Design of Parallel and High-Performance Computing

Fall 2013

Lecture: Linearizability

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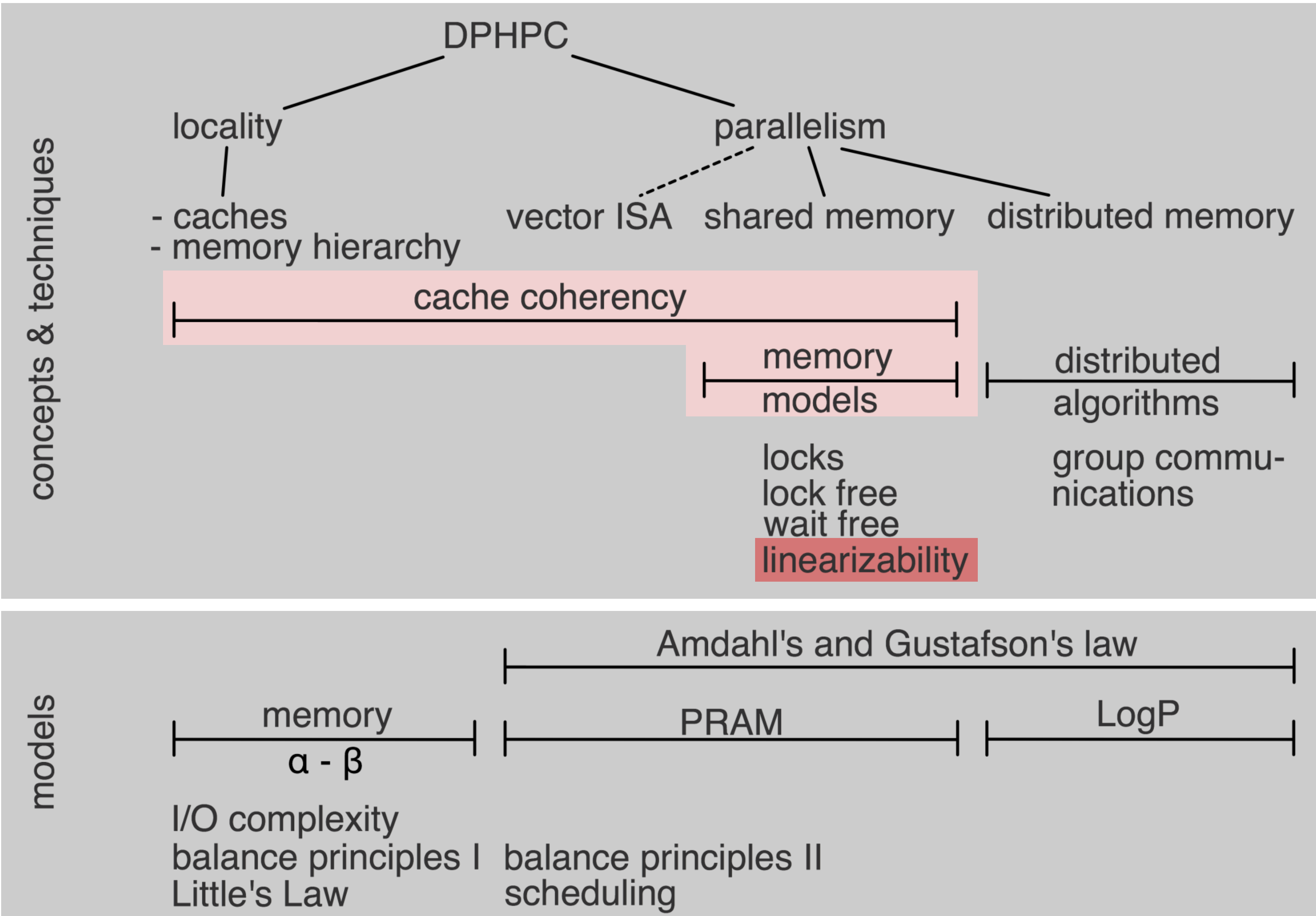
Review of last lecture

- **Cache-coherence is not enough!**
  - Many more subtle issues for parallel programs!

- **Memory Models**
  - Sequential consistency
  - Why threads cannot be implemented as a library ☺
  - Relaxed consistency models
  - x86 TLO+CC case study

- **Complexity of reasoning about parallel objects**

DPHPC Overview



Goals of this lecture

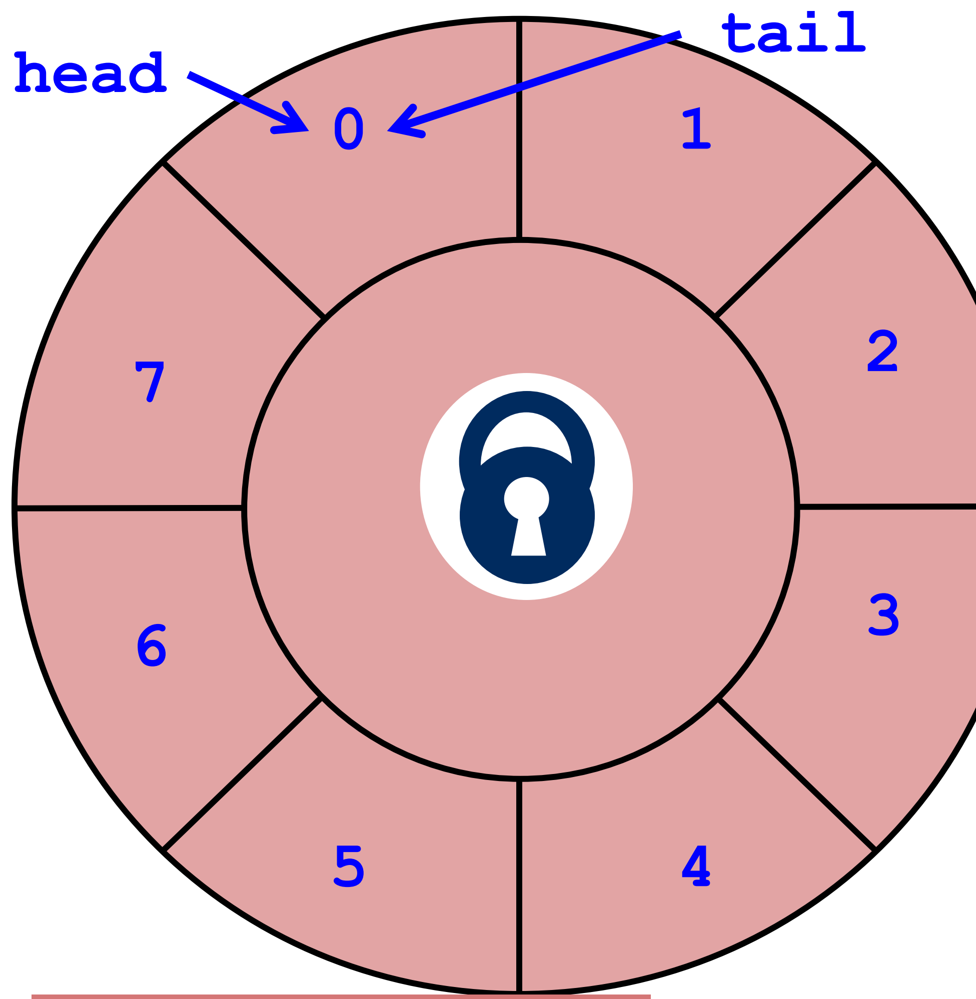
- **Queue:**
  - Locked
    C++ locking (small detour)
  - Wait-free two-thread queue
- **Linearizability**
  - Intuitive understanding (sequential order on objects!)
  - Linearization points
  - Linearizable executions
  - Formal definitions (Histories, Projections, Precedence)
- **Linearizability vs. Sequential Consistency**
  - Modularity

Lock-based queue

```
class Queue {

  private:
  int head, tail;
  std::vector<Item> items;
  std::mutex lock;

  public:
  Queue(int capacity) {
    head = tail = 0;
    items.resize(capacity);
  }
  ...
};
```



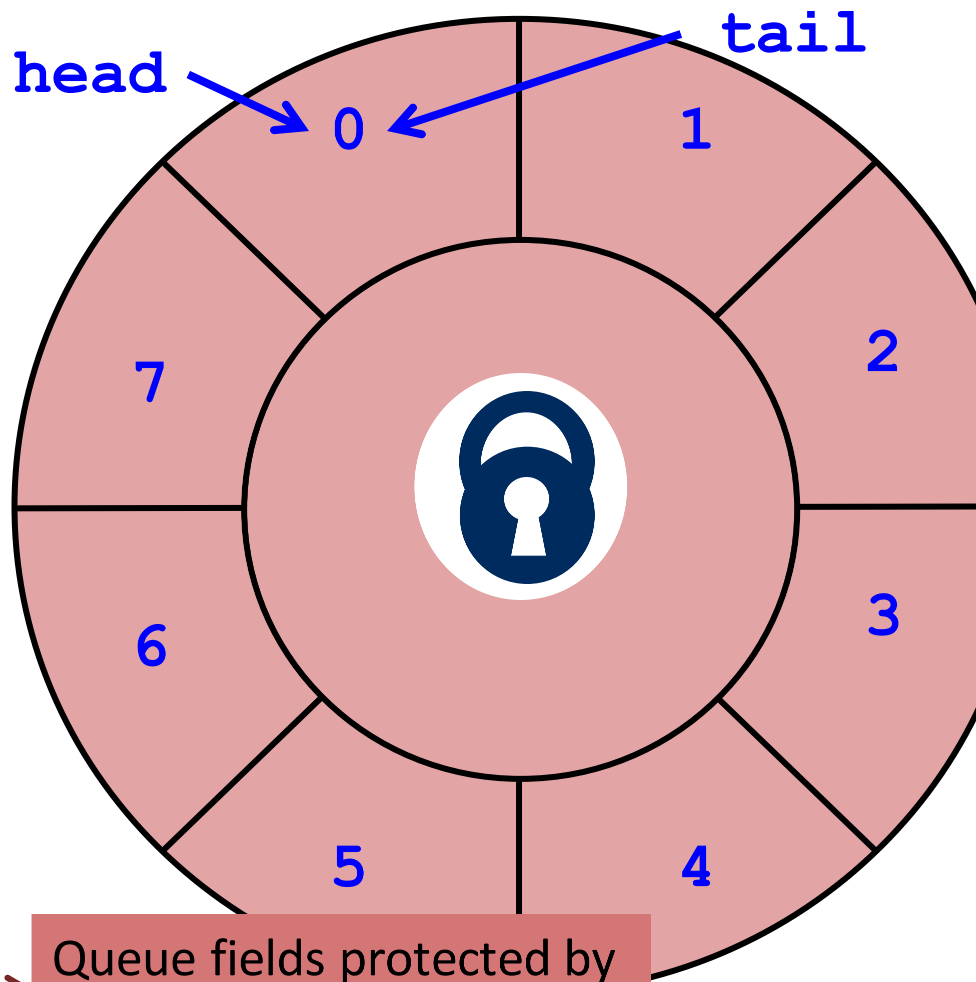
Queue fields protected by single shared lock!

Lock-based queue

```
class Queue {
 ...

 public:
 void enq(Item x) {
  std::lock_guard<std::mutex> l(lock)
  if(tail-head == items.size()) {
   throw FullException;
  }
  items[tail % items.size()] = x;
  tail = (tail+1)%items.size();
 }

 Item deq() {
  std::lock_guard<std::mutex> l(lock)
  if(tail == head) {
   throw FullException;
  }
  Item item = items[head % items.size()];
  head = (head+1)%items.size();
 }
};
```



Queue fields protected by single shared lock!

Class question: how is the lock ever unlocked?

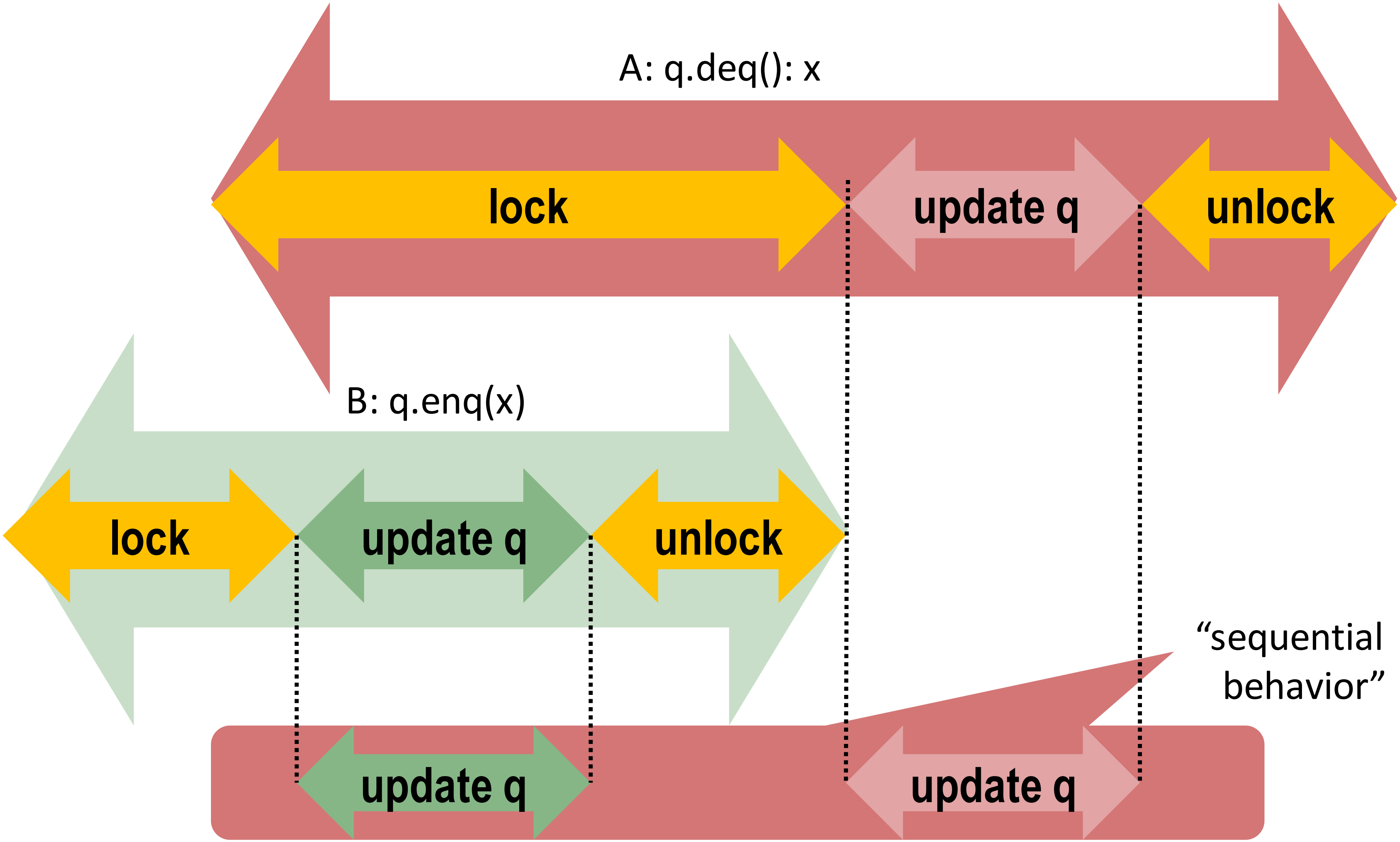
C++ Resource Acquisition is Initialization

- **RAII – suboptimal name**
- **Can be used for locks (or any other resource acquisitions)**
  - Constructor grabs resource
  - Destructor frees resource
- **Behaves as if**
  - Implicit unlock at end of block!
- **Main advantages**
  - Always free lock at exit
  - No “lost” locks due to exceptions or strange control flow (goto ☺)
  - Very easy to use

```
class lock_guard<typename mutex_impl> {
  mutex_impl &_mtx; // ref to the mutex

  public:
    scoped_lock(mutex_impl & mtx ) :  _mtx(mtx) {
       _mtx.lock();  //lock  mutex in constructor
    }
    ~scoped_lock() {
      _mtx.unlock(); //unlock mutex in destructor
    }
};
```

Example execution



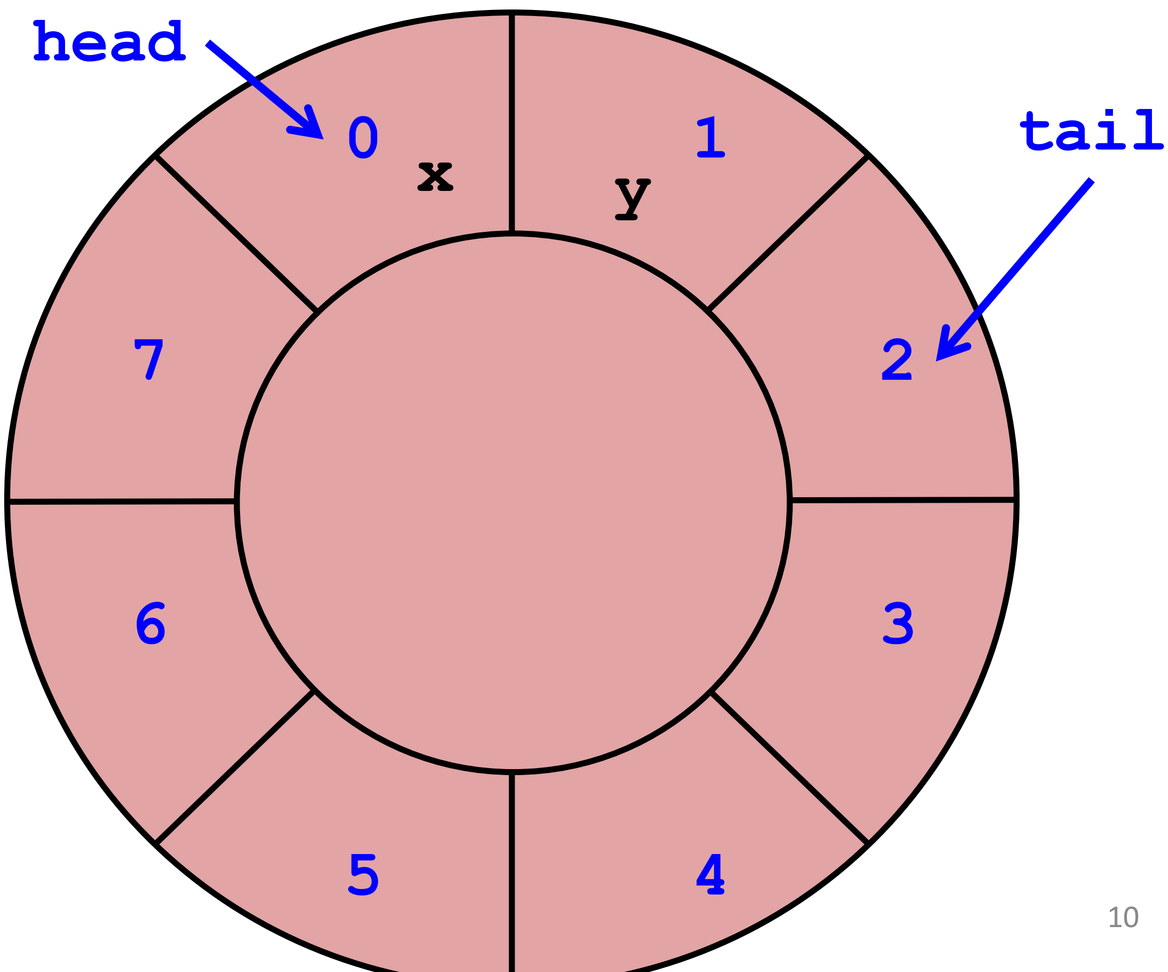
Correctness

- **Is the locked queue correct?**
  - Yes, only one thread has access if locked correctly
  - Allows us again to reason about pre- and postconditions
  - Smells a bit like sequential consistency, no?
- **Class question: What is the problem with this approach?**
  - Same as for SC ☺

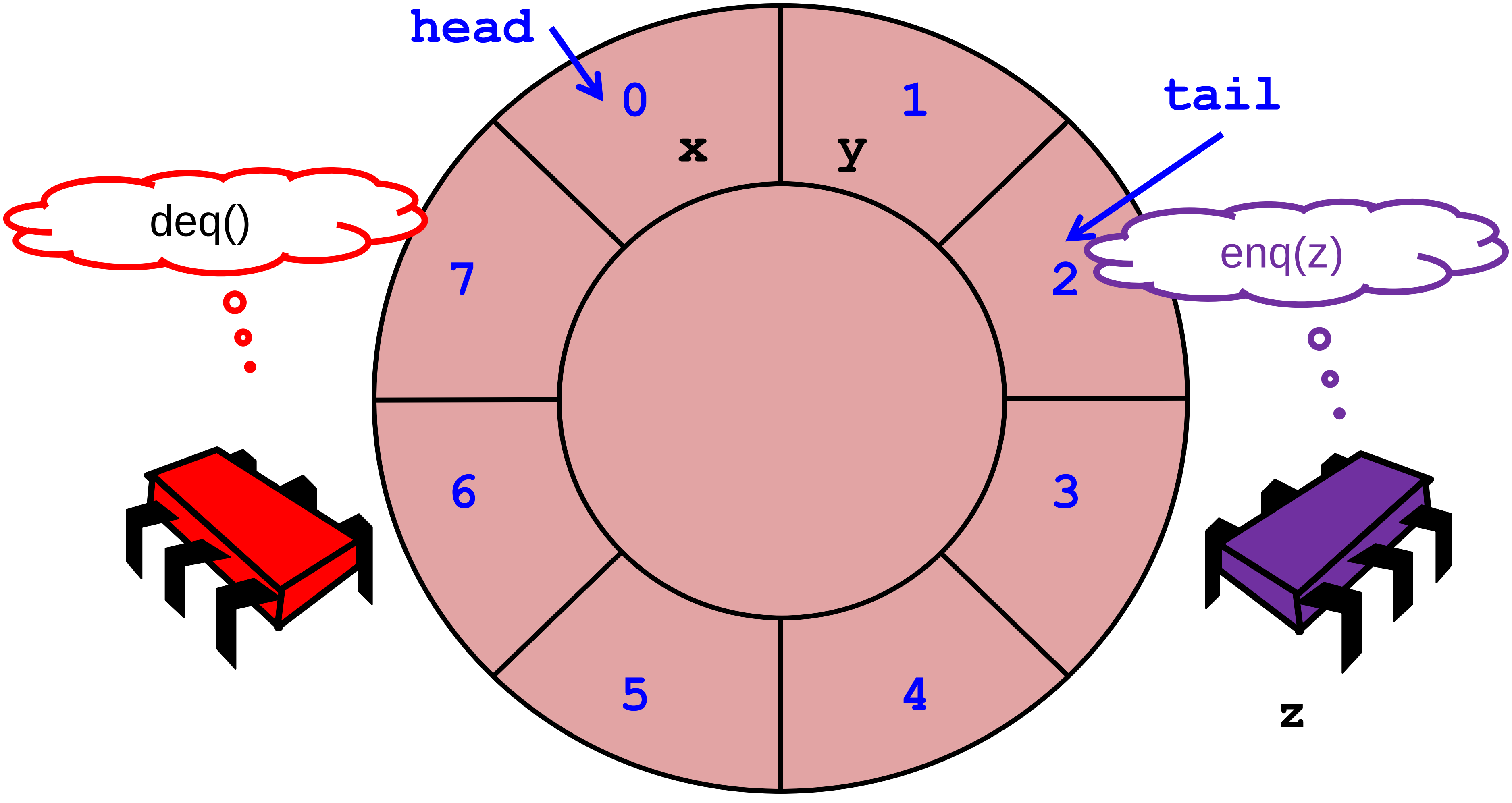
It does not scale!
What is the solution here?

Threads working at the same time?

- **Same thing (concurrent queue)**
- **For simplicity, assume only two threads**
  - Thread A calls only enq()
  - Thread B calls only deq()



Wait-free 2-Thread Queue



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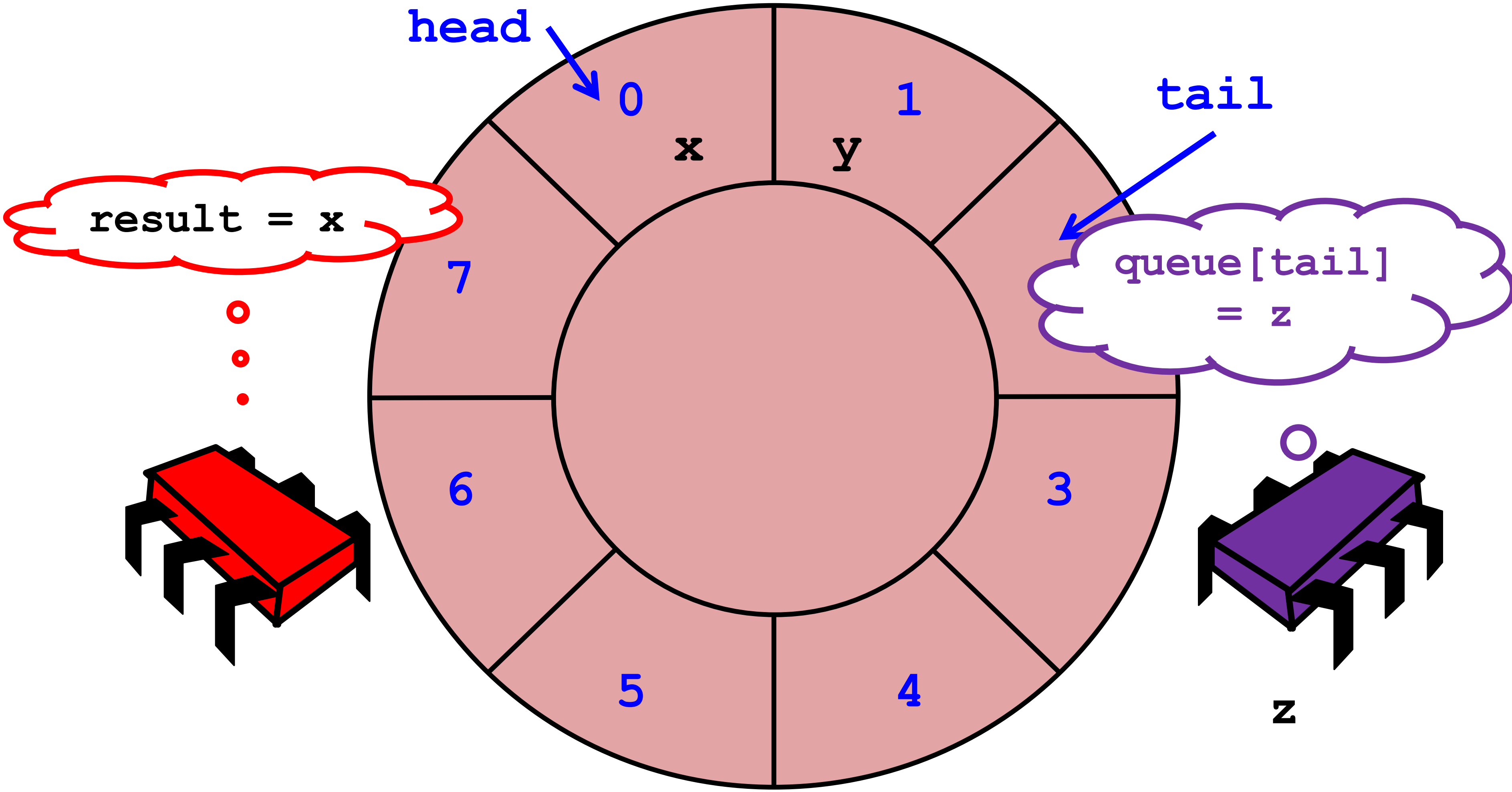
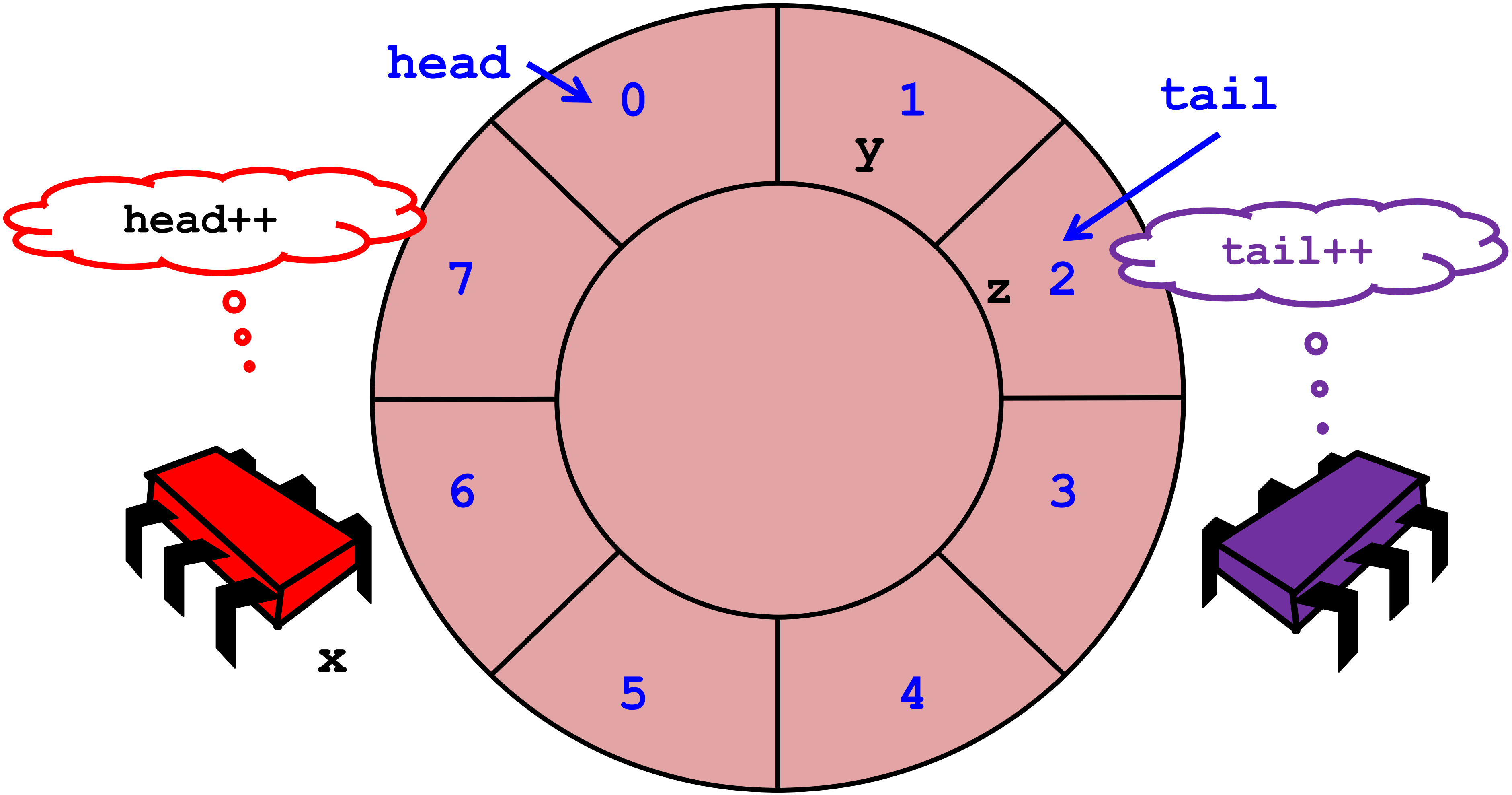


Wait-free 2-Thread Queue



Is this correct?

- **Hard to reason about correctness**
- **What could go wrong?**

```
void enq(Item x) {
  if(tail-head == items.size()) {
    throw FullException;
  }
  items[tail % items.size()] = x;
  tail = (tail+1)%items.size();
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```
Item deq() {
  if(tail == head) {
    throw EmptyException;
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  Item item = items[head % items.size()];
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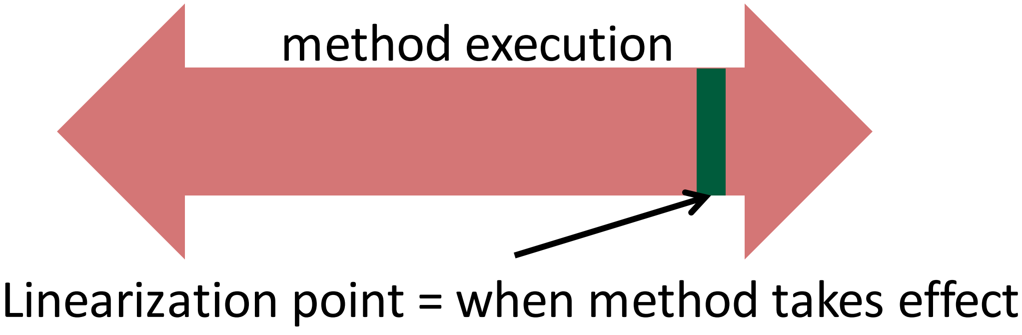
}
```

  - Nothing (at least no crash)
  - Yet, the **semantics** of the queue are funny (define "FIFO" now)!

Serial to Concurrent Specifications

- **Serial specifications are complex enough, so lets stick to them**
  - Define invocation and response events (start and end of method)
- **Extend the concept to concurrency: linearizability**
- **Each method should "take effect"**
  - Instantaneously
  - Between invocation and response events
- **Concurrent object is correct if this "sequential" behavior is correct**
  - Called "linearizable"



Linearizability

- **Sounds like a property of an execution …**
- **An object is called linearizable if all possible executions on the object are linearizable**
- **Says nothing about the order of executions!**

Example

```
void enq(Item x) {
  std::lock_guard<std::mutex> l(lock)
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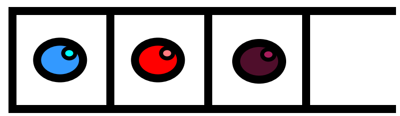

linearization points

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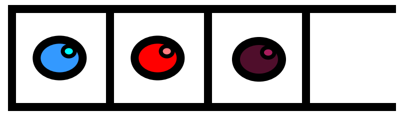

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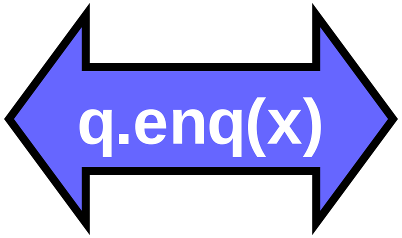

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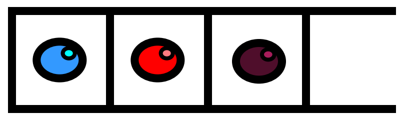

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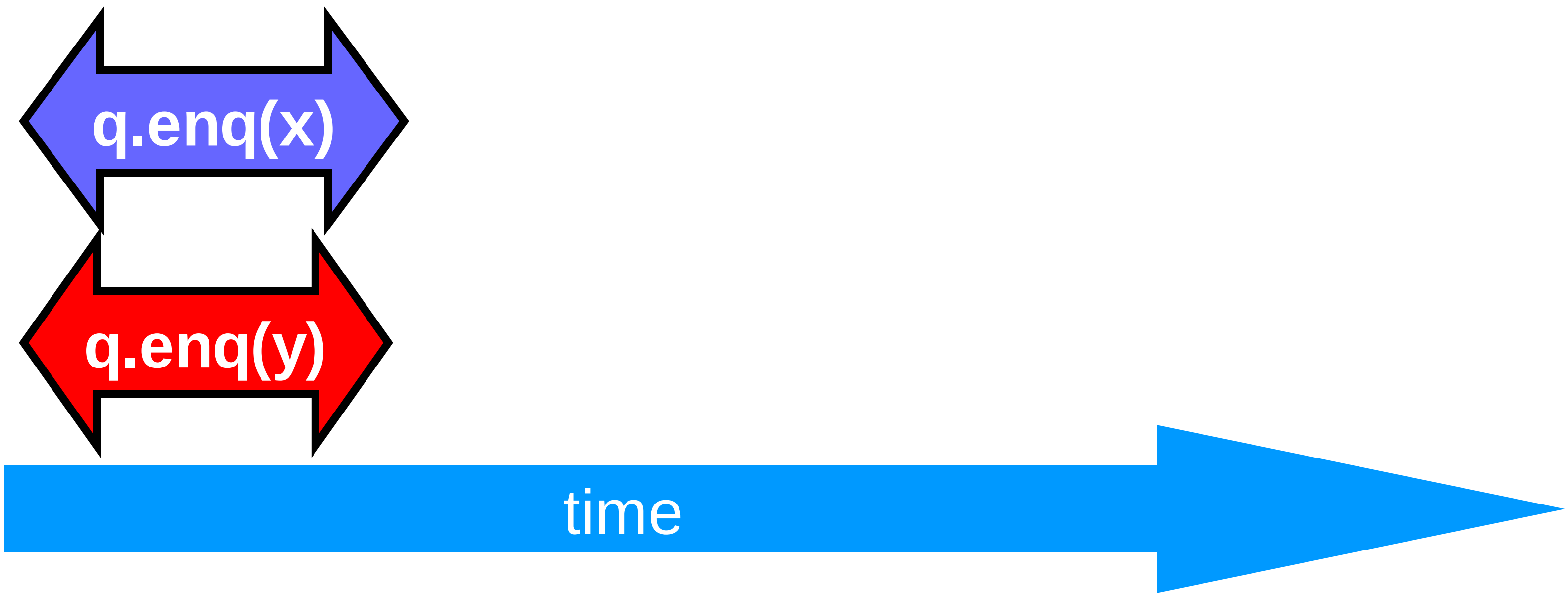

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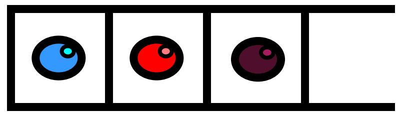

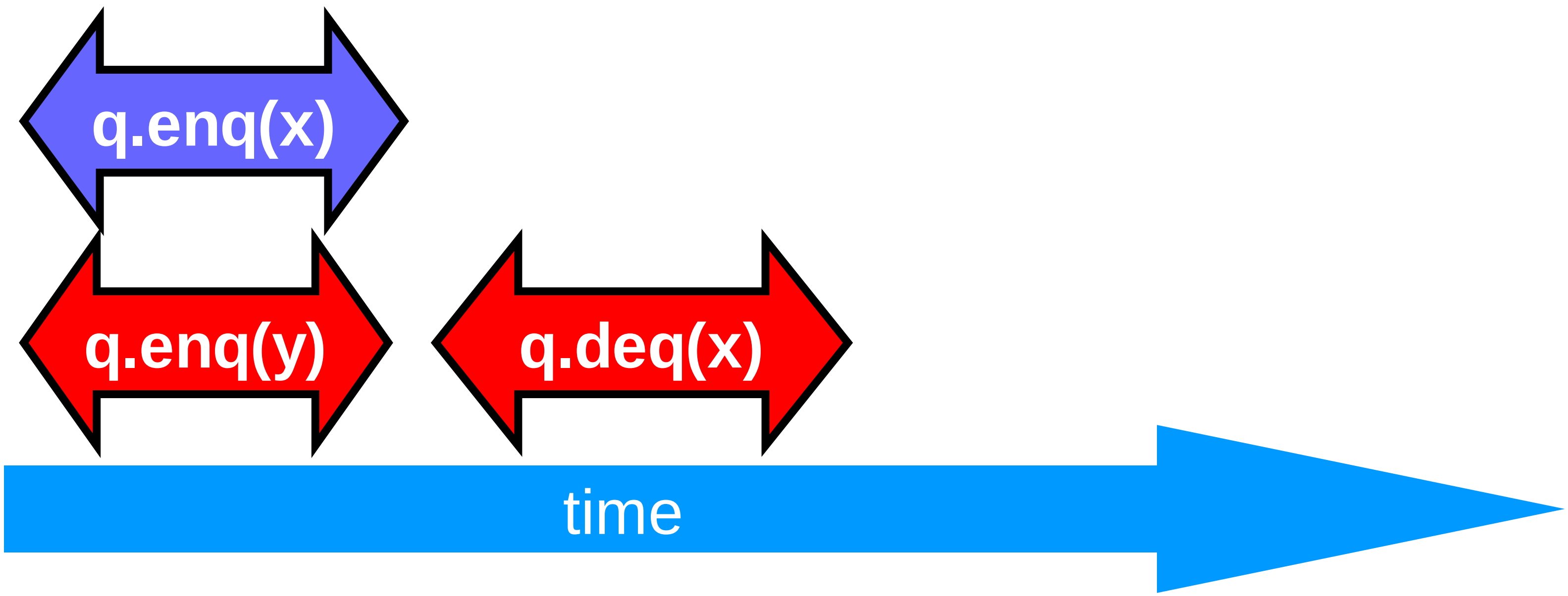

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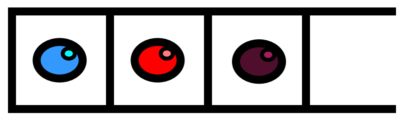

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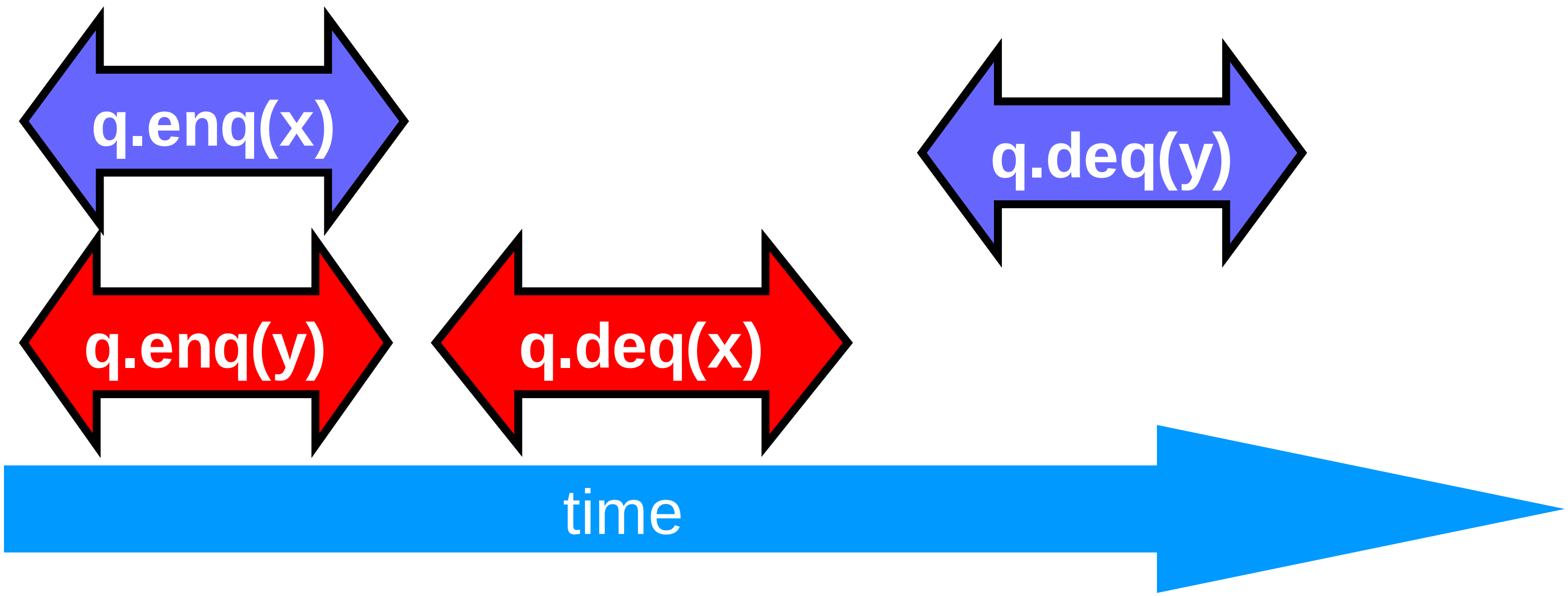

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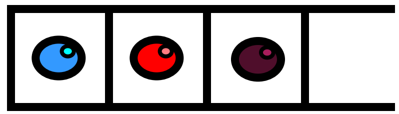

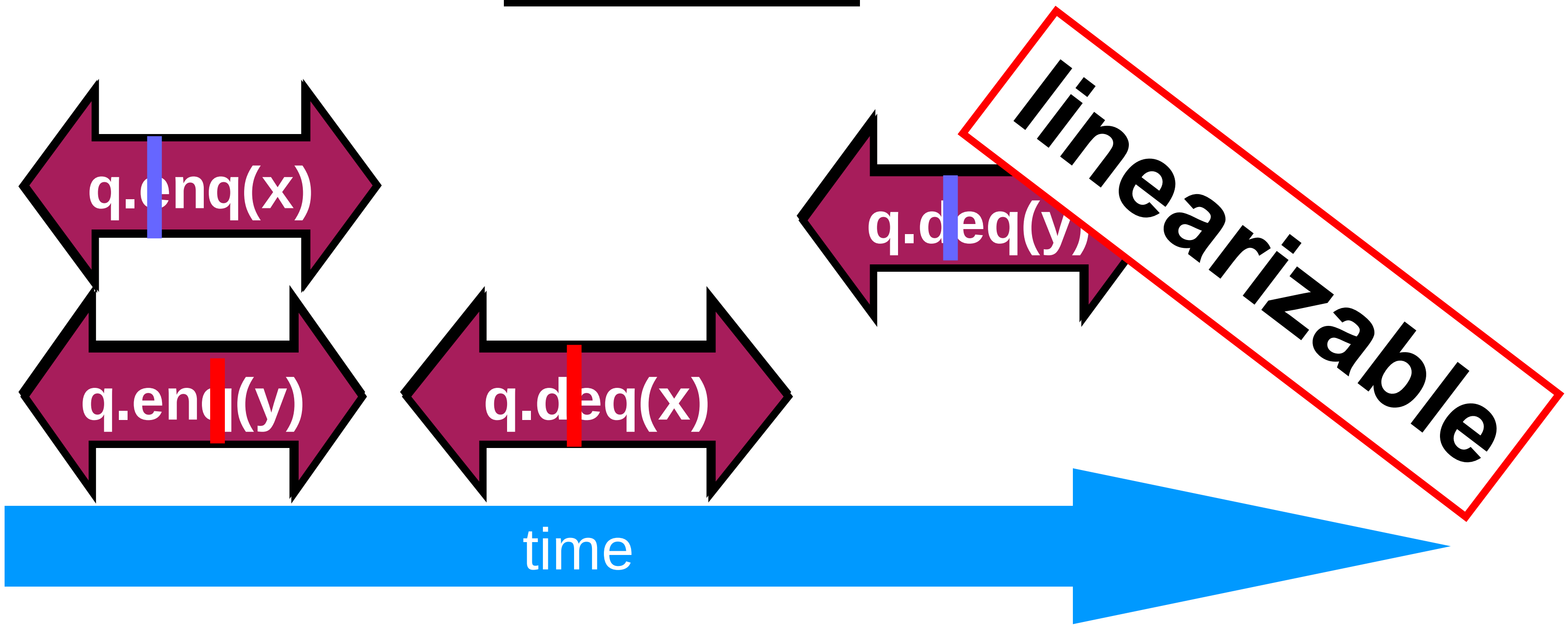

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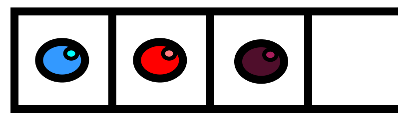
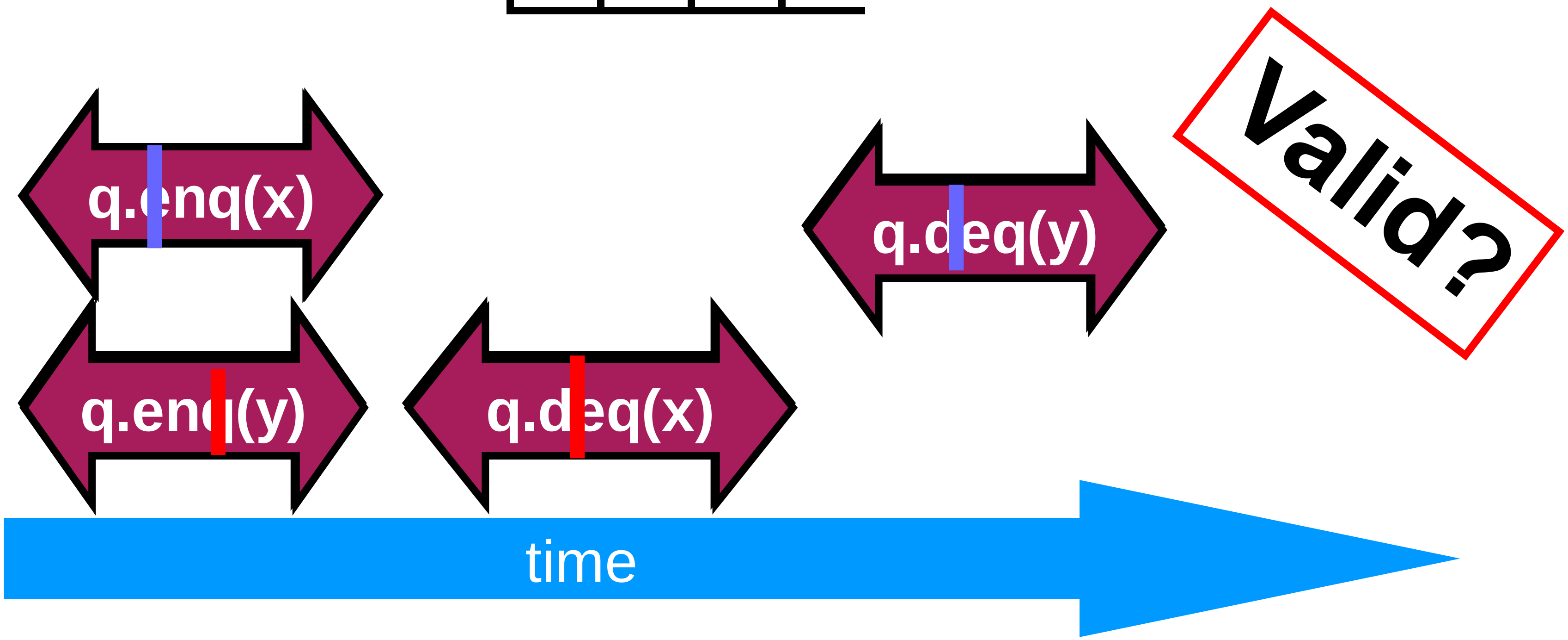
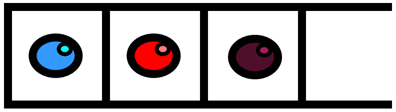
linearization points





Example 2



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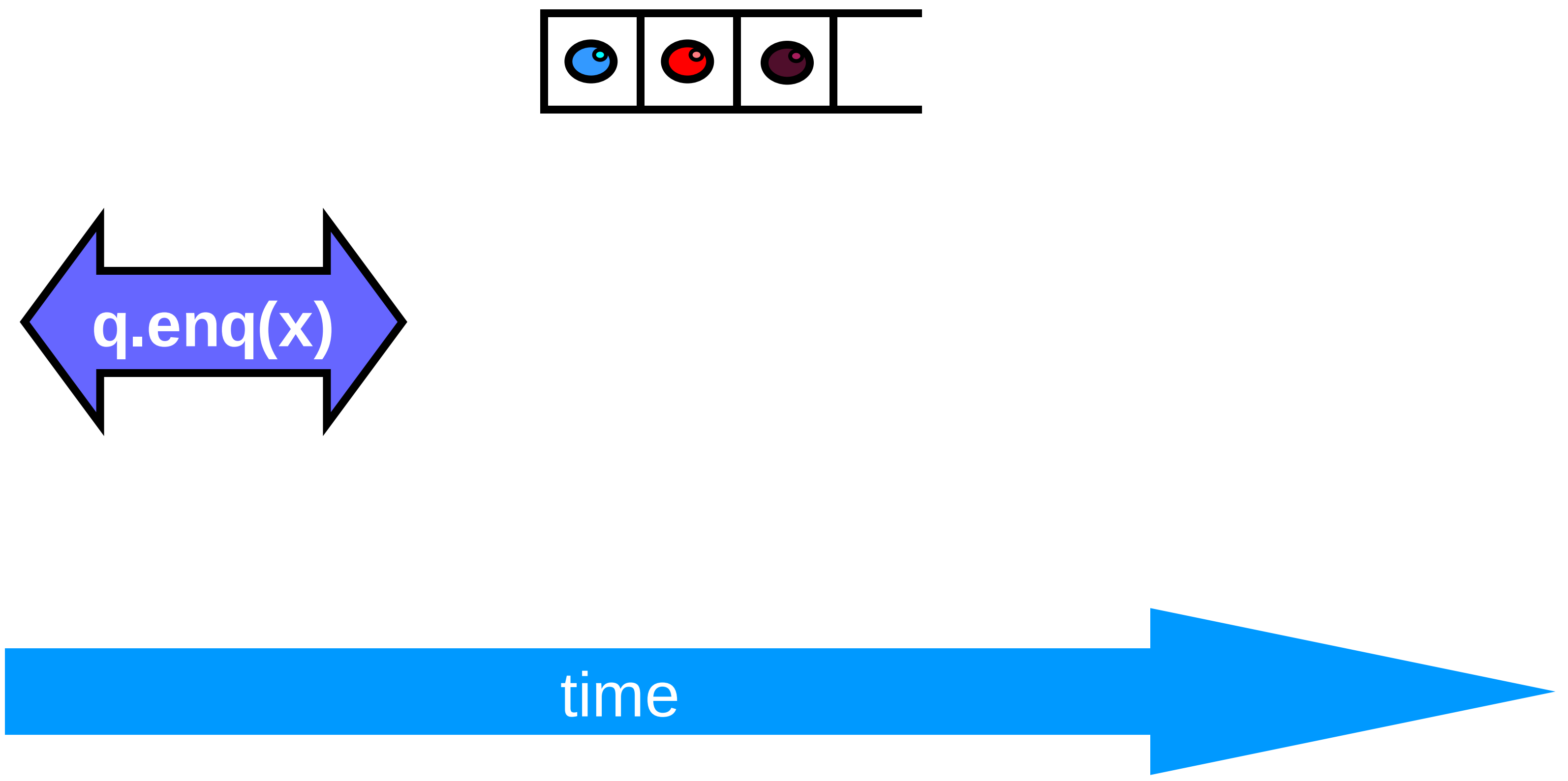

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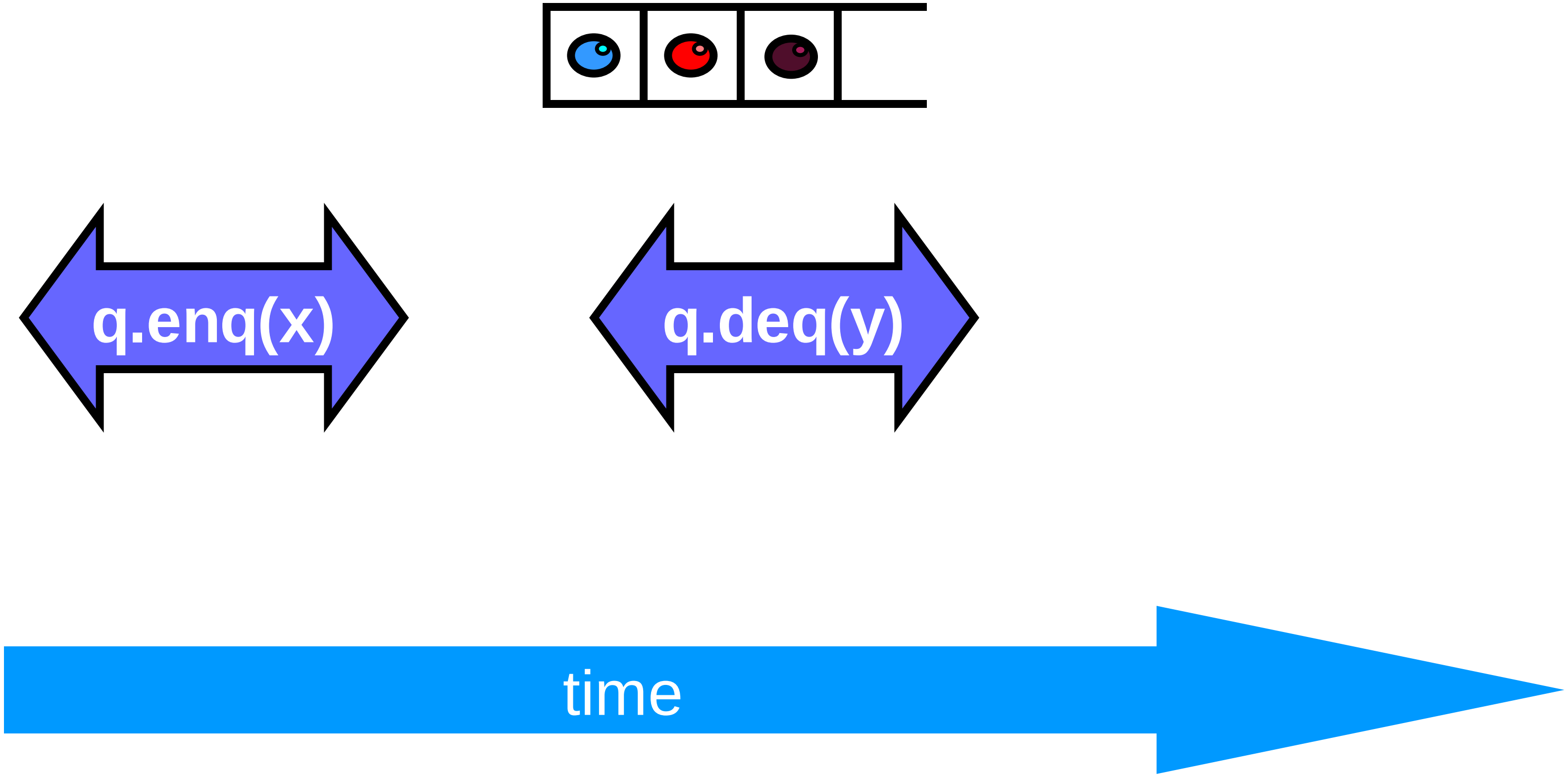

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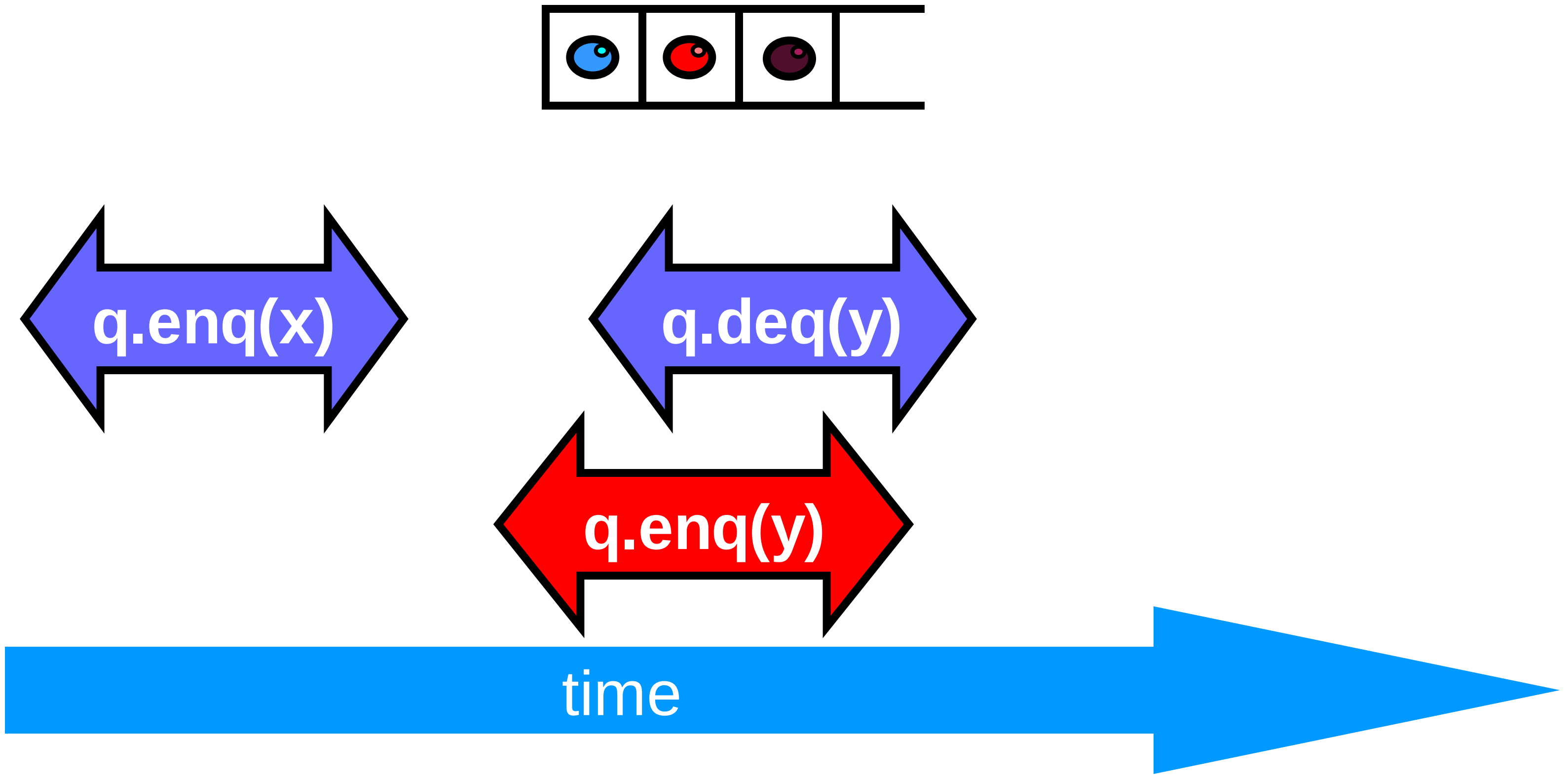

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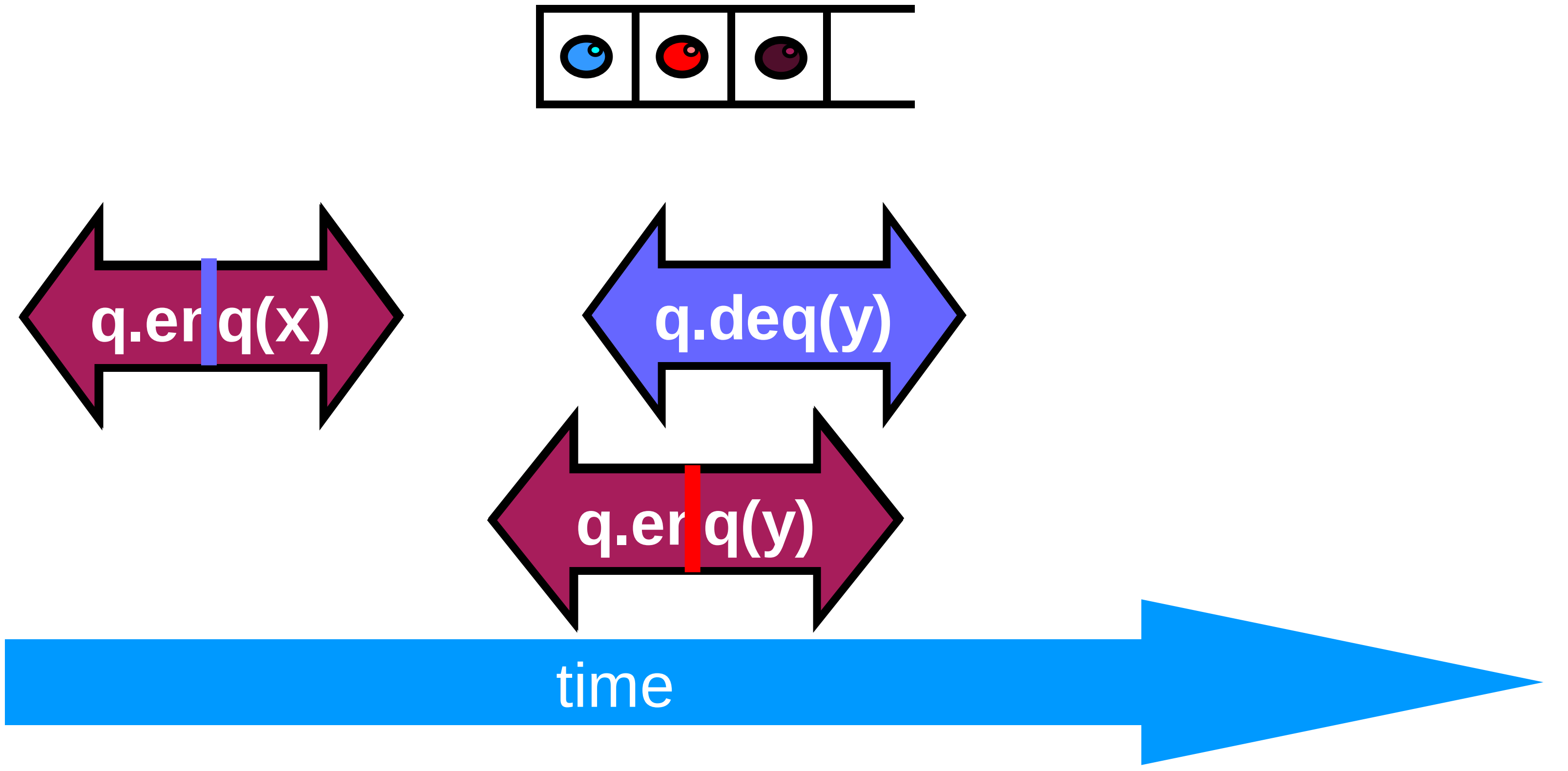

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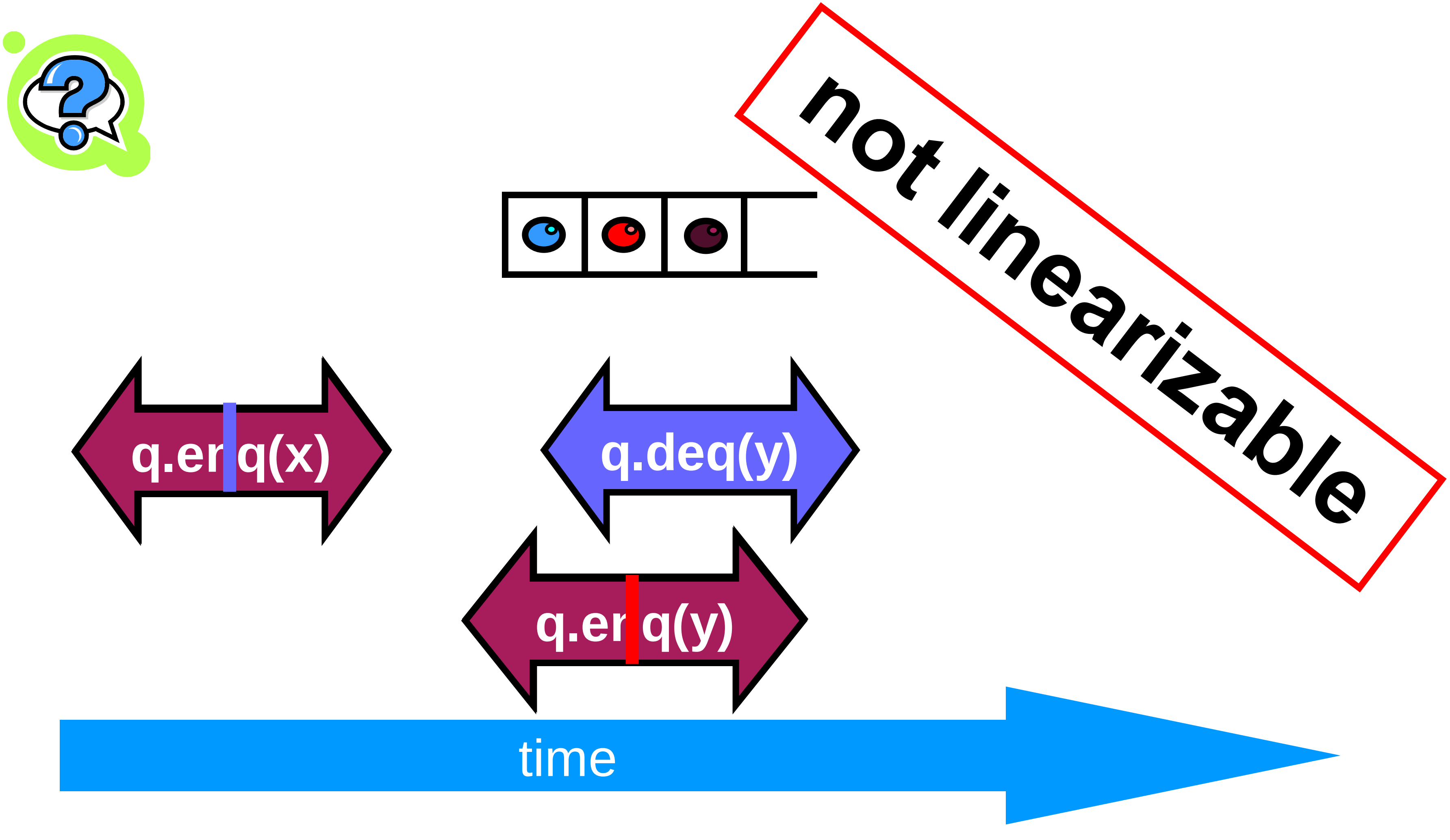
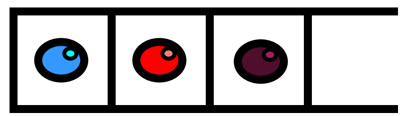


Example 3



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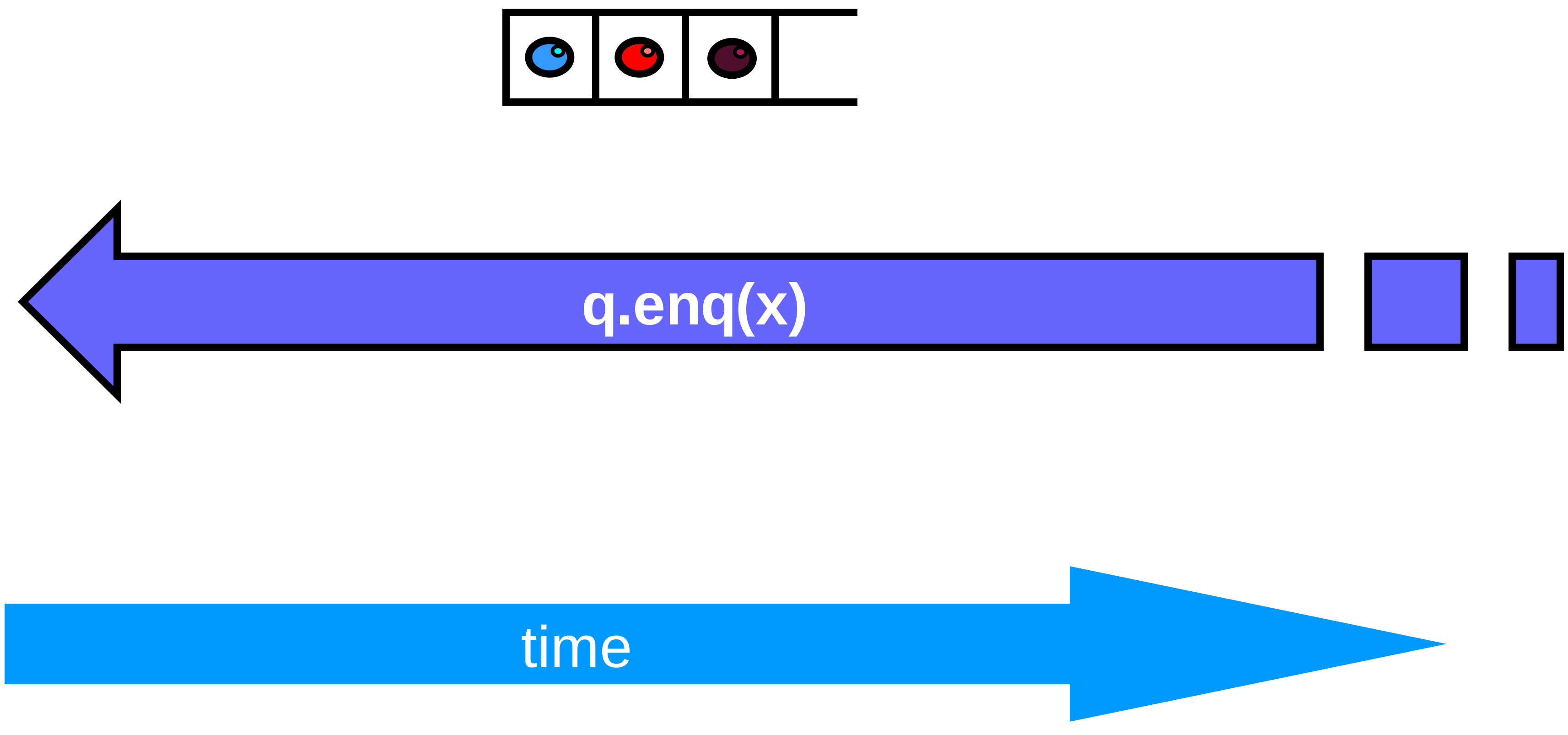

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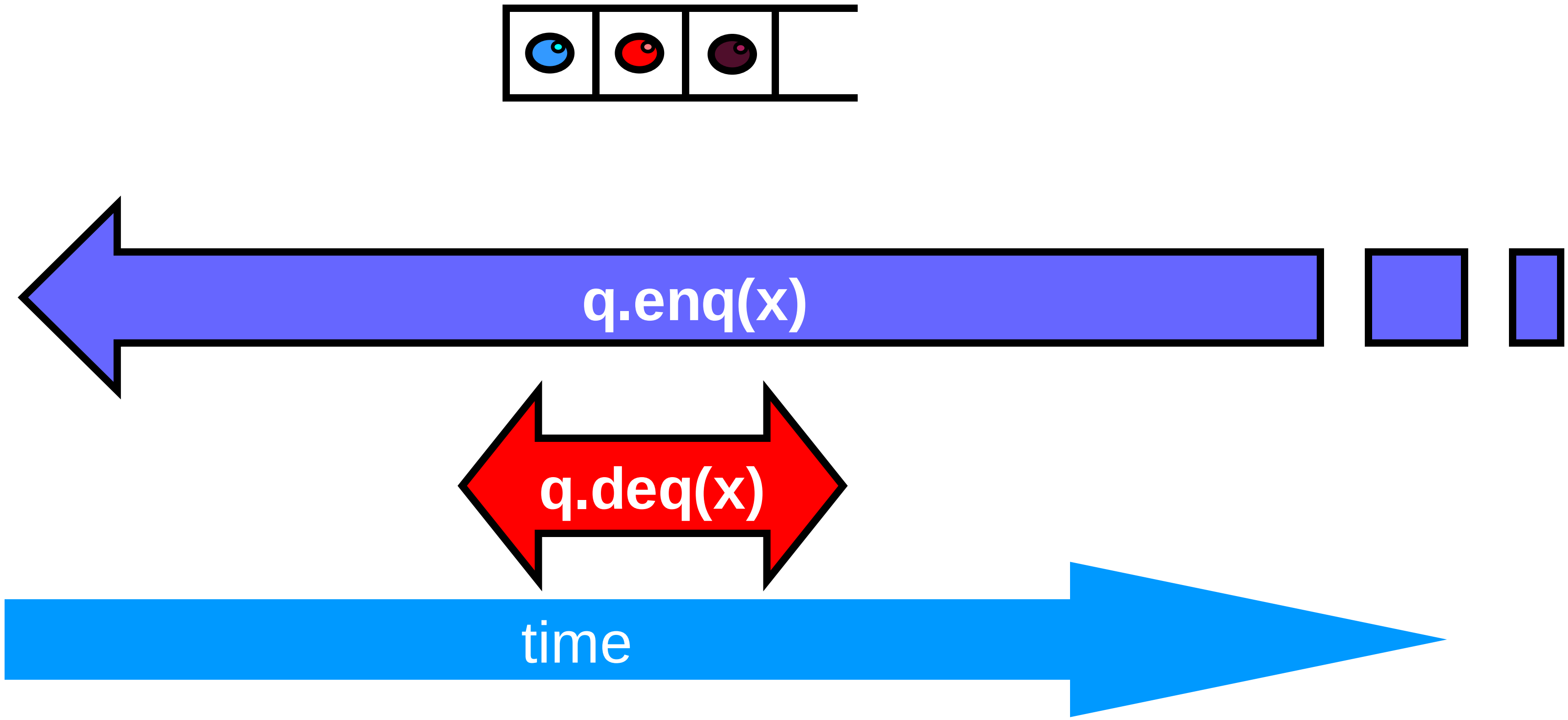

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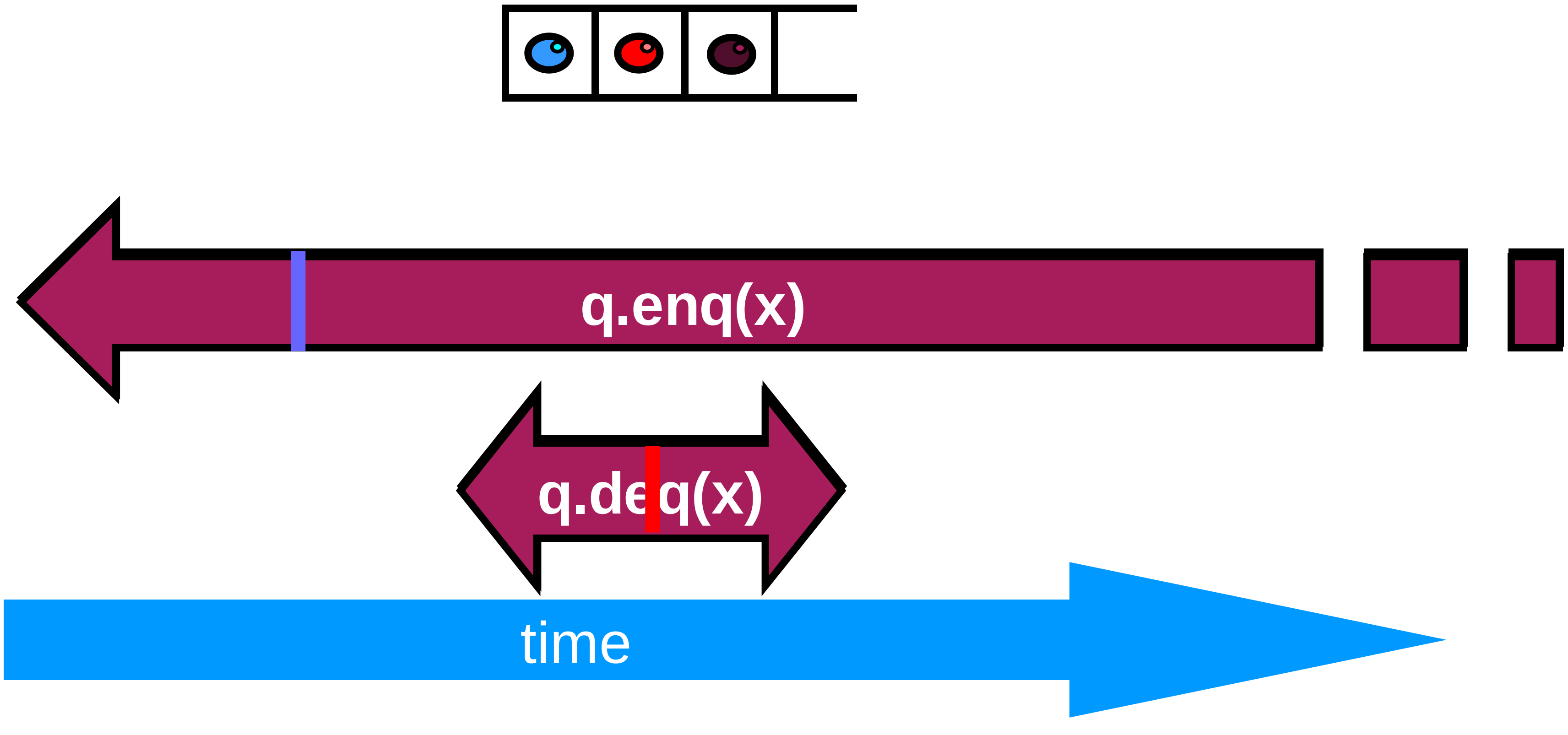

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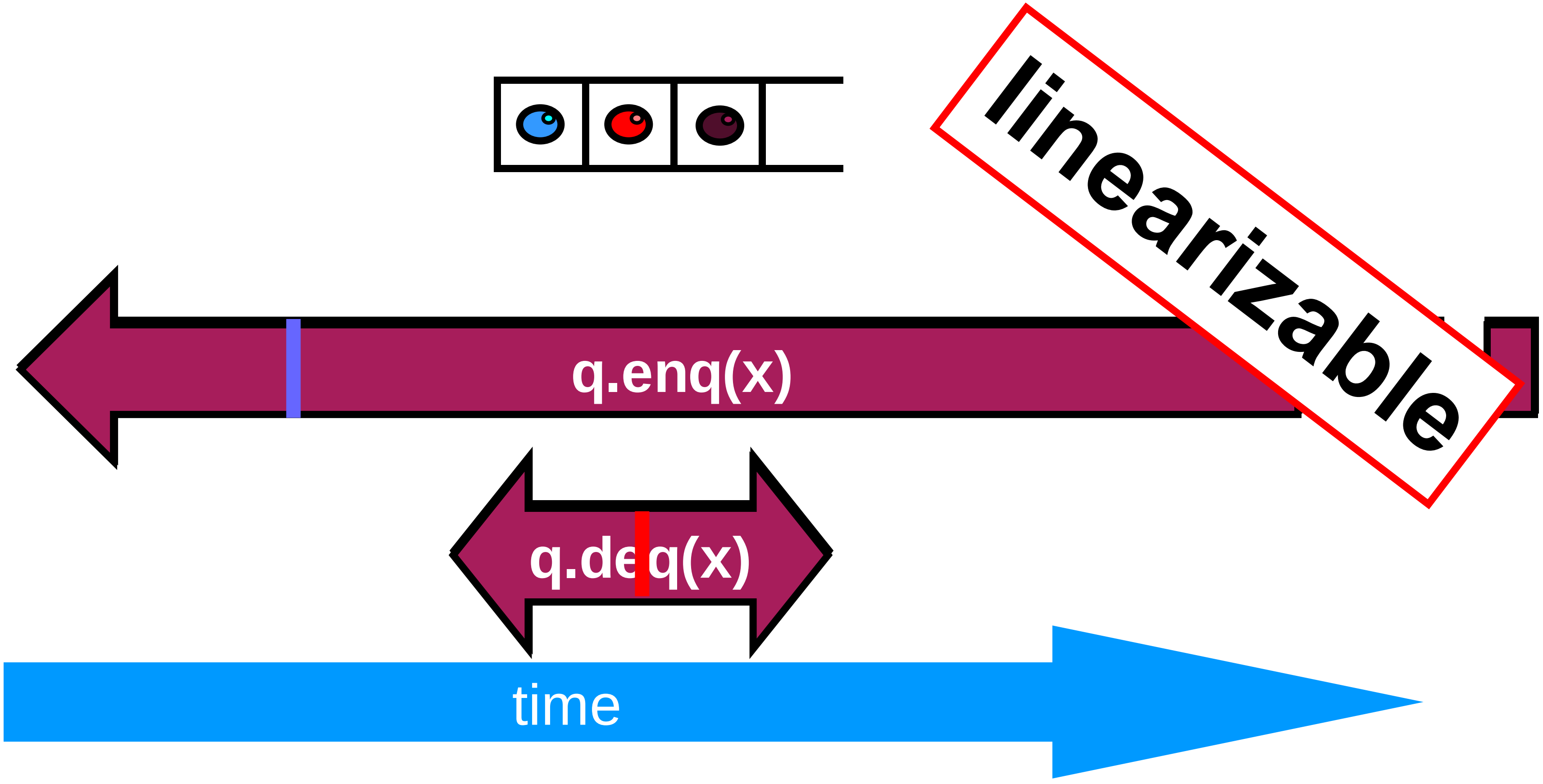

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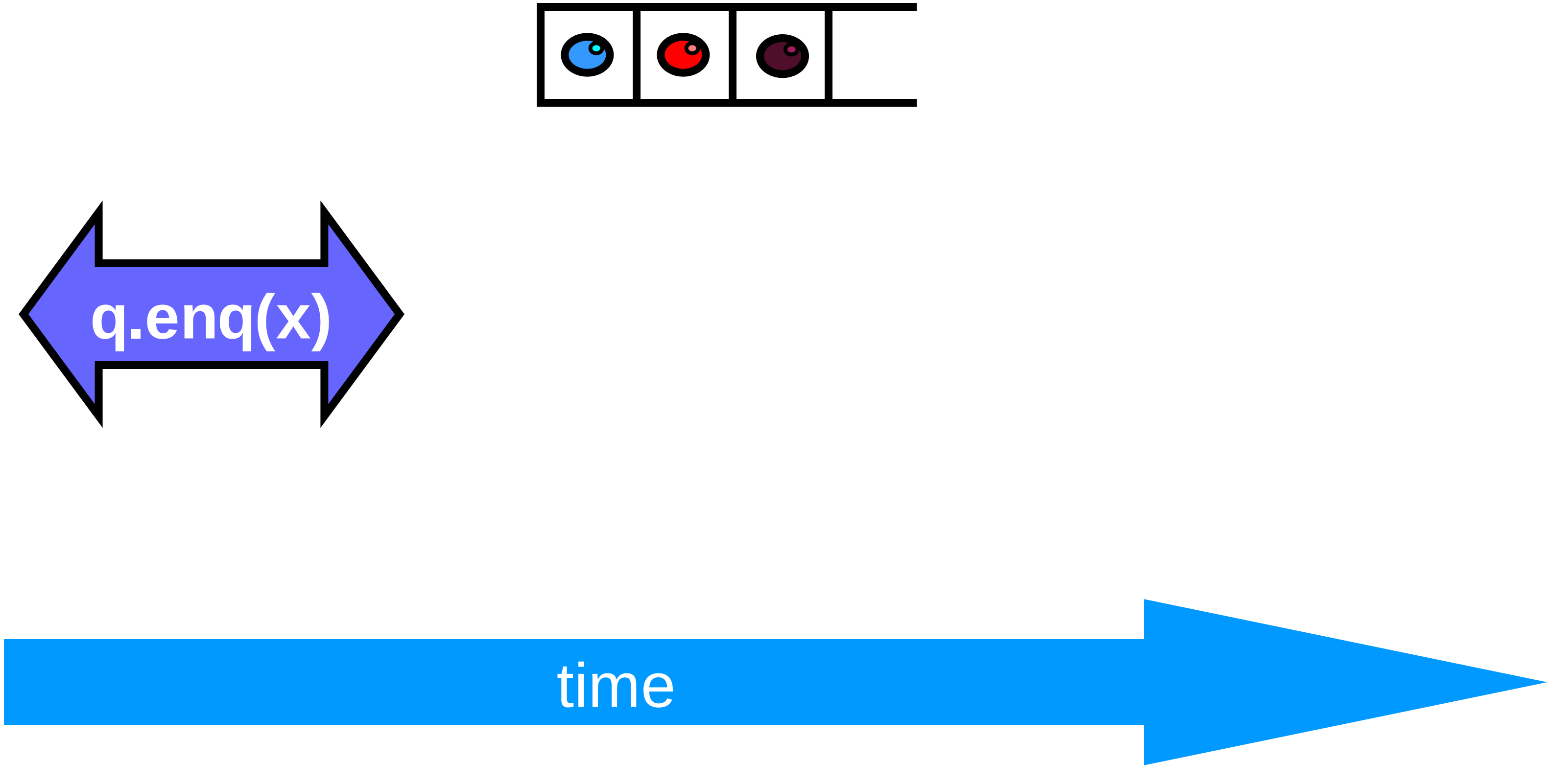

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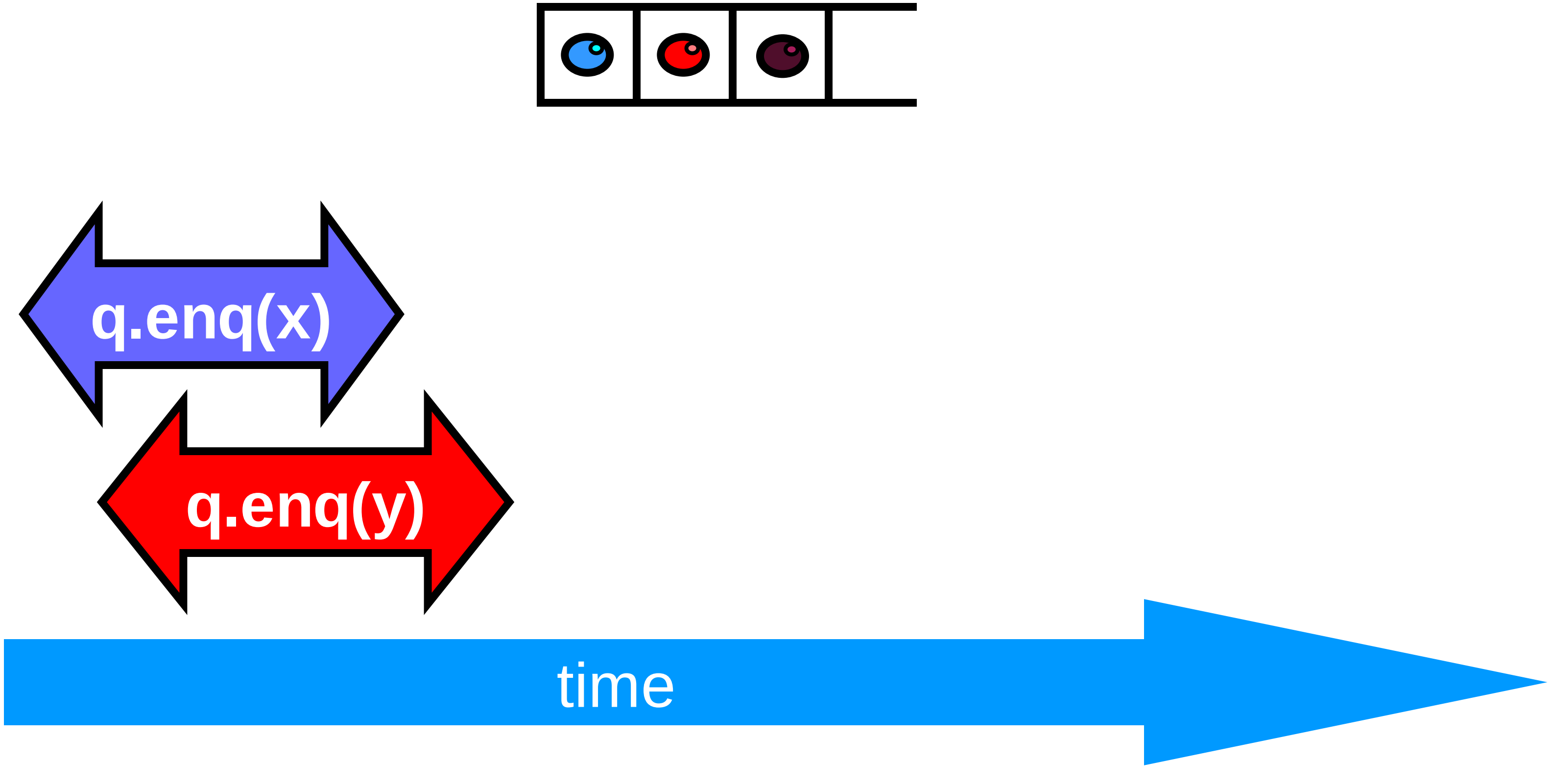

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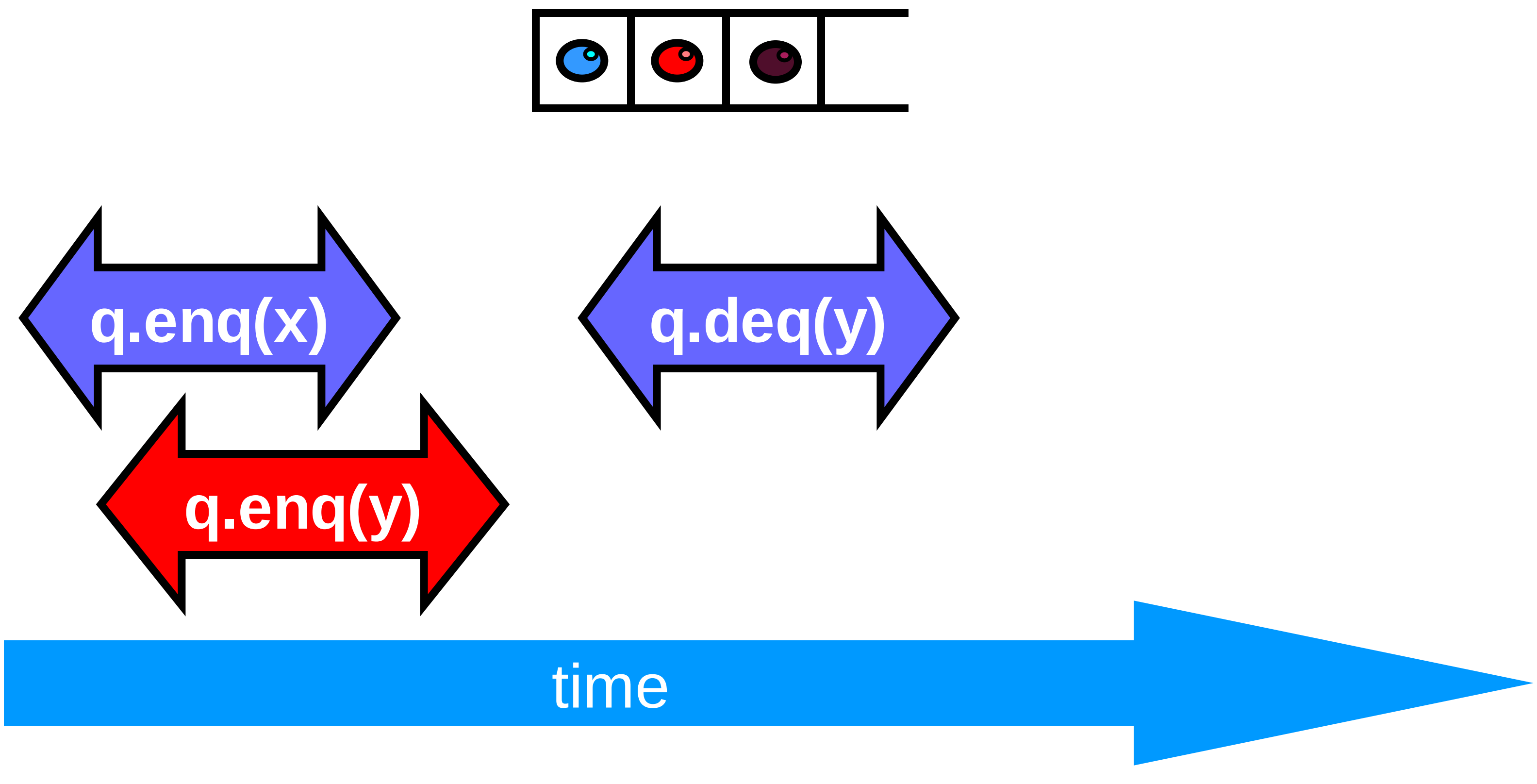

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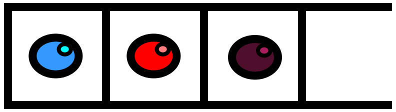

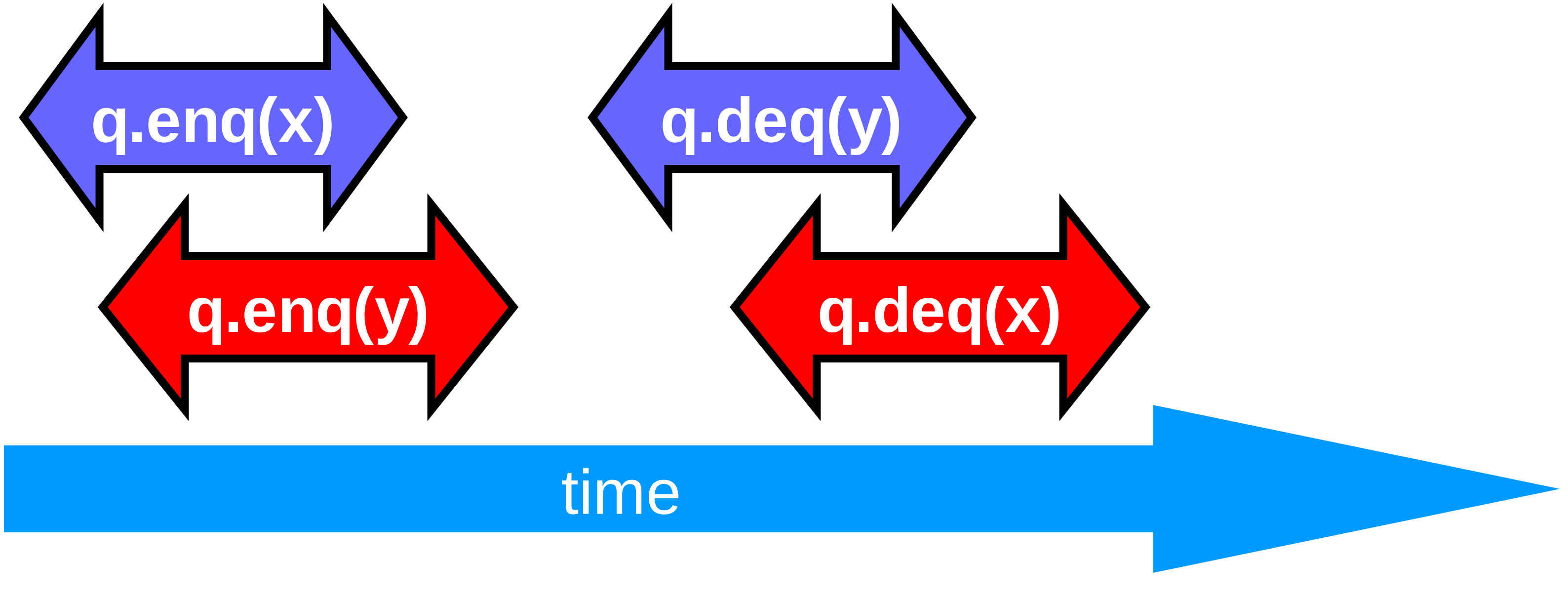

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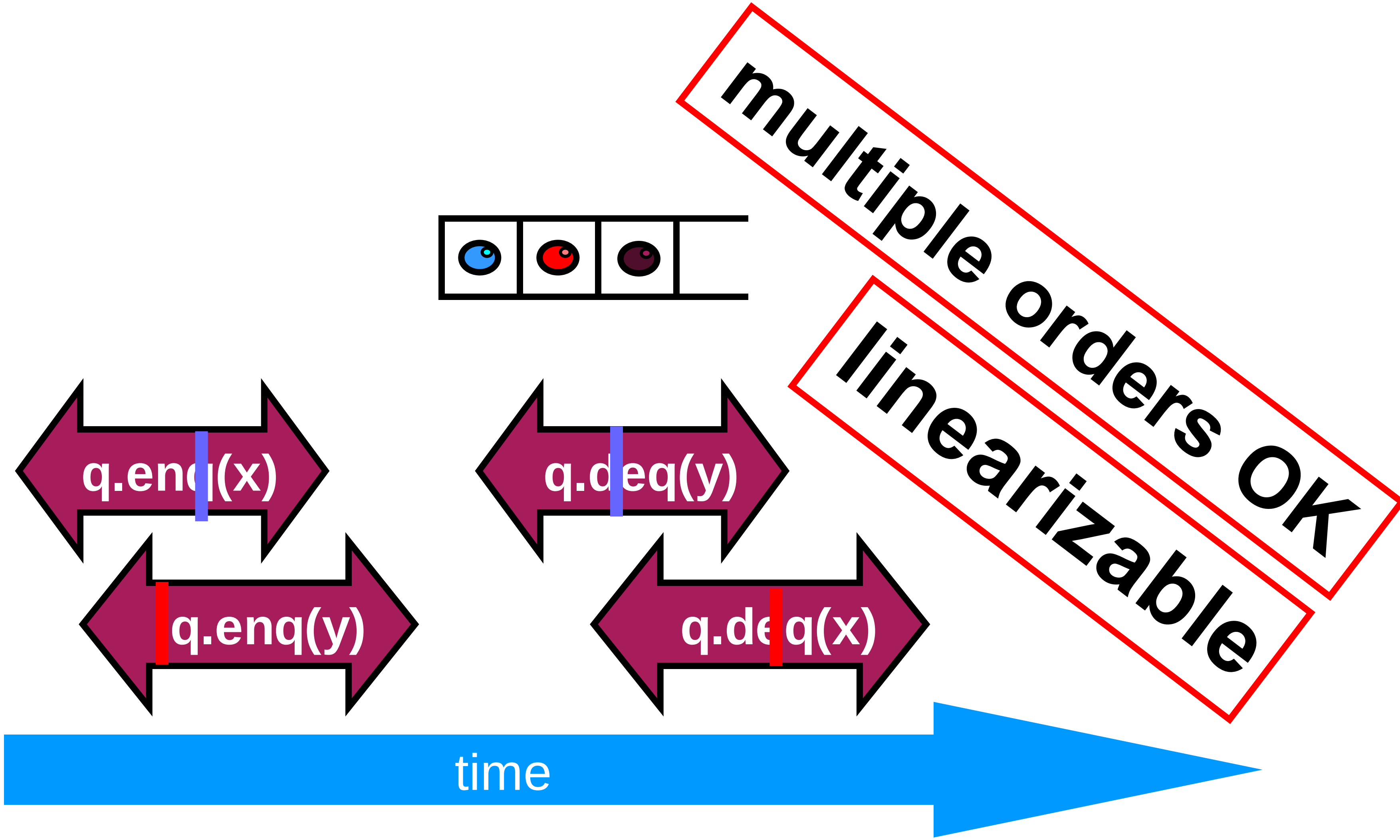
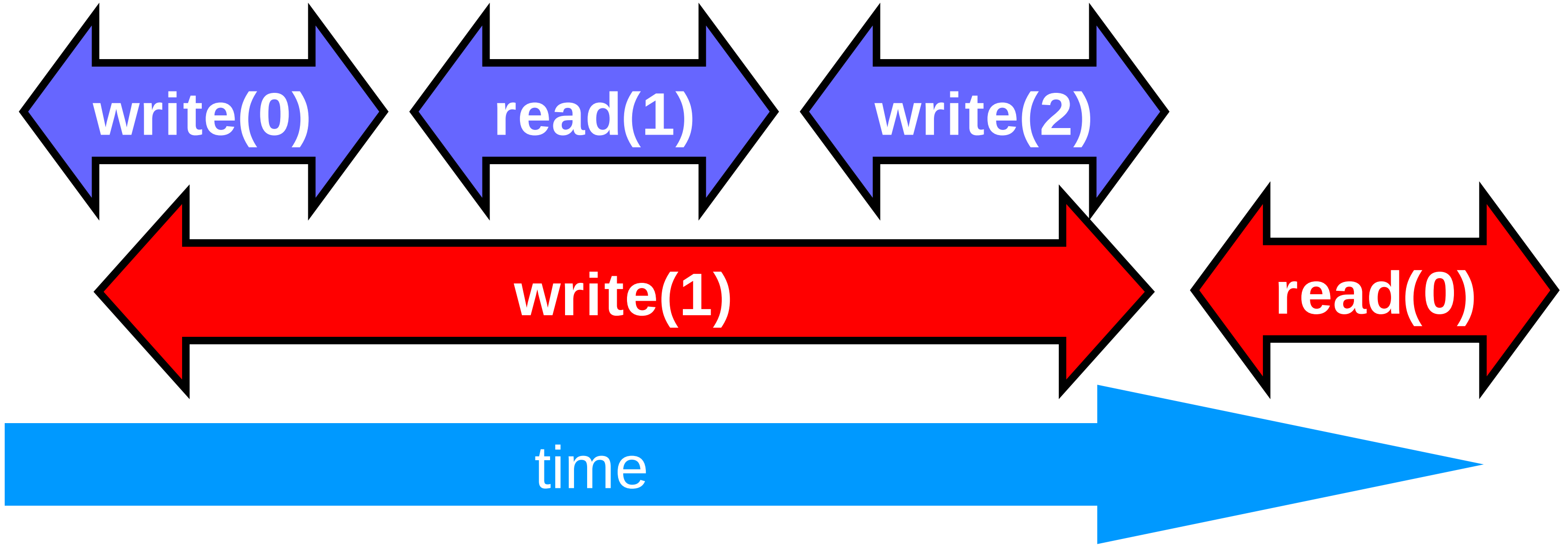


multiple orders OK
linearizable
q.enq(x)
q.enq(y)
q.deq(y)
q.deq(x)
time

Read/Write Register Example



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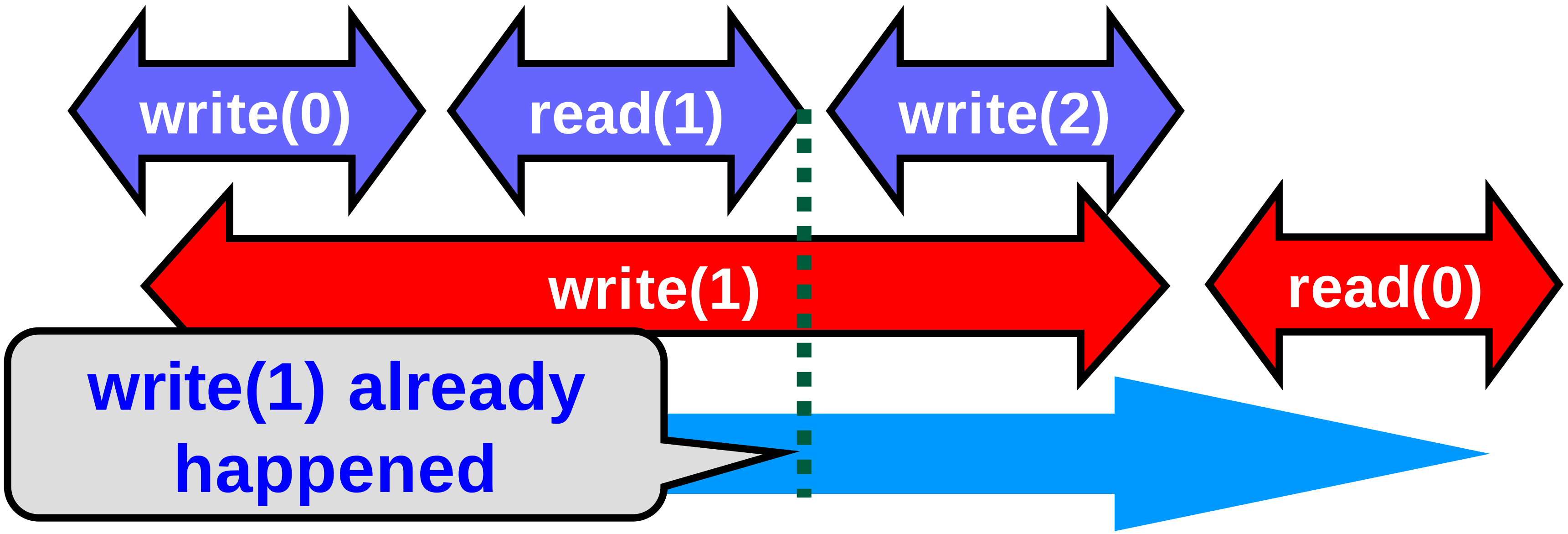

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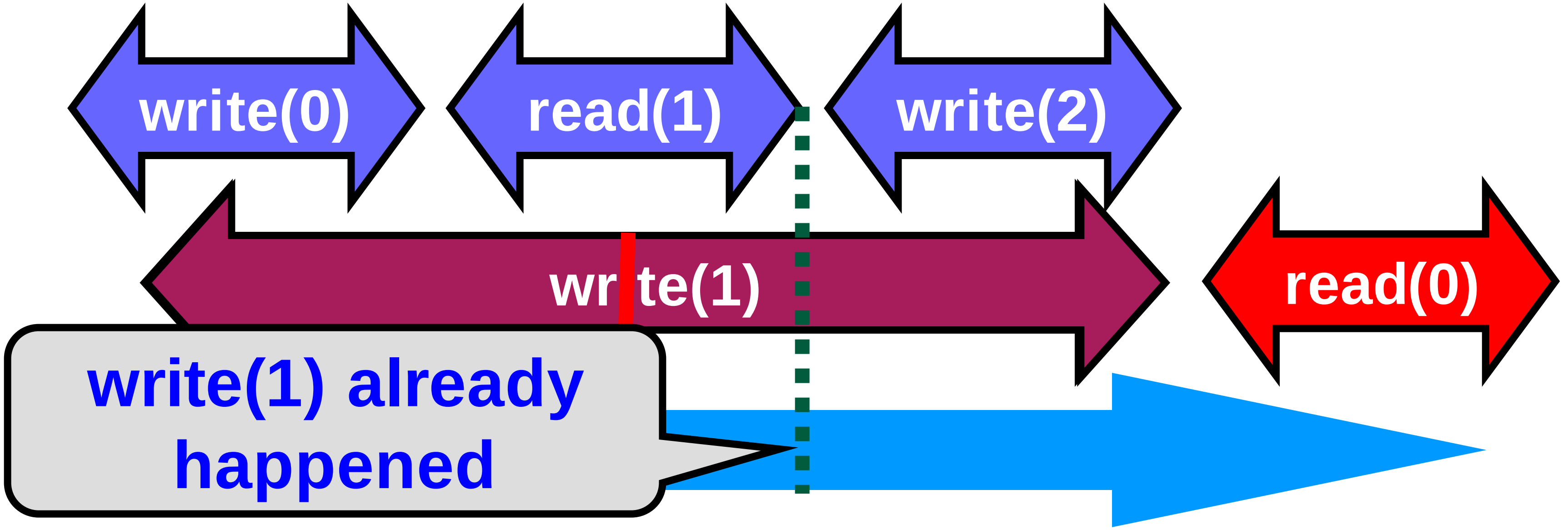

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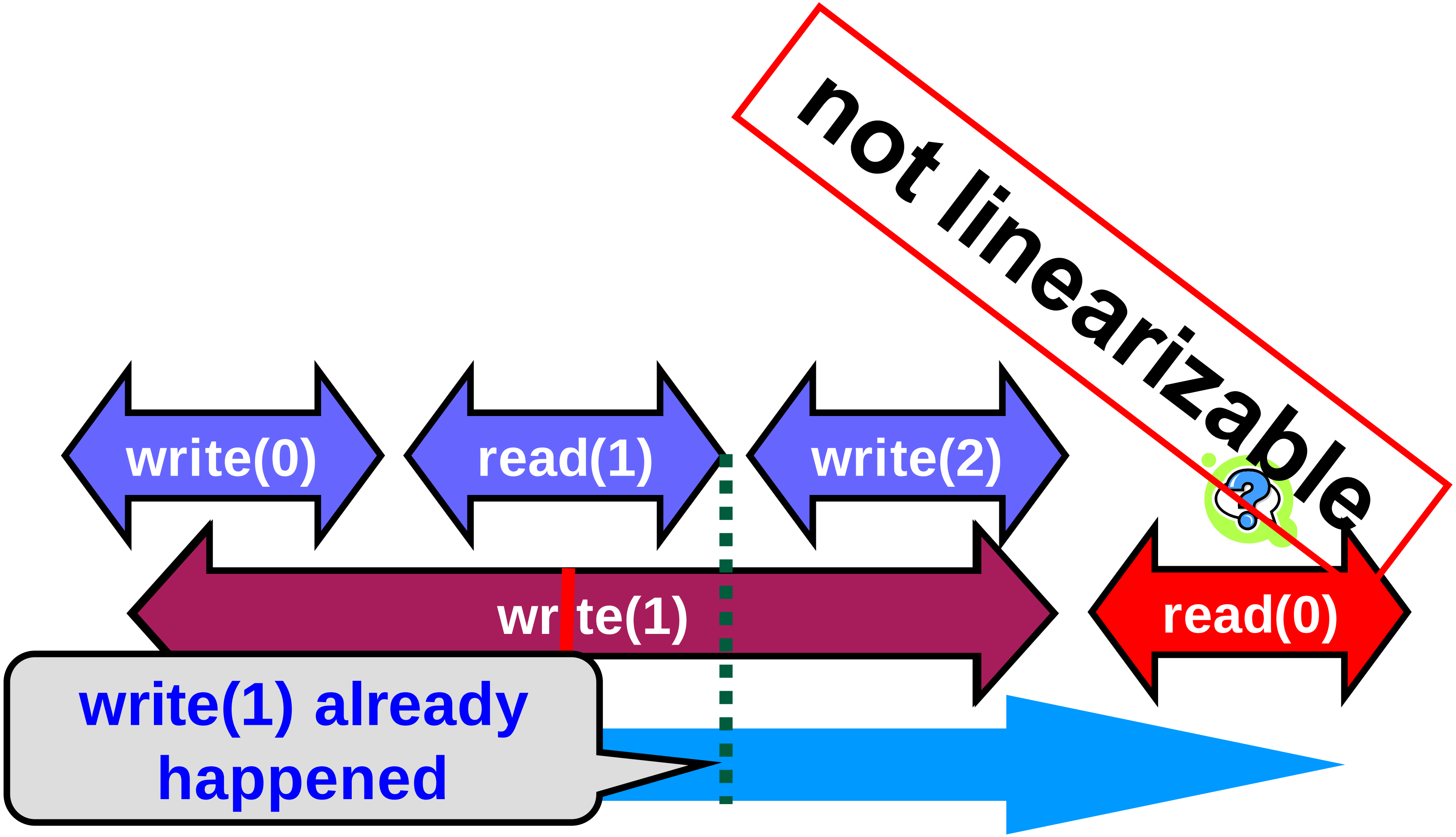

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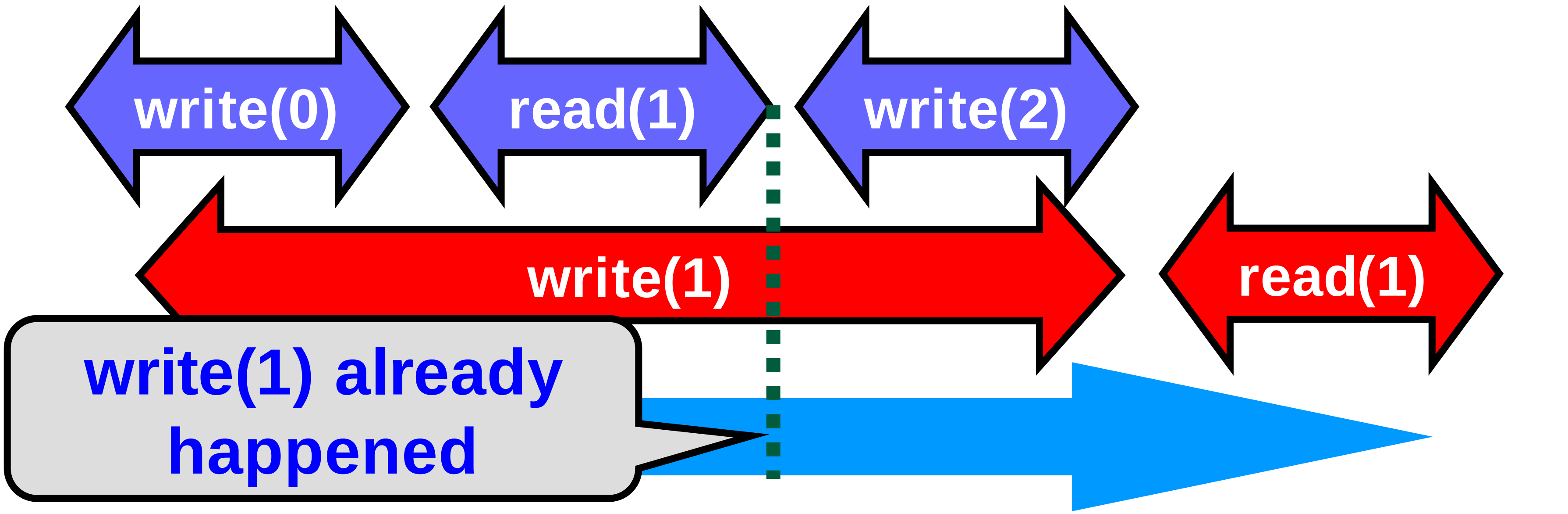

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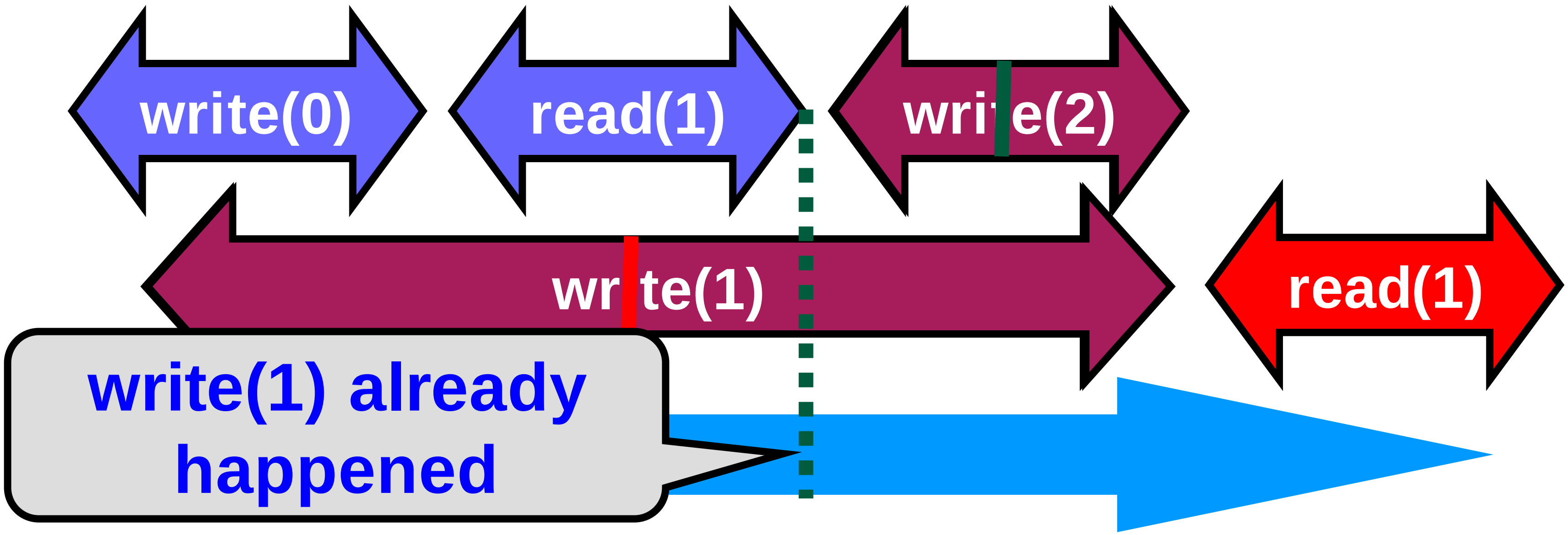

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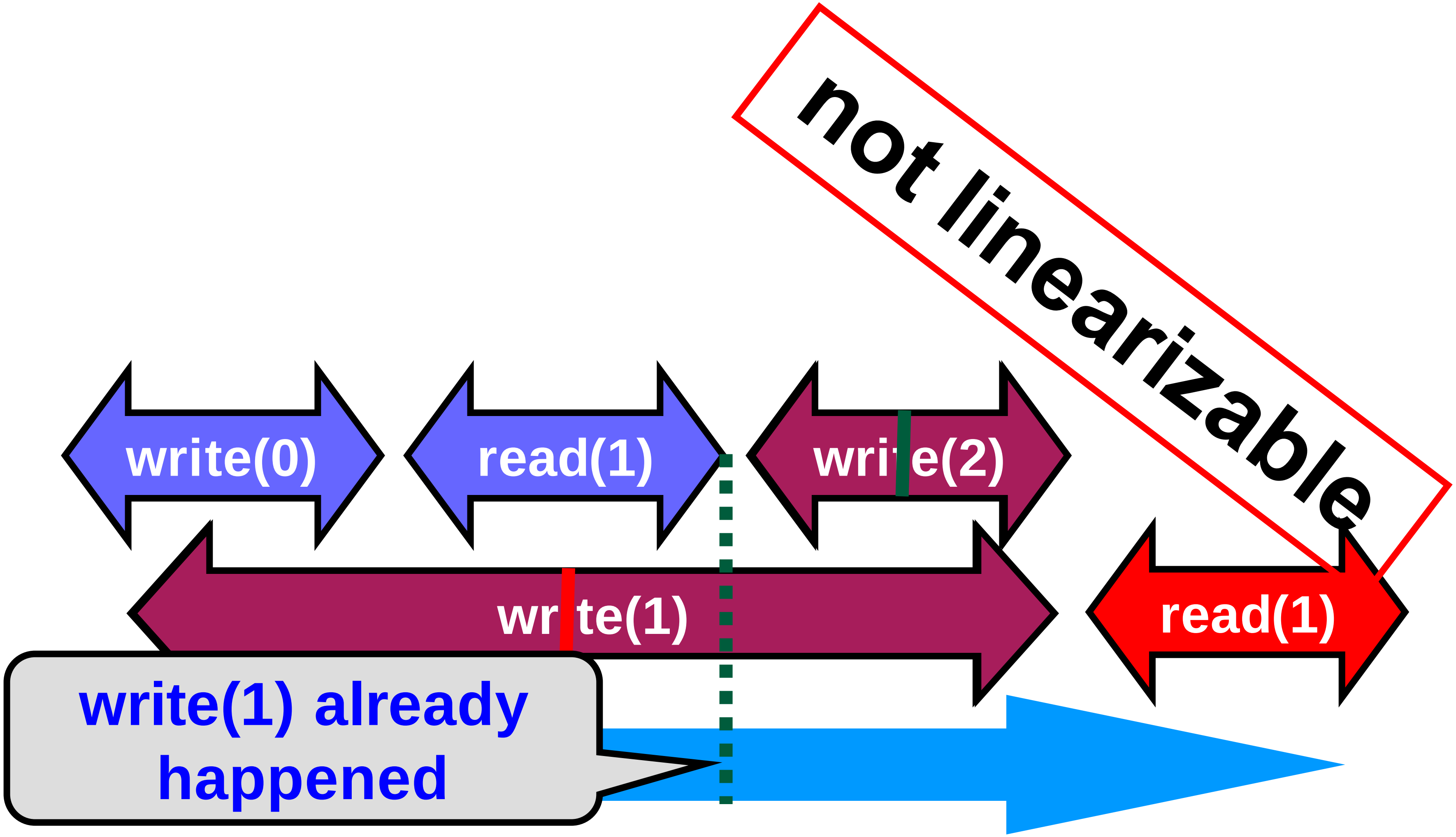

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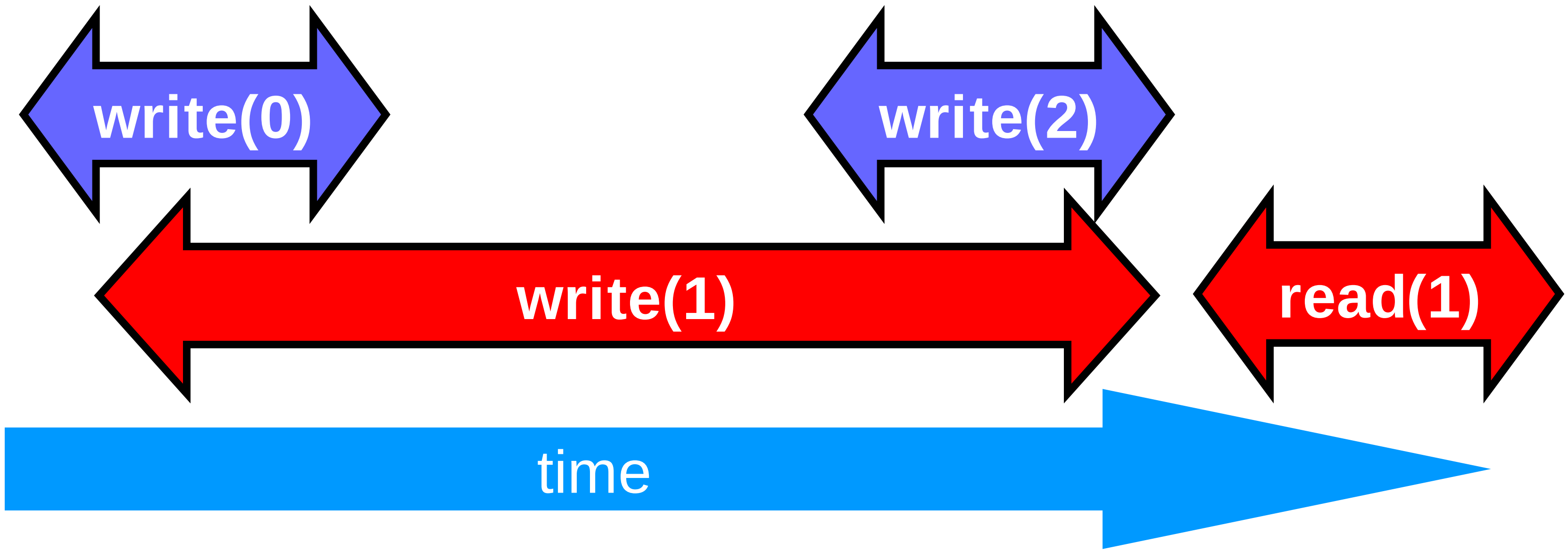

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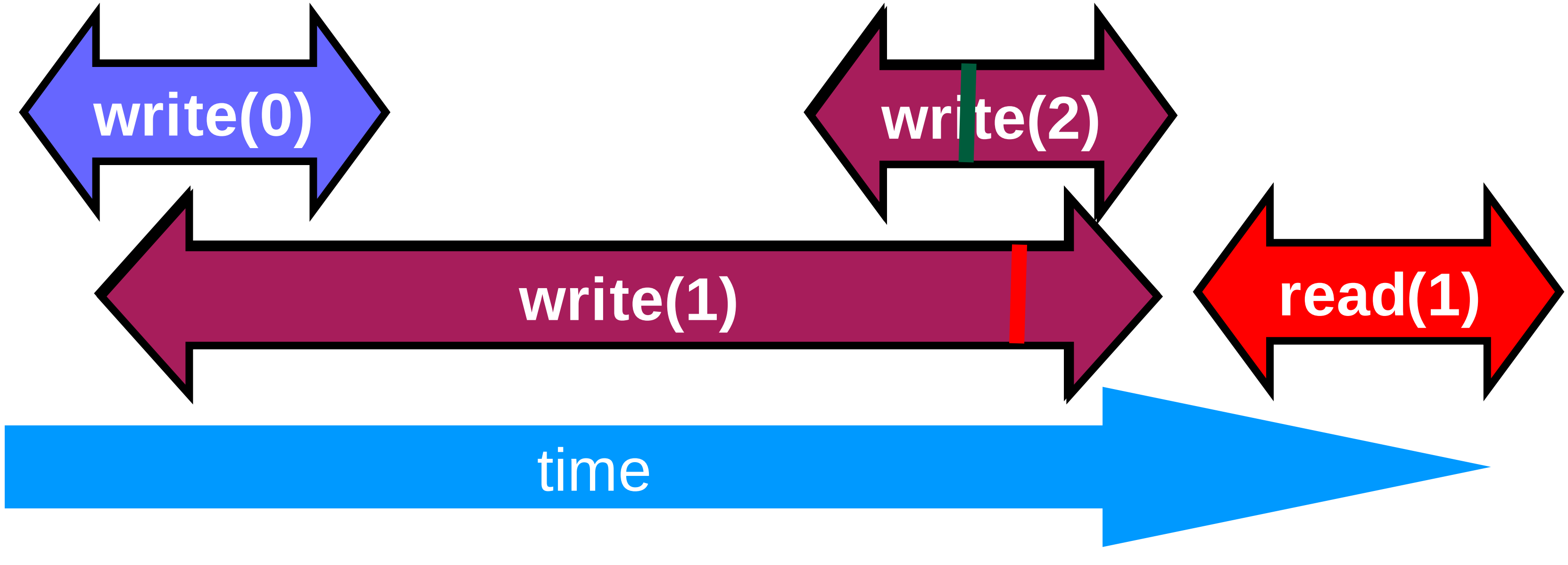

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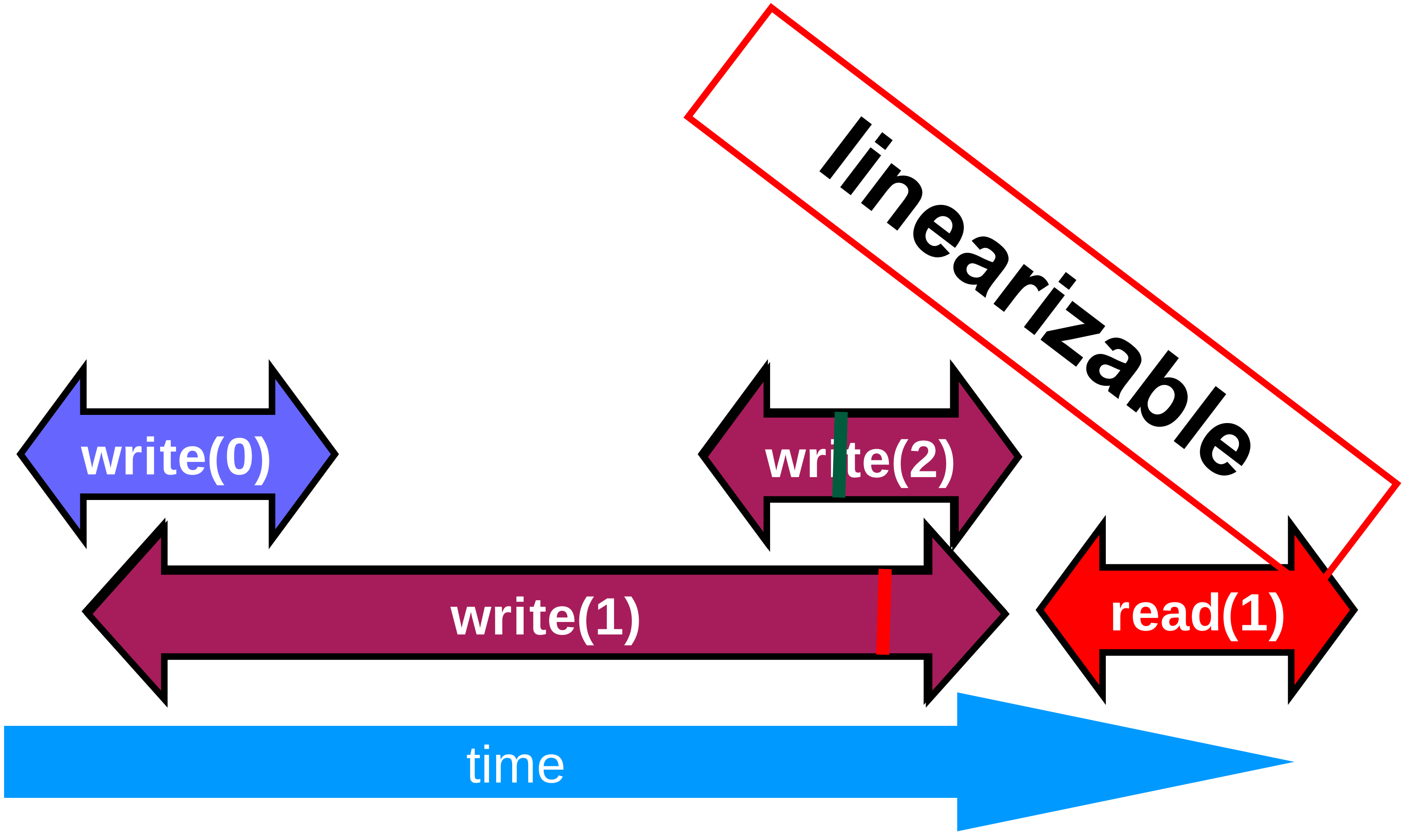

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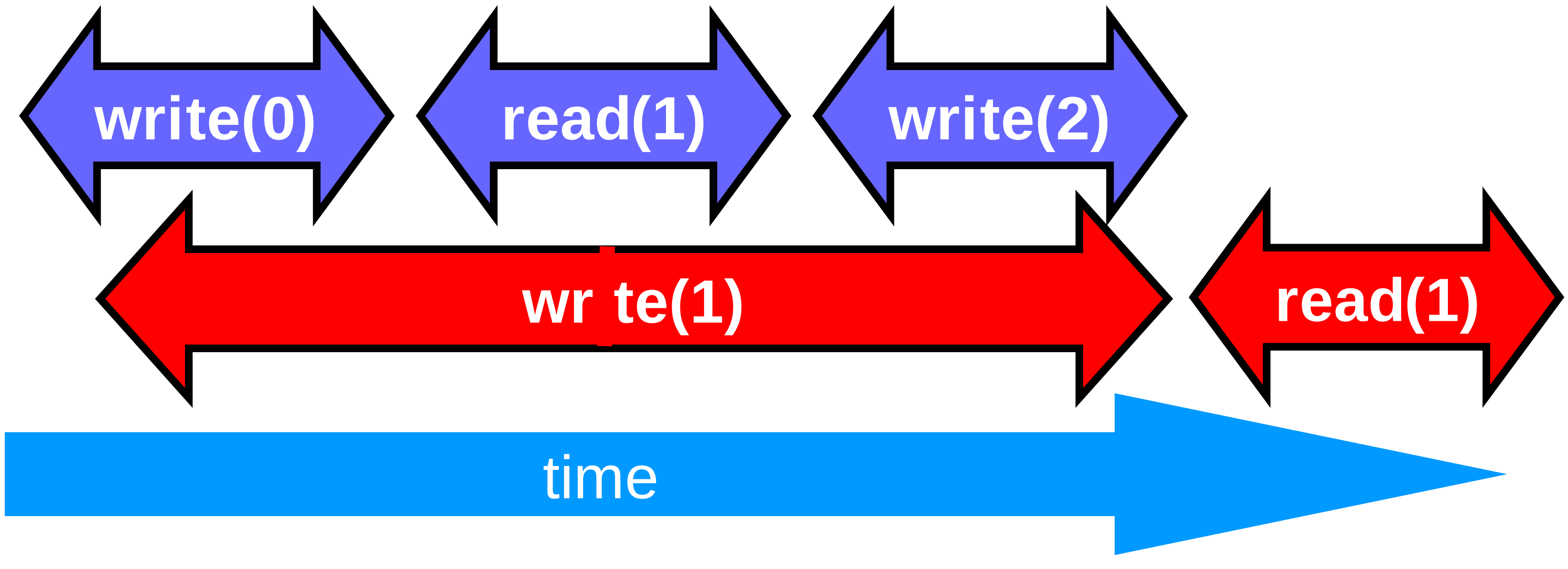
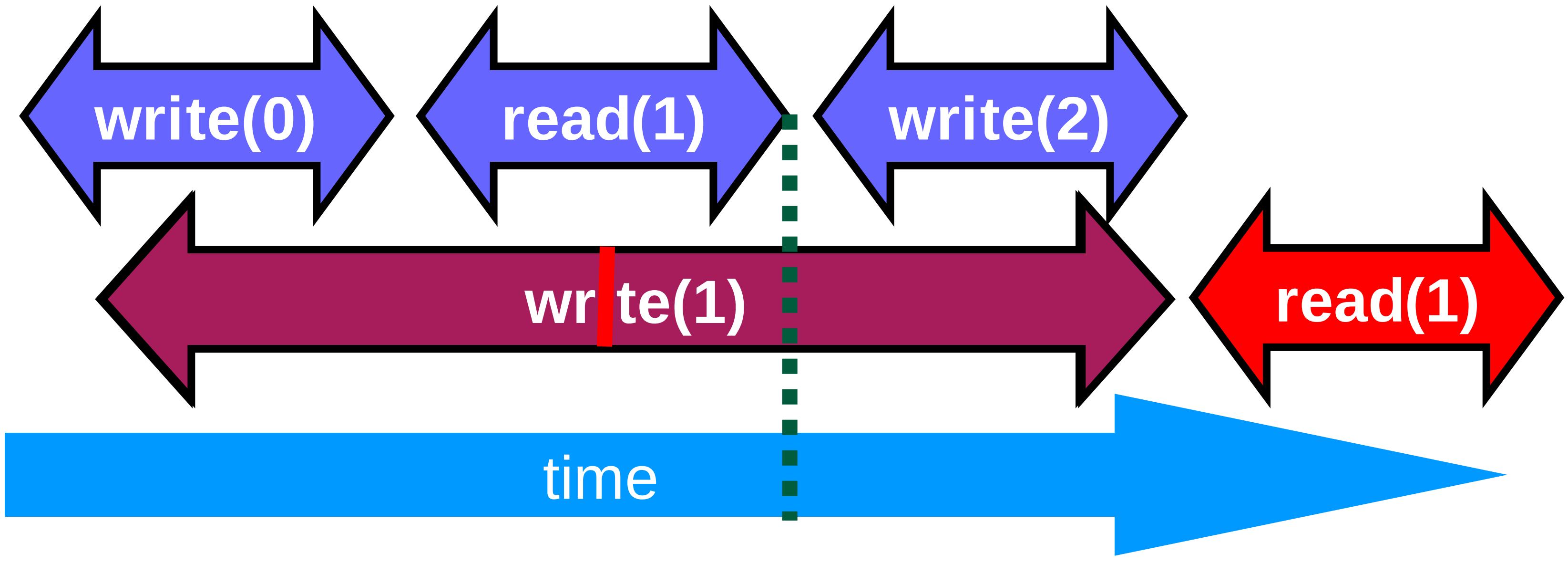
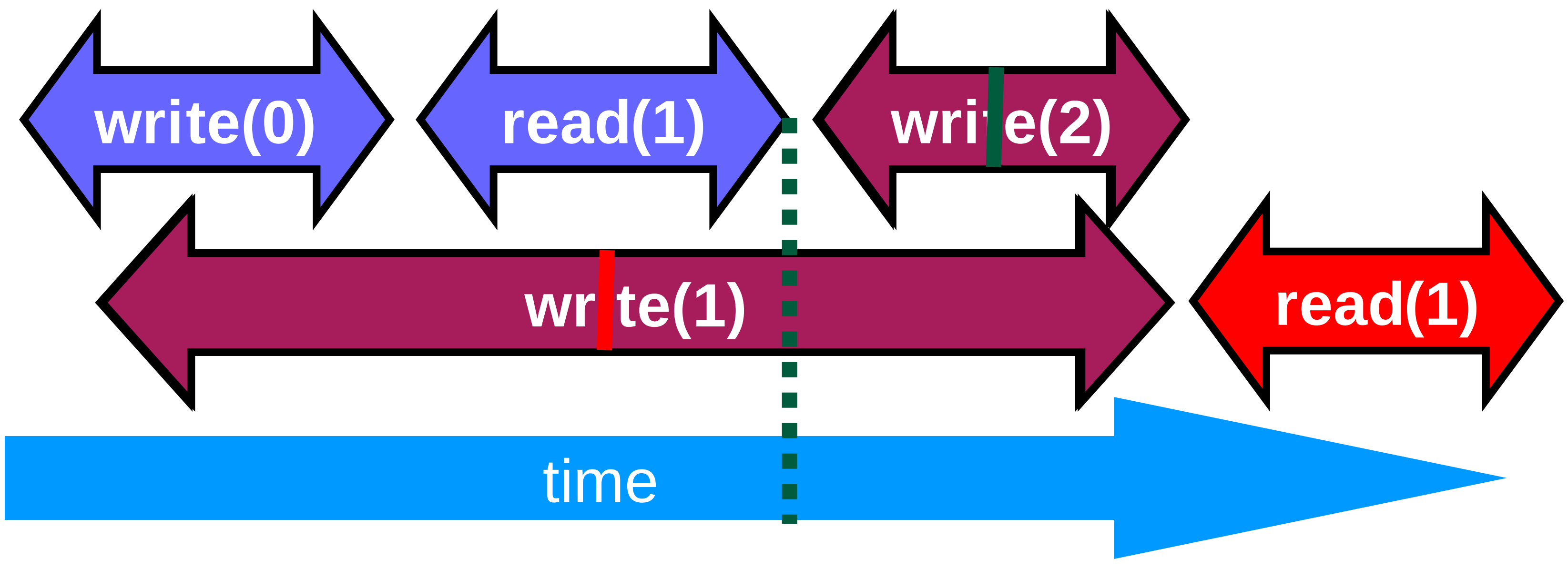


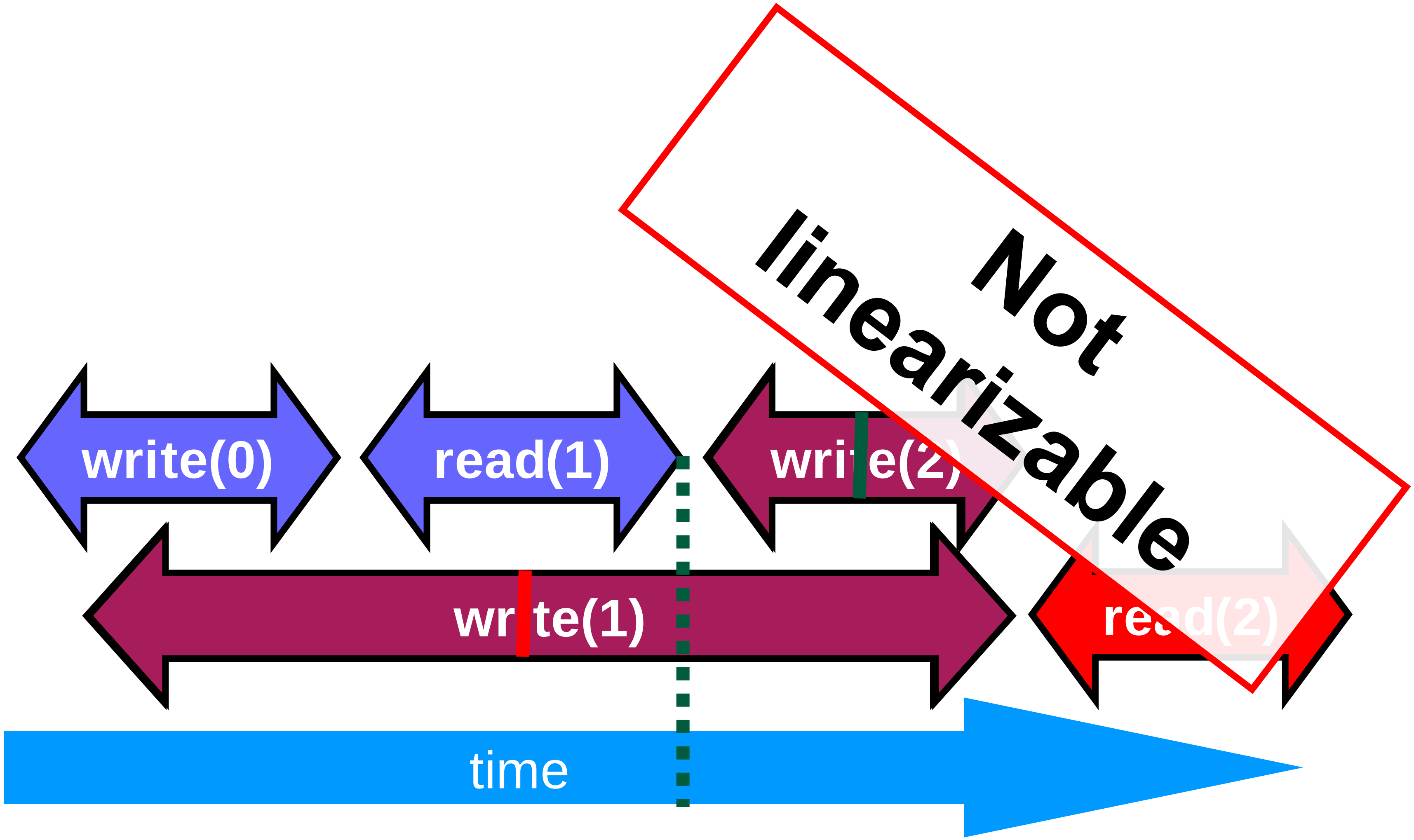
Read/Write Register Example



Read/Write Register Example



Read/Write Register Example

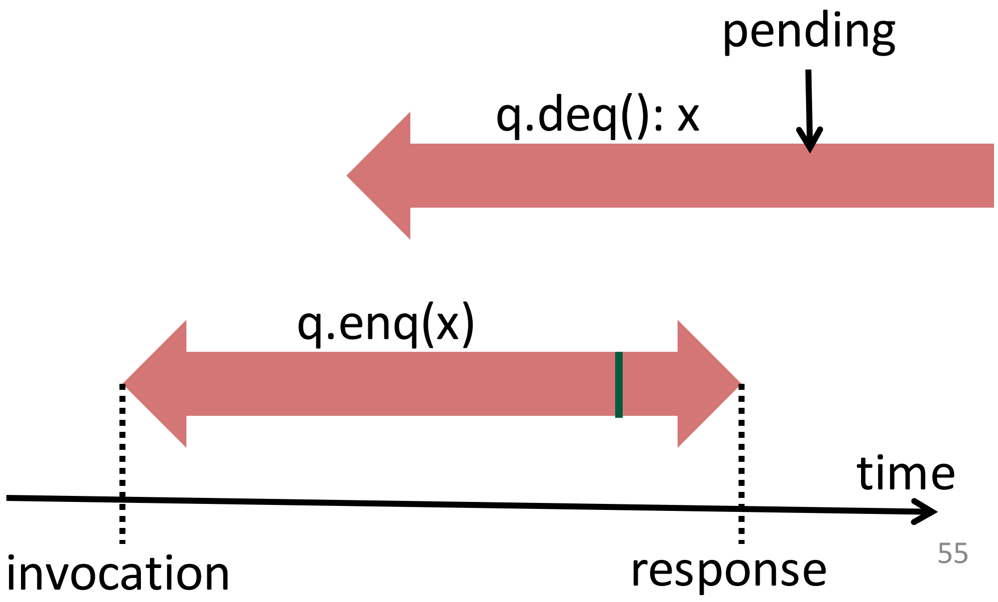


About Executions

- **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
- **Define a formal model for executions!**

Properties of concurrent method executions

- **Method executions take time**
  - May overlap
- **Method execution = operation**
  - Defined by invocation and response events
- **Duration of method call**
  - Interval between the events



Formalization - Notation

- **Invocation**

A: q.enq(x)

thread object method arguments

- **Response**

A: q:void

thread object result

A: q:FullException()

thread object exception

  - Method is implicit (correctness criterion)!

Concurrency

- **A concurrent system consists of a collection of sequential threads P_i**
- **Threads communicate via shared objects**

History

- **Describes an execution**
  - Sequence of invocations and responses
  - H=

A: q.enq(a)
A: q:void
A: q.enq(b)
B: p.eng(c)
B: p:void
B: q.deq()
B: q:a

Invocation and response match if
- thread names are the same
- objects are the same

Note: Method name is implicit!

Projections on Threads

- **Threads subhistory H|P ("H at P")**
  - Subsequences of all events in H whose thread name is P

H=	H|A=	H|B=
A: q.enq(a)	A: q.enq(a)	
A: q:void	A: q:void	
A: q.enq(b)	A: q.enq(b)	
B: p.enq(c)		B: p.enq(c)
B: p:void		B: p:void
B: q.deq()		B: q.deq()
B: q:a		B: q:a

Projections on Objects

- **Objects subhistory H|o (“H at o”)**
  - Subsequence of all events in H whose object name is o

H=

A: q.enq(a)
A: q:void
A: q.enq(b)
B: p.eng(c)
B: p:void
B: q.deq()
B: q:a

H|p=

B: p.eng(c)
B: p:void

H|q=

A: q.enq(a)
A: q:void
A: q.enq(b)
B: q.deq()
B: q:a

Sequential Histories

- **A history H is sequential if**

  A: q.enq(a)
  A: q:void
  B: p.enq(b)
  B: p:void
  B: q.deq(c)
  B: q:void
  B: q.enq()
  …

  - First event of H is an invocation
  - Each invocation (except possibly the last is immediately followed by a matching response
  - Each response is immediately followed by an invocation

  Method calls of different threads do not interleave

- **A history H is concurrent if**
  - It is not sequential

Well-formed histories

- **Per-thread projections must be sequential**

H=

A: q.enq(x)
B: p.enq(y)
B: p:void
B: q.deq()
A: q:void
B: q:x

H|A=

A: q.enq(x)
A: q:void

H|B=

B: p.enq(y)
B: p:void
B: q.deq()
B: q:x

Equivalent histories

- **Per-thread projections must be the same**

H=

A: q.enq(x)
B: p.enq(y)
B: p:void
B: q.deq()
A: q:void
B: q:x

G=

A: q.enq(x)
B: p.enq(y)
A: q:void
B: p:void
B: q.deq()
B: q:x

H|A=G|A=

A: q.enq(x)
A: q:void

H|B=G|B=

B: p.enq(y)
B: p:void
B: q.deq()
B: q:x

Legal Histories

- **Sequential specification allows to describe what behavior we expect and tolerate**
  - When is a single-thread, single-object history legal?

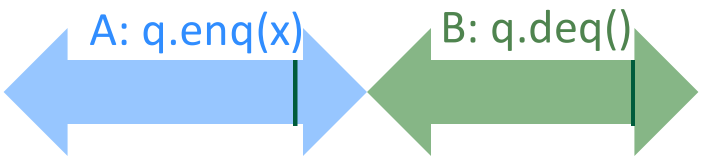
- **Recall: Example**
  - Preconditions and Postconditions
  - Many others exist!

- **A sequential (multi-object) history H is legal if**
  - For every object x
  - H|x adheres to the sequential specification for x

Precedence

A: q.enq(x)
B: q.enq(y)
B: q:void
A: q:void
B: q.deq()
B: q:x

A method execution precedes another if response event precedes invocation event

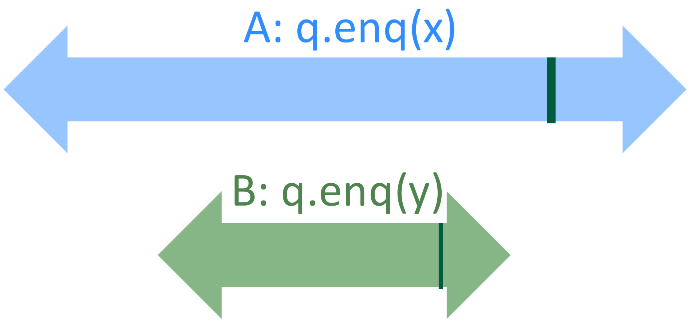


Precedence vs. Overlapping

- **Non-precedence = overlapping**

A: q.enq(x)
B: q.enq(y)
B: q:void
A: q:void
B: q.deq()
B: q:x

Some method executions overlap with others



Precedence relations

- **Given history H**
- **Method executions m_0 and m_1 in H**
  - $m_0 \rightarrow_H m_1$ (m_0 precedes m_1 in H) if
  - Response event of m_0 precedes invocation event of m_1
- **Precedence relation $m_0 \rightarrow_H m_1$ is a**
  - Strict partial order on method executions

    Irreflexive, antisymmetric, transitive
- **Considerations**
  - Precedence forms a total order if H is sequential
  - Unrelated method calls → overlap → concurrent

Definition Linearizability

- **A history H induces a strict partial order $<_H$ on operations**
  - $m_0 <_H m_1$ if $m_0 \rightarrow_H m_1$
- **A history H is linearizable if**
  - H can be extended to a history H'
    by appending responses to pending operations or dropping pending operations
  - H' is equivalent to some legal sequential history S and
  - $<_{H'} \subseteq <_S$
- **S is a linearization of H**

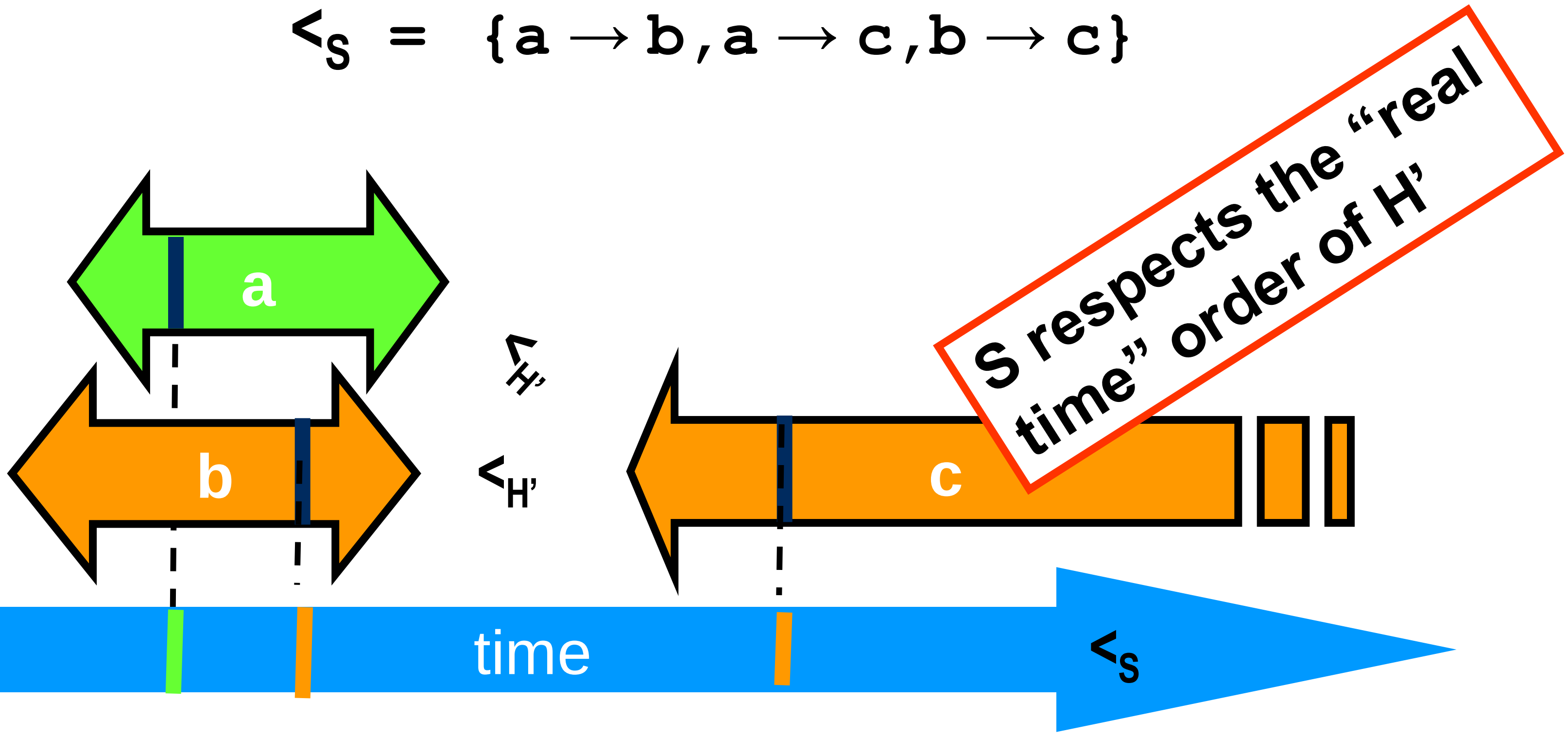
- **Remarks:**
  - For each H, there may be many valid extensions to H'
  - For each extension H', there may be many S
  - Interleaving at the granularity of methods

Ensuring $<_{H'} \subseteq <_S$

- Find an S that contains H'

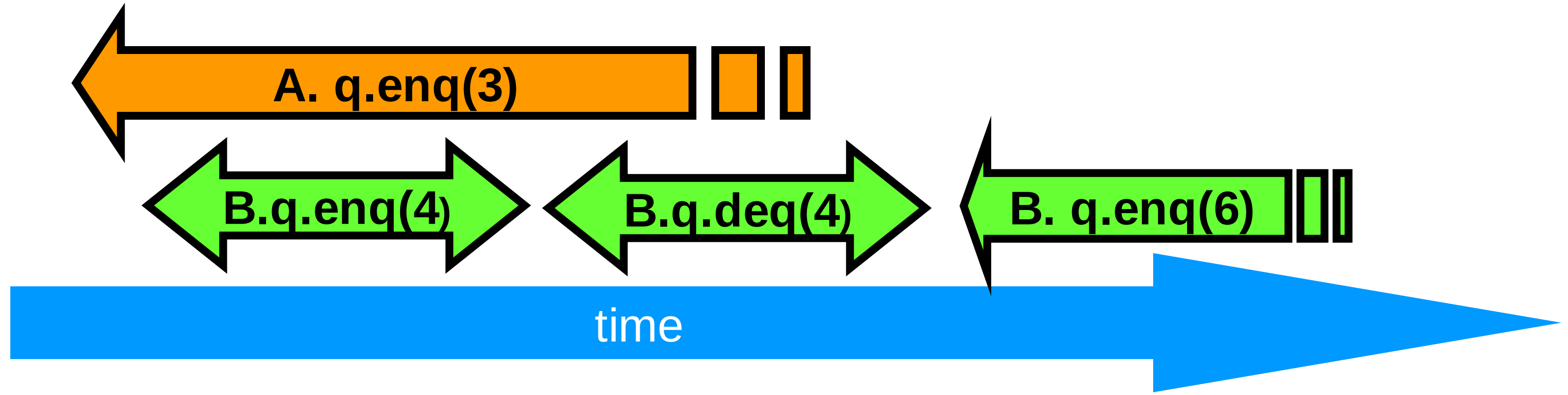
$$<_{H'} = \{a \rightarrow c, b \rightarrow c\}$$

$$<_S = \{a \rightarrow b, a \rightarrow c, b \rightarrow c\}$$



Example

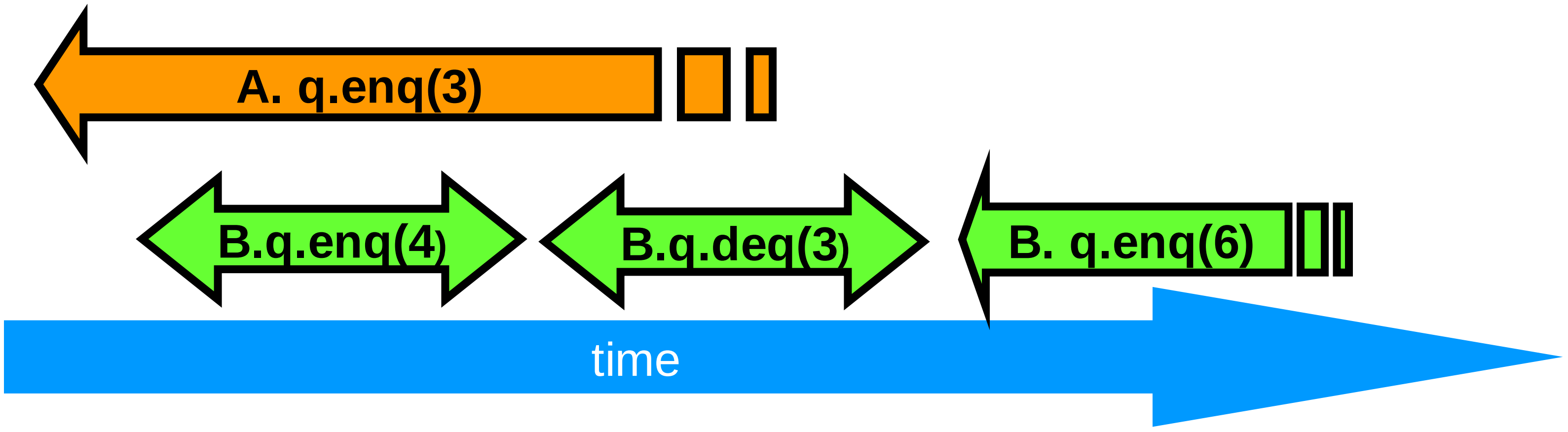
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
B q:enq(6)
```



Example

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

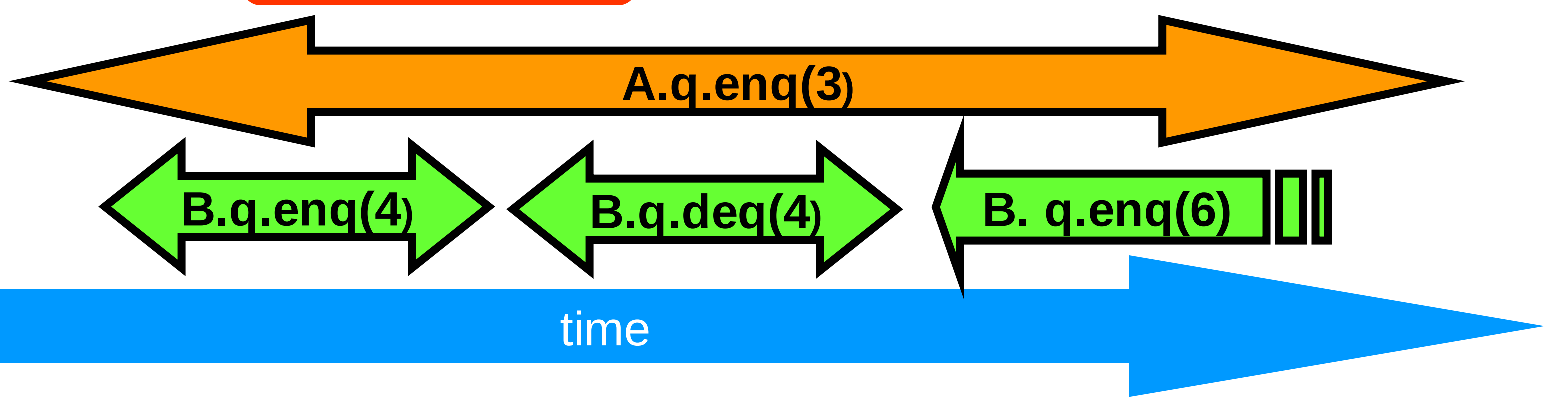
Complete this pending invocation



Example

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

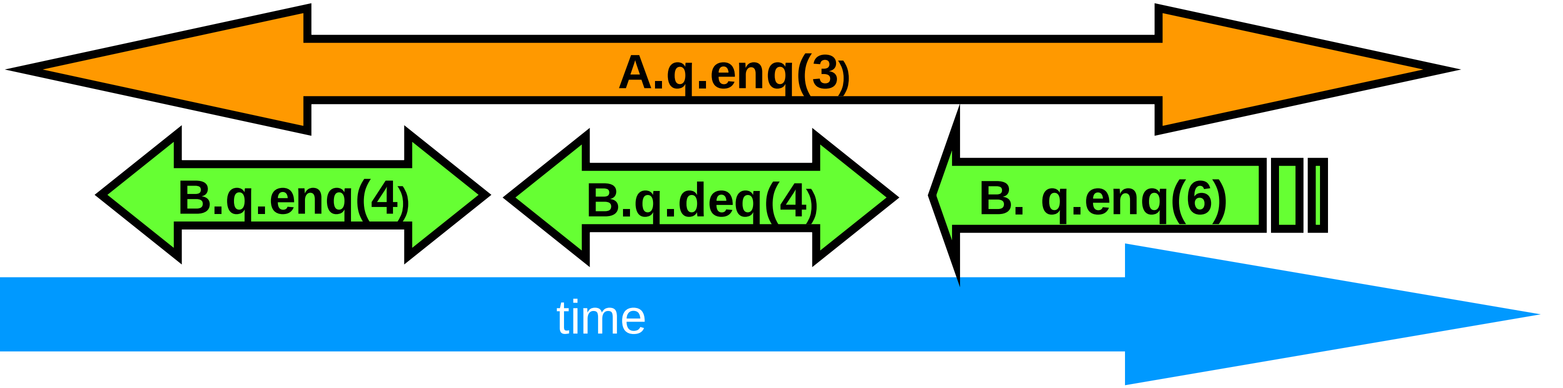
Complete this pending invocation



Example

discard this one

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

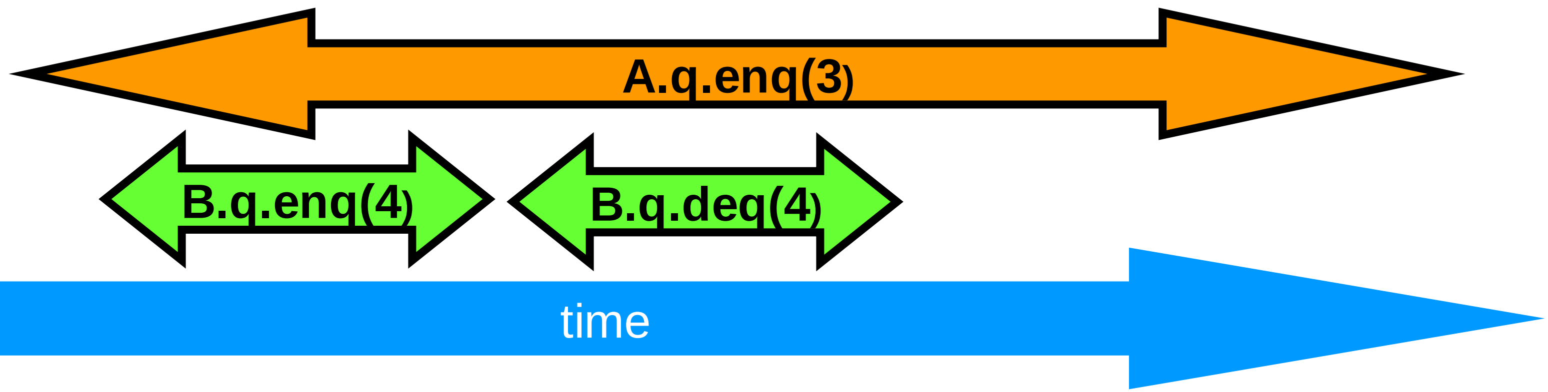


Example

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

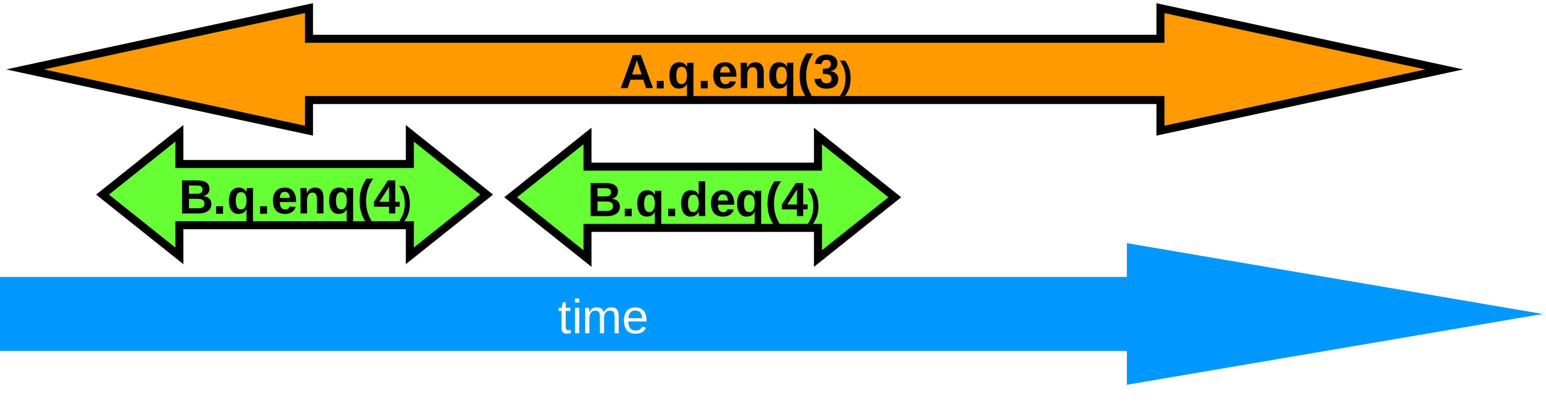
discard this one

```
A q:void
```



Example

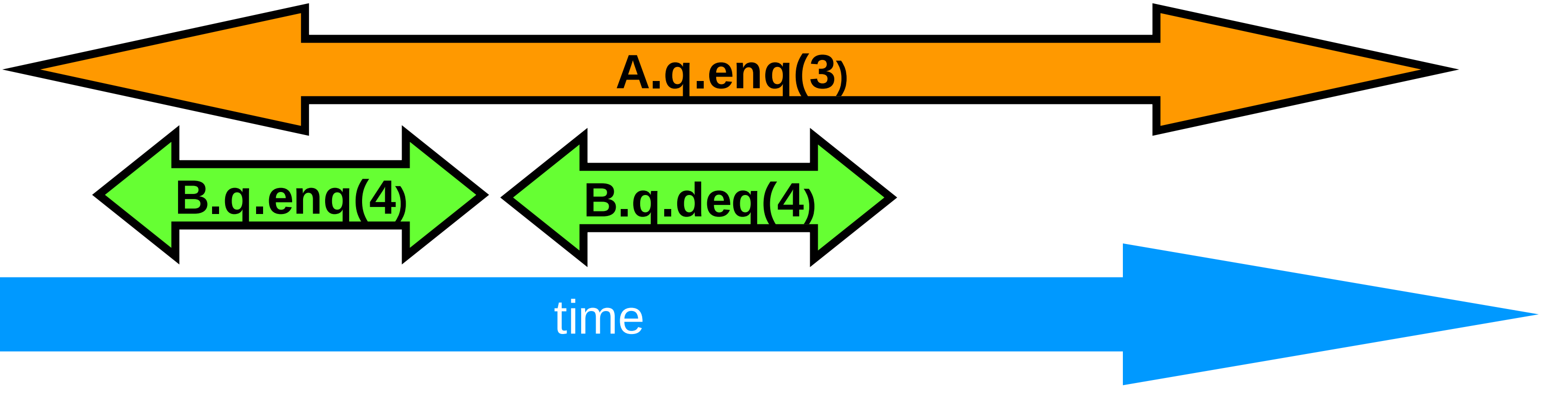
```
A q.enq(3)
B q.enq(4)
B q:void
B q.deq()
B q:4
A q:void
```



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
```

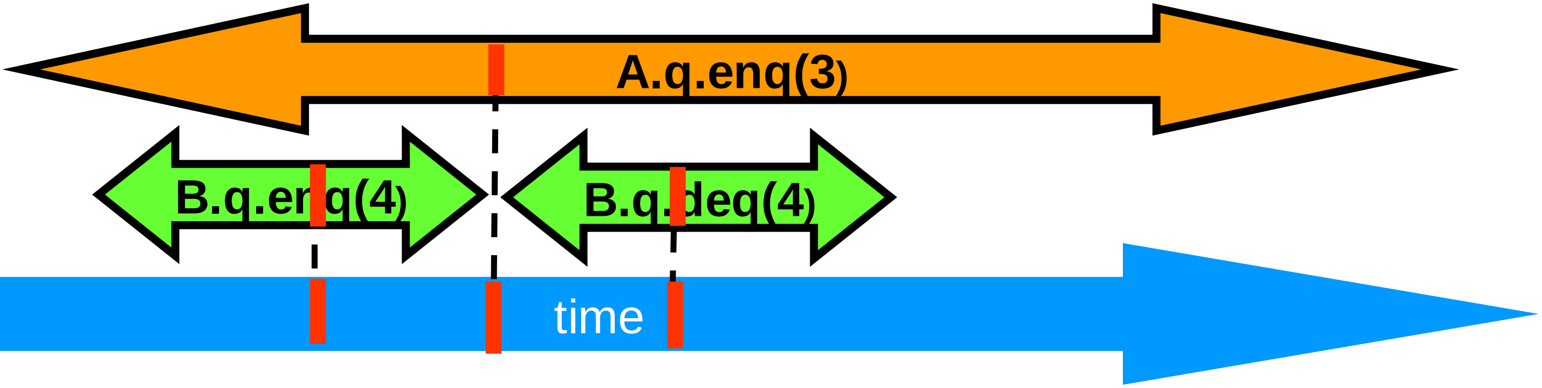


Example

```
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
```



Linearization Points

- **Identify one atomic step where a method "happens" (effects become visible to others)**
  - Critical section
  - Machine instruction (atomics, transactional memory …)
- **Does not always succeed**
  - One may need to define several different steps for a given method
  - If so, extreme care must be taken to ensure pre-/postconditions
- **All possible executions on the object must be linearizable**

```
void enq(Item x) {
  std::lock_guard<std::mutex> l(lock)
  if(tail-head == items.size()) {
    throw FullException;
  }
  items[tail % items.size()] = x;
  tail = (tail+1)%items.size();
}
```

```
Item deq() {
  std::lock_guard<std::mutex> l(lock)
  if(tail == head) {
    throw EmptyException;
  }
  Item item = items[head % items.size()];
  head = (head+1)%items.size();
}
```

Composition

- **H is linearizable iff for every object x, H|x is linearizable!**
  - Composing linearizable objects results in a linearizable system

- **Reasoning**
  - Consider linearizability of objects in isolation

- **Modularity**
  - Allows concurrent systems to be constructed in a modular fashion
  - Compose independently-implemented objects

Linearizability vs. Sequential Consistency

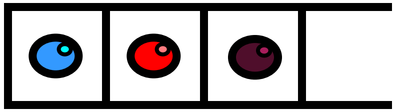
- **Sequential consistency**
  - Correctness condition
  - For describing hardware memory interfaces
  - Remember: not *existing* ones!

- **Linearizability**
  - Stronger correctness condition
  - For describing higher-level systems composed from linearizable components

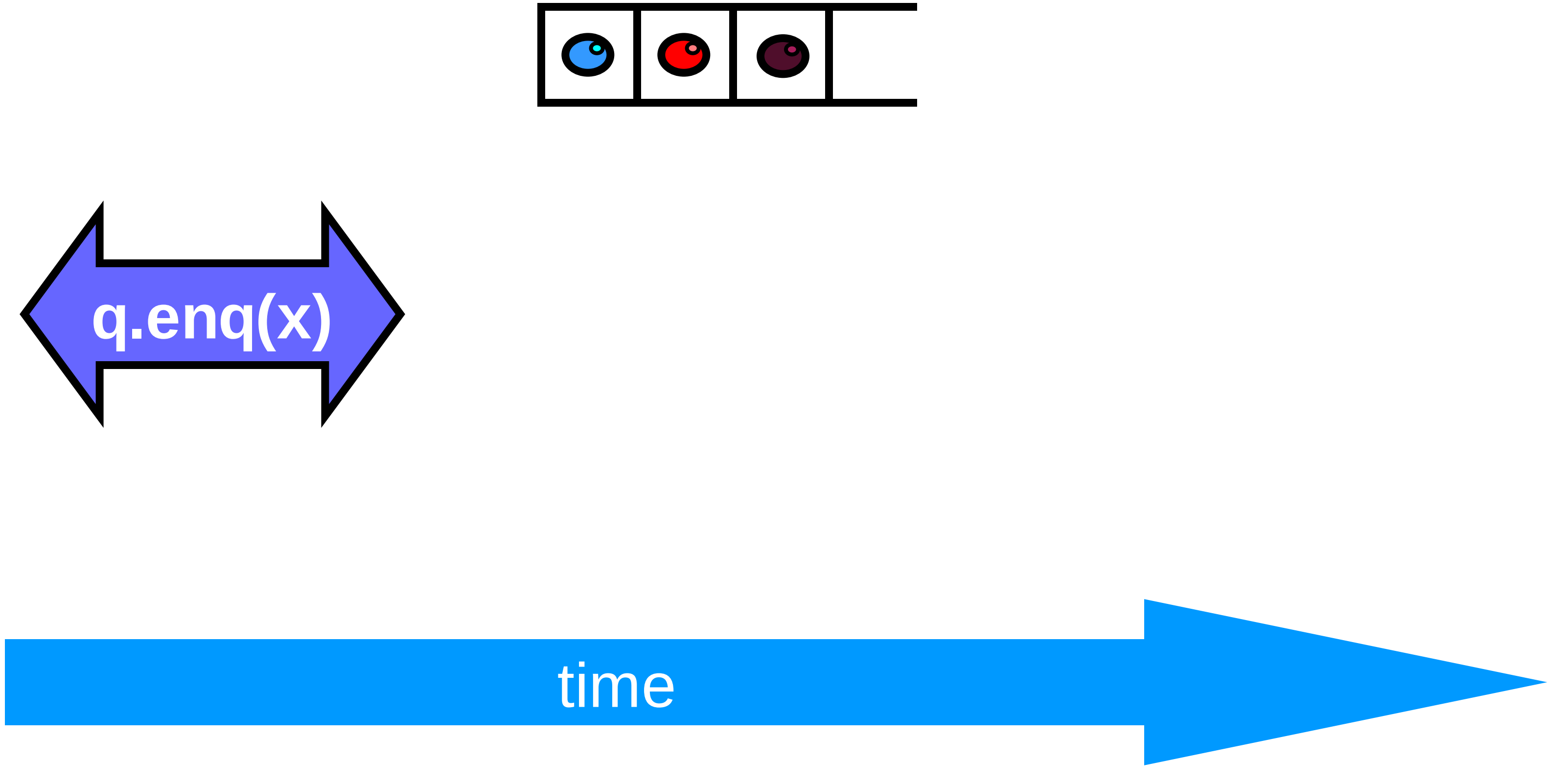
Map linearizability to sequential consistency

- **Variables with read and write operations**
  - Sequential consistency
- **Objects with a type and methods**
  - Linearizability
- **Map sequential consistency ↔ linearizability**
  - Reduce data types to variables with read and write operations
  - Model variables as data types with read() and write() methods
- **Sequential consistency**
  - A history H is sequential if it can be extended to H’ and H’ is equivalent to some sequential history S
  - Note: Precedence order ($<_H \subseteq <_S$) does not need to be maintained

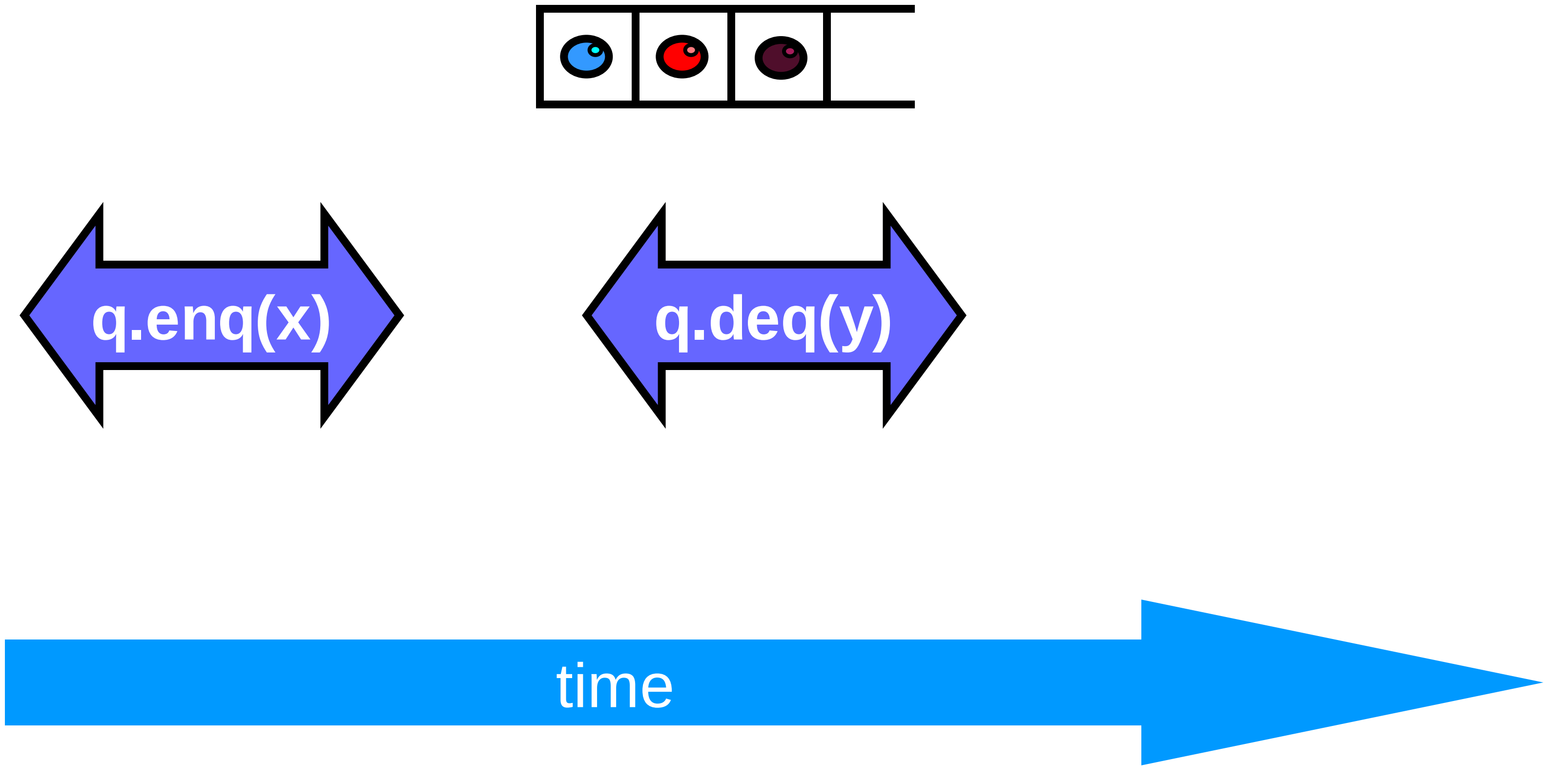
Example



Example

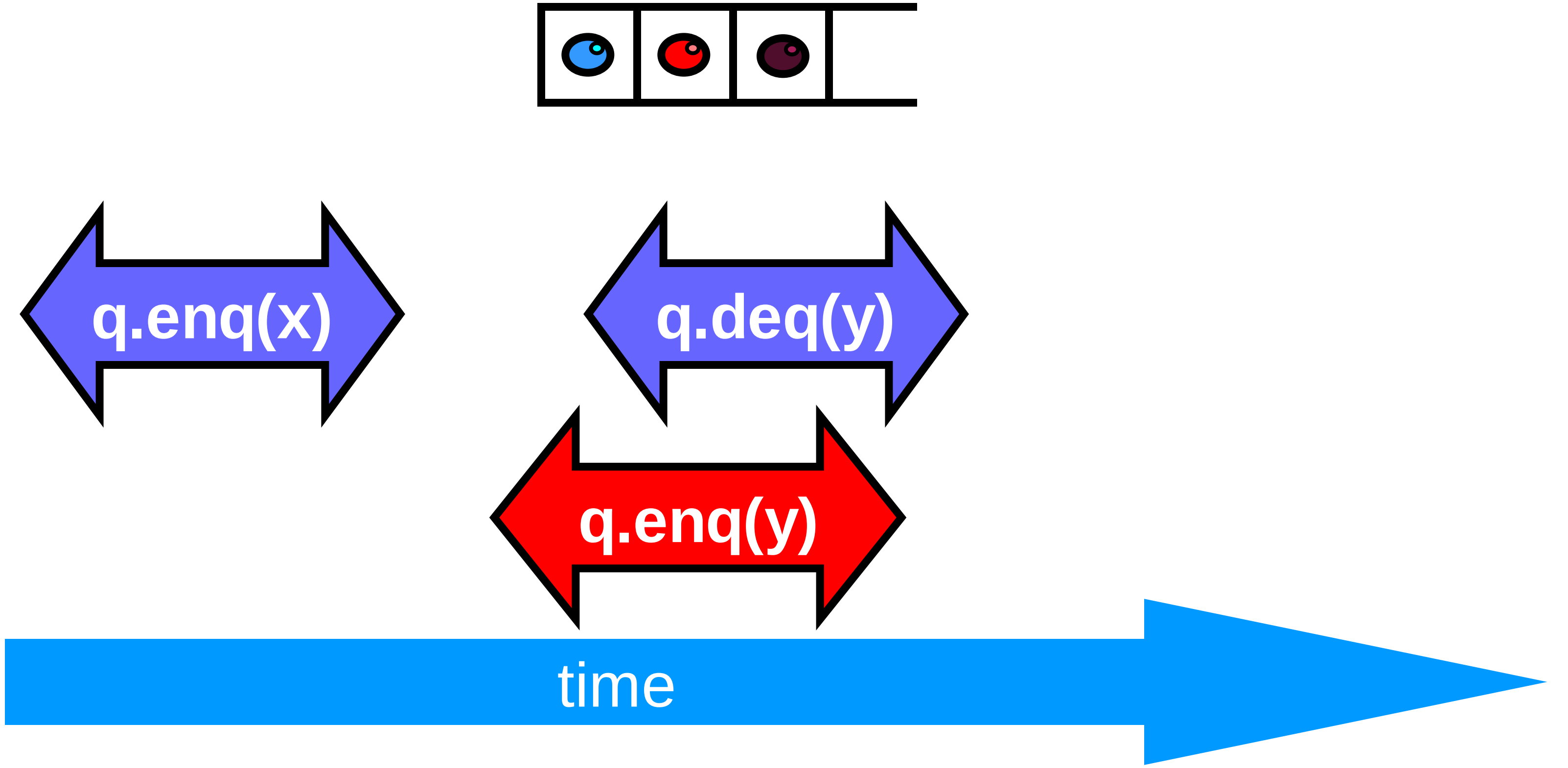


Example



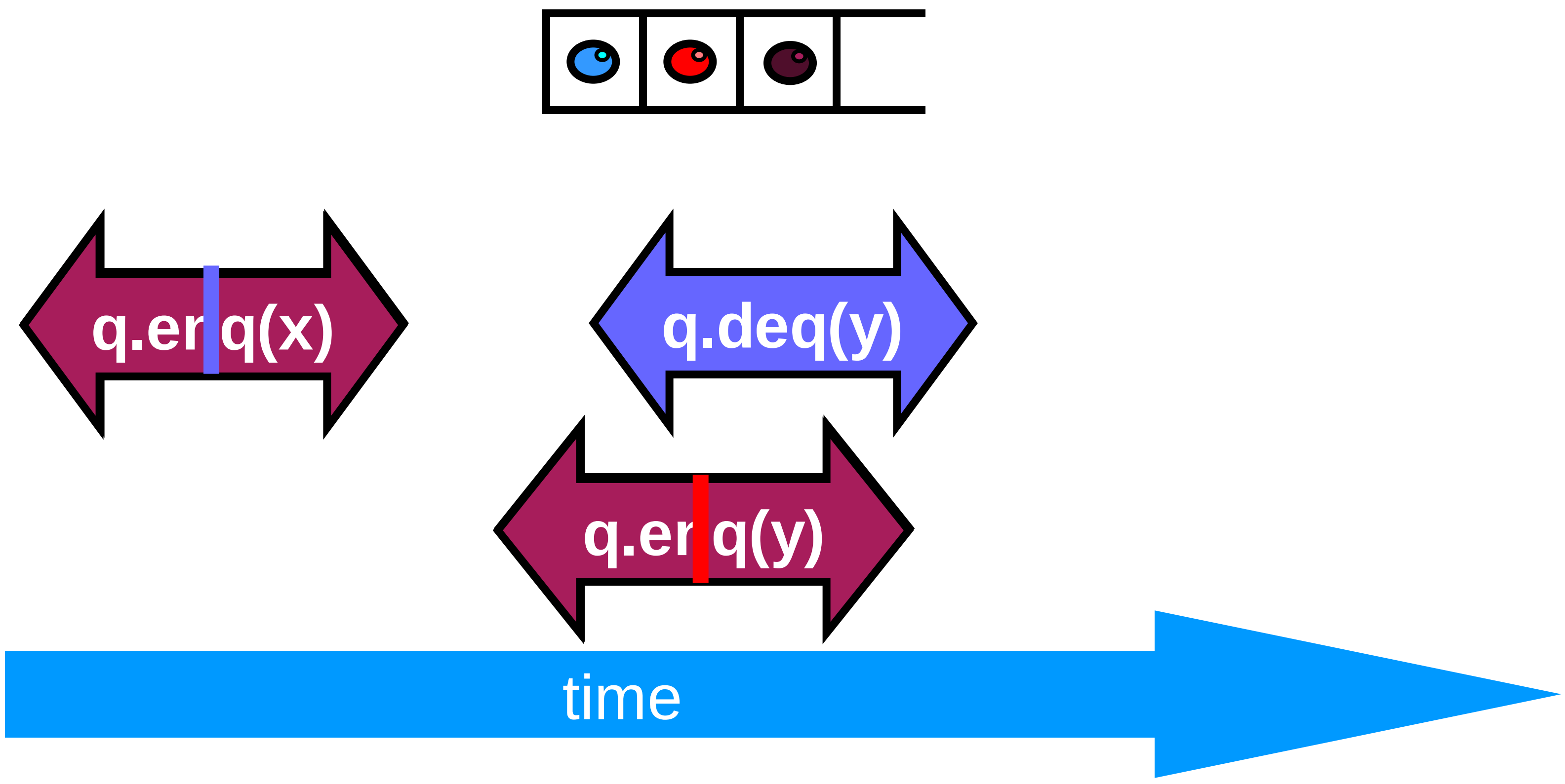
Example

Linearizable?



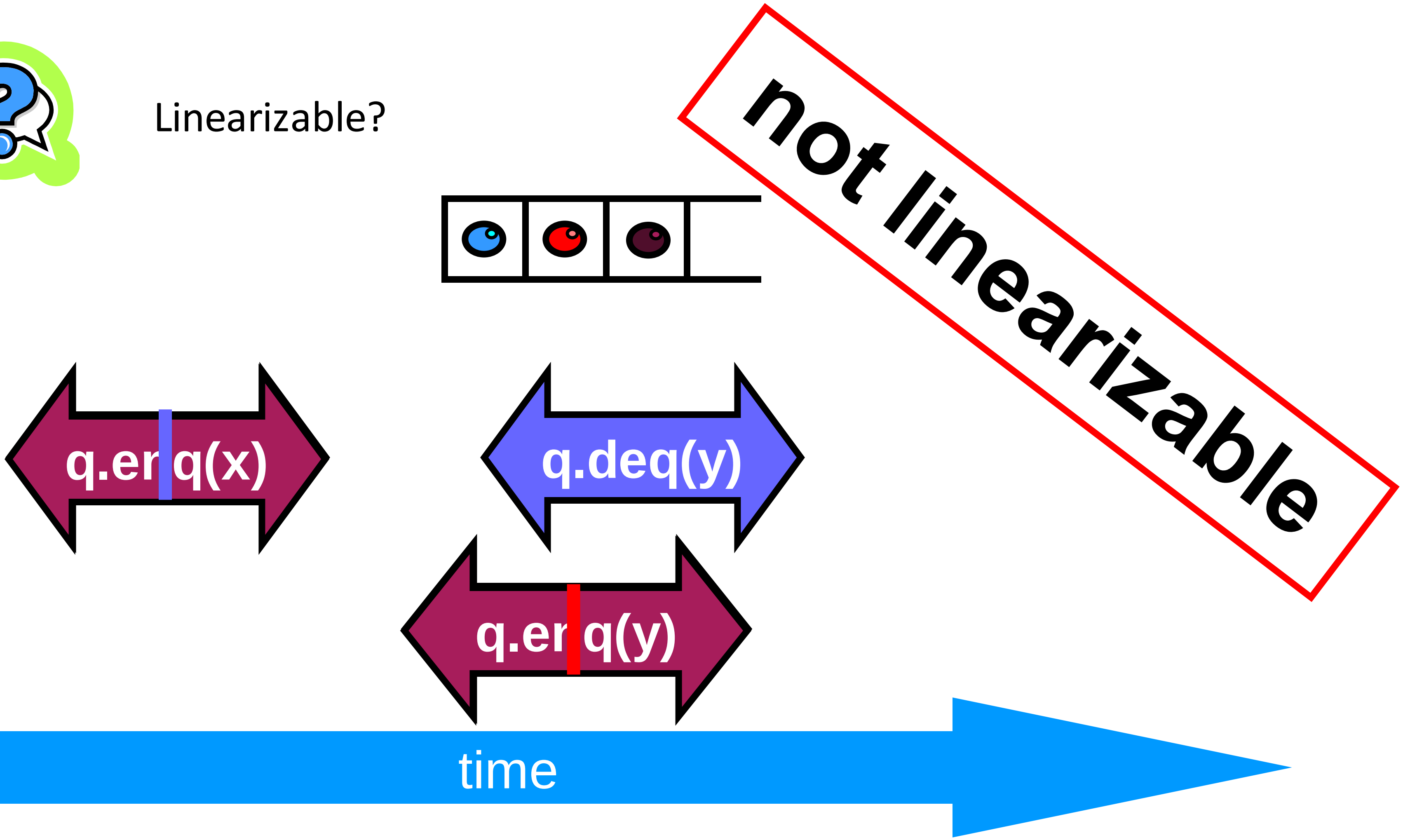
Example

Linearizable?



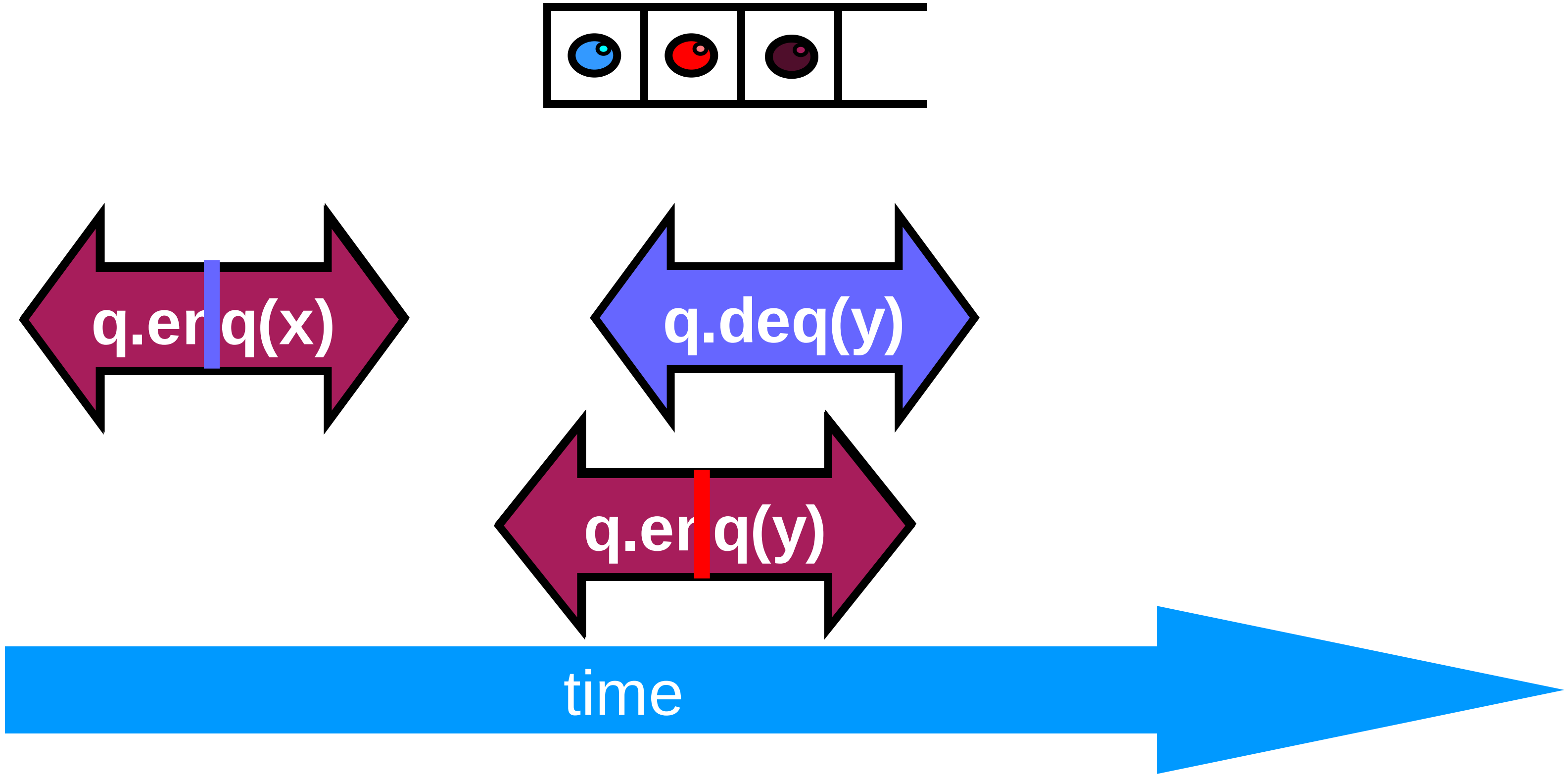
Example

Linearizable?



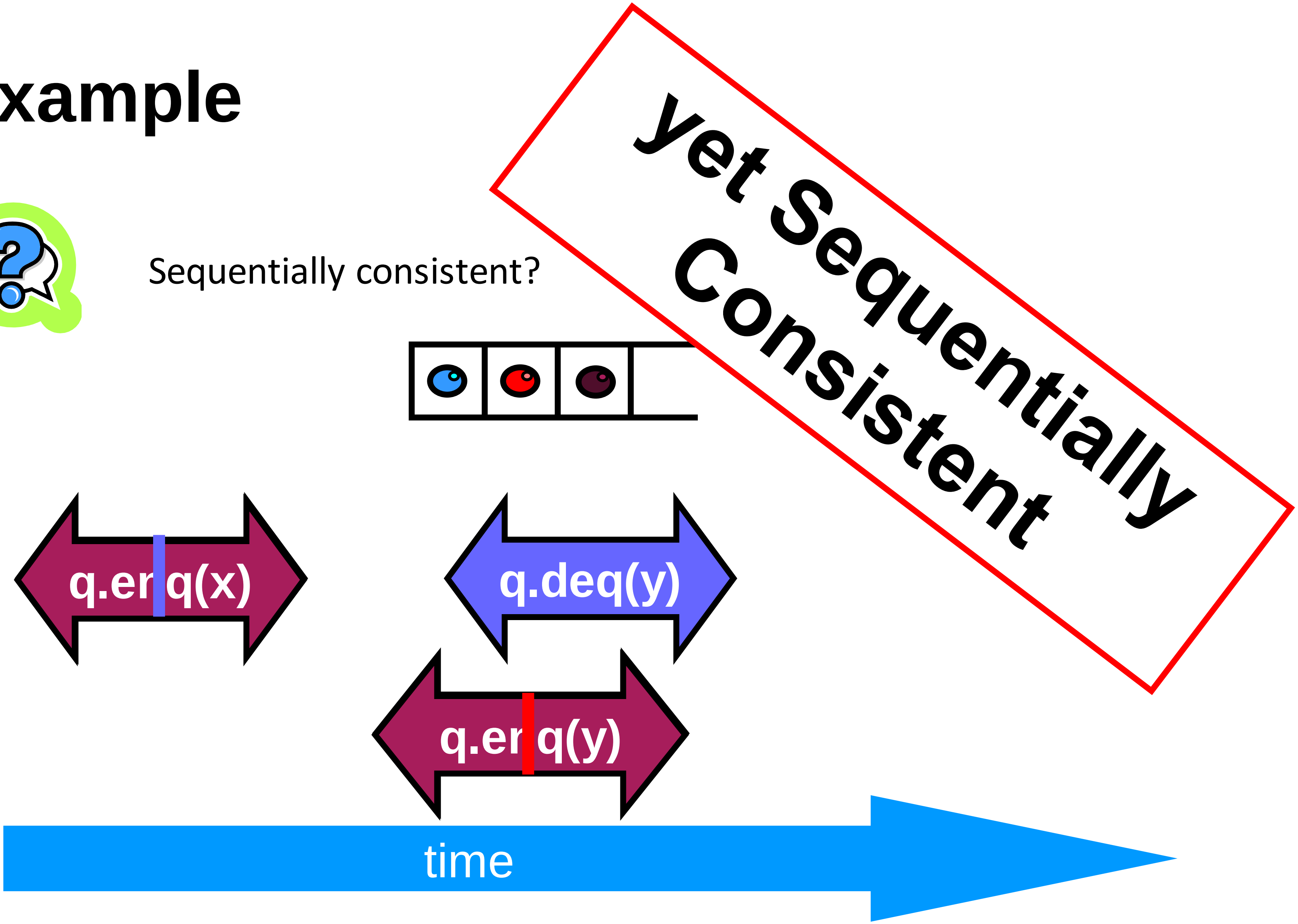
Example

Sequentially consistent?



Example

Sequentially consistent?



Properties of sequential consistency

- **Theorem: Sequential consistency is not compositional**

H=

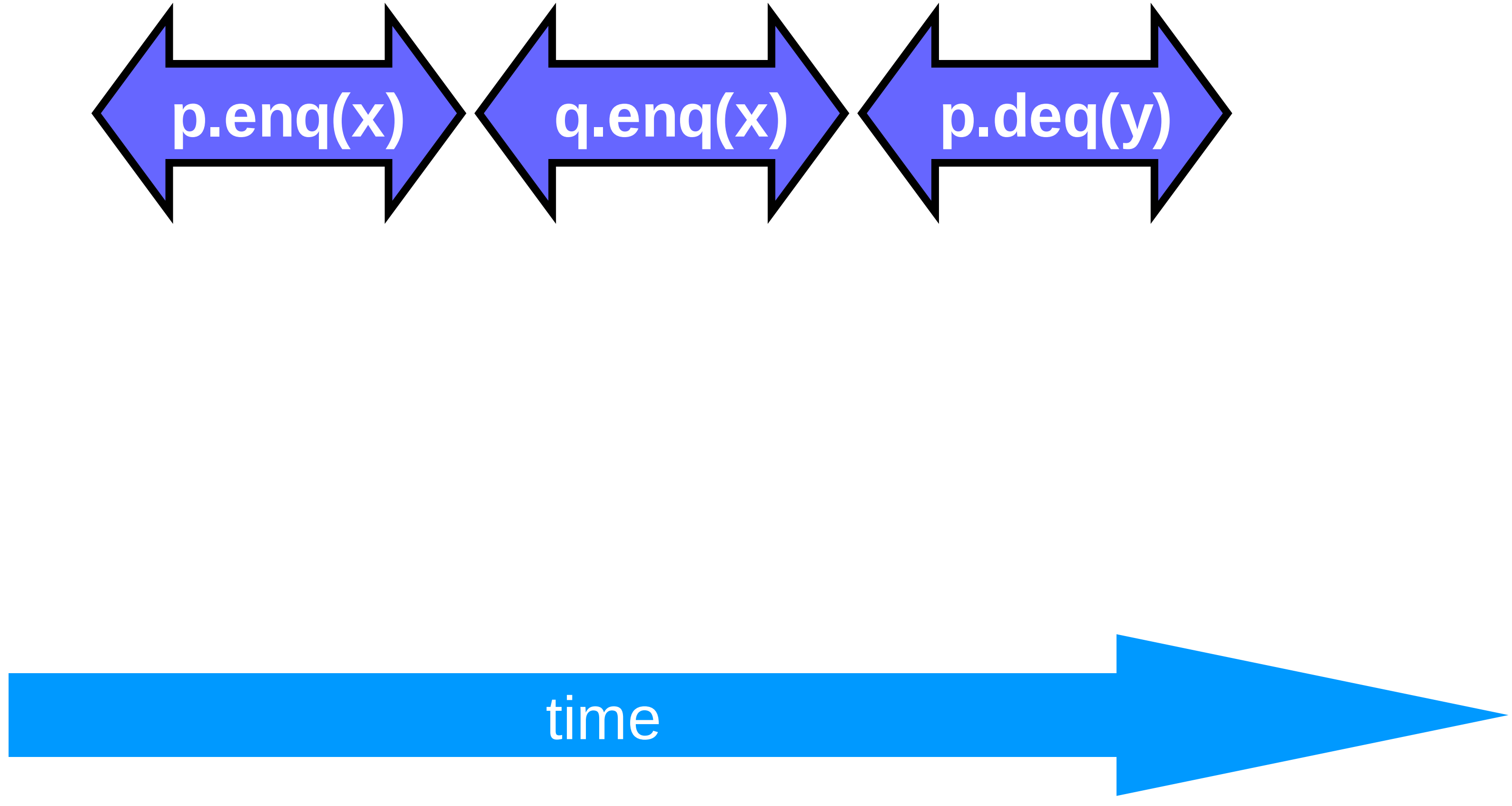
A: p.enq(x)
A: p:void
B: q.enq(y)
B: q:void
A: q.enq(x)
A: q:void
B: p.enq(y)
B: p:void
A: p.deq()
A: p:y
B: q.deq()
B: q:x

Compositional would mean:
"If H|p and H|q are sequentially consistent,
then H is sequentially consistent!"

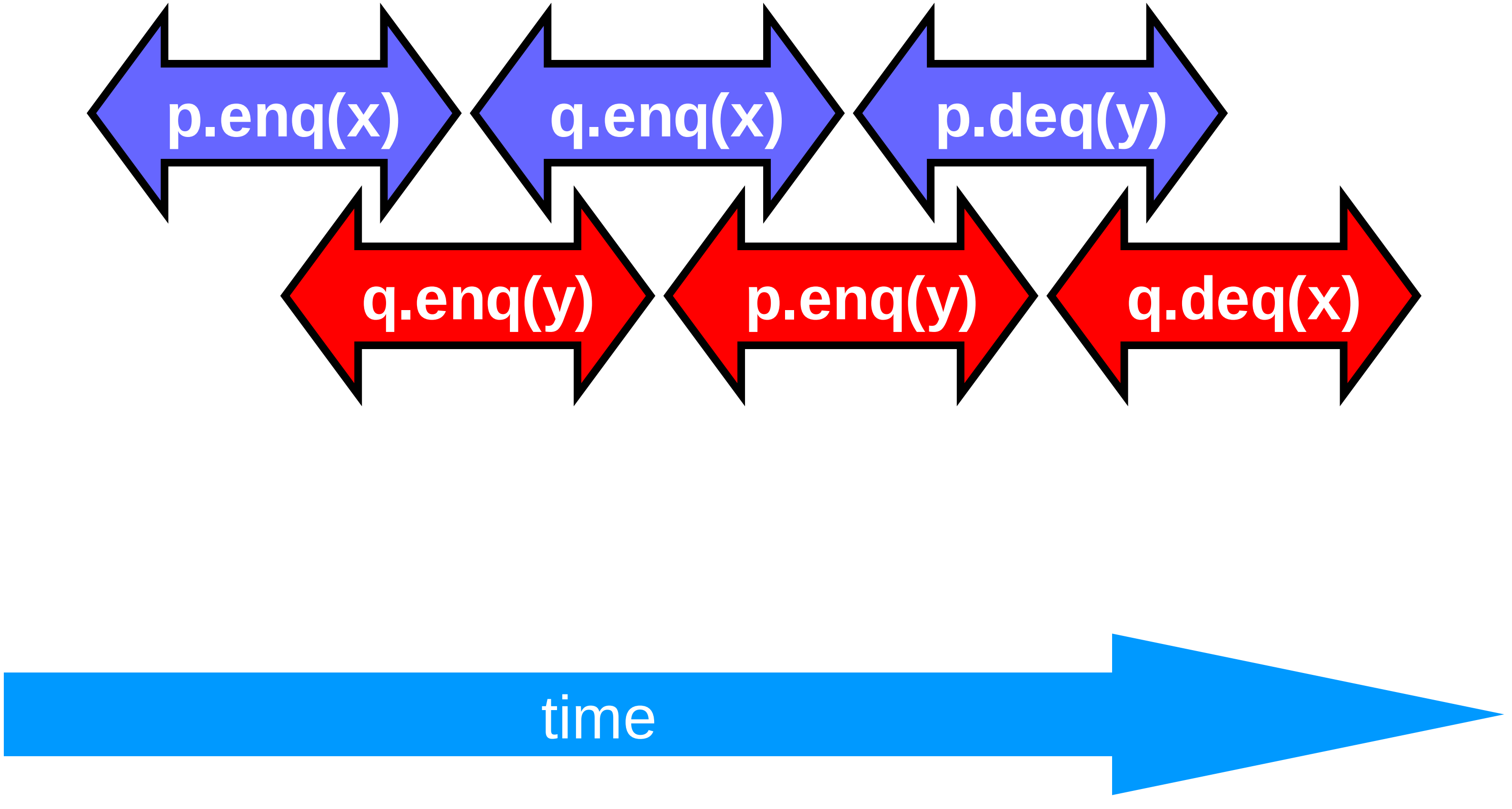
This is not guaranteed for SC schedules!

See following example!

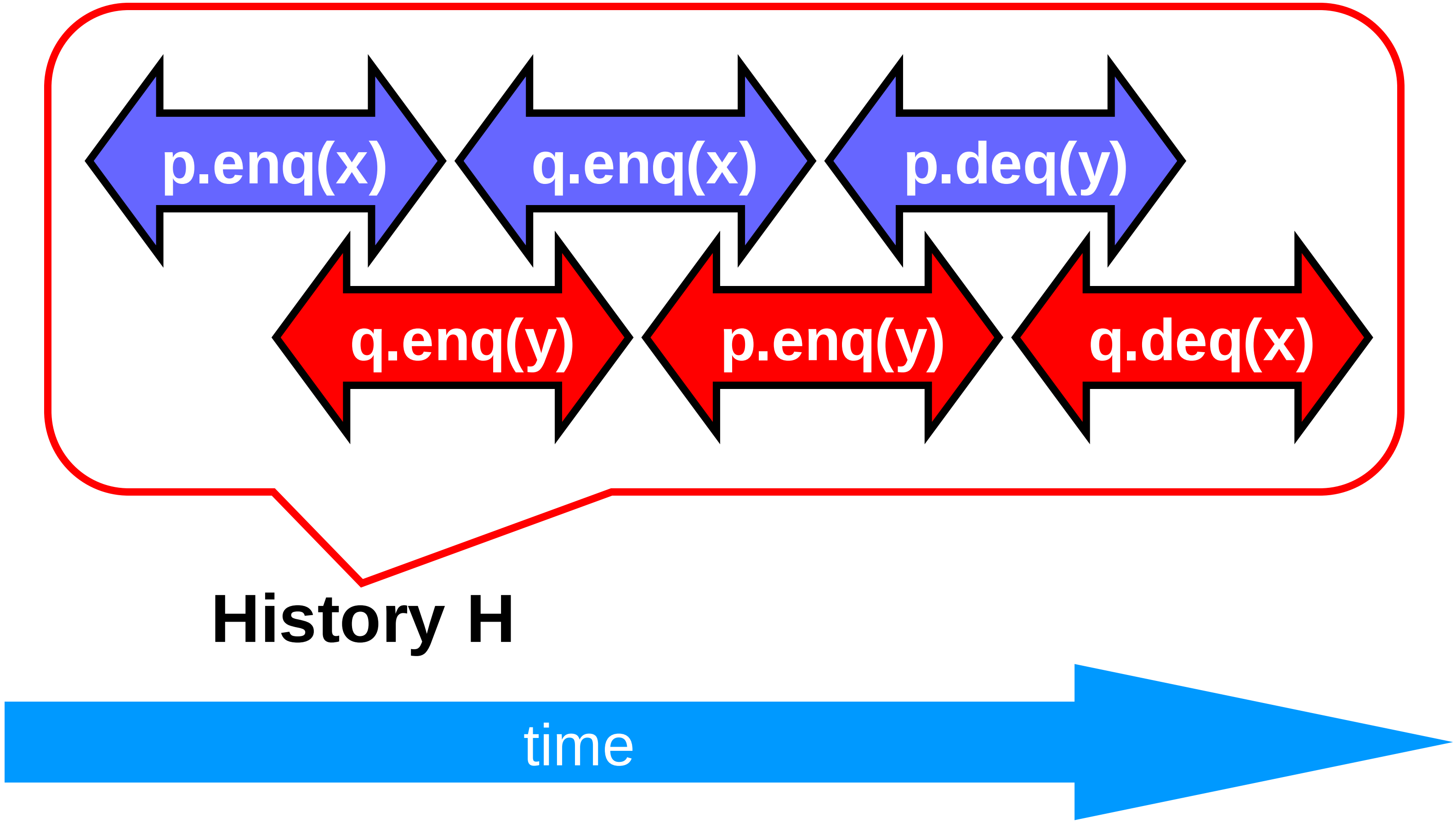
FIFO Queue Example



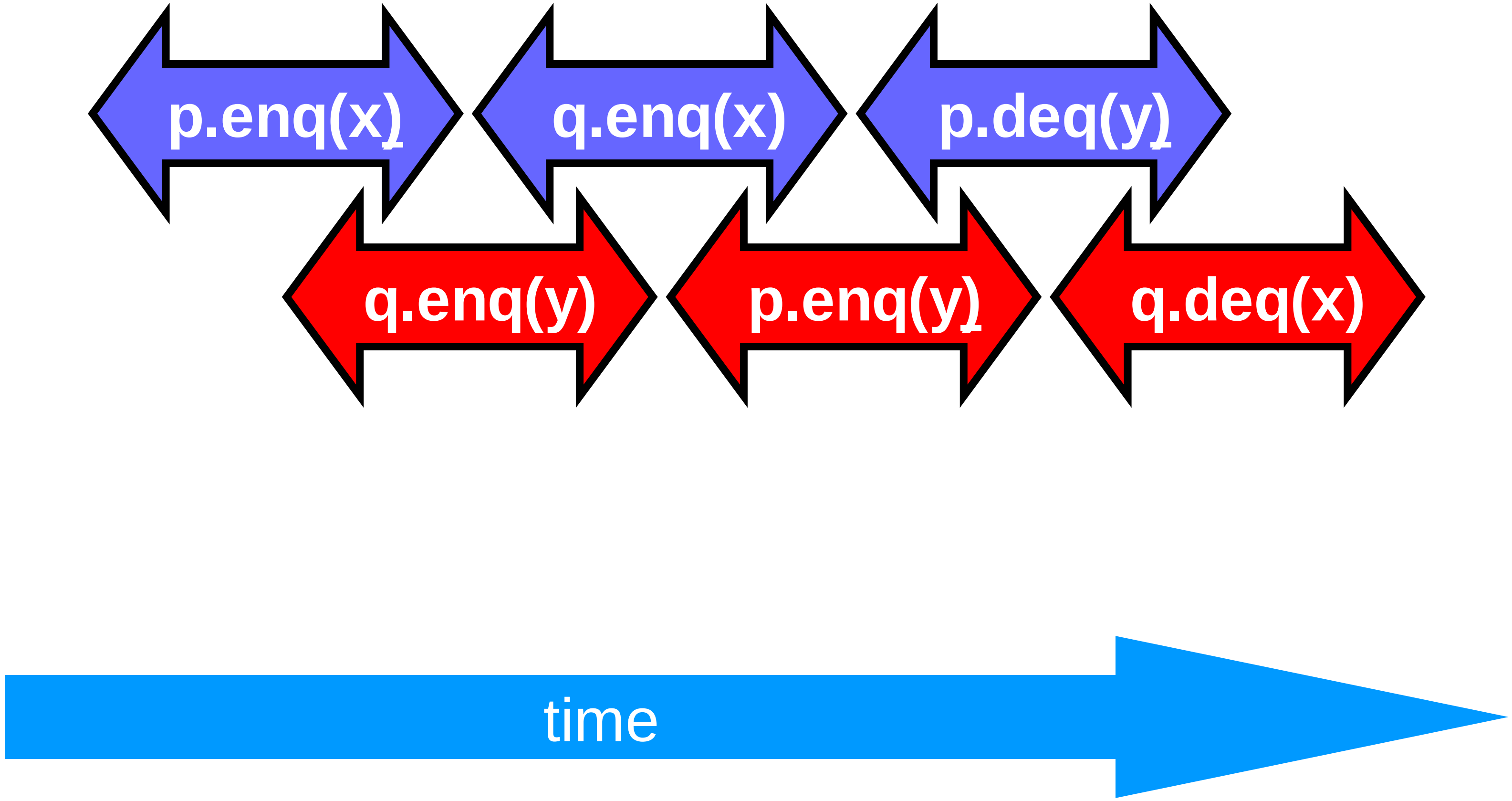
FIFO Queue Example



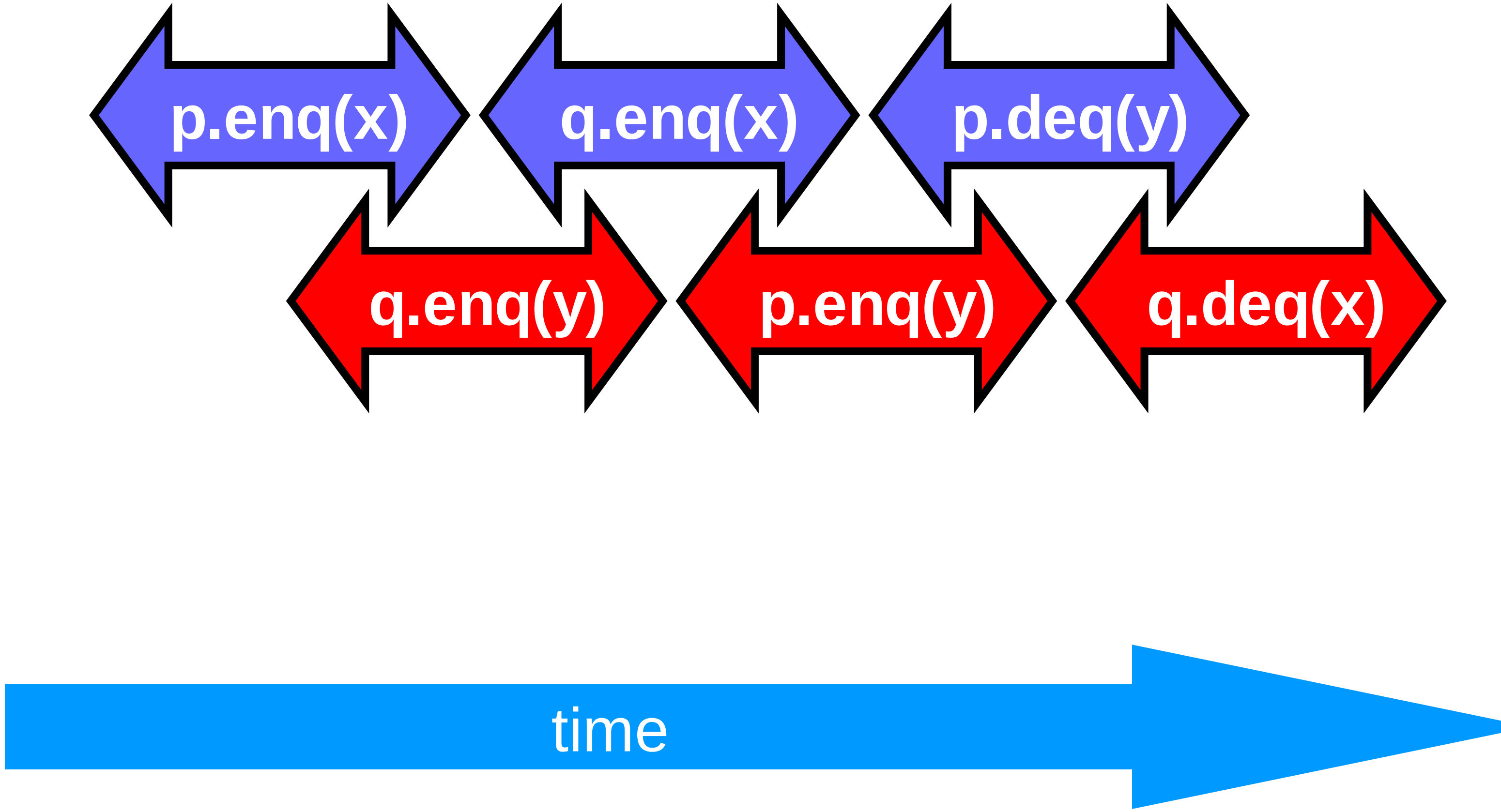
FIFO Queue Example



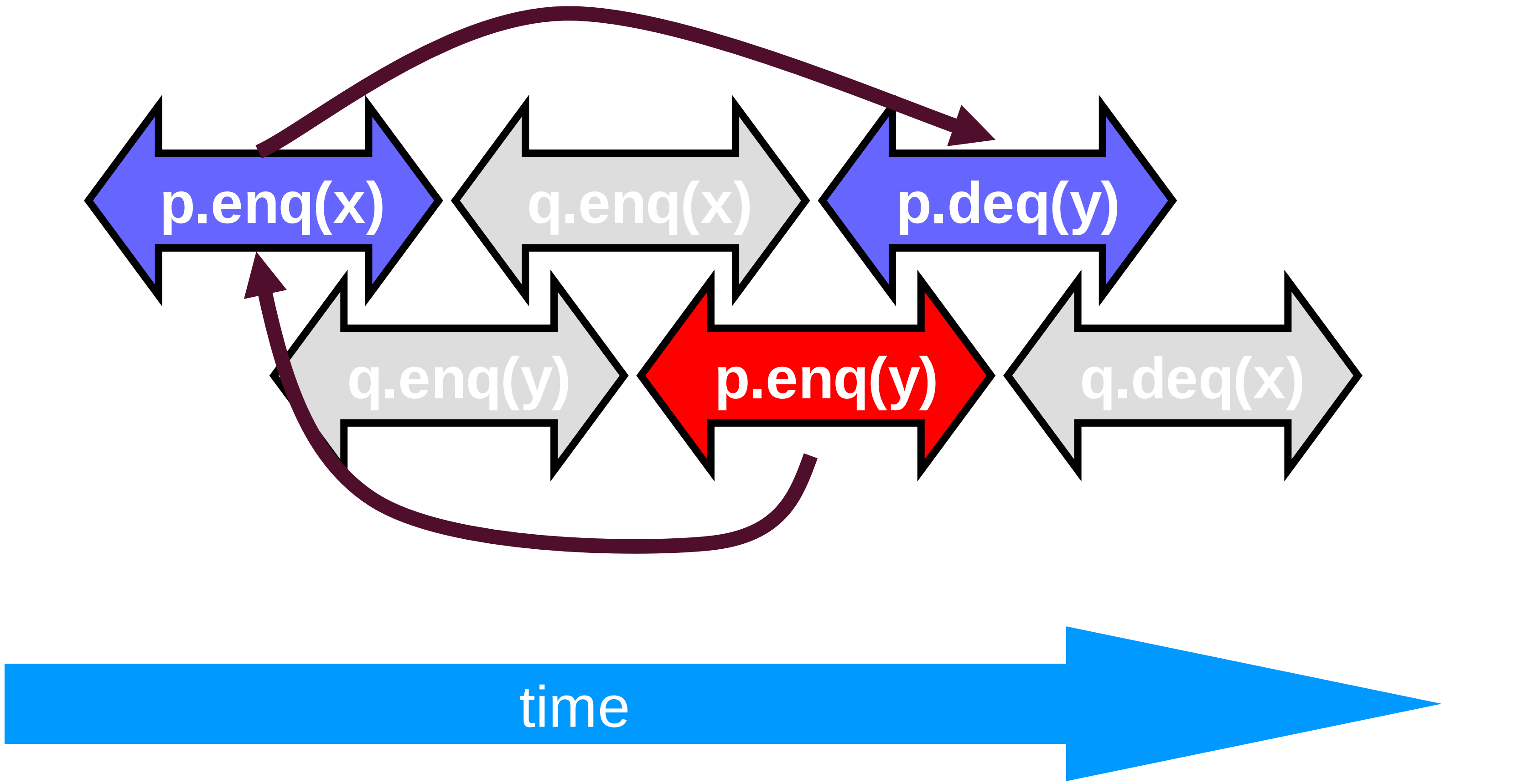
H|p Sequentially Consistent



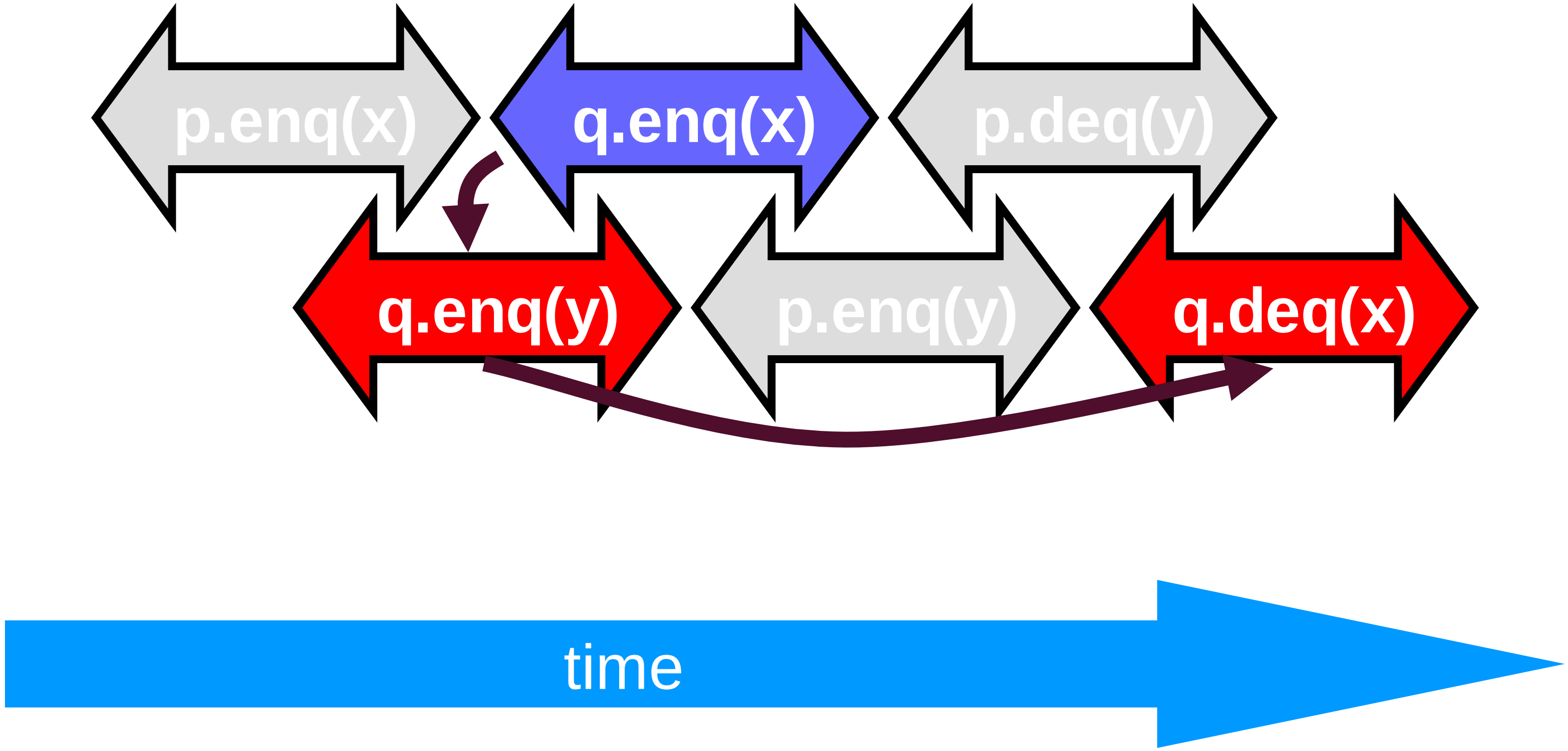
H|q Sequentially Consistent



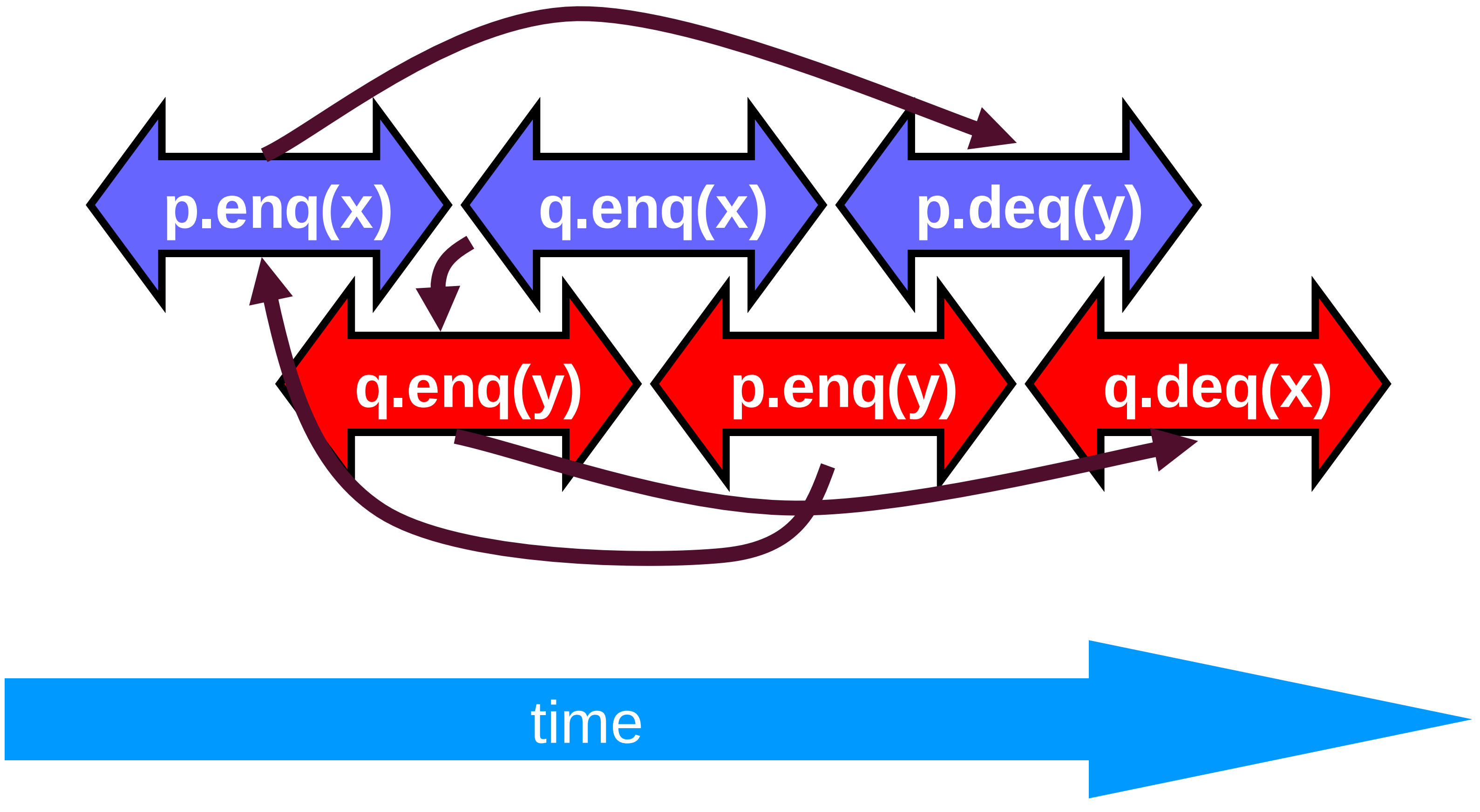
Ordering imposed by p



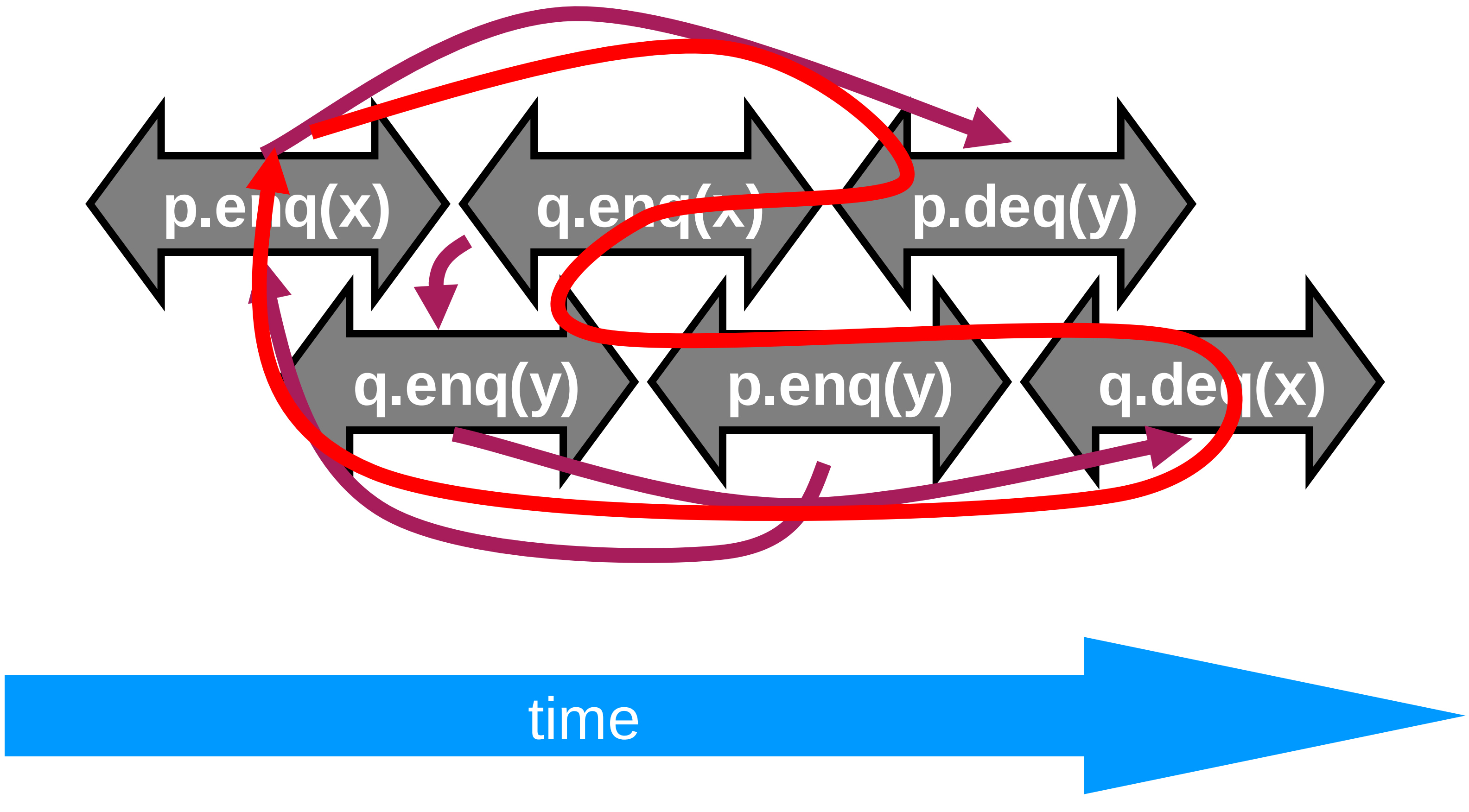
Ordering imposed by q



Ordering imposed by both



Combining orders



Example in our notation

- **Sequential consistency is not compositional**

H=	H|p=	(H|p)|A=	(H|p)|B=
A: p.enq(x)	A: p.enq(x)	A: p.enq(x)	B: p.enq(y)
A: p:void	A: p:void	A: p:void	B: p:void
B: q.enq(y)	B: p.enq(y)	A: p.deq()	
B: q:void	B: p:void	A: p:y	
A: q.enq(x)	A: p.deq()		
A: q:void	A: p:y		
B: p.enq(y)			
B: p:void			
A: p.deq()			
A: p:y			
B: q.deq()			
B: q:x			

H|p is sequentially consistent!

Example in our notation

- **Sequential consistency is not compositional**

H=	H|q=	(H|q)|A=	(H|q)|B=
A: p.enq(x)	B: q.enq(y)	A: q.enq(x)	B: q.enq(y)
A: p:void	B: q:void	A: q:void	B: q:void
B: q.enq(y)	A: q.enq(x)		B: q.deq()
B: q:void	A: q:void		B: q:x
A: q.enq(x)	B: q.deq()		
A: q:void	B: q:x		
B: p.enq(y)			
B: p:void			
A: p.deq()			
A: p:y			
B: q.deq()			
B: q:x			

H|q is sequentially consistent!

Example in our notation

- **Sequential consistency is not compositional**

H=

A: p.enq(x)
A: p:void
B: q.enq(y)
B: q:void
A: q.enq(x)
A: q:void
B: p.enq(y)
B: p:void
A: p.deq()
A: p:y
B: q.deq()
B: q:x

H|A=

A: p.enq(x)
A: p:void
A: q.enq(x)
A: q:void
A: p.deq()
A: p:y

H|B=

B: q.enq(y)
B: q:void
B: p.enq(y)
B: p:void
B: q.deq()
B: q:x

H is not sequentially consistent!

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**

Study Goals

- **Define linearizability with your own words!**
- **Describe the properties of linearizability!**
- **Explain the differences between sequential consistency and linearizability!**

- **Given a history H**
  - Identify linearization points
  - Find equivalent sequential history S
  - Decide and explain whether H is linearizable
  - Decide and explain whether H is sequentially consistent
  - Give values for the response events such that the execution is linearizable

Language Memory Models

- **Which transformations/reorderings can be applied to a program**
- **Affects platform/system**
  - Compiler, (VM), hardware
- **Affects programmer**
  - What are possible semantics/output
  - Which communication between threads is legal?
- **Without memory model**
  - Impossible to even define “legal” or “semantics” when data is accessed concurrently
- **A memory model is a contract**
  - Between platform and programmer

History of Memory Models

- **Java's original memory model was broken**
  - Difficult to understand => widely violated
  - Did not allow reorderings as implemented in standard VMs
  - Final fields could appear to change value without synchronization
  - Volatile writes could be reordered with normal reads and writes

    => counter-intuitive for most developers

- **Java memory model was revised**
  - Java 1.5 (JSR-133)
  - Still some issues (operational semantics definition)

- **C/C++ didn't even have a memory model until recently**
  - Not able to make any statement about threaded semantics!
  - Introduced in C++11 and C11
  - Based on experience from Java, more conservative

Everybody wants to optimize

- **Language constructs for synchronization**
  - Java: volatile, final, synchronized, …
  - C++: atomic, (**NOT volatile**!) …

- **Without synchronization (defined language-specific)**
  - Compiler, (VM), architecture
  - Reorder and appear to reorder memory operations
  - Maintain sequential semantics per thread
  - Other threads may observe any order (have seen examples before)

Java and C++ High-level overview

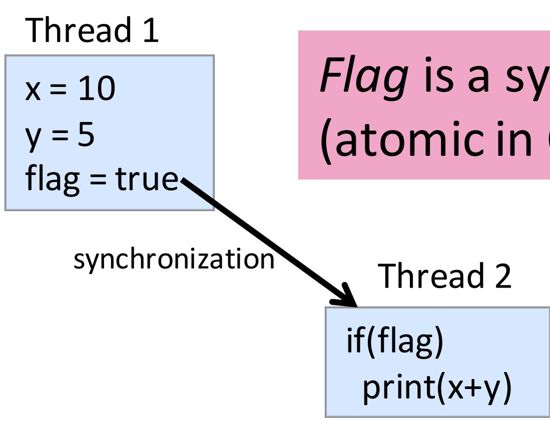
- **Relaxed memory model**
  - No global visibility ordering of operations
  - Allows for standard compiler optimizations
- **But**
  - Program order for each thread (sequential semantics)
  - Partial order on memory operations (with respect to synchronizations)
  - Visibility function defined
- **Correctly synchronized programs**
  - Guarantee sequential consistency
- **Incorrectly synchronized programs**
  - Java: maintain safety and security guarantees

    Type safety etc. (require behavior bounded by casuality)
  - C++: undefined behavior

    No safety (anything can happen/change)

Communication between Threads Intuition

- **Not guaranteed unless by:**
  - Synchronization
  - Volatile/atomic variables
  - Specialized functions/classes (e.g., java.util.concurrent,)



Flag is a synchronization variable (atomic in C++, volatile in Java),

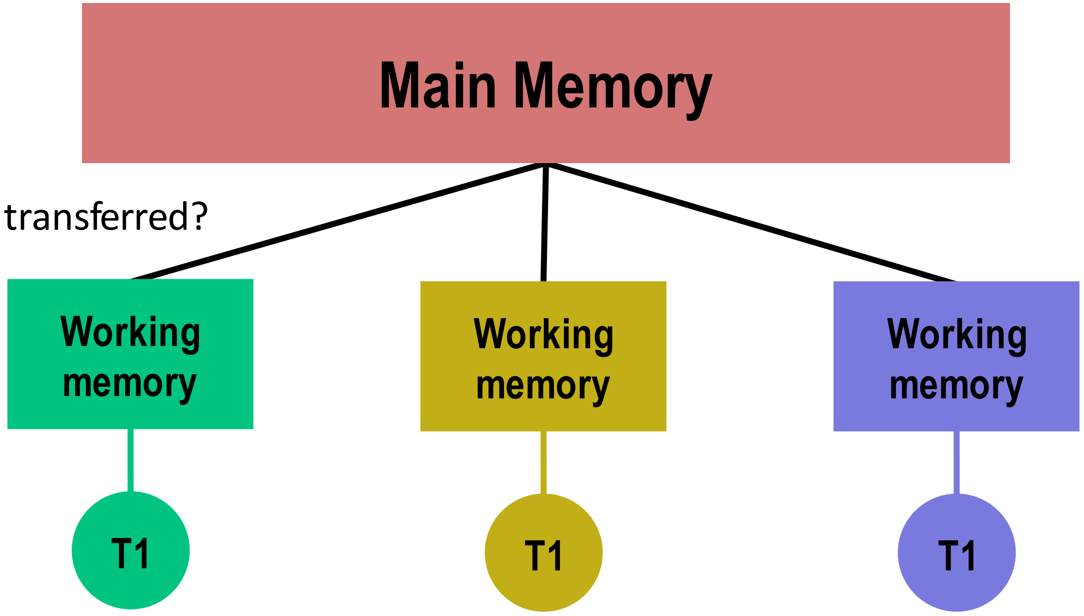
i.e., all memory written by T1 must be visible to T2 after it reads the value true for *flag*!

Memory Model Intuition

- **Abstract relation between threads and memory**
  - Local thread view!

When are values transferred?

abstraction of caches **and** registers



- **Does not talk about classes, objects, methods, …**
  - Linearizability is a higher-level concept!

Lock Synchronization

- **Java**

```
synchronized (lock) {
  // critical region
}
```

  - Synchronized methods as syntactic sugar

- **C++**

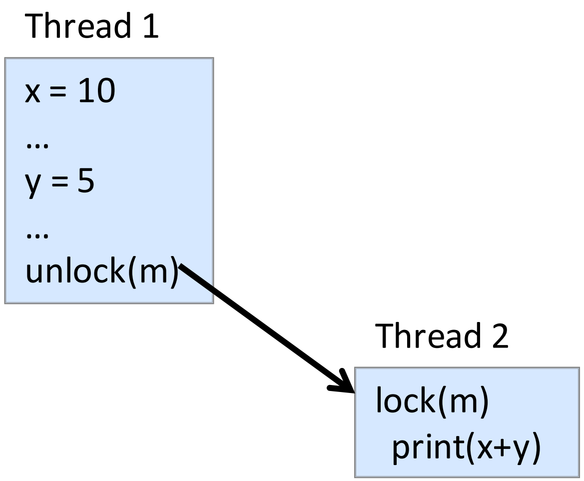
```
{
  unique_lock<mutex> l(lock);
  // critical region
}
```

  - Many flexible variants

- **Semantics:**
  - mutual exclusion
  - at most one thread may own a lock
  - a thread B trying to acquire a lock held by thread A blocks until thread A releases lock
  - note: threads may wait forever (no progress guarantee!)

Memory semantics

- **Similar to synchronization variables**



  - All memory accesses before an unlock …
  - are ordered before and are visible to …
  - any memory access after a matching lock!

Synchronization Variables

- **Variables can be declared volatile (Java) or atomic (C++)**

- **Reads and writes to synchronization variables**
  - Are totally ordered with respect to all threads
  - Must not be reordered with normal reads and writes

- **Compiler**
  - Must not allocate synchronization variables in registers
  - Must not swap variables with synchronization variables
  - May need to issue memory fences/barriers
  - …

Synchronization Variables

- **Write to a synchronization variable**
  - Similar memory semantics as unlock (no process synchronization!)
- **Read from a synchronization variable**
  - Similar memory semantics as lock (no process synchronization!)

```
class example {
 int x = 0;
 atomic<bool> v = false

 public void writer() {
    x = 42;
    v = true;
 }

 public void reader() {
    if(v) {
      print(x)
    }
 }
```

Thread 1

Thread 2

Without volatile, a platform may reorder these accesses!

Memory Model Rules

- **Java/C++: Correctly synchronized programs will execute sequentially consistent**
- **Correctly synchronized = data-race free**
  - iff all sequentially consistent executions are free of data races
- **Two accesses to a shared memory location form a data race in the execution of a program if**
  - The two accesses are from different threads
  - At least one access is a write and
  - The accesses are not synchronized