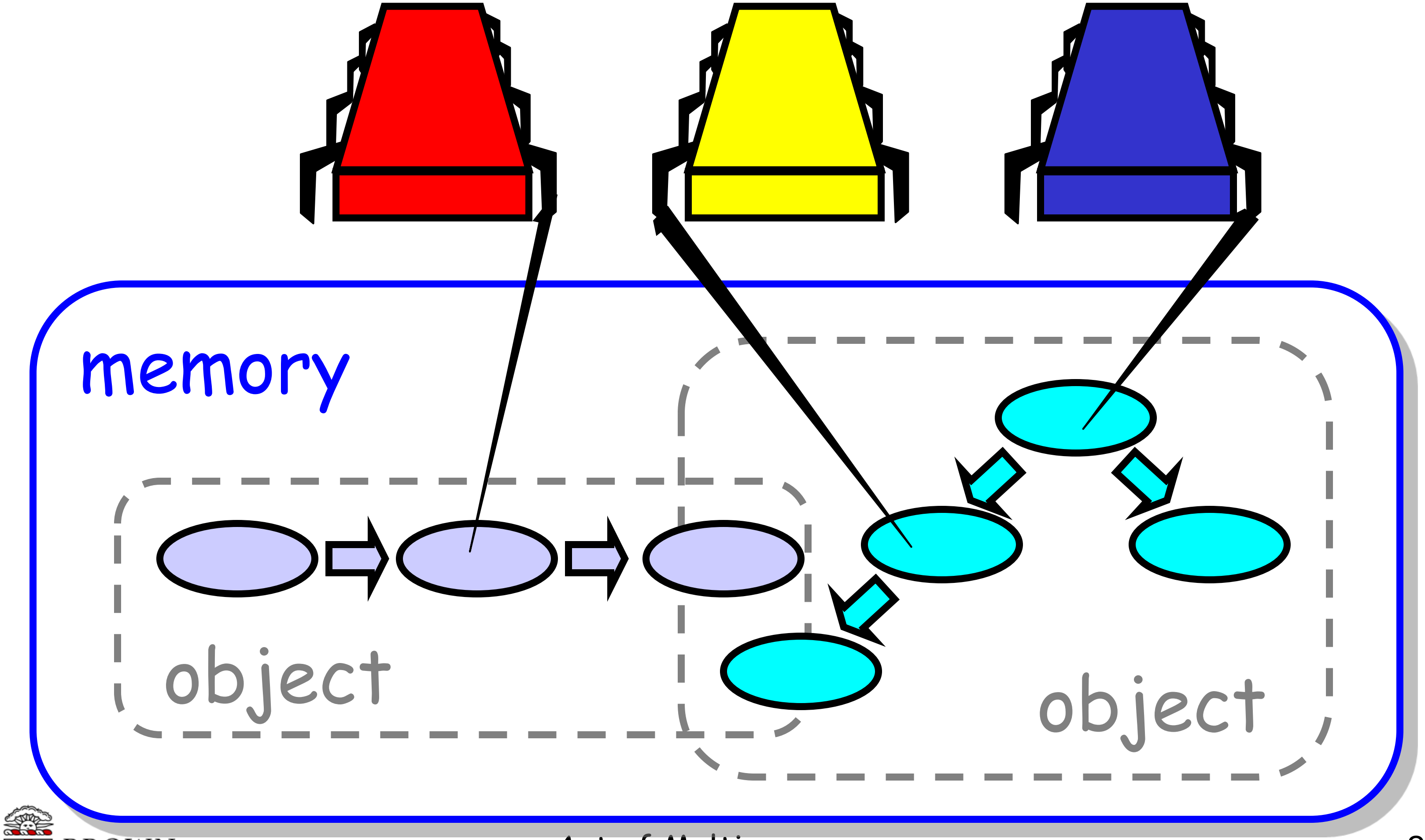
Concurrent Objects

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

Concurrent Computaton



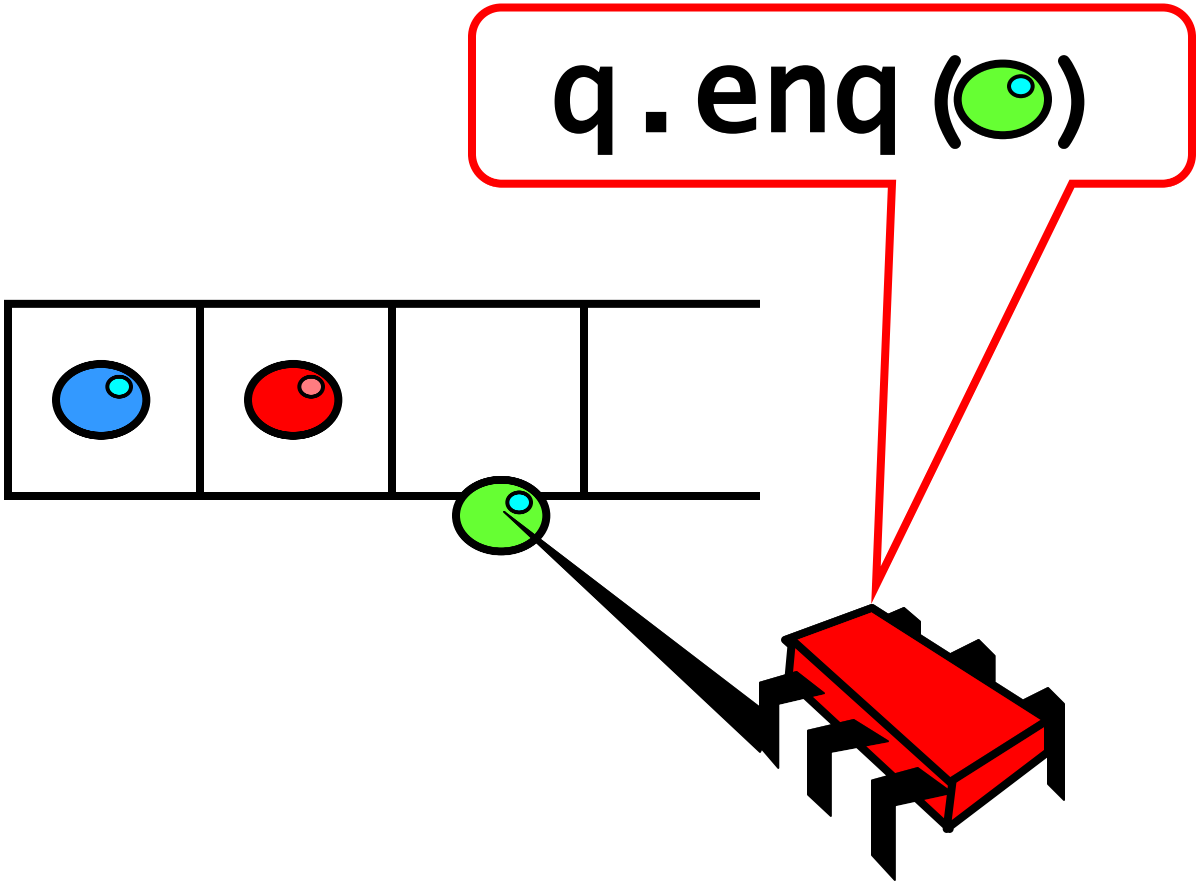
Objectivism

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

Objectivism

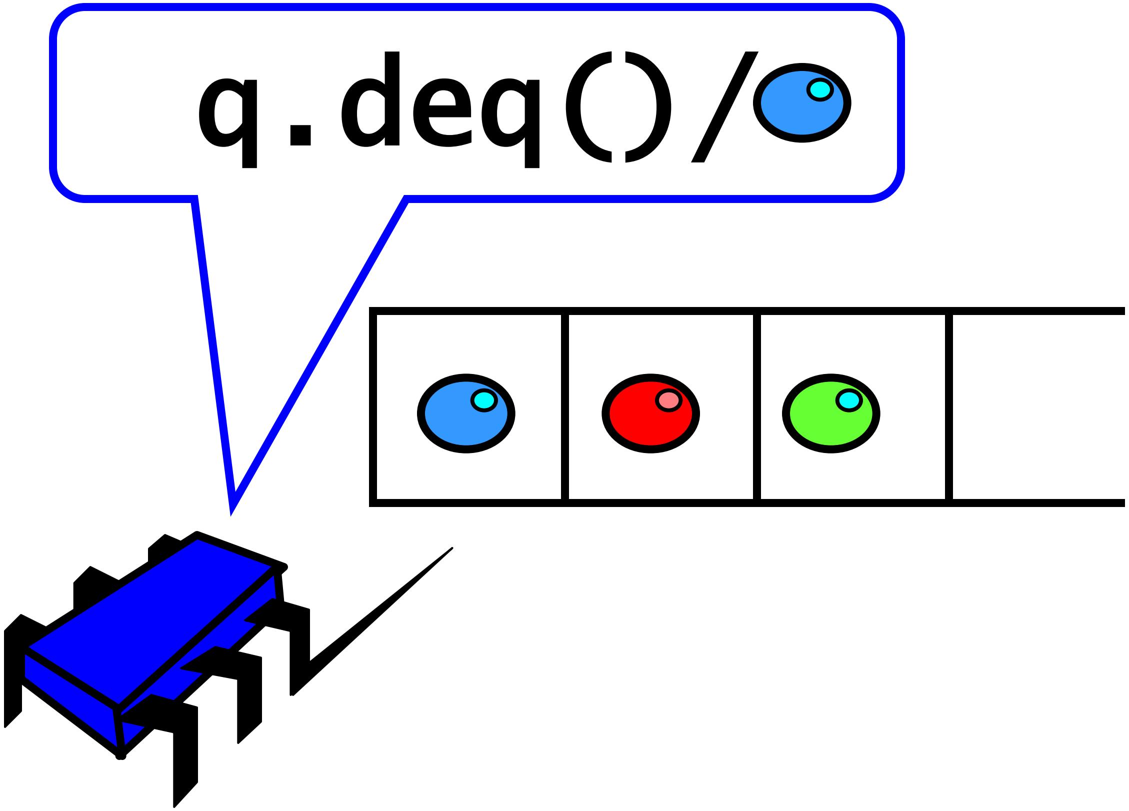
- What is a concurrent object?
  - How do we **describe** one?
  - How do we **tell if we're right**?

FIFO Queue: Enqueue Method



q.enq(●)

FIFO Queue: Dequeue Method



q.deq()/●

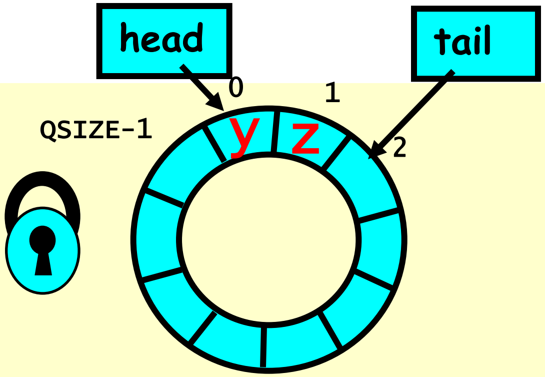
Implementation: Deq

```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized T deq() {
   while (tail – head == 0)
     this.wait();
   T result = items[head % QSIZE]; head++;
   this.notifyAll();
   return result;
  }
  …
}}
```

Implementation: Deq



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```

Method calls mutually exclusive

Implementation: Deq

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Is queue empty?

Implementation: Deq

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```

Release lock if need to wait

Implementation: Deq

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actual update

Implementation: Deq

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Notify waiting threads that you put something in the queue

Implementation: Deq

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   while (tail – head == 0)
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   this.notifyAll();
   return result;
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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

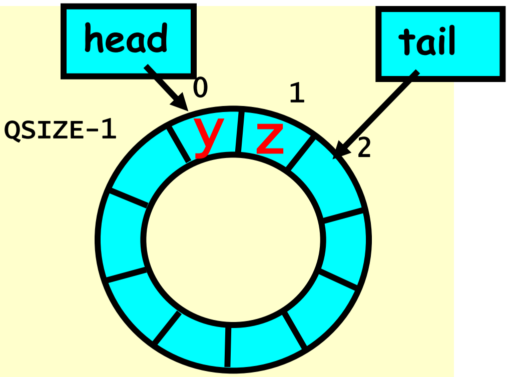
Lock-free 2-Thread Queue

```
public class LockFreeQueue {

  int head = 0, tail = 0;
  Item[QSIZE] items;

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

Lock-free 2-Thread Queue



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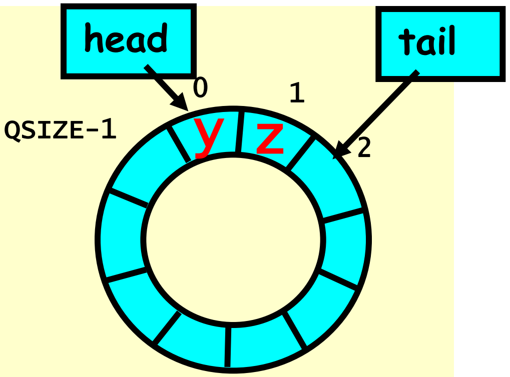

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     return item;
}}
```

Queue is up ut a lock!

How do we define "correct" when modifications are not exclusive?

Defining correct 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 …

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

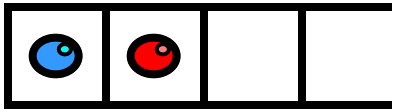
Why Sequential Specifications Totally Rock

- 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



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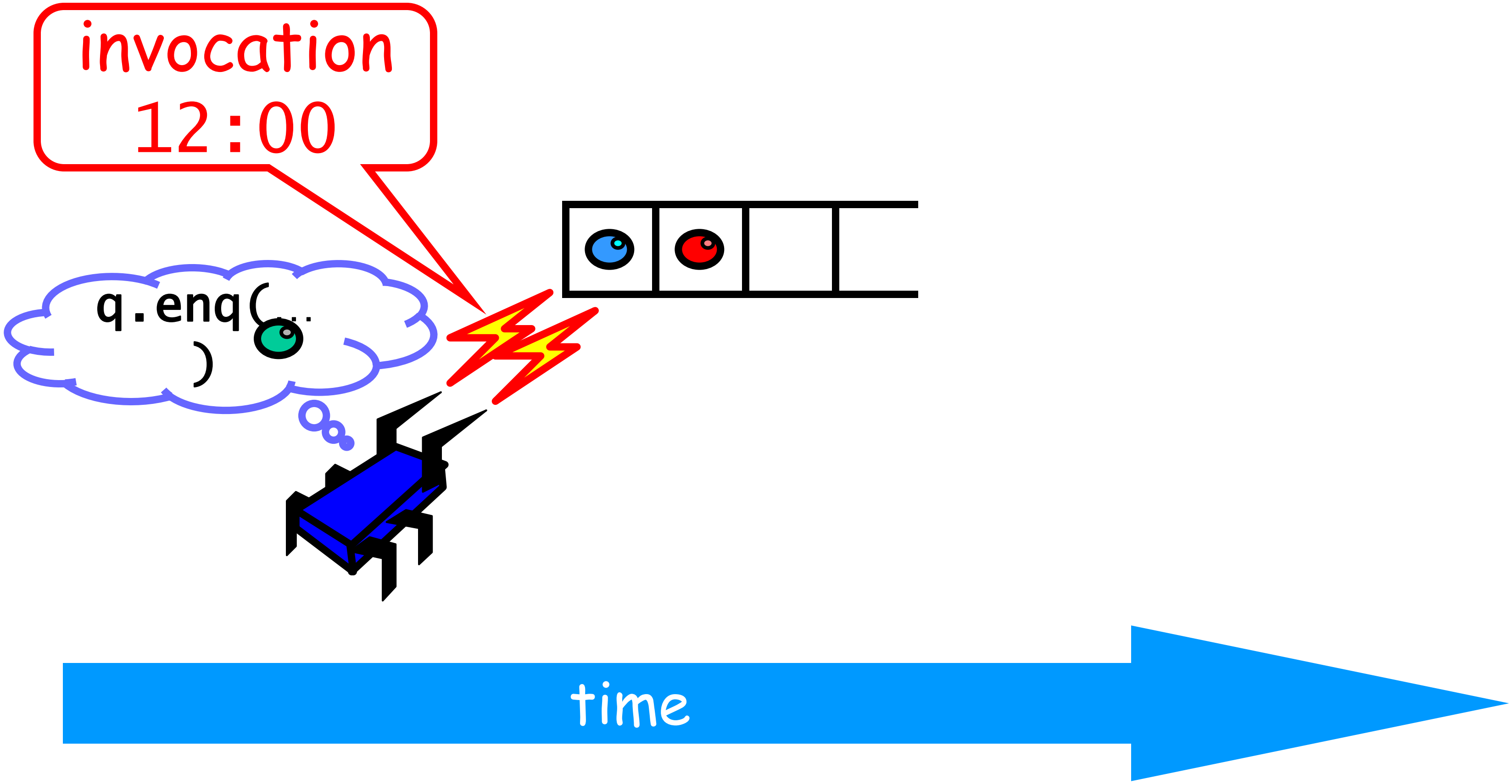

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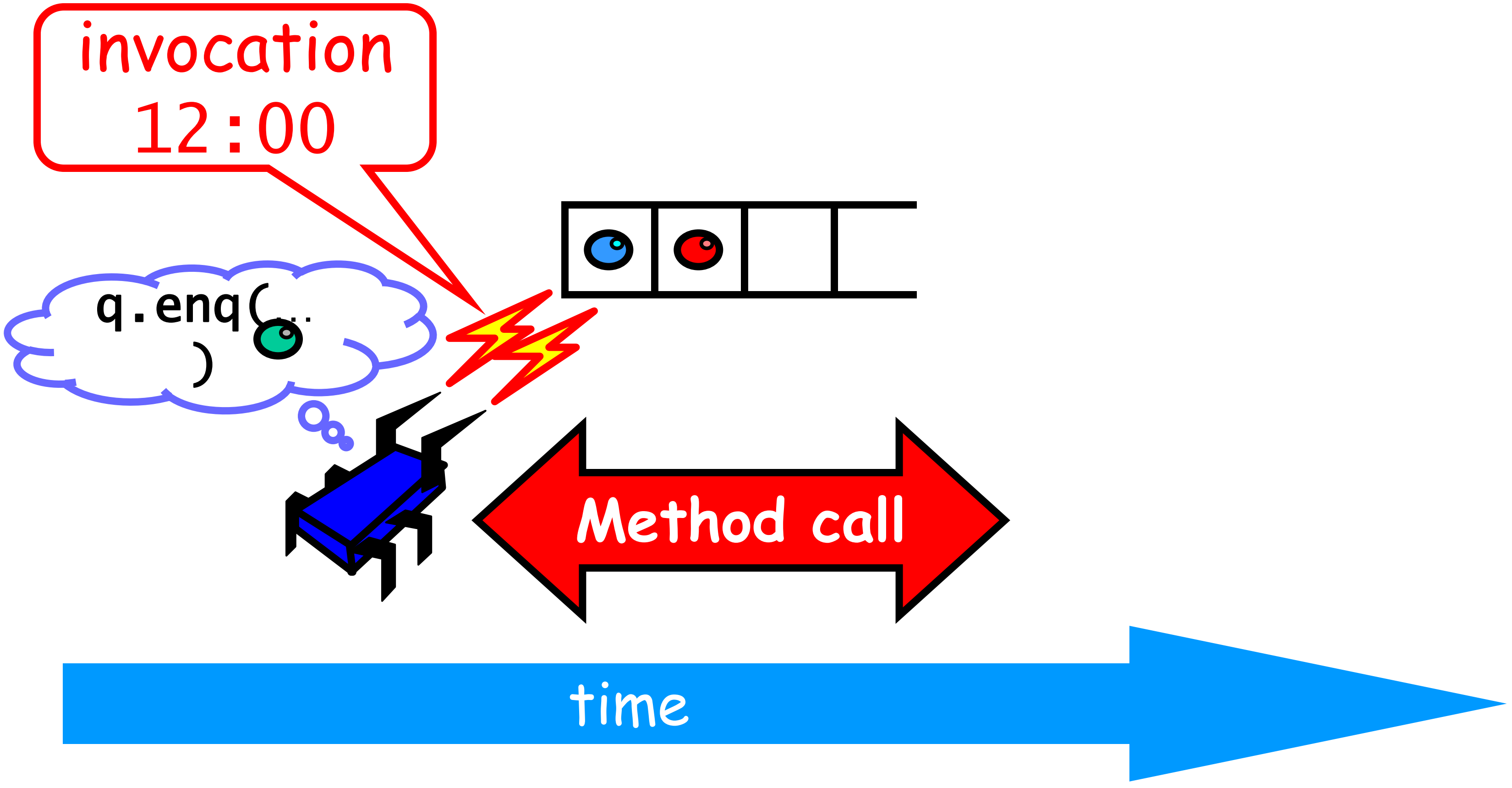

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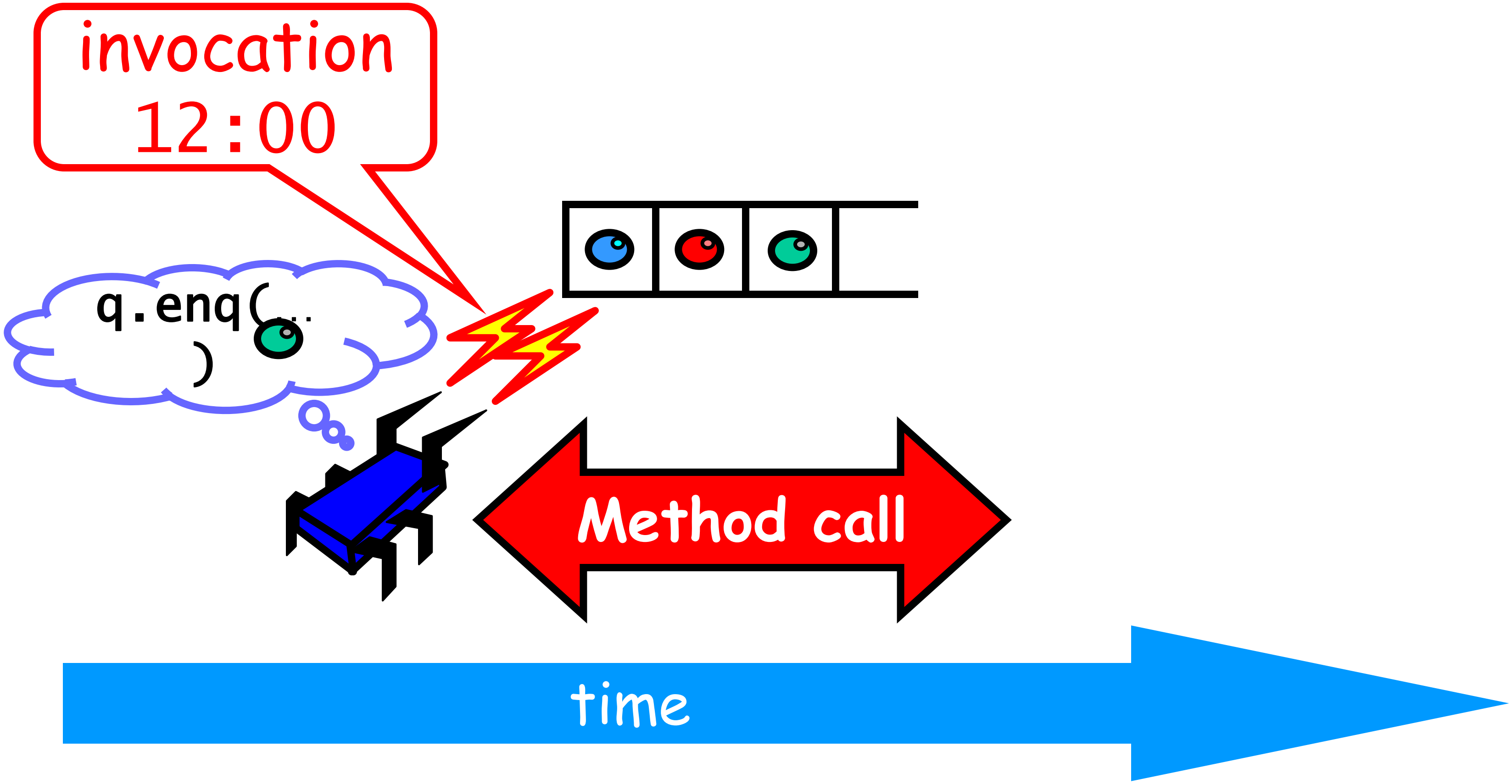

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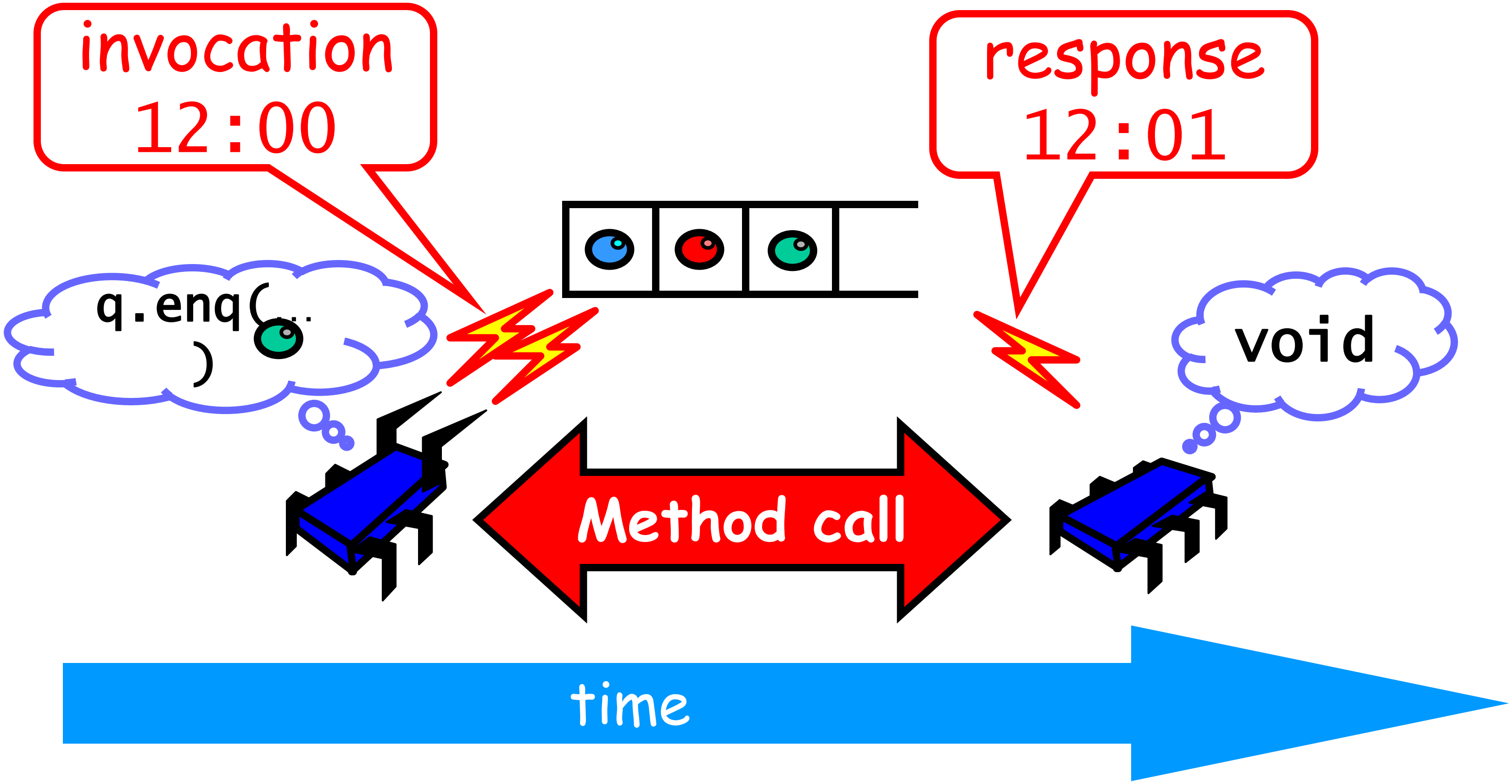
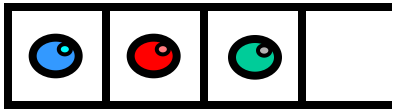


Sequential vs Concurrent

- 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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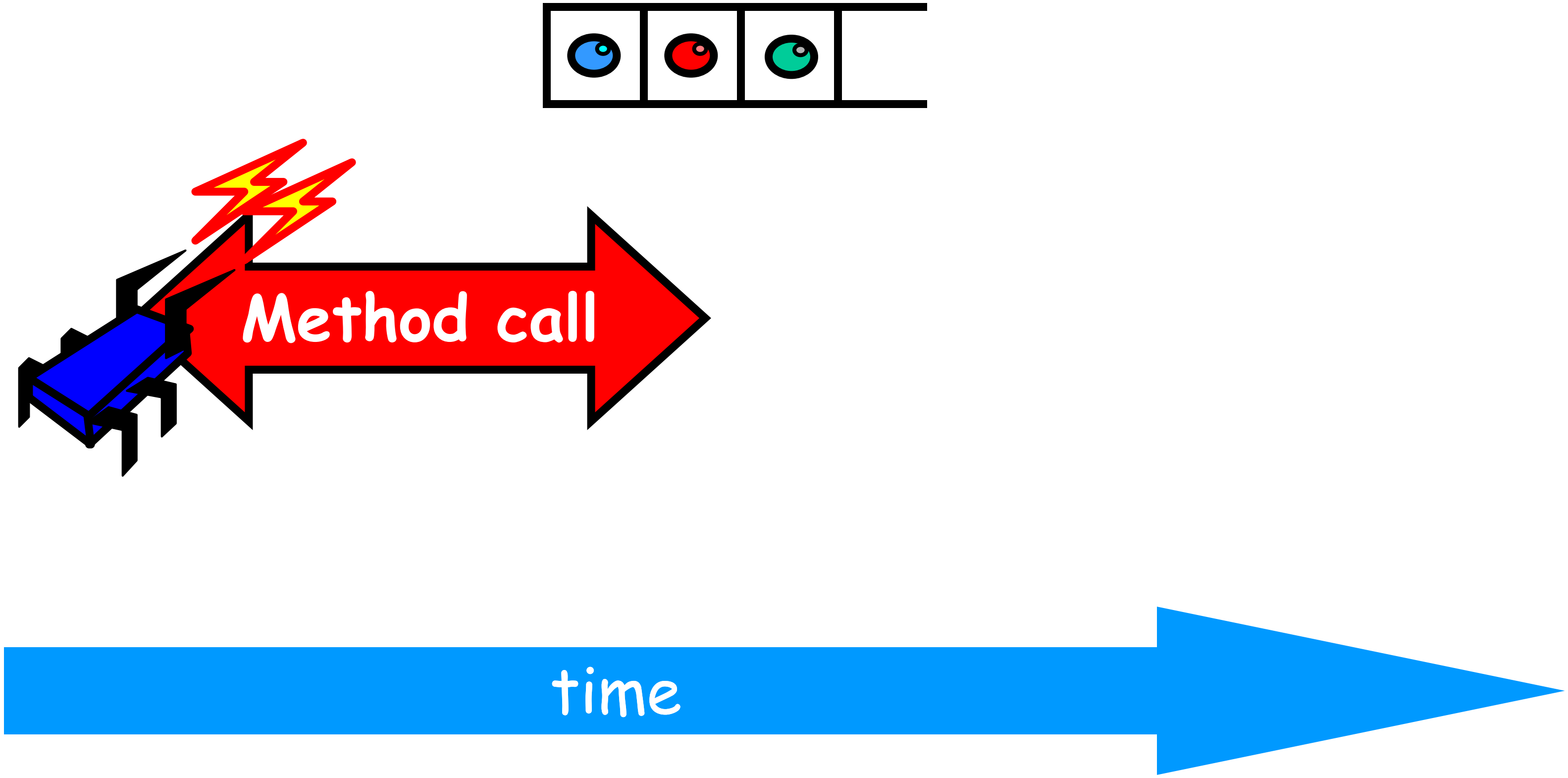

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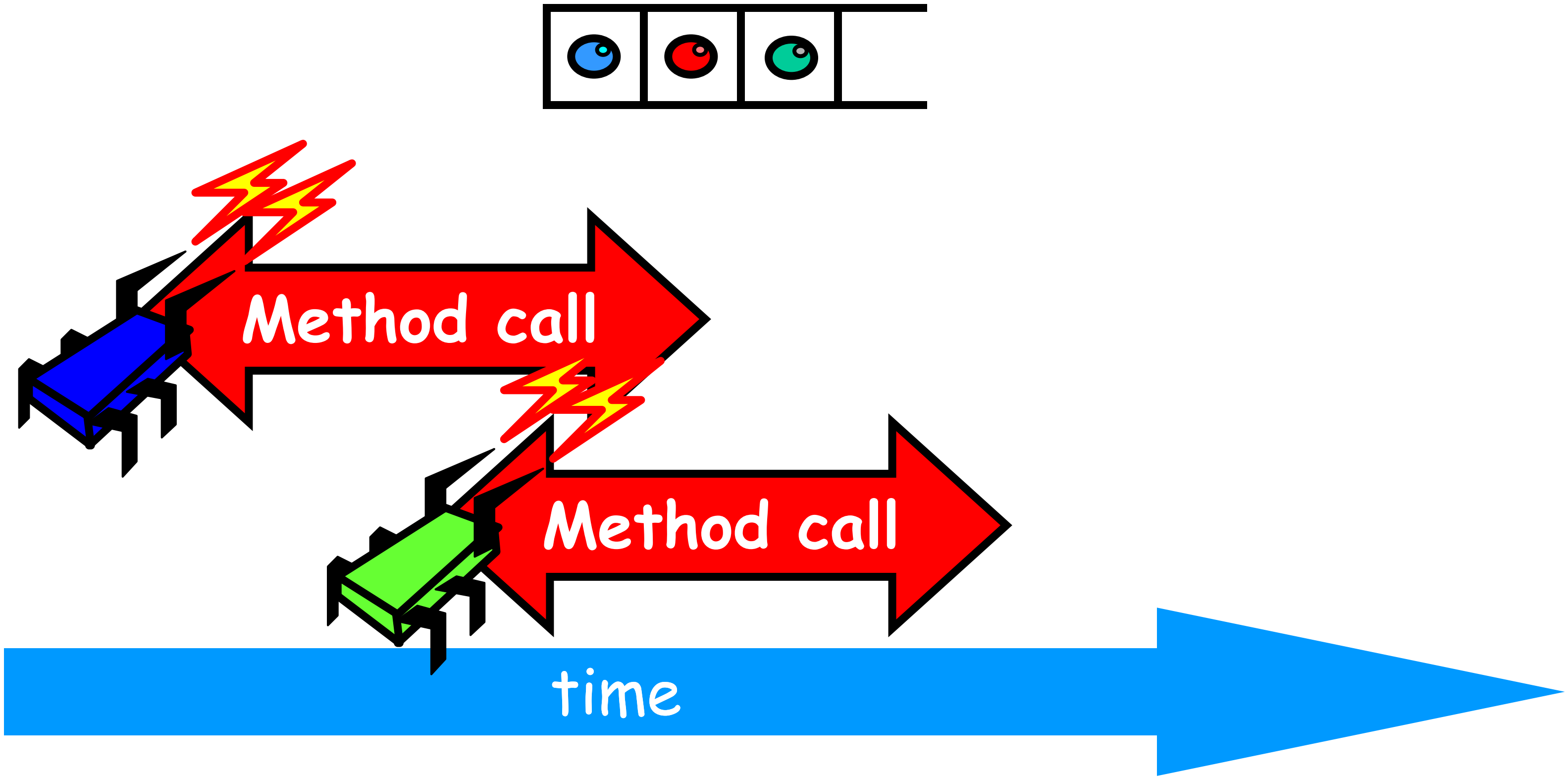

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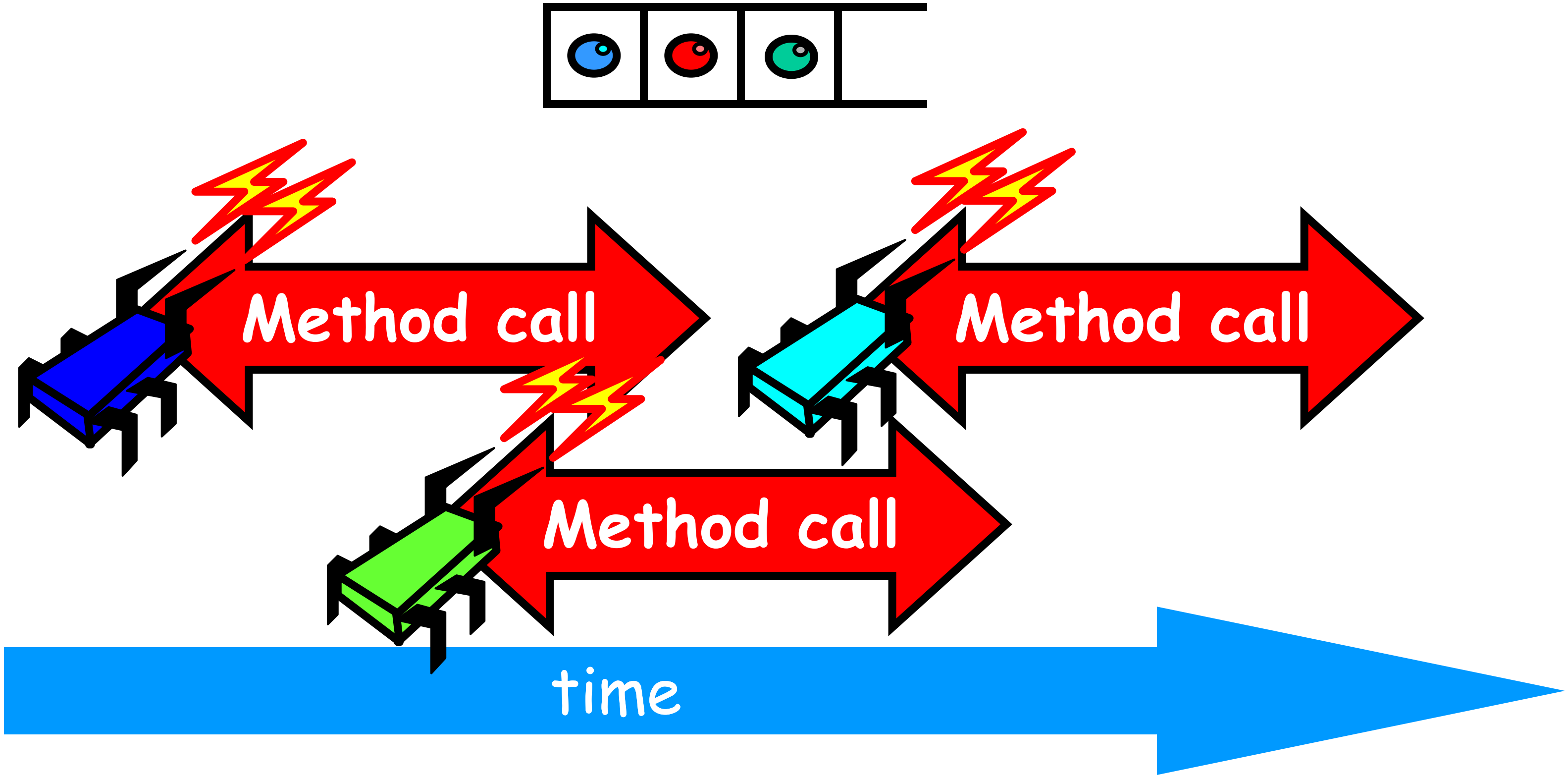

Sequential vs Concurrent

- 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

- 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…

```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized void enq(T x) {
   while (tail – head == QSIZE)
      this.wait();
   items[tail % QSIZE] = x; tail++;
   this.notifyAllAll();
  }
  …
}}
```

Intuitively…

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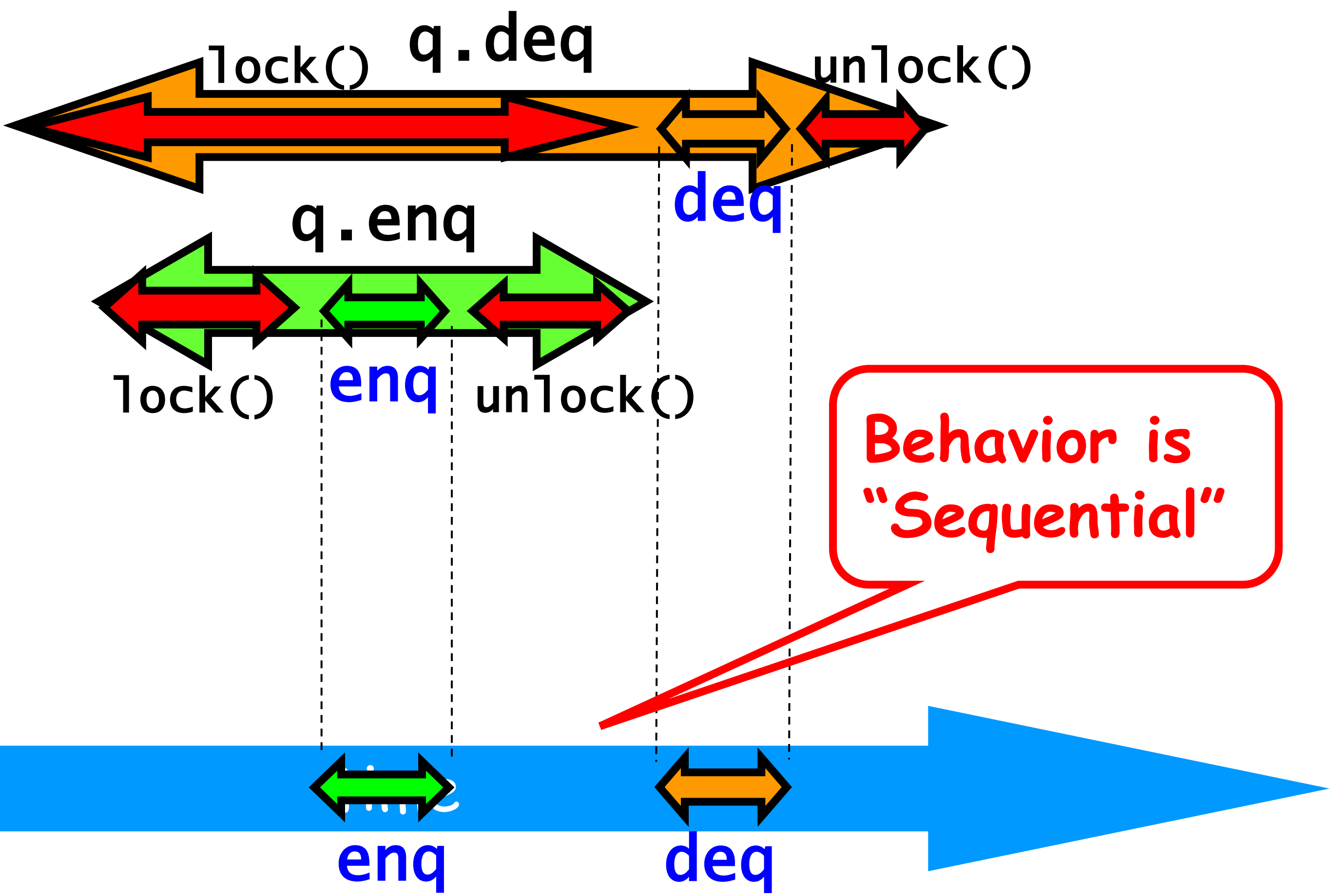
```

Queue is updated while holding lock (mutually exclusive)

Intuitively

Lets capture the idea of describing the concurrent via the sequential



Behavior is "Sequential"

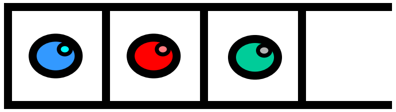
Linearizability

- 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…
- A linearizable object: one all of whose possible executions are linearizable

Example



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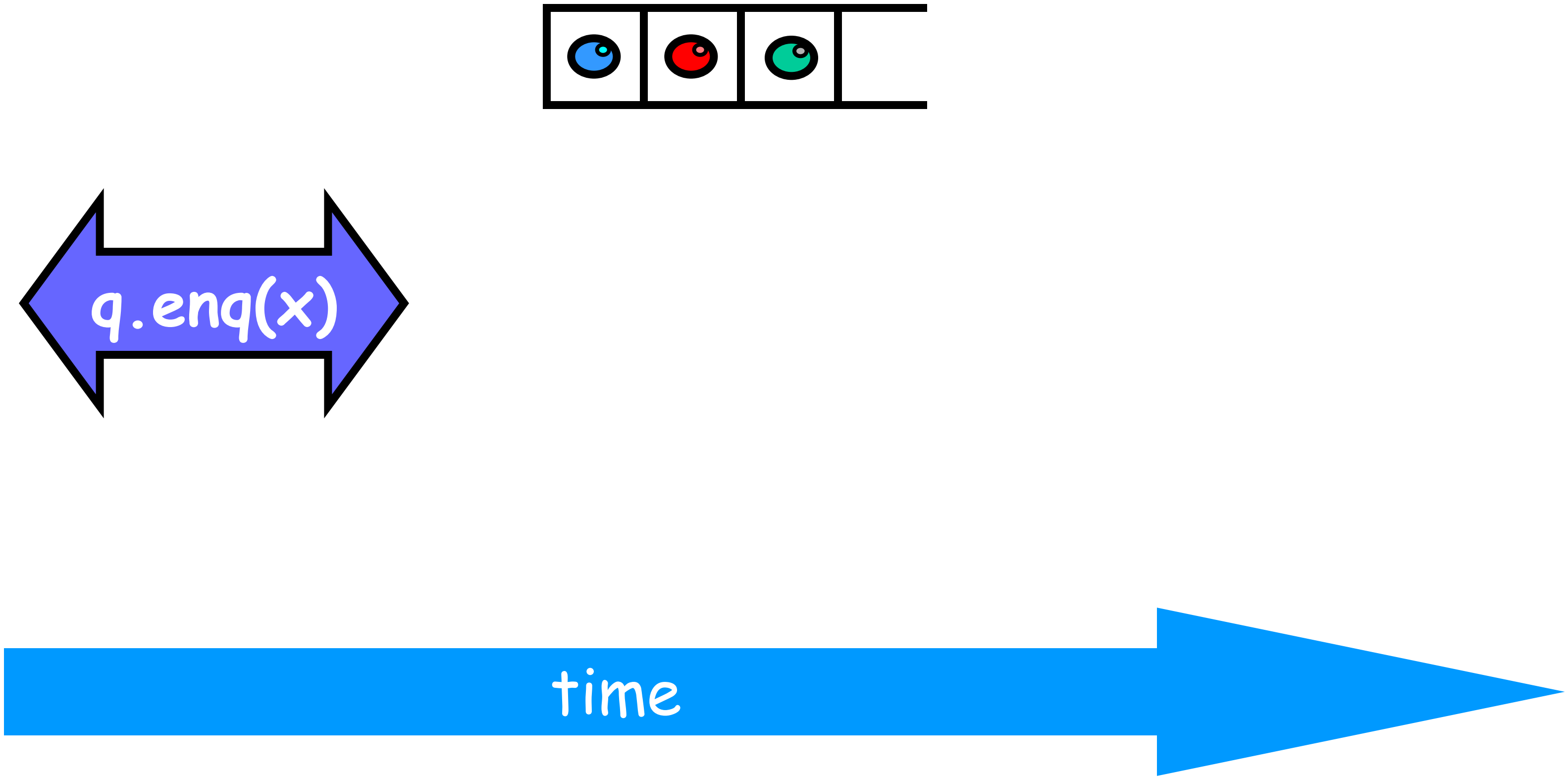

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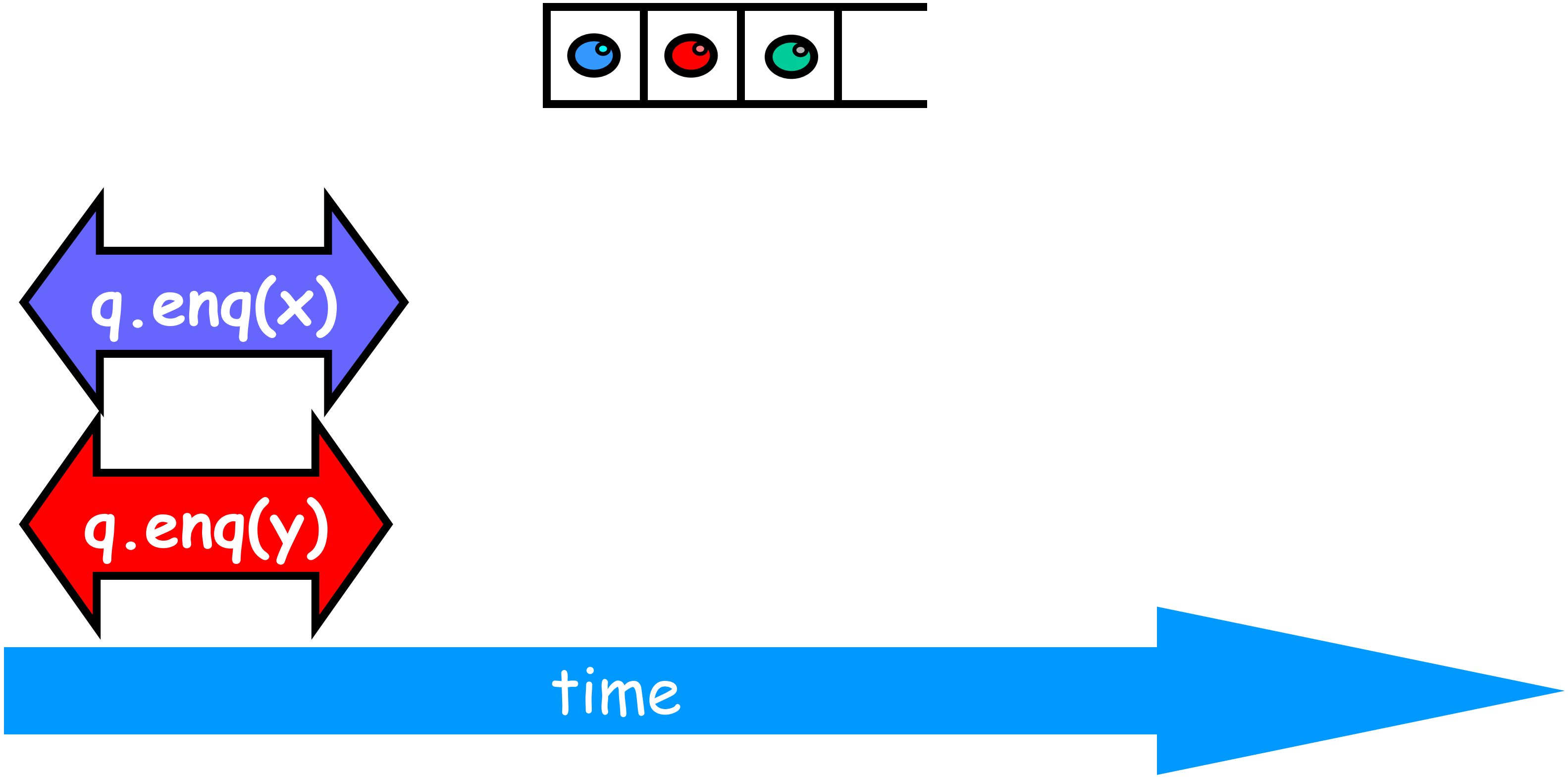

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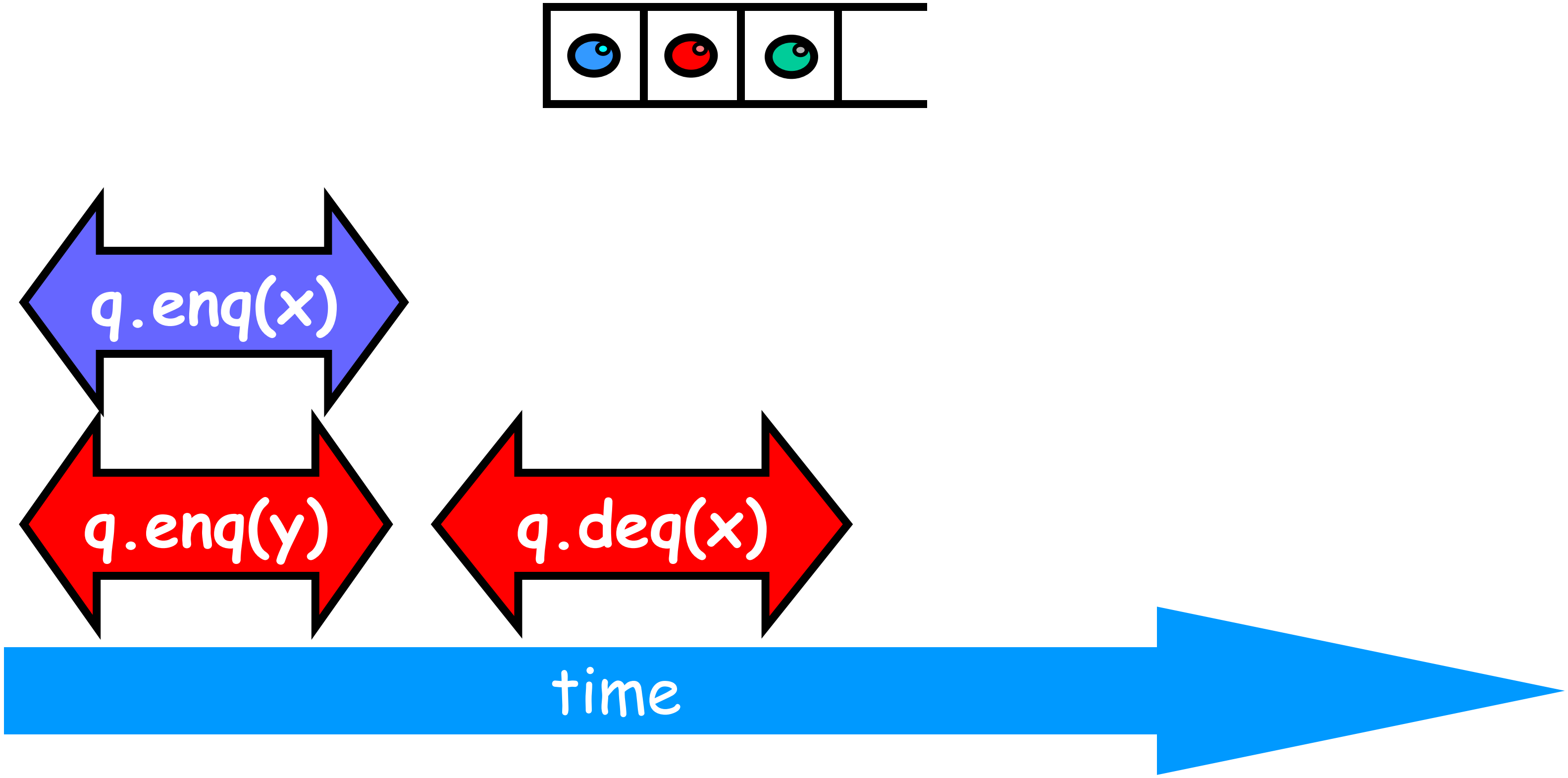

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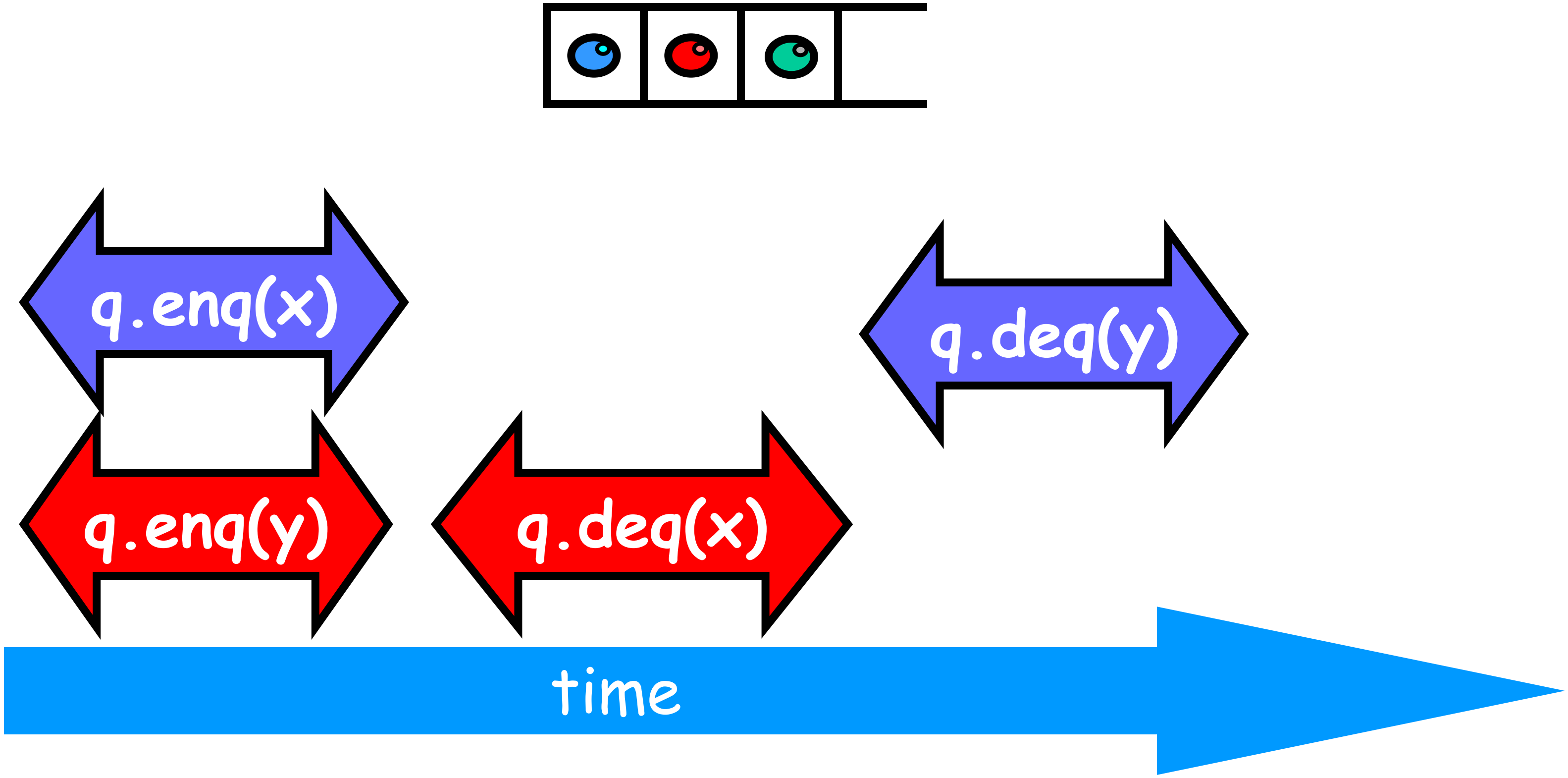

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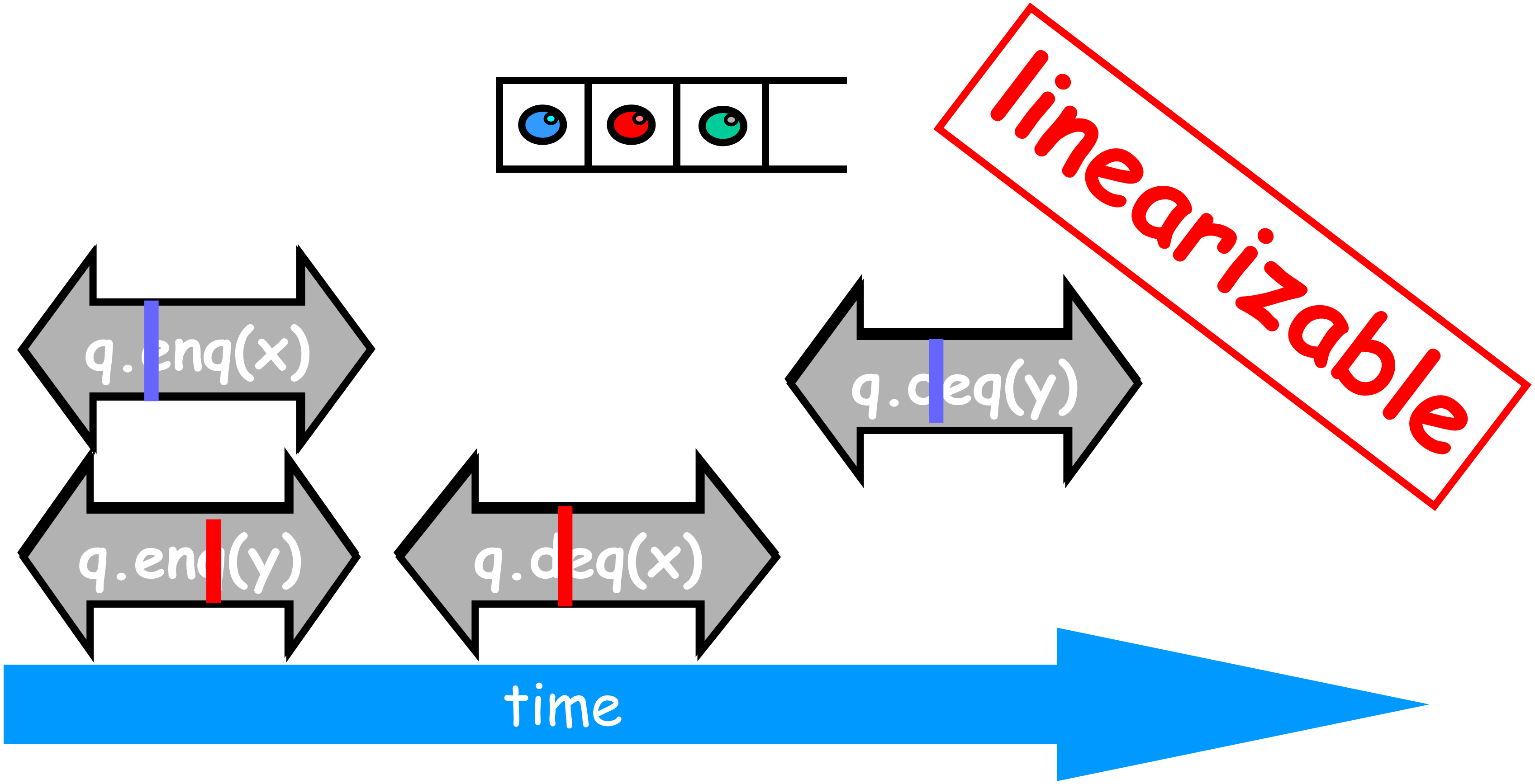

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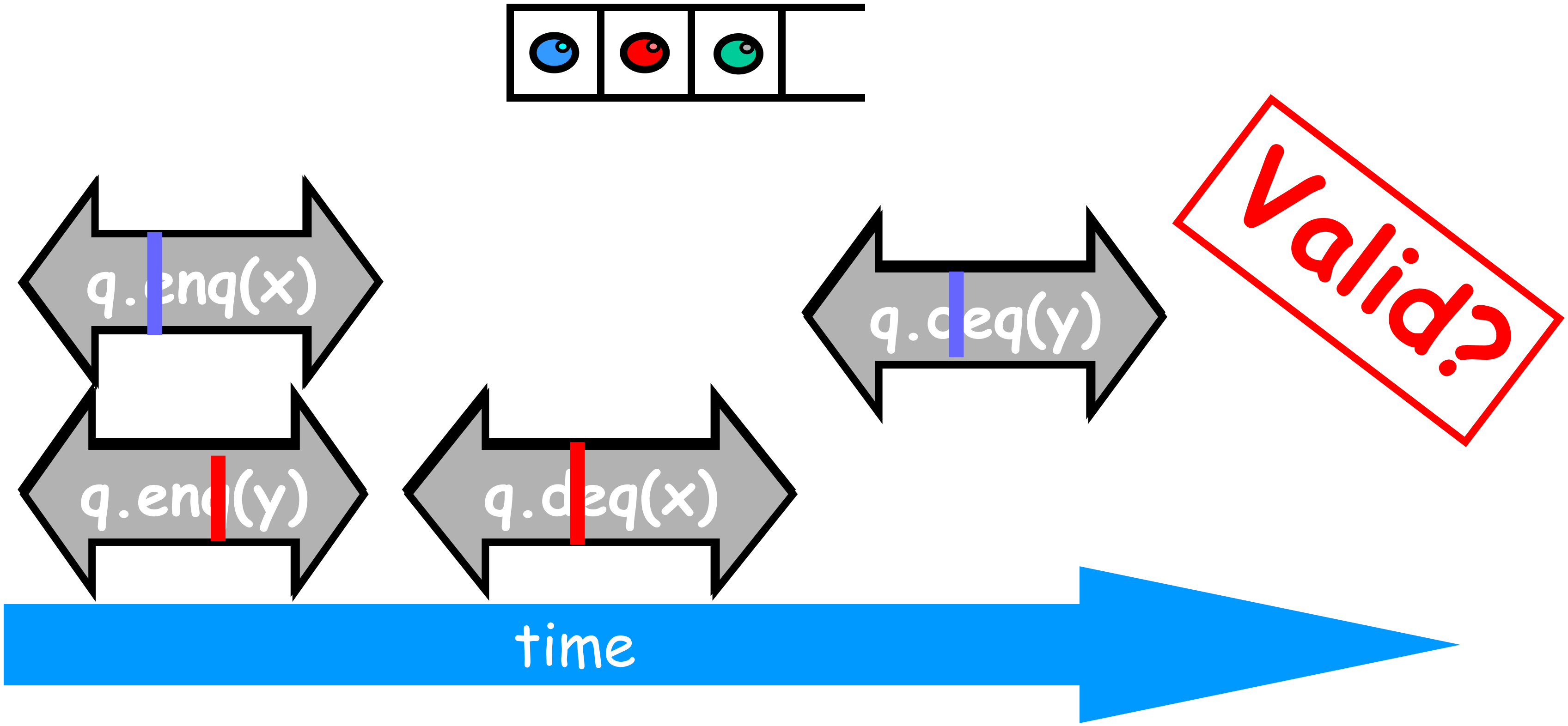

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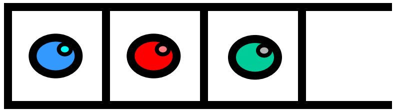

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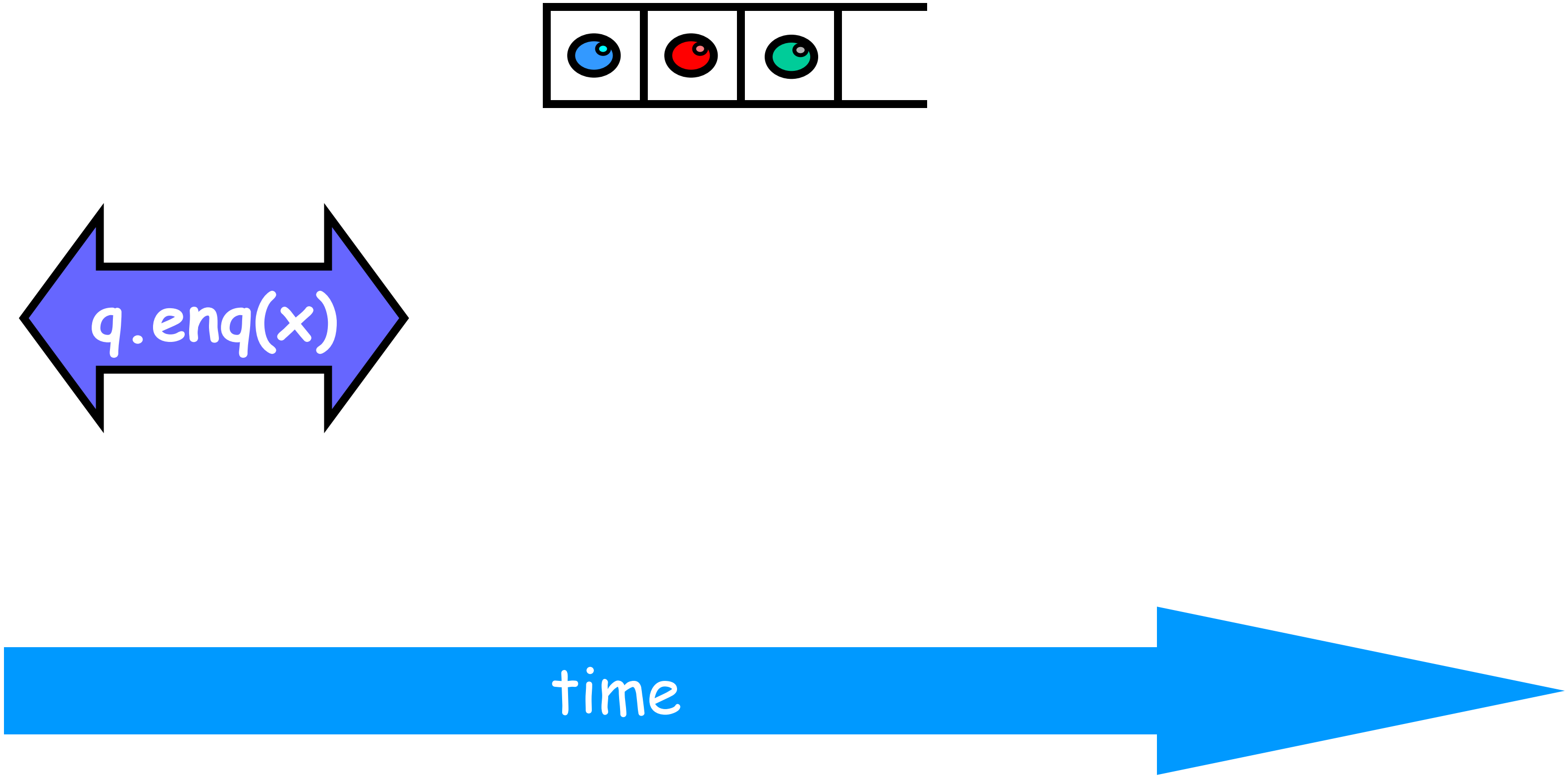

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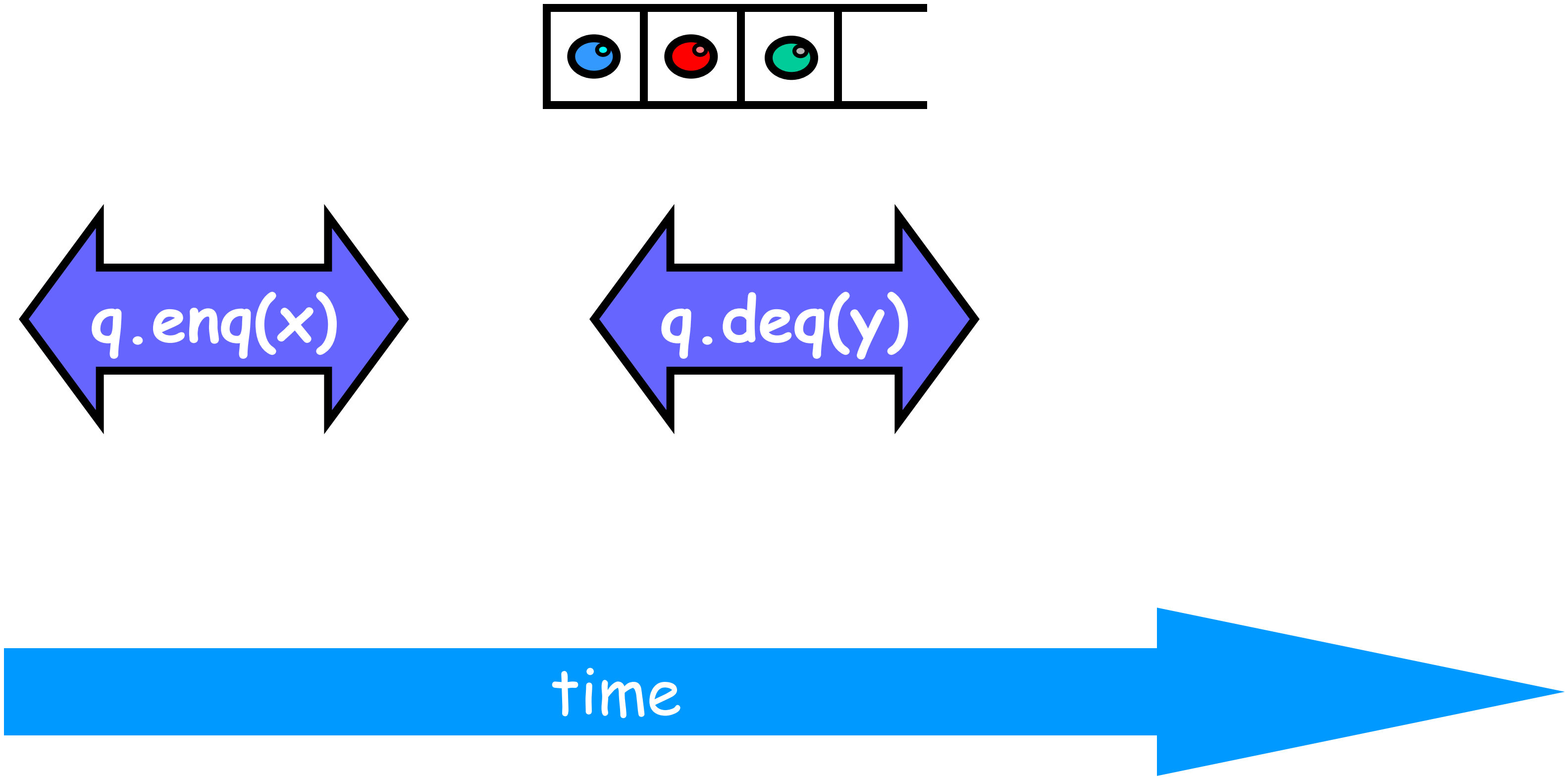

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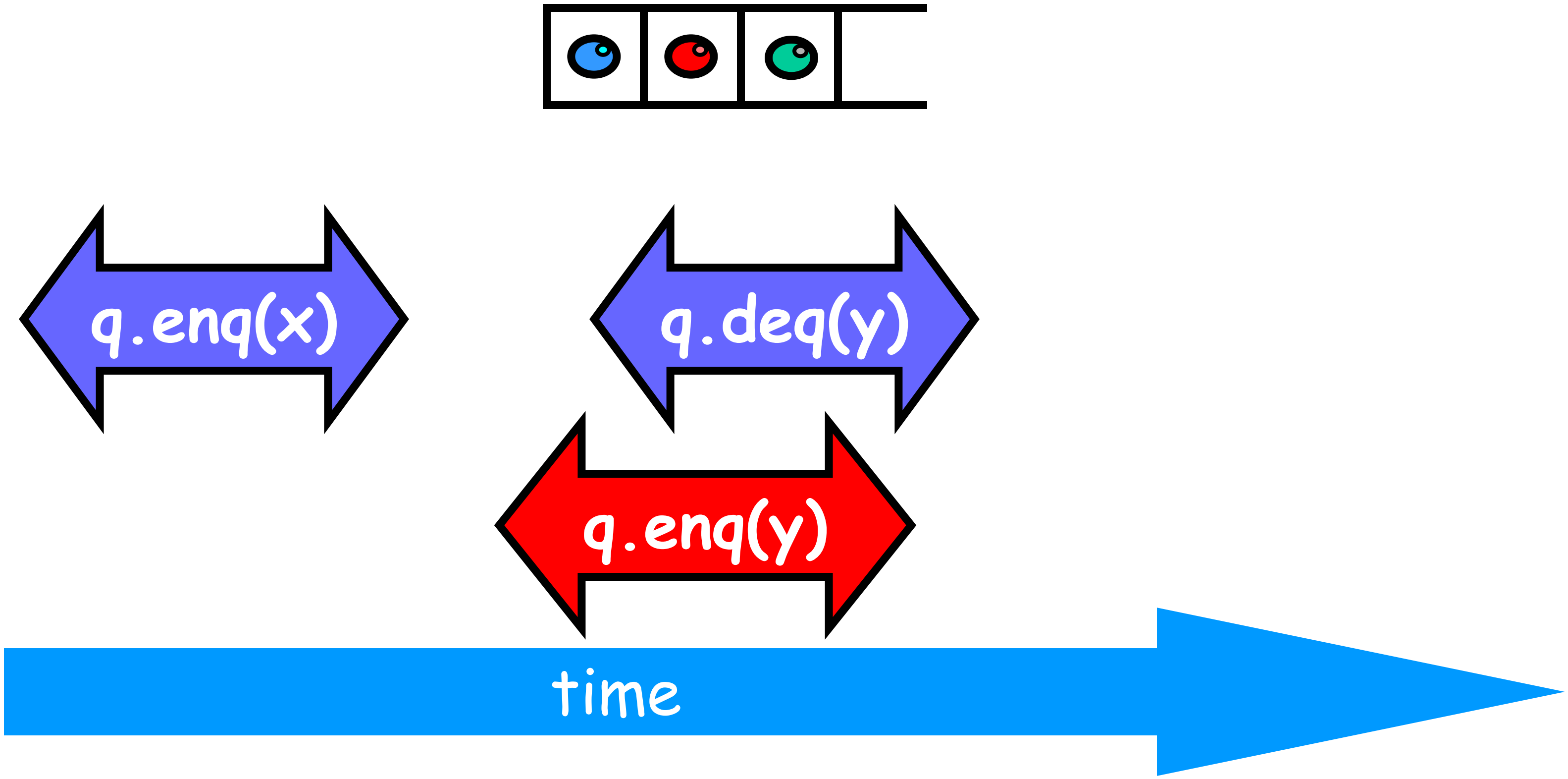

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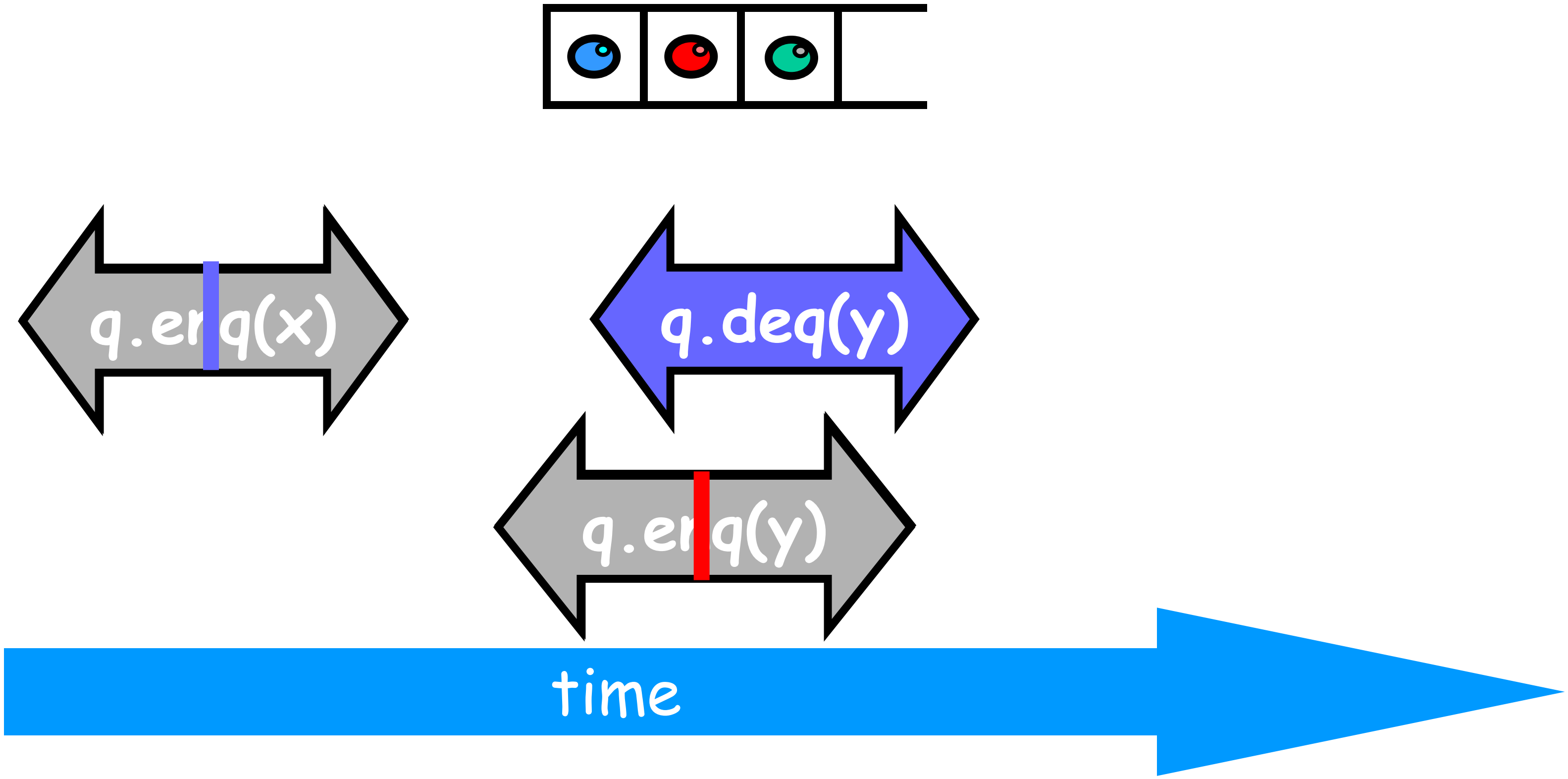

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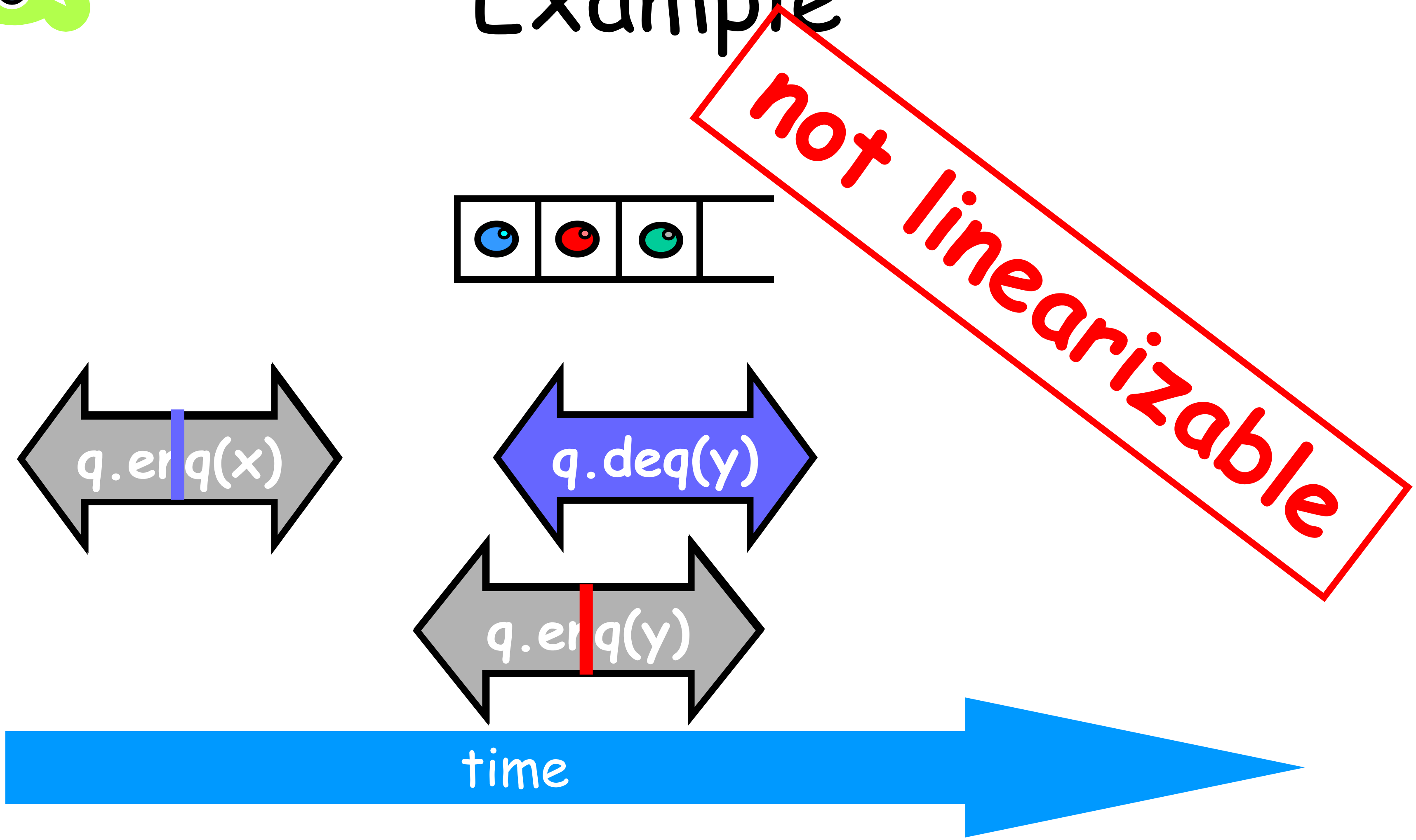

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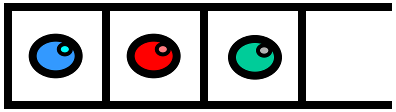

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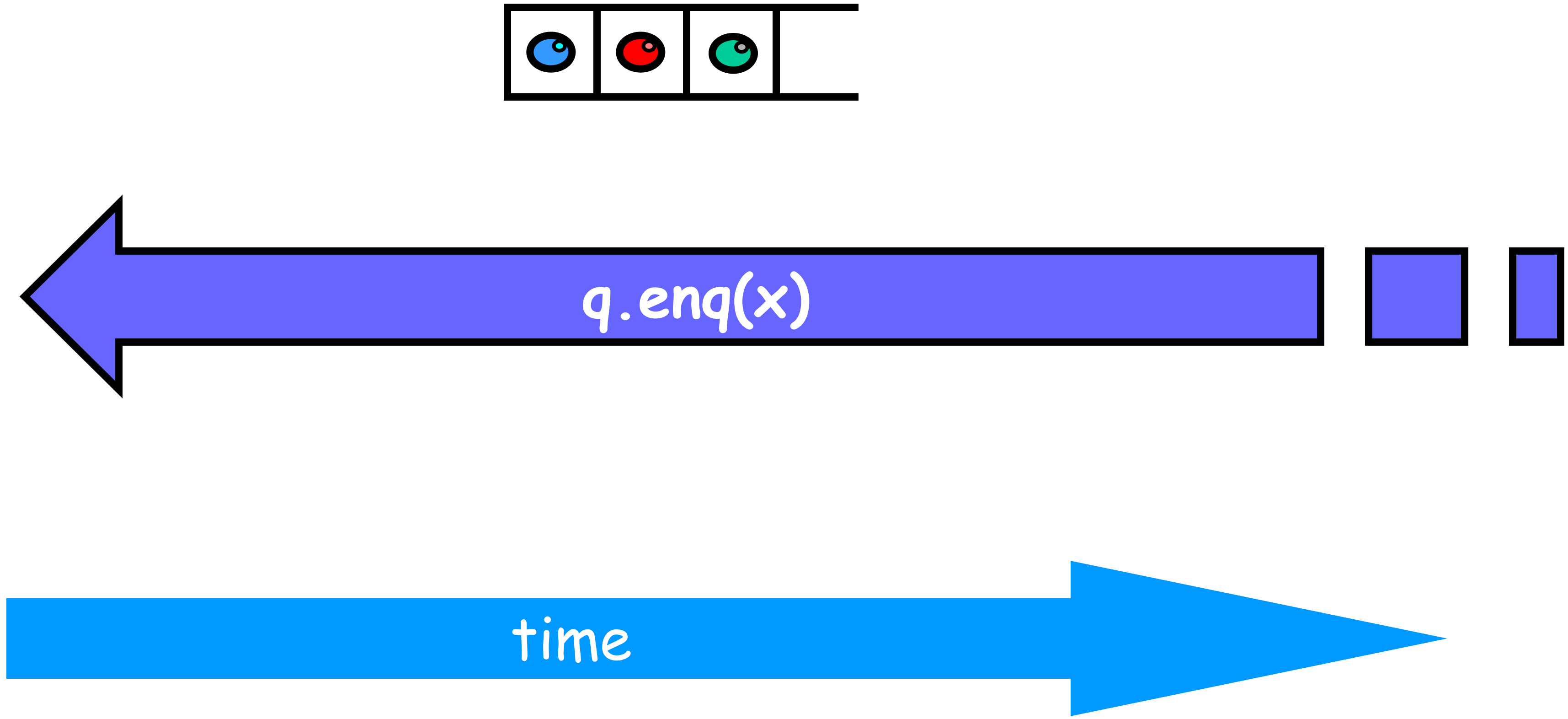

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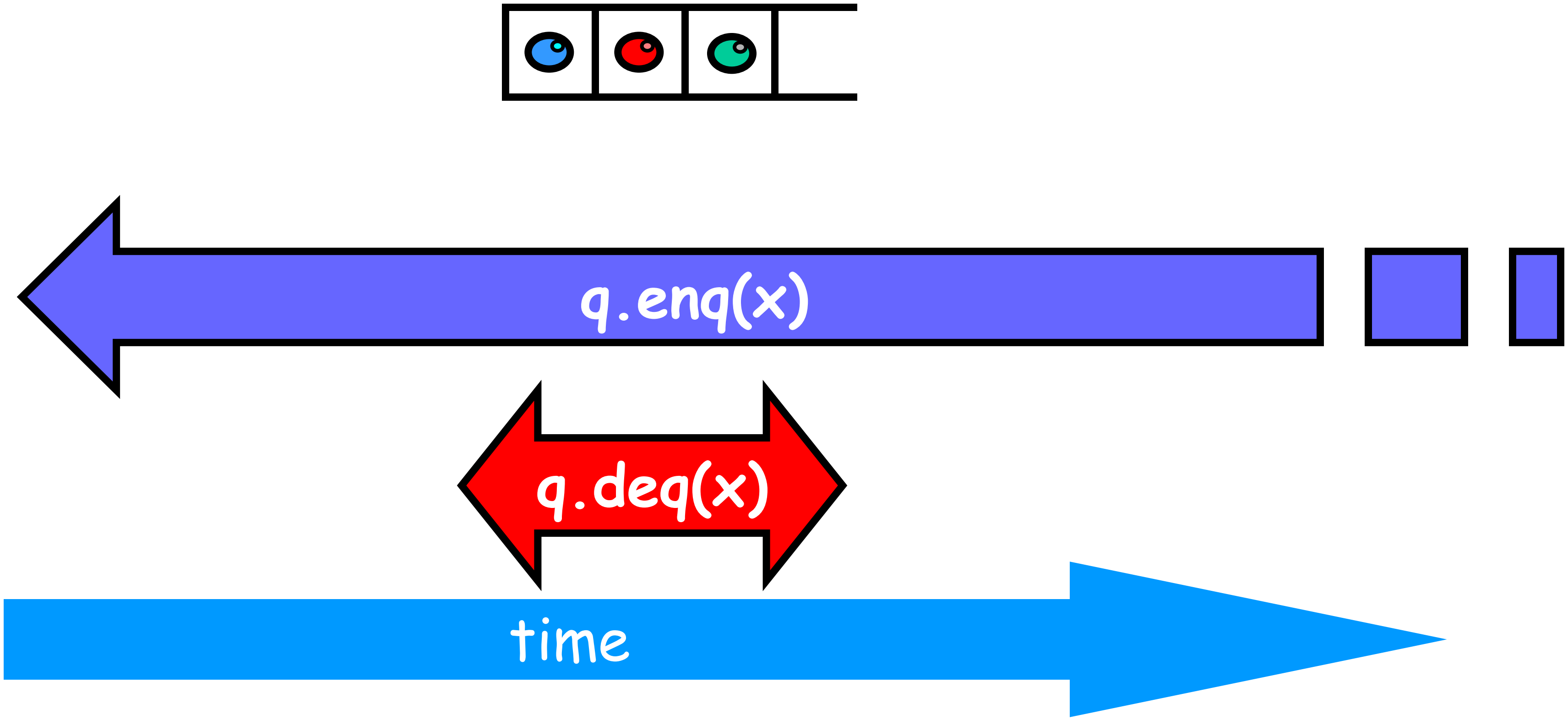

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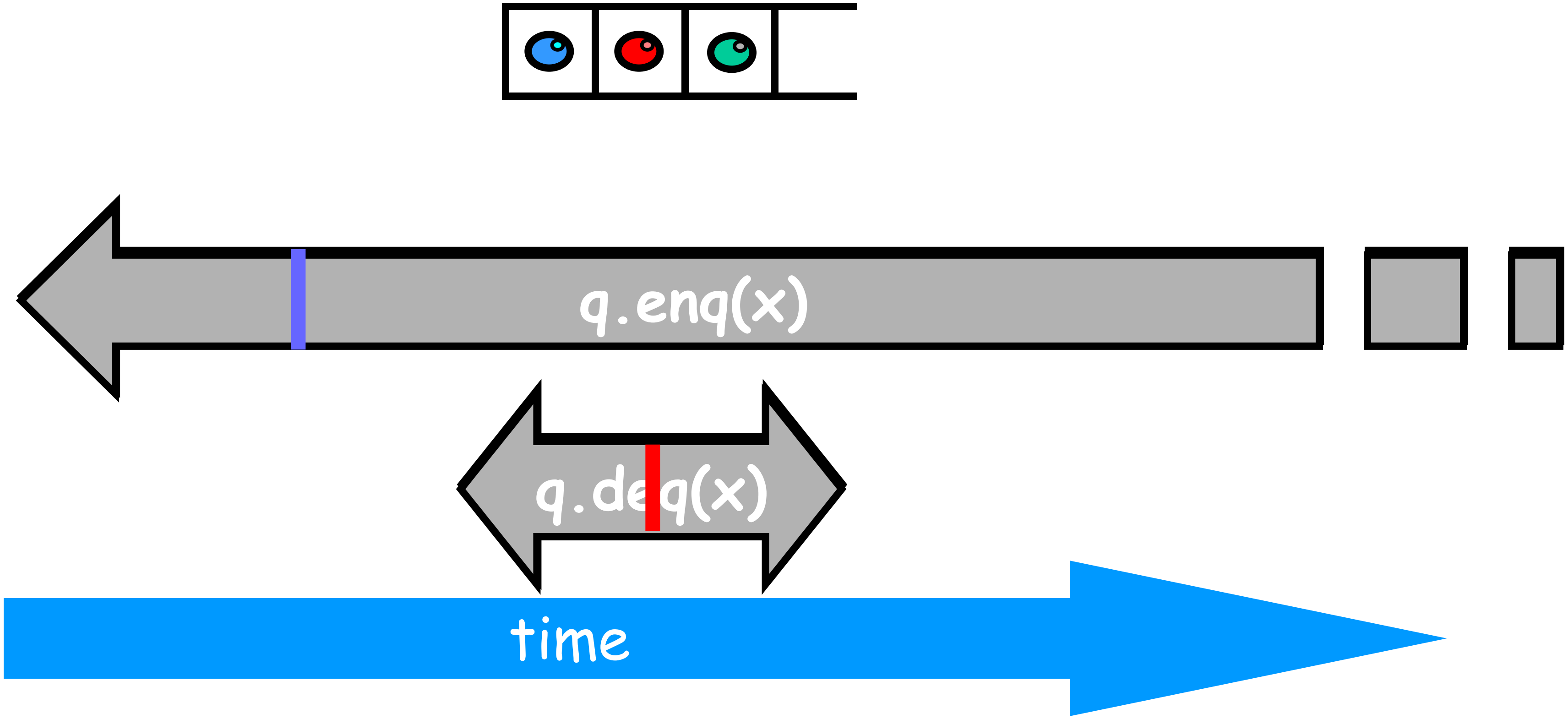

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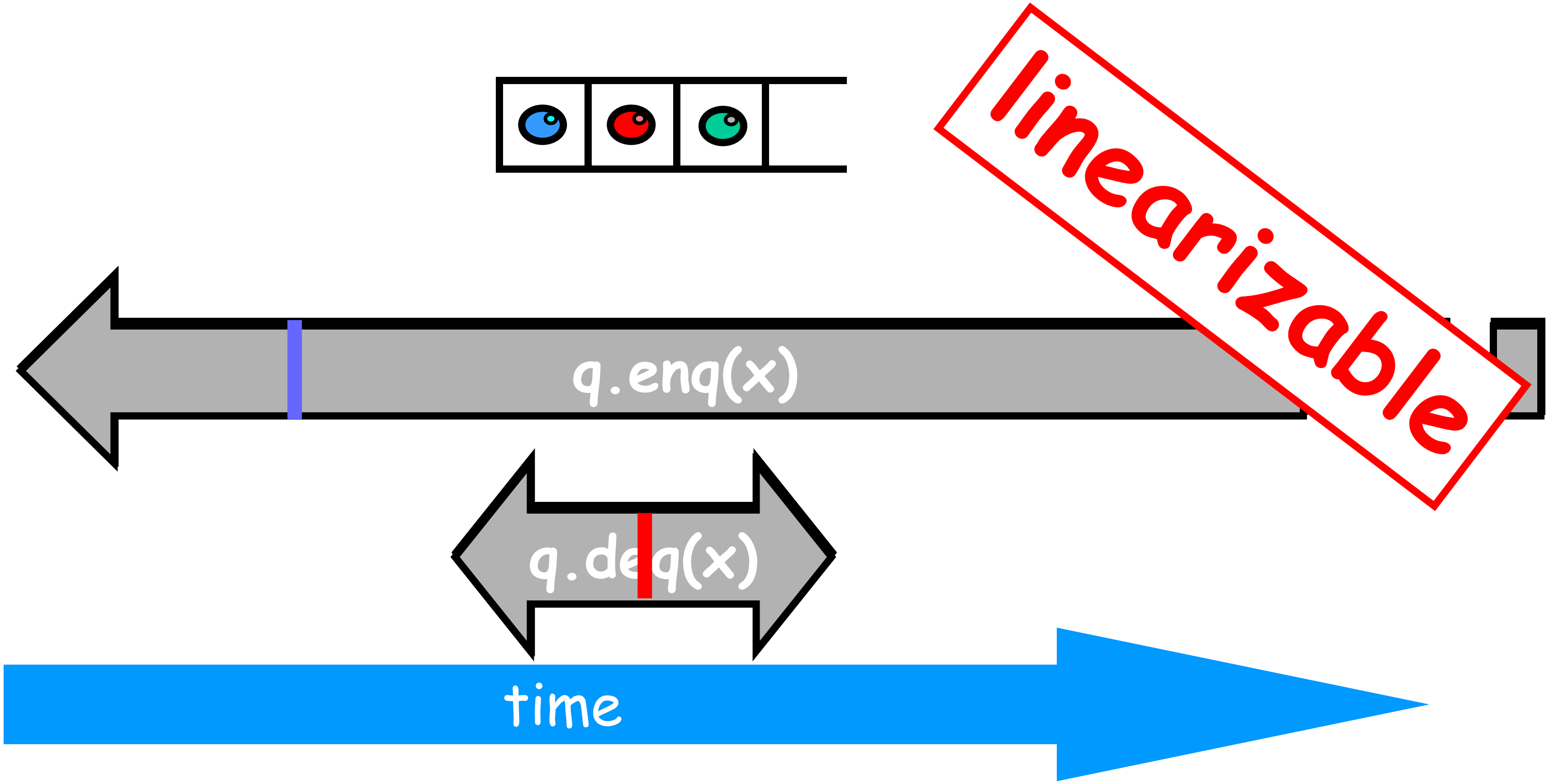

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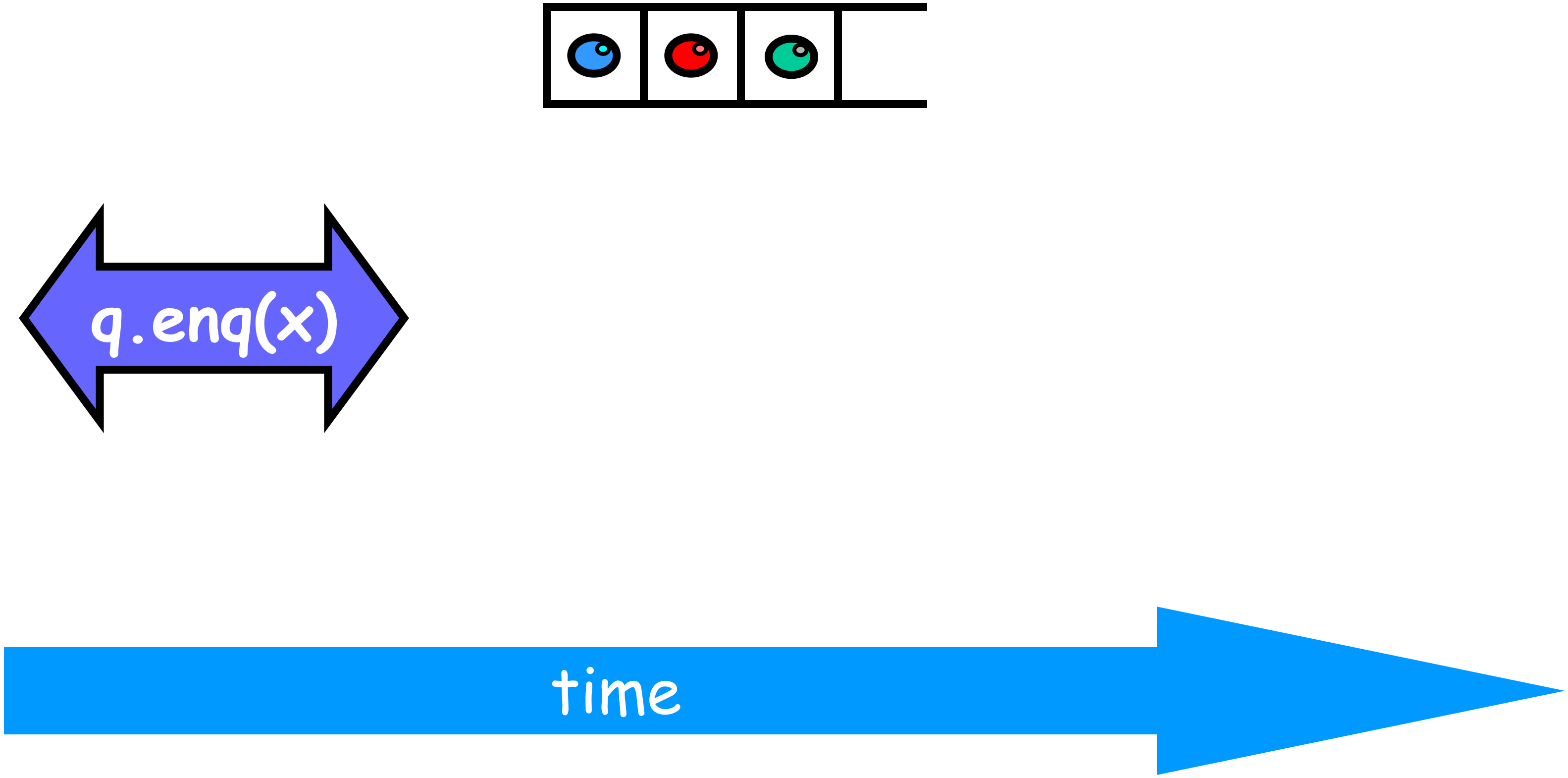

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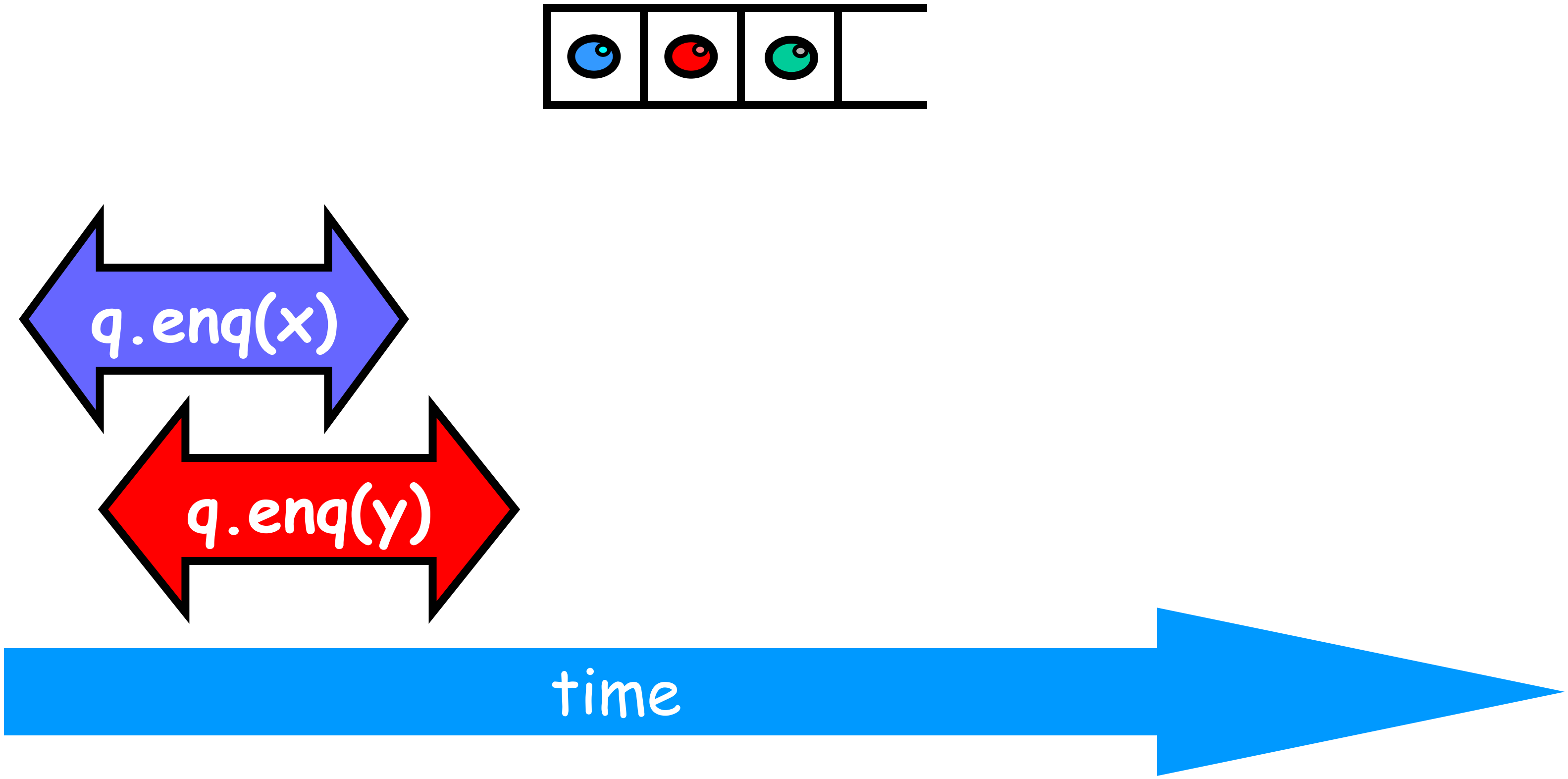

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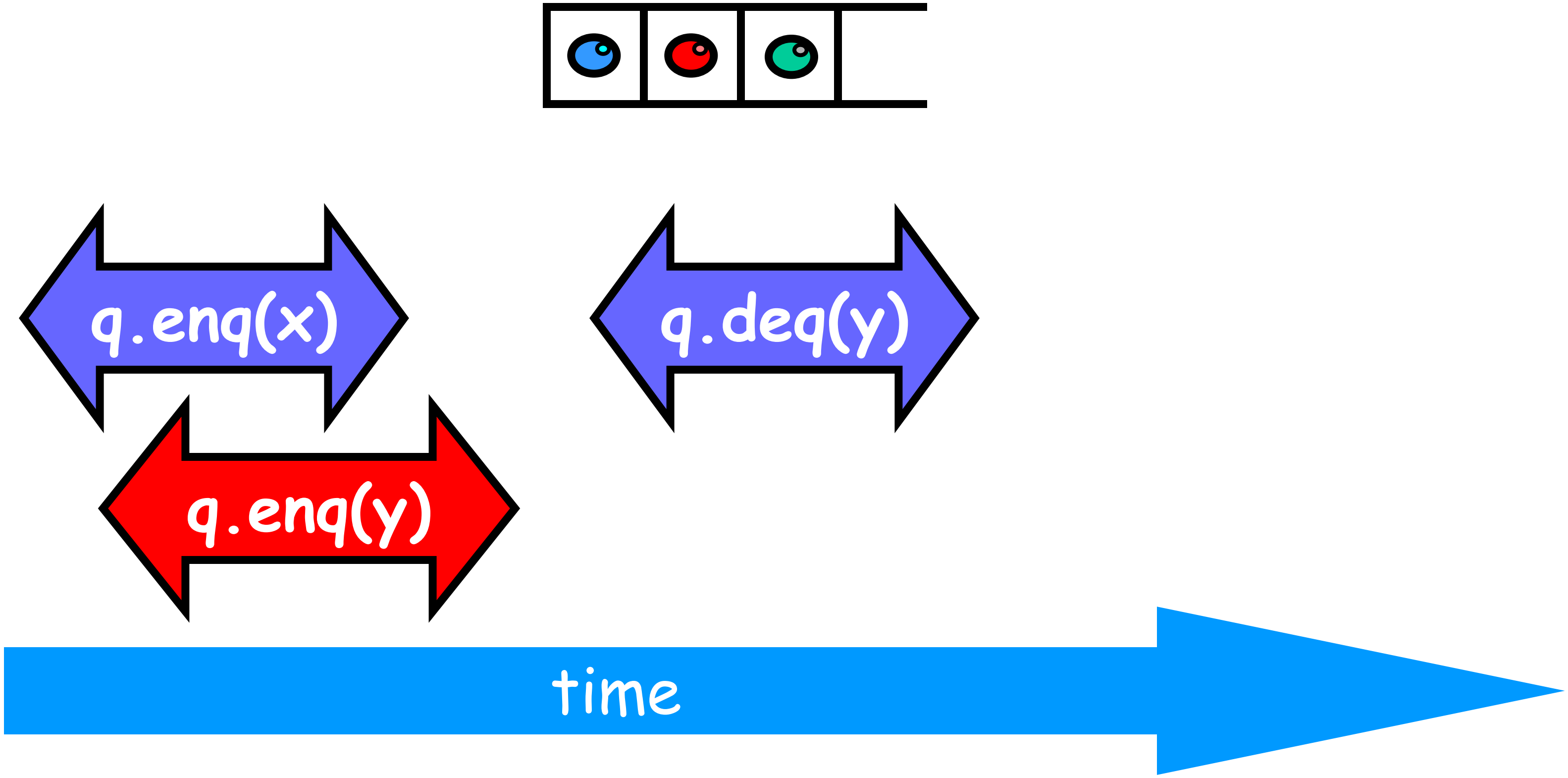

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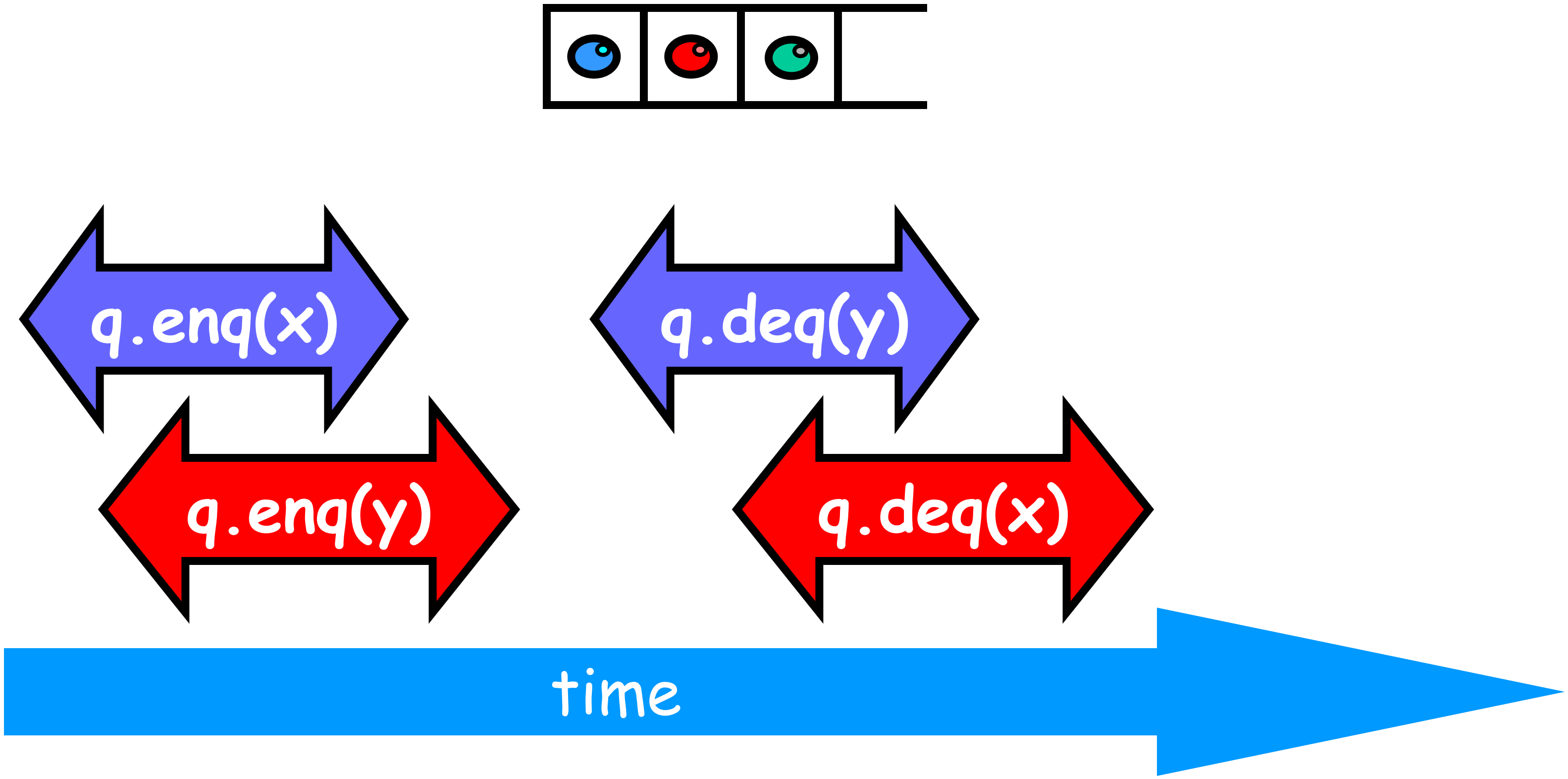

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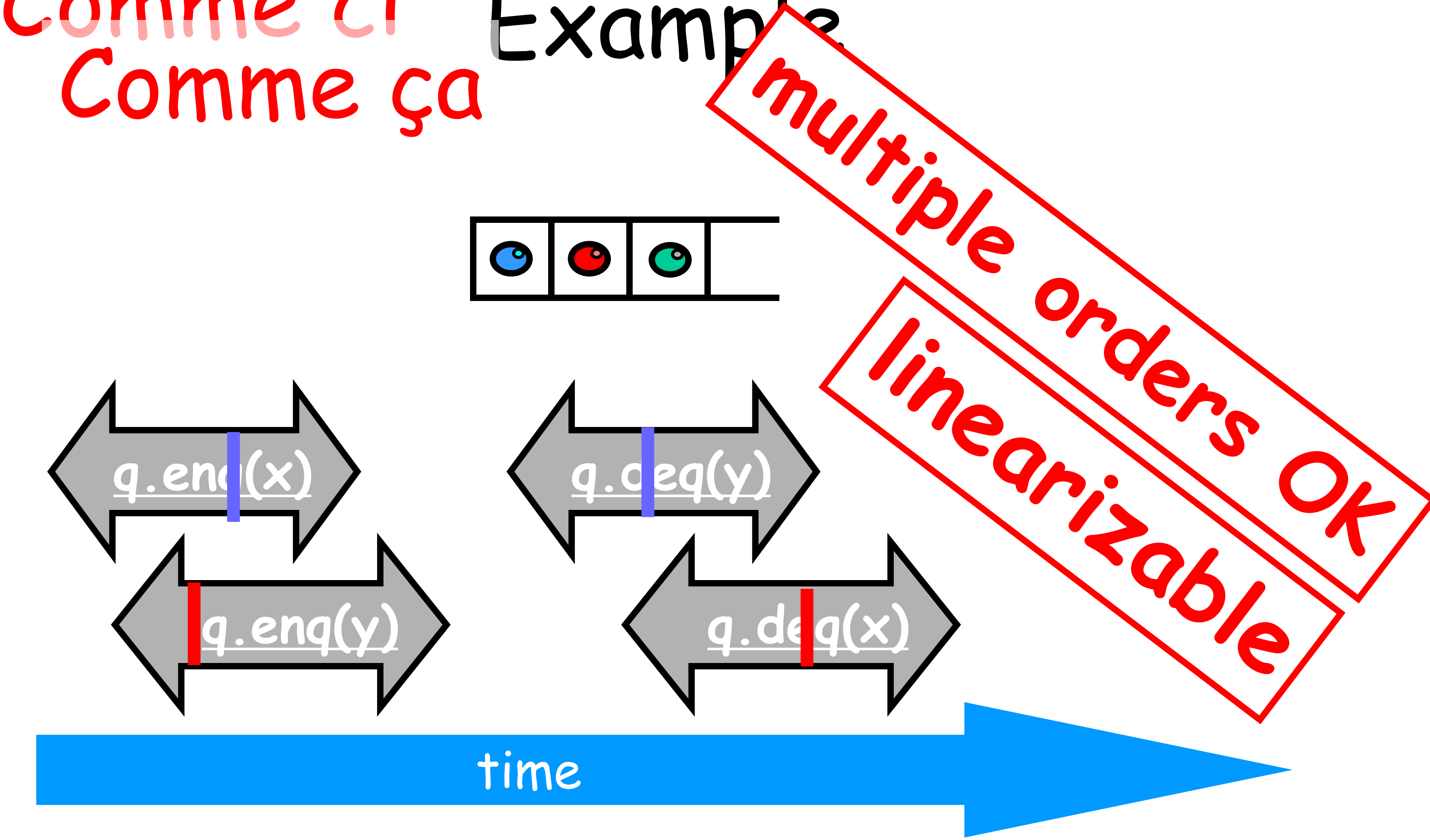
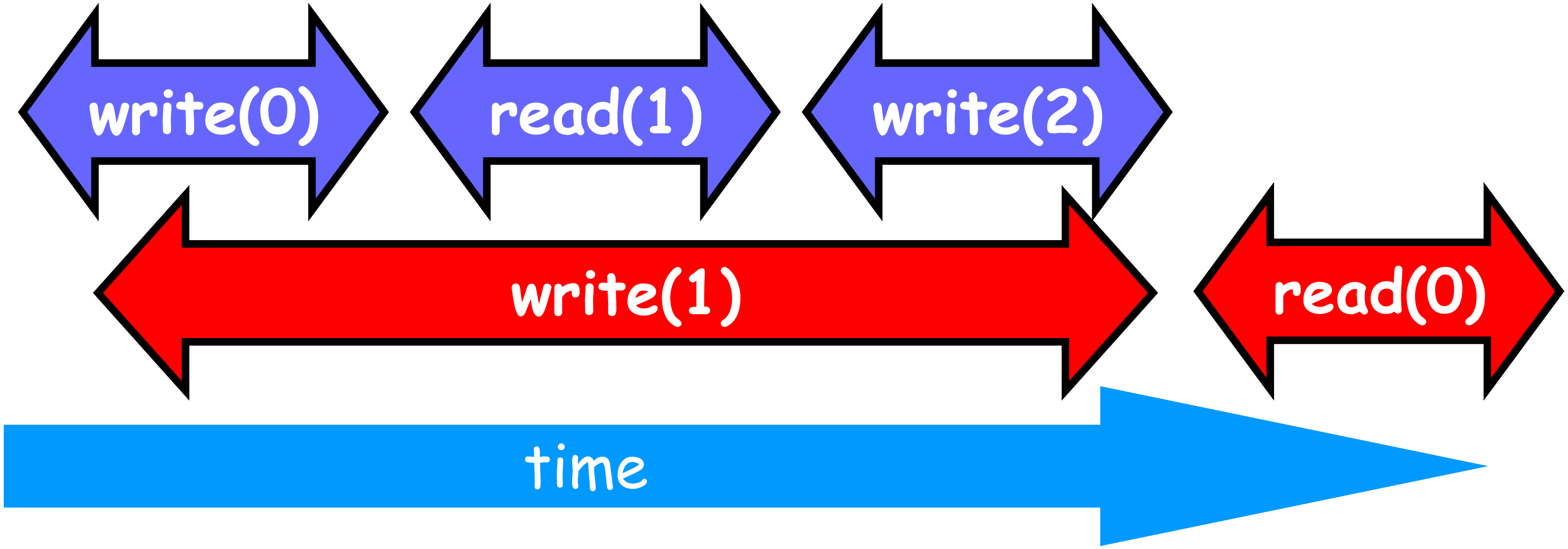


Read/Write Register Example



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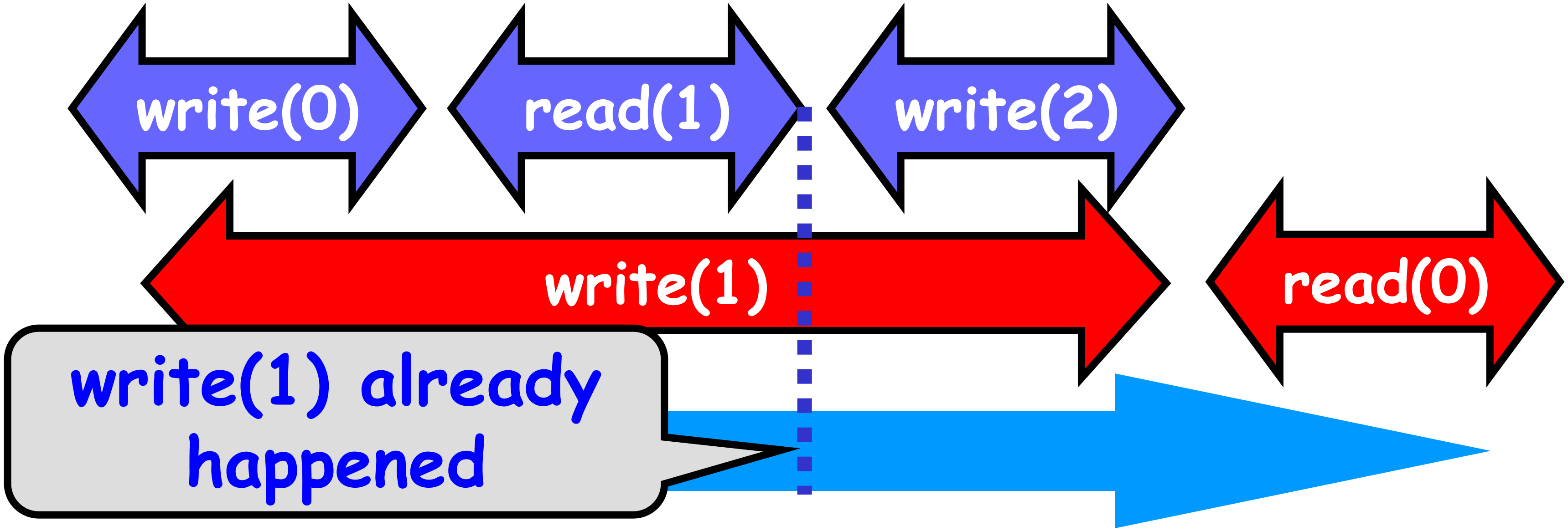

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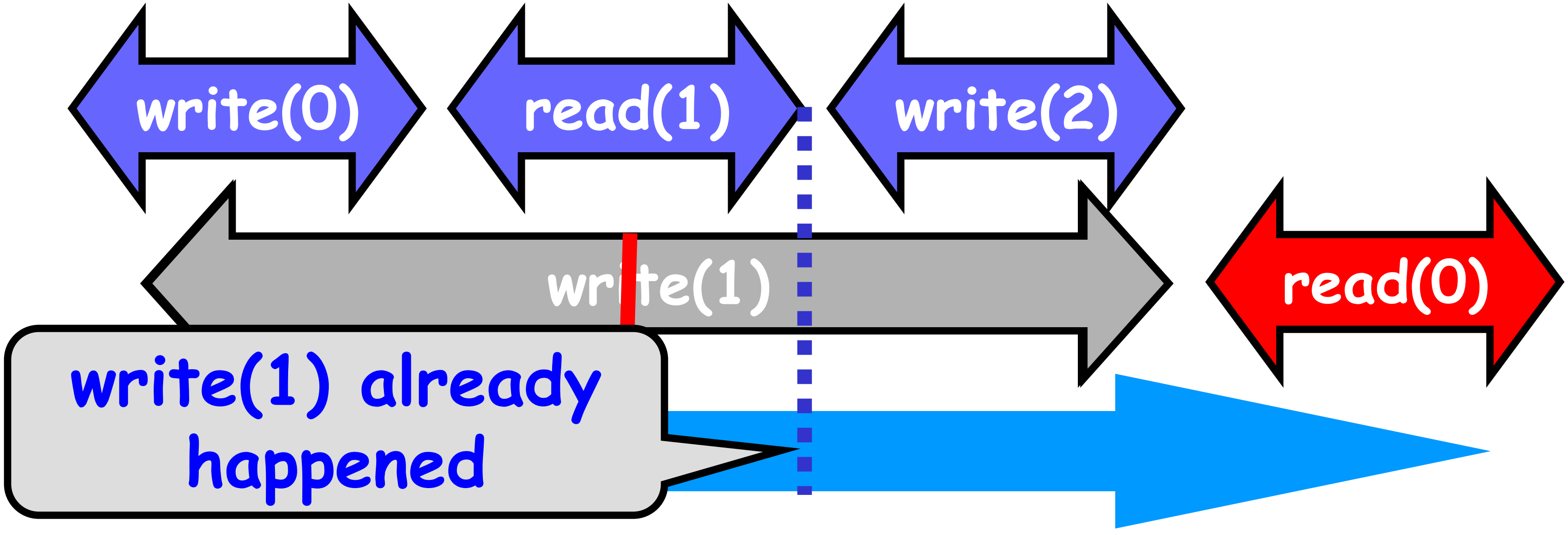

write(1) already happened

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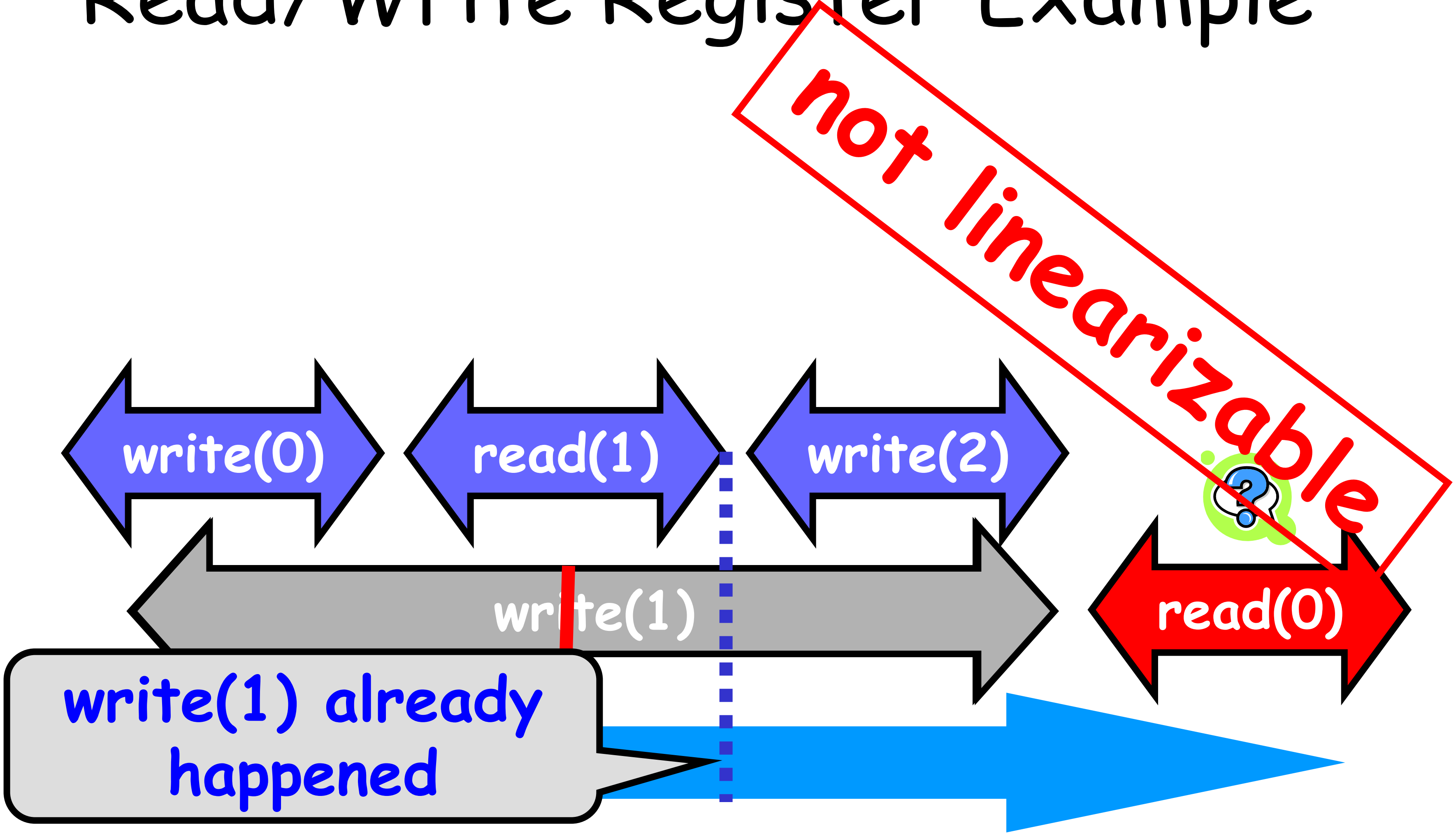

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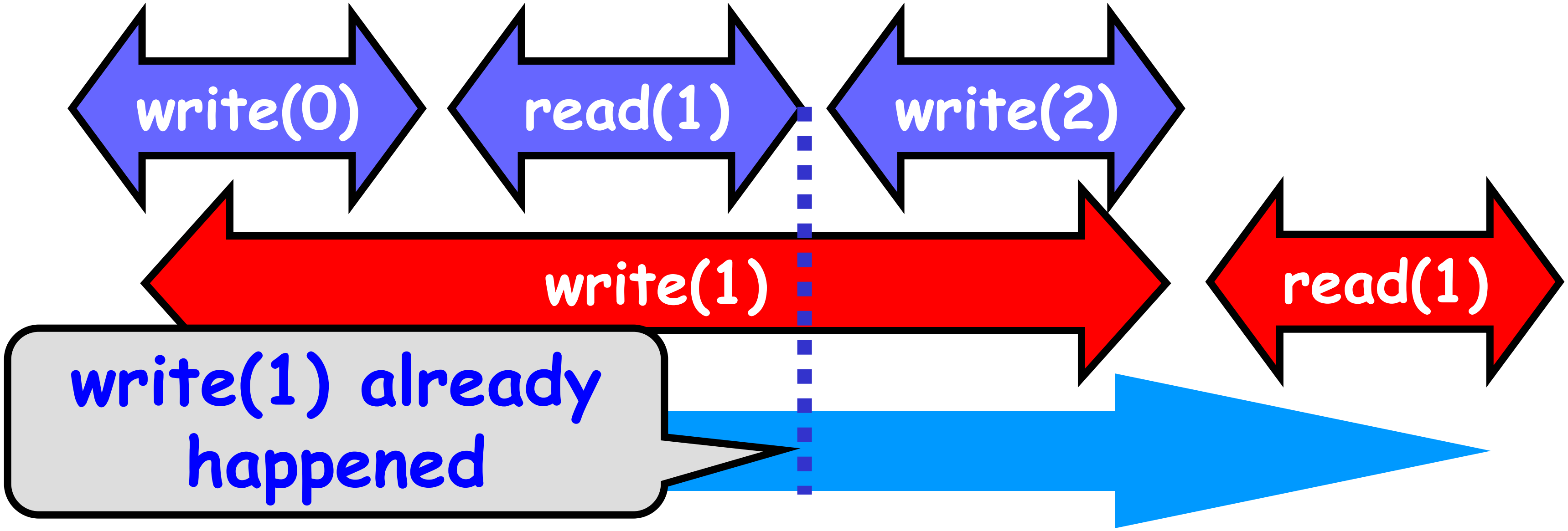

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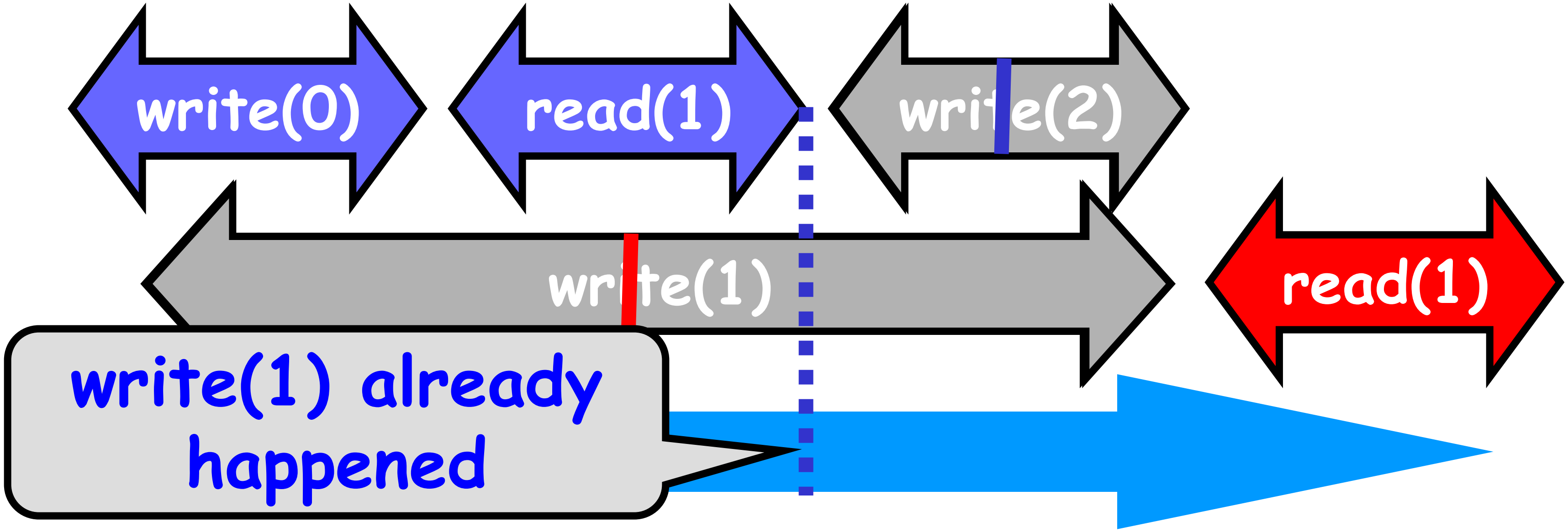

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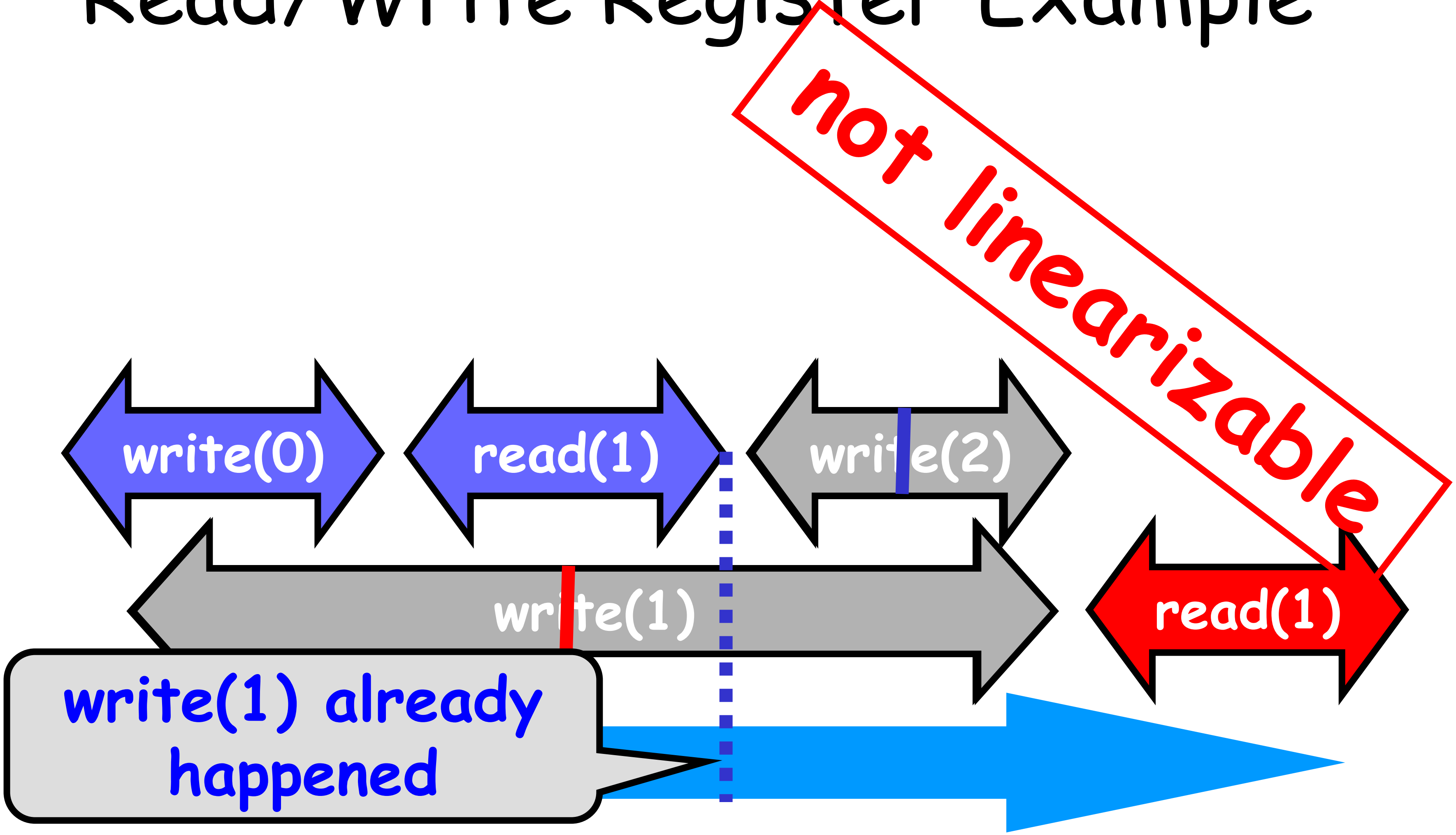

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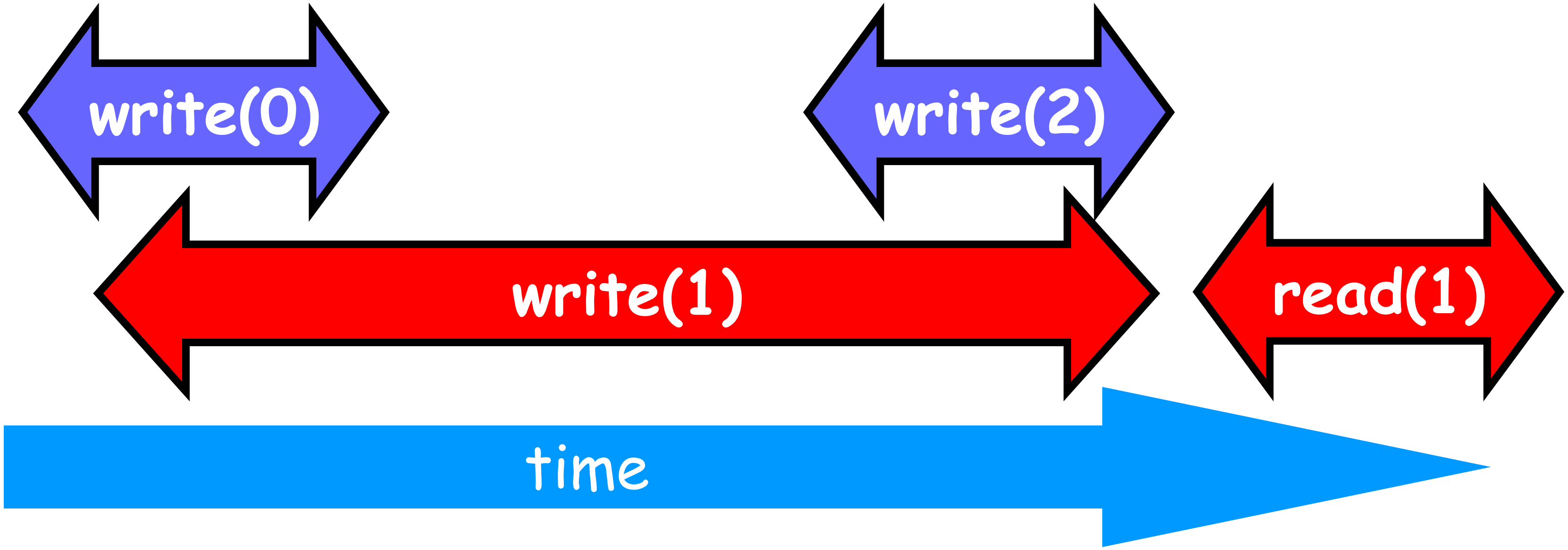

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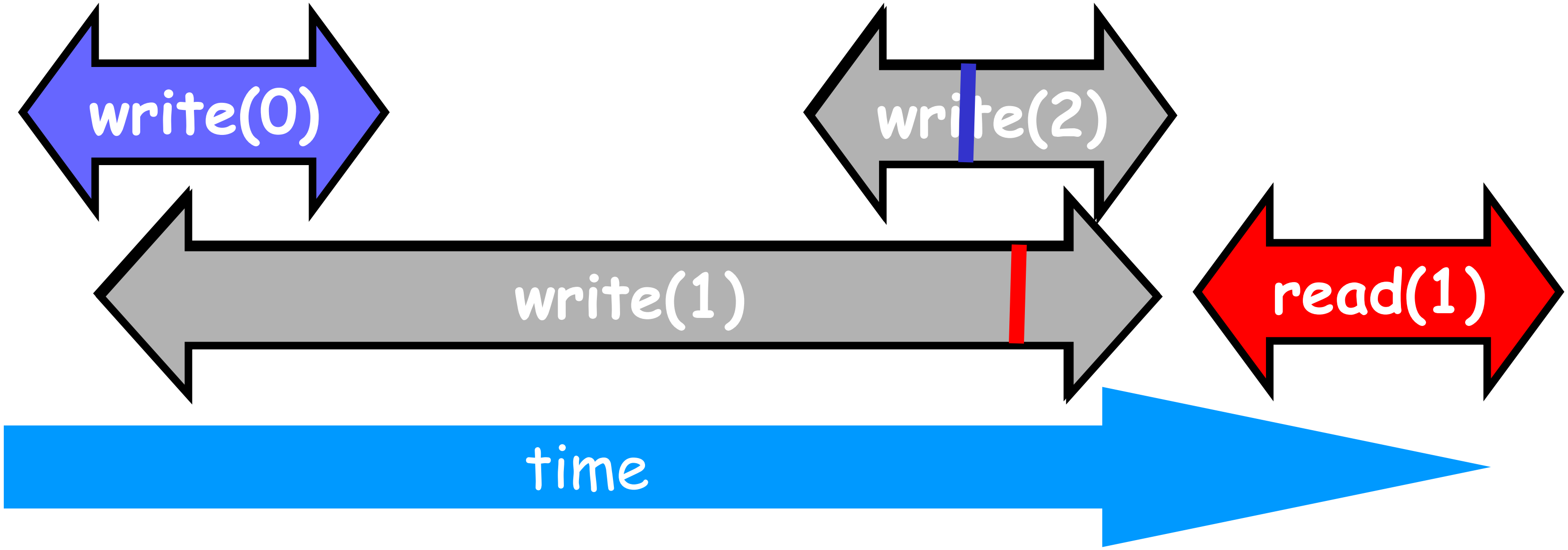

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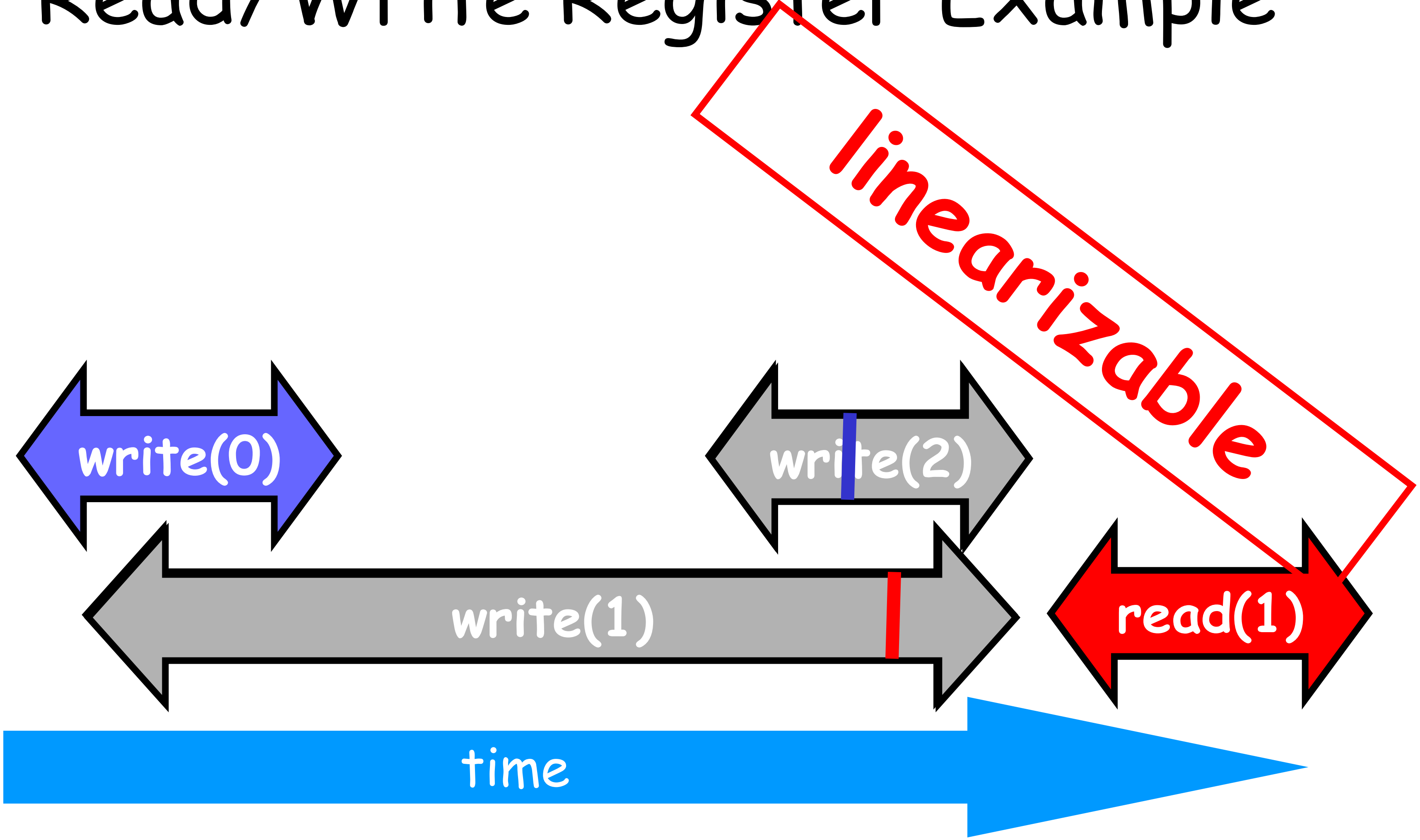

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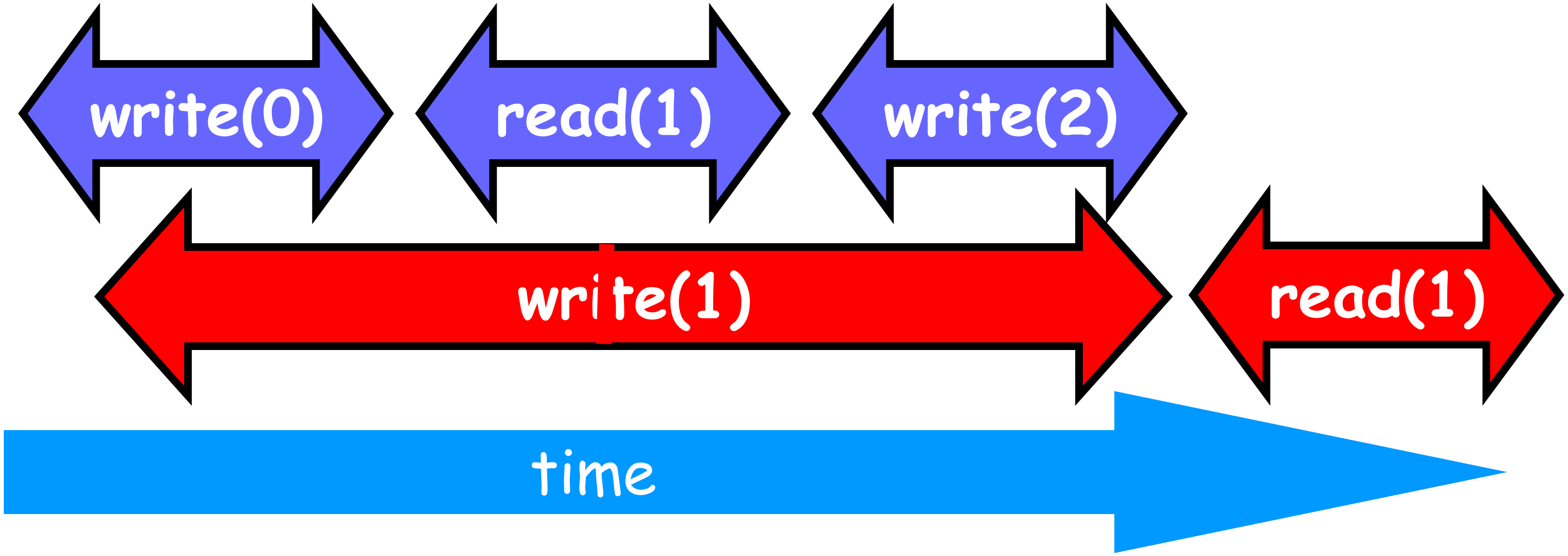
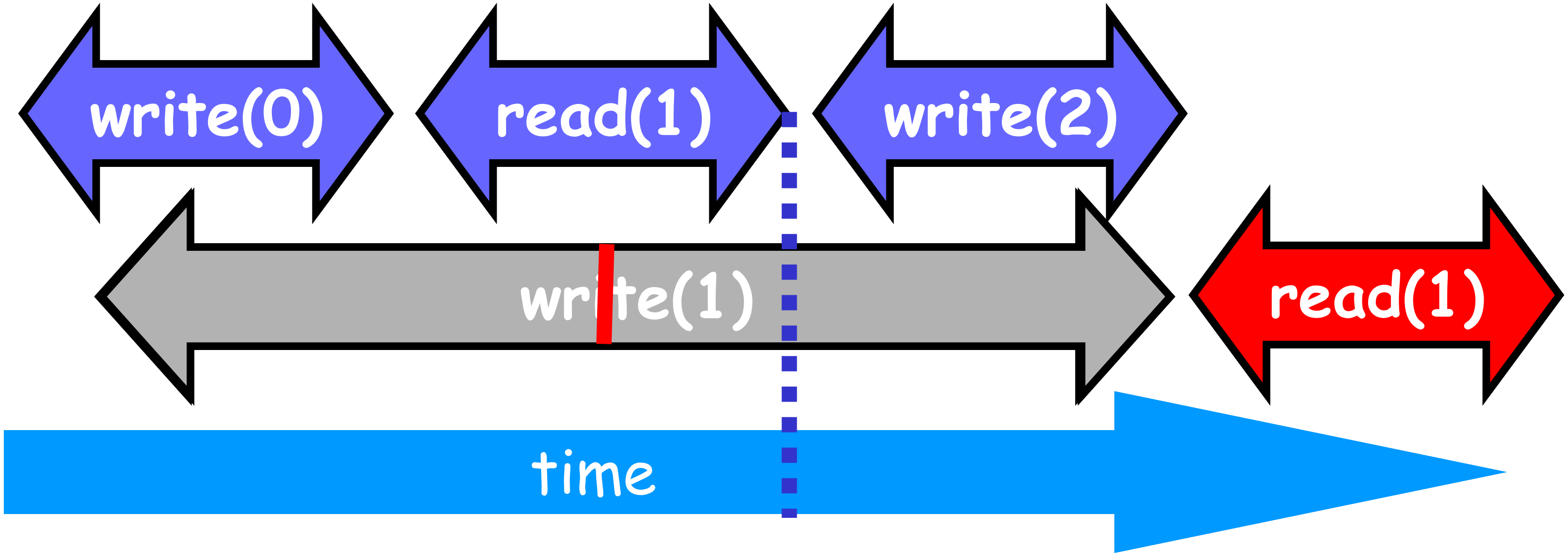
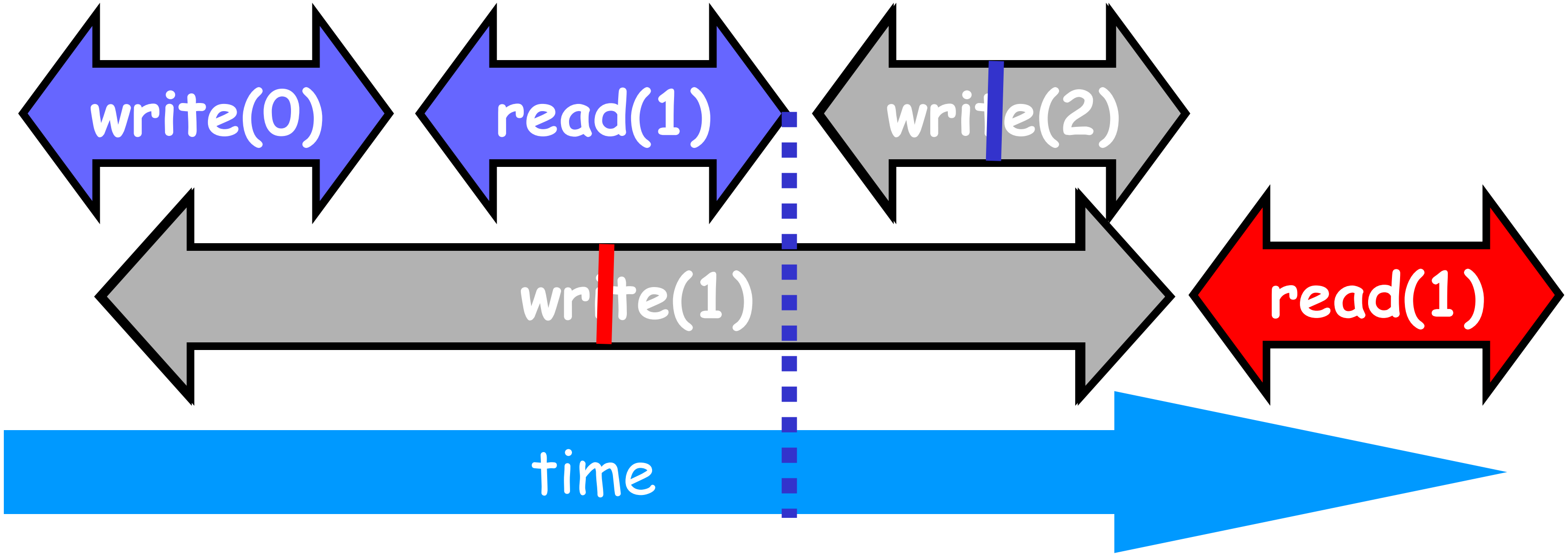


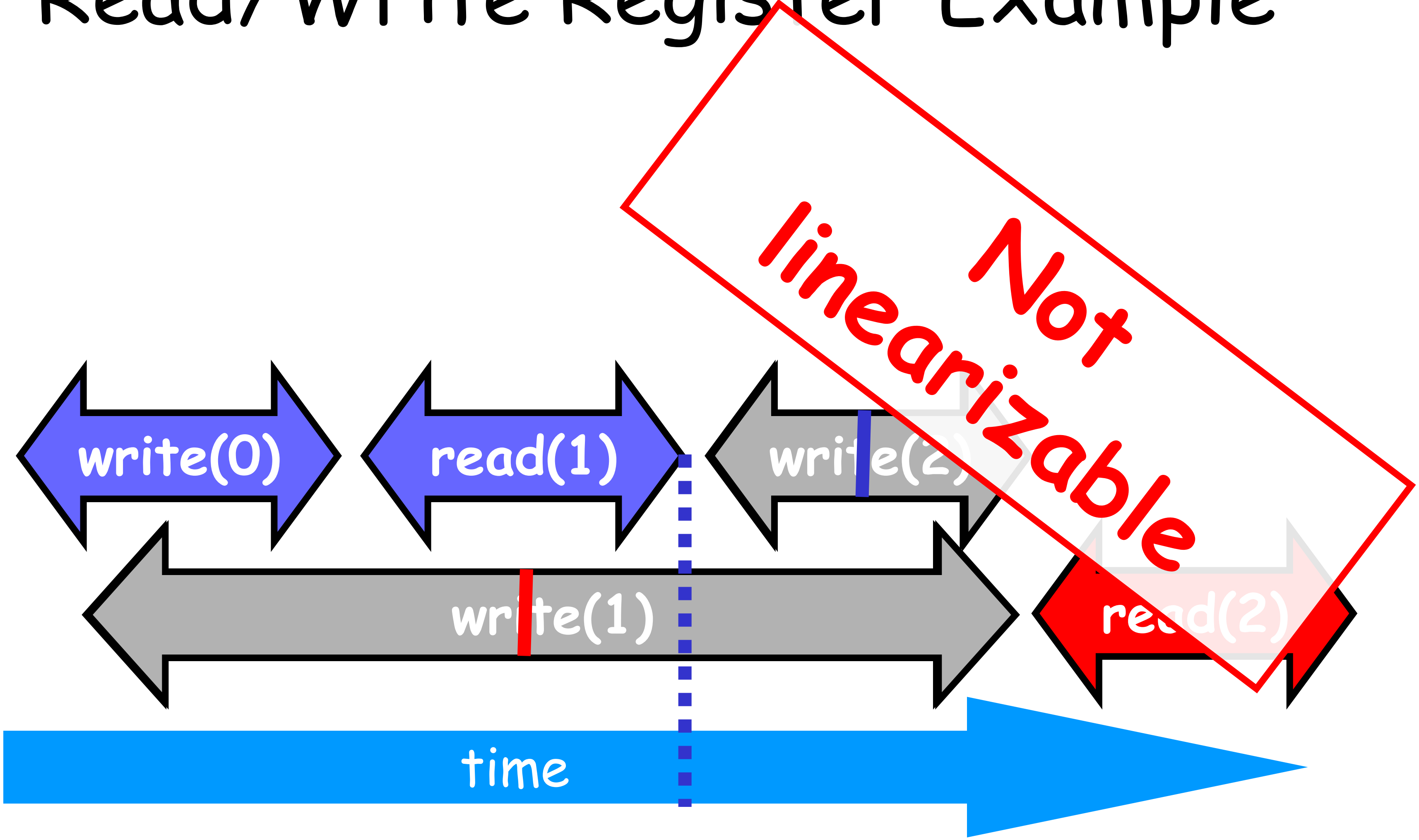
Read/Write Register Example



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
    - Ask me 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

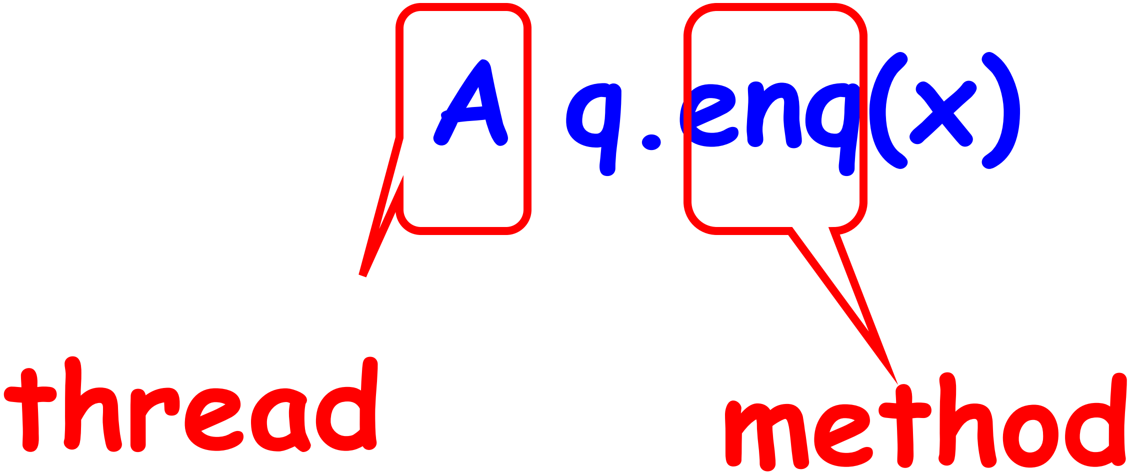
A q.enq(x)

Invocation Notation

A q.enq(x)

thread

Invocation Notation

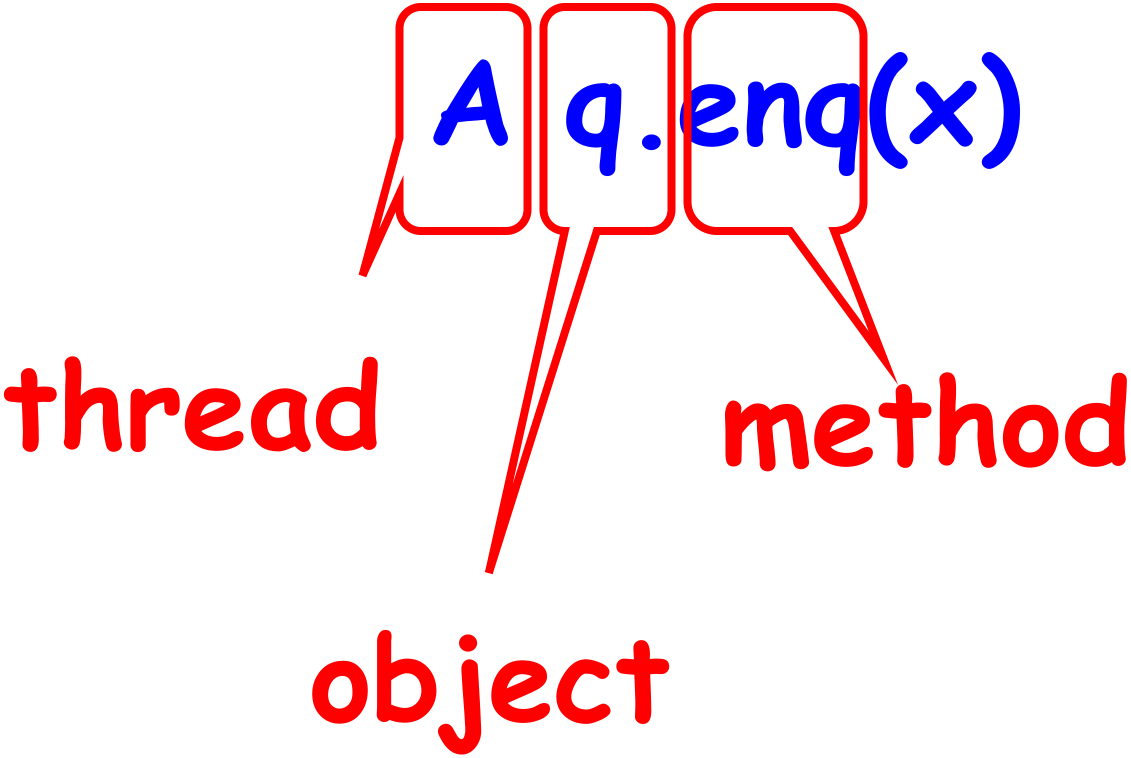


A q.enq(x)

thread

method

Invocation Notation



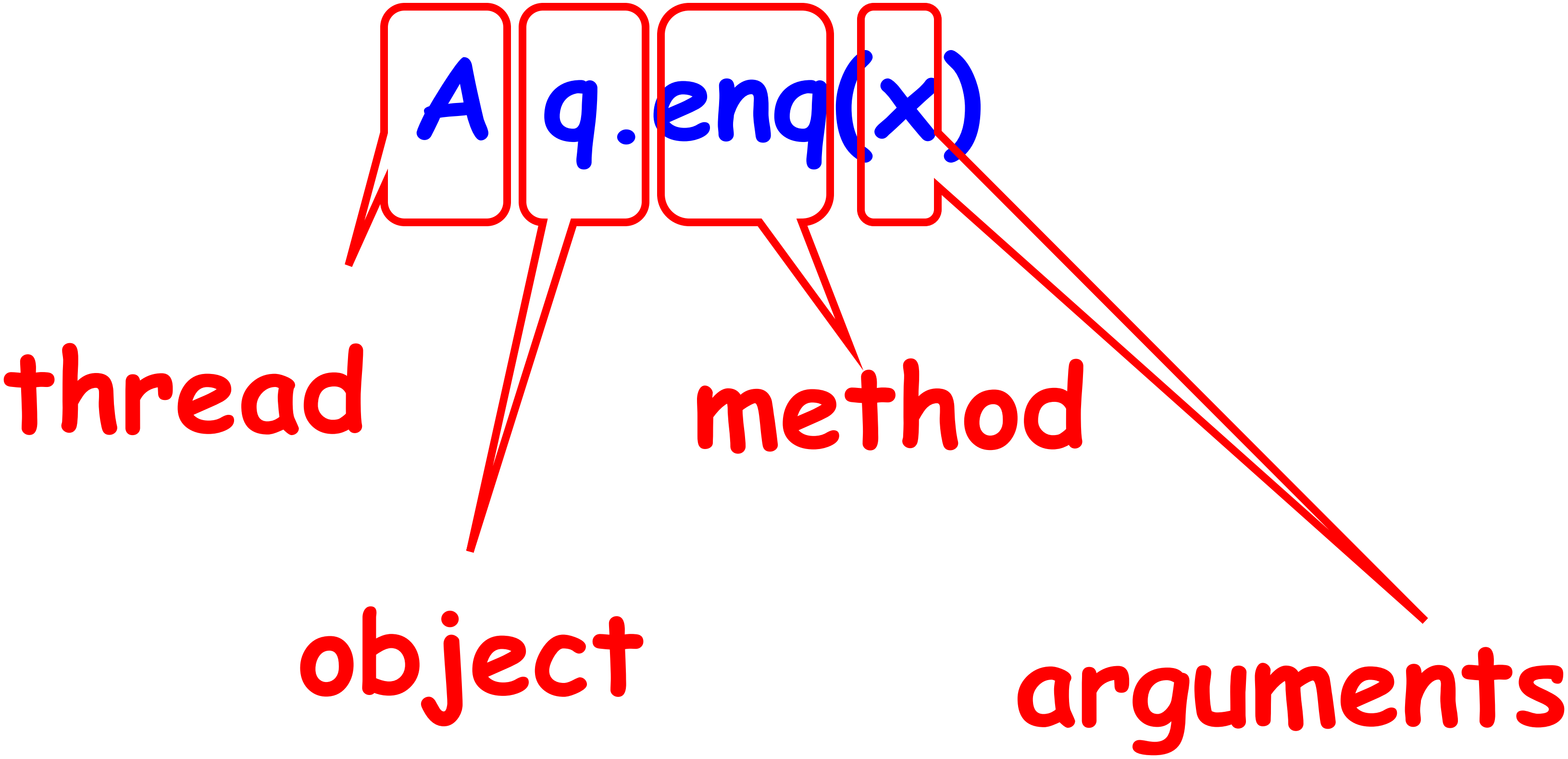
A q.enq(x)

thread

method

object

Invocation Notation



A q.enq(x)

thread

object

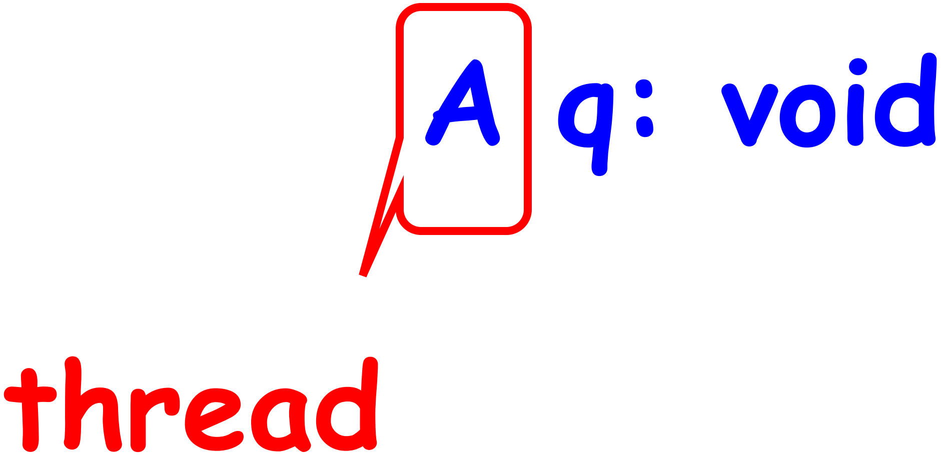
method

arguments

Response Notation

A q: void

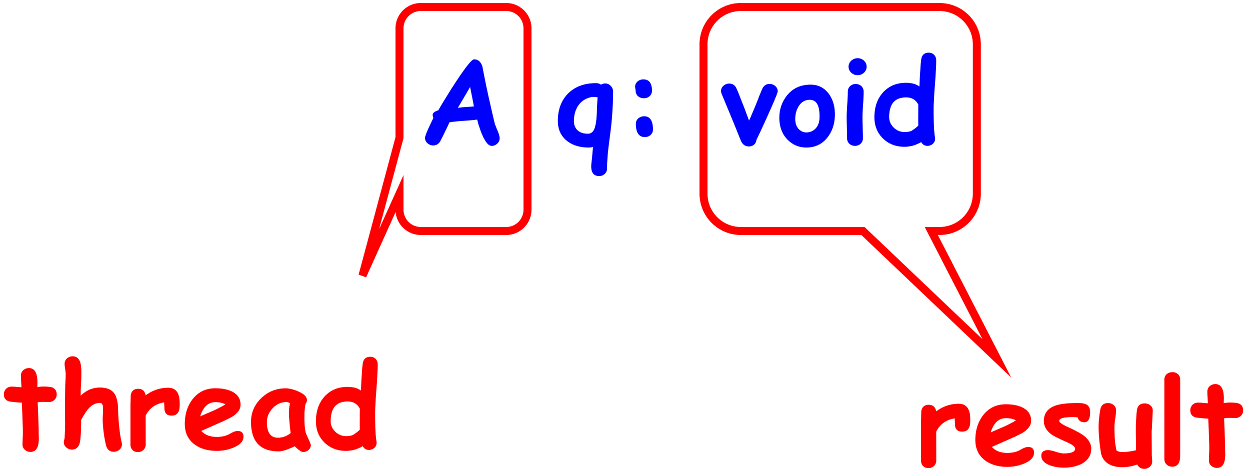
Response Notation



A q: void

thread

Response Notation

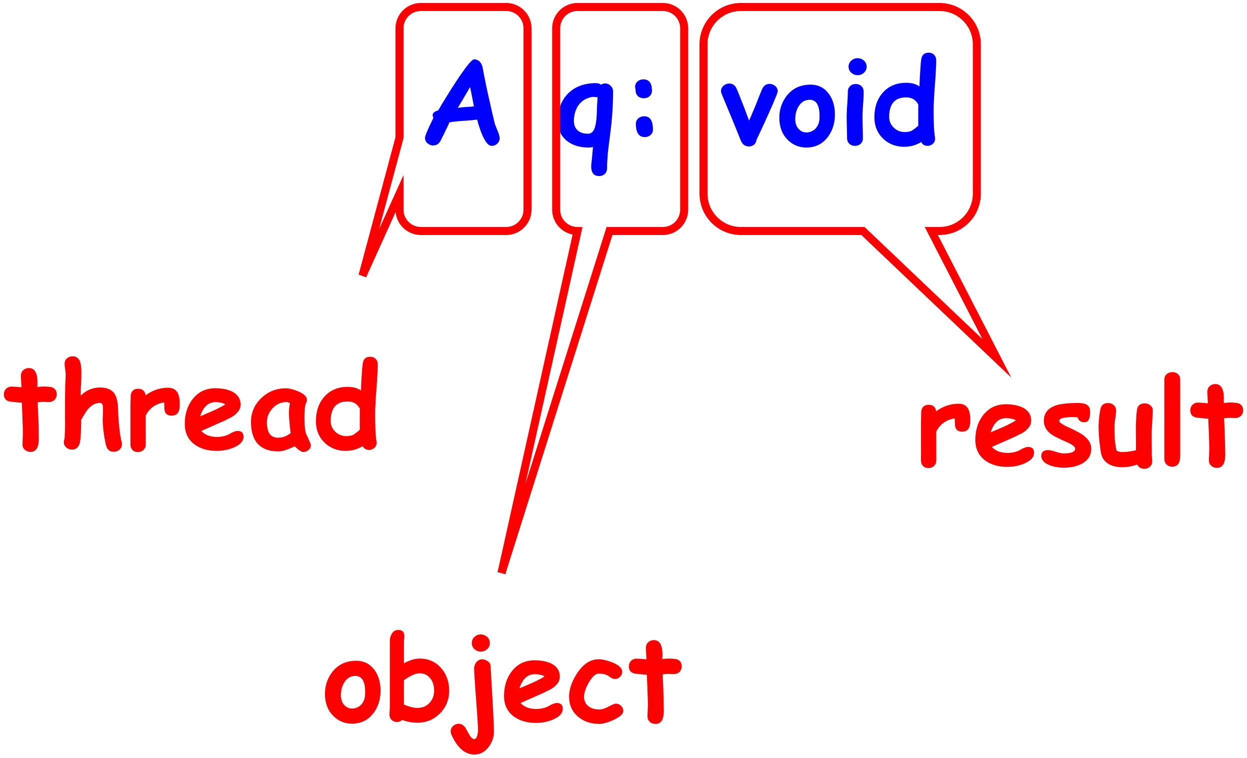


A q: void

thread

result

Response Notation



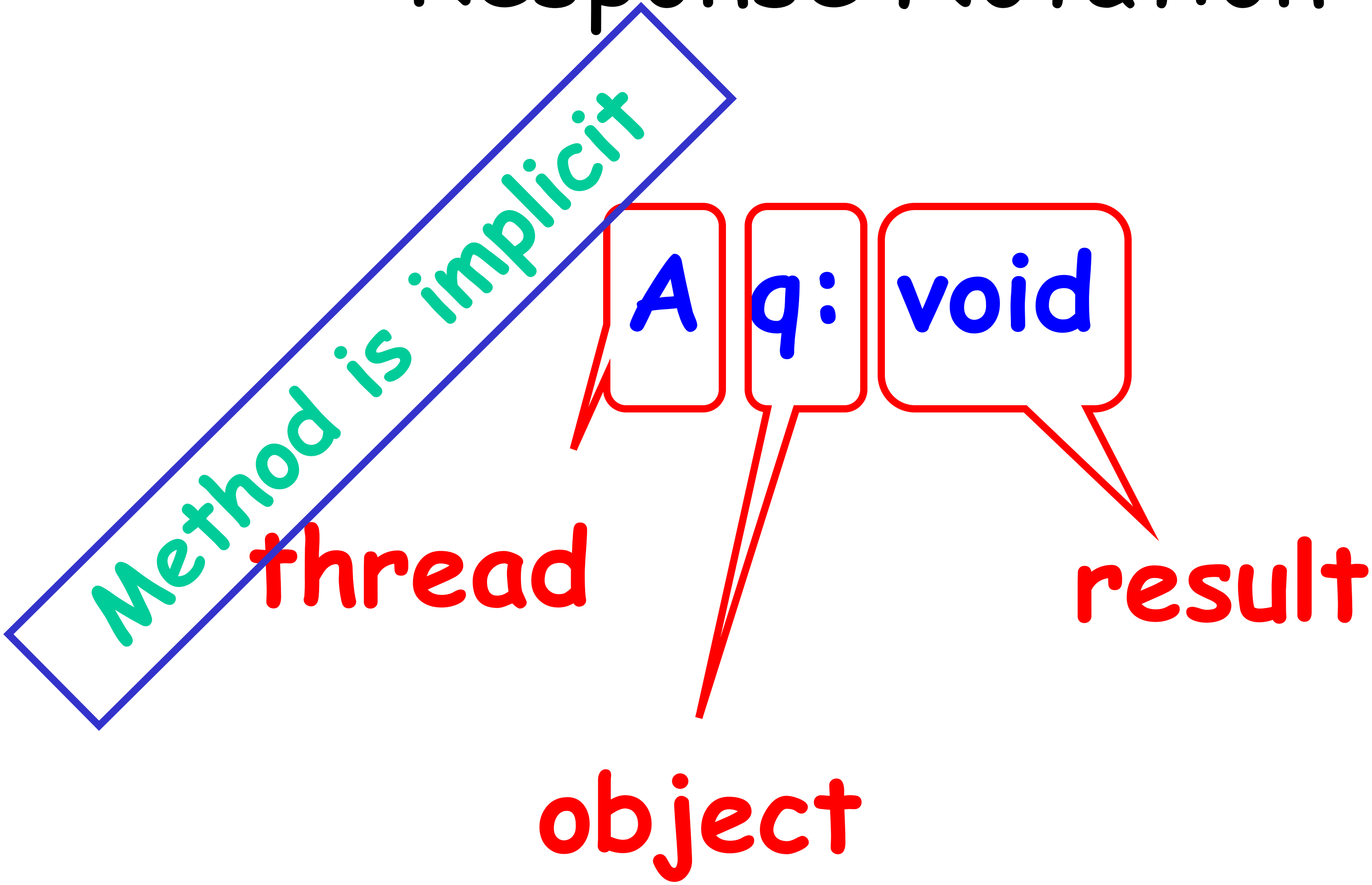
A q: void

thread

object

result

Response Notation



A q: void

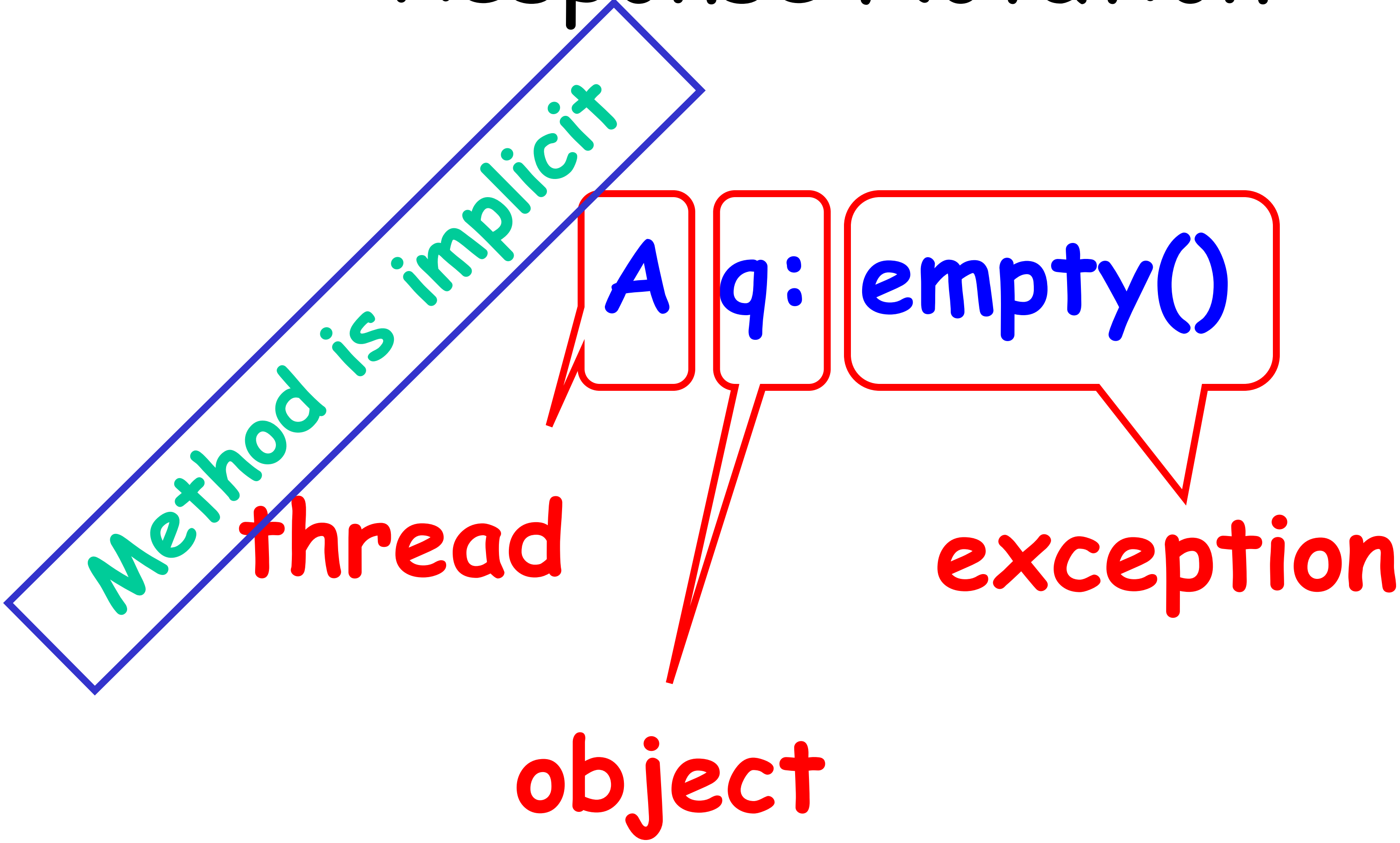
Method is implicit

thread

object

result

Response Notation



A q: empty()

thread

object

exception

Method is implicit

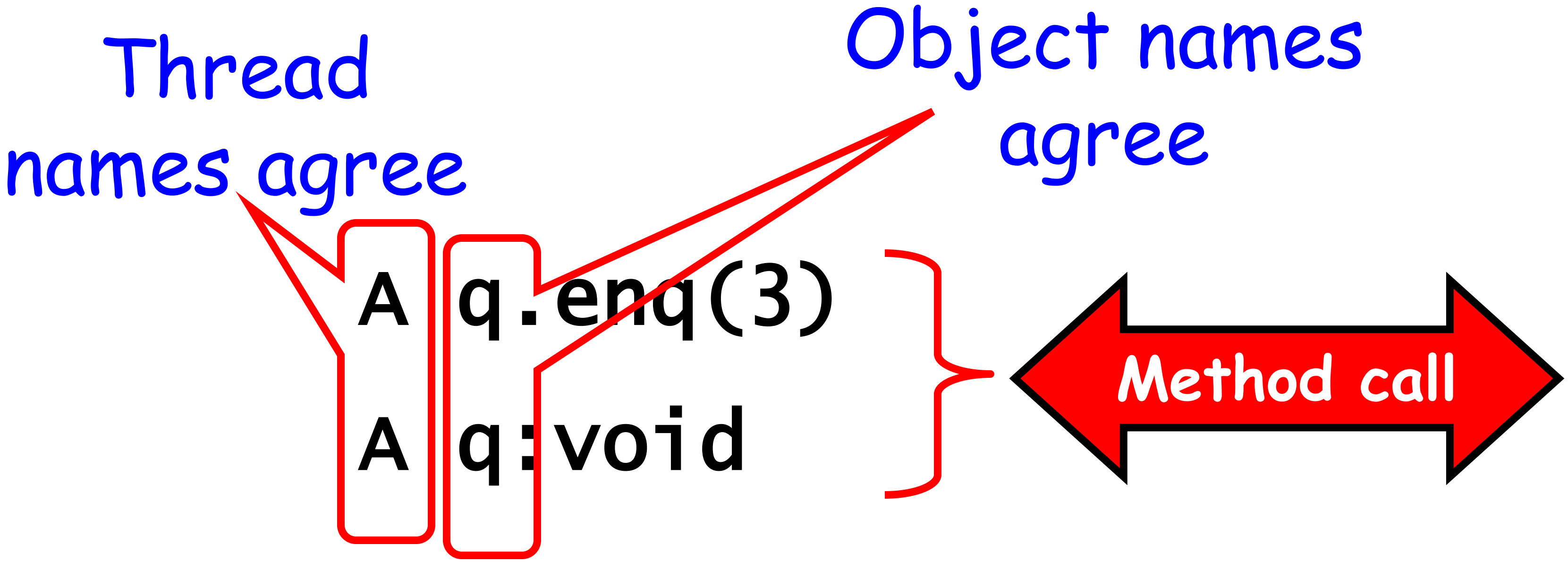
History - Describing an Execution

```
      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
```

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

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

```
       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

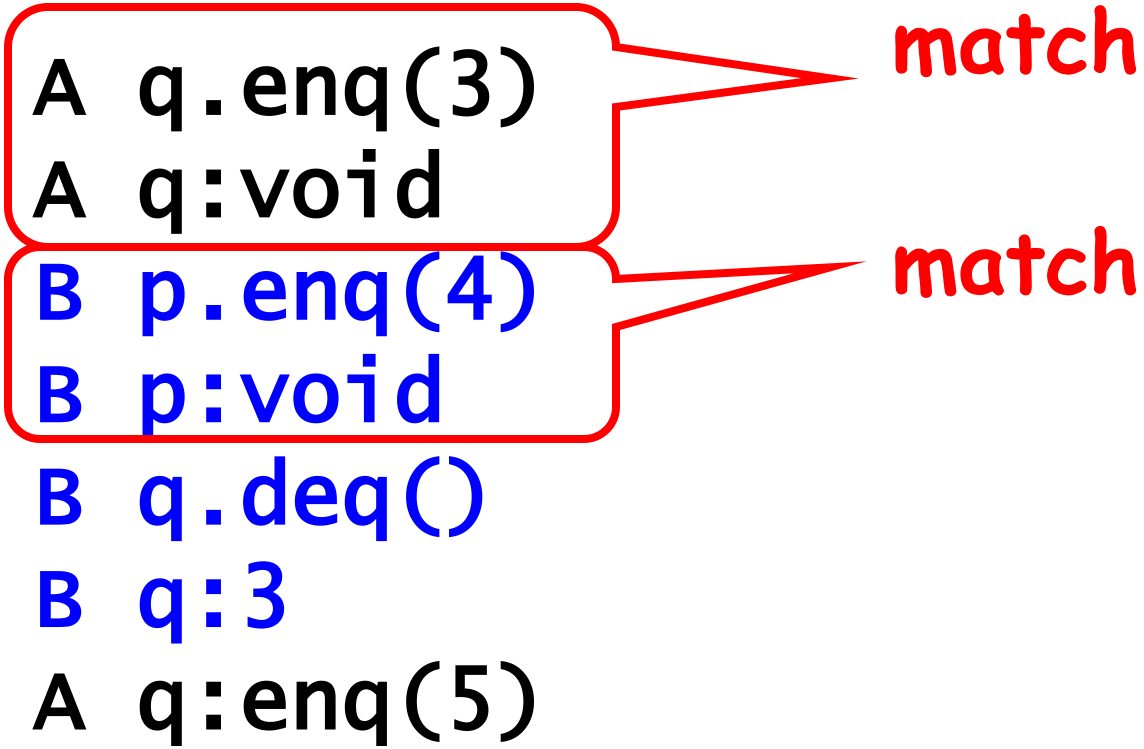
```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
A q:enq(5)
```

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)
```

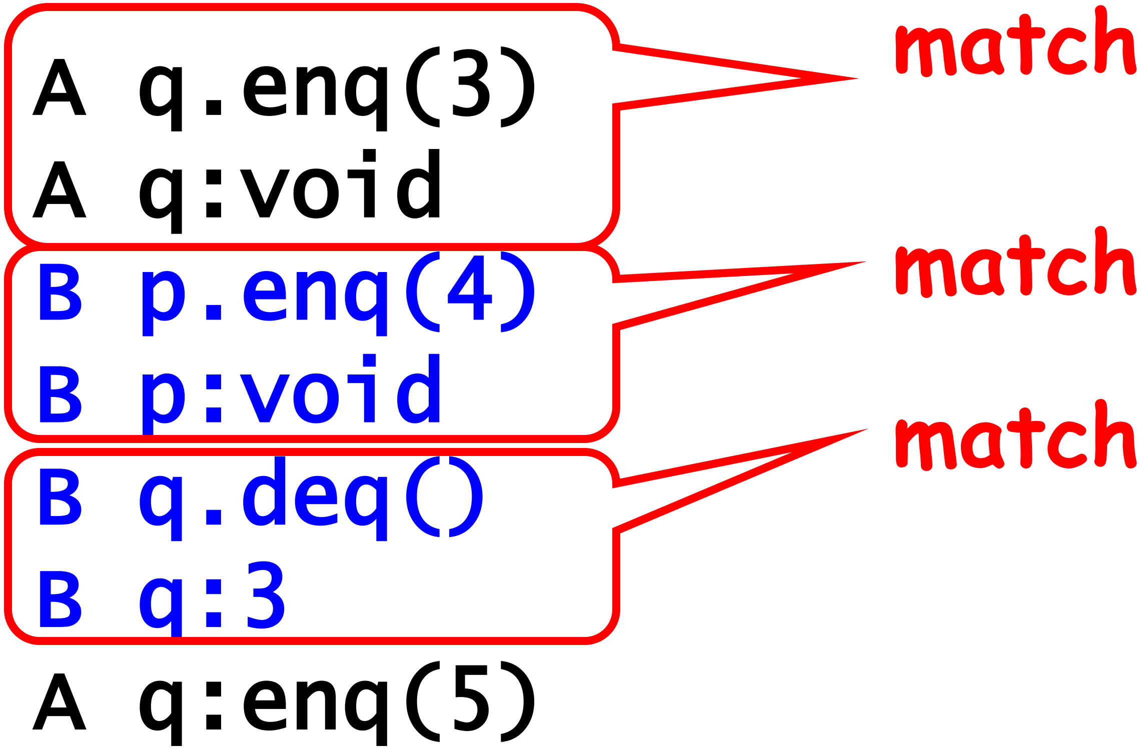
match

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



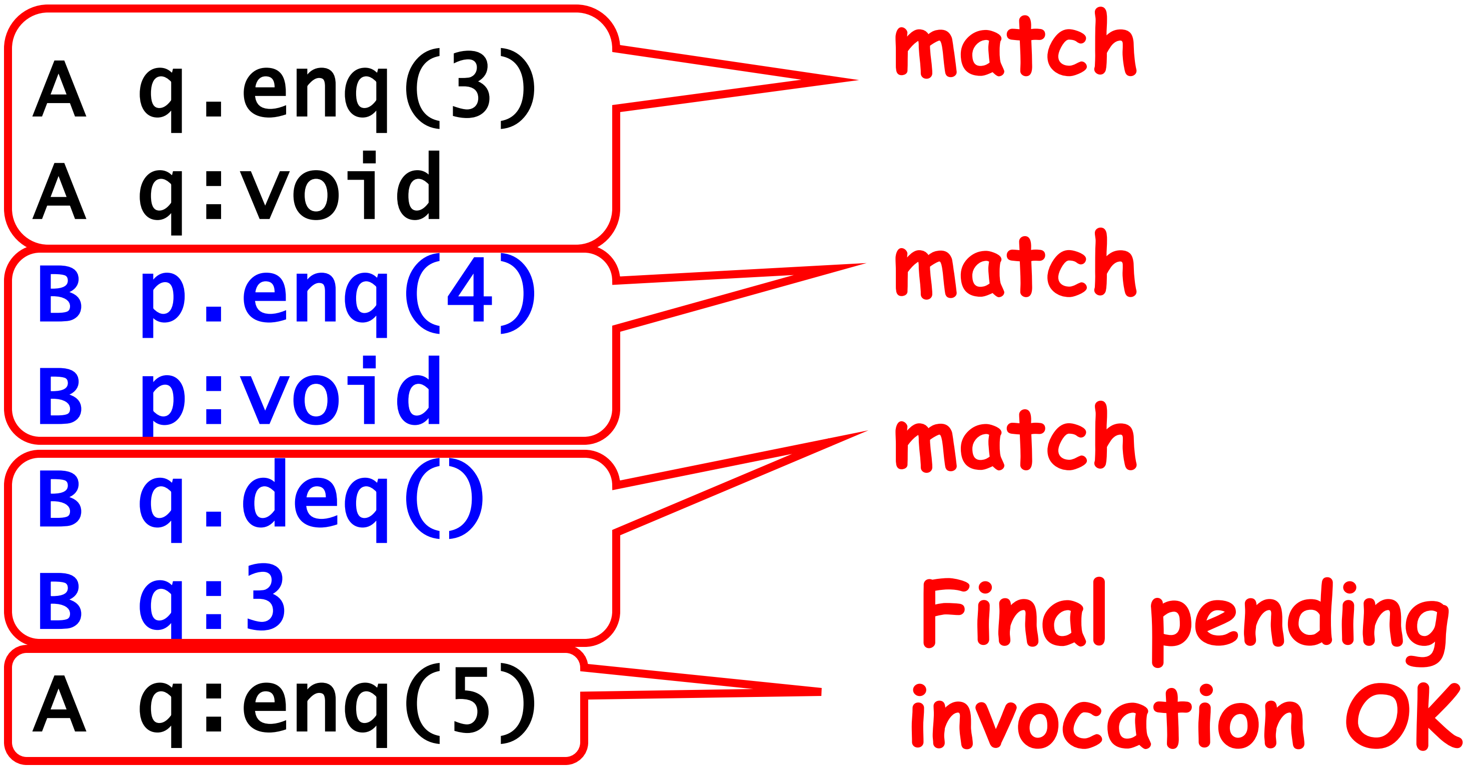
```
A q.enq(3)
A q:void
B p.enq(4)
B p:void
B q.deq()
B q:3
A q:enq(5)
```

match

match

match

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=

```
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
```

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

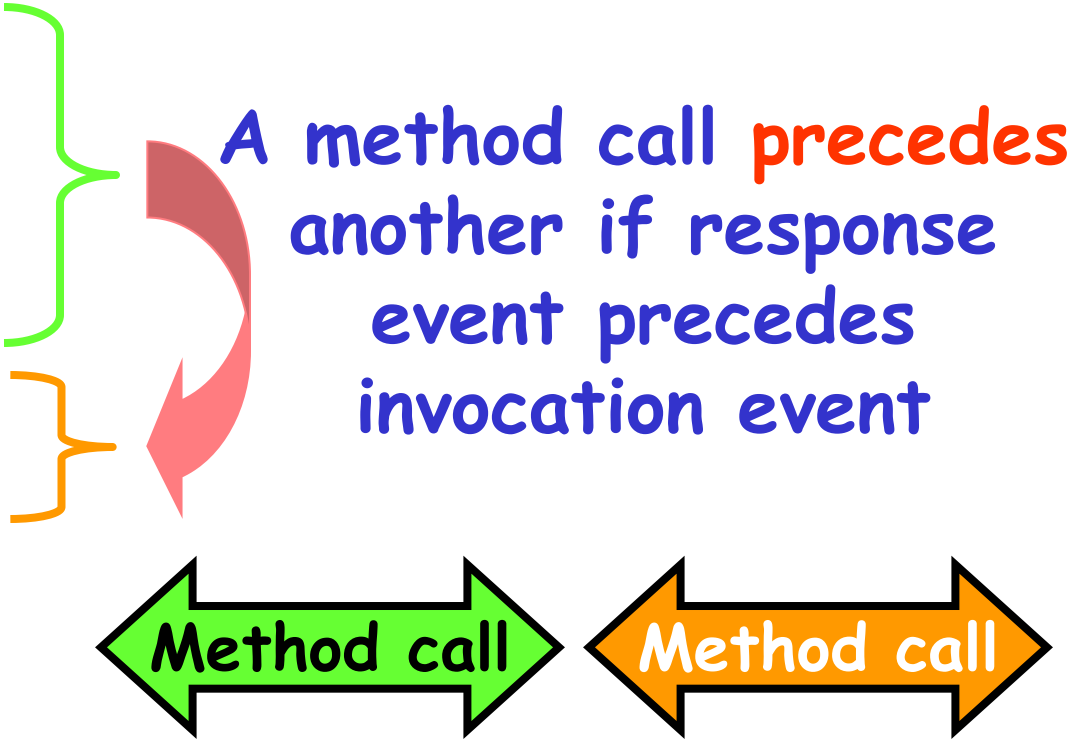
- A sequential specification is some way of telling whether a
  - Single-thread, single-object history
  - Is legal
- For example:
  - Pre and post-conditions
  - But plenty of other techniques exist …

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
```

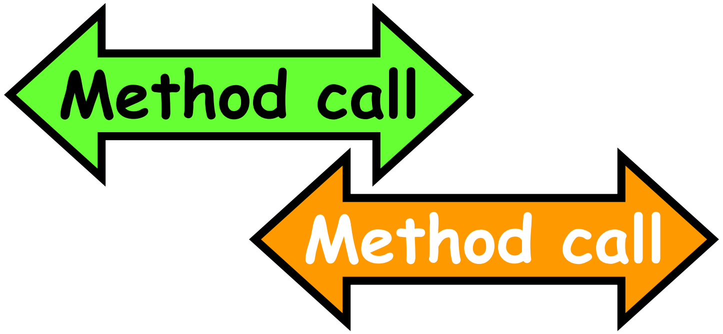


A method call **precedes** another if response event precedes invocation event

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

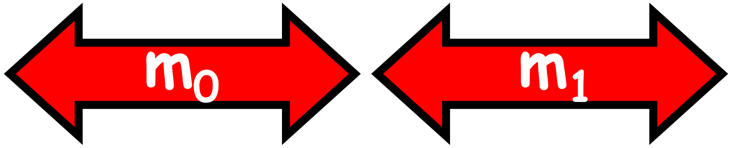


Method call

Method call

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

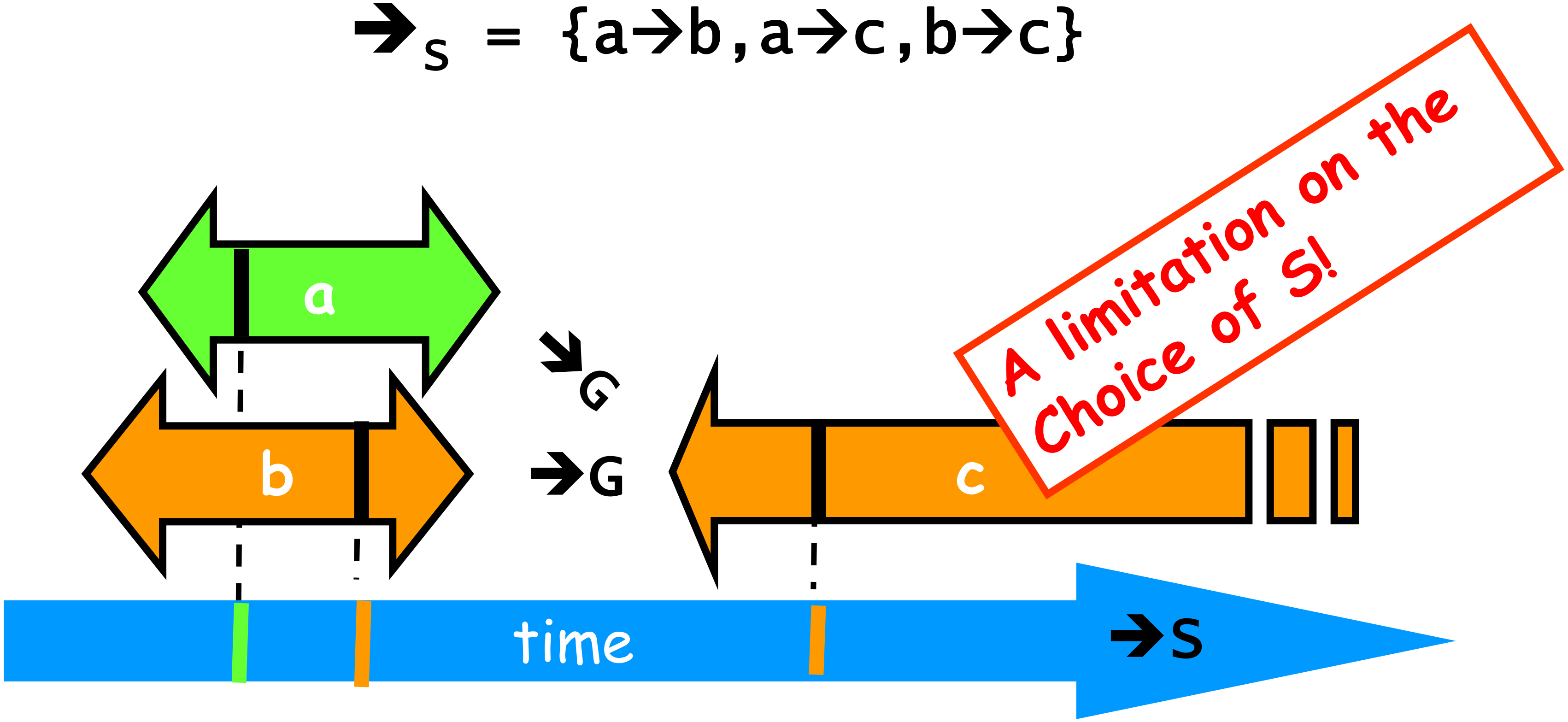
Linearizability

- 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 $\rightarrow_G \subset \rightarrow_S$

What is $\rightarrow_G \subset \rightarrow_S$

$\rightarrow_G$ = {a→c,b→c}

$\rightarrow_S$ = {a→b,a→c,b→c}



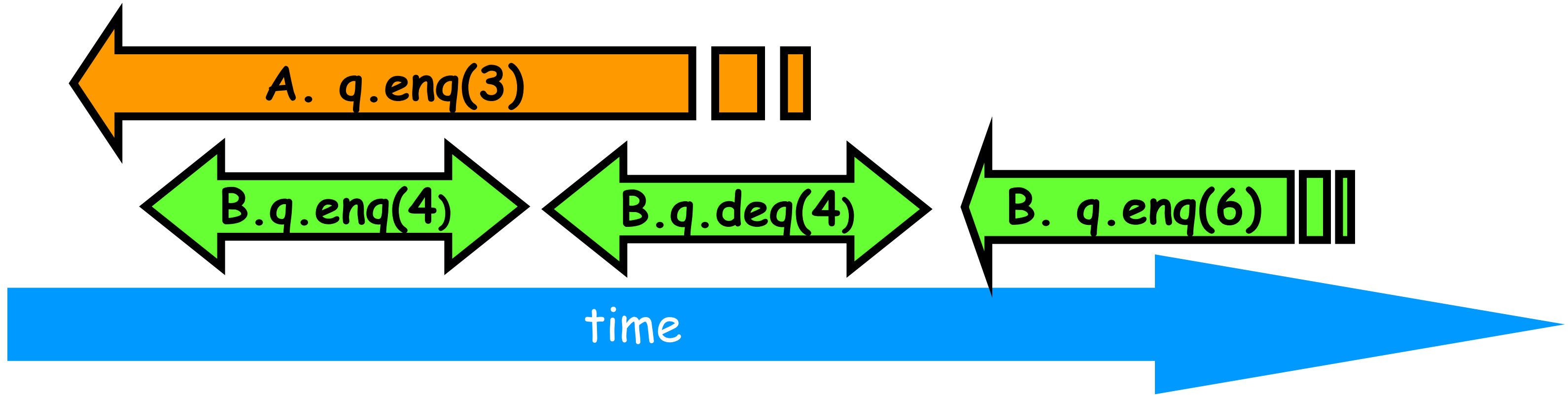
A limitation on the Choice of S!

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**

Example

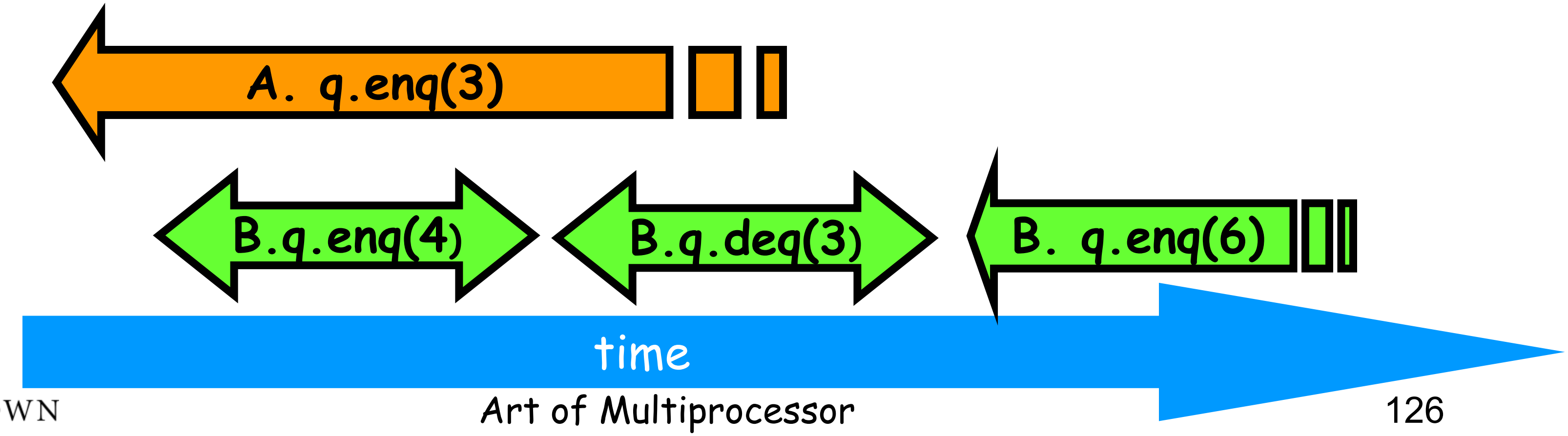
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
B q:enq(6)
```



Example

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

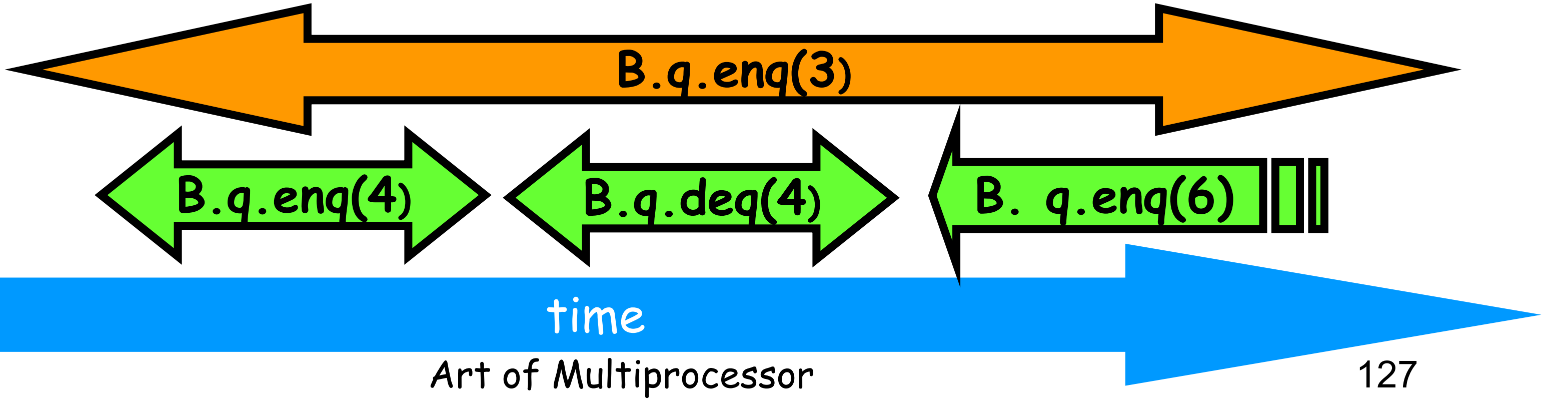
Complete this pending invocation



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
```

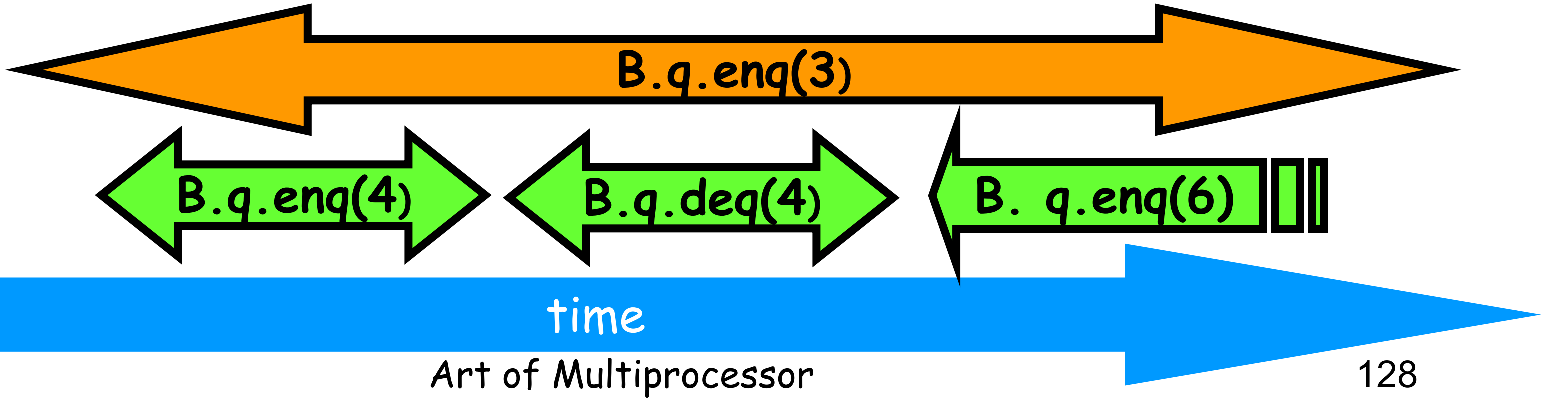
Complete this pending invocation



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

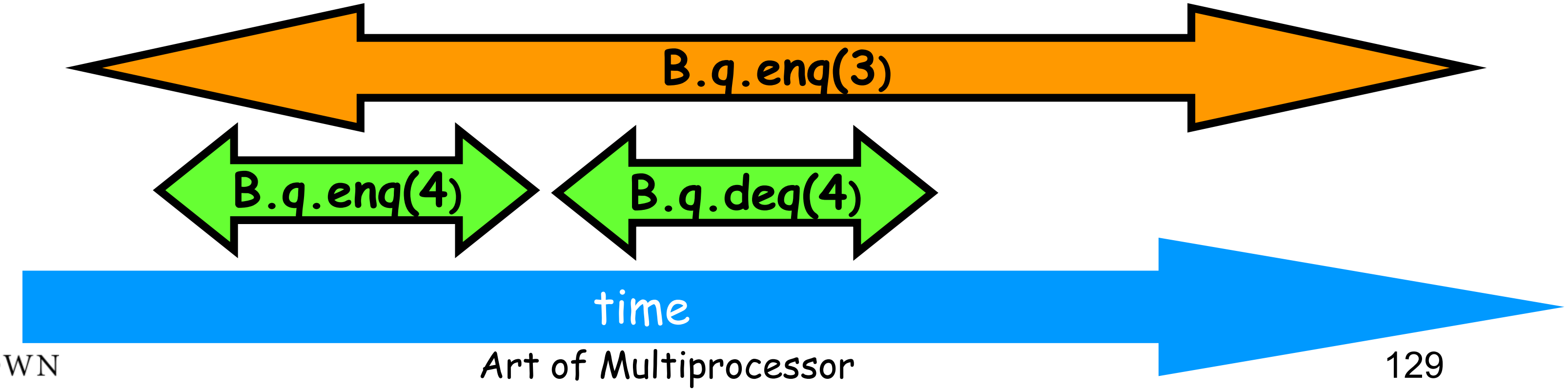


Example

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

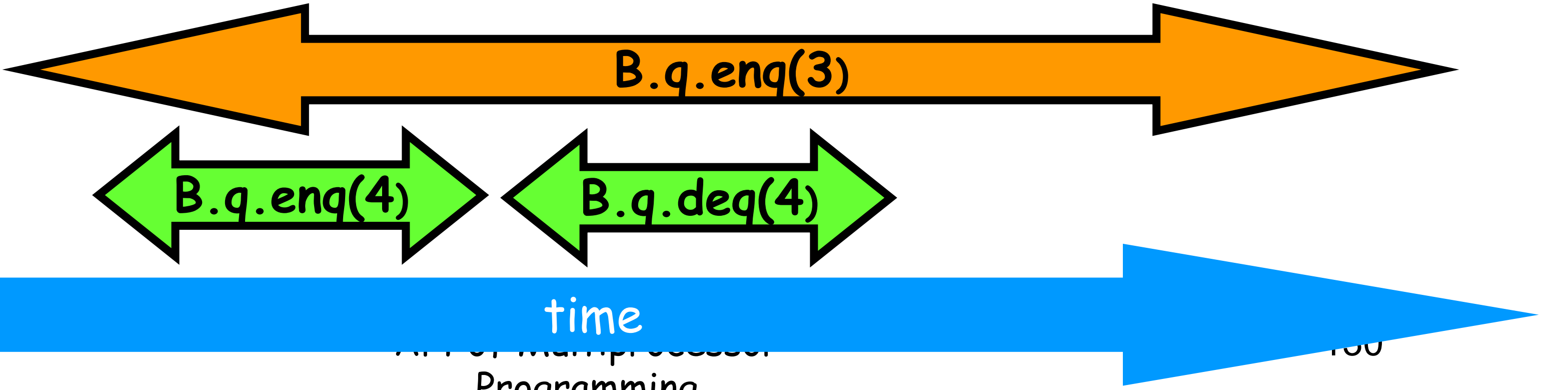
A q:void
```

discard this one



Example

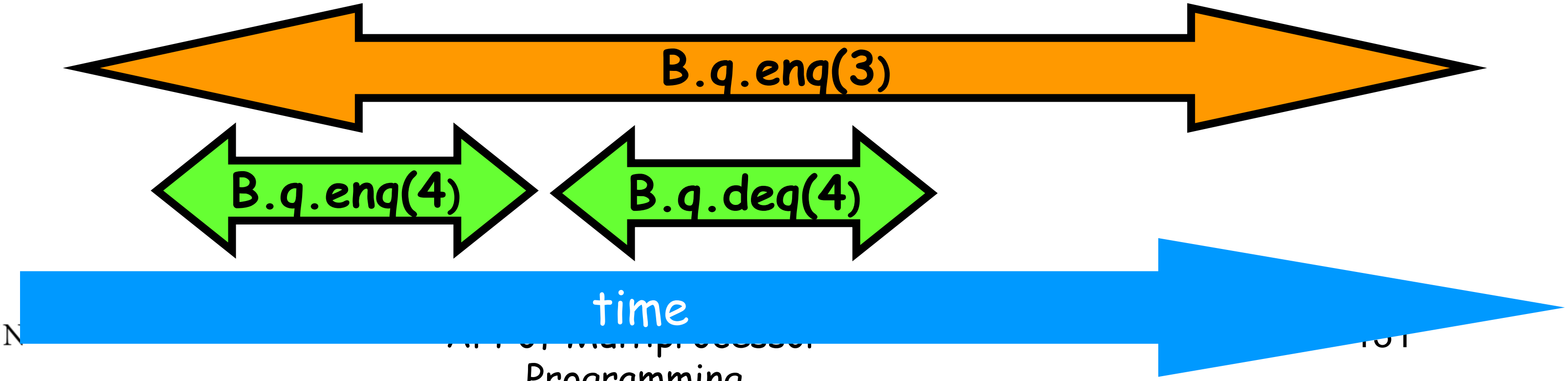
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
A q:void
```



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
```

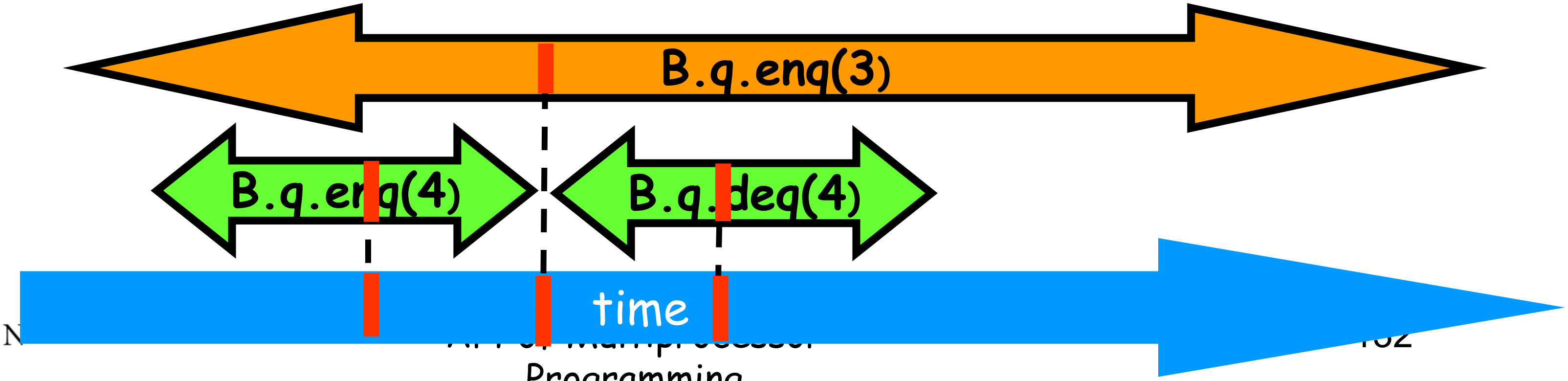


Example

```
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
```



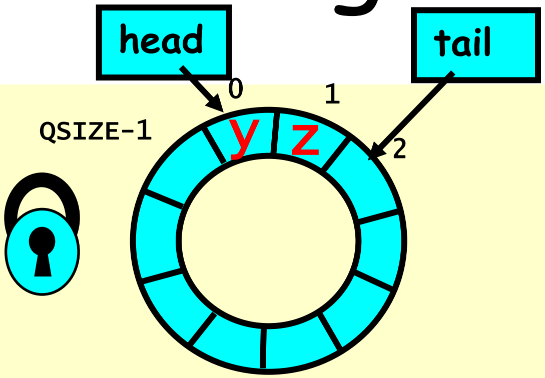
Composability Theorem

- 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 Lineraizability: Locking



```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized void enq(T x) {
   while (tail – head == QSIZE)
     this.wait();
   items[tail % QSIZE] = x; tail++;
   this.notifyAll();
  }
  …
}}
```

Implementation: Enq

```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized void enq(Tt x) {
   while (tail – head == QSIZE)
     this.wait();
   items[tail % QSIZE] = x; tail++;
   this.notifyAll();
  }
  …
}}
```

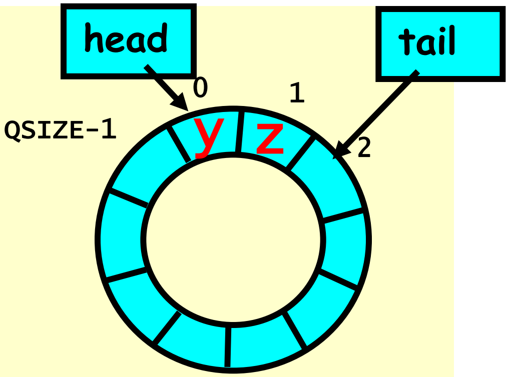
Linearization order is order lock released

More Reasoning: Lock-free

```
public class LockFreeQueue {

  int head = 0, tail = 0;
  Item[QSIZE] items;

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



More Reasoning

```
public class LockFreeQ

  int head = 0, tail =
  Item[QSIZE] items;

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

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”
- 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**

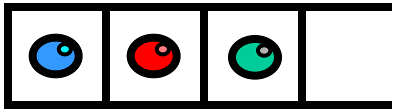
~~Where $\rightarrow_G \subset \rightarrow_S$~~

Differs from linearizability

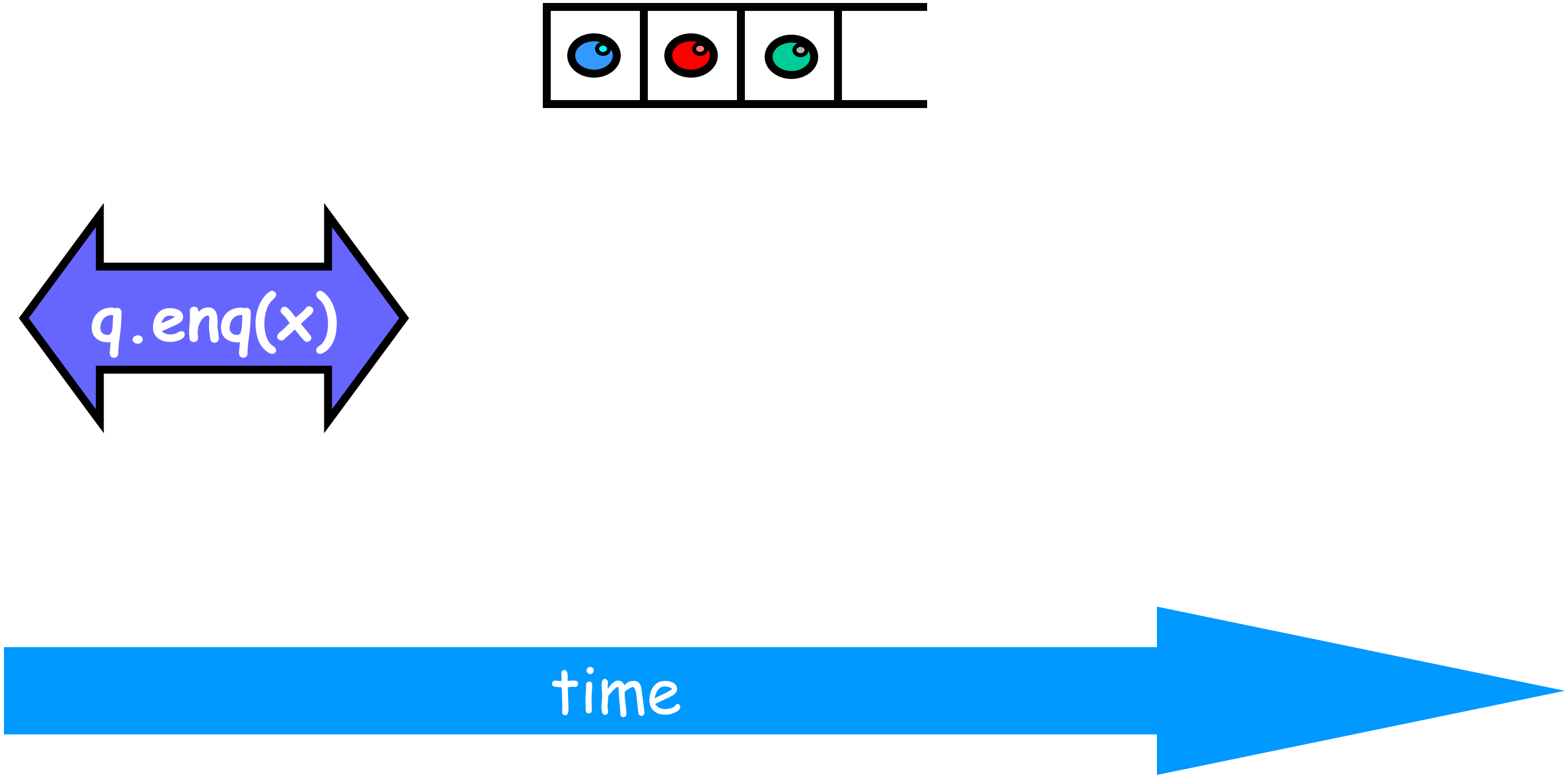
Alternative: Sequential Consistency

- 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

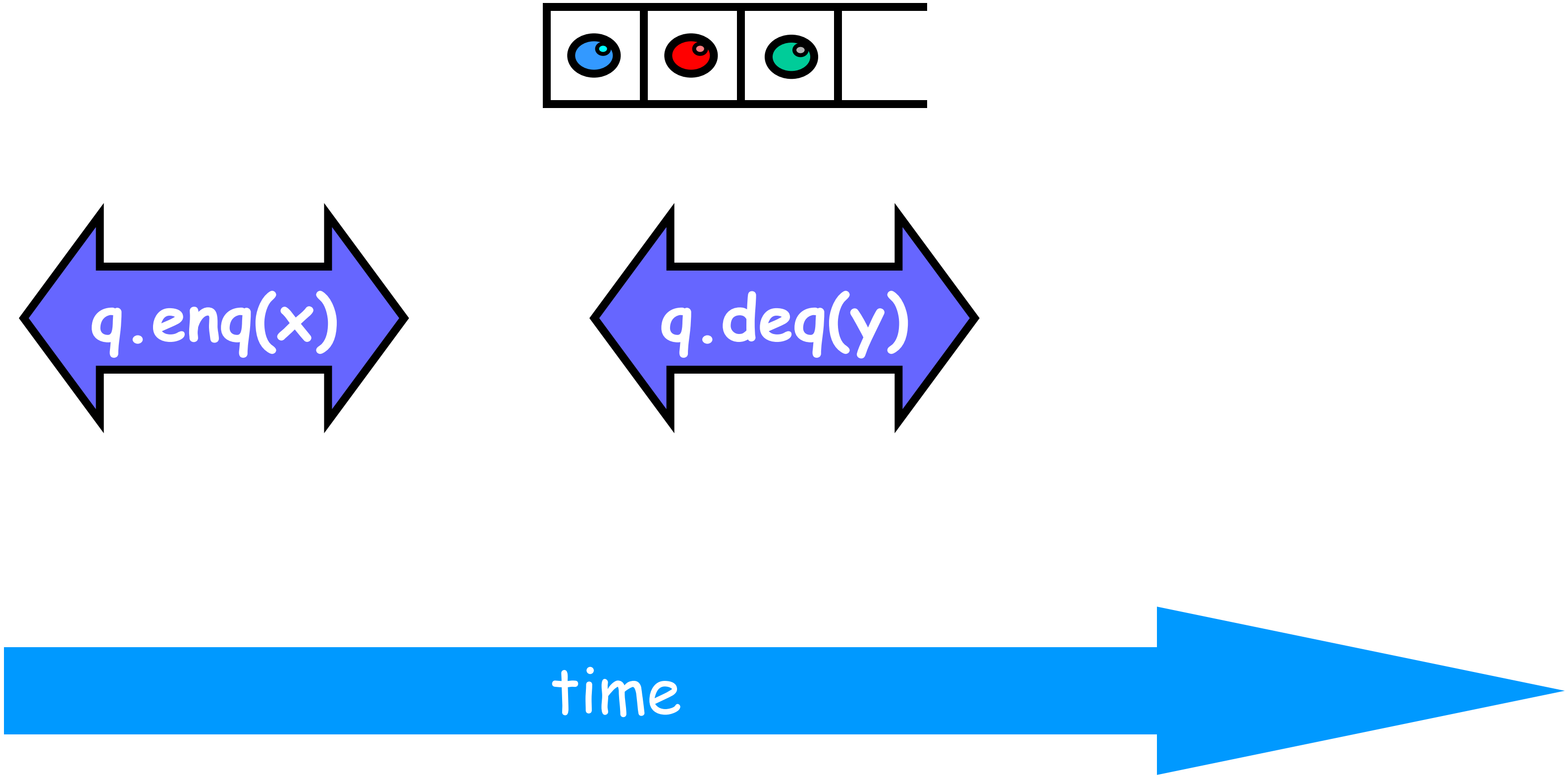
Example



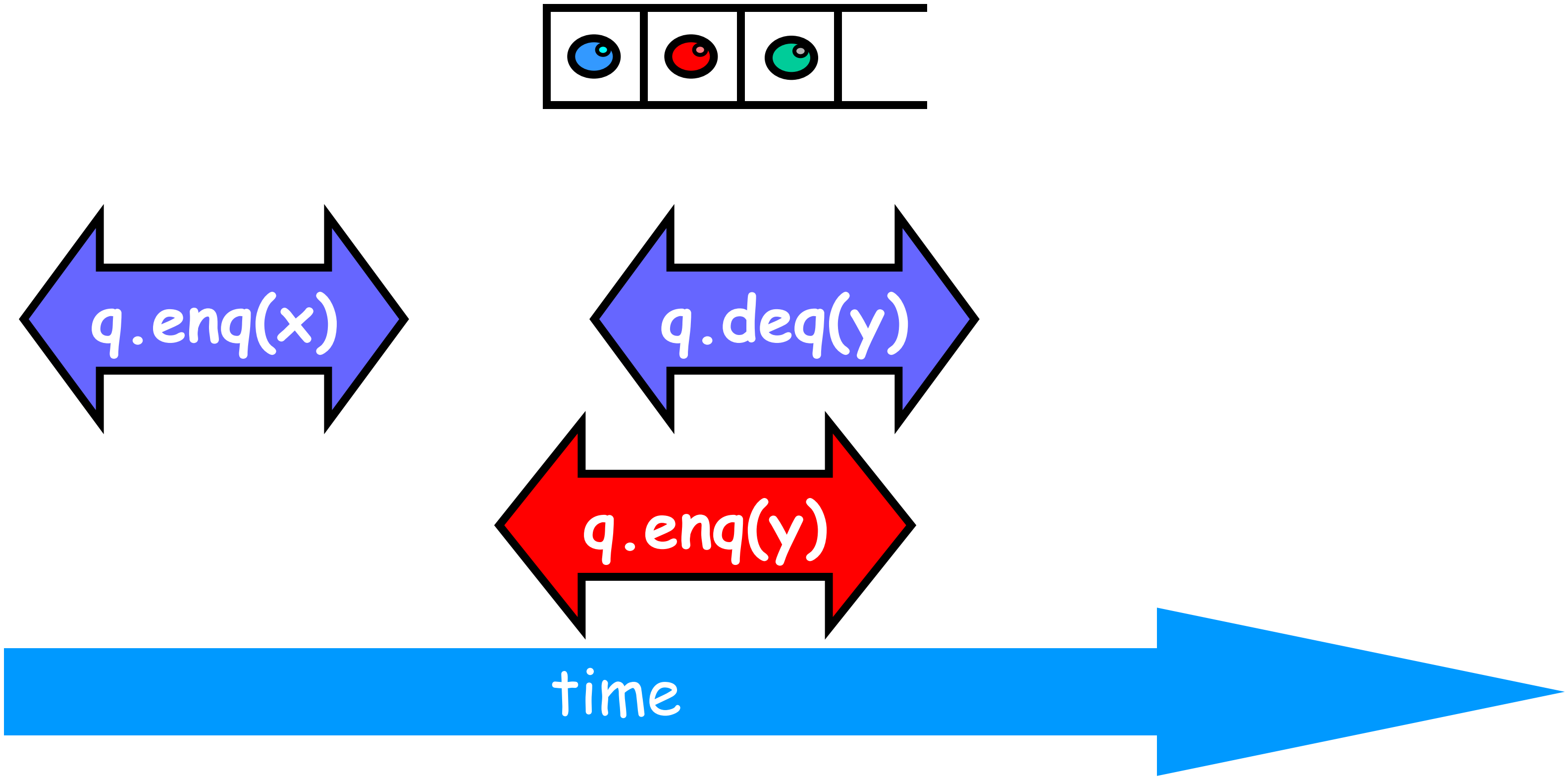
Example



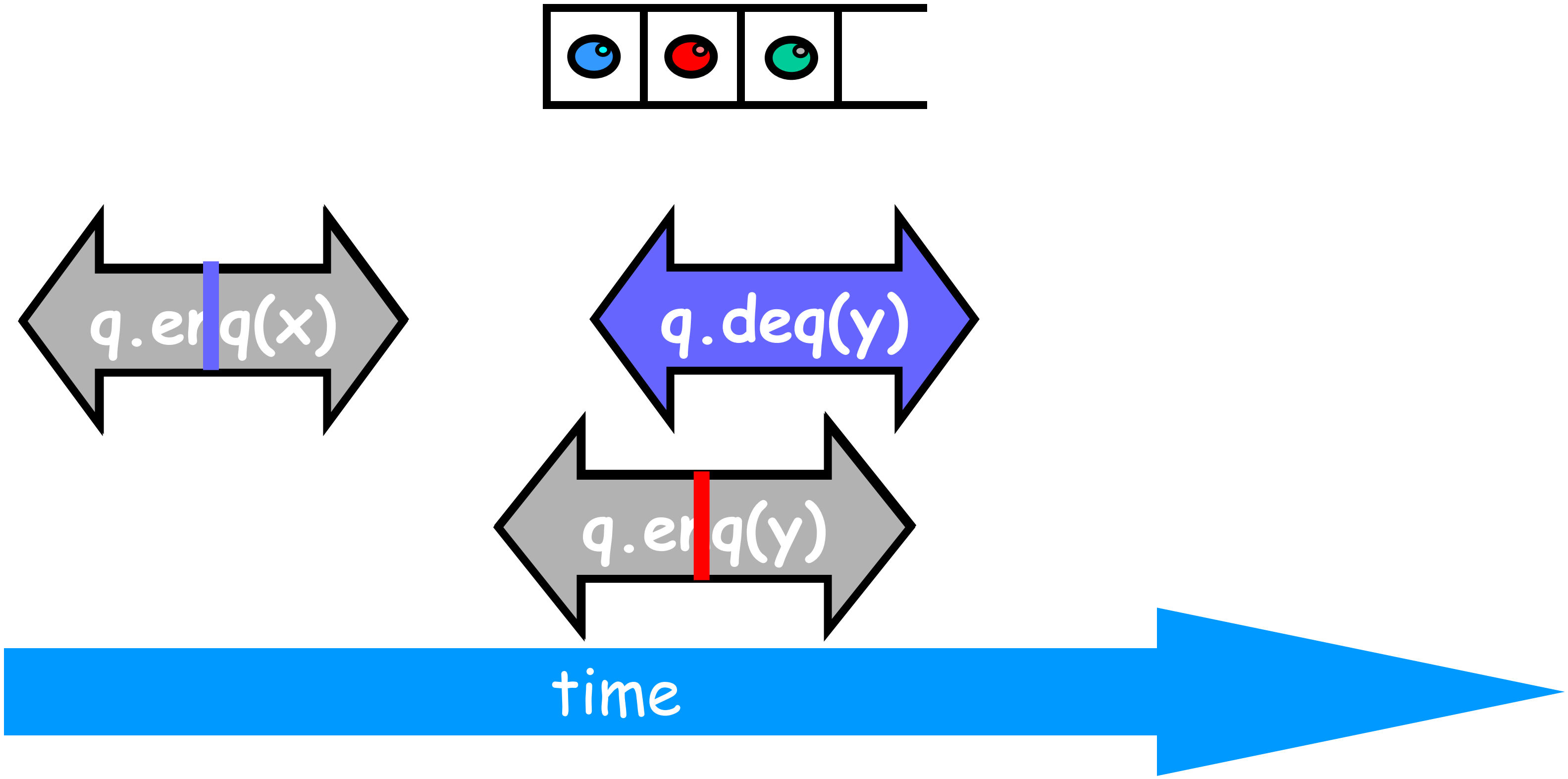
Example



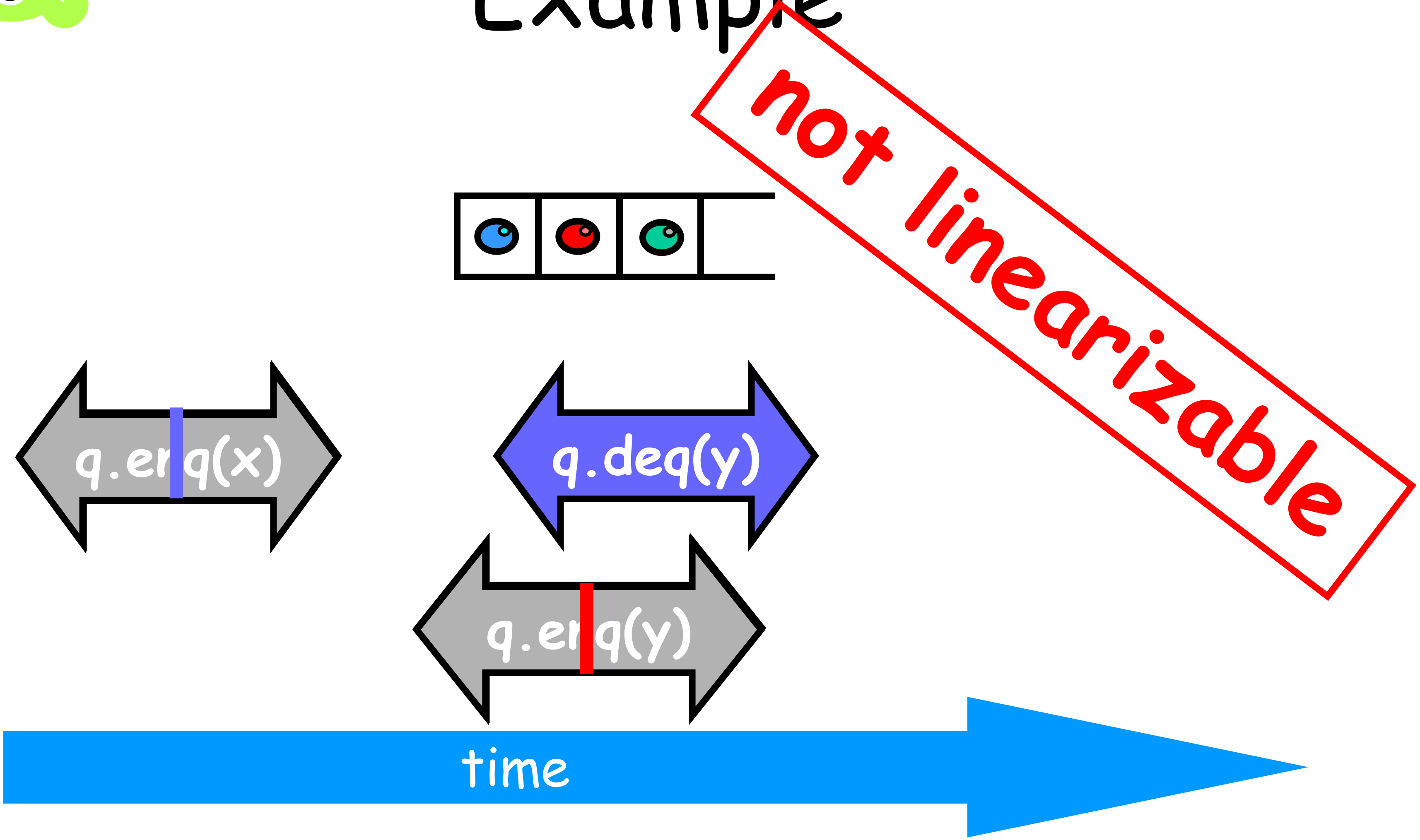
Example



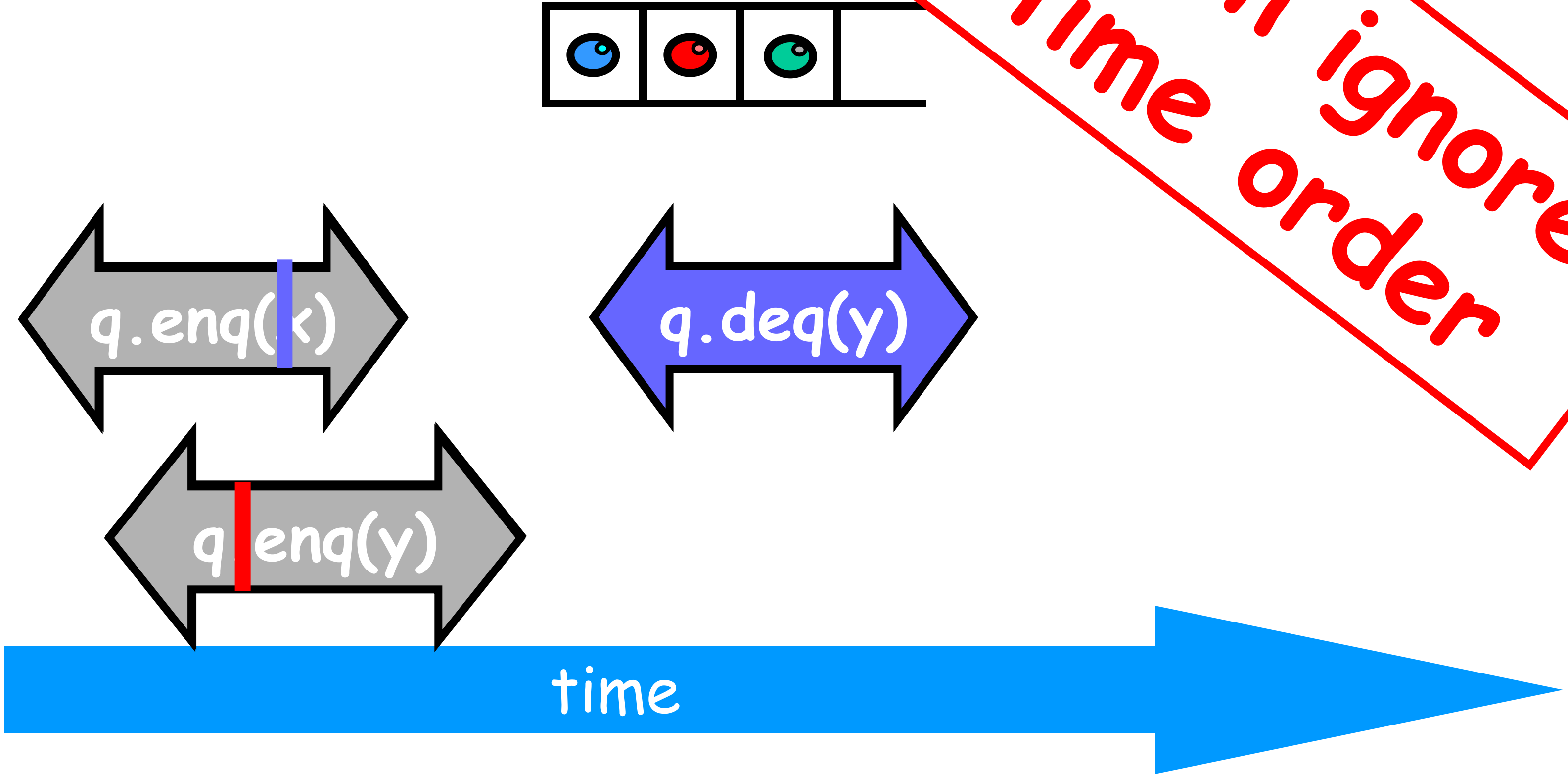
Example

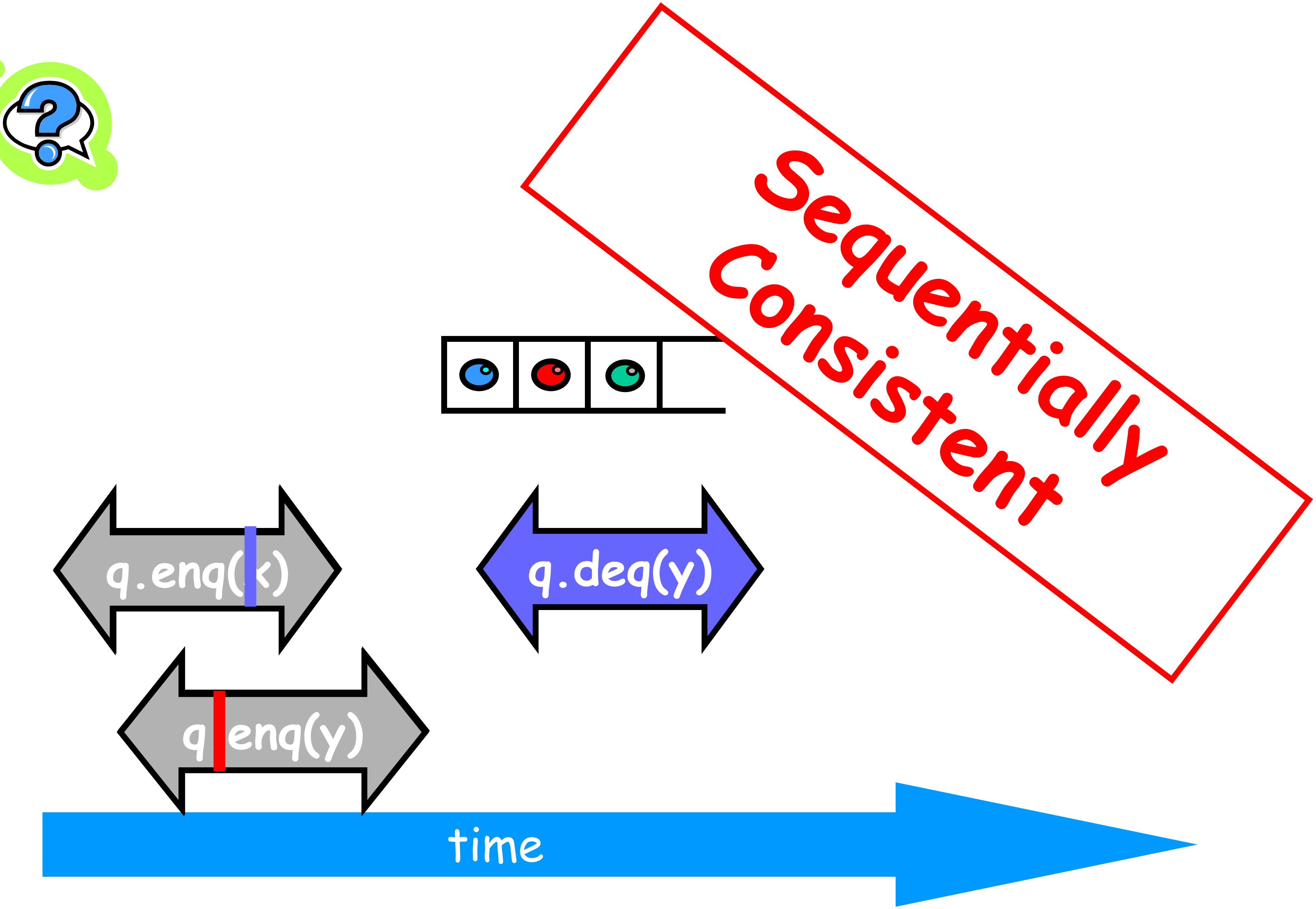


Example



If we can ignore real-time order



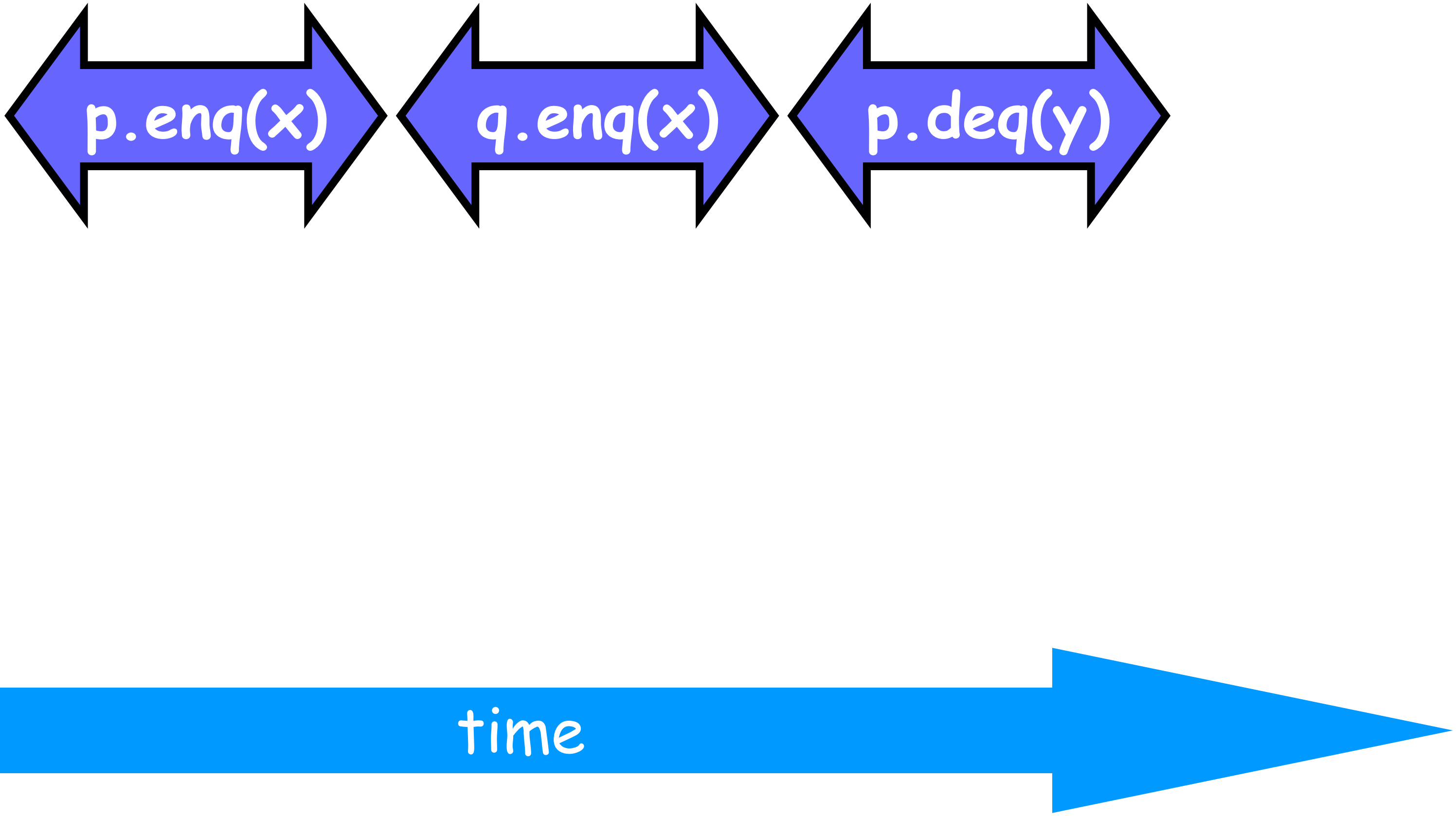

Sequentially Consistent
q.enq(x)
q.enq(y)
q.deq(y)
time

Theorem

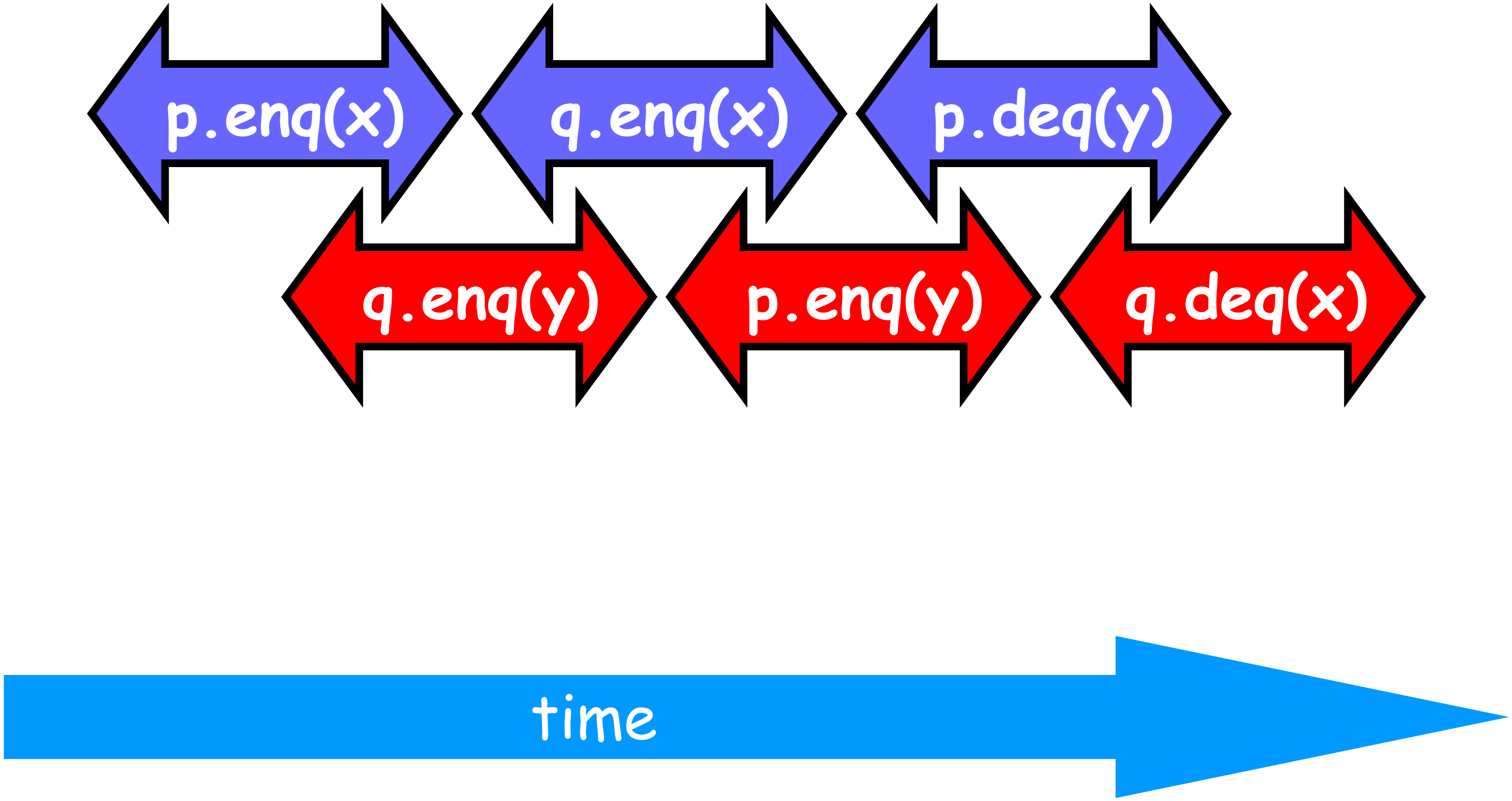
Sequential Consistency is not a local property

(and thus we lose compasability…)

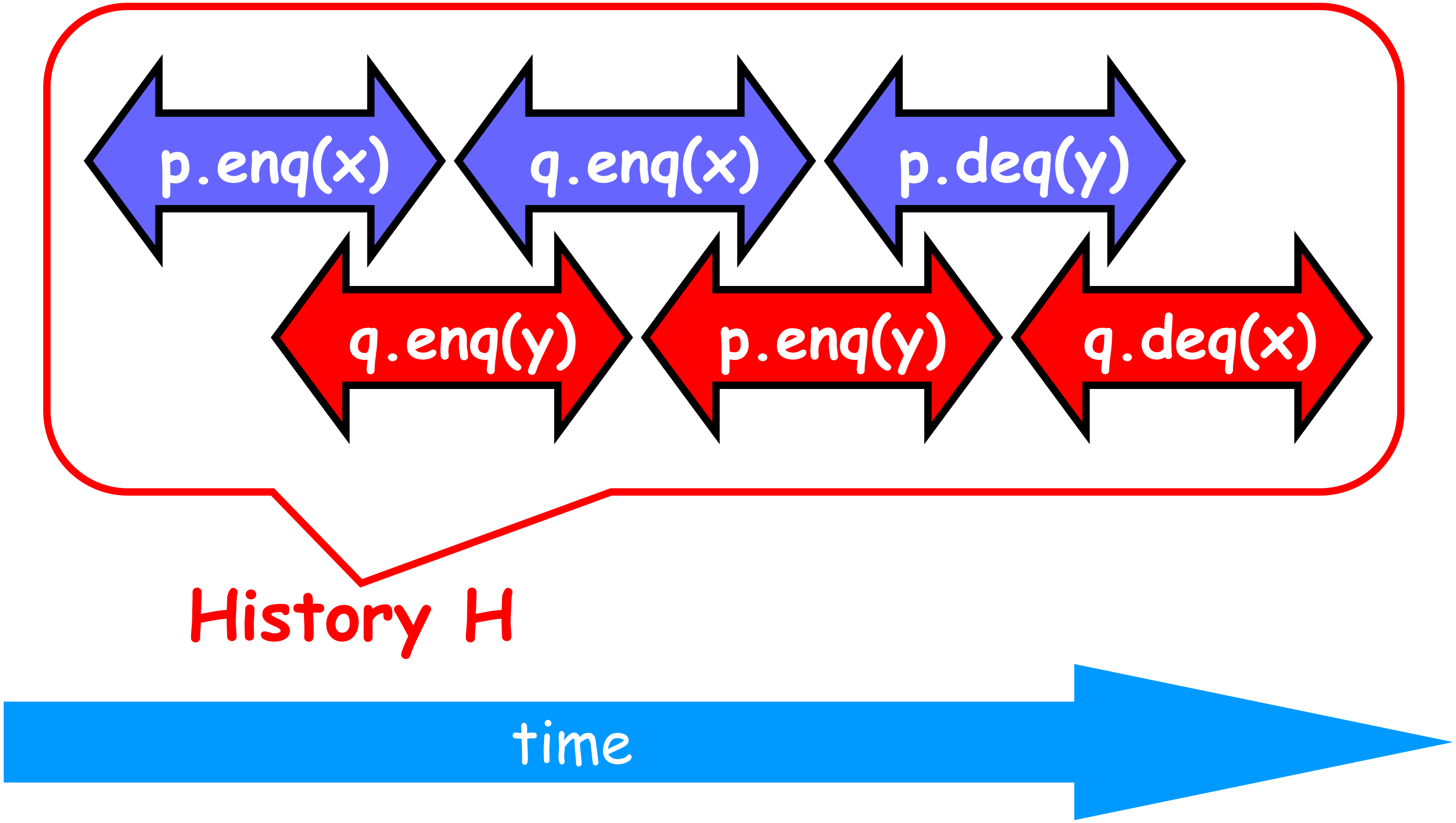
FIFO Queue Example



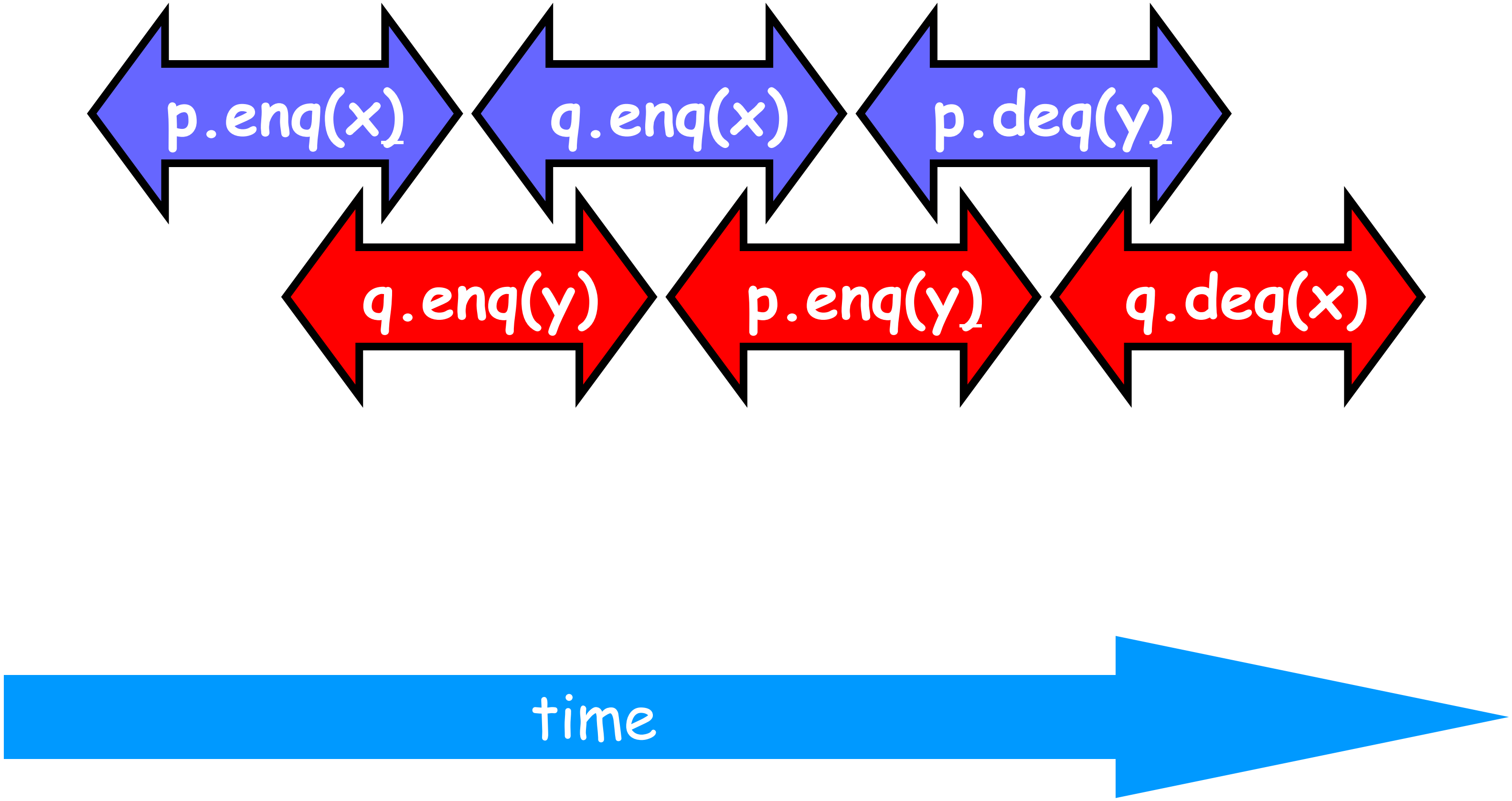
FIFO Queue Example



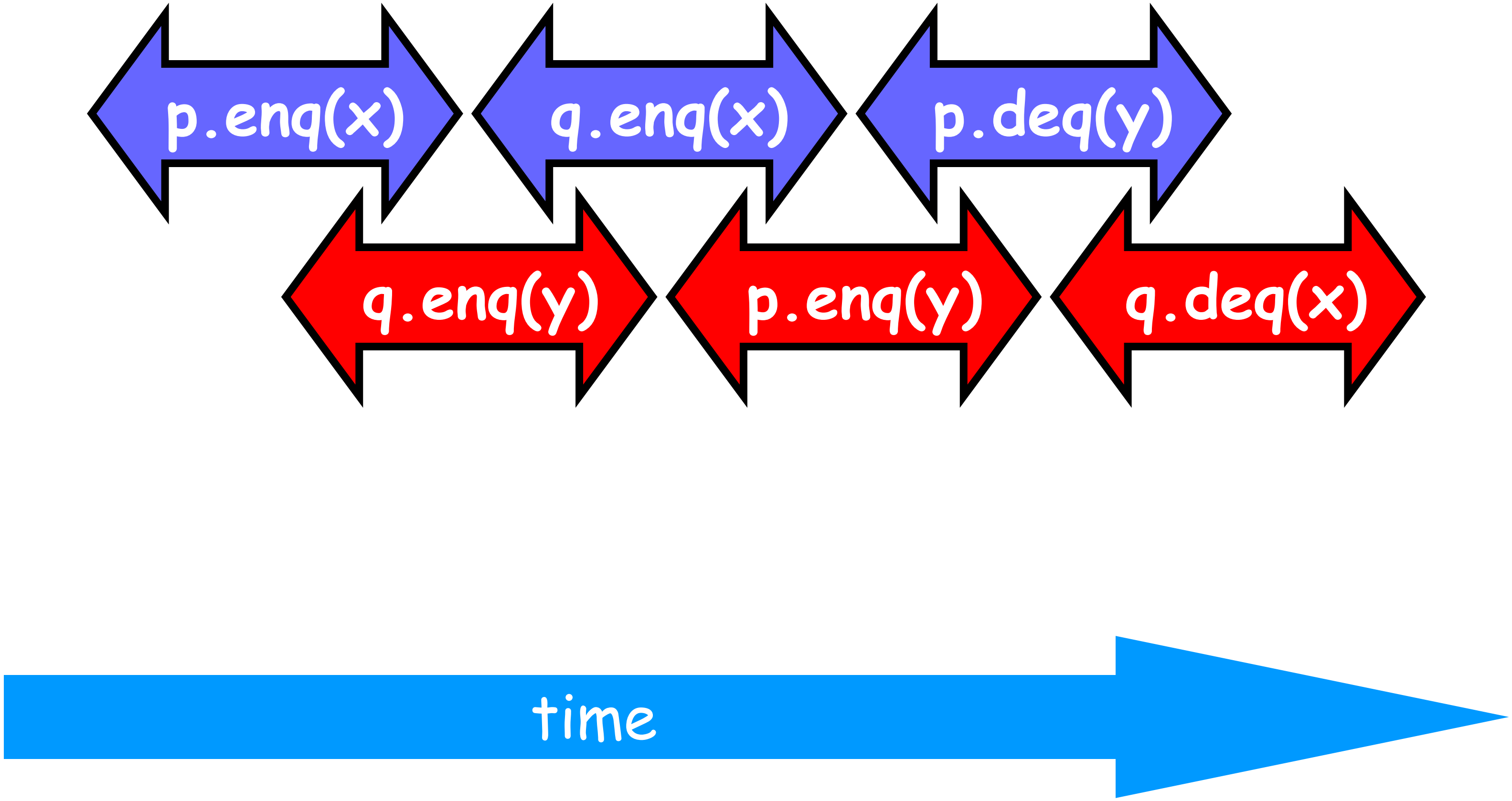
FIFO Queue Example



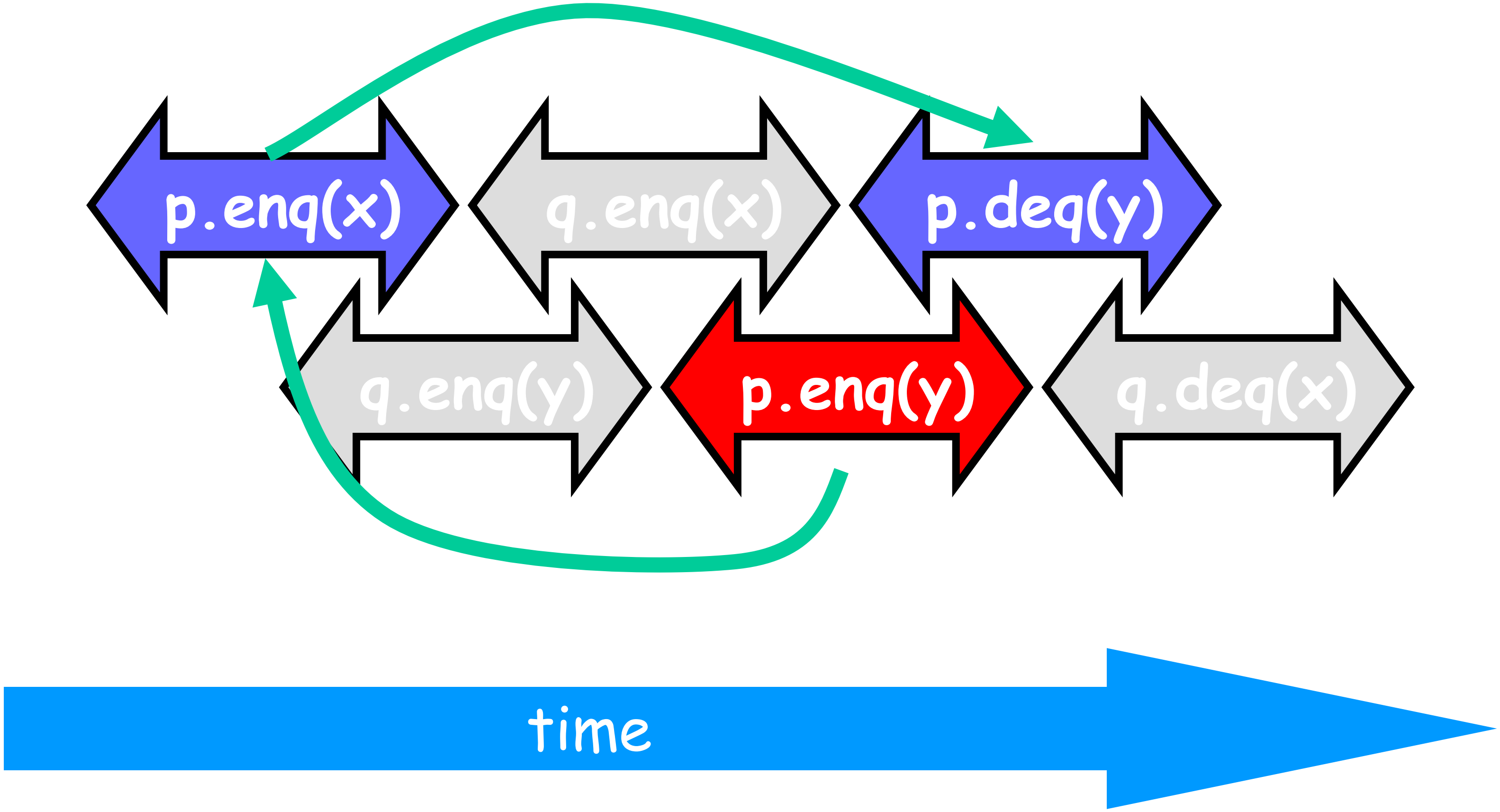
H|p Sequentially Consistent



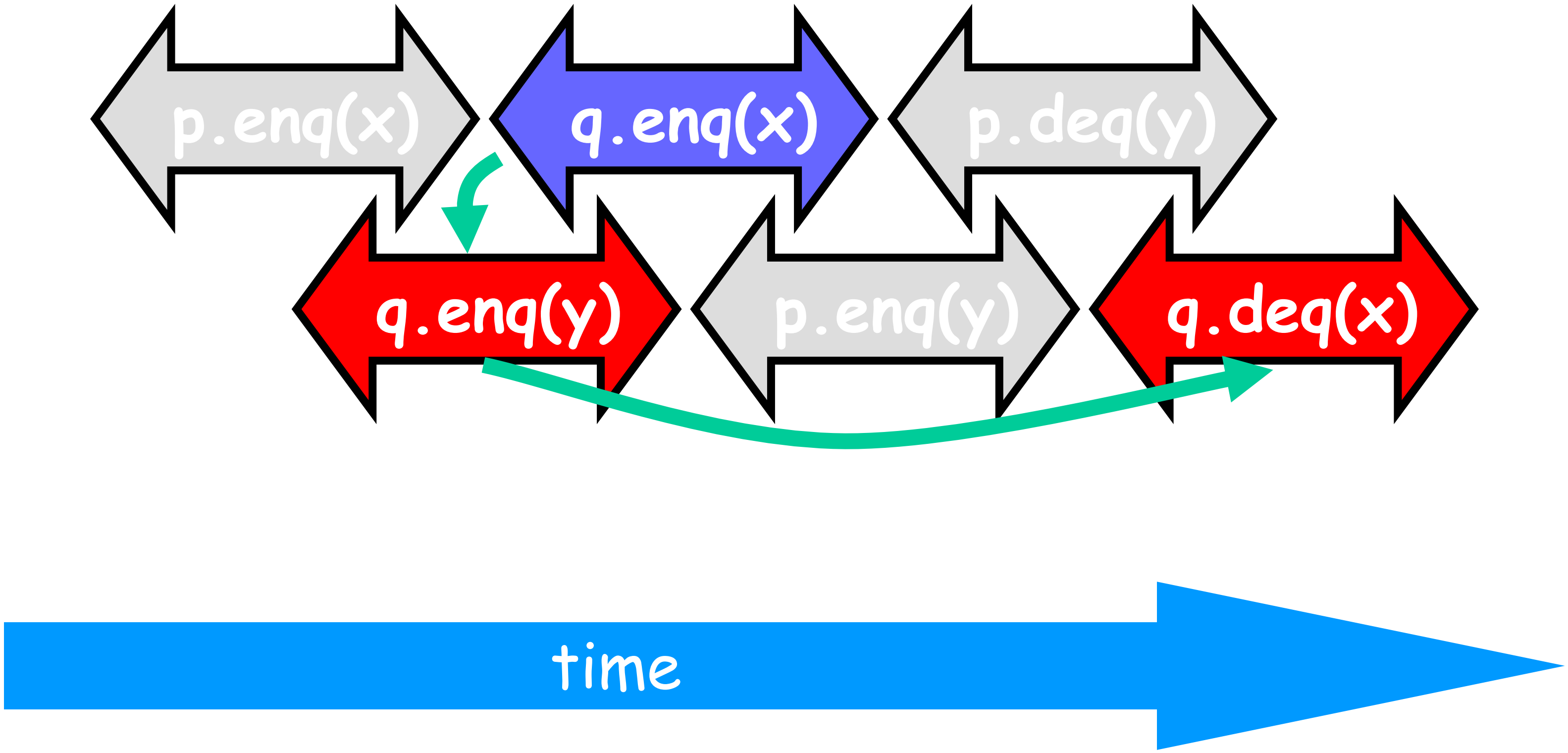
H|q Sequentially Consistent



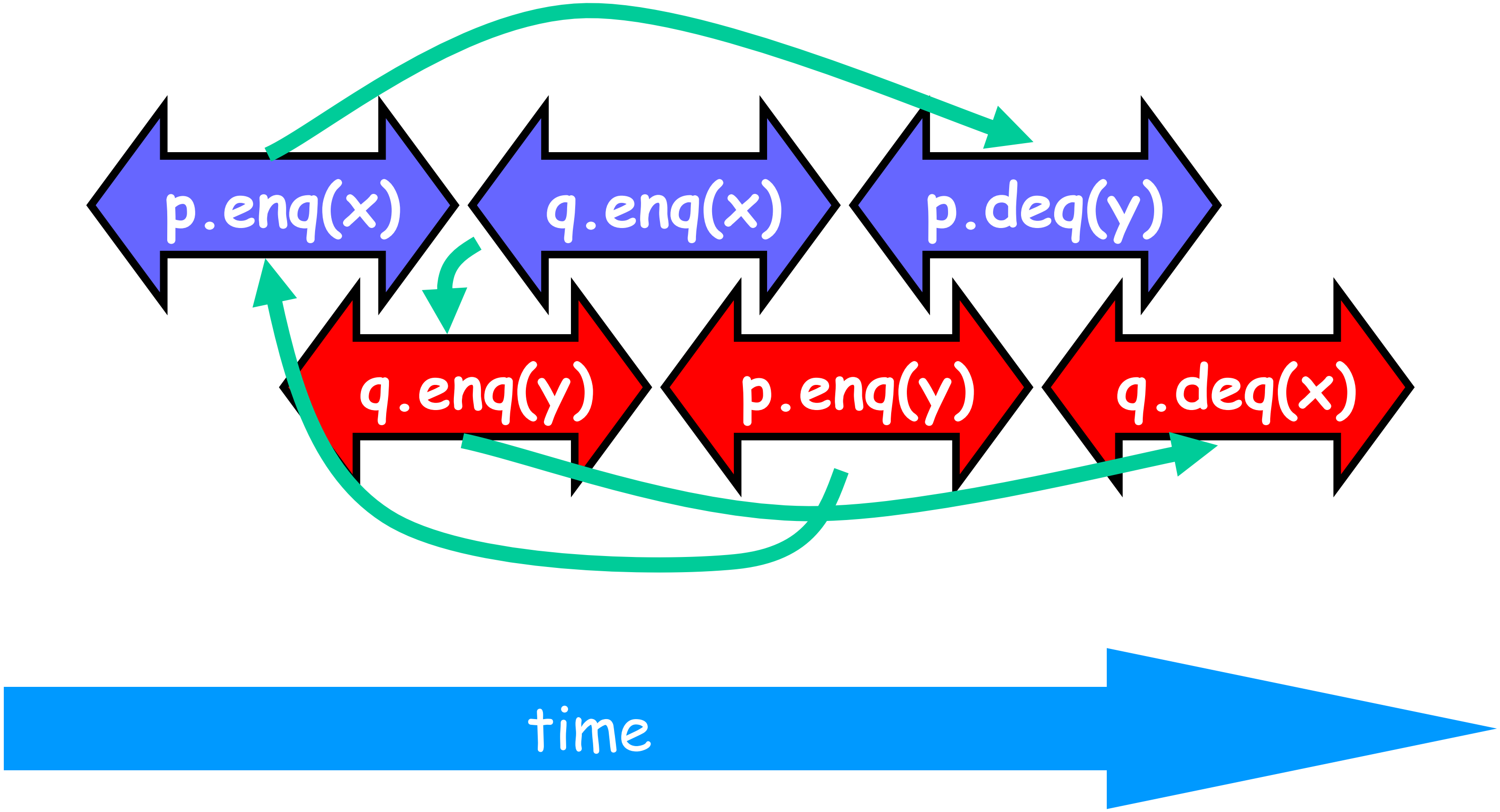
Ordering imposed by p



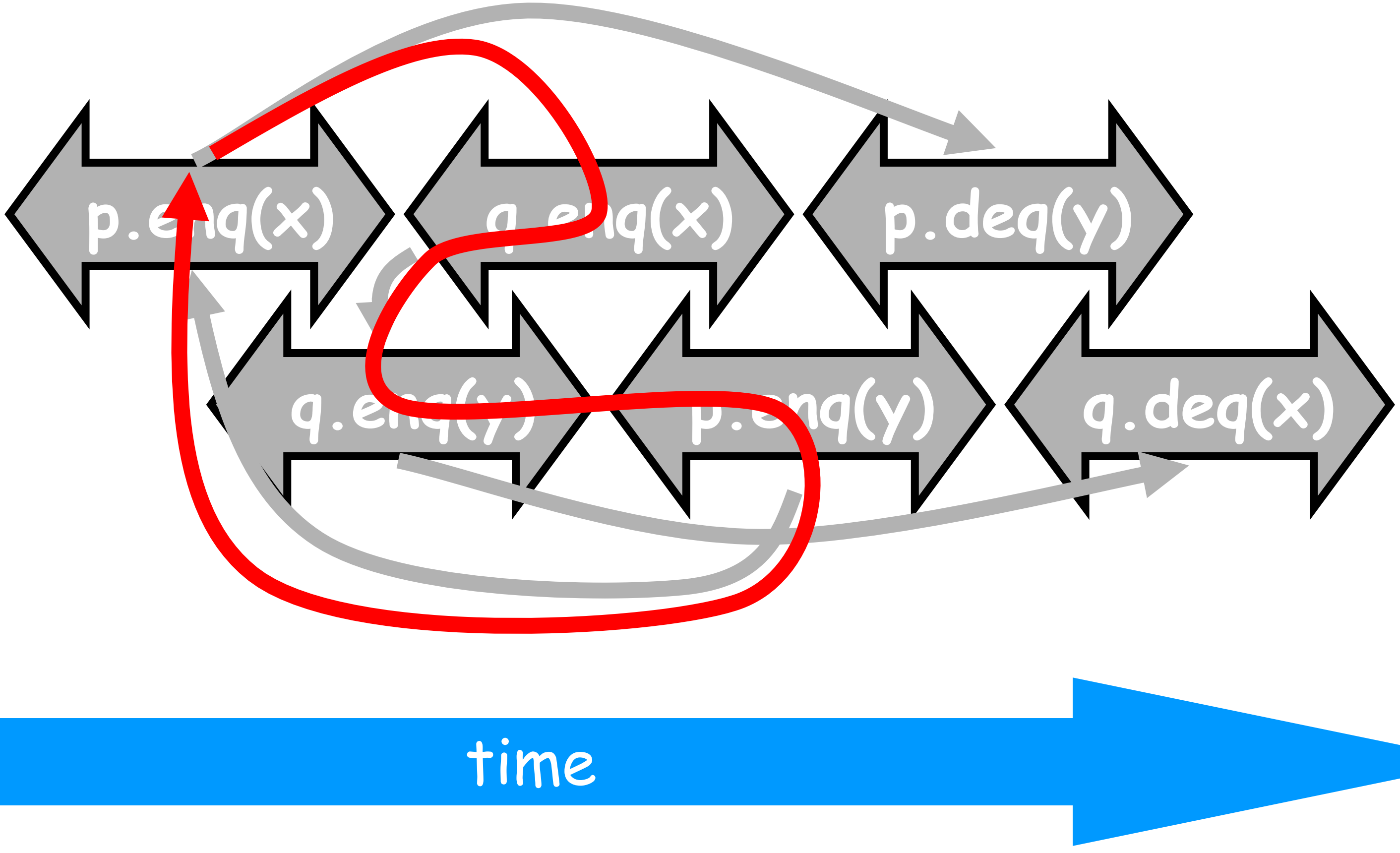
Ordering imposed by q



Ordering imposed by both



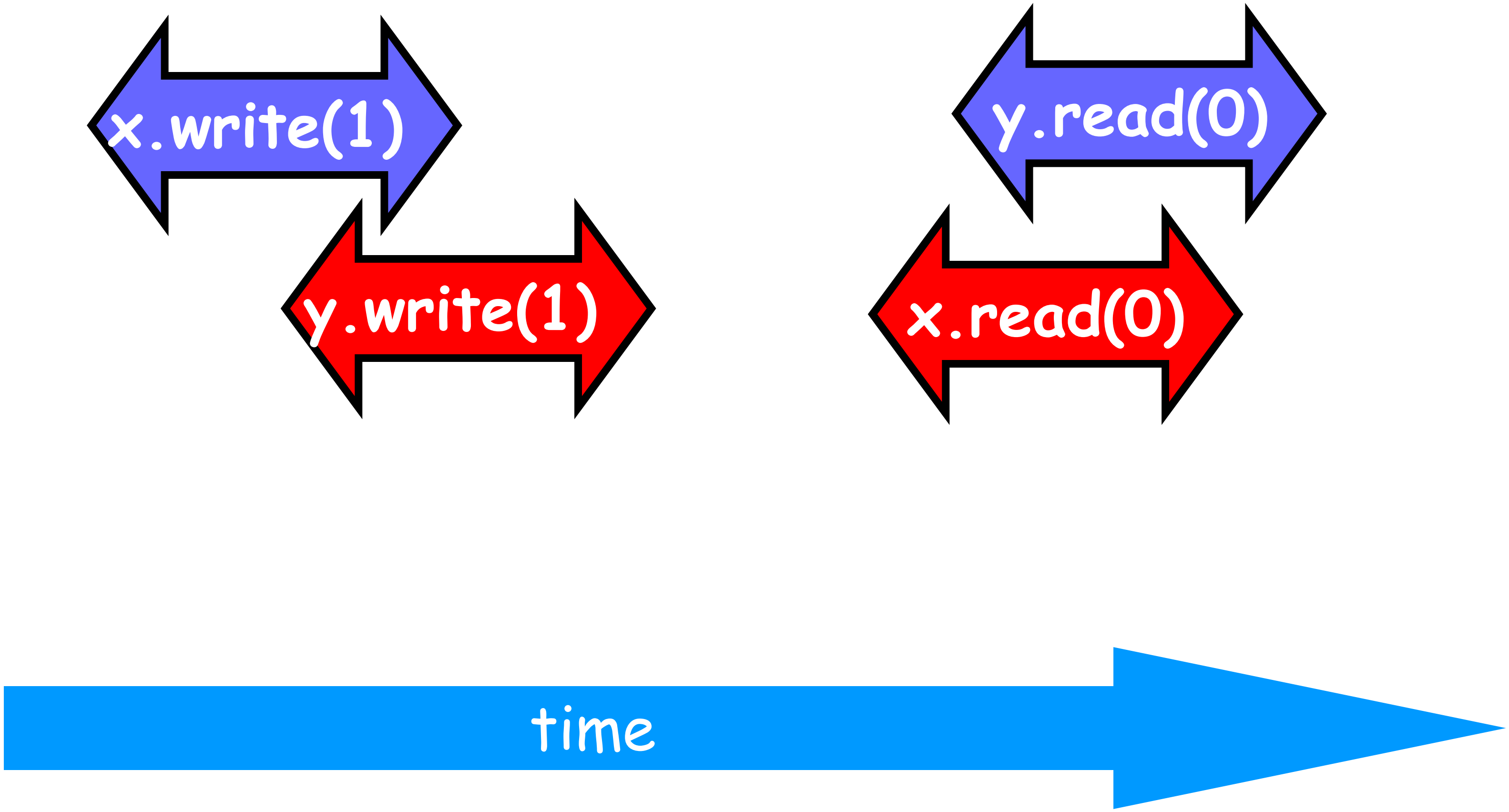
Combining orders



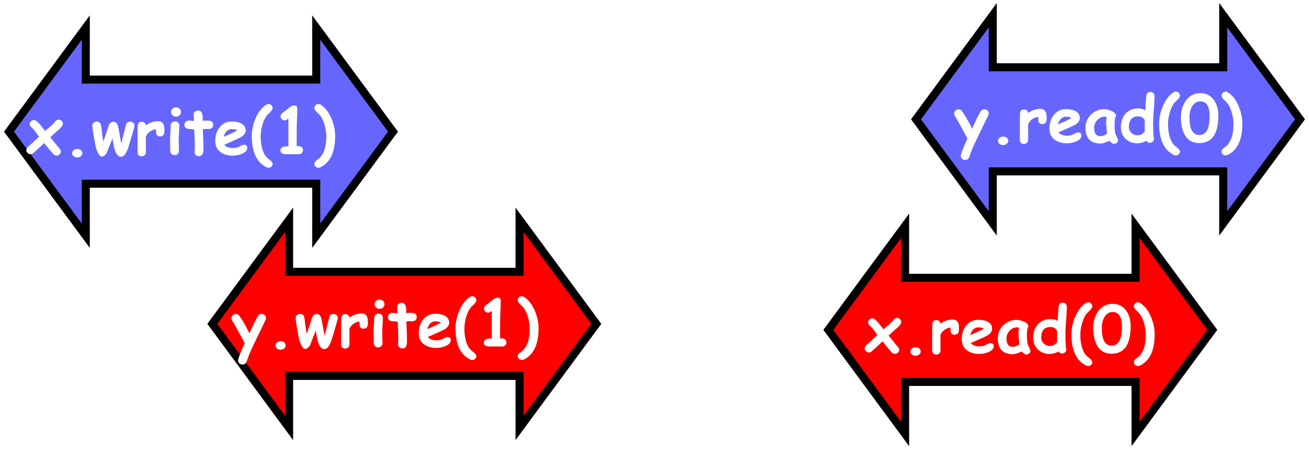
Fact

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

The Flag Example

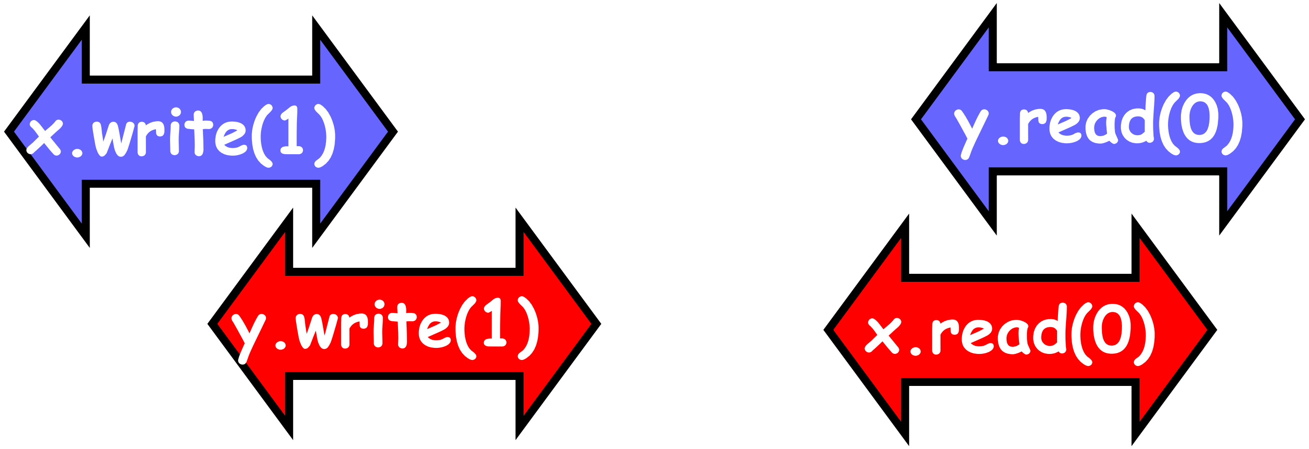


The Flag Example



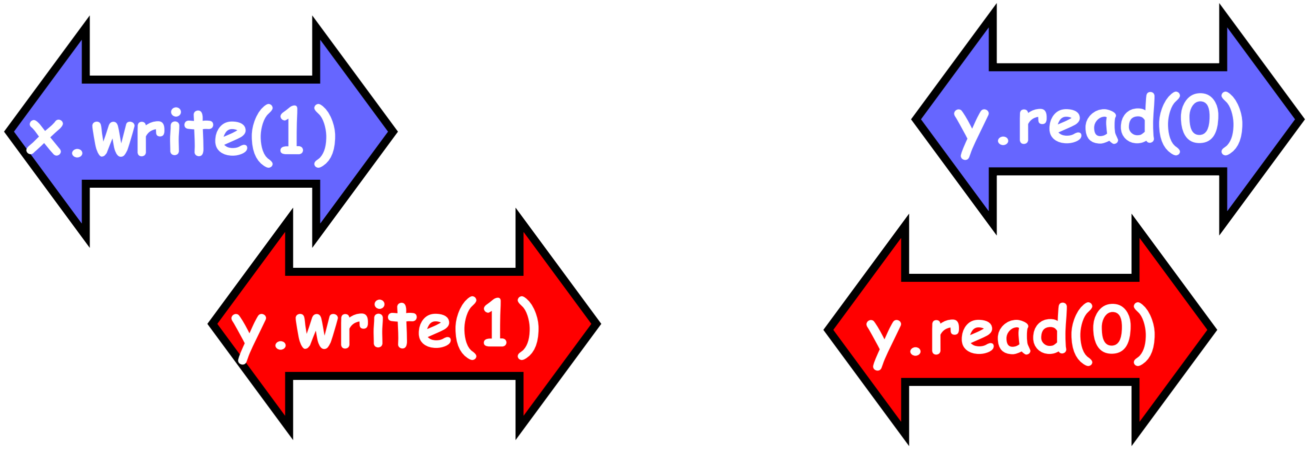
- Each thread's view is sequentially consistent
  - It went first

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

Opinion2: But It Feels So Right …

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

Memory 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.

Revisionist History

- Flag violation history is actually OK
  - processors delay writing to memory
  - Until after reads have been issued.
- Otherwise unacceptable delay between read and write instructions.
- Who knew you wanted to 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
- 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
- Like synchronized methods in Java™
- Problems
  - Blocking
  - No concurrency

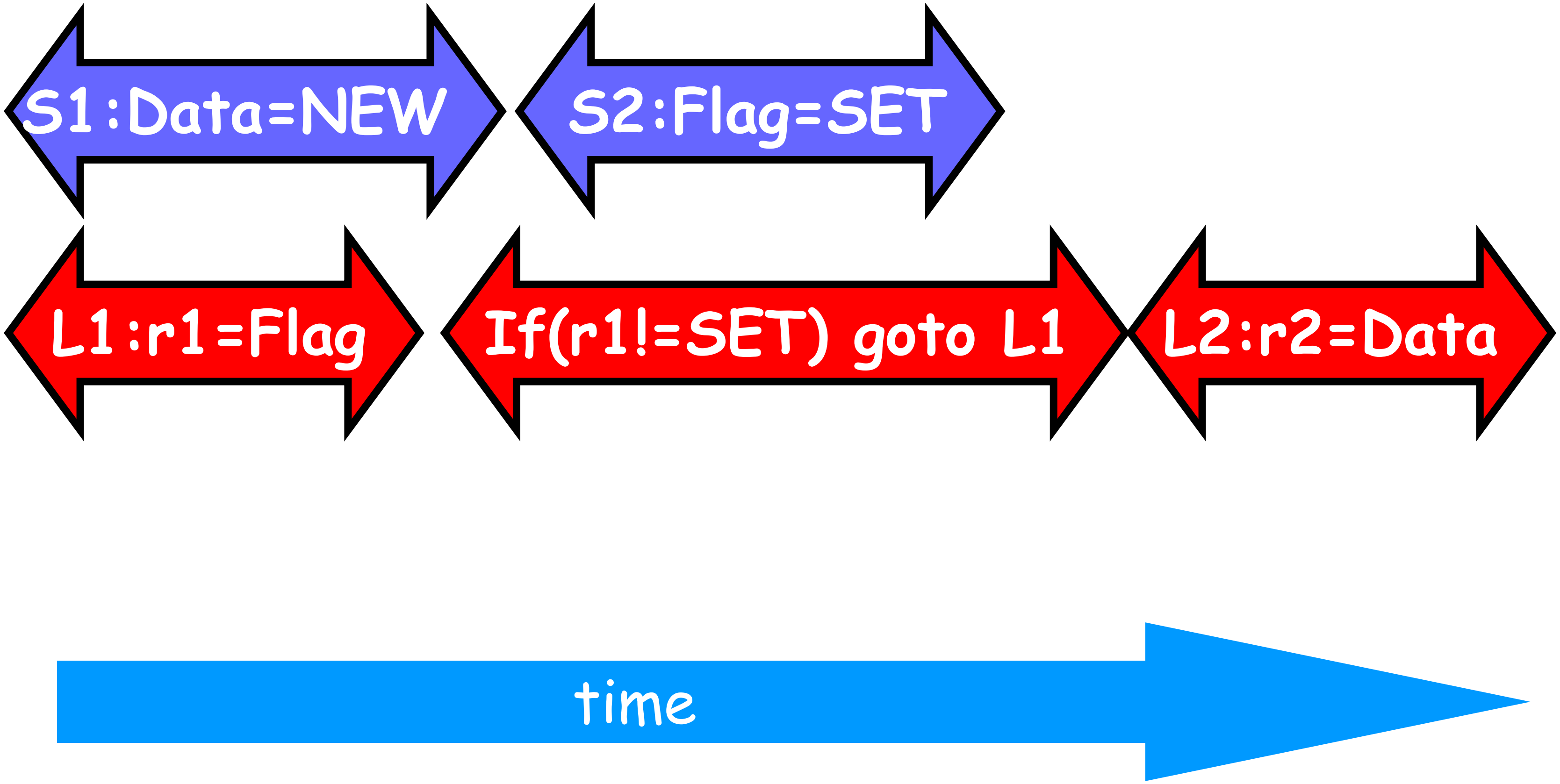
Summary

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

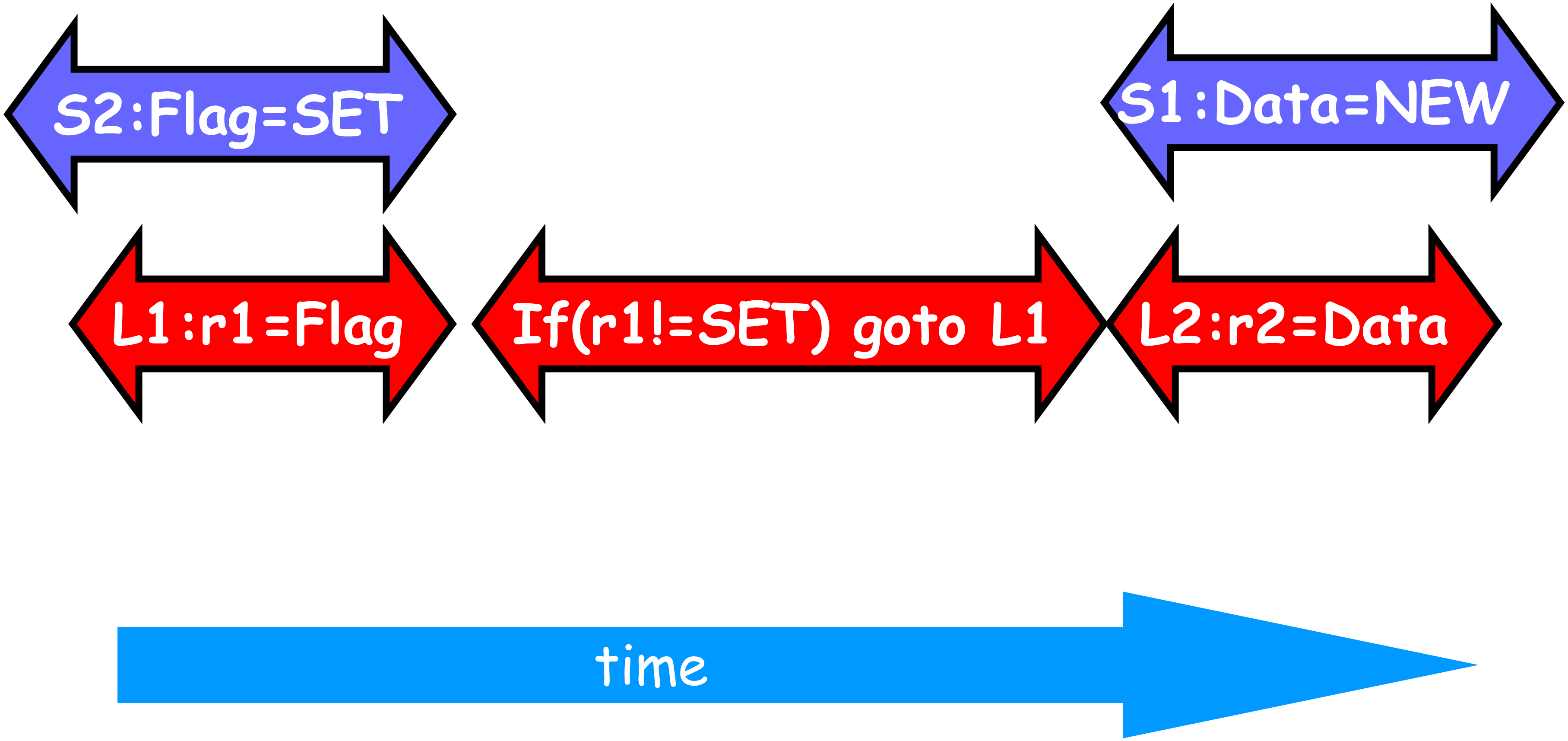
Summary

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

With multi core, What happens ?



S1 and S2 can be reordered



S2:Flag=SET

S1:Data=NEW

L1:r1=Flag

If(r1!=SET) goto L1

L2:r2=Data

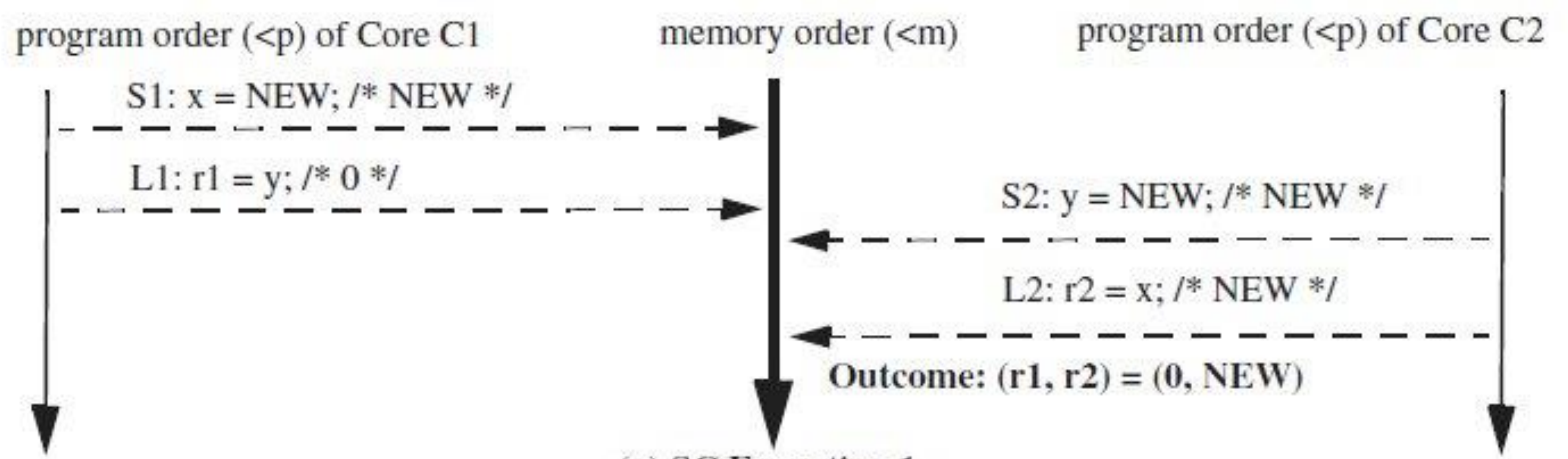
time

Dekker's algorithm

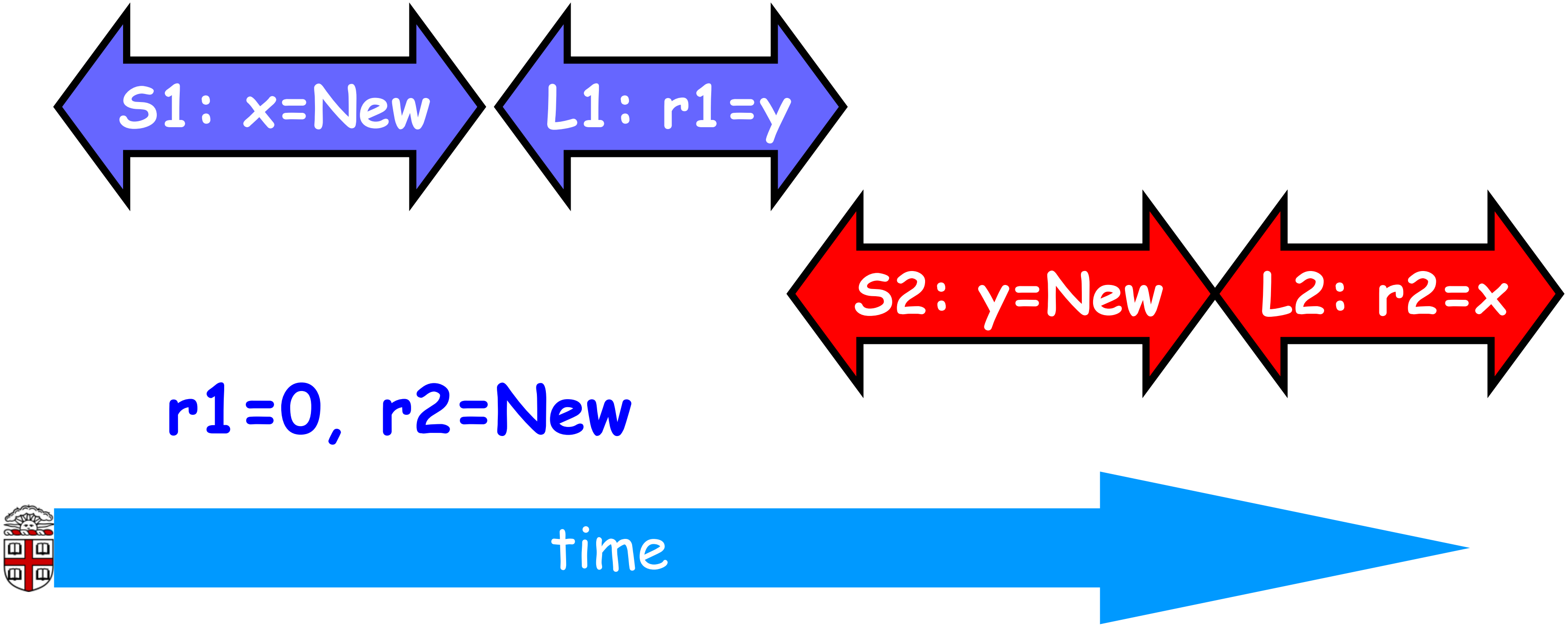
Initially, x=0 & y=0

```
Core C1       Core C2
S1: x=New;  S2: y=New;
L1: r1=y;     L2: r2=x;
```

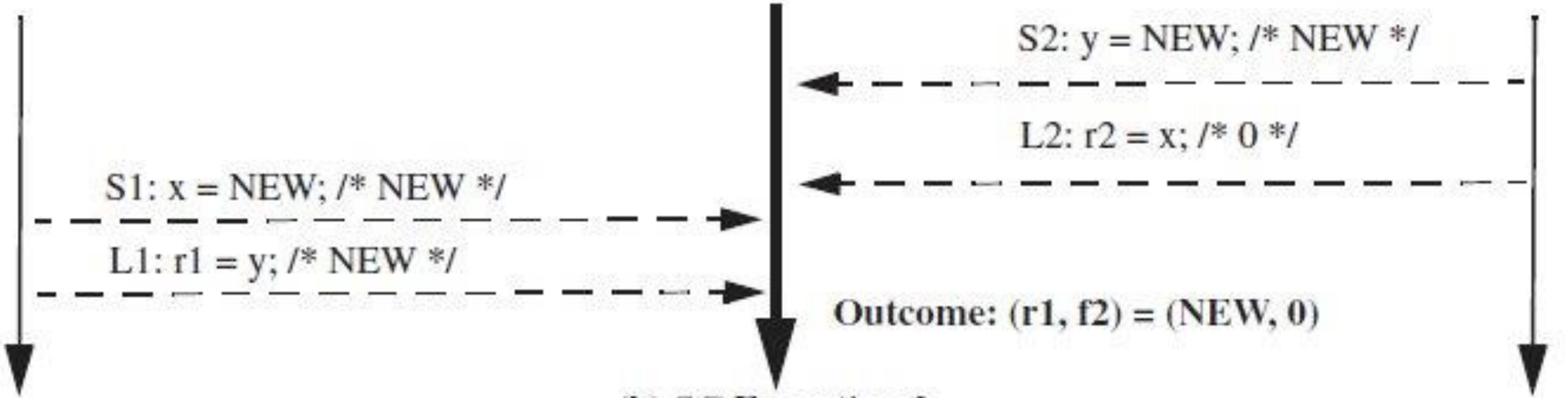
Can both r1 and r2 be set to 0 ?



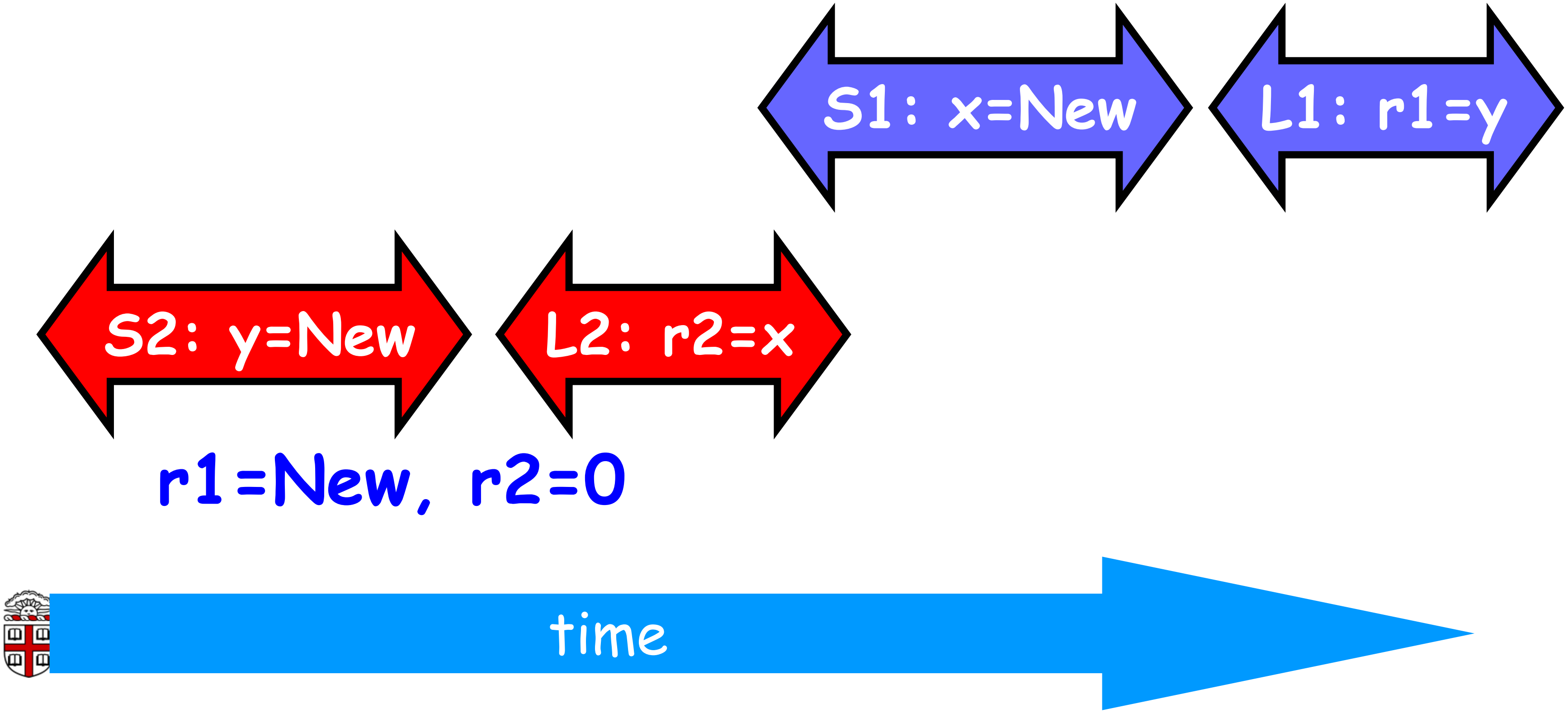
(a) SC Execution 1



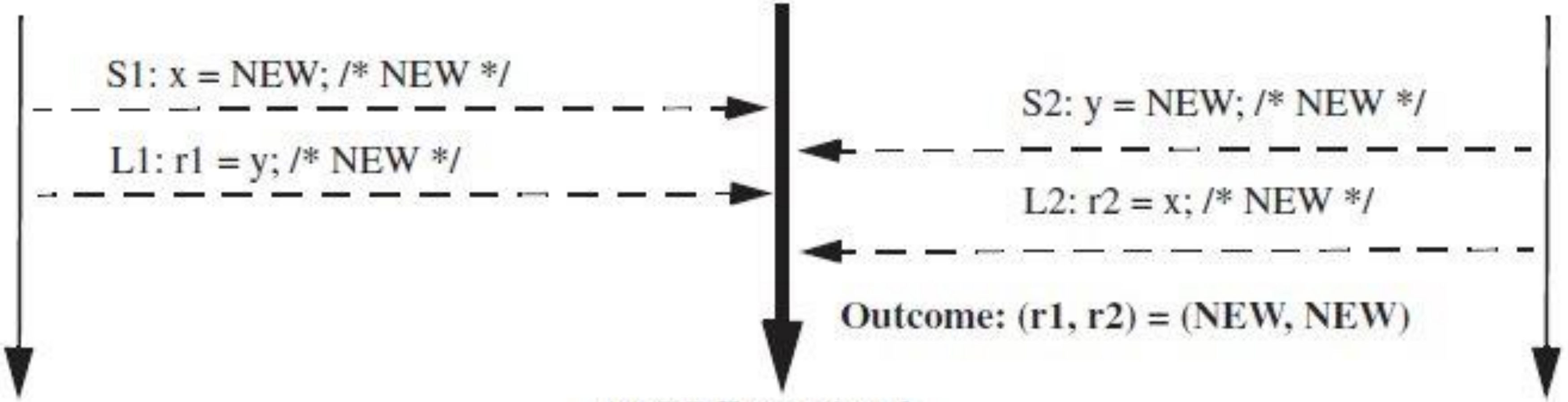
r1=0, r2=New



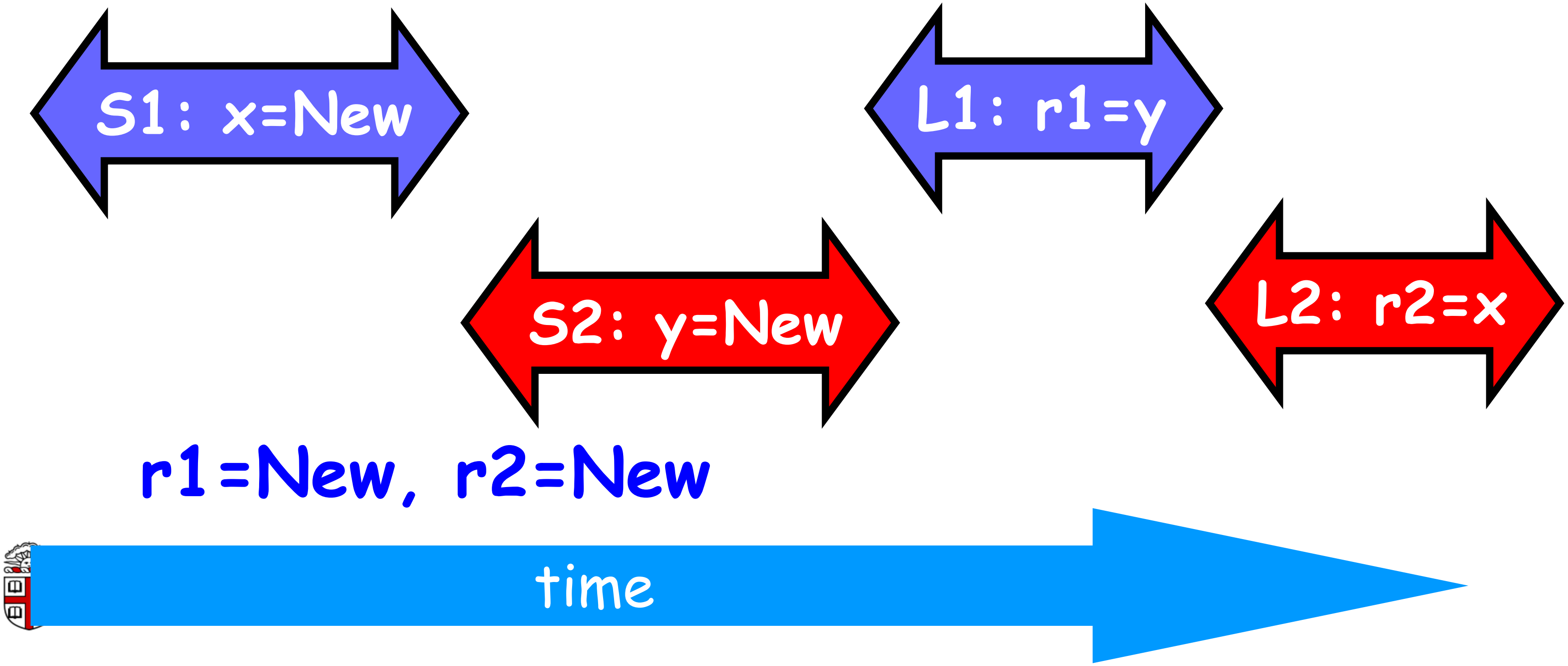
(b) SC Execution 2



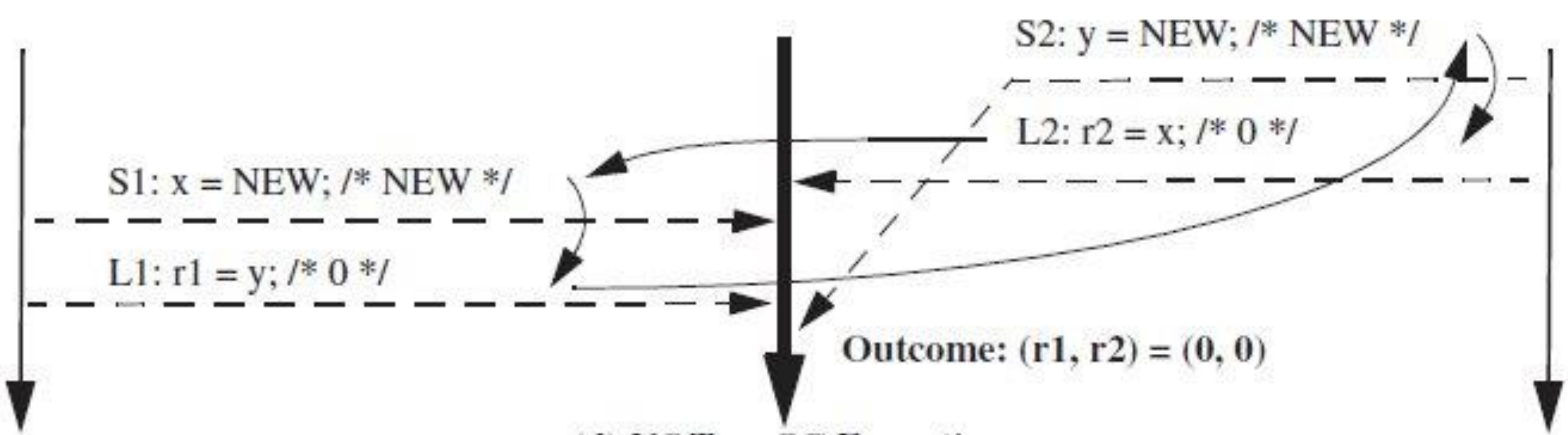
r1=New, r2=0



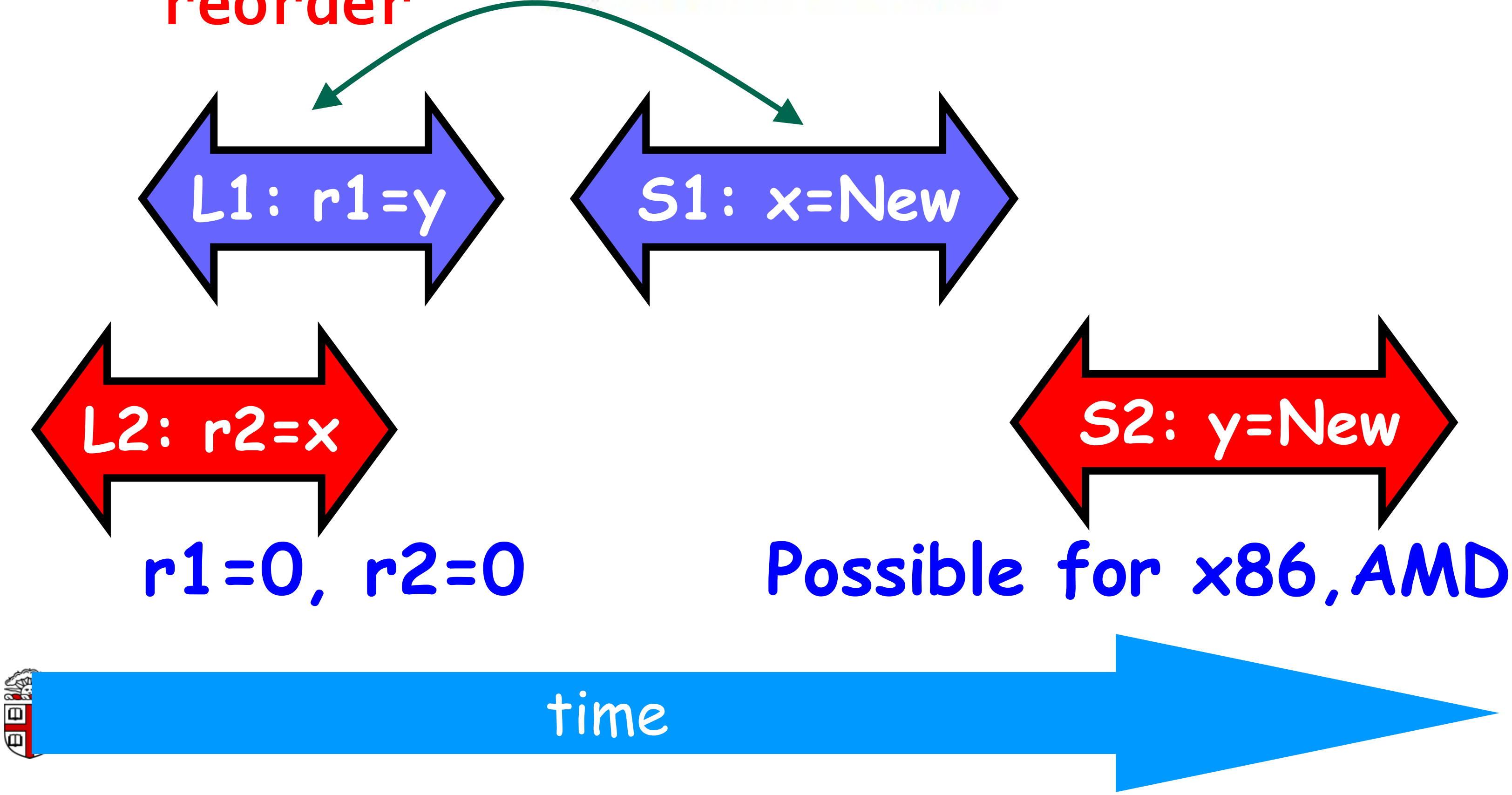
(c) SC Execution 3



r1=New, r2=New



(d) NOT an SC Execution



r1=0, r2=0

Possible for x86,AMD

An SC execution requires

- All cores insert their loads and stores into the order <m respecting their program order, regardless of whether they are to the same or different addresses
- Every load gets its value from the last store before it to the same address

SC ordering Rules

		Operation 2		
		Load	Store	RMW
Operation 1	Load	X	X	X
	Store	X	X	X
	RMW	X	X	X

X denotes an enforced ordering

Total Store Order

- SPARC
- X86

- Remnants of the write buffer
- Write takes longer
  - It sometimes does, too
  - Needs to get the write permission

Total Store Order

- Load -> Load
- Load -> Store
- Store -> Store
- Store -> Load (omitted for TSO)

- Omitting the 4th constraint allows each core to use a write buffer

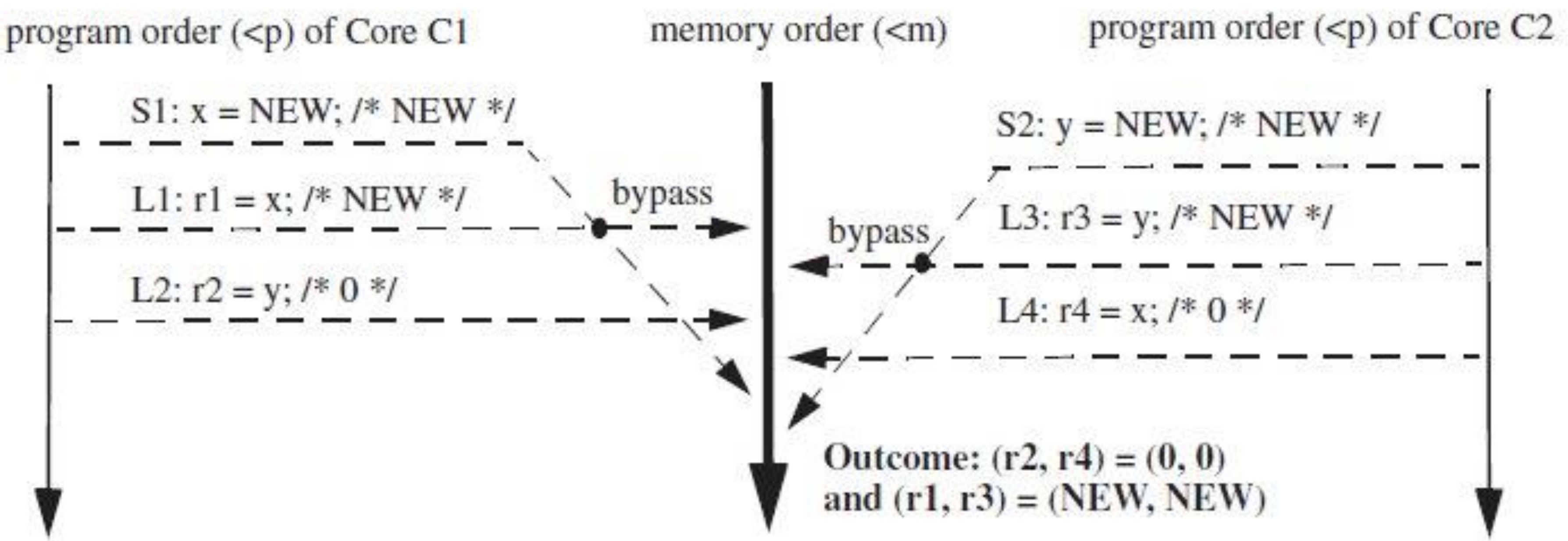
TSO behavior

Initially, x=0 & y=0

Core C1	Core C2
S1: x=New;	S2: y=New;
L1: r1=x;	L3: r3=y;
L2: r2=y;	L4: r4=x;

If r2=0 & r4=0, can r1 or r3 be set to 0 ?

Bypassing



r1=New & r3=New !!!

To make TSO sequentially consistent

- Use FENCE
- FENCE ensures the memory operations before the FENCE get placed before the memory operations after the FENCE on the core

TSO ordering Rules

Operation 1	Operation 2			
	Load	Store	RMW	FENCE
Load	X	X	X	X
Store	B	X	X	X
RMW	X	X	X	X
FENCE	X	X	X	X

B denotes bypassing if on the same address