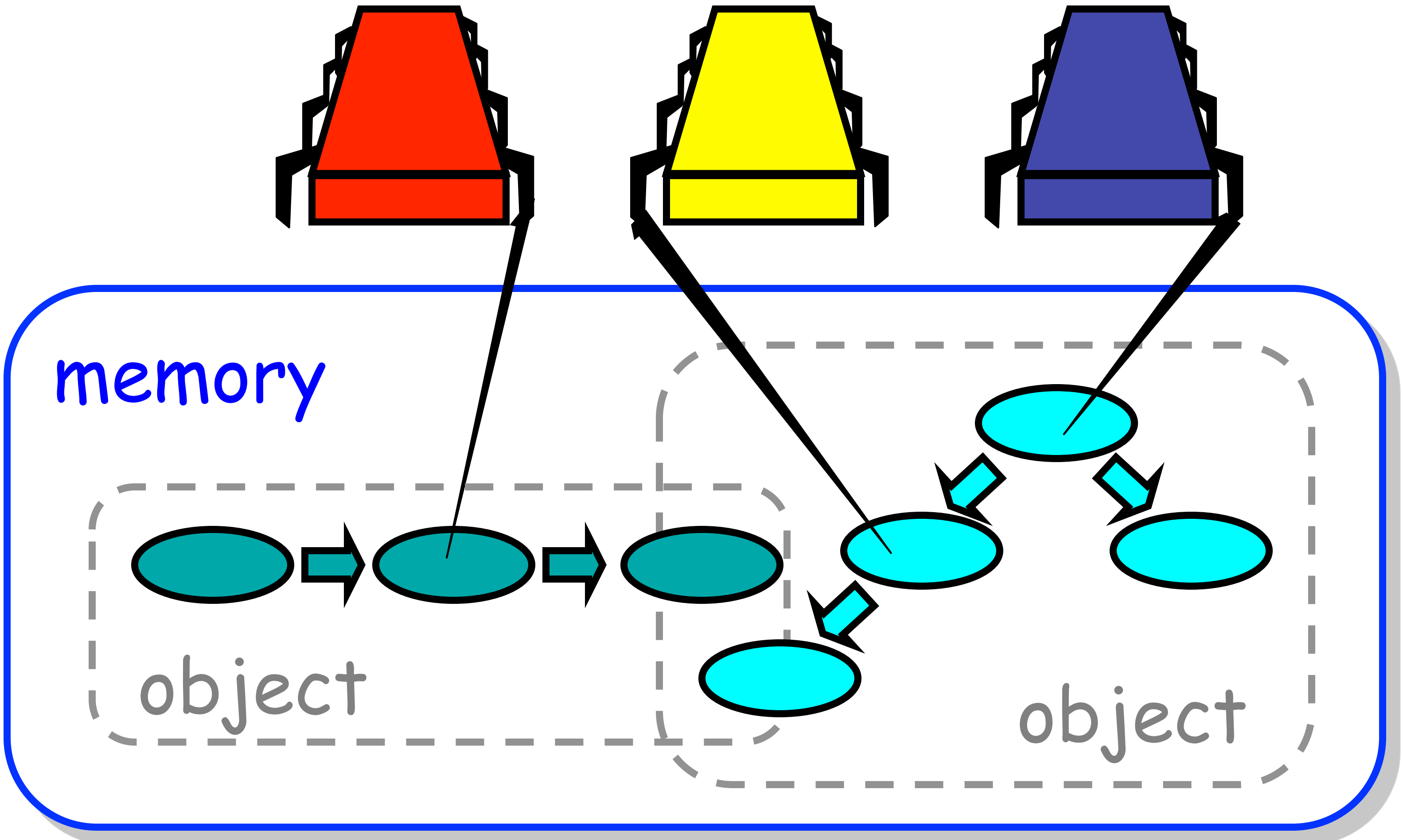
Concurrent Objects



Companion slides for
The Art of Multiprocessor Programming
by Maurice Herlihy & Nir Shavit

Concurrent Computation



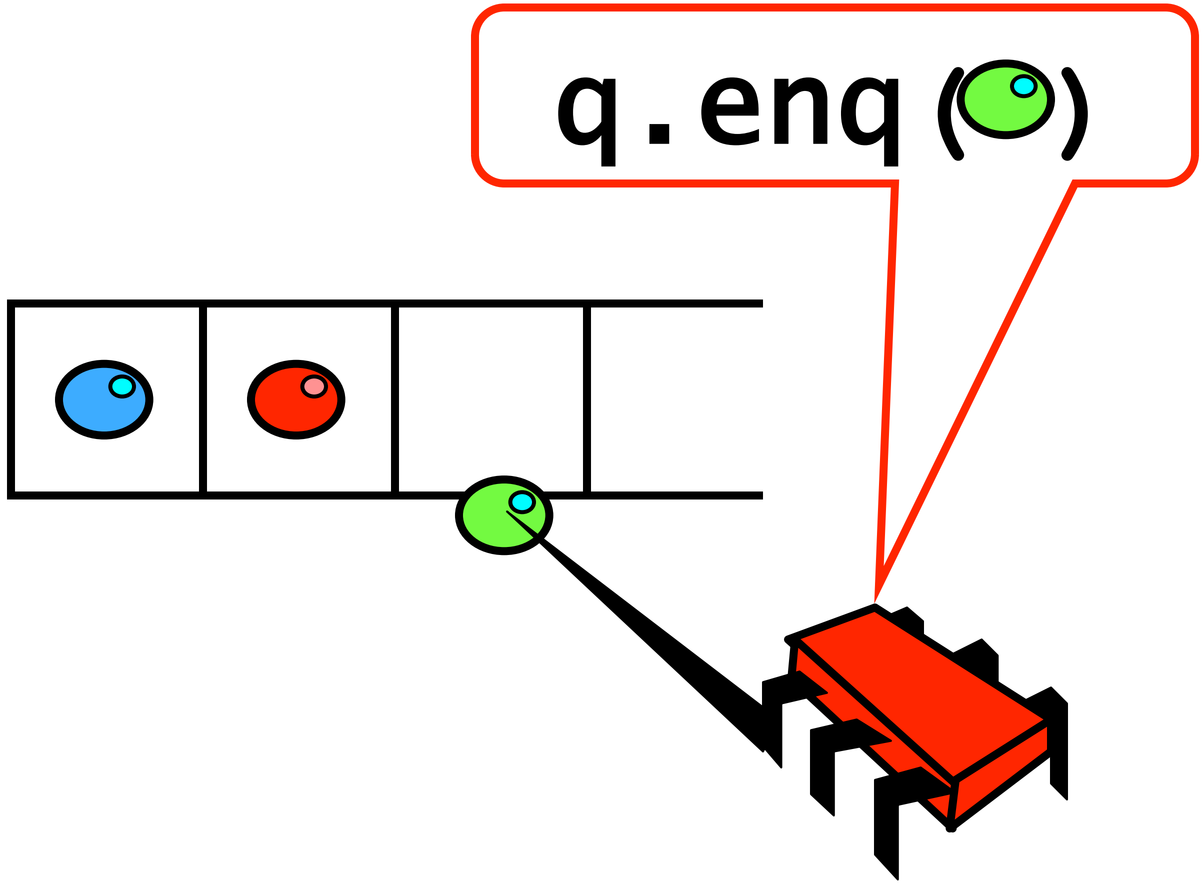
Objectivism

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

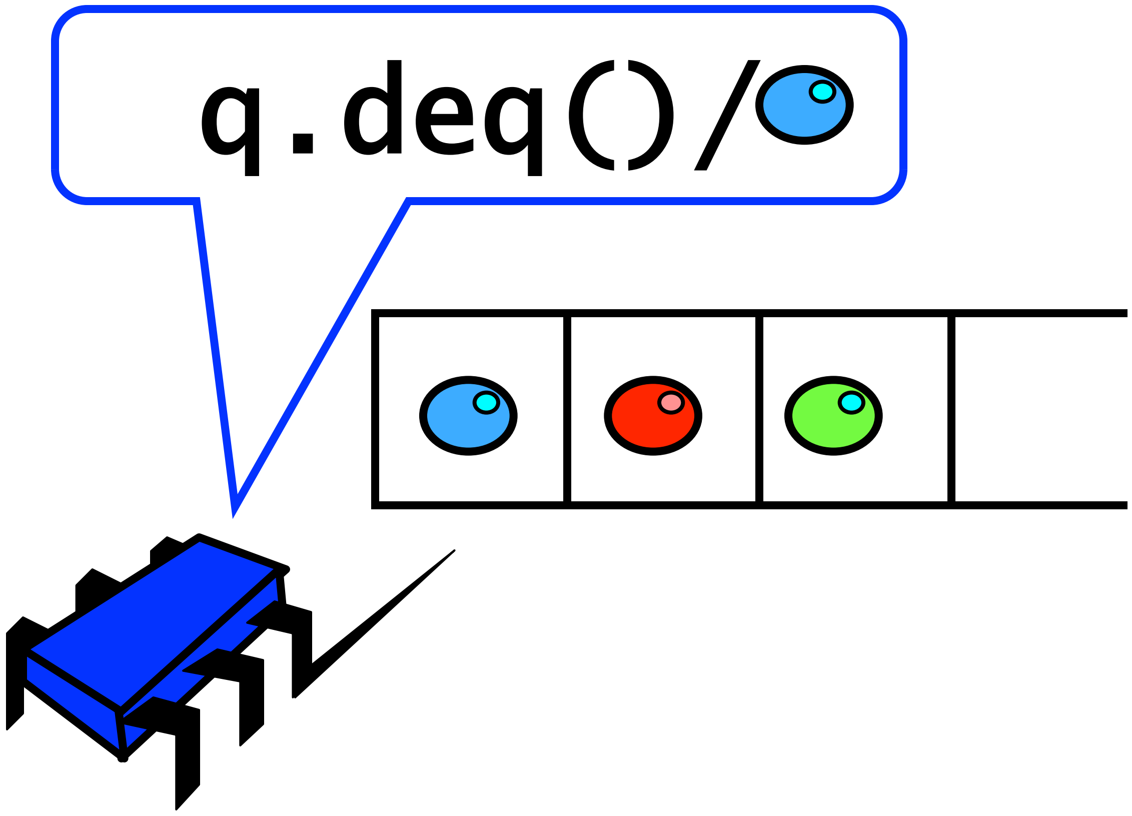
Objectivism

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

FIFO Queue: Enqueue Method



FIFO Queue: Dequeue Method



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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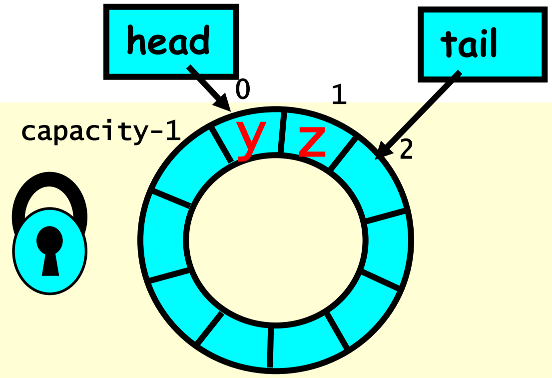
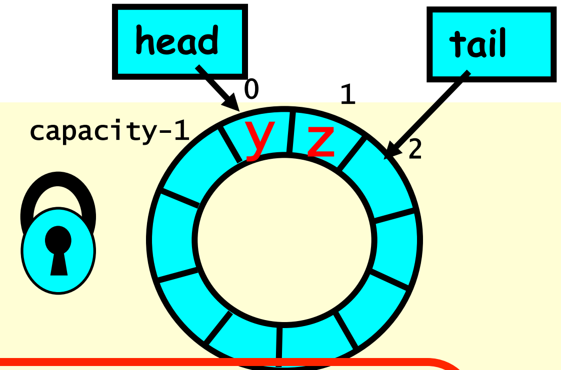


Queue fields protected by single shared lock

A Lock-Based Queue

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  public LockBasedQueue(int capacity) {
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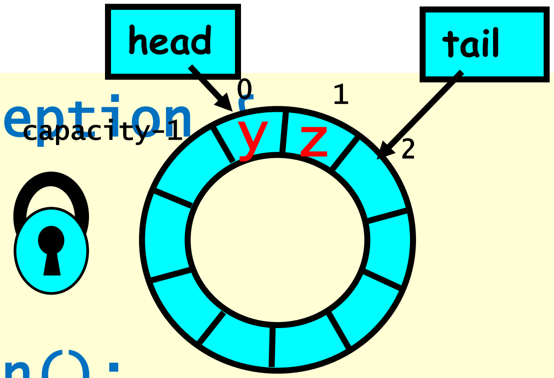
    items = (T[]) new Object[capacity];
}
```

Initially head = tail

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();
  }
}
```

Implementation: Deq

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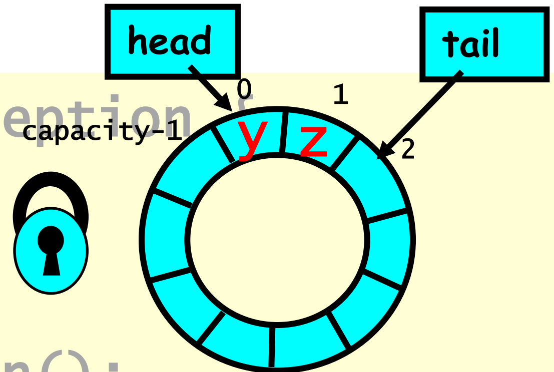

Method calls mutually exclusive

Implementation: Deq

```
public T deq() throws EmptyException {
  lock.lock();
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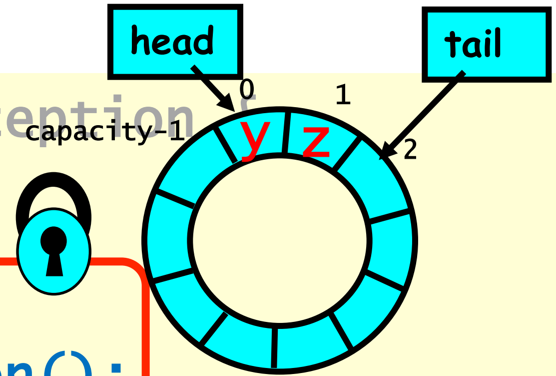

If queue empty throw exception

Implementation: Deq

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public T deq() throws EmptyException {
  lock.lock();
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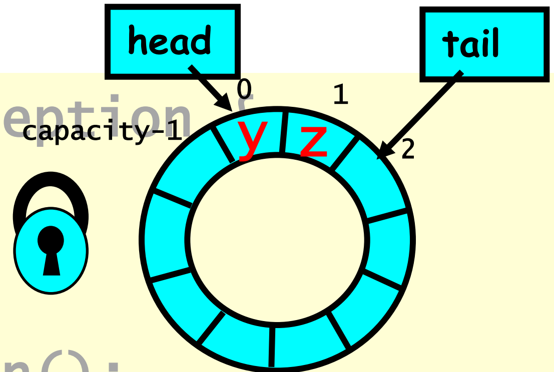

Queue not empty: remove item and update head

Implementation: Deq

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

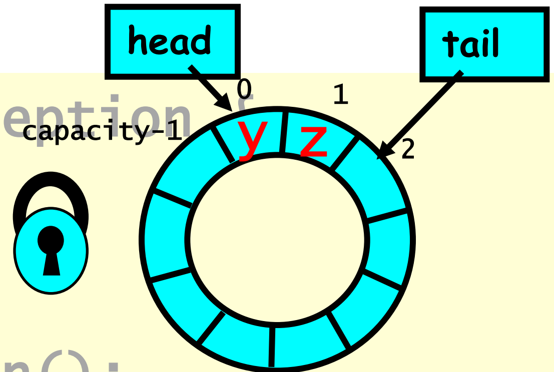

Return result

Implementation: Deq

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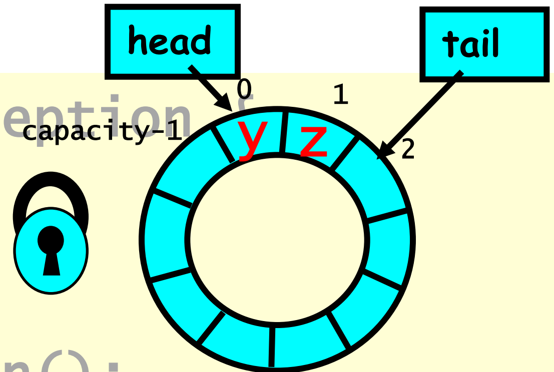

Release lock no matter what!

Implementation: Deq

```
public T deq() throws EmptyException {
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    head++;
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  } finally {
    lock.unlock();
  }
}
```

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

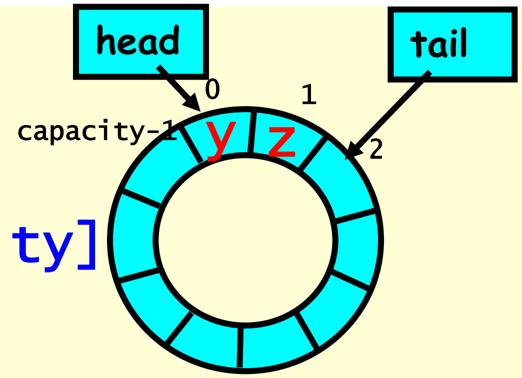
Wait-free 2-Thread Queue

```
public class WaitFreeQueue {

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

  public void enq(Item x) {
    while (tail-head == capacity); // busy-wait
    items[tail % capacity] = x; tail++;
  }
  public Item deq() {
     while (tail == head);     // busy-wait
     Item item = items[head % capacity]; head++;
     return item;
}}
```

Wait-free 2-Thread Queue




```
public class LockFreeQueue {

  int head = 0, tail = 0;
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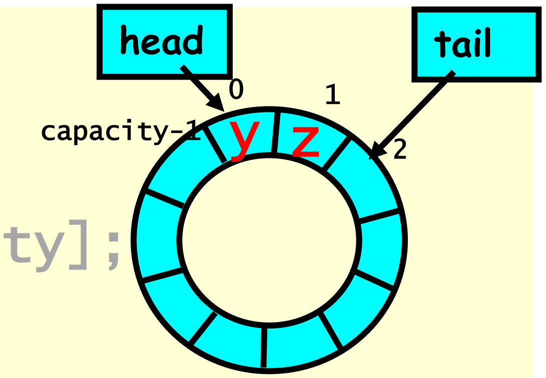
Lock-free 2-Thread Queue

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+;
     return item;
}}
```

Queue is up ... ur a lock!

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

Defining concurrent queue implementations

- 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, 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

Pre and PostConditions for Dequeue

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

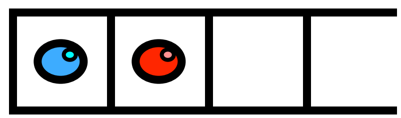
Why Sequential Specifications Totally Rock

- Interactions among methods captured by side-effects 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

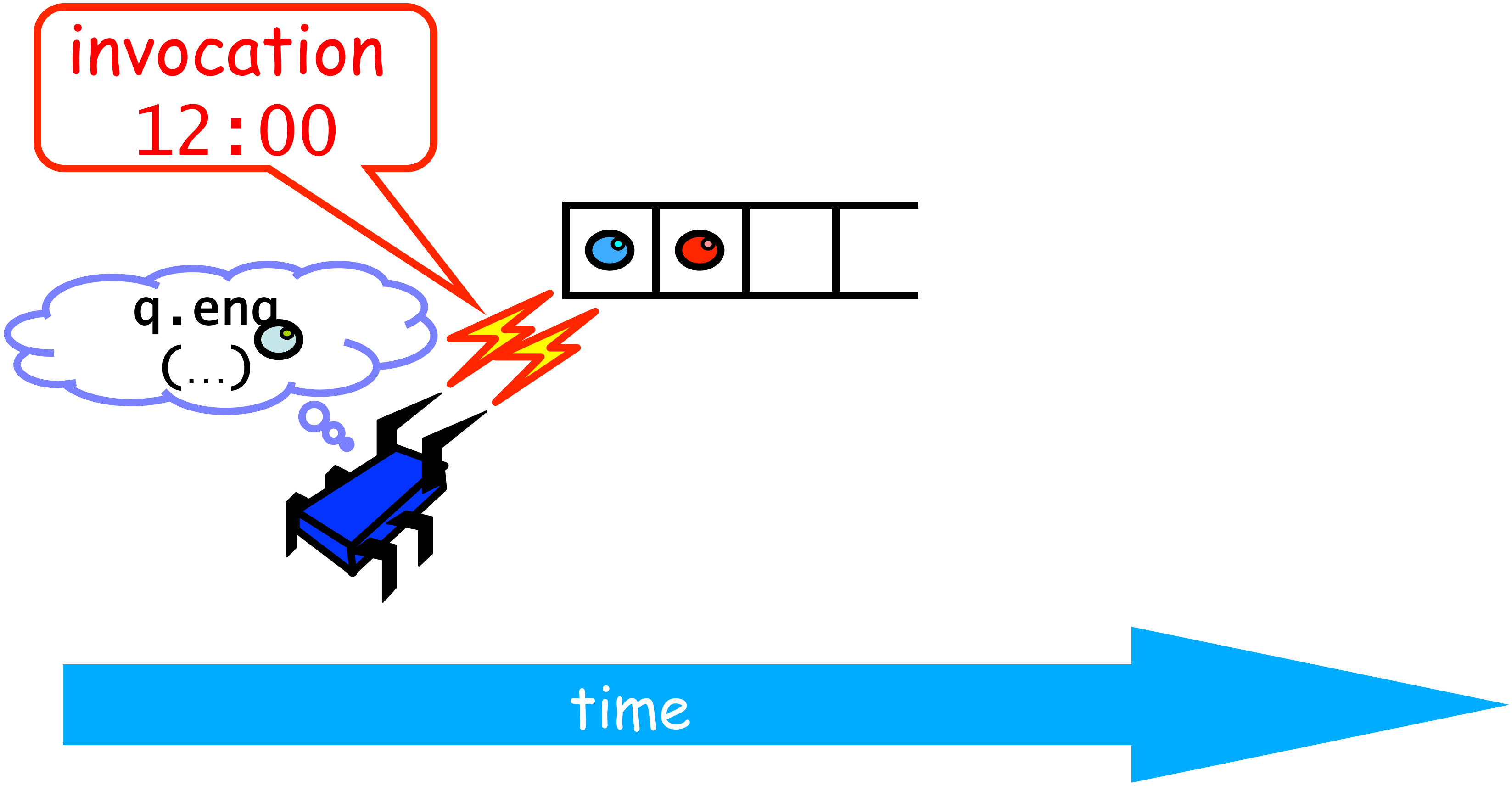
What About Concurrent Specifications ?

- Methods?
- Documentation?
- Adding new methods?

Methods Take Time



Methods Take Time



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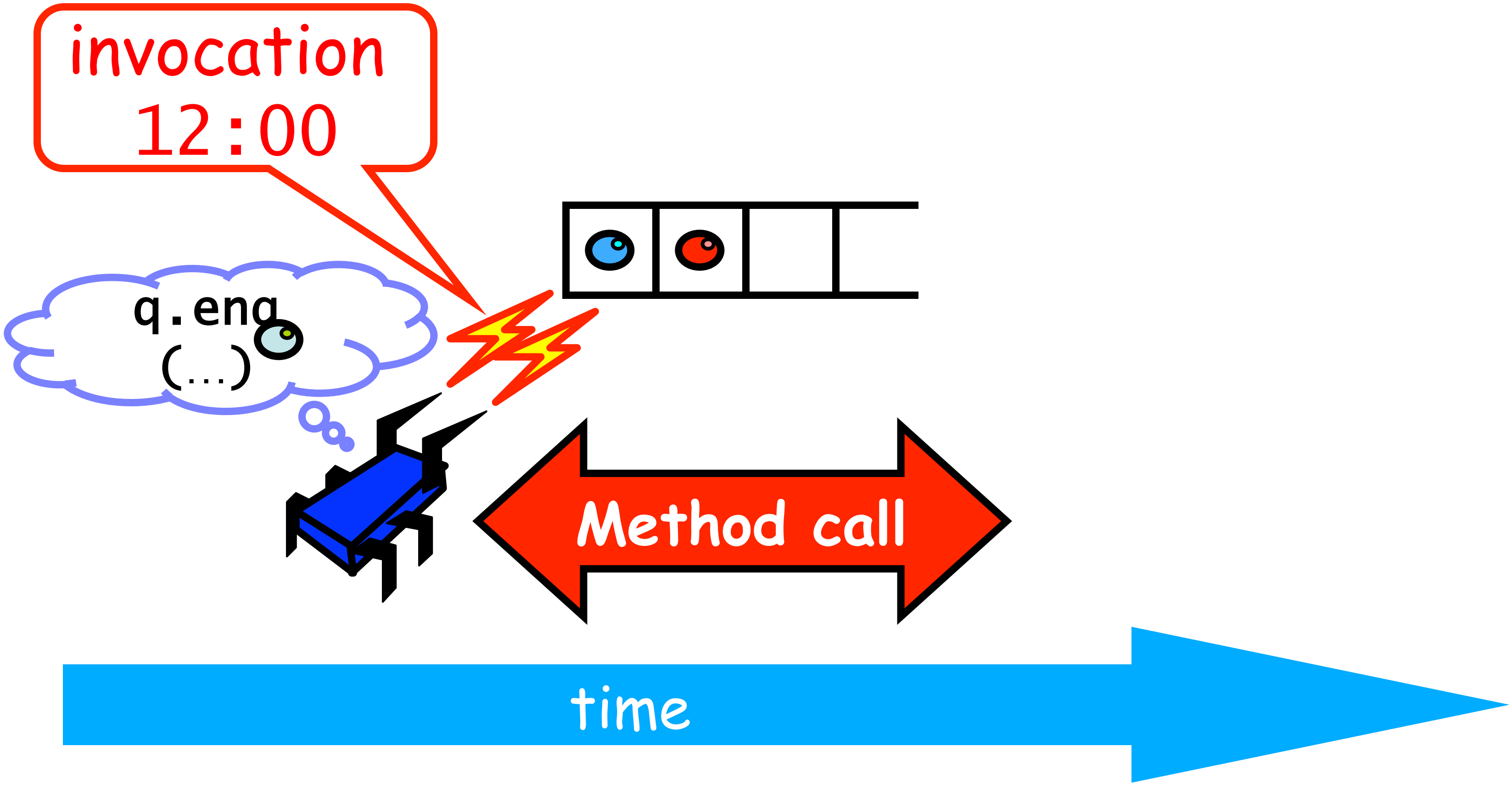

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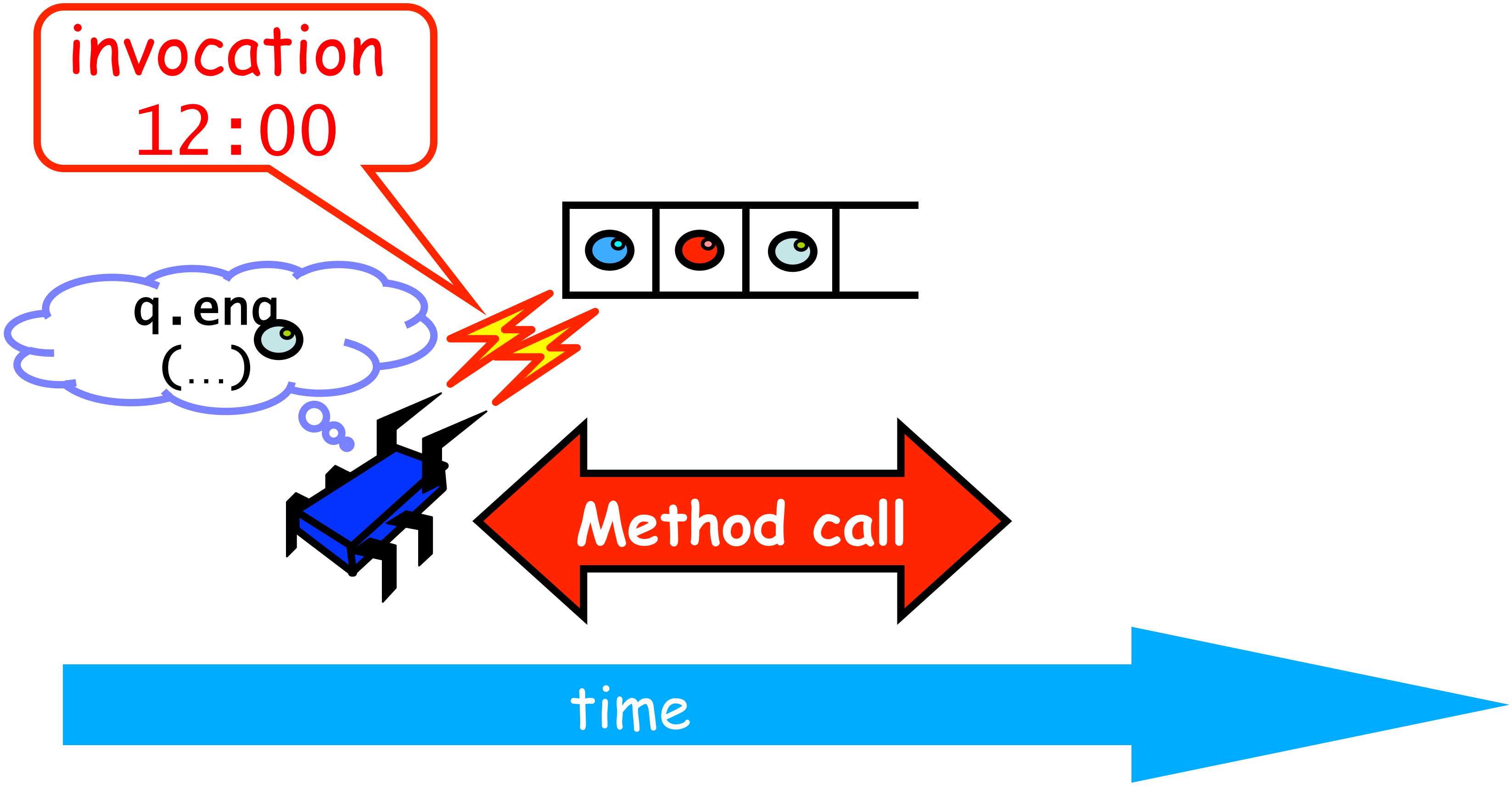

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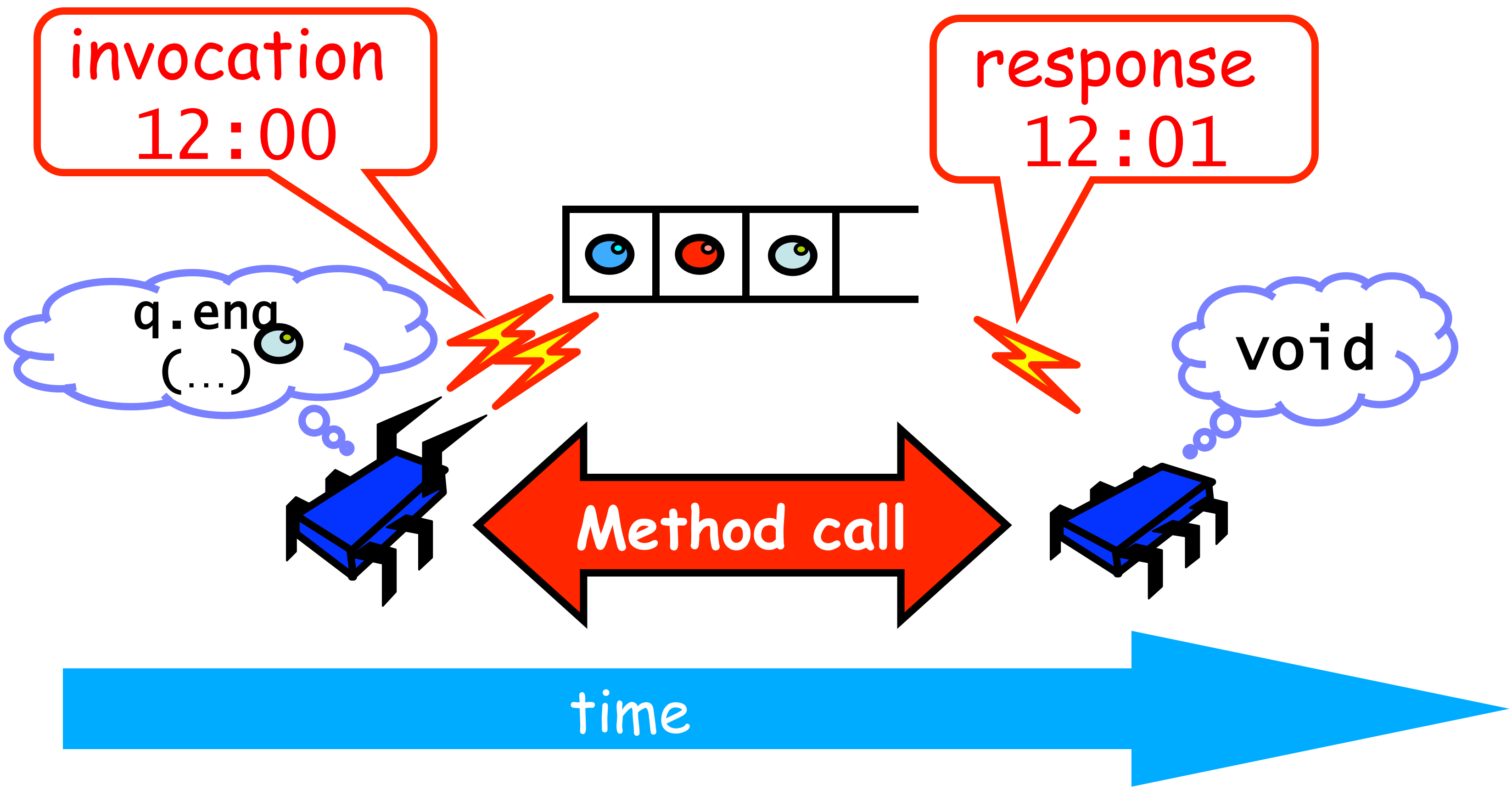
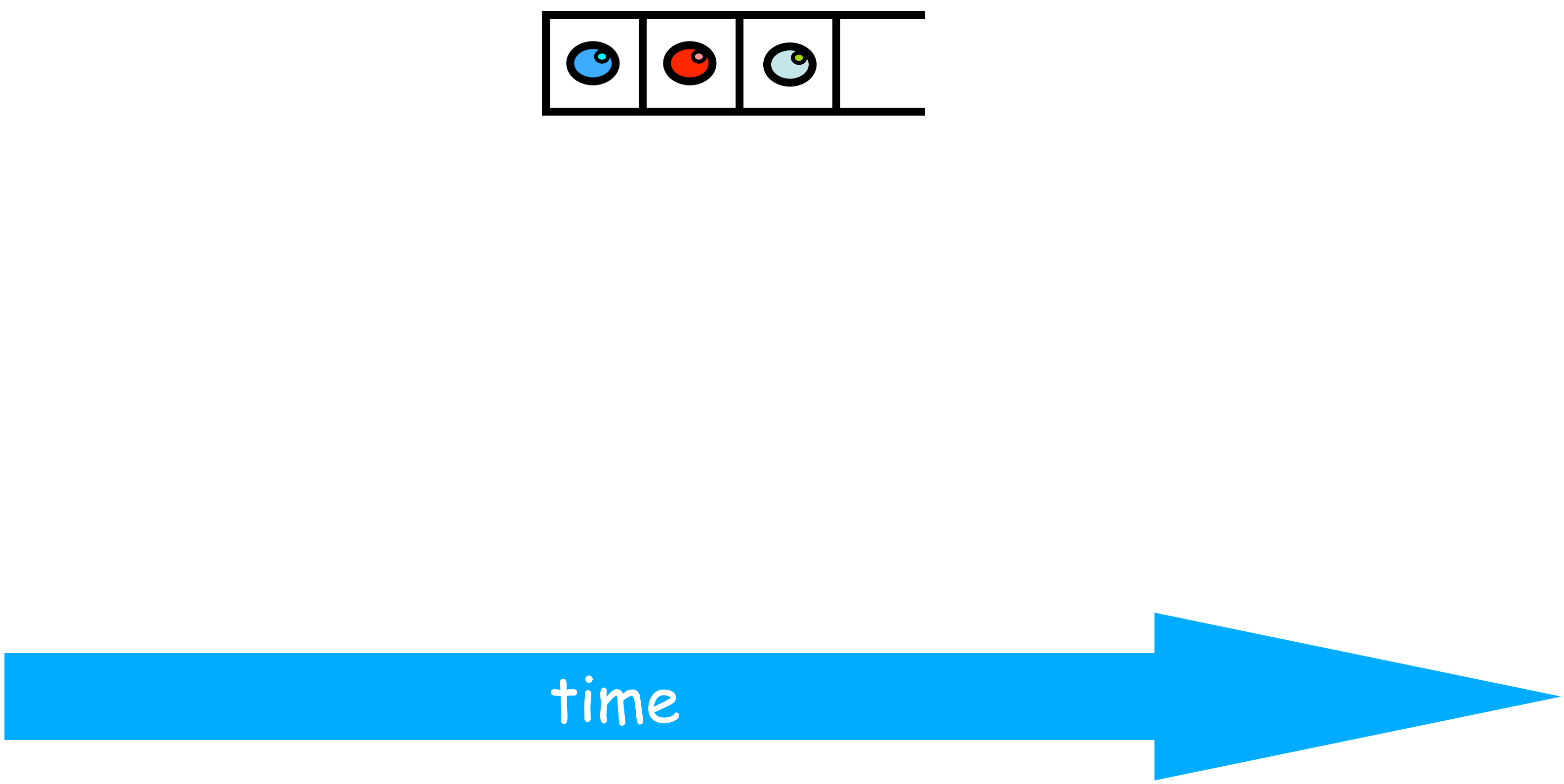


Sequential vs Concurrent

- 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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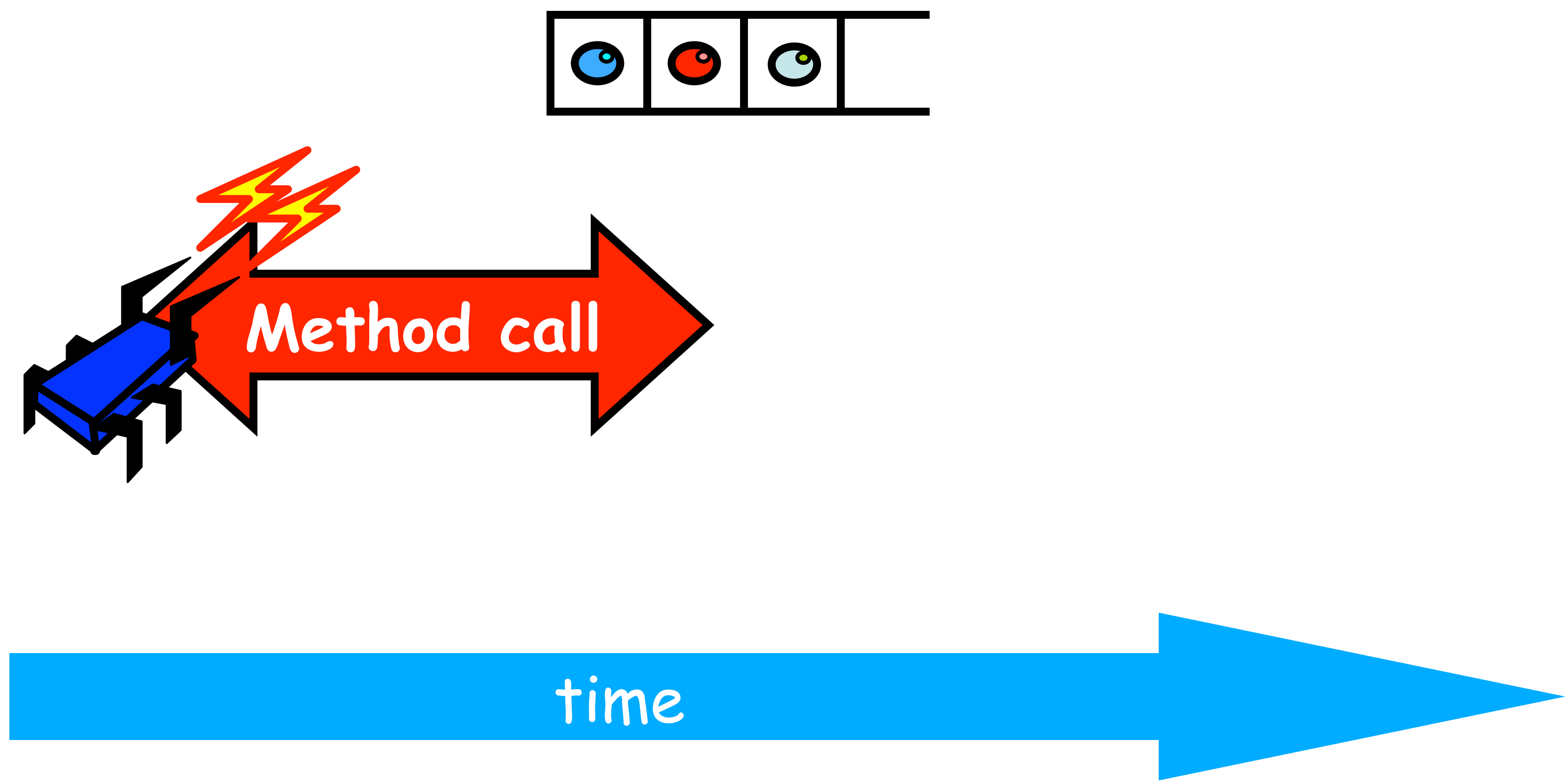

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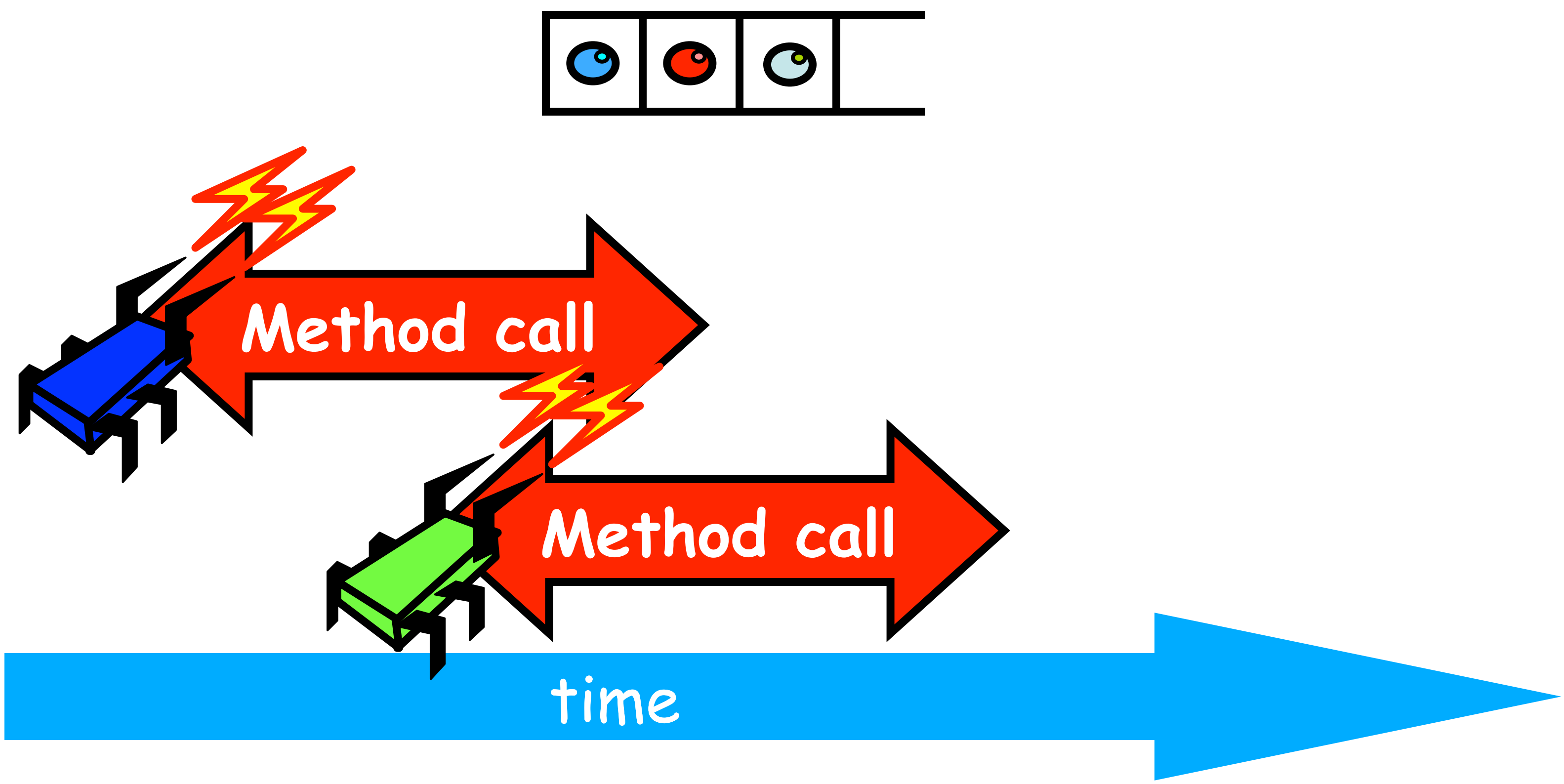
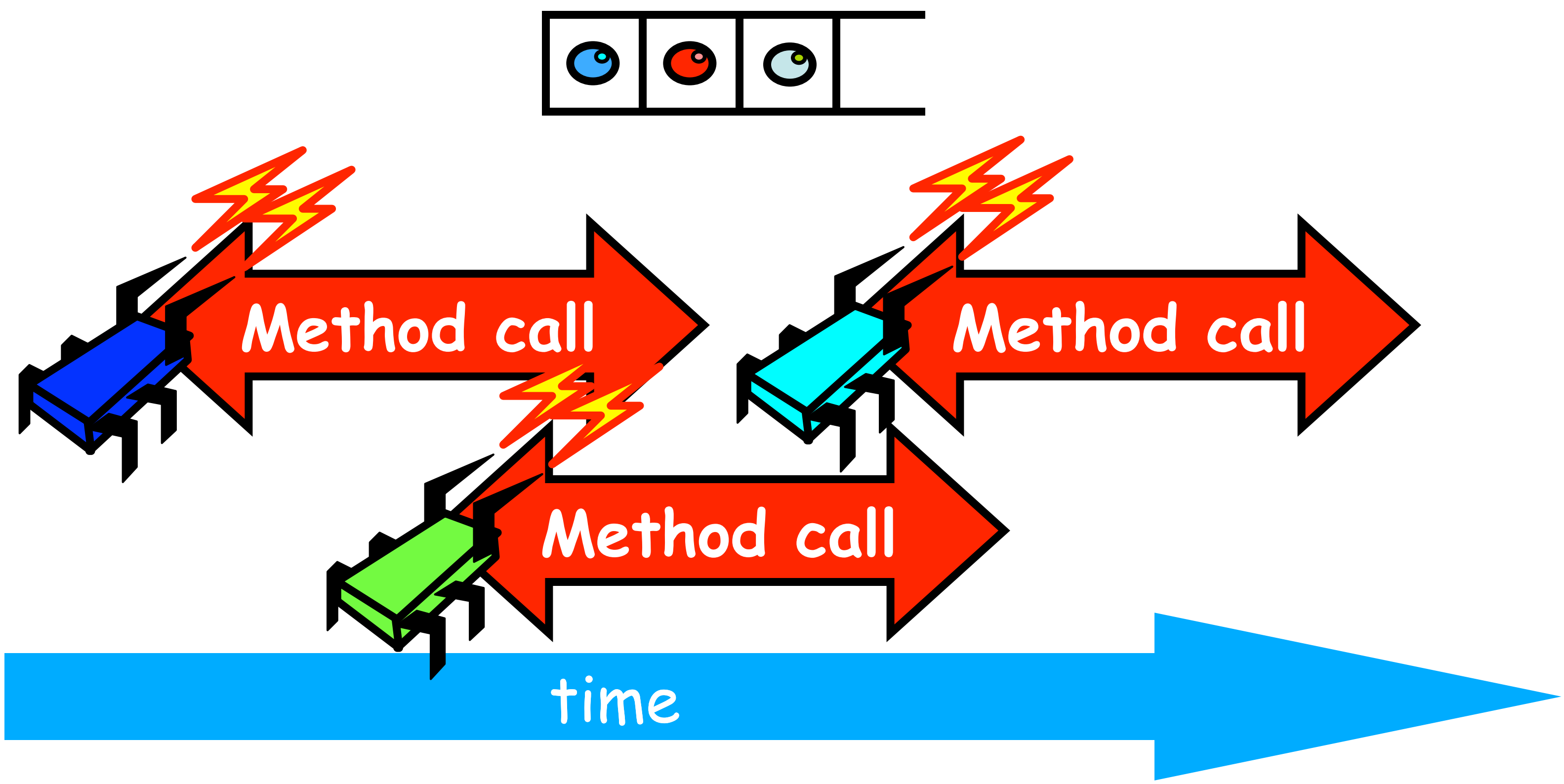


Concurrent Methods Take Overlapping Time



Sequential vs Concurrent

- Sequential:
  - Object needs meaningful state only ***between*** method calls
- Concurrent
  - Because method calls overlap, 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 enqs overlap?
    - Two deqs? 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

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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…

```
public T deq() throws EmptyException {
  lock.lock();
  try {
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  } finally {
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  }
}
```
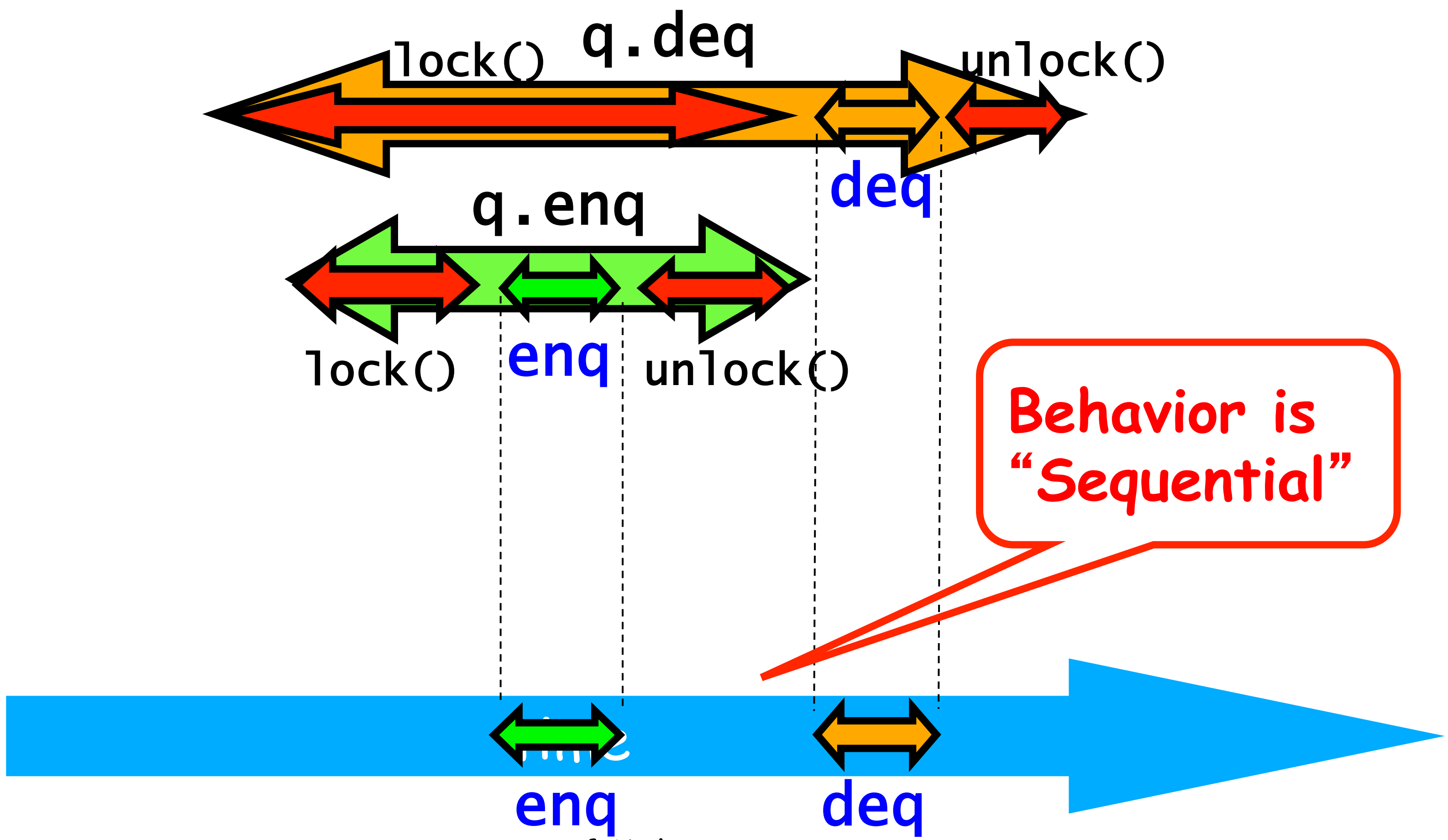

All modifications of queue are done mutually exclusive

Intuitively

Lets capture the idea of describing the concurrent via the sequential



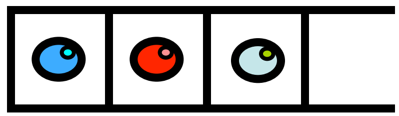
Linearizability

- Each method should
  - "take effect"
  - Instantaneously
  - Between invocation and response events
- Object is correct if this "sequential" behavior is correct
- Ordering must be maintained between request and responses (addendum)
- 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 all of whose possible executions are linearizable

Example



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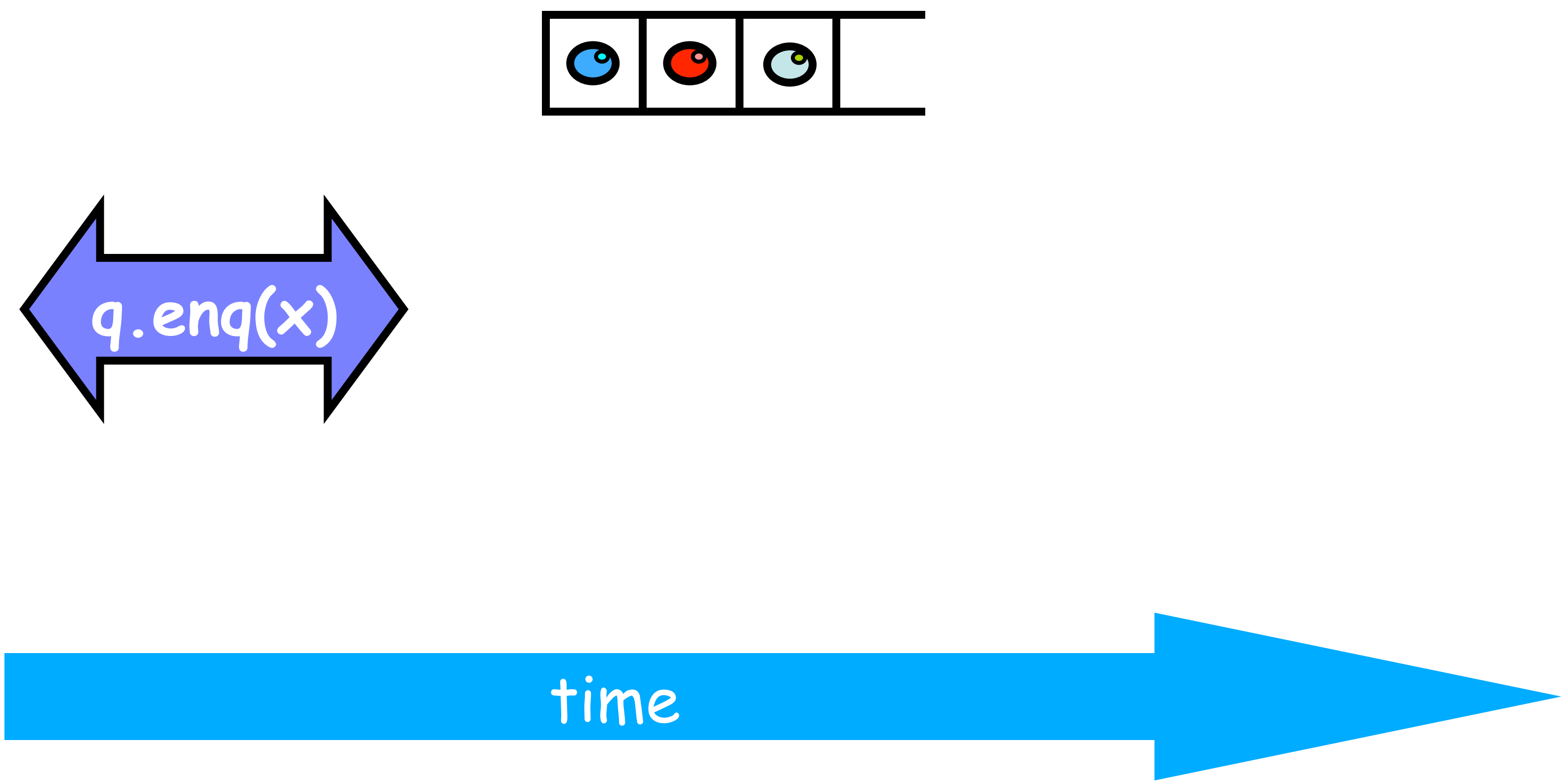

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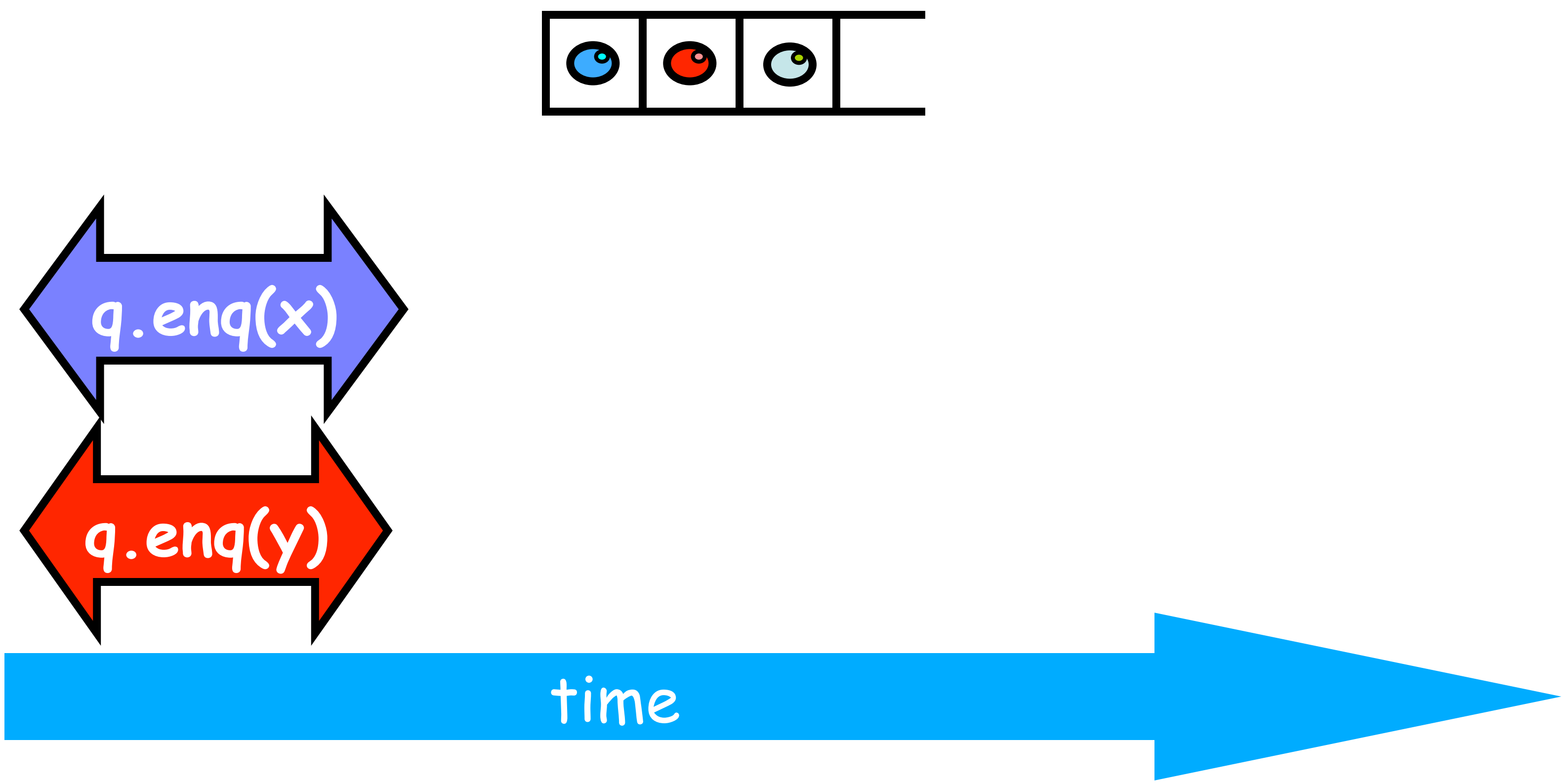

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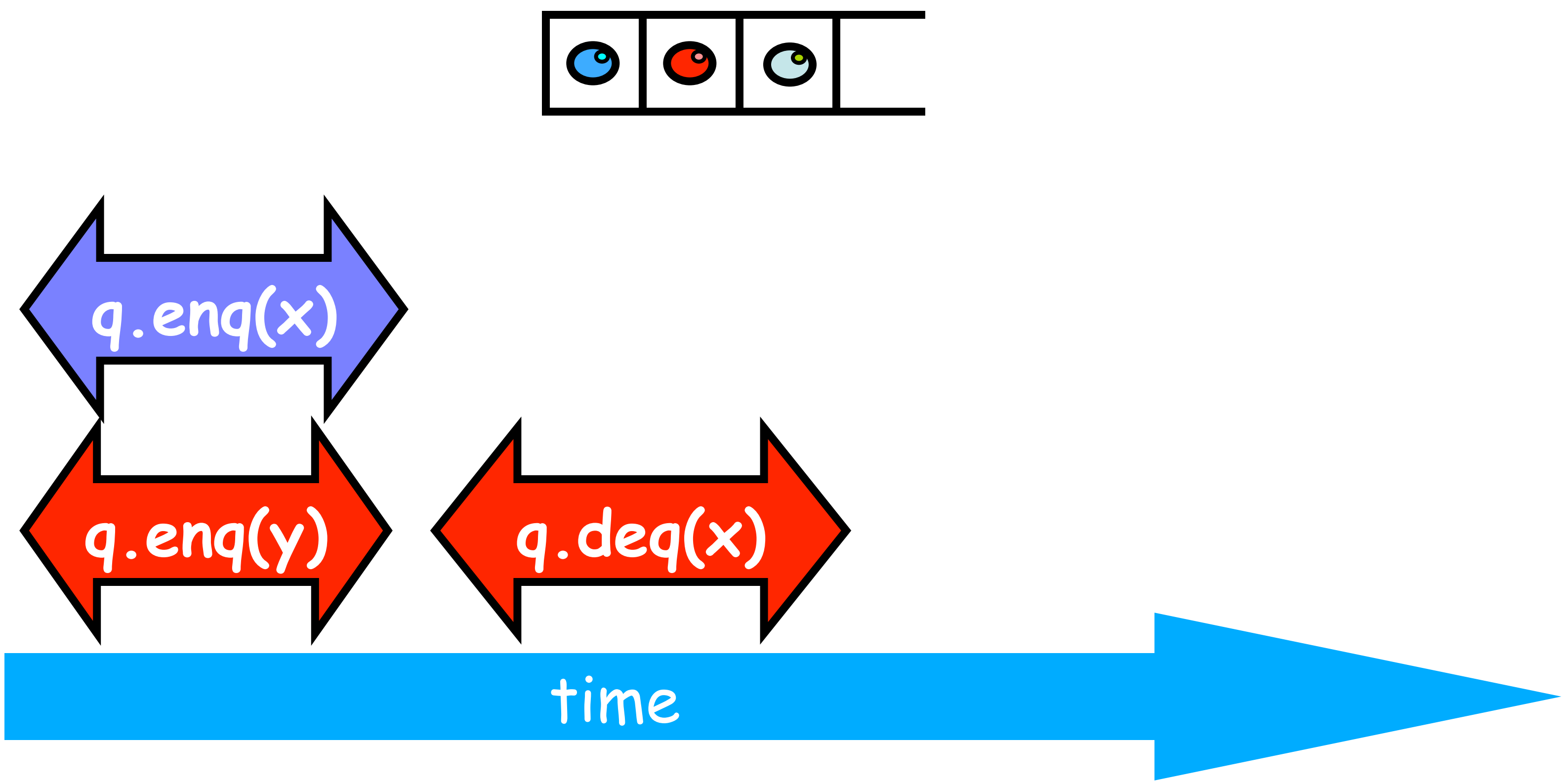

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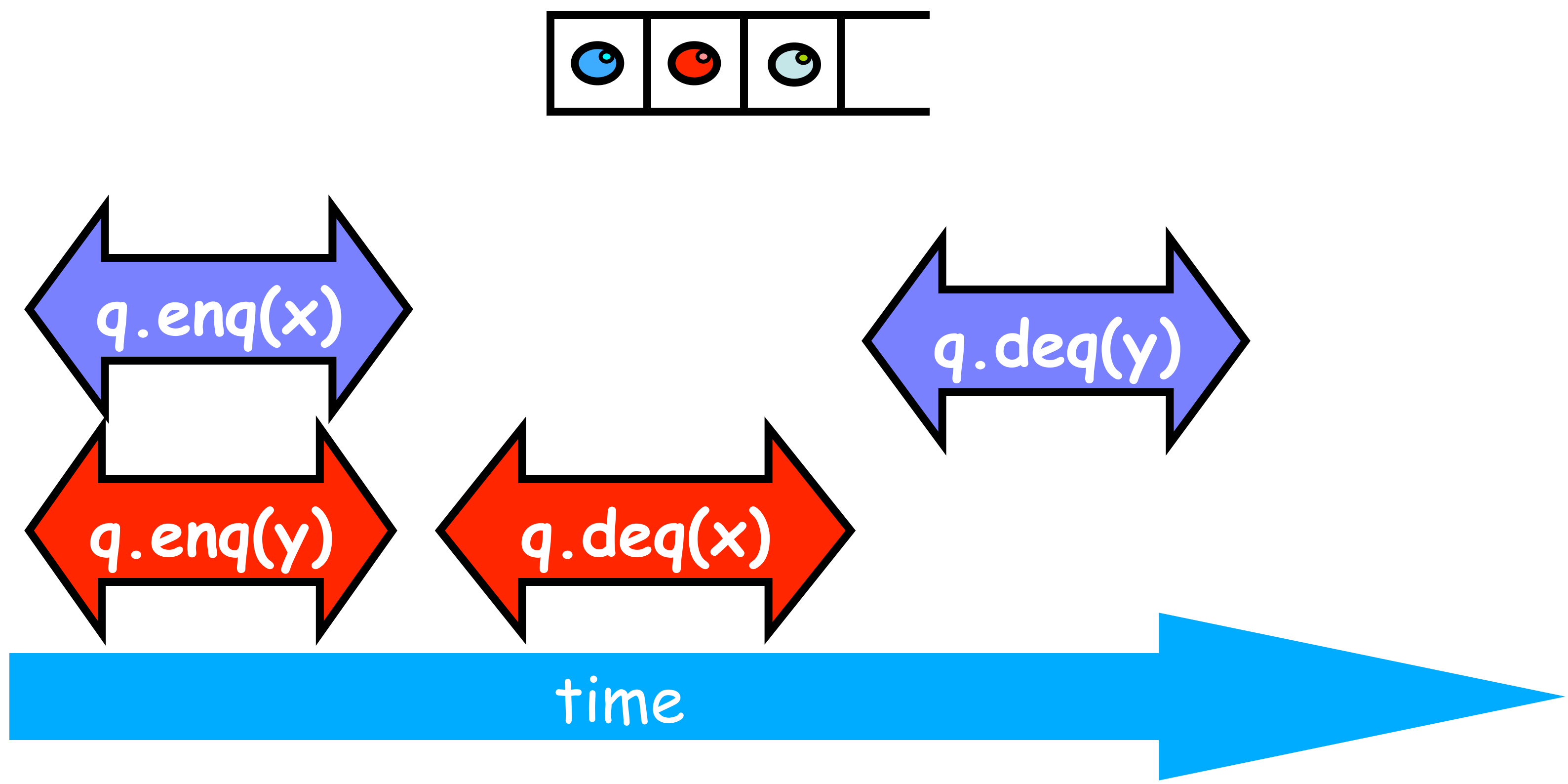

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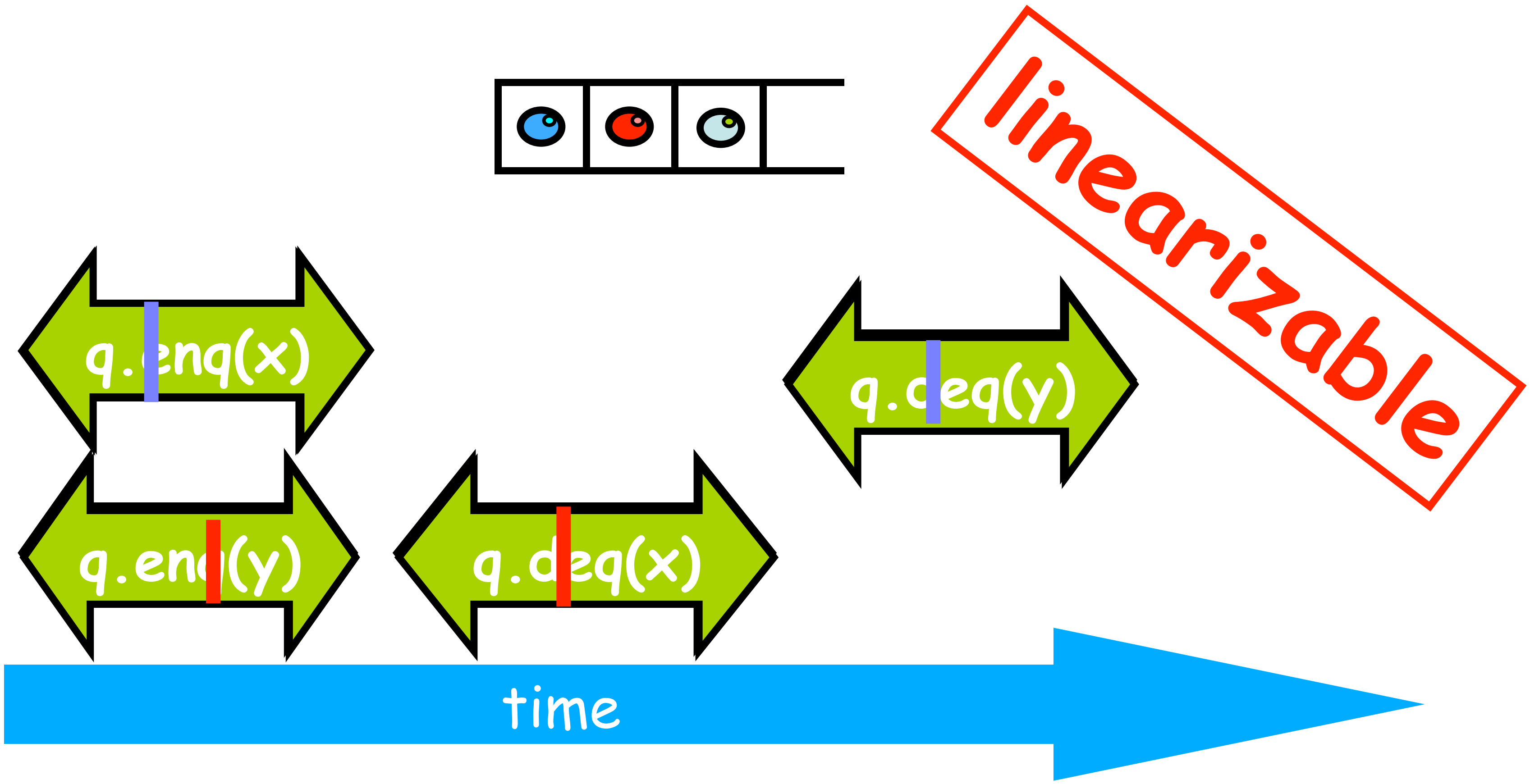

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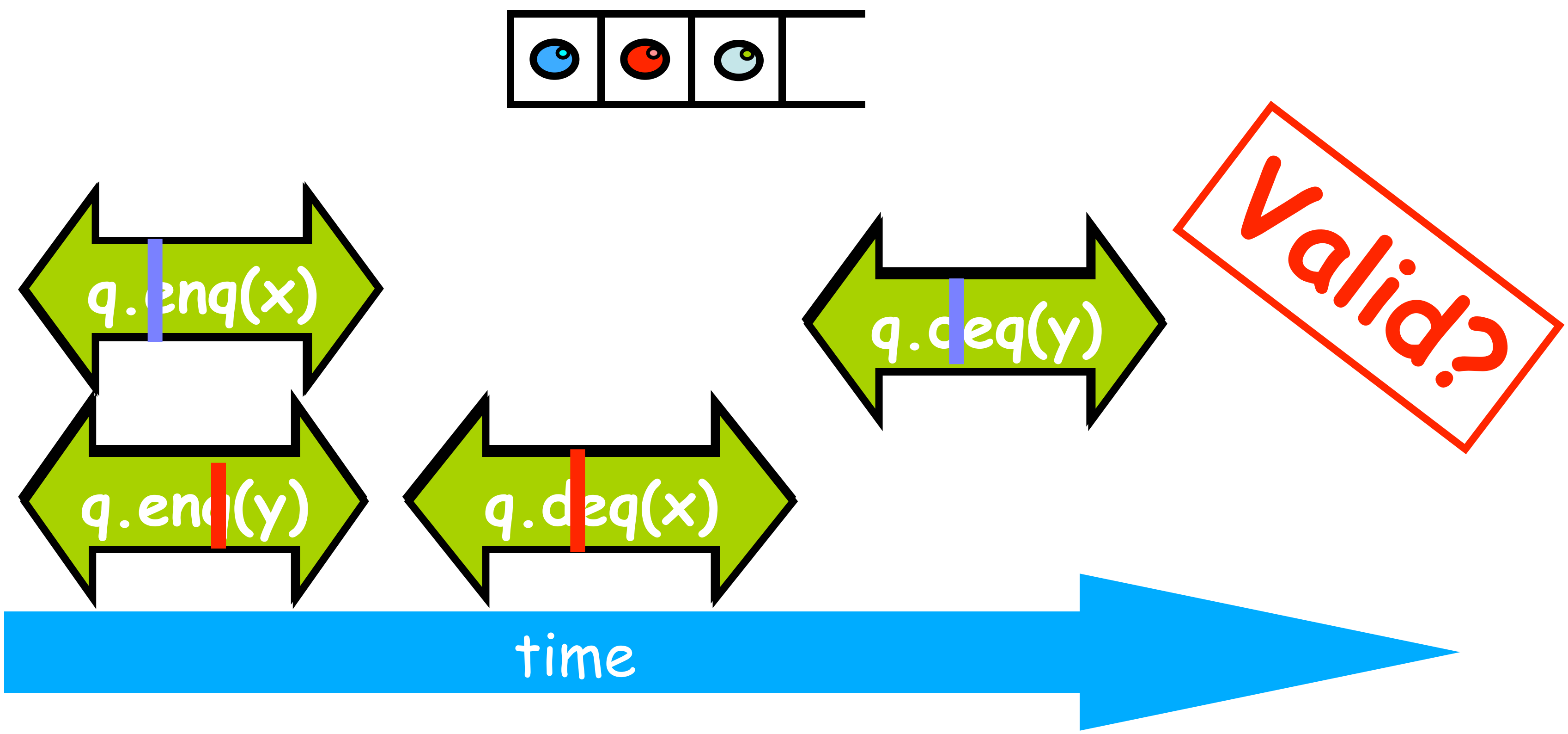

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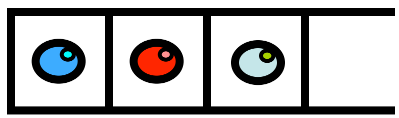

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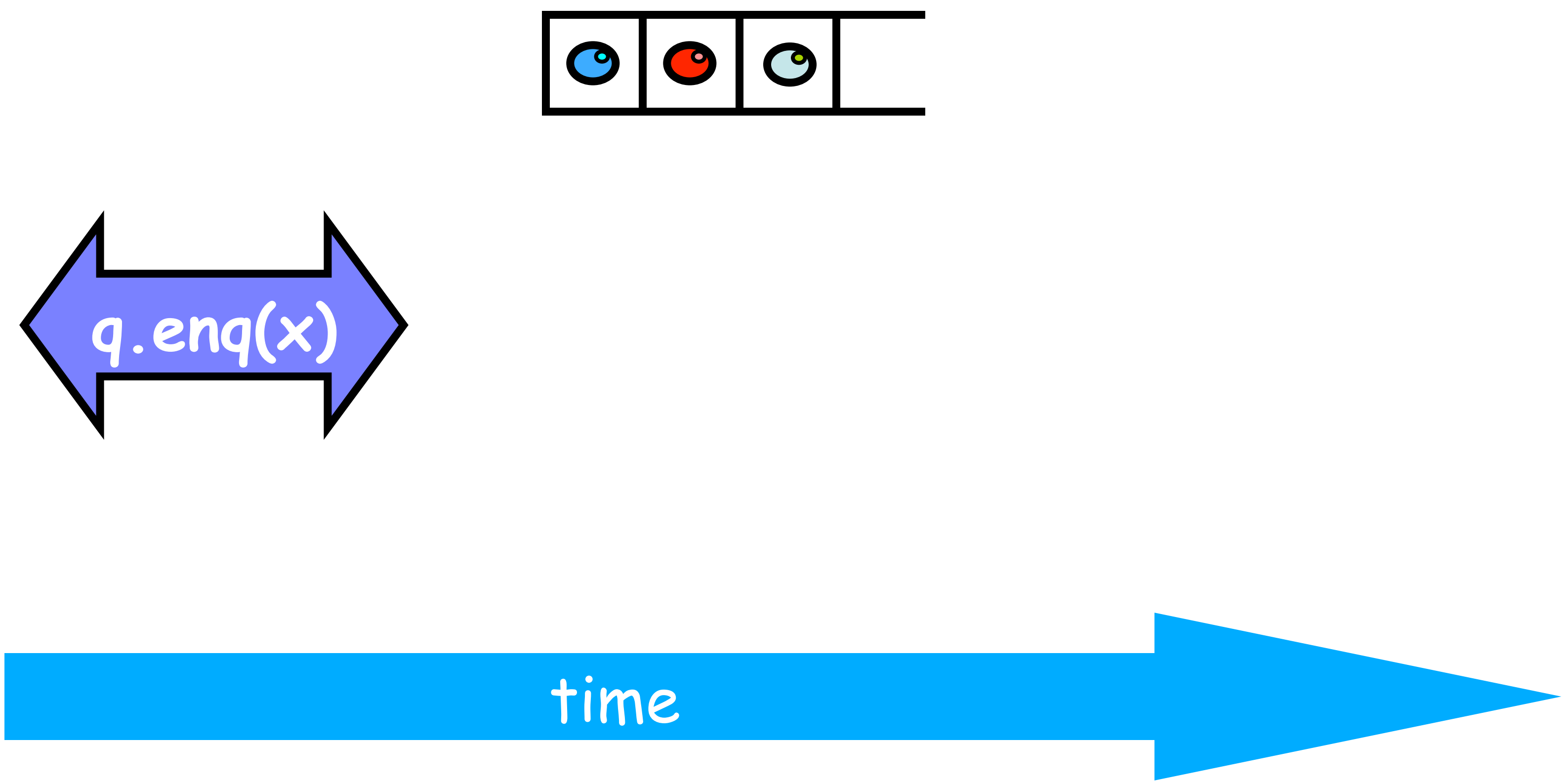

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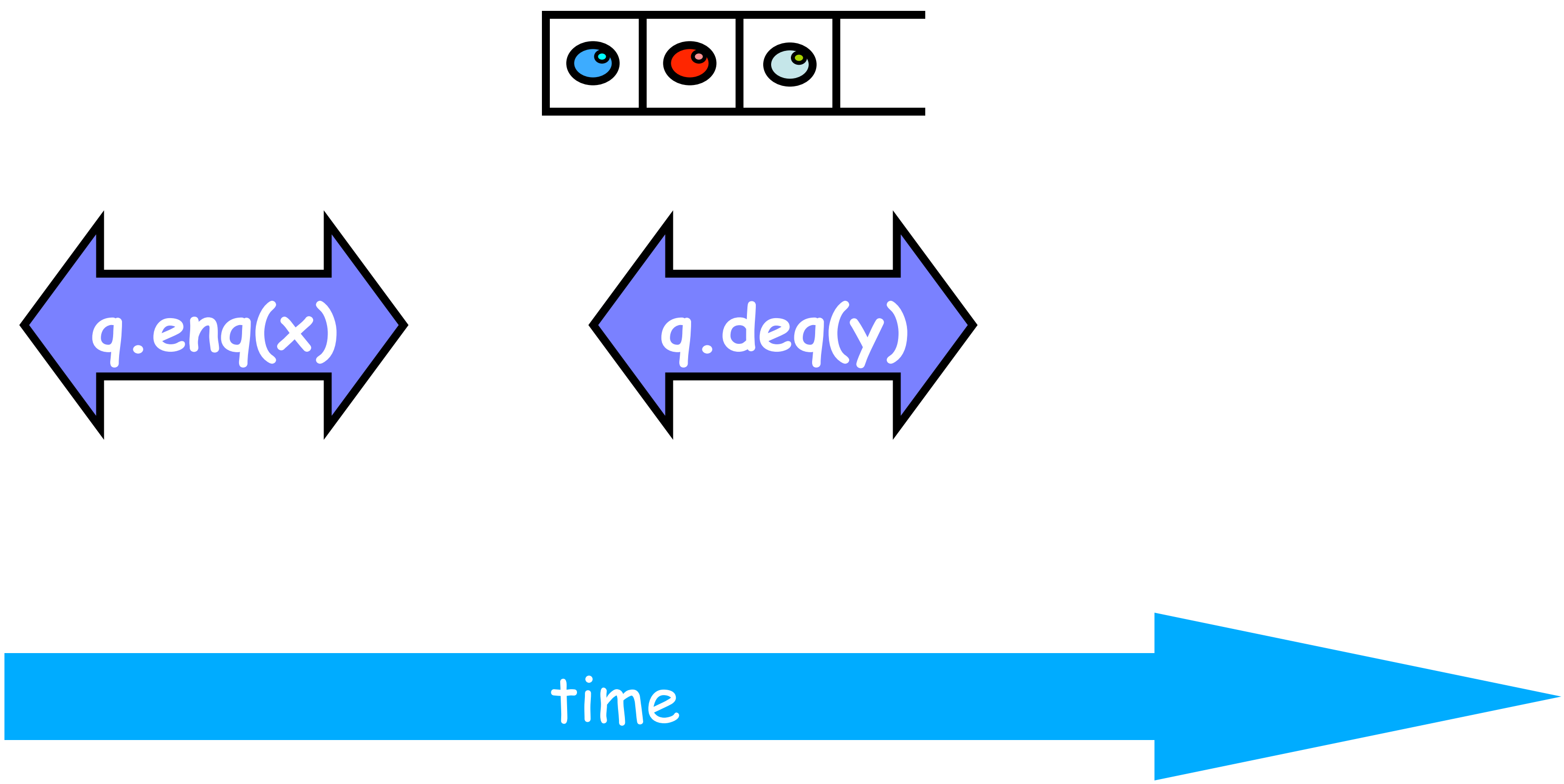

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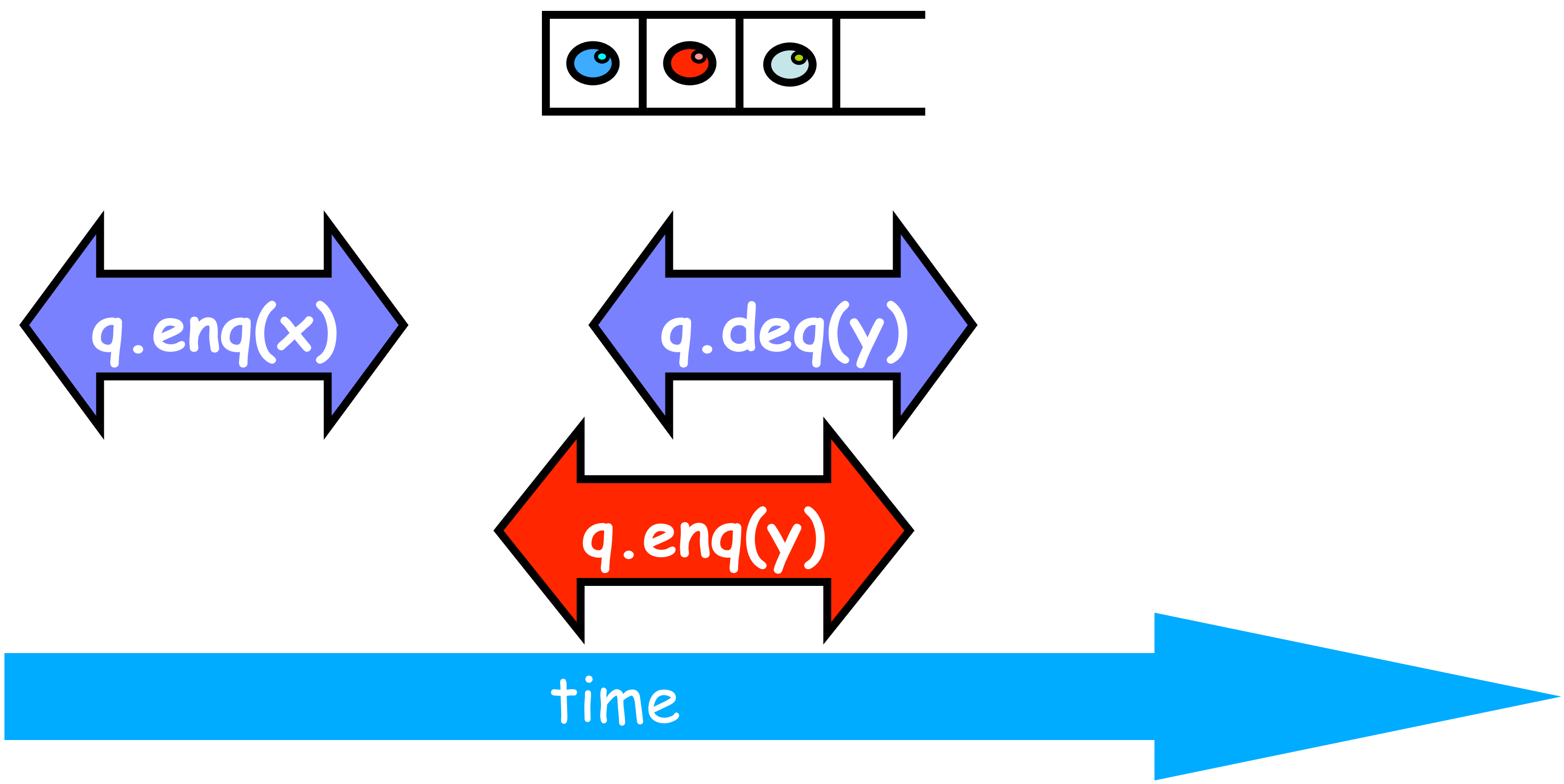

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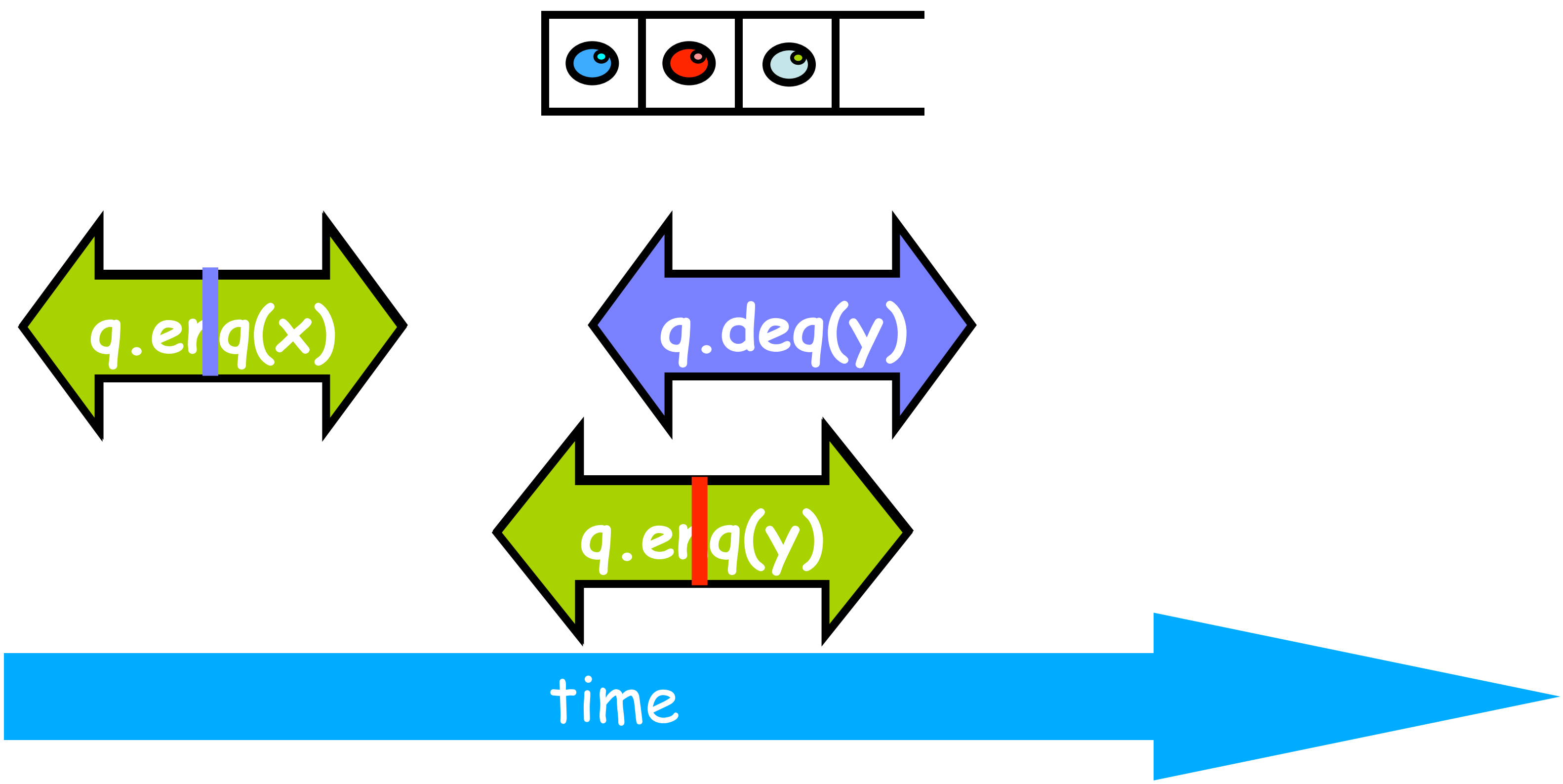

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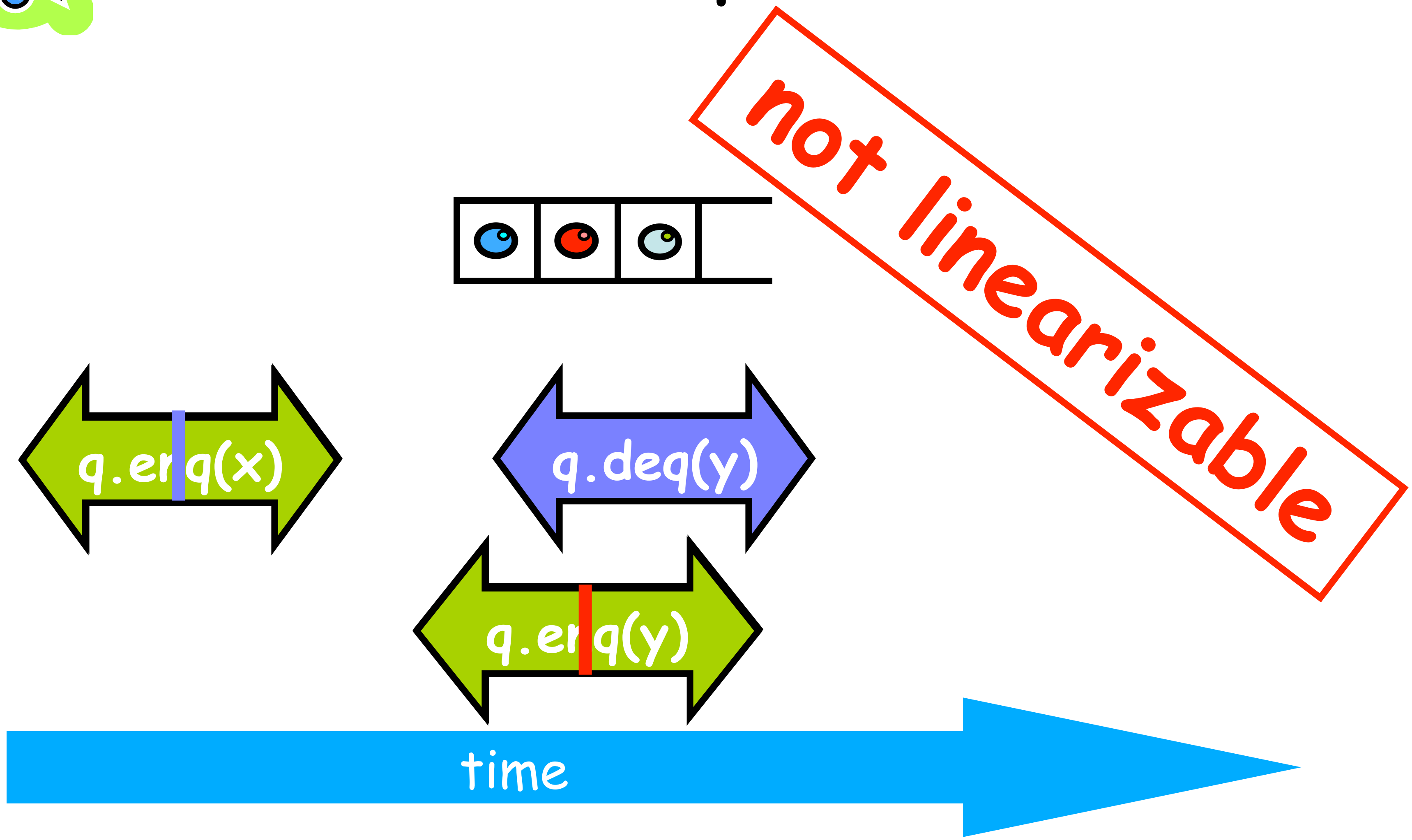

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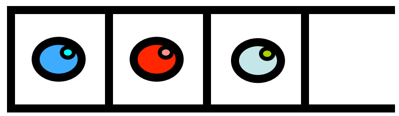

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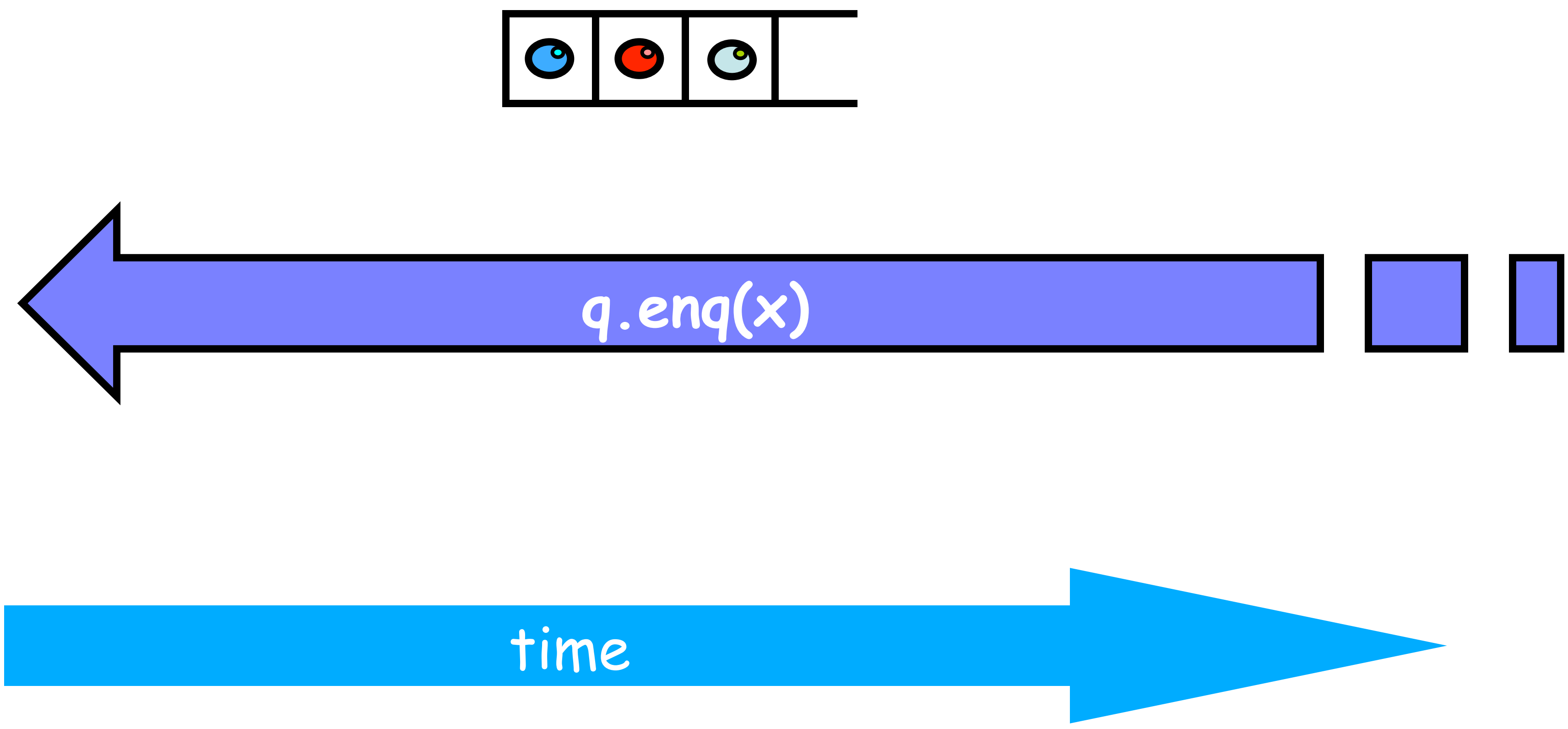

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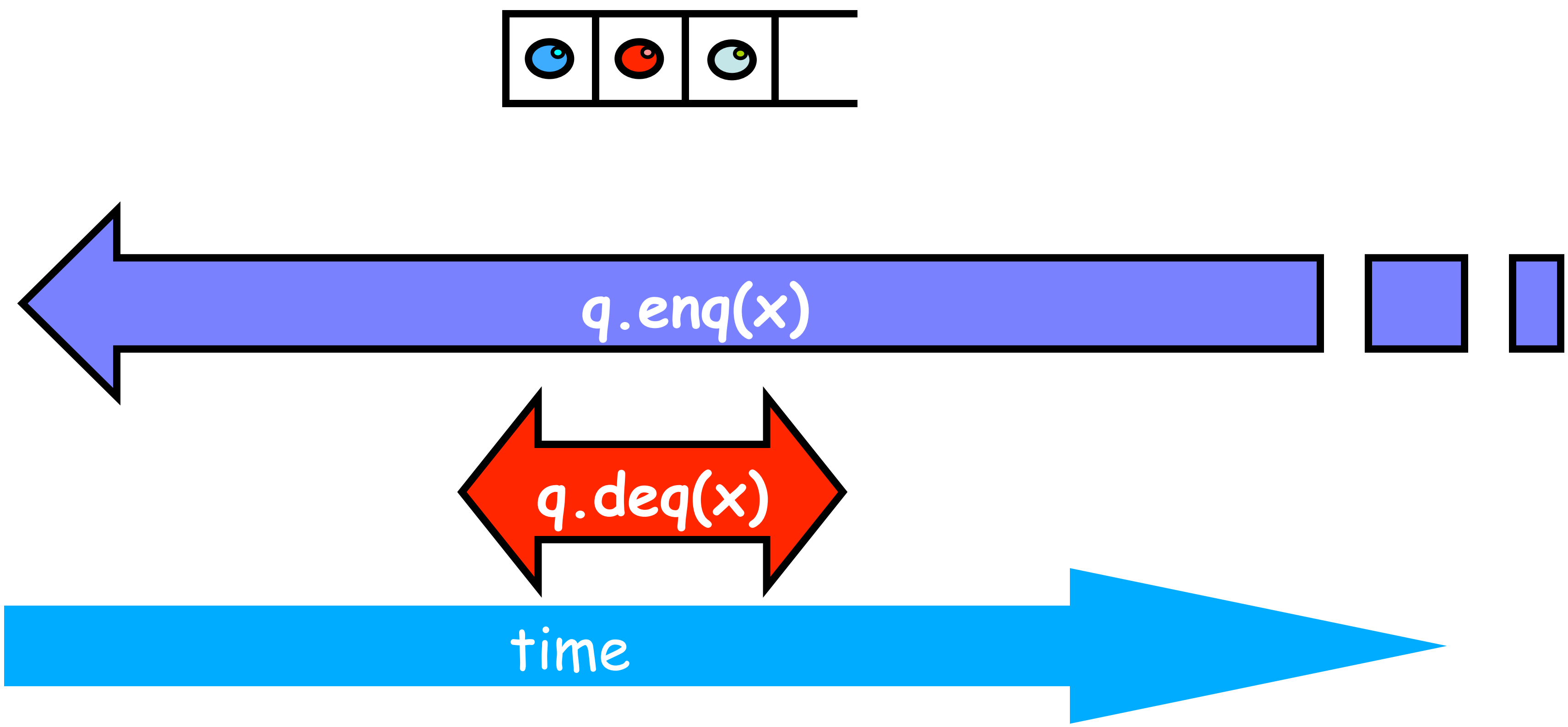

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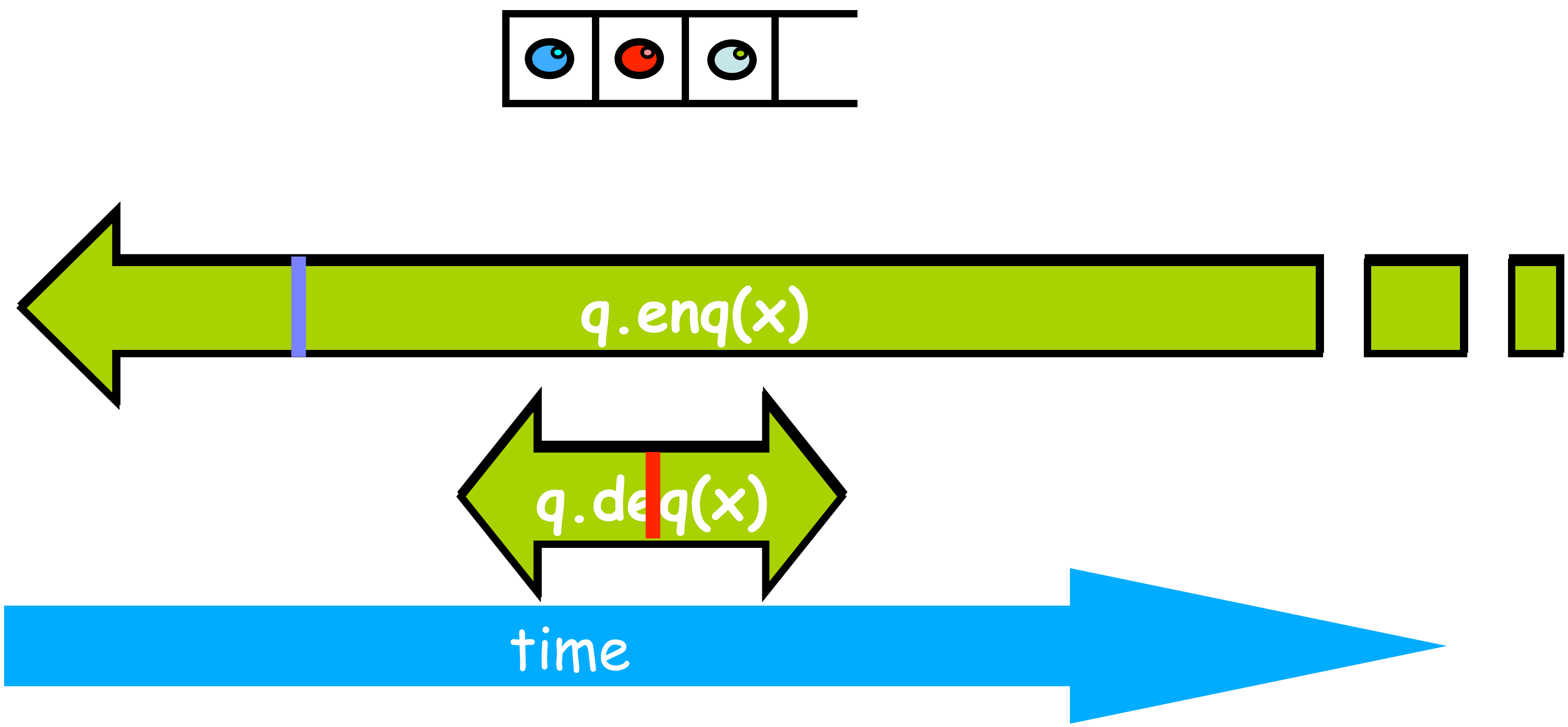

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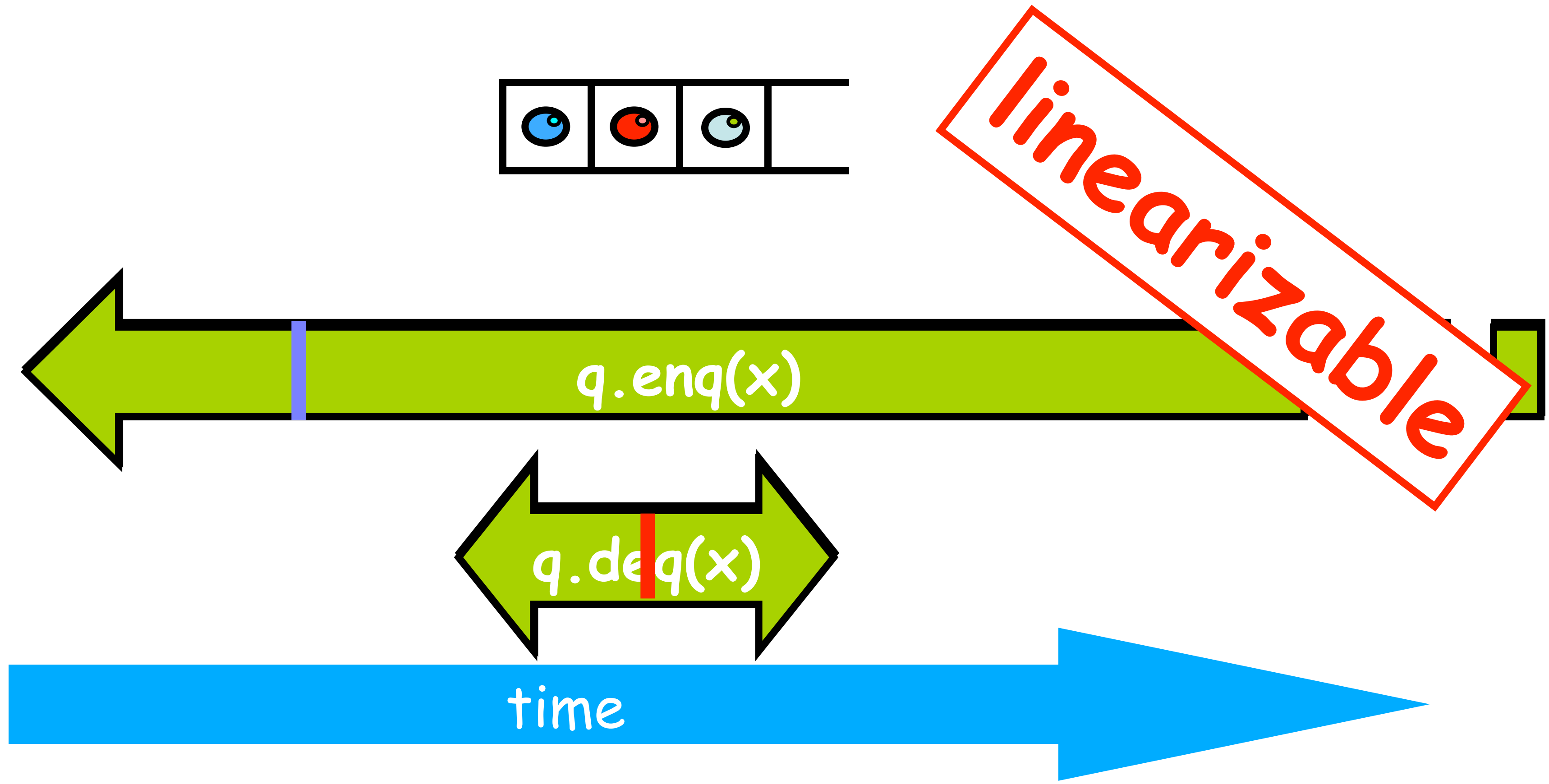

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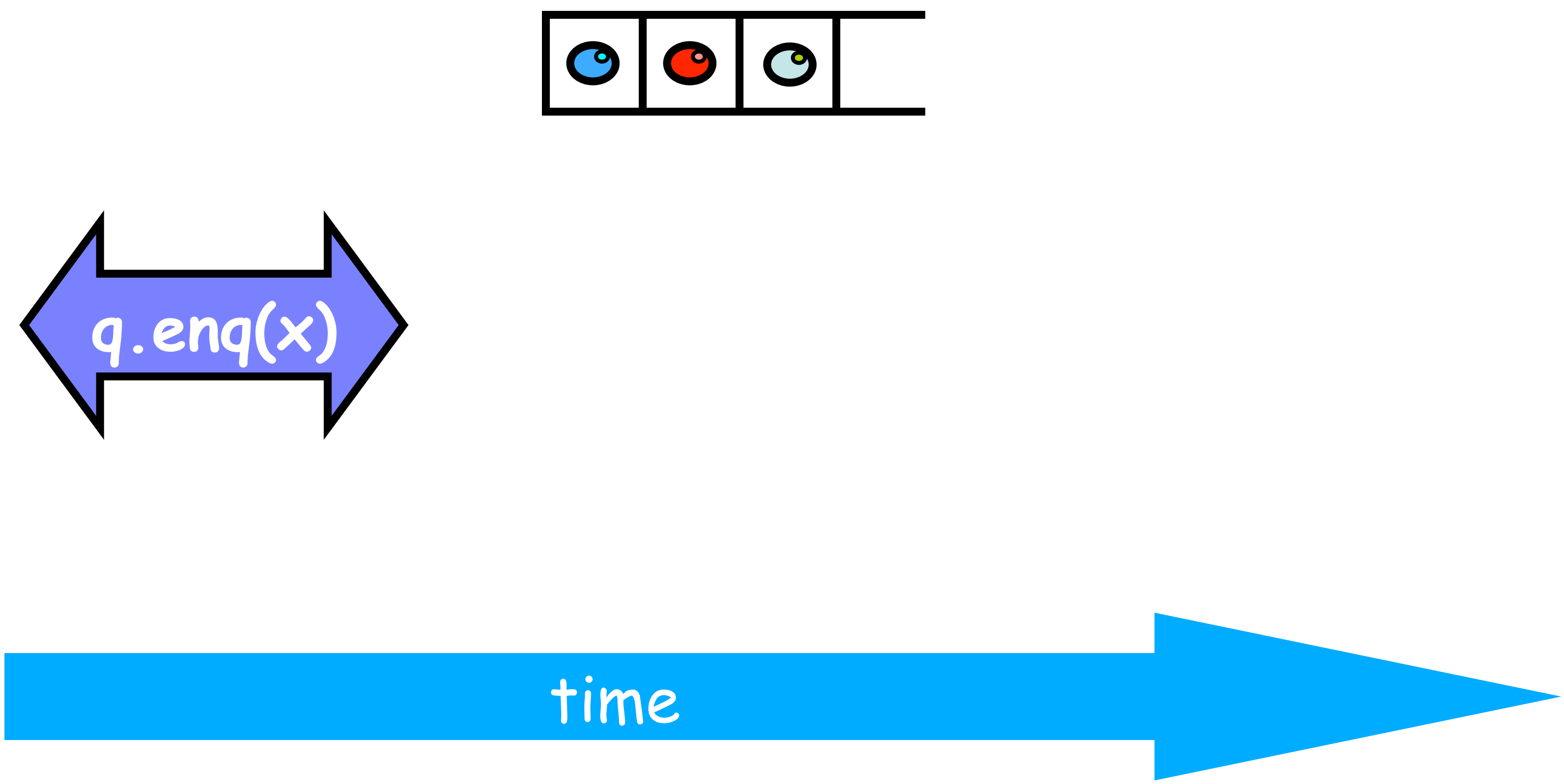

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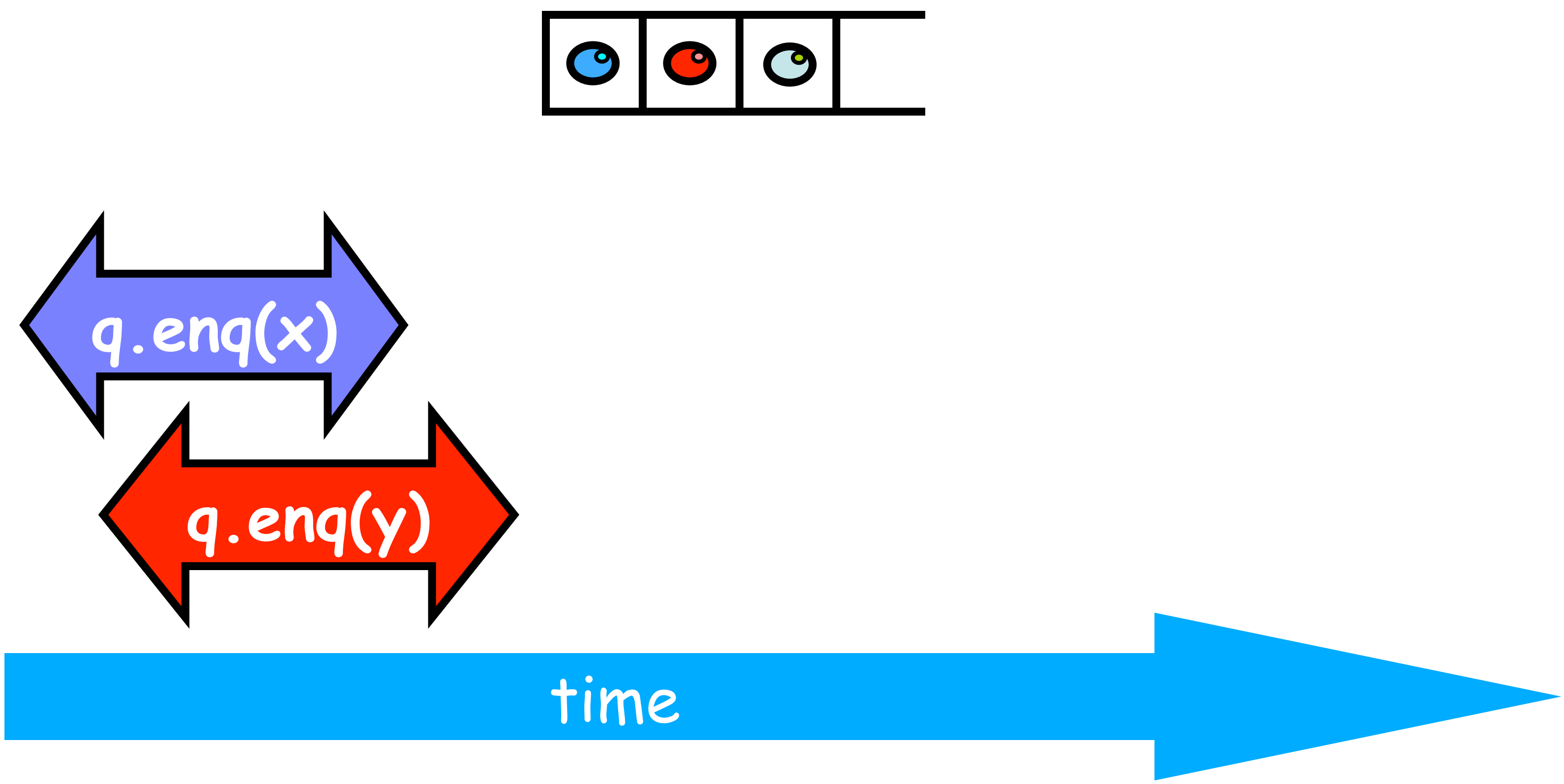

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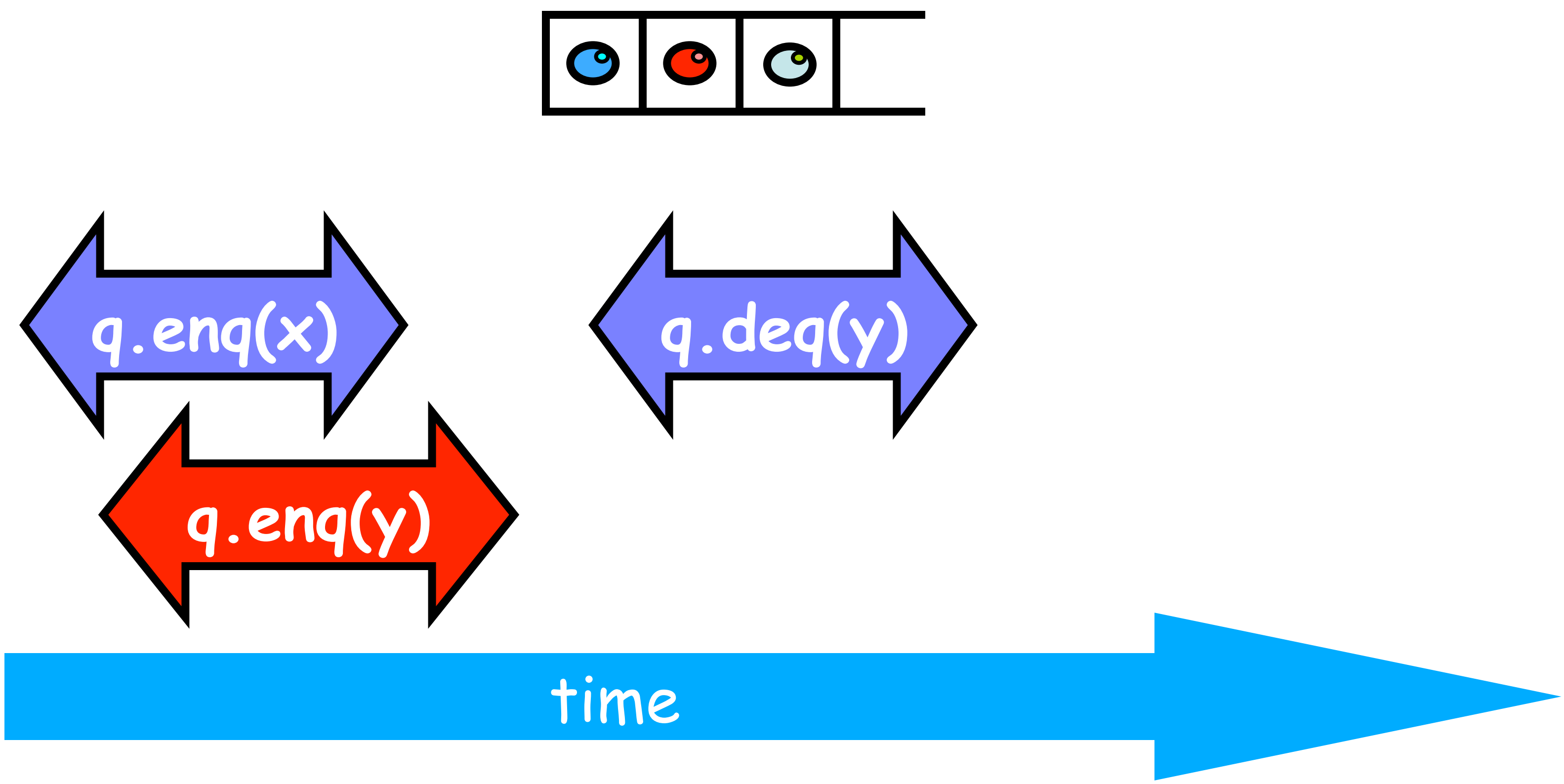

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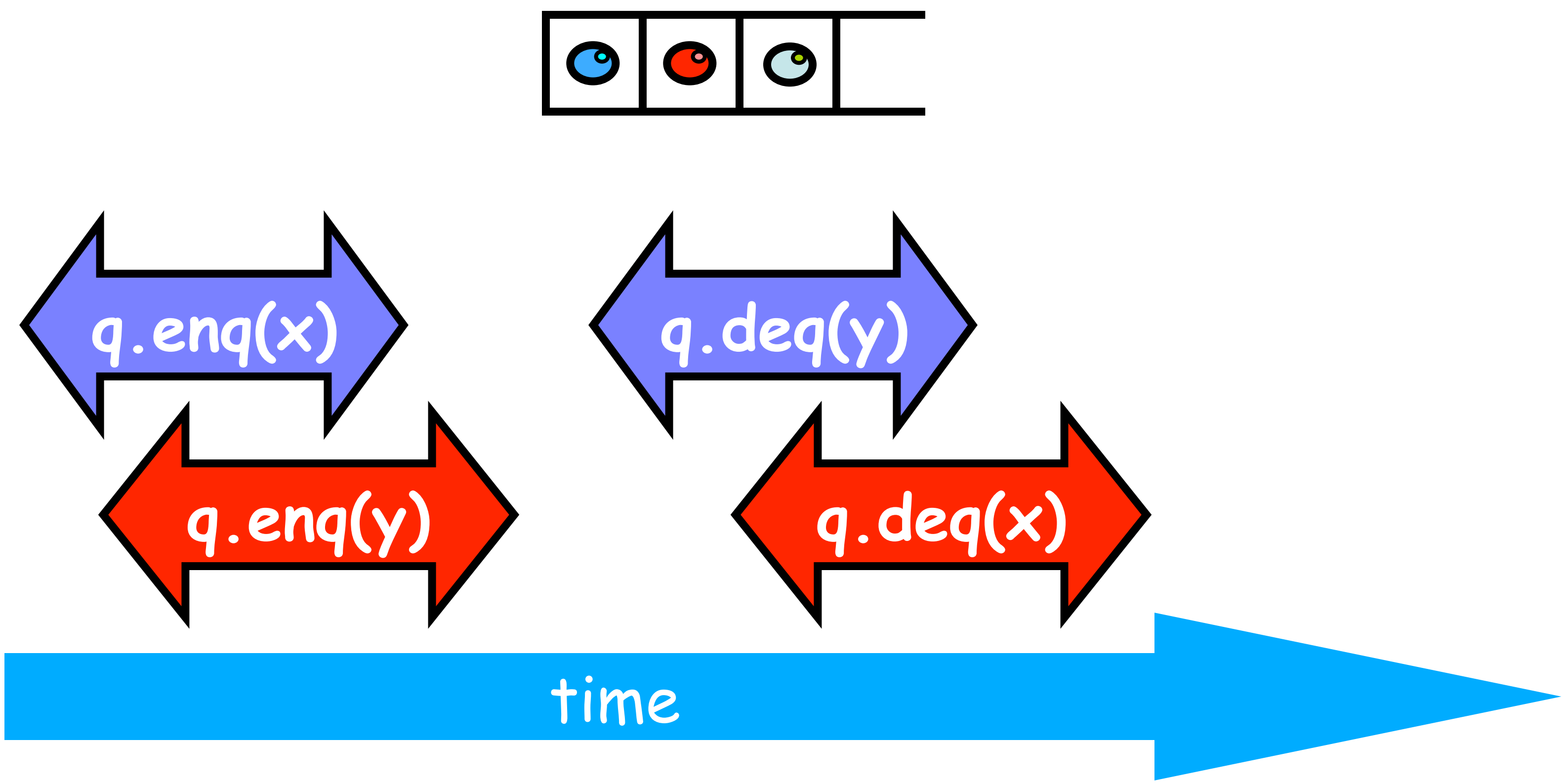

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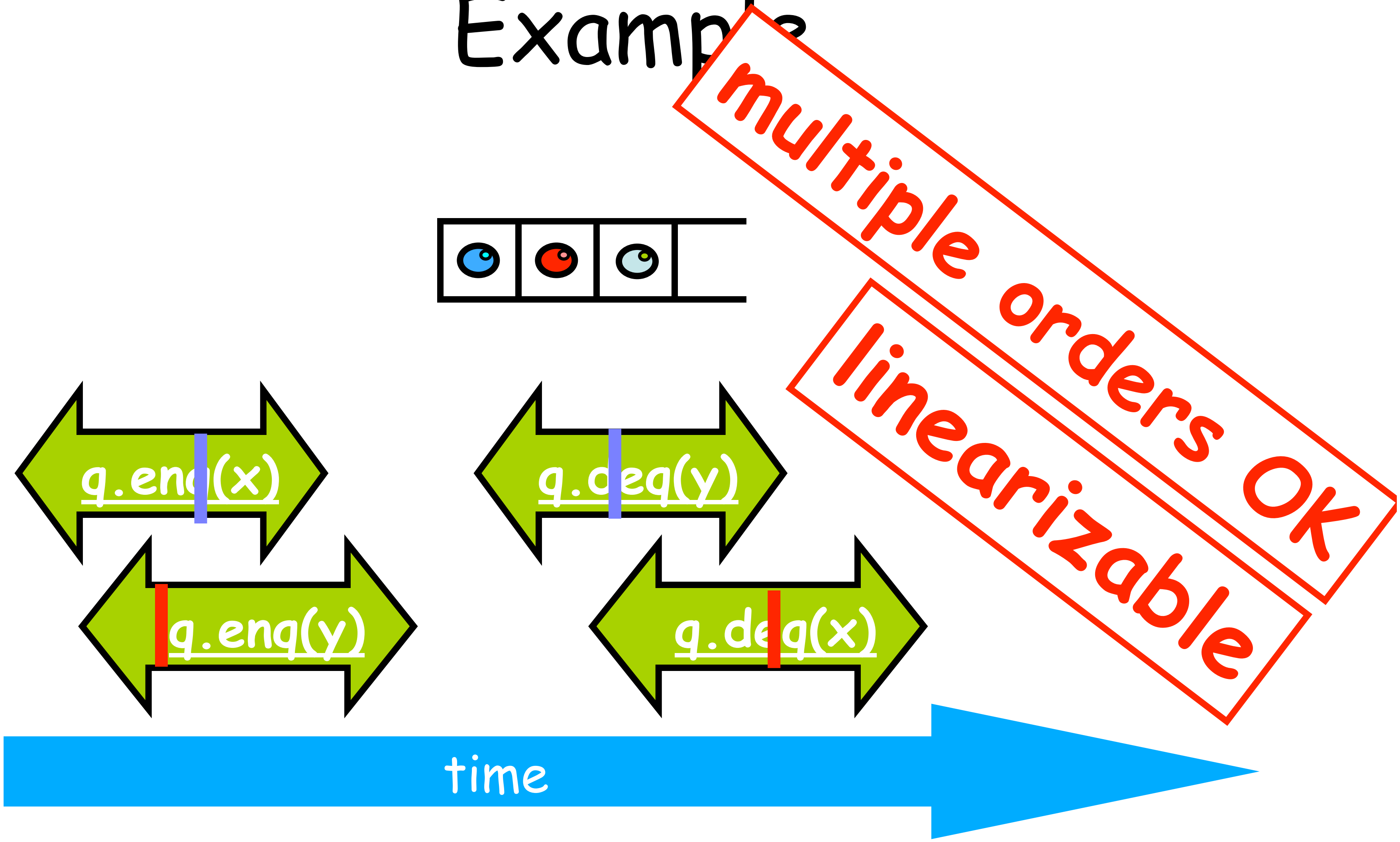
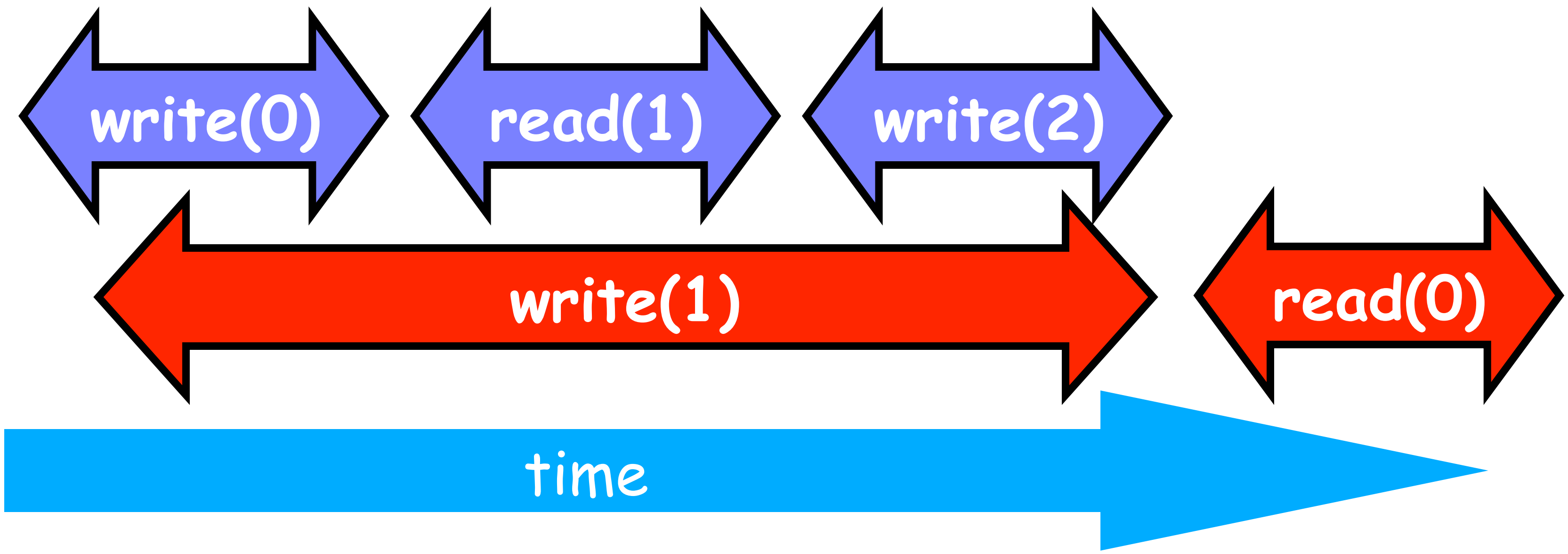

multiple orders OK
linearizable
q.enq(x)
q.enq(y)
q.deq(y)
q.deq(x)
time

Read/Write Register Example



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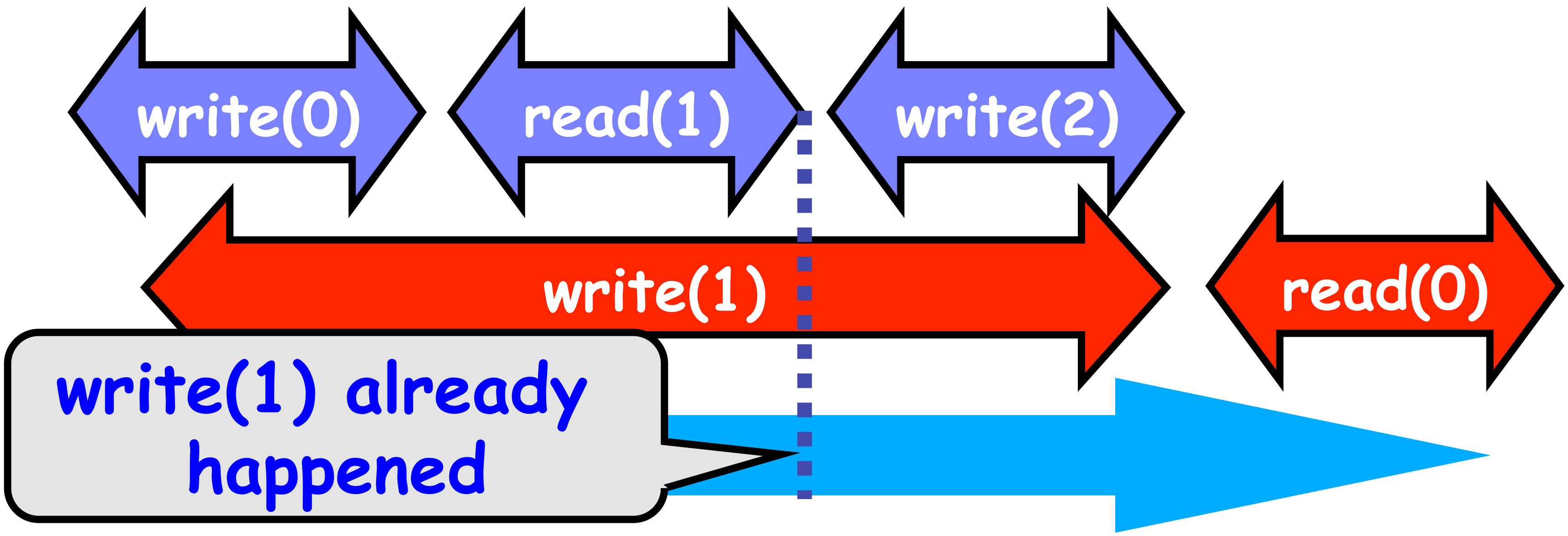
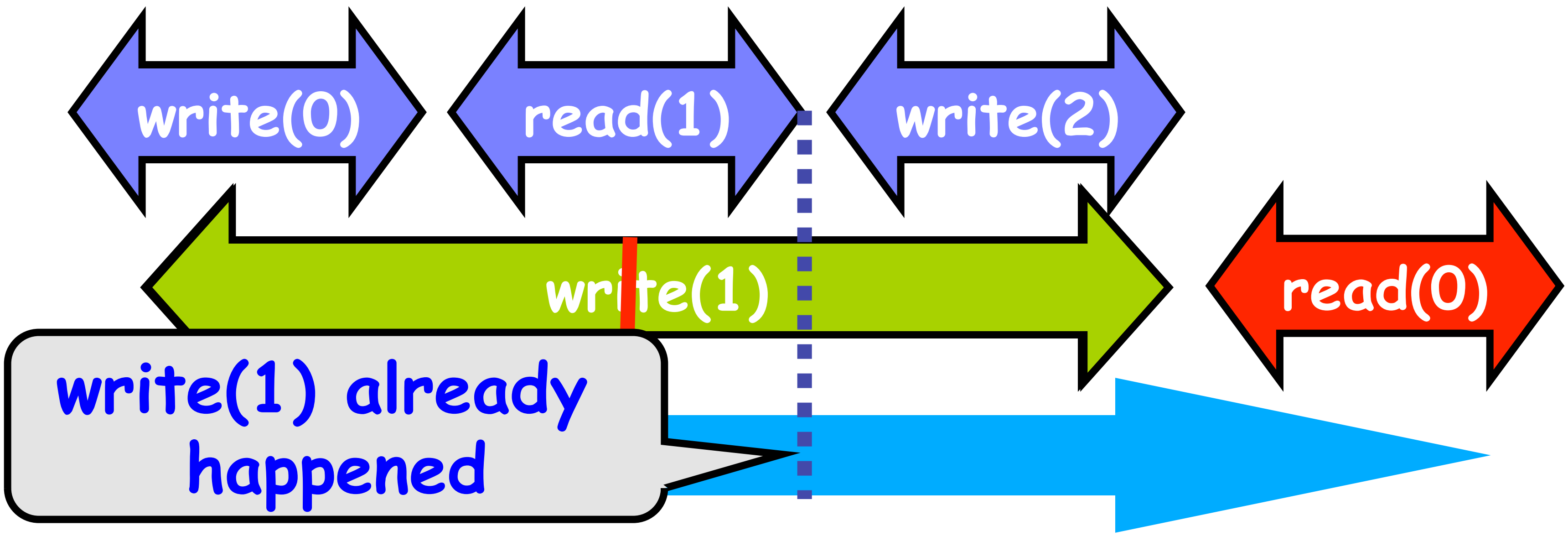
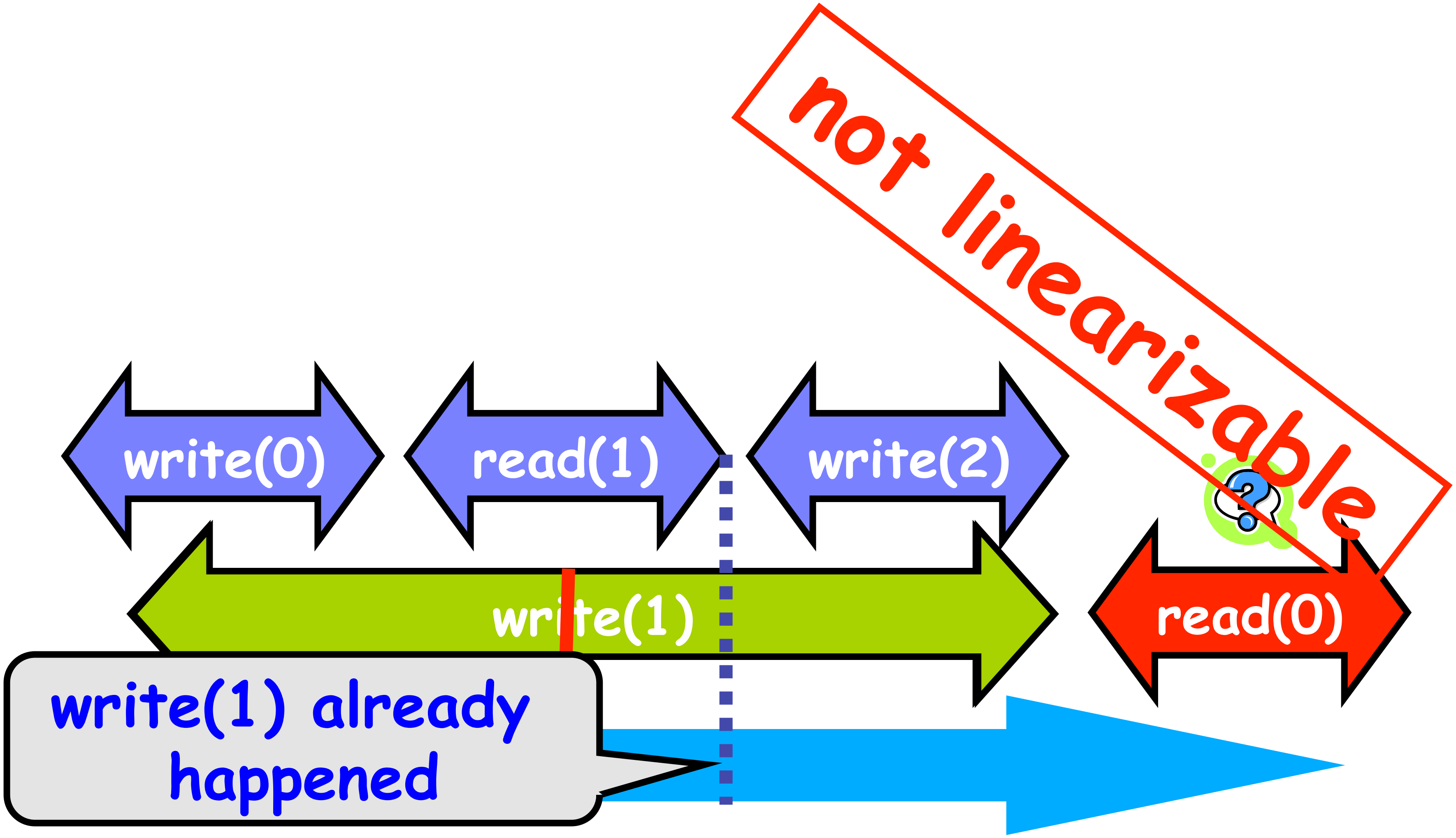


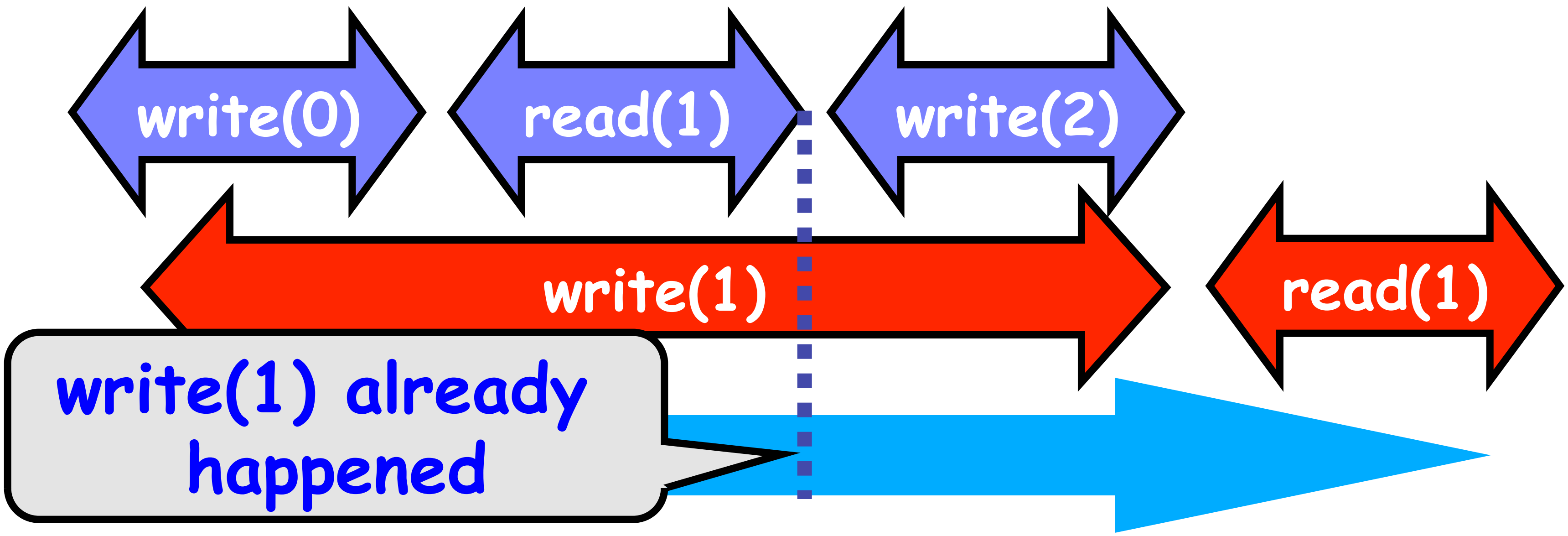
Read/Write Register Example



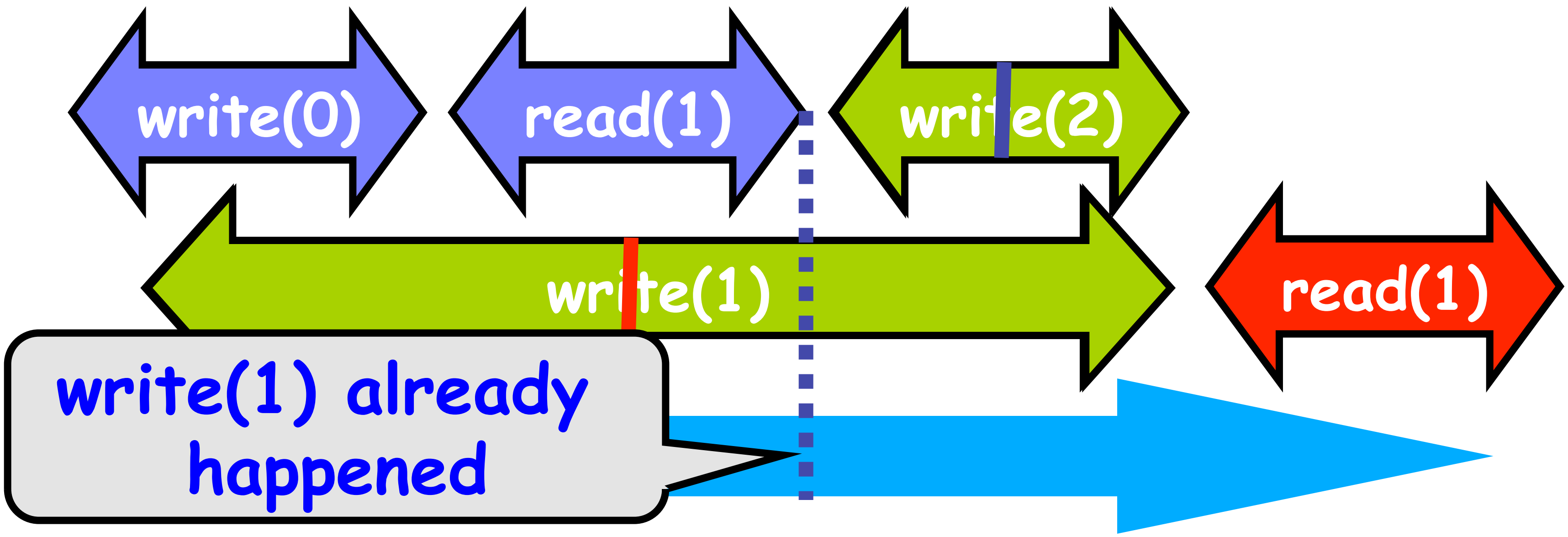
Read/Write Register Example



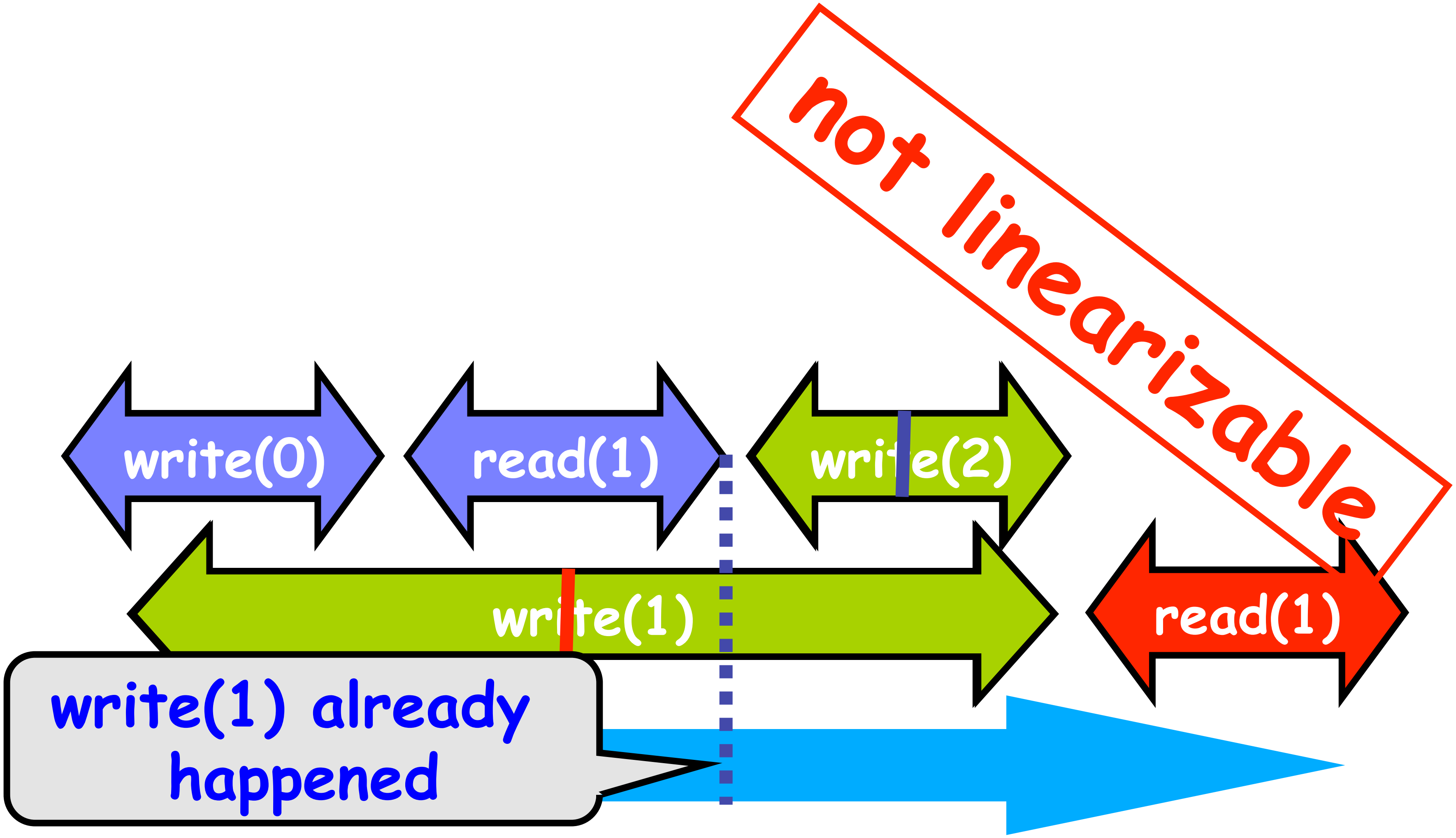
Read/Write Register Example



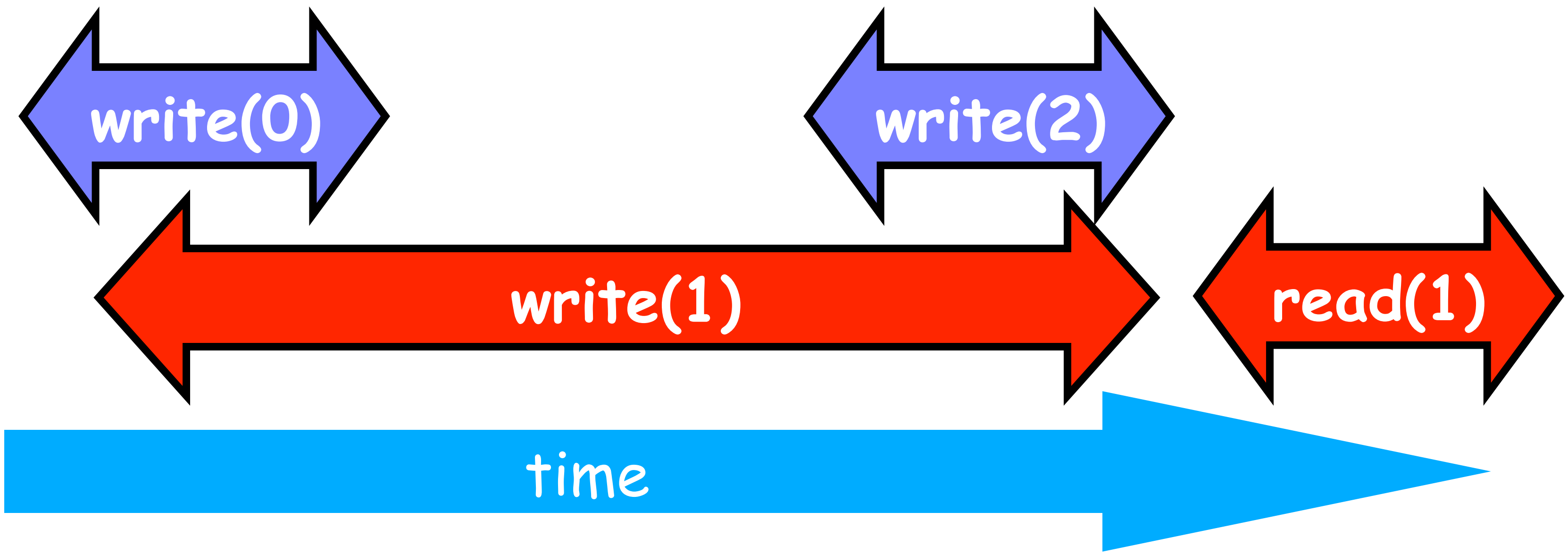
Read/Write Register Example



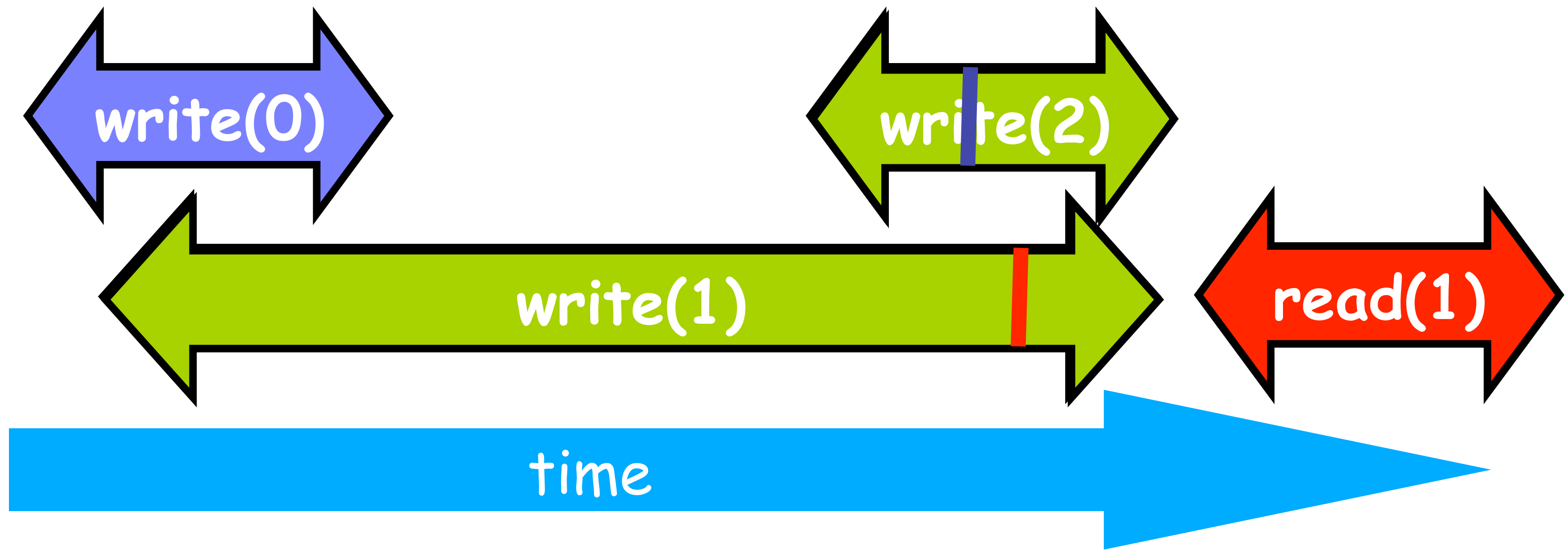
Read/Write Register Example



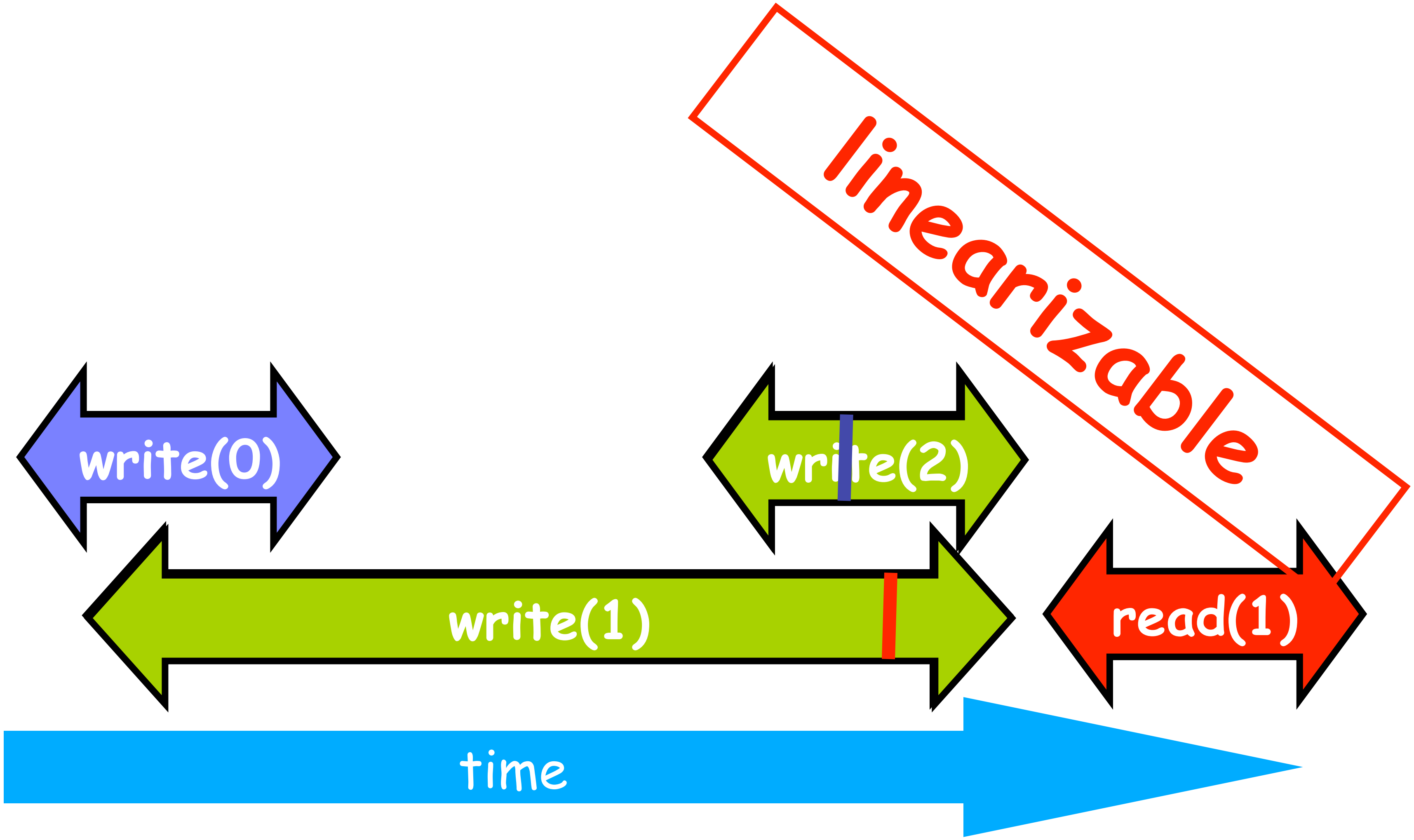
Read/Write Register Example



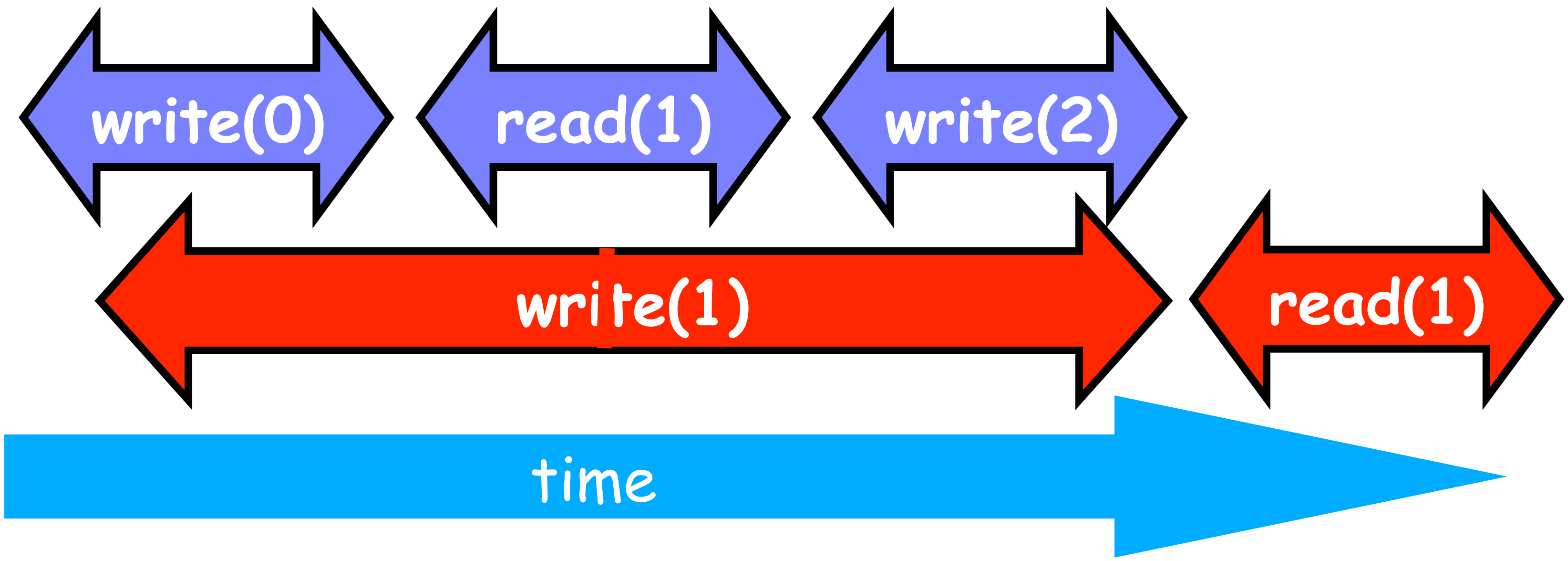
Read/Write Register Example



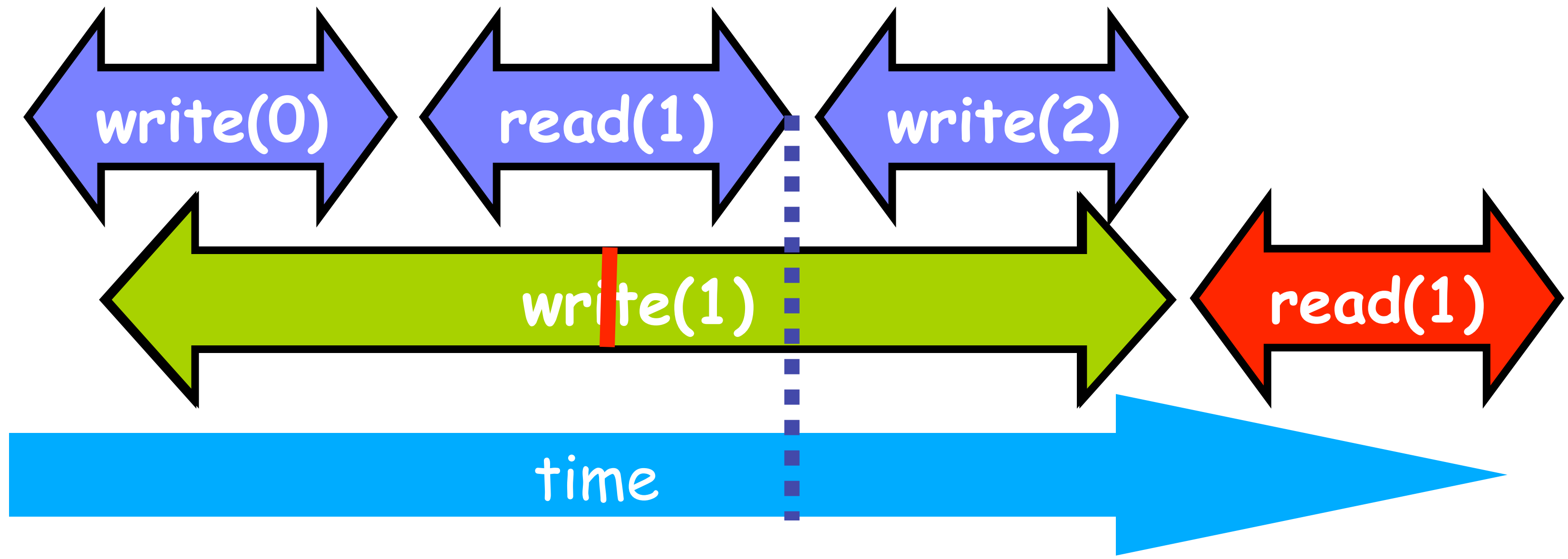
Read/Write Register Example



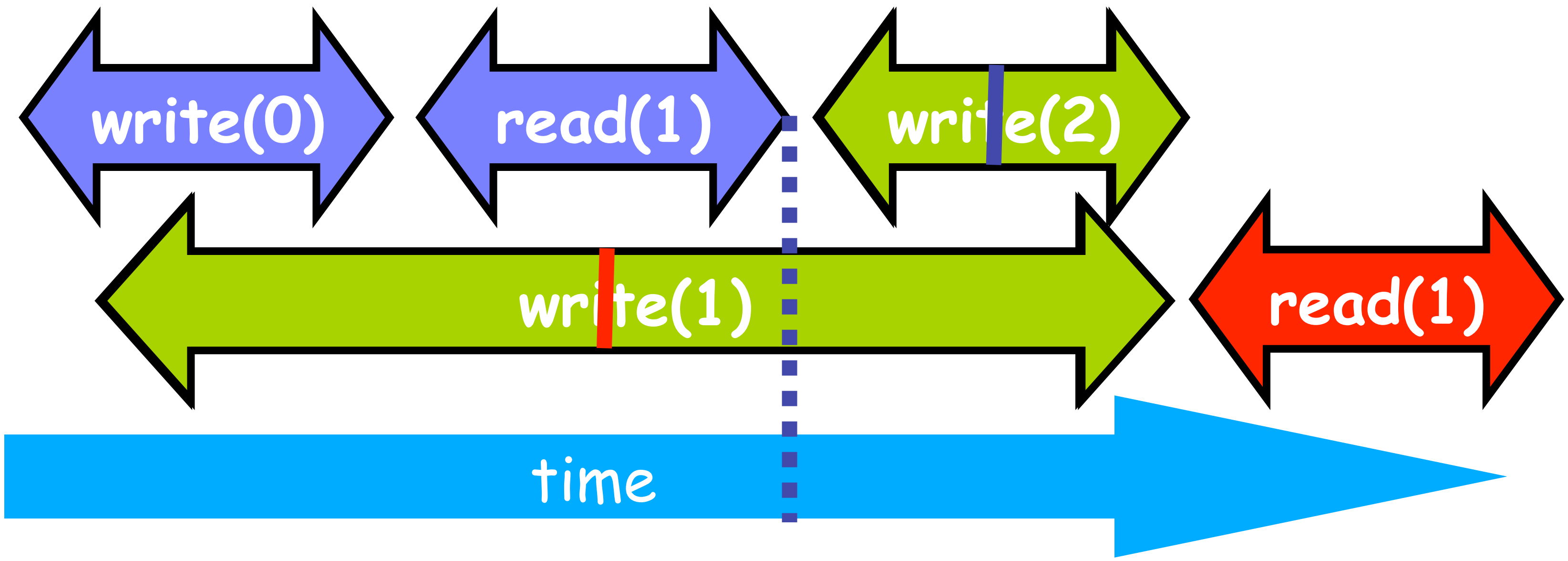
Read/Write Register Example



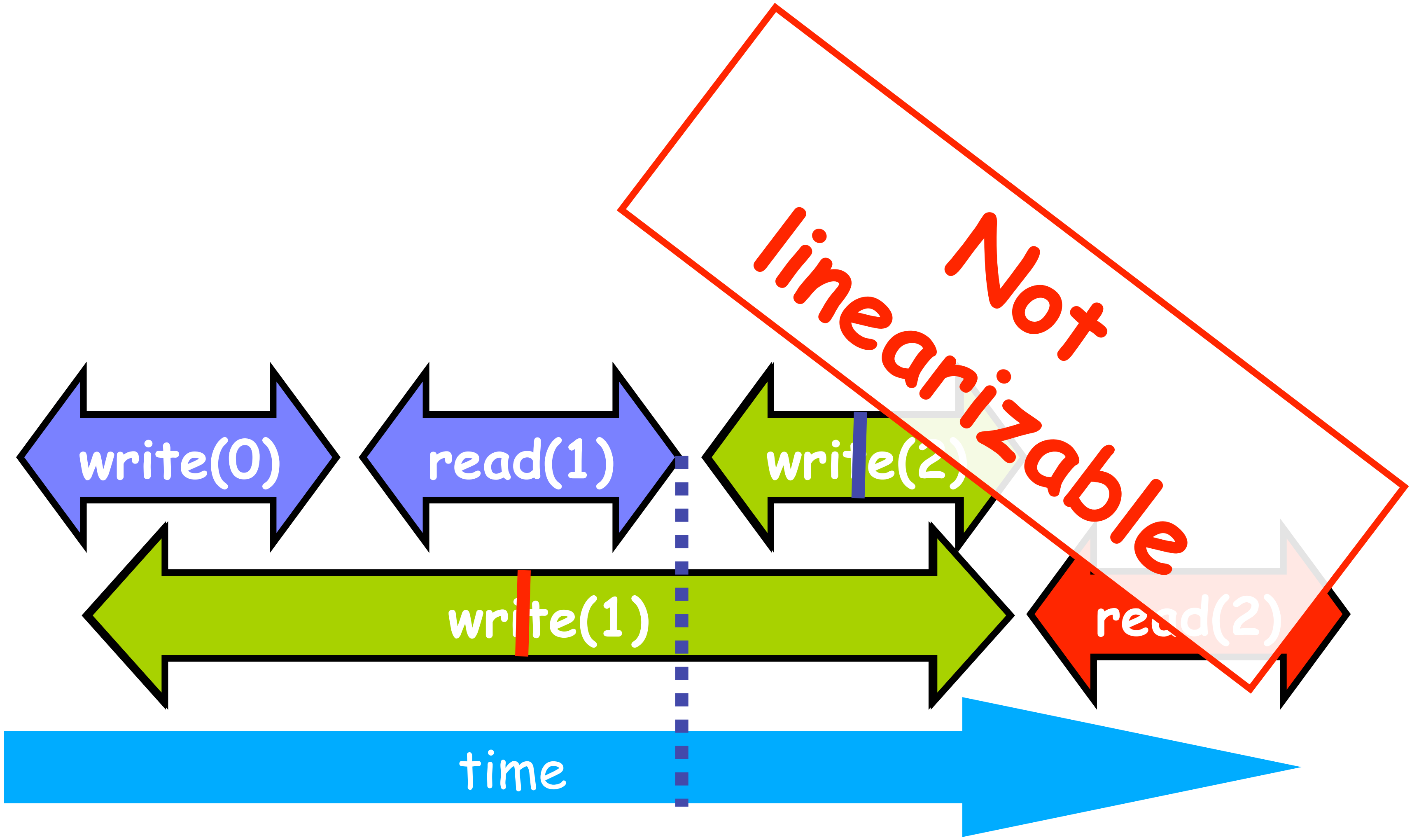
Read/Write Register Example



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

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

A q.enq(x)

thread

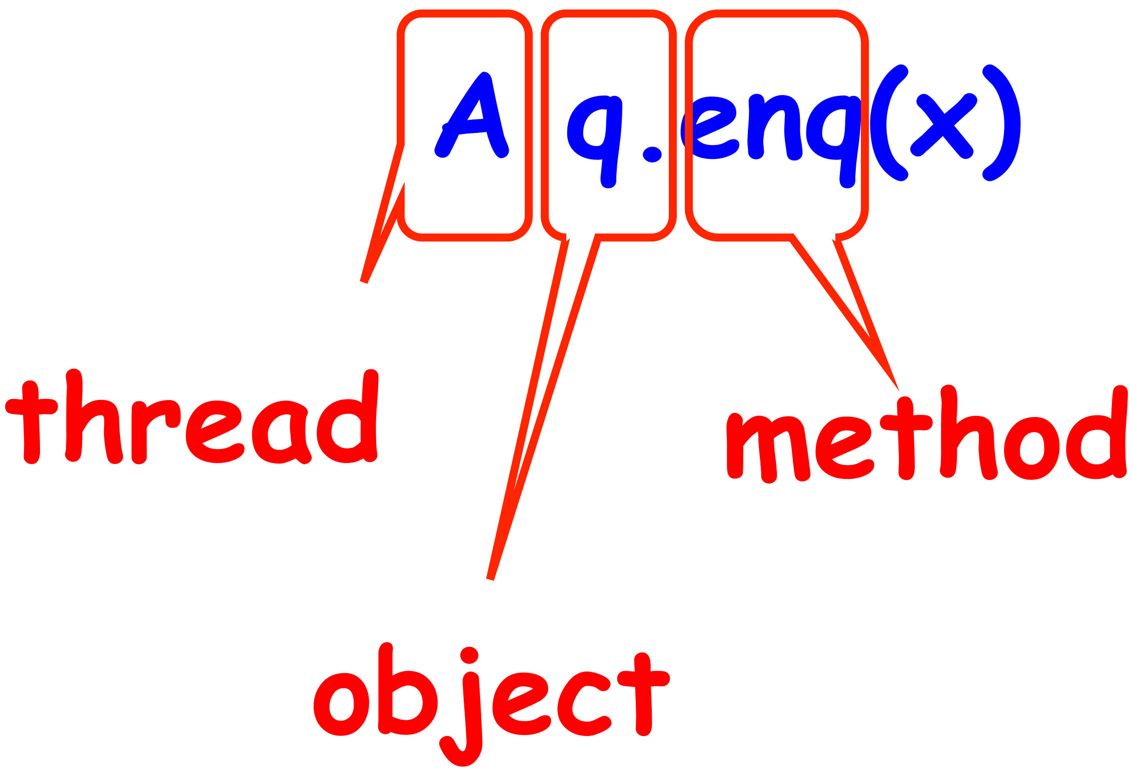
Invocation Notation

A q.enq(x)

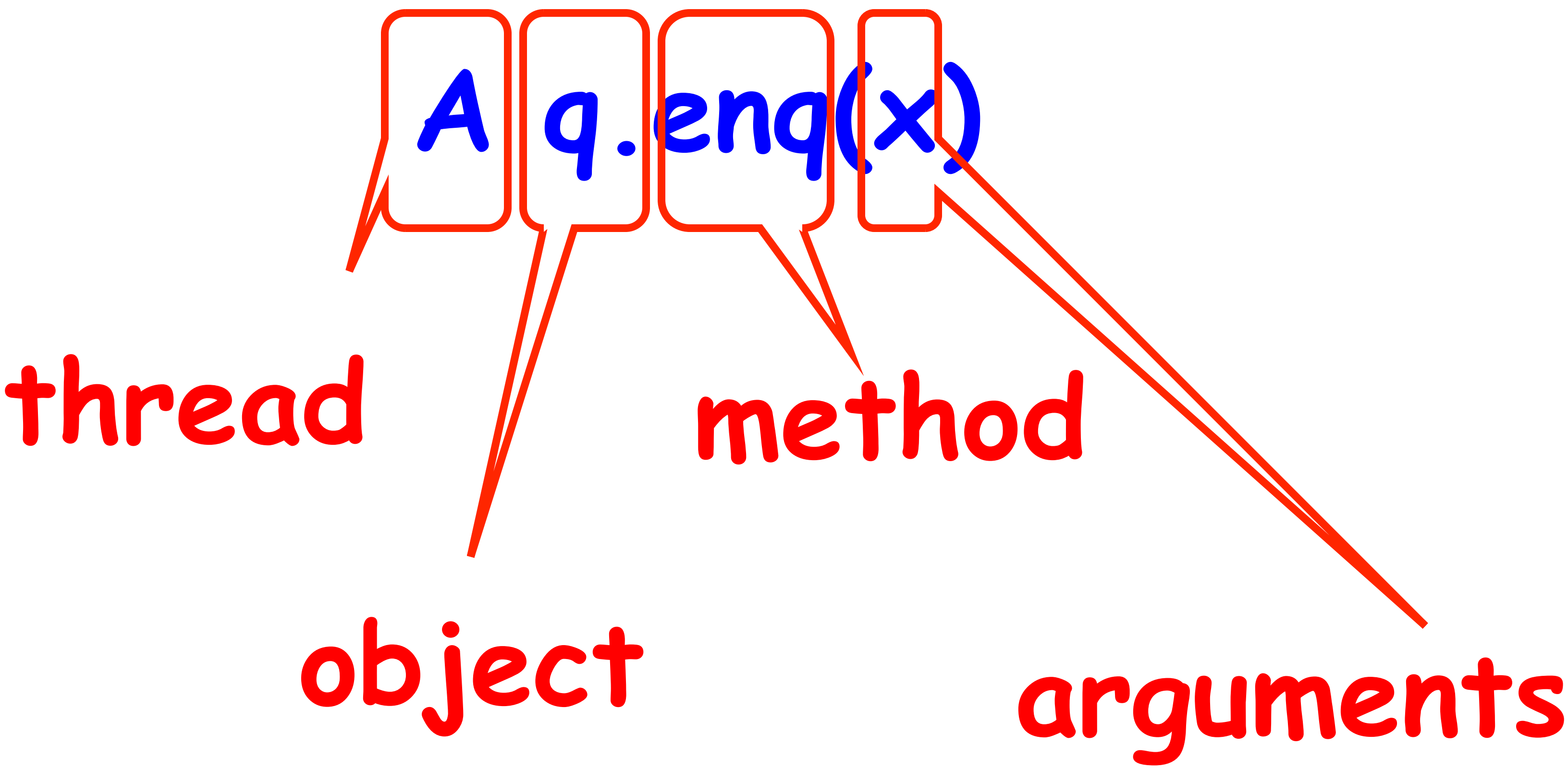
thread

method

Invocation Notation



Invocation Notation



Response Notation

A q: void

Response Notation

A q: void

thread

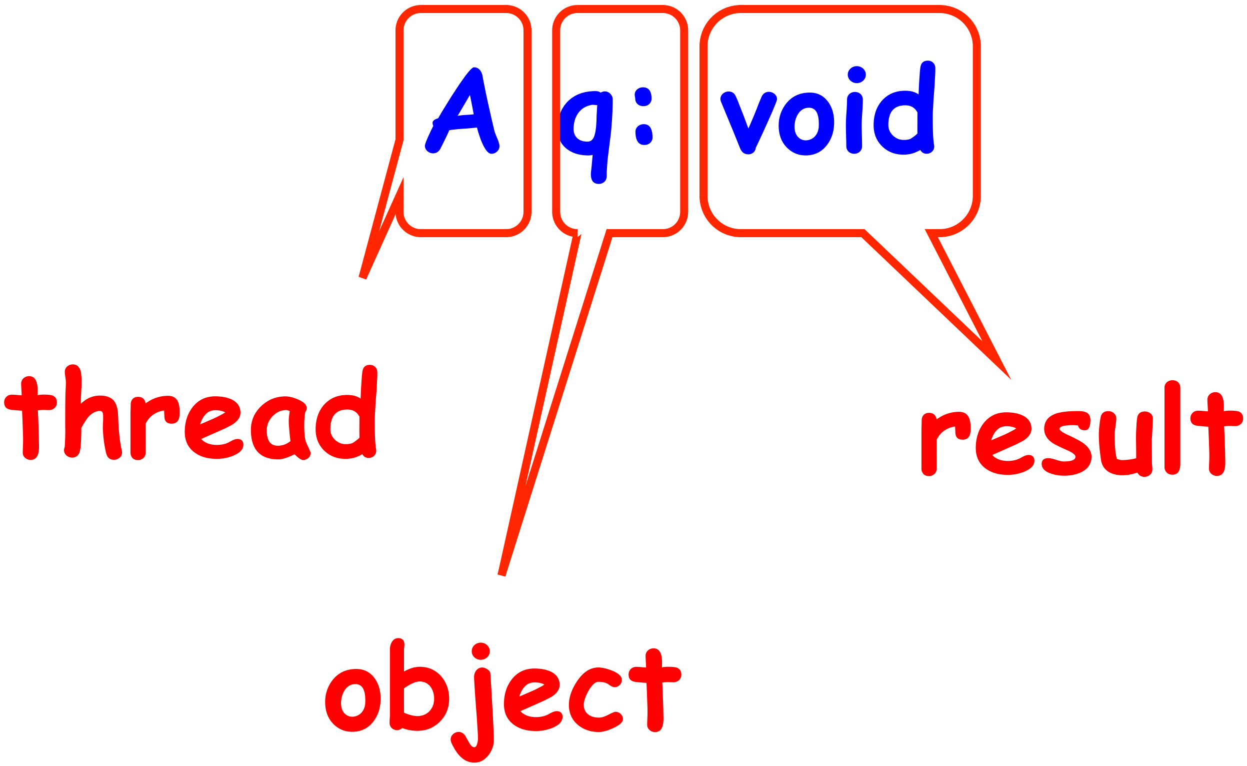
Response Notation

A q: void

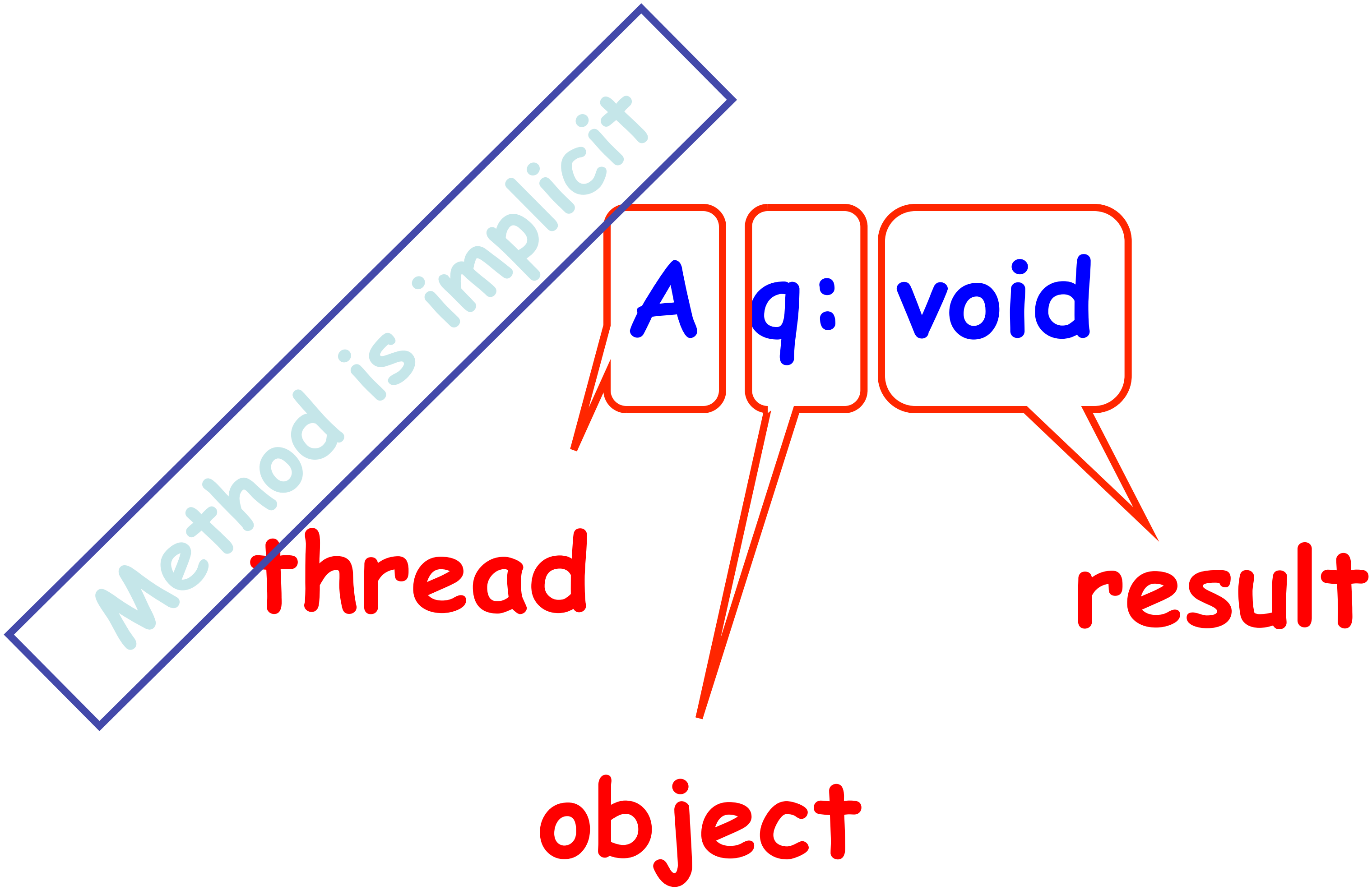
thread

result

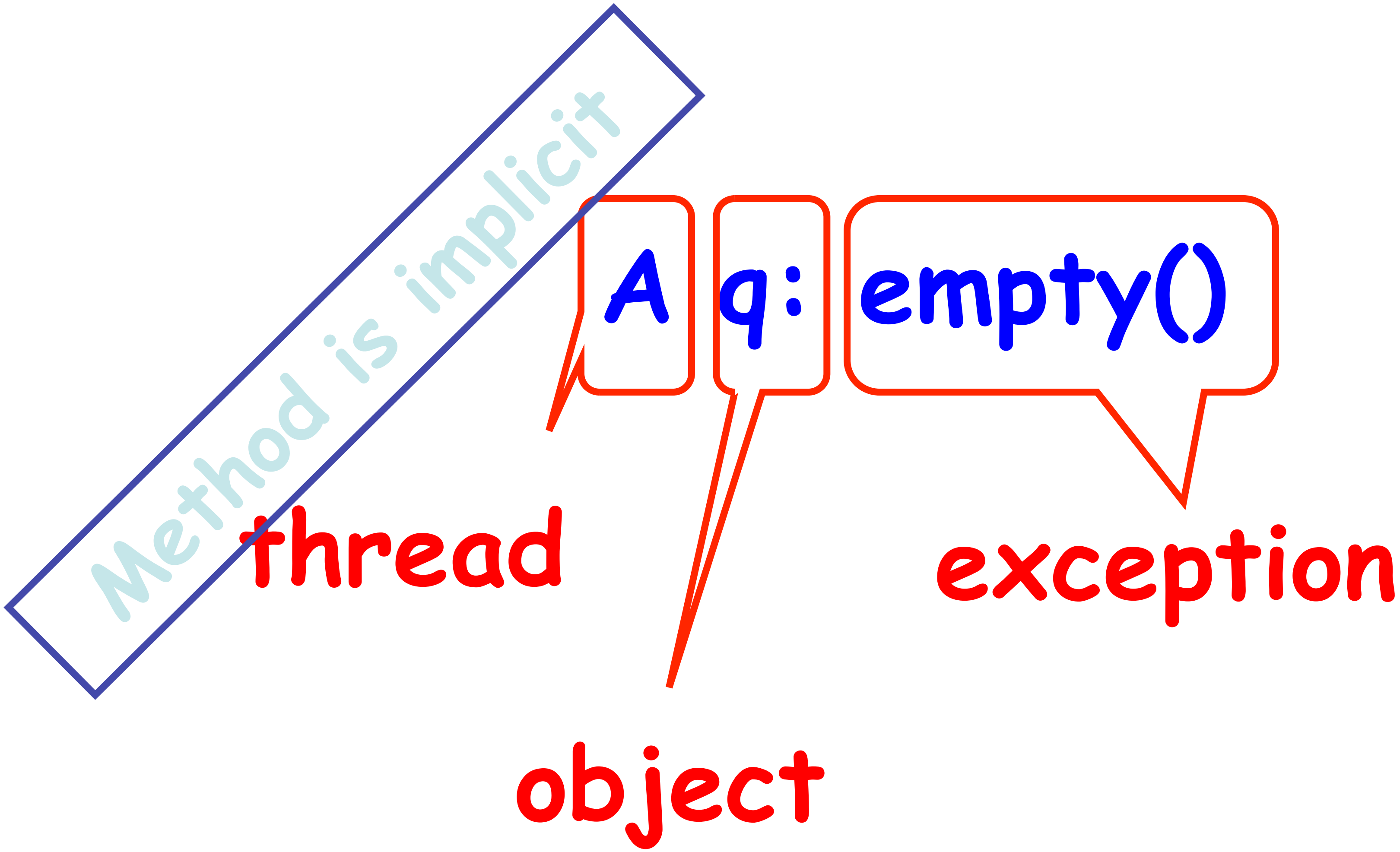
Response Notation



Response Notation



Response Notation



History - Describing an Execution

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

H = { A q:void … B q.deq() }

Sequence of invocations and responses

Definition

- 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

```
    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

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
```

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

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

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

- H|A = G|A
- H|B = G|B

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

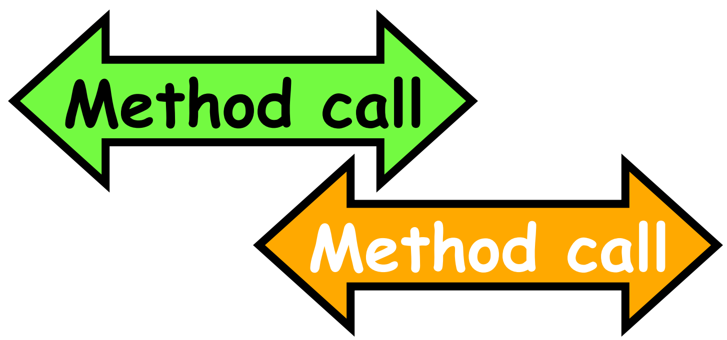
```
A q.enq(3)
B p.enq(4)
B p.void
A q:void
B q.deq()
B q:3
```

A method call **precedes** another if response event precedes invocation event

Non-Precedence

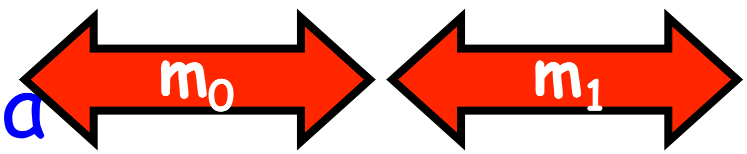
```
A q.enq(3)
B p.enq(4)
B p.void
B q.deq()
A q:void
B q:3
```

Some method calls **overlap** one another



Notation

- Given
  - History **H**
  - method executions **m_0** and **m_1** in **H**
- We say $m_0 \rightarrow_H m_1$, if
  - **m_0** precedes **m_1**
- Relation **$m_0 \rightarrow_H m_1$** is a
  - Partial order
  - Total order if **H** is sequential

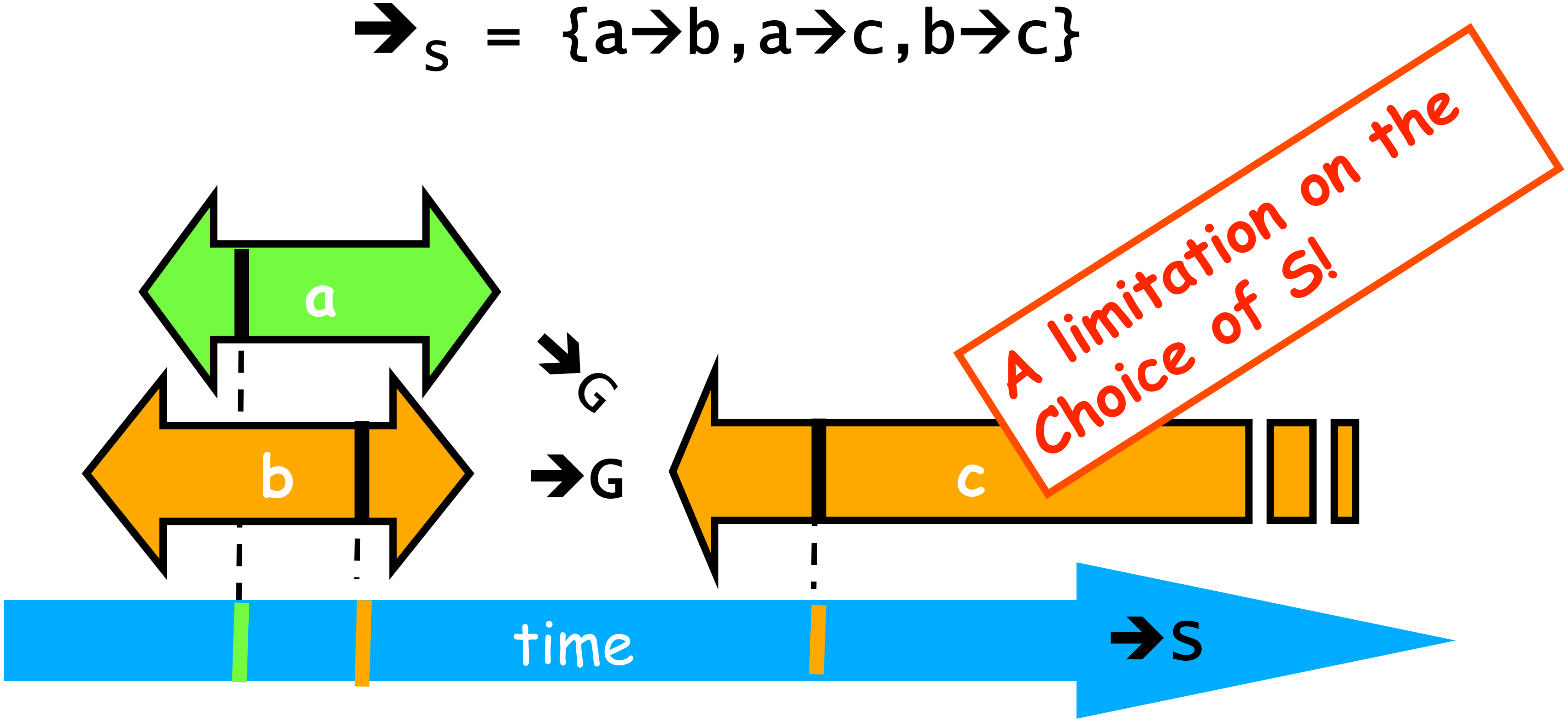


Linearizability

- 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 $\rightarrow_G \subset \rightarrow_S$

What is $\rightarrow_G \subset \rightarrow_S$

$\rightarrow_G$ = {a→c,b→c}
$\rightarrow_S$ = {a→b,a→c,b→c}

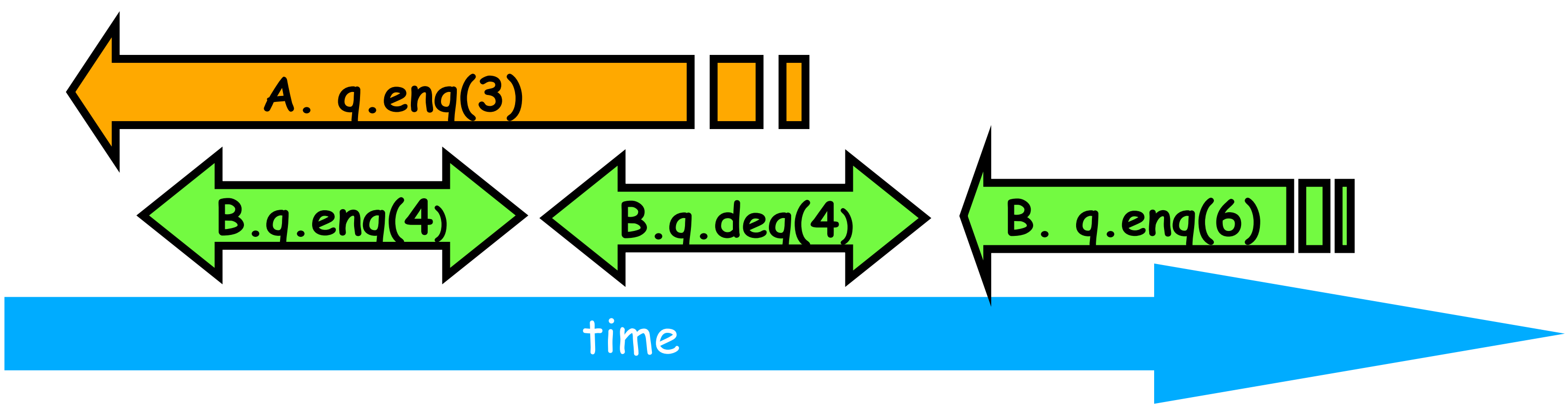


Remarks

- 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**

Example

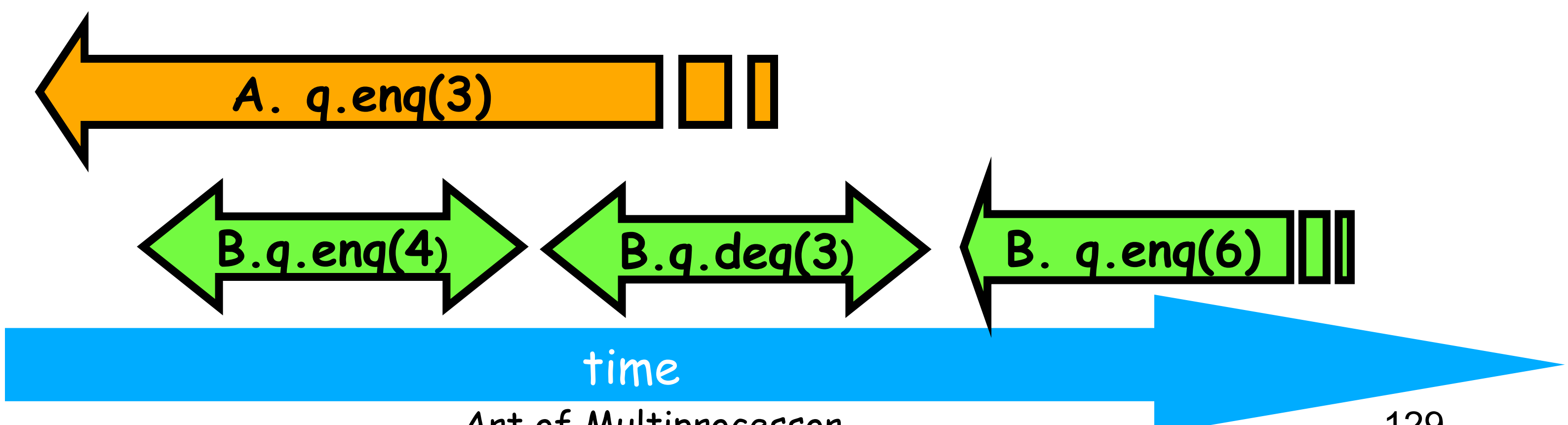
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
B q:enq(6)
```



Example

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

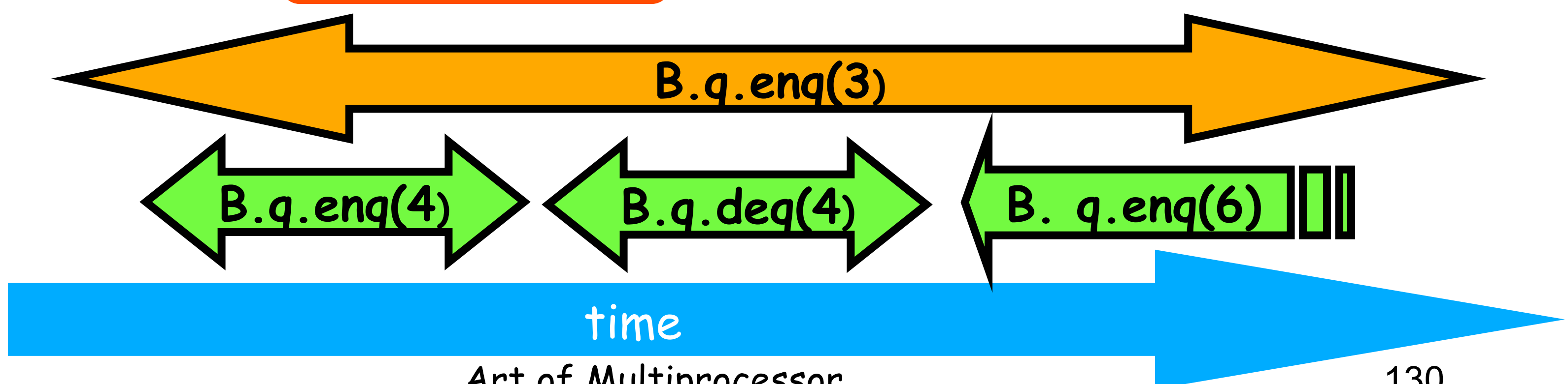
Complete this pending invocation



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
```

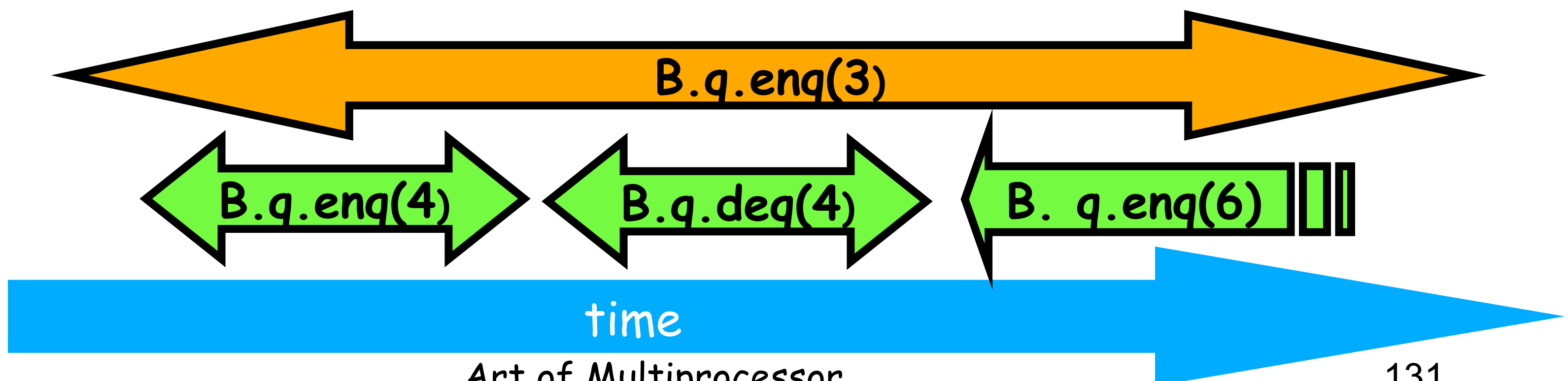
Complete this pending invocation



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
```

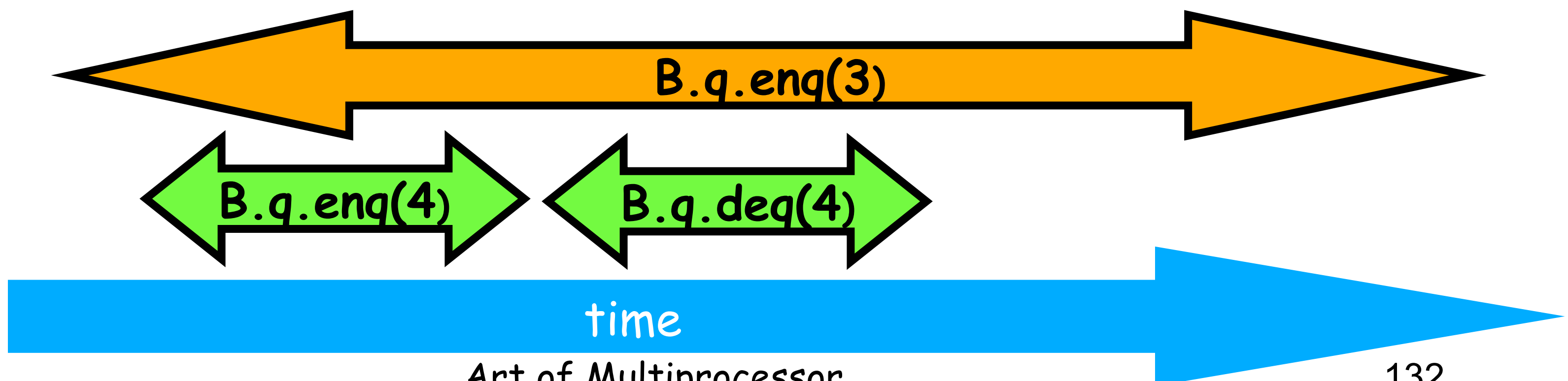
discard this one (refers to: B q:enq(6))



Example

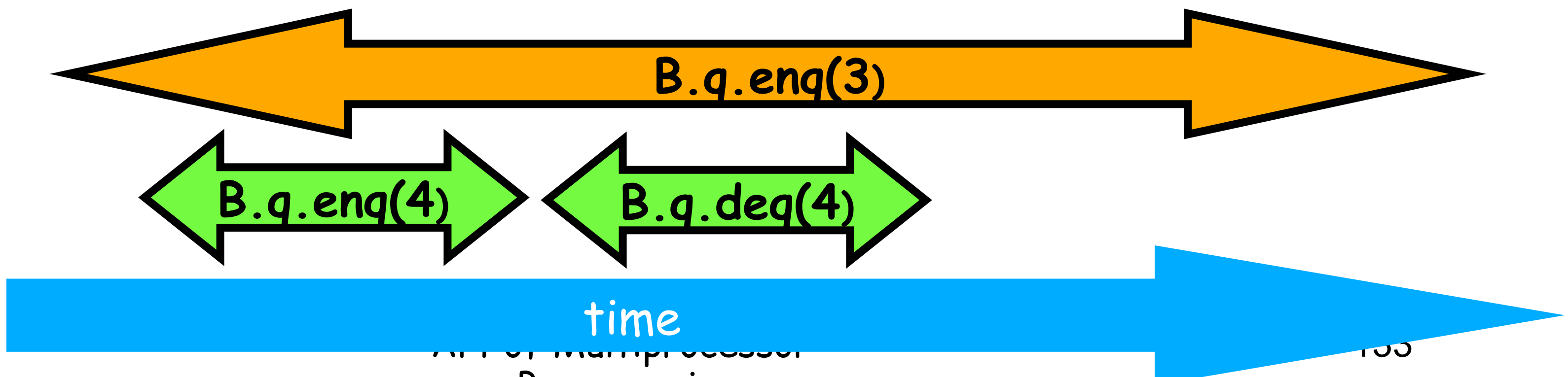
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4

A q:void
```

discard this one



Example

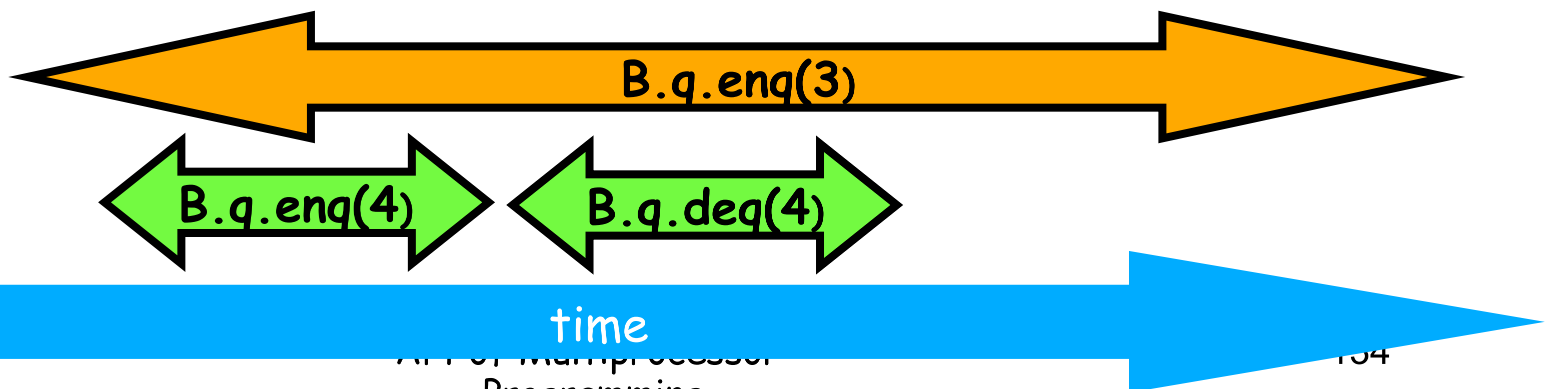
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
A q:void
```



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
```

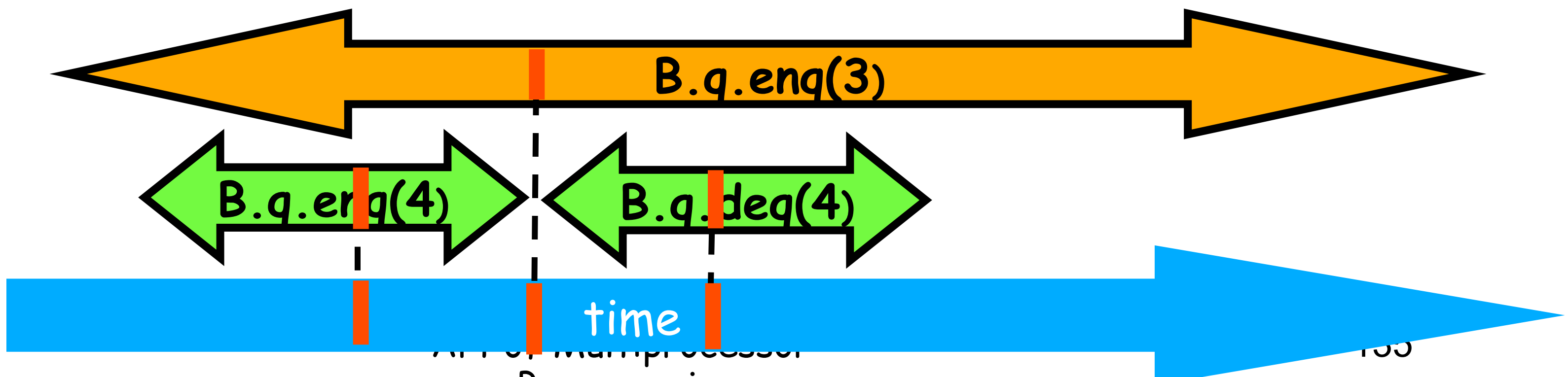


Example

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



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***.

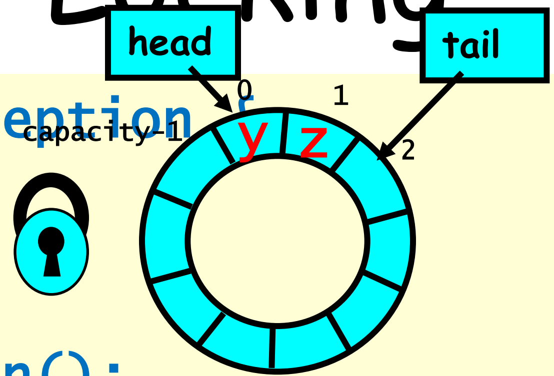
Composability Theorem

- History H is linearizable if and only if
  - For every object x
  - H|x is linearizable

Why Does Composability Matter?

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

Reasoning About Lineraizability: Locking



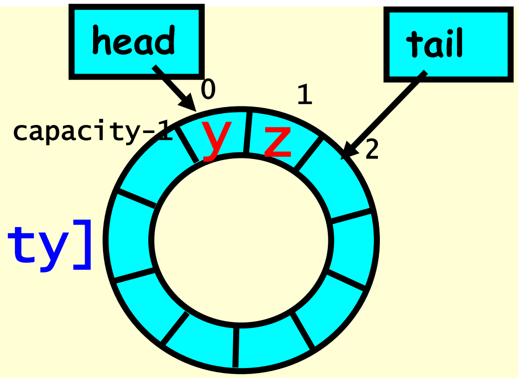

```
public T deq() throws EmptyException {
  lock.lock();
  try {
    if (tail == head)
       throw new EmptyException();
    T x = items[head % items.length];
    head++;
    return x;
  } finally {
    lock.unlock();
  }
}
```

Reasoning About Lineraizability: 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: Lock-free




```
public class LockFreeQueue {

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

  public void enq(Item x) {
    while (tail-head == capacity); // busy-wait
    items[tail % capacity] = x; tail++;
  }
  public Item deq() {
     while (tail == head);     // busy-wait
     Item item = items[head % capacity]; head++;
     return item;
}}
```

More Reasoning

```
public cla... ...FreeQ

  int ... ...ail = ...
  i... ... new Ob...

  ...oid enq(Item x) {
    ...le (tail-head == capacity); // busy-wait
    ...tems[tail % capacity] = x; tail++;
  }
  public Item deq() {
     while (tail == head);     // busy-wait
     Item item = items[head % capacity]; head++;
     return item;
}}
```

Remember that there is only one enqueuer and only one dequeuer

Linearization order is order head and tail fields modified

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"
- There is a lot of ongoing research in verification community to build tools that can verify/debug concurrent implementations wrt linearizability

Alternative: Sequential Consistency

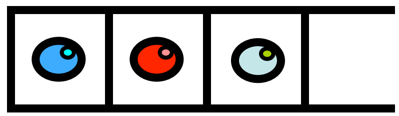
- History H is ***Sequentially Consistent*** if it can be extended to **G** by
  - Appending zero or more responses to pending invocations
  - Discarding other pending invocations
- So that G is equivalent to a
  - Legal sequential history **S**
  - ~~Where $\rightarrow_G \subset \rightarrow_S$~~

Differs from linearizability

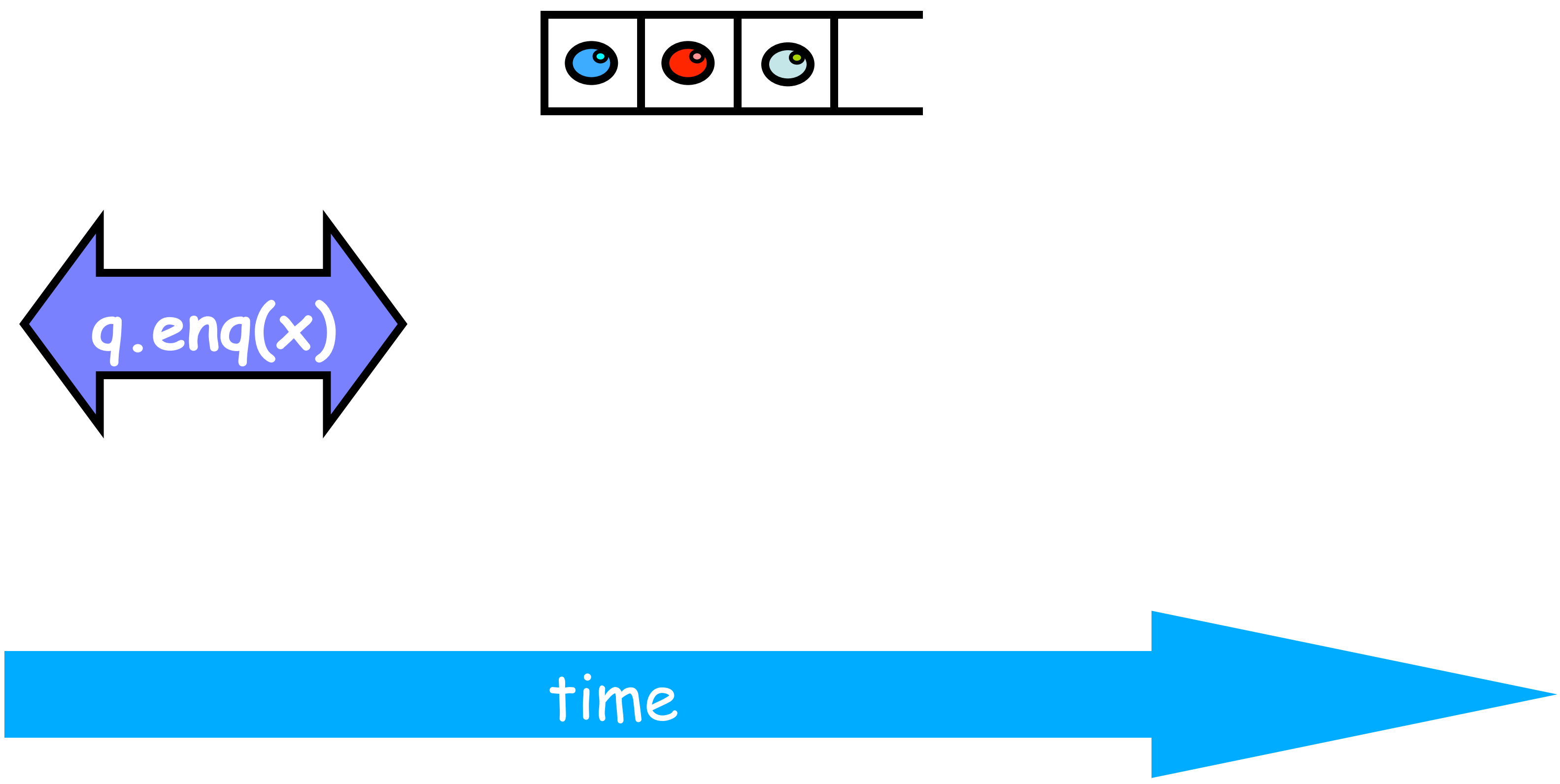
Alternative: Sequential Consistency

- 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

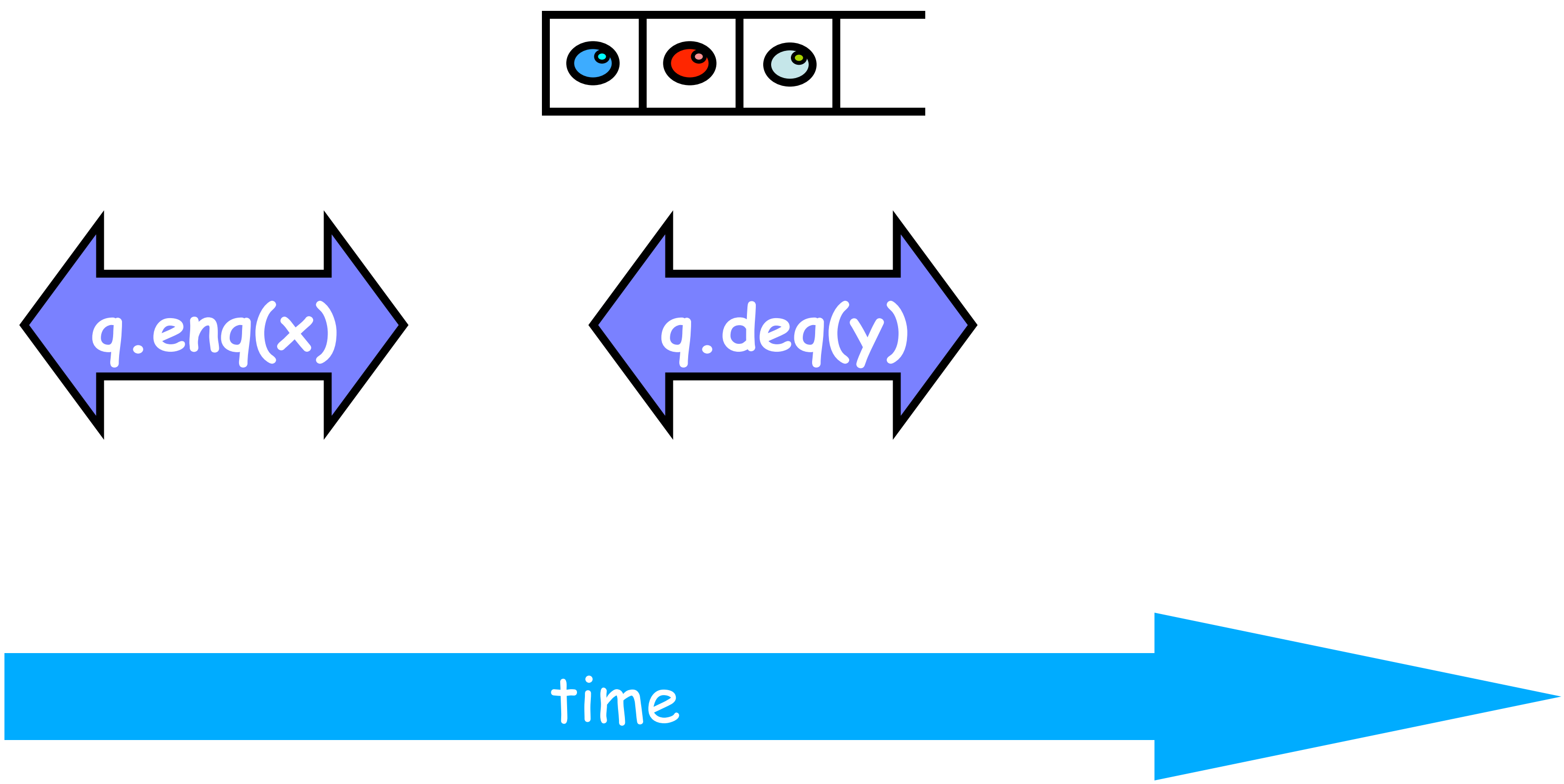
Example



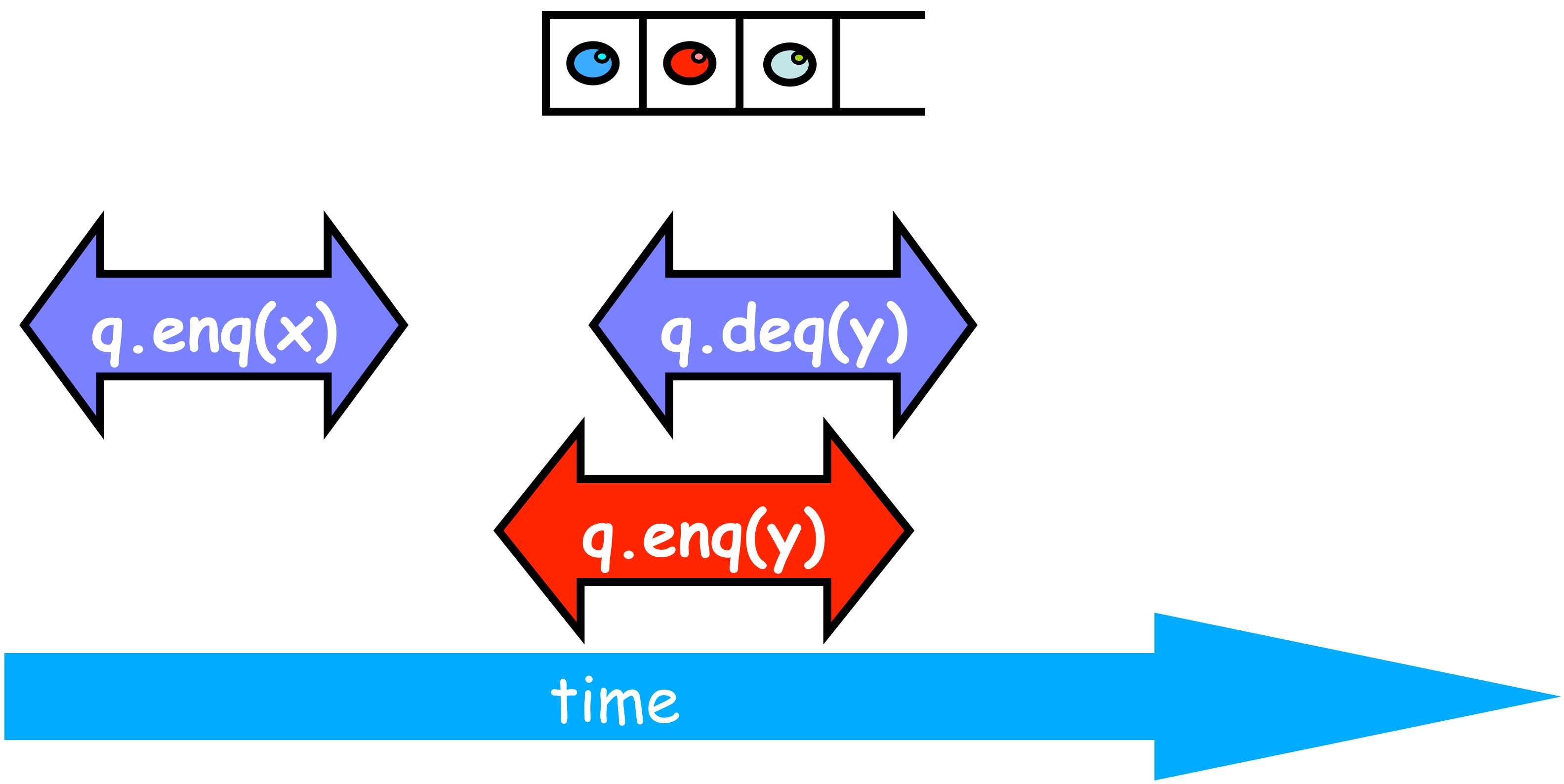
Example



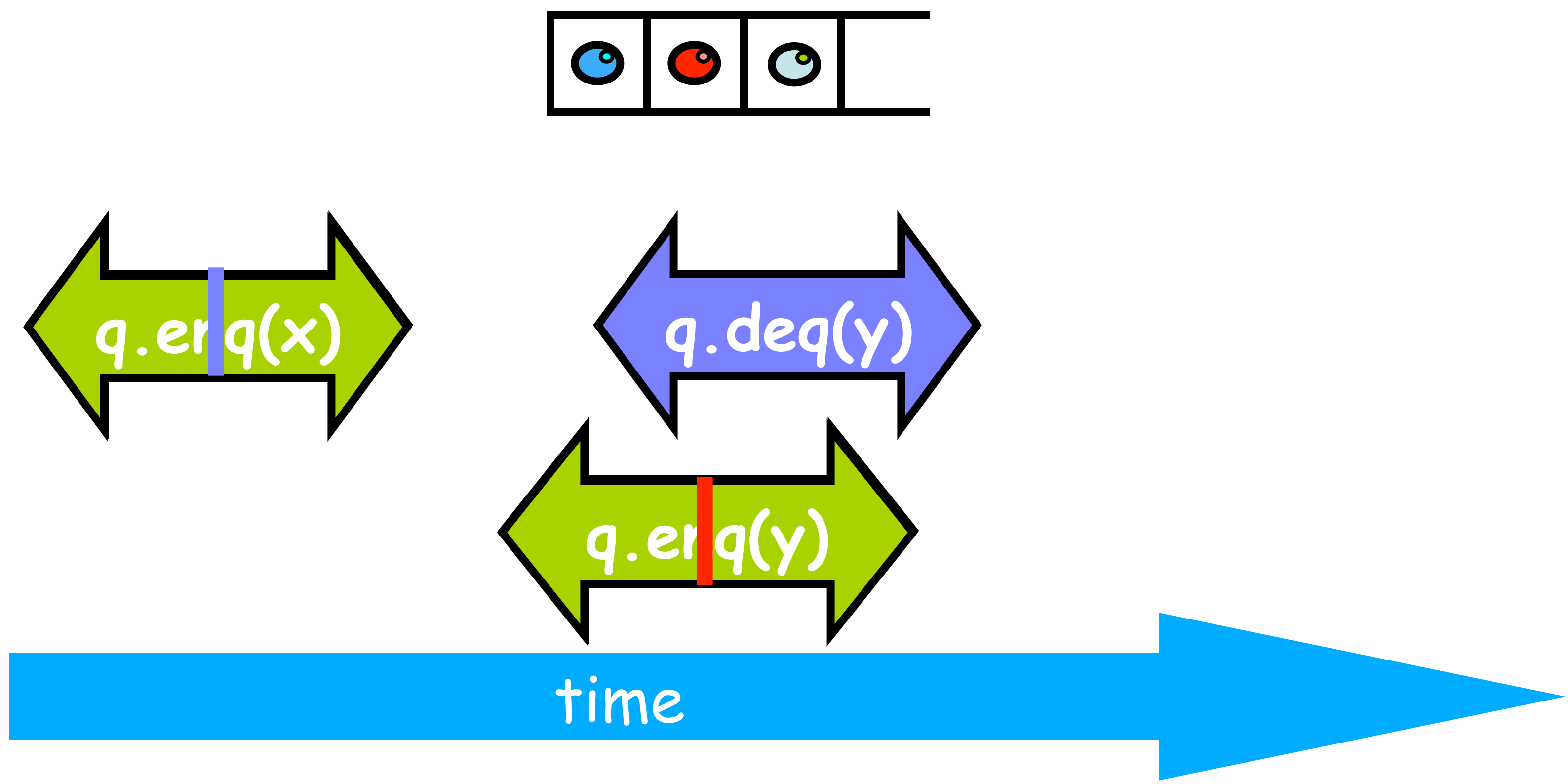
Example



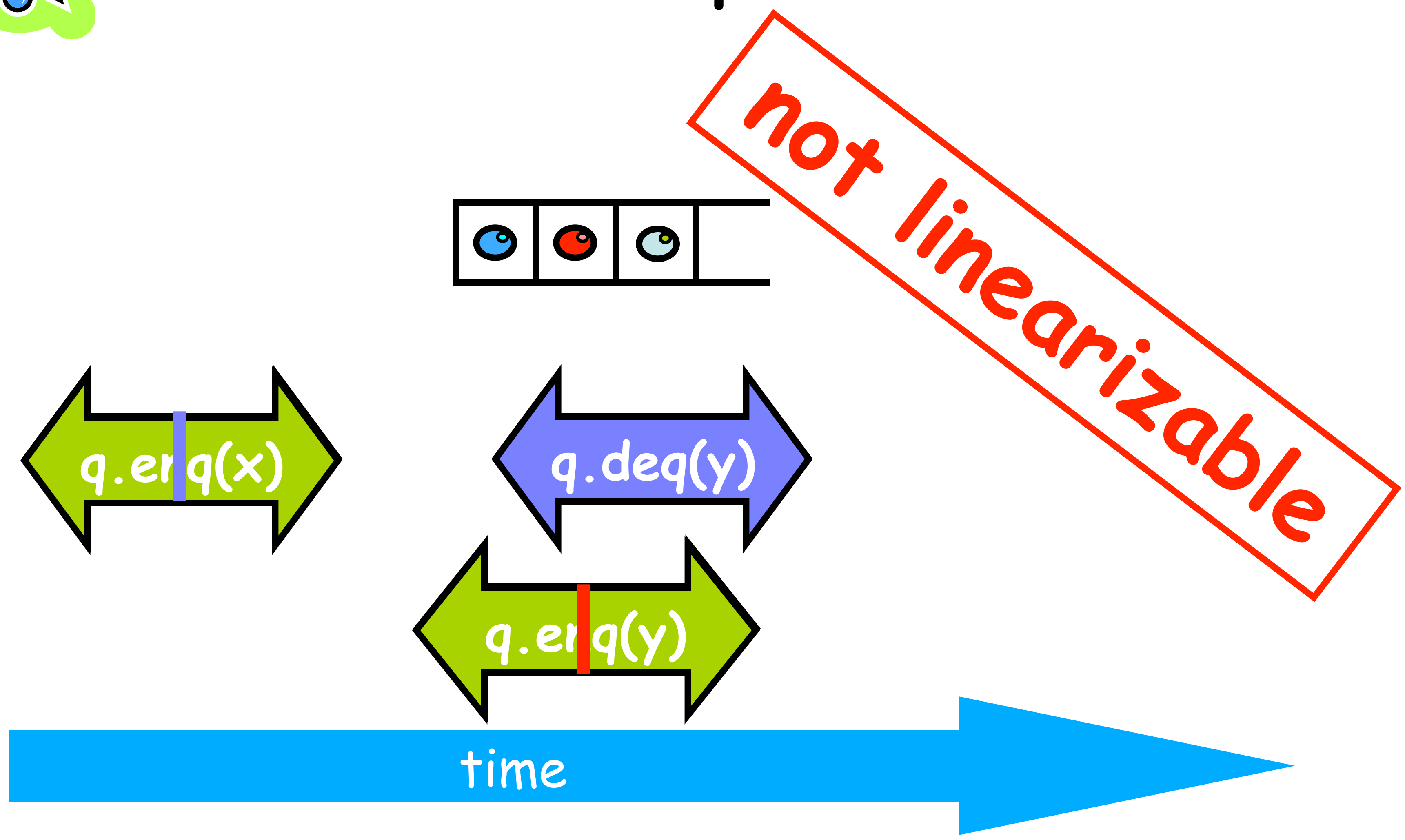
Example



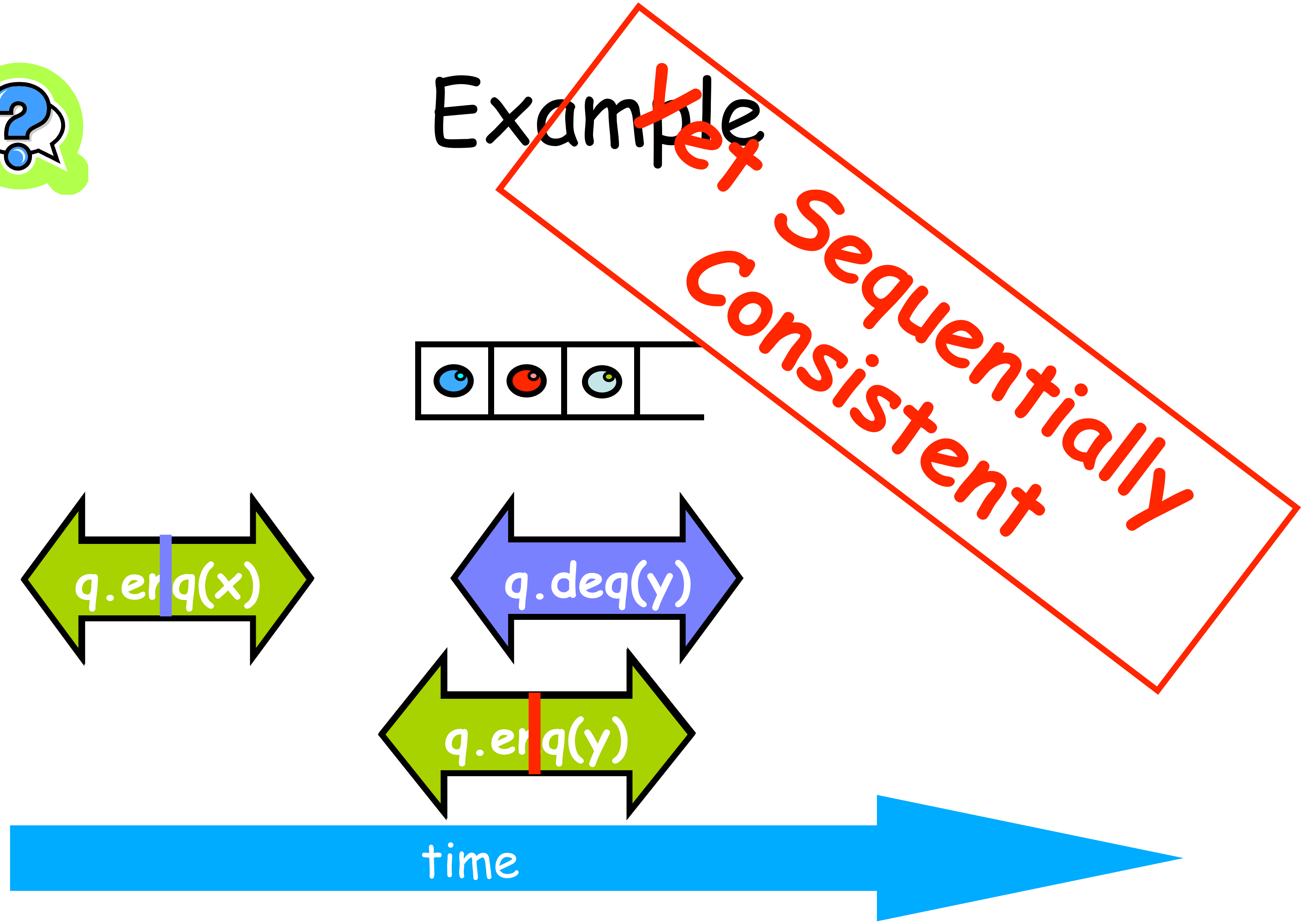
Example



Example



Example

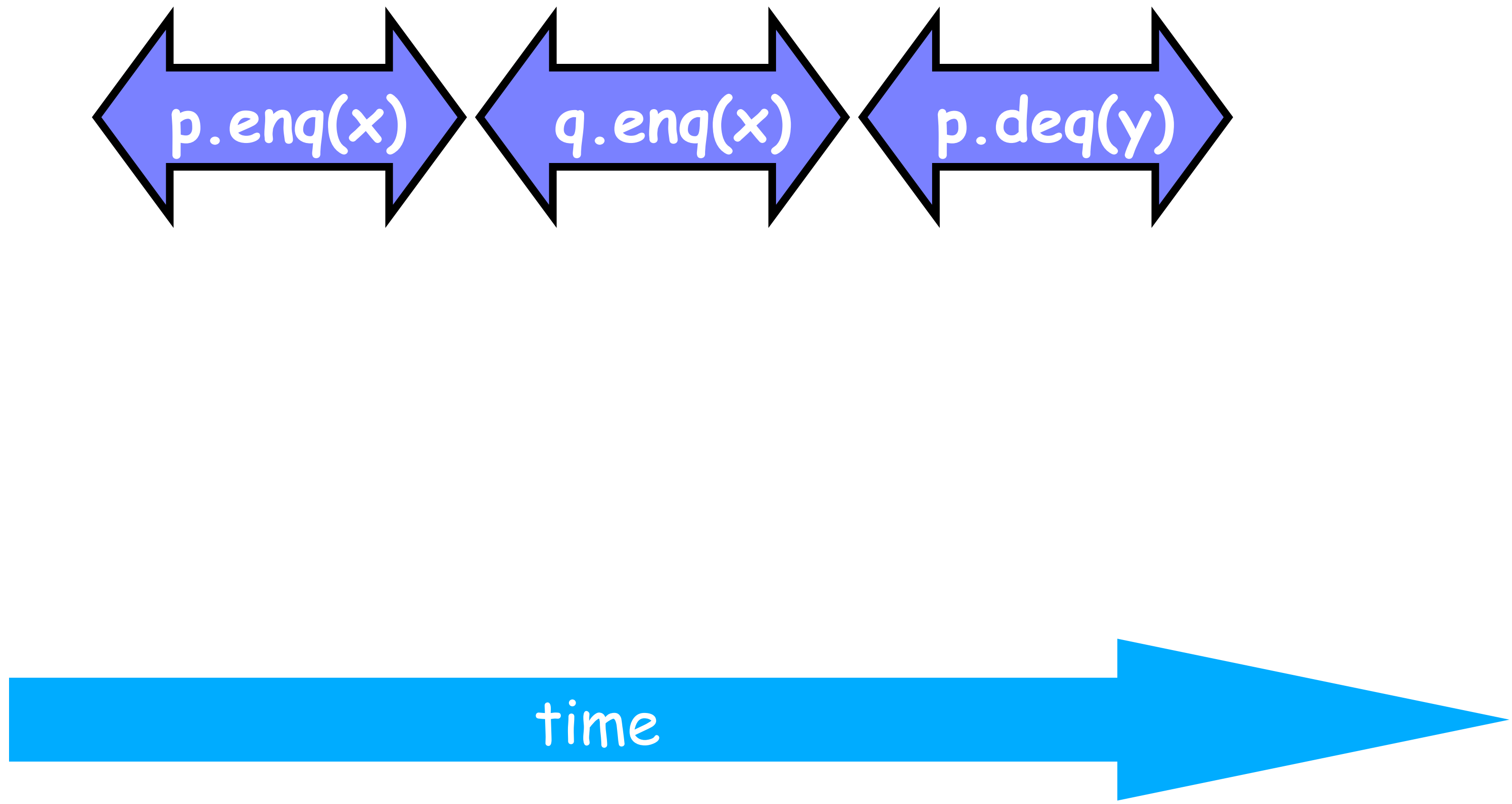


Theorem

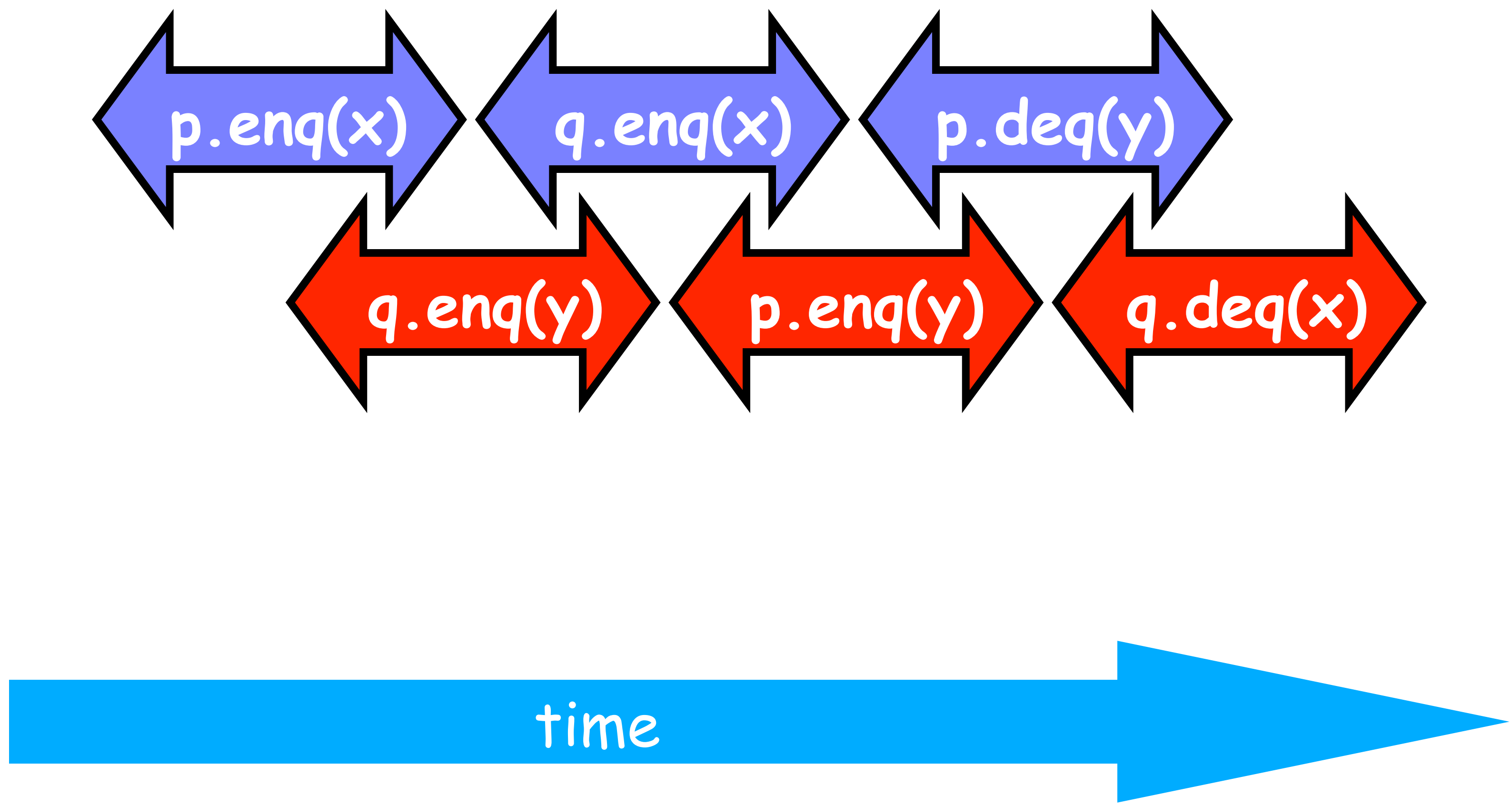
Sequential Consistency is not a local property

(and thus we lose composability…)

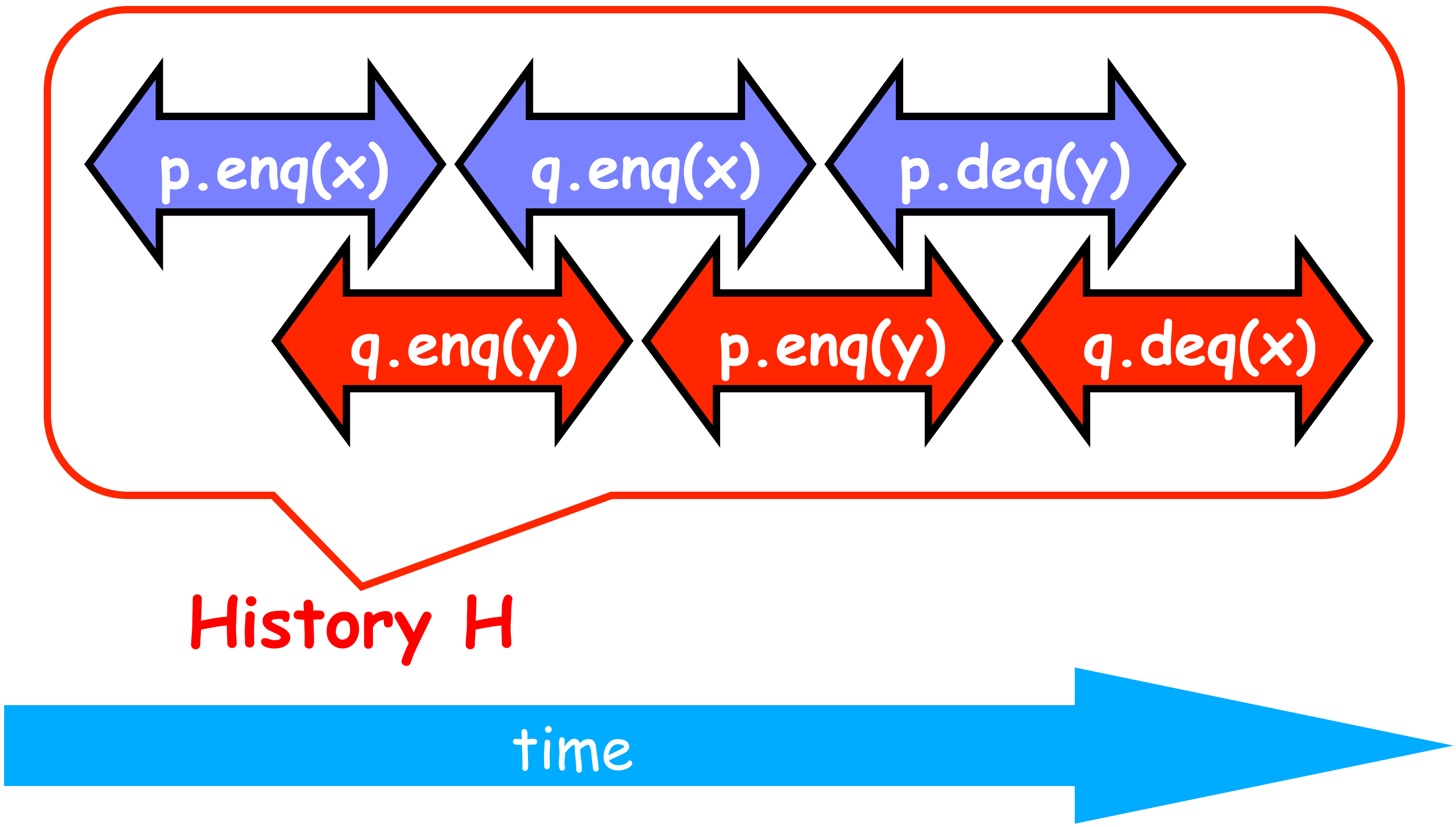
FIFO Queue Example



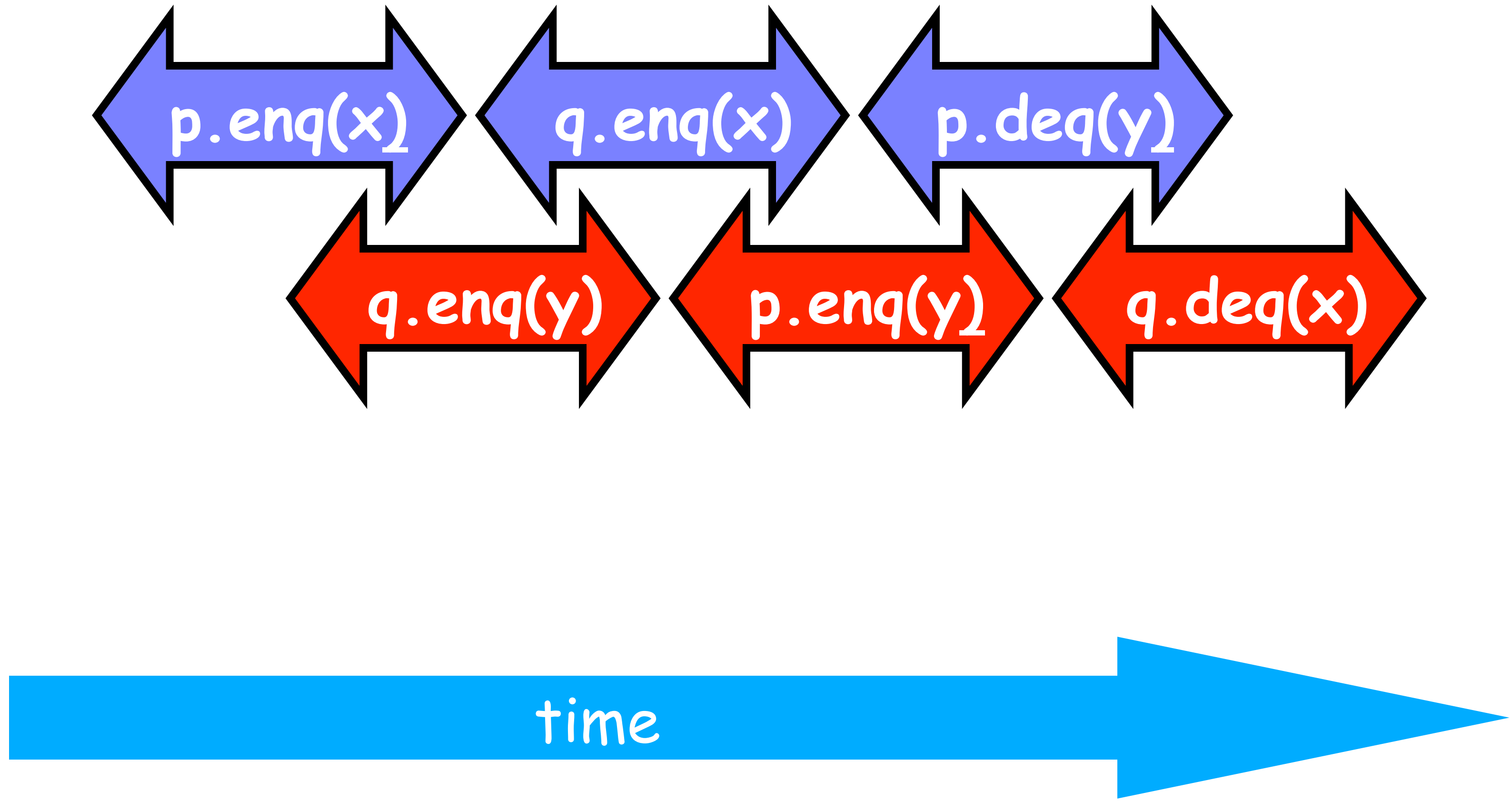
FIFO Queue Example



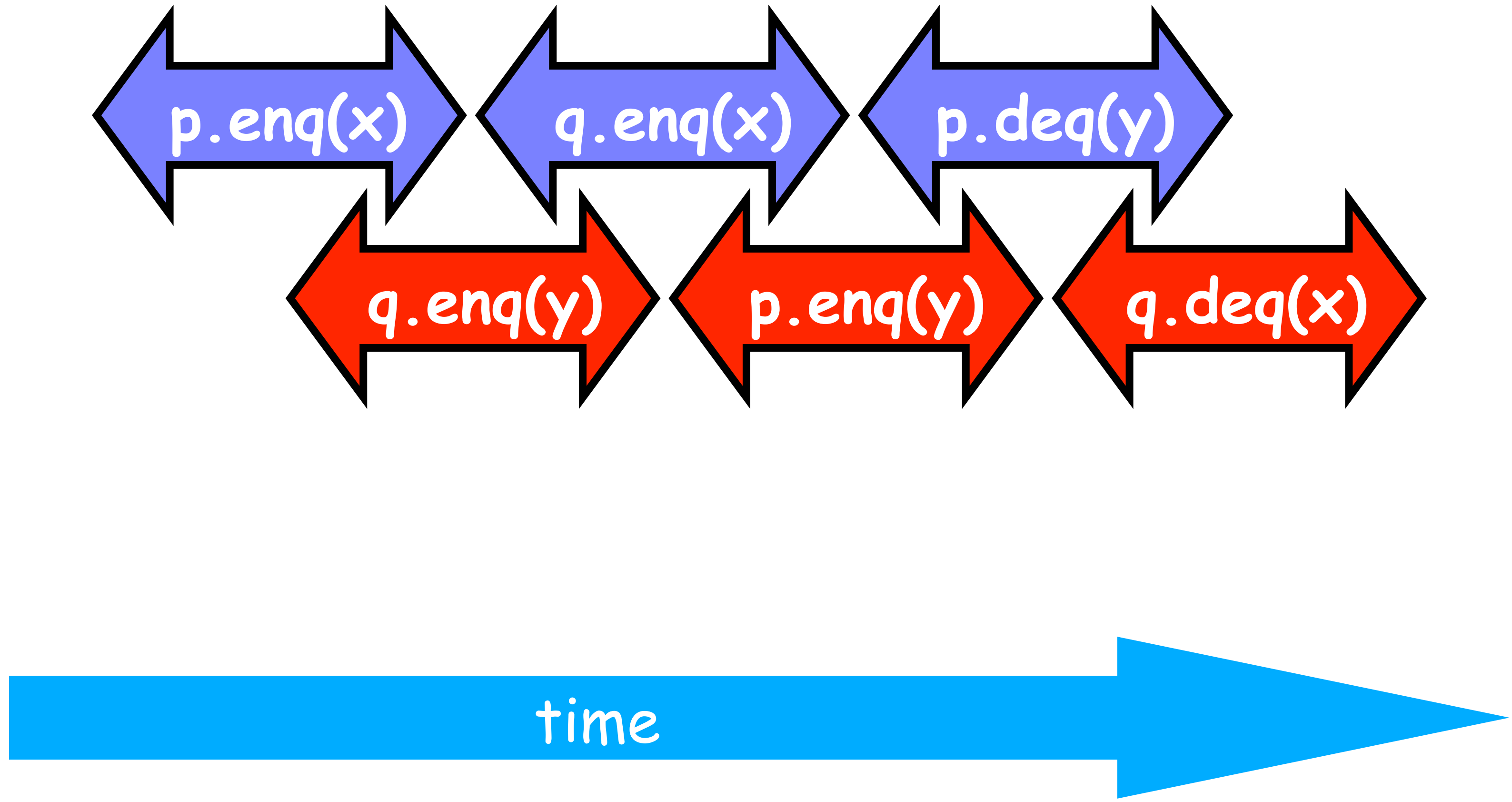
FIFO Queue Example



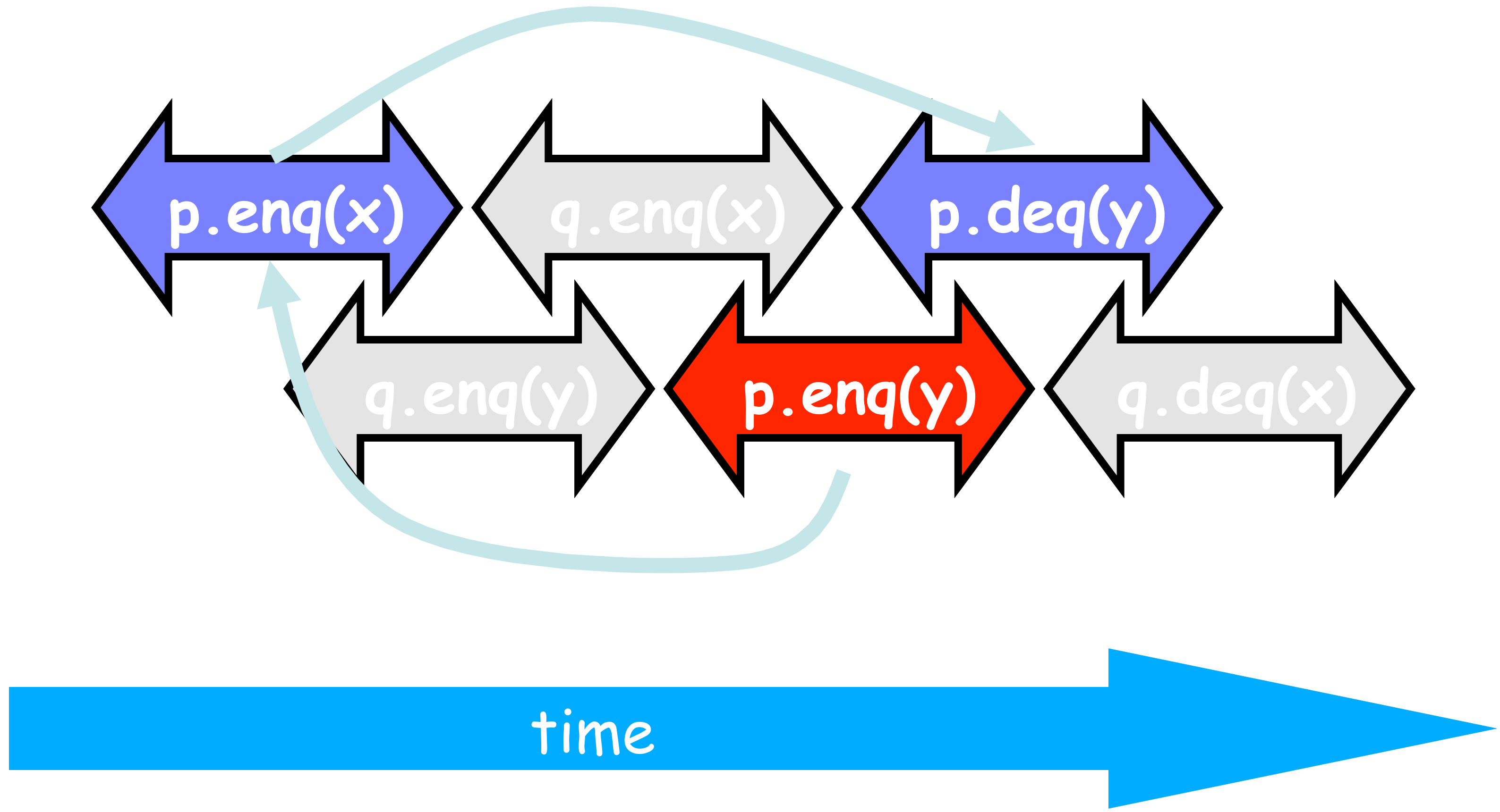
H|p Sequentially Consistent



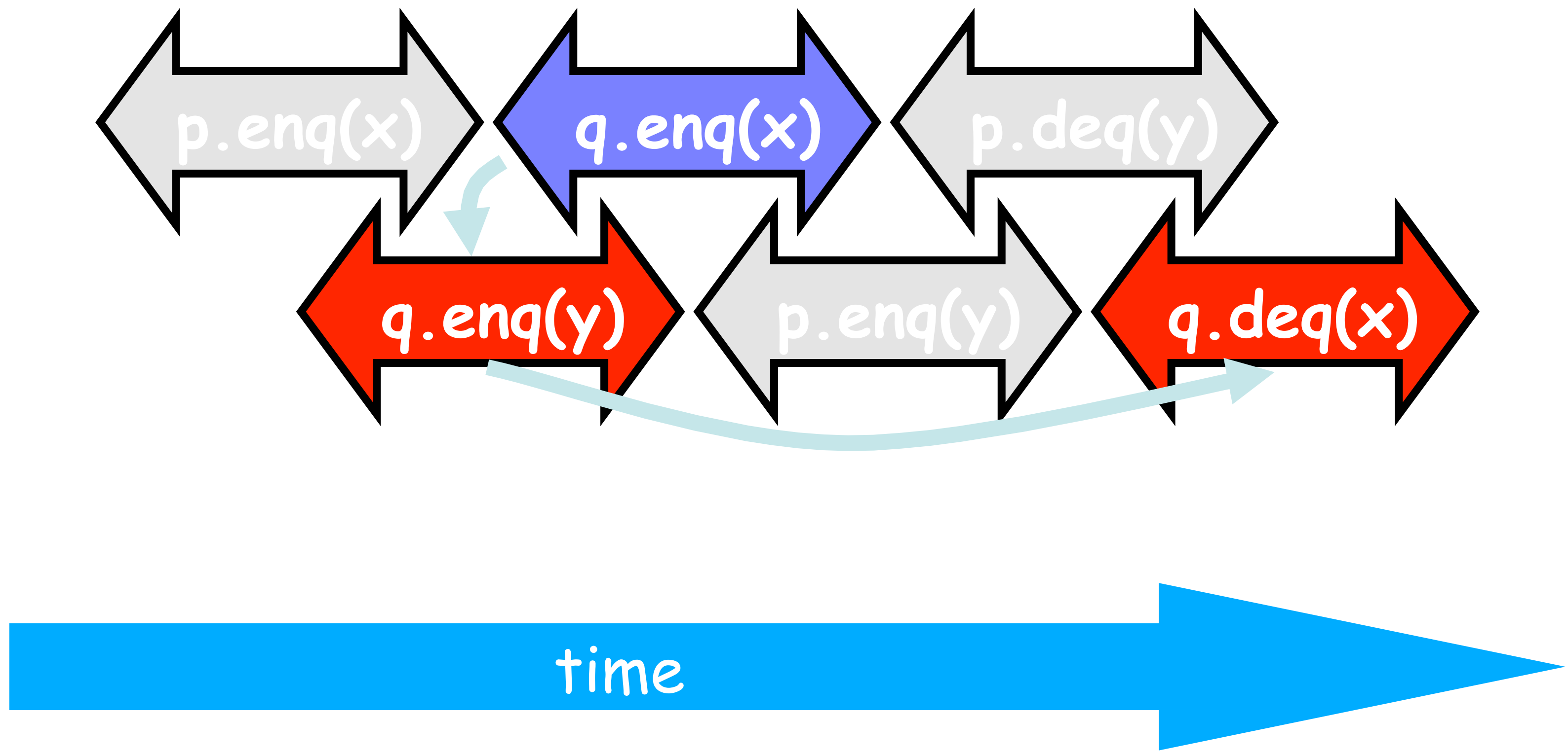
H|q Sequentially Consistent



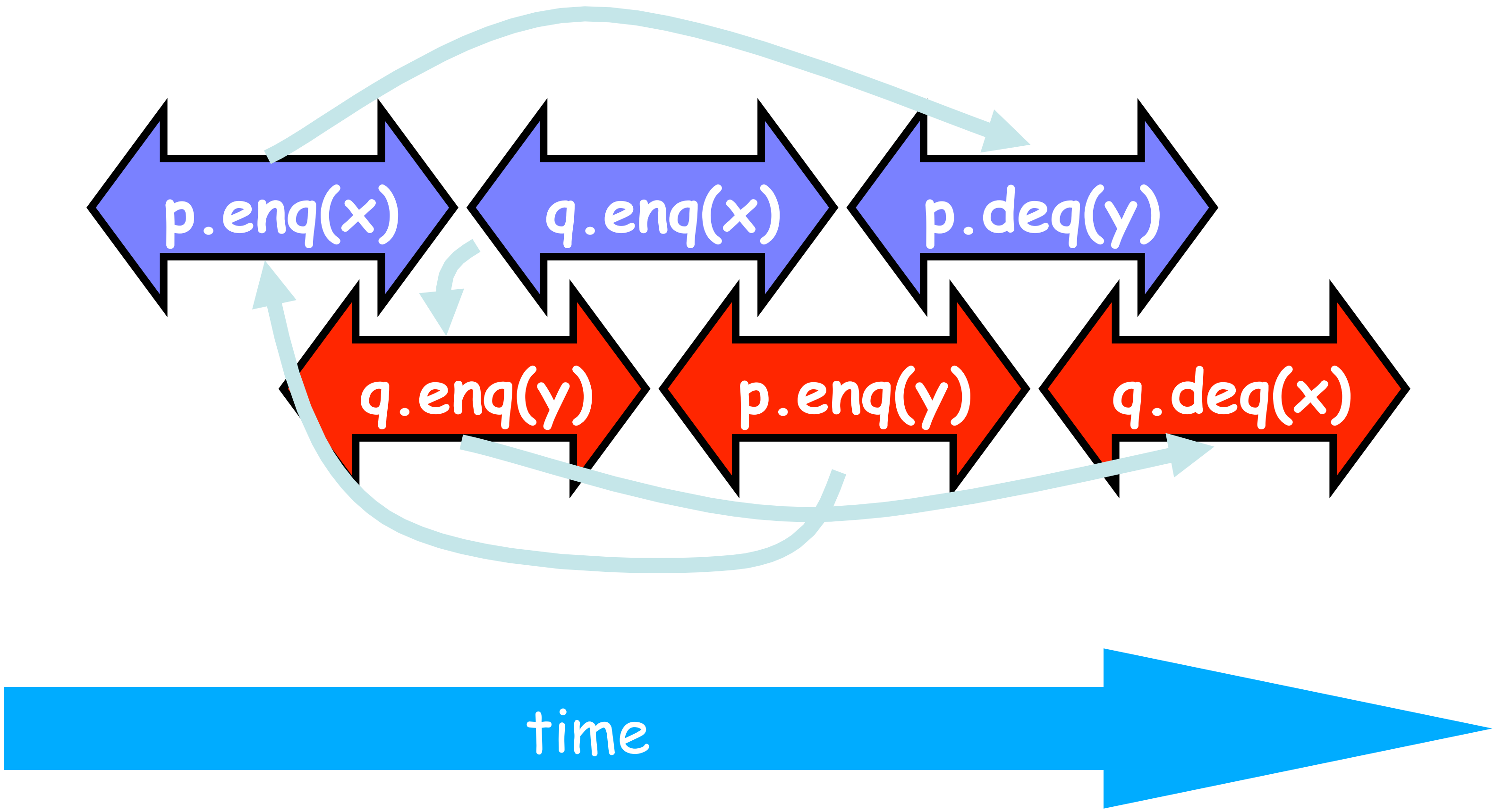
Ordering imposed by p



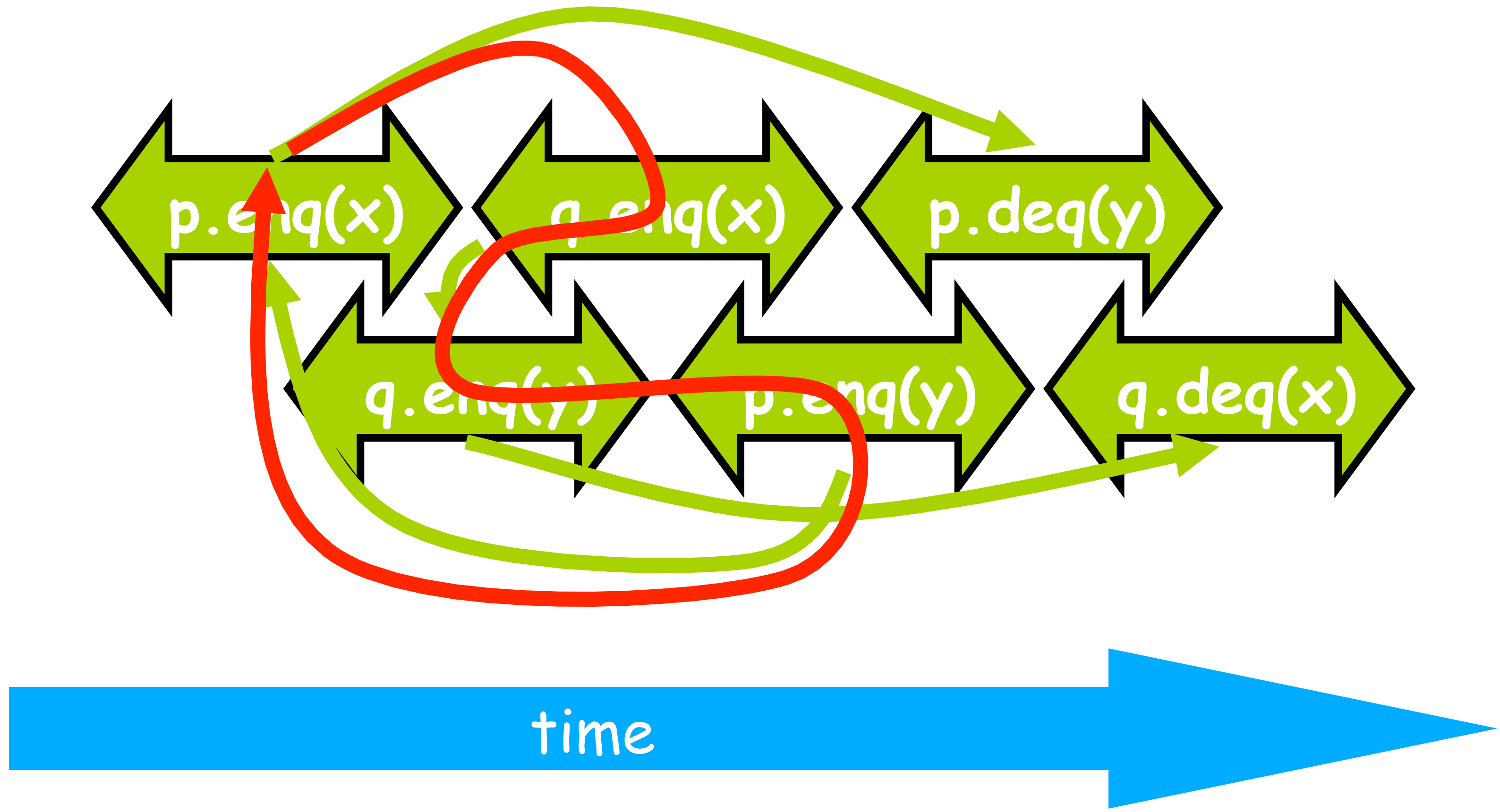
Ordering imposed by q



Ordering imposed by both



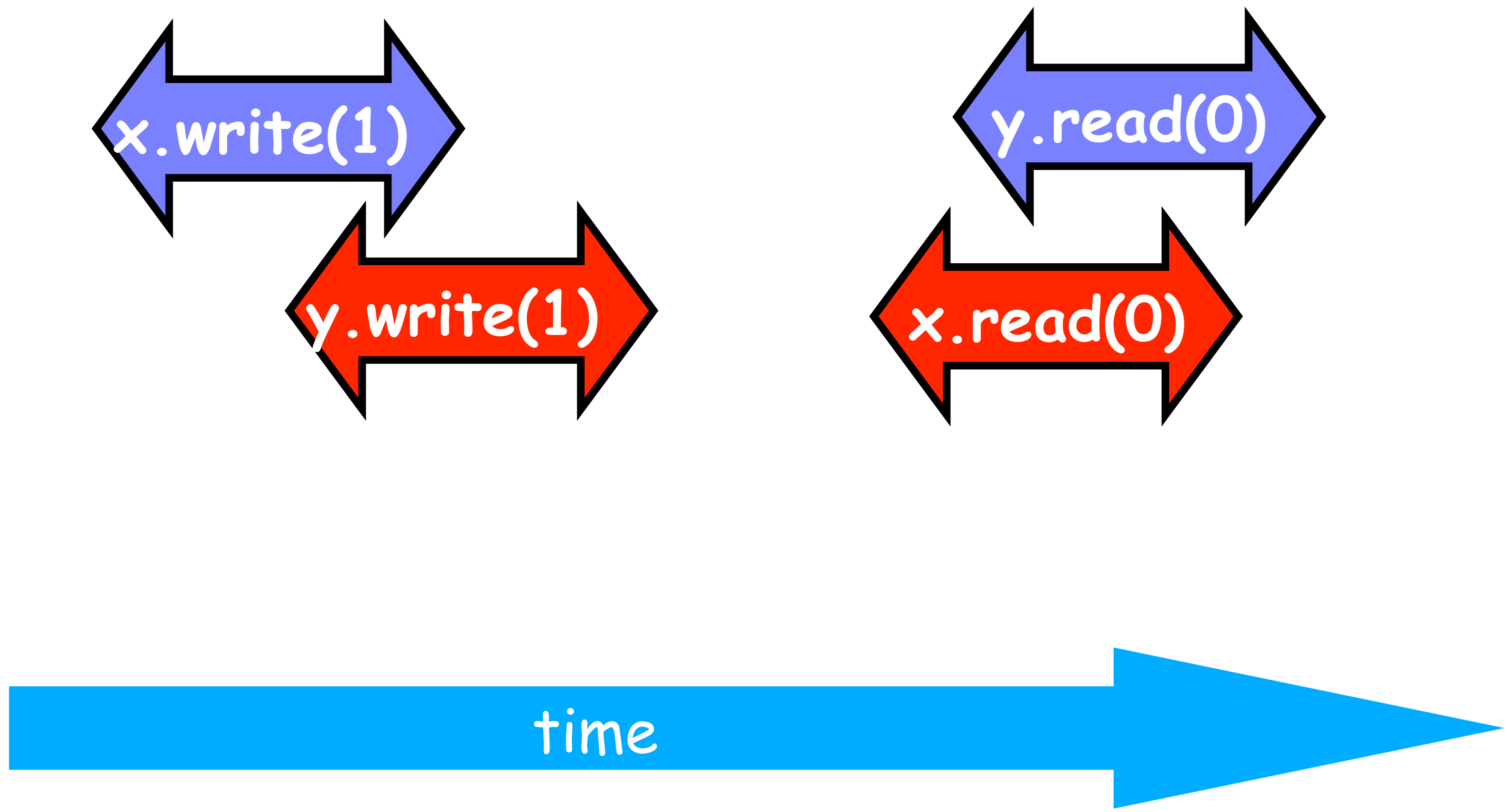
Combining orders



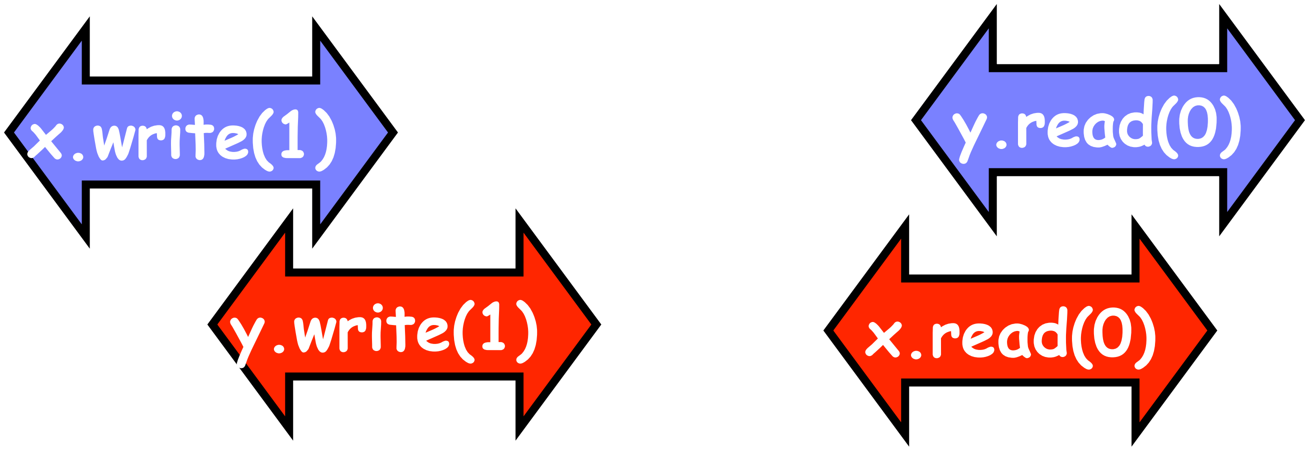
Fact

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

The Flag Example

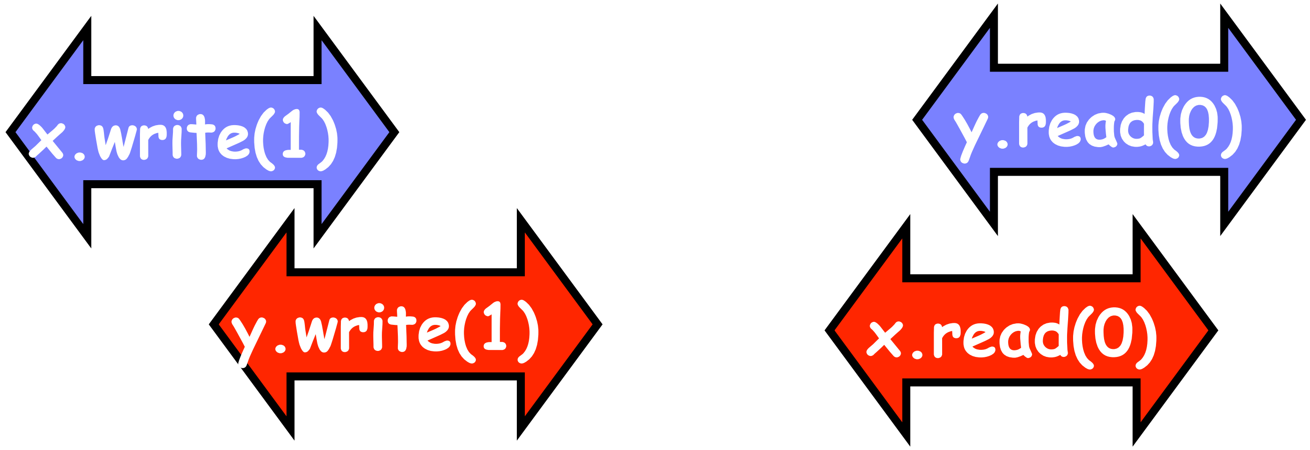


The Flag Example



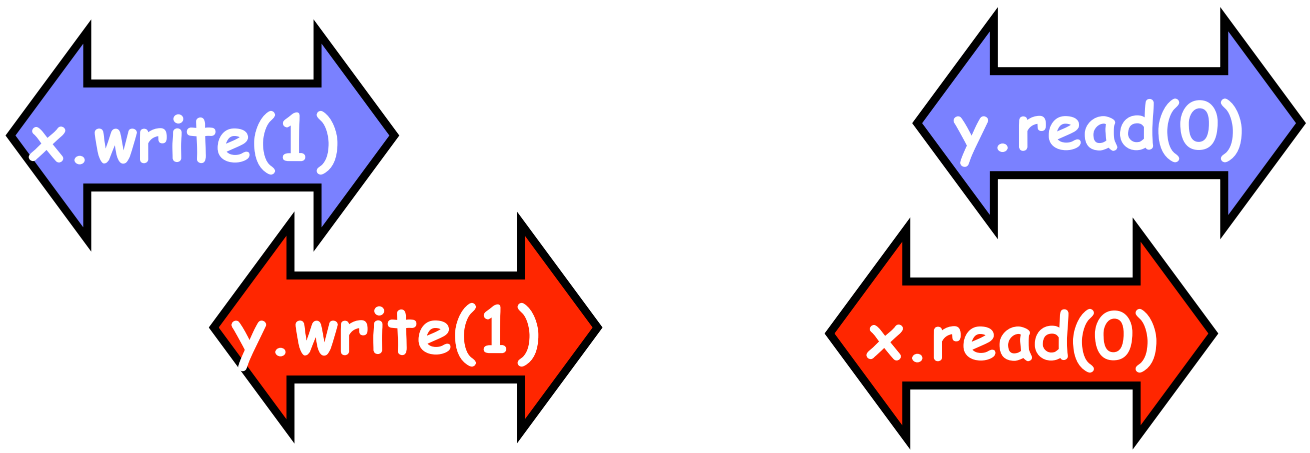
- Each thread's view is sequentially consistent
  - It went first

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 …

Opinion1: It’s Wrong

- This pattern
  - Write mine, read yours
- Heart of mutual exclusion
  - Peterson
  - Bakery, etc.
- It’s non-negotiable!

Opinion2: But It Should be Allowed …

- 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 Hierarchy

- On modern multiprocessors, processors do not read and write directly to memory.
- Memory accesses are very slow compared to processor speeds,
- Instead, each processor reads and writes directly to a cache

Memory Operations

- To read a memory location,
  - load data into cache.
- To write a memory location
  - update cached copy,
  - Lazily write cached data back to memory

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.

Bottomline..

- 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 synchronize?

Who knew you wanted to synchronize?

- Writing to memory = mailing a letter
- Vast majority of reads & writes
  - Not for synchronization
  - No need to idle waiting for post office
- If you want to synchronize
  - Announce it explicitly
  - Pay for it only when you need it

Explicit Synchronization

- 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"

Real-World Hardware Memory

- Weaker than sequential consistency
- Examples: TSO, RMO, Intel x86…
- But you can get sequential consistency at a price
- OK for expert, tricky stuff
  - assembly language, device drivers, etc.
- Linearizability more appropriate for high-level software

Critical Sections

- Easy way to implement linearizability
  - Take sequential object
  - Make each method a critical section
- Problems
  - Blocking
  - No concurrency

Linearizability

- Linearizability
  - Operation takes effect instantaneously between invocation and response
  - Uses sequential specification, locality implies composablity
  - Good for high level objects

Correctness: Linearizability

- Sequential Consistency
  - Not composable
  - Harder to work with
  - Good way to think about hardware models
- We will use *linearizability* as 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?

Maximal vs. Minimal

- Minimal progress: in <u>some</u> suffix of H, some pending active invocation has a matching response (some method call eventually completes).

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Maximal vs. Minimal

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- **Maximal progress:** in every H, every pending active invocation has a matching response (every always completes).

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

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