ETH Zürich

Chair of Software Engineering

Concepts of Concurrent Computation

Bertrand Meyer
Sebastian Nanz

Lecture 8: Lock-free approaches

Today's lecture

In this lecture you will learn about:

- Problems of the locking-based approach to shared-memory concurrent programming
- Lock-free programming, a synchronization technique based on atomic read-modify-write primitives
- Software transactional memory (STM), a synchronization mechanism based on the idea of database transactions
- Linearizability and sequential consistency, two correctness conditions for concurrent objects

Motivation

What's wrong with locks? (1)

- It's difficult to program with locks, because it's easy to ...
  - ... forget a lock: danger of data races.
  - ... take too many locks: danger of deadlock.
  - ... take locks in the wrong order: danger of deadlock.
  - ... take the wrong lock: the relation between the lock and the data it protects is not explicit in the program.
- Locks cause blocking:
  - Danger of *priority inversion*: if a lower-priority thread is preempted while holding a lock, higher-priority threads cannot proceed.
  - Danger of *convoying*: other threads queue up waiting while a thread holding a lock is blocked.

What's wrong with locks? (2)

- Two concepts related to locks:
  - *lock overhead* (increases with more locks): time for acquiring and releasing locks, and other resources
  - *lock contention* (decreases with more locks): the situation that multiple processes wait for the same lock
- For performance, the developer has to carefully choose the granularity of locking: both lock overhead and contention need to be small.
- Locks are also problematic for designing fault-tolerant systems: If a faulty process halts while holding a lock, no other process can obtain the lock.

What's wrong with locks? (3)

- Locks are not composable in general, i.e. they don't support modular programming (building larger programs from smaller blocks).

```
class Account {
    int balance;
    synchronized void deposit(int amount) {
        balance = balance + amount;
    }
    synchronized void withdraw(int amount) {
        balance = balance - amount;
    }
}
```

- How to implement the following method?

```
void transfer(Account acc1, Account acc2, int amount)
```

What's wrong with locks? (4)

- Although deposit and withdraw are correctly implemented by themselves, the following is incorrect:

```
void transfer(Account acc1, Account acc2, int amount) {
    acc1.withdraw(amount);
    acc2.deposit(amount);
}
```

- Instead we would have to add explicit locking code:

```
void transfer(Account acc1, Account acc2, int amount) {
    synchronized (acc1) {
        synchronized (acc2) {
            acc1.withdraw(amount);
            acc2.deposit(amount);
        }
    }
}
```

Concurrent programming without locking

- Use a pure message-passing approach:
  - Since no data is shared, there is no need for locks
  - Of course message-passing approaches have their own drawbacks, for example
    - potentially larger overhead of messaging
    - the need to copy data which has to be shared
    - potentially slower access to data, e.g. to read-only data structures which need to be shared
- If a shared-memory approach is preferred, the only alternative to using locks is to make the implementation of a concurrent program *lock-free*.

Lock-free approaches

- Lock-free programming using atomic read-modify-write primitives, such as compare and swap (CAS)
- *Software transactional memory (STM)*, a programming model based on the idea of database transactions

Lock-free programming

Lock-free programming

- *Lock-free programming* is the idea to write shared-memory concurrent programs that don't use locks but can still ensure thread-safety
- Instead of locks, use stronger atomic operations such as compare-and-swap (atomic read-modify-write primitives)
    - These primitives typically have to be provided by hardware
- Coming up with general lock-free algorithms is hard
- Hence usually one focuses on developing lock-free data structures: stack, list, queue, buffer, ...

Classes of lock-free algorithms

- For lock-free algorithms one typically distinguishes between the following two classes:
  - *lock-free*: some process completes in a finite number of steps (free from deadlock)
  - *wait-free*: all processes complete in a finite number of steps (free from starvation)
- Wait-free implies lock-free

Compare-and-swap (recap)

- *Compare-and-swap (CAS)* takes three parameters: the address of a memory location, an old and a new value
- The new value is atomically written to the memory location if the content of the location agrees with the old value

```
CAS (x, old, new)
  do
    if *x = old then
      *x := new;
      result := true
    else
      result := false
    end
  end
```

Simple lock-free stack (1)

- Using CAS, we obtain the following lock-free implementation of a stack, due to (Treiber, 1986)
- A stack of elements (here of integer type) is represented as a linked list of nodes
- The top of the stack is denoted by the node *head*

```
class Node {
    Node* next;
    int item;
}

Node* head; // top of the stack
```

Simple lock-free stack (2)

- In the implementation of push and pop, a common pattern in lock-free algorithms is used:
    1. read a value from the current state
    2. compute an updated value based on the read value
    3. atomically update the state by swapping the new for the old value

```
void push (int value) {
    Node* oldHead;
    Node* newHead := new Node();
    node.item := value;
    do {
        oldHead := head;
        newHead.next := head;
    } while (!CAS(&head, oldHead, newHead));
}
```

Simple lock-free stack (3)

- If the state changes between steps 1 and 3, the CAS-operation fails and the algorithm is repeated until success

```
int pop () {
    Node* oldHead;
    Node* newHead;
    do {
        oldHead := head;
        if(oldHead = null) return EMPTY;
        newHead := oldHead.next;
    } while(!CAS(&head, oldHead, newHead));
    return oldHead.item;
}
```

The ABA problem (1)

- In the stack example, the following has to be avoided:
  - T_1: starts pop() – reads value of current head as X
  - T_2: executes pop(), removing X from the stack
  - T_2: modifies the stack arbitrarily
  - T_2: executes push(X), putting X back on the stack
  - T_1: finishes pop() – CAS succeeds, since X is on top

The ABA problem (2)

- This problematic pattern is called the *ABA problem*:
  - a value is read from state A
  - the state is changed to state B
  - the CAS operation does not distinguish between A and B, so it assumes it is still A
- The problem is avoided in the simple stack example as push always puts a *new* node, and the old node's memory location is not freed up yet (if the memory address would be reused)

Lock-free programming: Discussion

- Lock-free programming can provide good performance in *some* situations, avoiding some of the problems mentioned for locks (e.g. priority inversion)
- It's difficult to correctly implement lock-free algorithms (see ABA-problem)
- Most work confined to data structures: for these well-established algorithms and implementations are available
- One main restriction is that most read-modify-write primitives operate only on a single word: this leads to unnatural structuring of algorithms

Software Transactional Memory (STM)

Motivation

- As we have seen, lock-free programming has disadvantages in practice: algorithms can become very complex and have an unnatural structure
- This is because conventional atomic primitives can only operate on one word at a time
- Software transactional memory (STM) aims at simplifying atomic updates of multiple independent words
- STM uses the idea of transaction from database management systems

Database transactions

- Database transaction: a sequence of operations performed within a database managament systems, enjoying the ACID properties:
  - Atomicity: Transactions appear to execute completely, or not at all.
  - Consistency: Transactions preserve consistency of the database.
  - Isolation: Other operations cannot access data modified by a currently incomplete transaction.
  - Durability: All committed transactions are guaranteed to persist.
- In the context of STM, we are mostly interested in Atomicity and Isolation.

(Hardware) transactional memory

- Software transactional memory is based on earlier ideas of a multiprocessor hardware architecture to support lock-free programming: (hardware) transactional memory (Herlihy and Moss, 1993)
- Not yet implemented, but implementation suggested:
    - adding some specialized cache
    - modifying cache coherence protocols, which maintain consistency between caches and memory and do much of the task already

Software transactional memory

- Because of the lag of hardware implementation, development has focused on software implementations of the transaction idea, starting with the work of (Shavit and Touitou, 1995)
- **Idea:** Allow code to be enclosed by an atomic-block, with the guarantee that it executes atomically with respect to other atomic-blocks
- Currently mostly research prototypes
- The functional language Haskell offers some nice support

STM implementations

- Many implementation variants are possible
- Optimistic implementation approach:
    - atomic-block runs without locking, but writes instead to a transaction log
    - upon completion of the atomic-block, the log is validated and if found consistent the changes are committed
    - if validation fails, the block is reexecuted

STM: Discussion

- Advantages:
  - Simple and effective programming model
  - Transactions may be composed (Harris et al., 2005)
  - Increased concurrency, no waiting for resources
- Disadvantages:
  - Restrictions on operations within atomic-blocks: since roll-back must be available, no externally observable effects such as IO are allowed
  - Performance loss with respect to fine-grained locking: with current implementations, the overhead of transaction logs and consistency checking amortizes only with larger numbers of processing units

Linearizability

Sequential objects

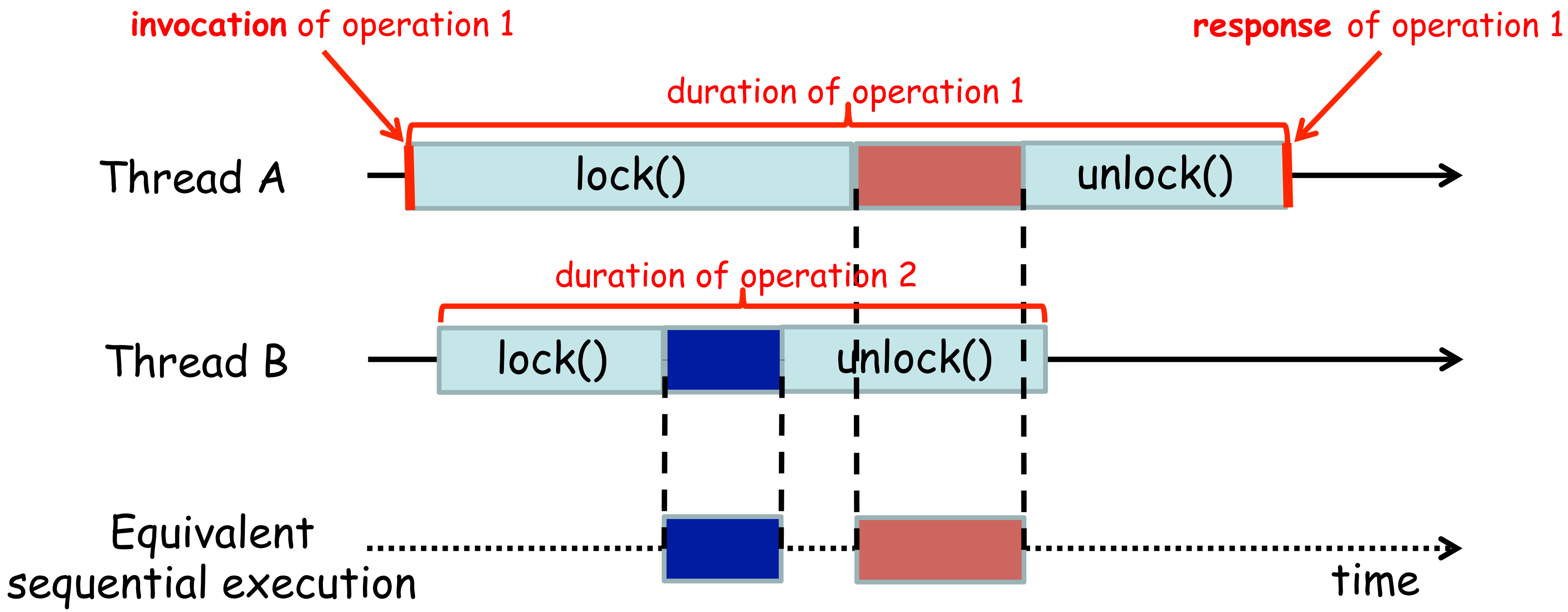
- We can understand the execution of a system as operations of a collection of (sequential) processes on data objects
- Each object has a type, describing its possible values and the operations for modifying them
- What does it mean for such objects to be correct?
- In a sequential system, where there is only one process, it is easy to specify the behavior of each operation:
    - Pre- and postconditions can be used
    - Intermediate states are never visible upon invocation of an operation

Concurrent objects

- In a concurrent system, operations can potentially be invoked on objects which are in intermediate states
- Hence it is more difficult to define correctness for concurrent objects
- *Linearizability* provides a correctness condition for concurrent objects

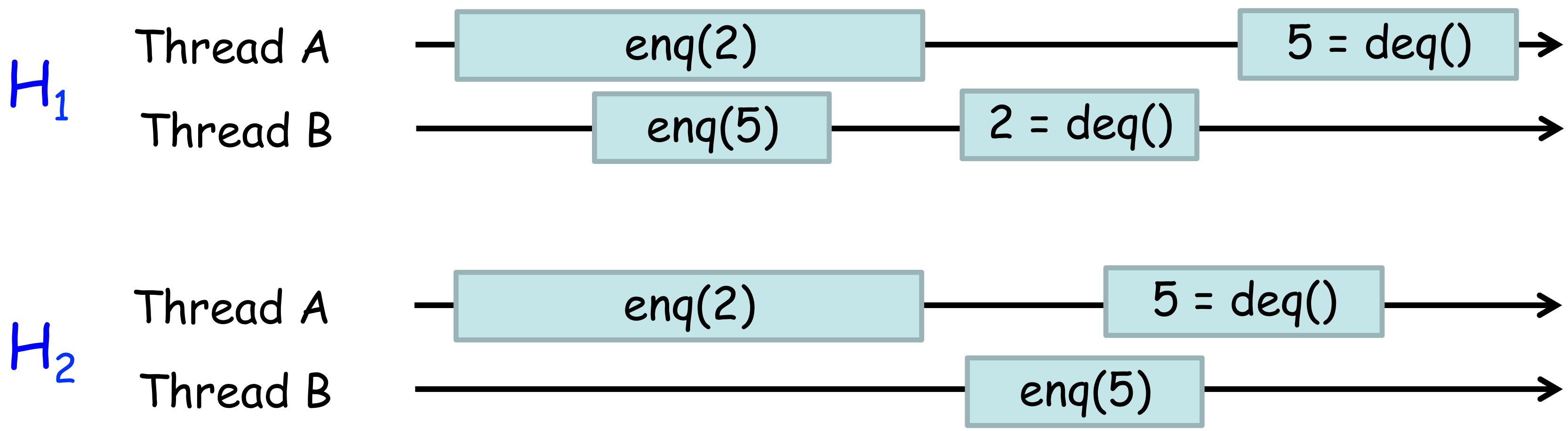
Linearizability: Intuition

- **Idea:** A concurrent object is linearizable if every concurrent execution of its operations can be shown to be "equivalent" to a sequential execution



Using the semantics of an object

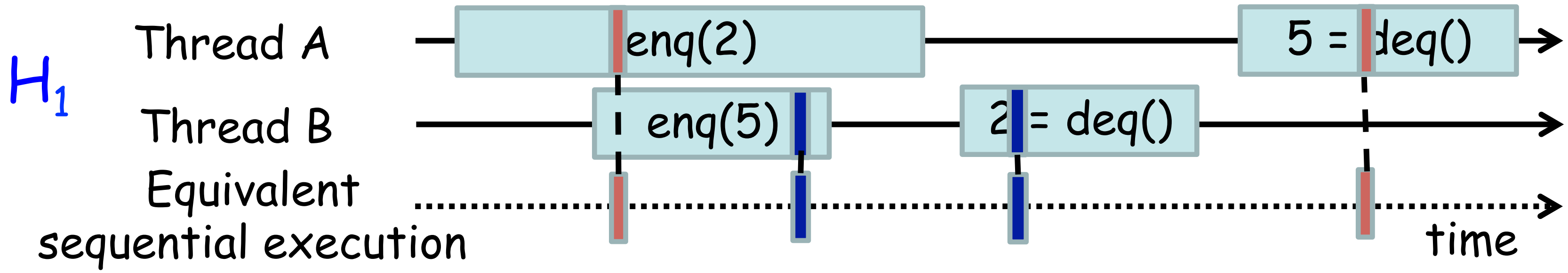
- Imagine an object implementing a FIFO queue with two operations enq(x) and deq().
- To decide whether a concurrent execution is correct, we have to use the object's intended semantics.



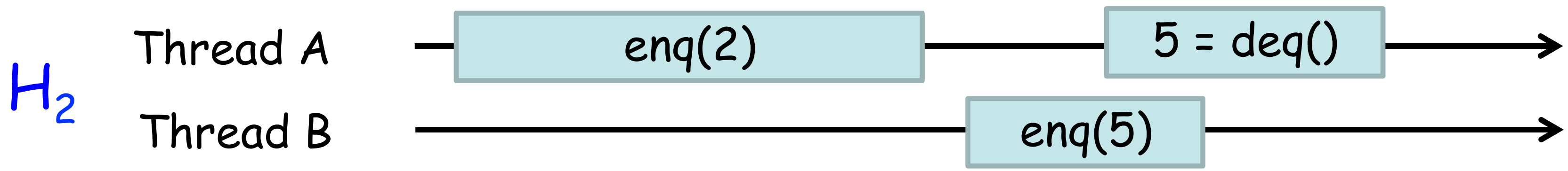
- History H_1 is acceptable, it agrees with the semantics.
- History H_2 is not acceptable: enq(2) was completed before enq(5) started, so 5 couldn't have been dequeued earlier.

Observation

- **Observation:** Each operation should appear to "take effect" instantaneously at some moment between its invocation and response



- For the second history, no equivalent sequential execution can be found:



Histories

- A call of an operation is split into two events:
  - Invocation: [A q.op(a_1, ..., a_n)]
  - Response: [A q:Ok(r)]
- **Notation:**
  - A: thread ID
  - q: object
  - op(a_1, ..., a_n): invocation of call with arguments
  - Ok(r): successfull response of call with result r
- A *history* is a sequence of invocation and response events
- **Example:** History H_1 can be written as

  [A q.enq(2)], [B q.enq(5)], [B q:Ok], [A q:Ok],
  [B q.deq()], [B q:Ok(2)], [A q.deq()], [A q:Ok(5)]

Projections

- We can define projections on objects and on threads
- Assume we have a history

  H = [A q1.enq(2)], [B q2.enq(5)], [B q2:Ok], [A q1:Ok],
  [B q1.deq()], [B q1:Ok(2)], [A q2.deq()], [A q2:Ok(5)]

- *Object projection*:

  H|q1 = [A q1.enq(2)], [A q1:Ok], [B q1.deq()], [B q1:Ok(2)]

- *Thread projection*:

  H|A = [A q1.enq(2)], [A q1:Ok], [A q2.deq()], [A q2:Ok(5)]

Sequential histories

- A response *matches* an invocation if their object and thread names agree.
- A history is *sequential* if it starts with an invocation and each invocation, except possibly the last, is immediately followed by a matching response

H = [A q.enq(2)], [A q:Ok], [B q.enq(5)], [B q:Ok], ...

- A sequential history is *legal* if it agrees with the sequential specification of each object.

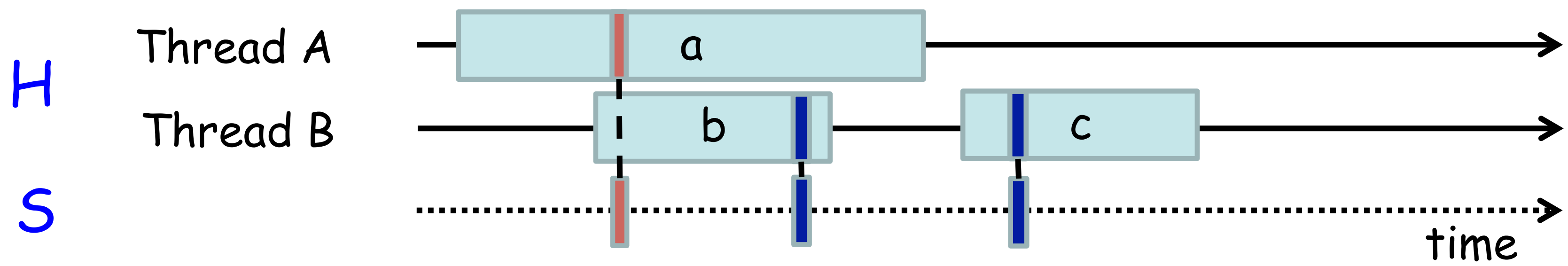
More definitions

- A call op_1 *precedes* another call op_2 (op_1 -> op_2) if op_1's response event occurs before op_2's invocation event
- We write $->_H$ for the precedence relation induced by H
- Example: q.enq(2) -> q.enq(5) in history H
- An invocation is *pending* if it has no matching response
- A history is *complete* if it does not have pending responses
- complete(H) is the subhistory of H with all pending invocations removed

Linearizability

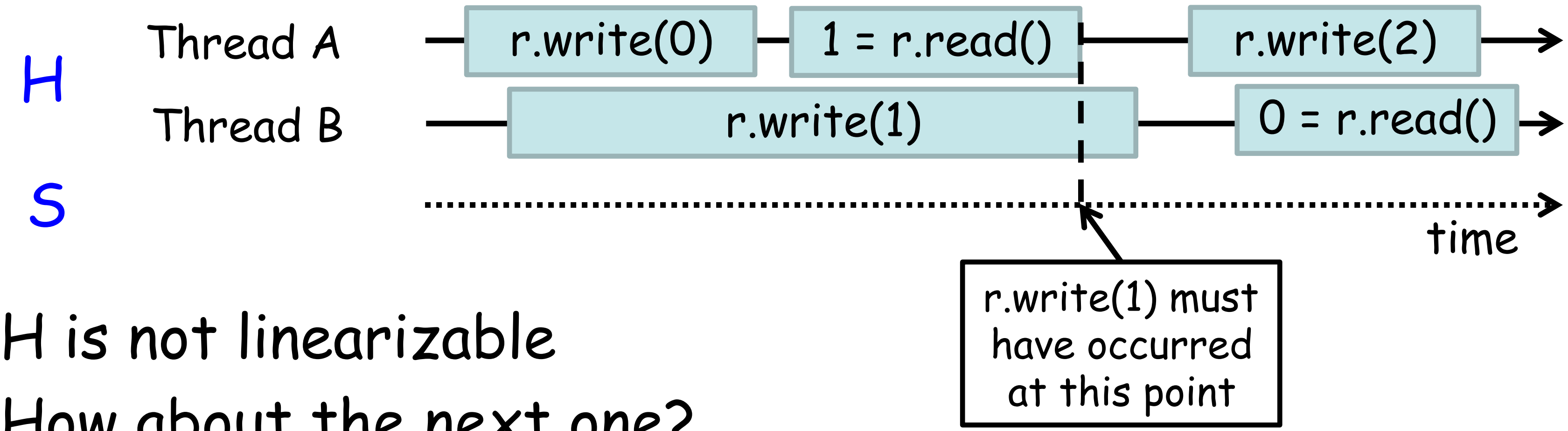
- Two histories H and G are *equivalent* if H|A = G|A for all threads A
- A history H is *linearizable* if it can be extended by appending zero or more response events to a history G such that:
  - complete(G) is equivalent to a legal sequential history S
  - $\to_H \subseteq \to_S$
- **Example:**

$\to_H$ = {a -> c, b -> c}
$\to_S$ = {a -> b, a -> c, b -> c}

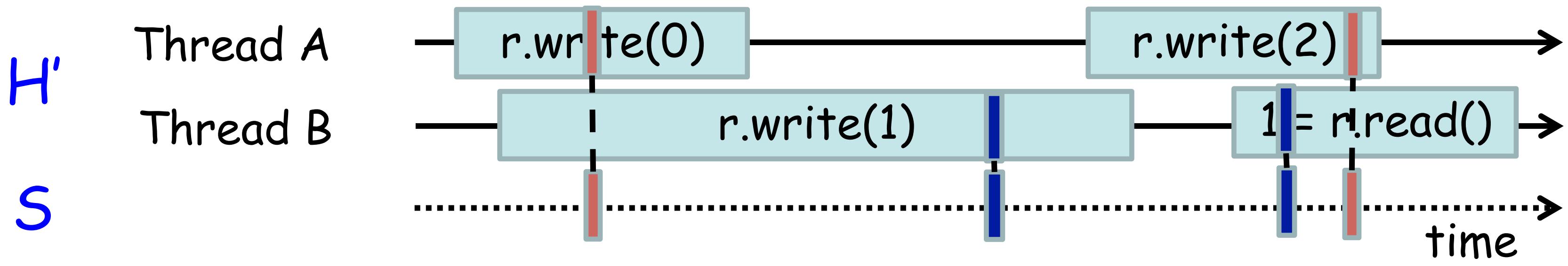


Example: Linearizability

- Read/write registers:



- H is not linearizable
- How about the next one?

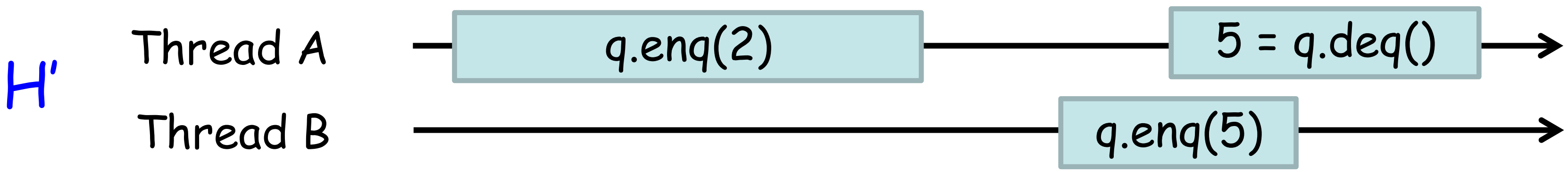


- H' is linearizable

Sequential consistency

- A history H is *sequentially consistent* if it can be extended by appending zero or more response events to a history G such that:
    - complete(G) is equivalent to a legal sequential history S
- **Idea:** Calls from a particular thread appear to take place in program order
- H is not sequentially consistent:

- H' is sequentially consistent but not linearizable:



Compositionality

- Every linearizable history is also sequentially consistent.
- Linearizability is *compositional*: H is linearizable if and only if for each object H|x is linearizable.
- Sequential consistency on the other hand is not compositional.