Shared Memory Synchronization Rides Again: Lock Freedom

cs378h

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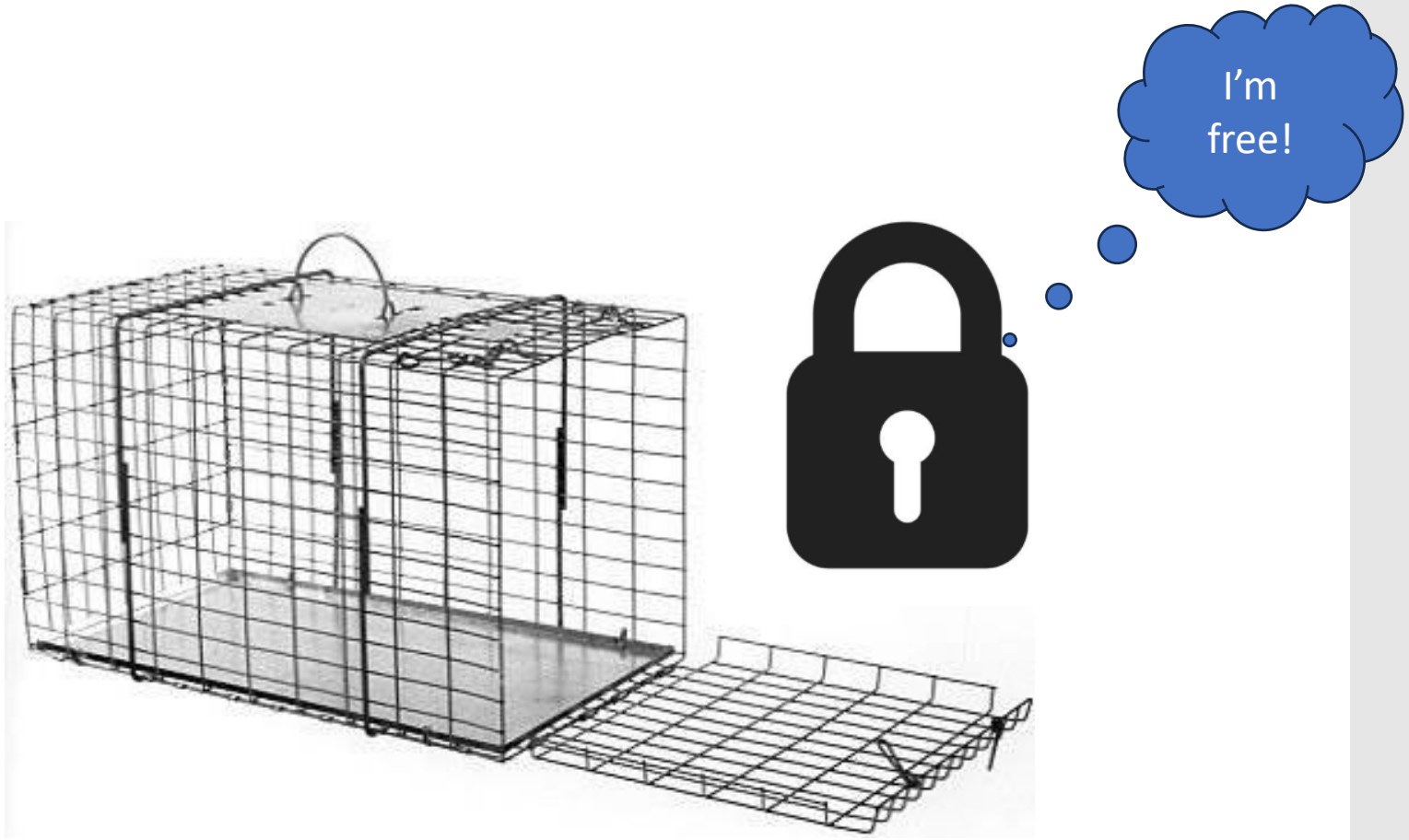

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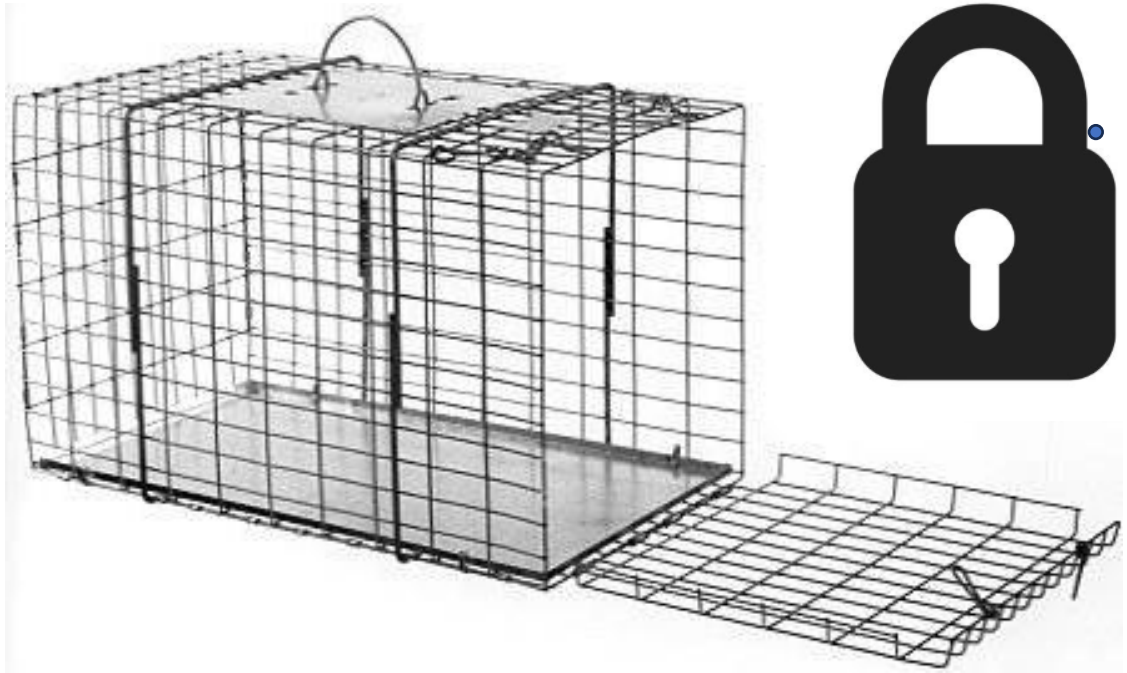

Today

Questions?

Administrivia

- Faux Quiz

Agenda:

- Lock Freedom

Faux Quiz Questions: 5 min, pick any 2

- What is obstruction freedom, wait freedom, lock freedom?
- How can one compose lock free data structures?
- What is the difference between linearizability and strong consistency? Between linearizability and serializability?
- What is the ABA problem? Give an example.
- How do lock-free data structures deal with the “inconsistent view” problem?

Non-Blocking Synchronization

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Locks: a litany of problems

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- Deadlock

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- Priority inversion

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Solution: don’t use locks

Non-Blocking Synchronization

Locks: a litany of problems

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Lock-free programming

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- Subset of a broader class: ***Non-blocking Synchronization***

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- Built on atomic instructions like CAS + clever algorithmic tricks
- Lock-free *algorithms* are hard, so
- General approach: encapsulate lock-free algorithms in data structures
  - Queue, list, hash-table, skip list, etc.
  - New LF data structure → research result

Basic List Append

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{
  int data;
  struct Node *next;
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void append(Node** head_ref, int new_data) {
    Node* new_node = mknode(new_data, head_ref);
    if (*head_ref == NULL) {
        *head_ref = new_node;
        return;
    }
    while (last->next != NULL)
        last = last->next;
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}
```

- Is this thread safe?
- What can go wrong?

Example: List Append

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   int data;
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};
```

```
void append(Node** head_ref, int new_data) {
    Node* new_node = mknode(new_data, head_ref);
    lock();
    if (*head_ref == NULL) {
       *head_ref = new_node;
    } else {
       while (last->next != NULL)
          last = last->next;
       last->next = new_node;
    }
    unlock();
}
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- What property do the locks enforce?

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- Can we ensure consistent view (invariants hold) sans mutual exclusion?

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- What property do the locks enforce?
- What does the mutual exclusion ensure?
- Can we ensure consistent view (invariants hold) sans mutual exclusion?
- Key insight: allow inconsistent view and fix it up algorithmically

Example: List Append

```
void append(Node** head_ref, int new_data) {
    Node* new_node = mknode(new_data);
    new_node->next = NULL;
    while(TRUE) {
        Node * last = *head_ref;
        if(last == NULL) {
            if(cas(head_ref, new_node, NULL))
                break;
        }
        while(last->next != NULL)
            last = last->next;
        if(cas(&last->next, new_node, NULL))
            break;
    }
}
```

```
struct Node
    data;
uct Node *next;
```

e?

nsure?

- Can we ensure consistent view (invariants hold) sans mutual exclusion?
- Key insight: allow inconsistent view and fix it up algorithmically

Example: SP-SC Queue

```
next(x):
    if(x == Q_size-1) return 0;
    else return x+1;

Q_get(data):
    t = Q_tail;
    while(t == Q_head)
      ;
    data = Q_buf[t];
    Q_tail = next(t);
```

```
Q_put(data):
    h = Q_head;
    while(next(h) == Q_tail)
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    Q_buf[h] = data;
    Q_head = next(h);
```

- Single-producer single-consumer
- Why/when does this work?

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- Single-producer single-consumer
- Why/when does this work?

1. Q_head is last write in Q_put, so Q_get never gets “ahead”.
2. *single* p,c only (as advertised)
3. Requires fence before setting Q head
4. Devil in the details of “wait”
5. No lock → “optimistic”

Lock-Free Stack

```
struct Node
{
  int data;
  struct Node *next;
};
```

```
void push(int t) {
    Node* node = new Node(t);
    do {
        node->next = head;
    } while (!cas(&head, node, node->next));
}

bool pop(int& t) {
   Node* current = head;
   while(current) {
       if(cas(&head, current->next, current)) {
           t = current->data;
           return true;
       }
       current = head;
       }
   return false;
}
```

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           return true;
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- Why does is it work?

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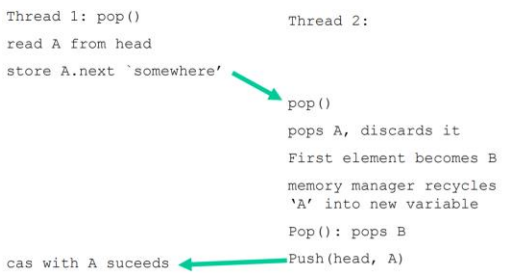
- Why does is it work?
- Does it enforce all invariants?

Lock-Free Stack: ABA Problem



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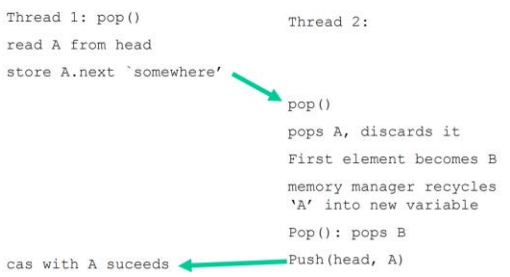

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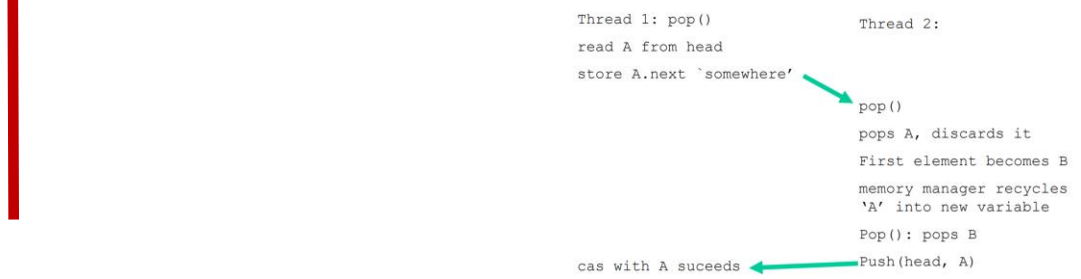

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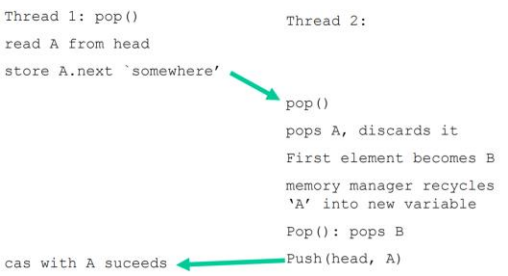

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Node* pop() {
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    while(current) {
```

```
Node * node = pop();
delete node;
node = new Node(blah_blah);
push(node);
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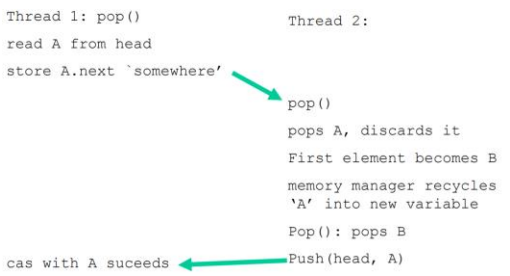

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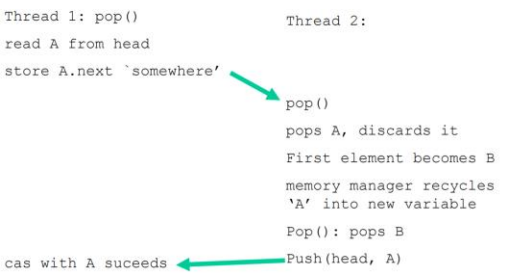

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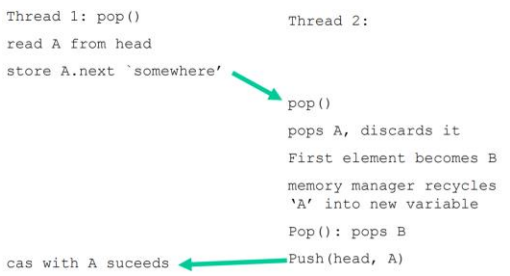

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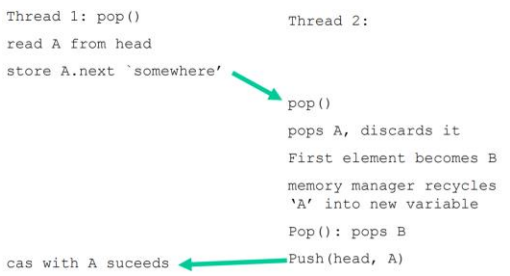


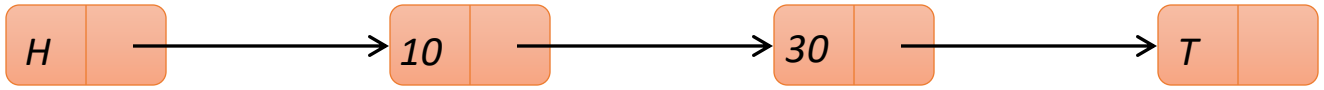
ABA Problem

- Thread 1 observes shared variable → ‘A’
- Thread 1 calculates using that value
- Thread 2 changes variable to B
  - if Thread 1 wakes up now and tries to CAS, CAS fails and Thread 1 retries
- Instead, Thread 2 changes variable back to A!
  - CAS succeeds despite mutated state
  - Very bad if the variables are pointers

- Keep update count → DCAS
- Avoid re-using memory
- Multi-CAS support → HTM

Correctness: Searching a sorted list

- find(20):



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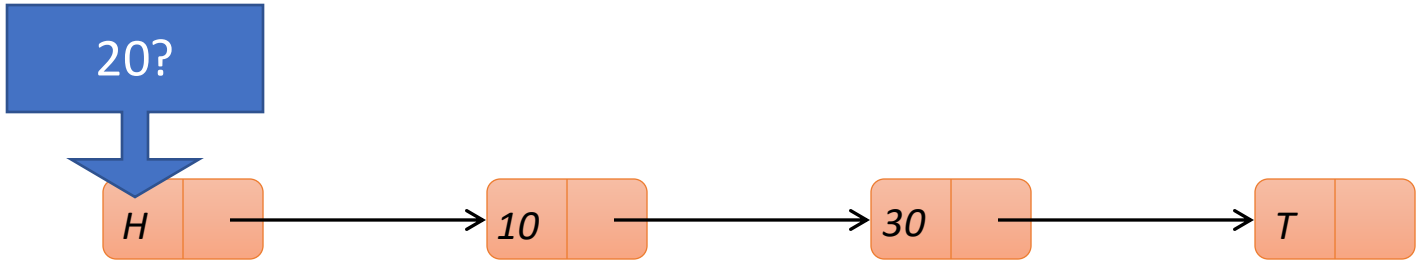

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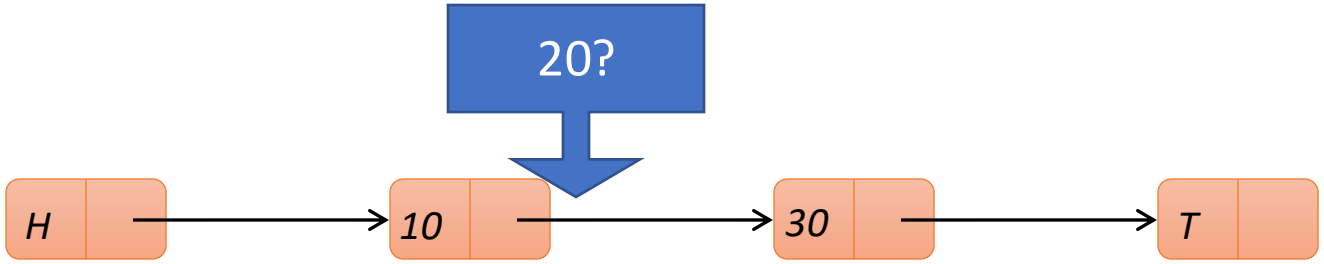

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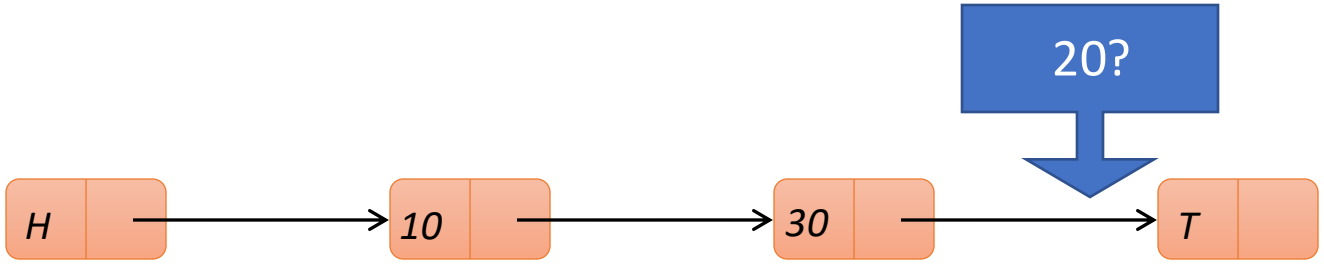
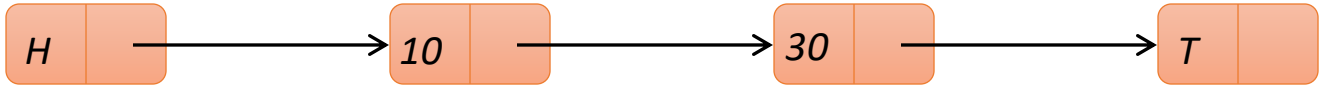


find(20) -> false

Inserting an item with CAS

- insert(20):



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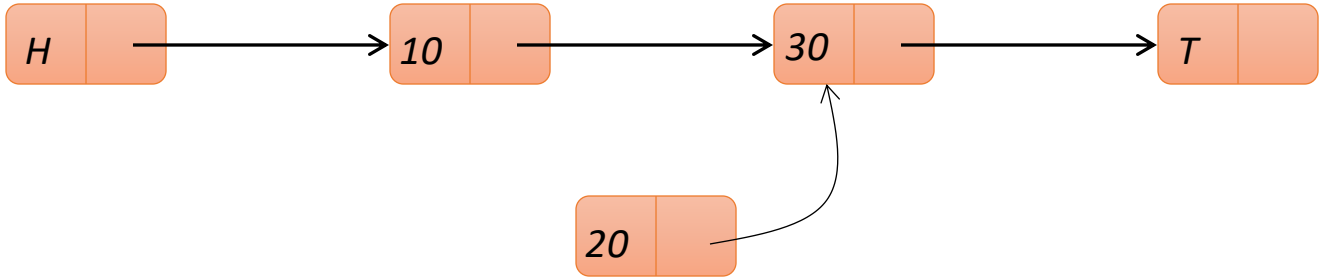

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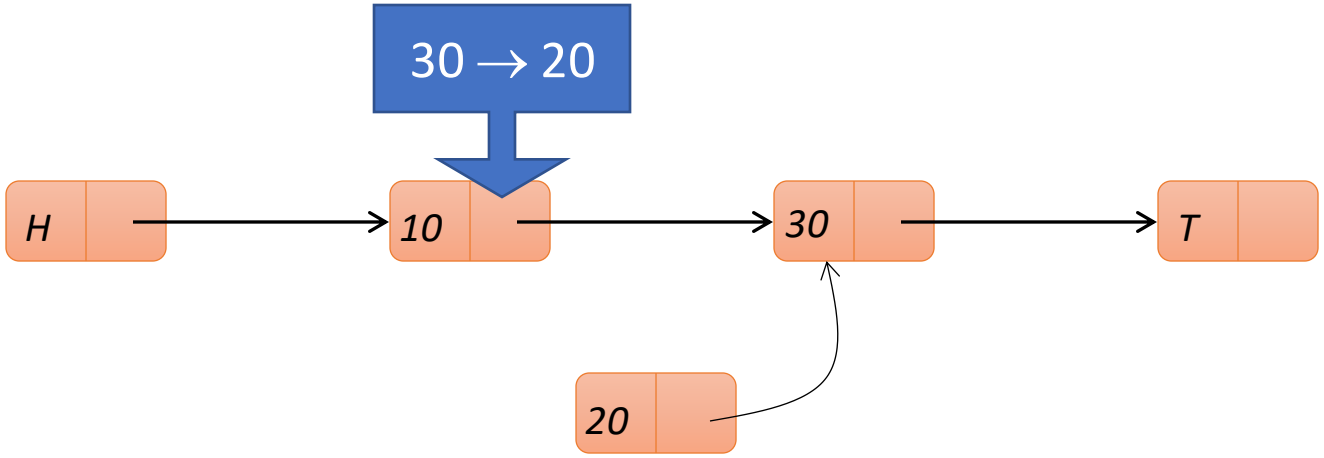

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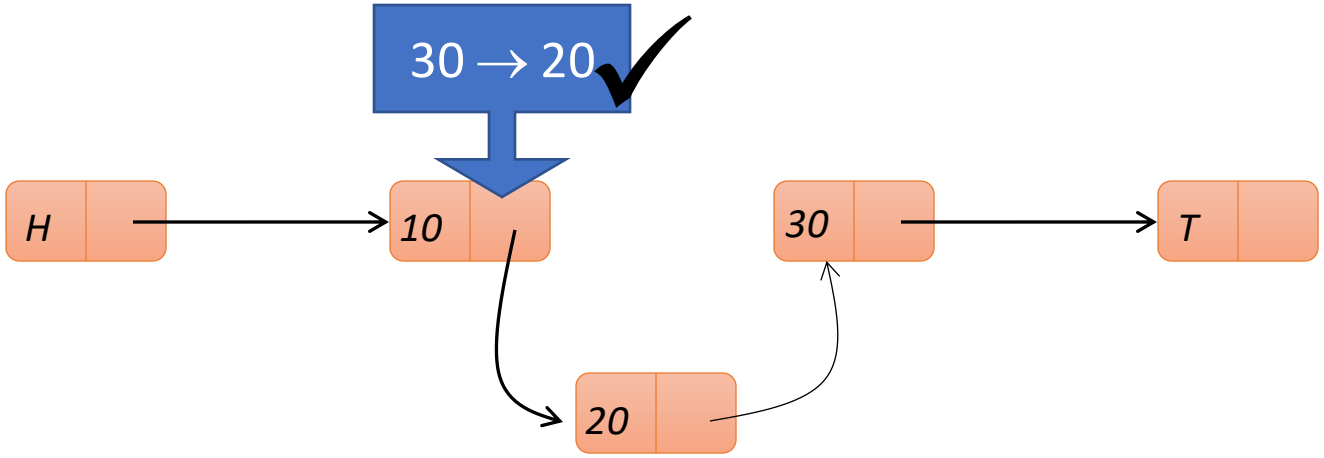
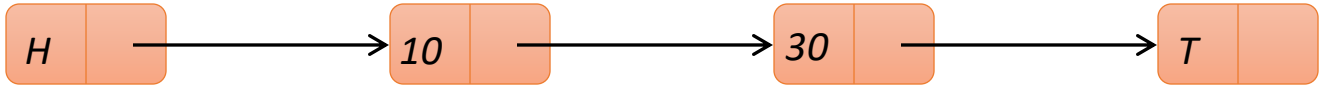


insert(20) -> true

Inserting an item with CAS



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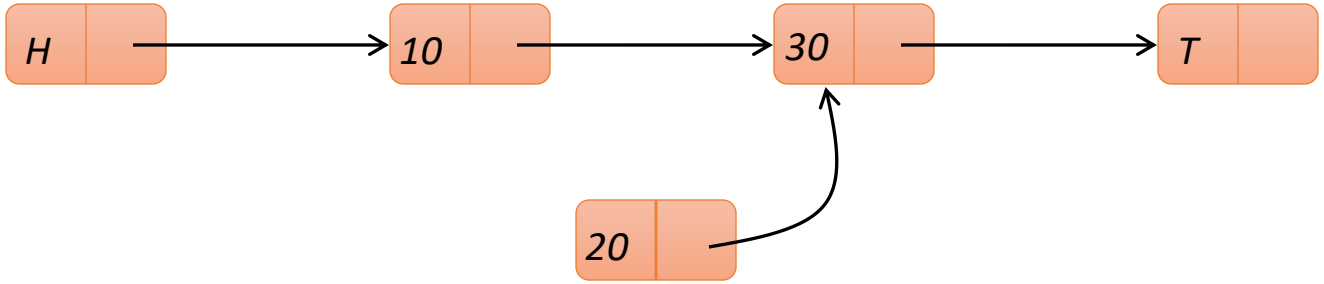

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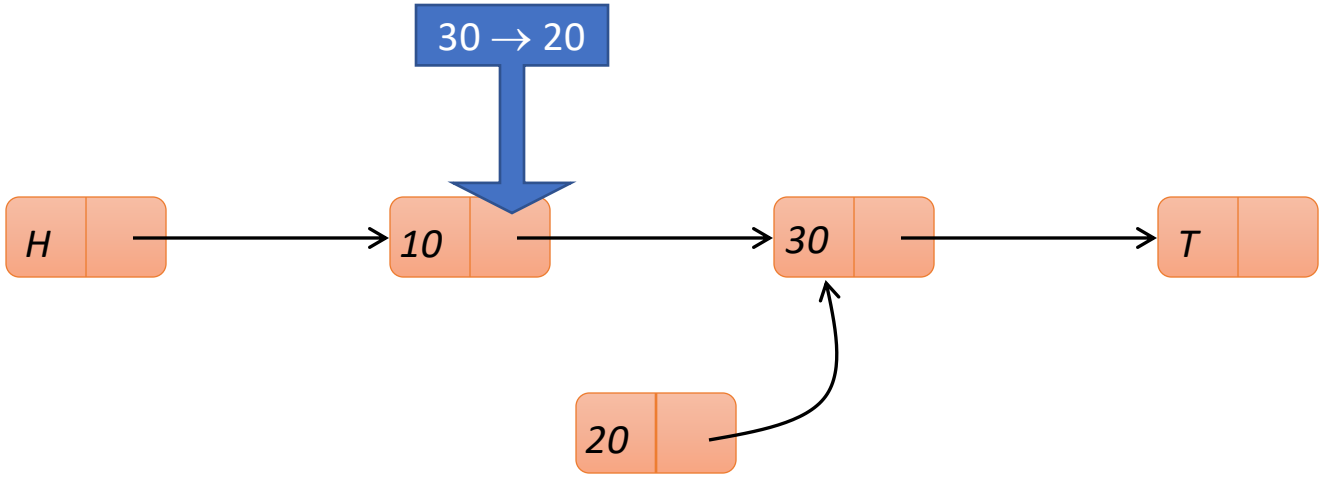
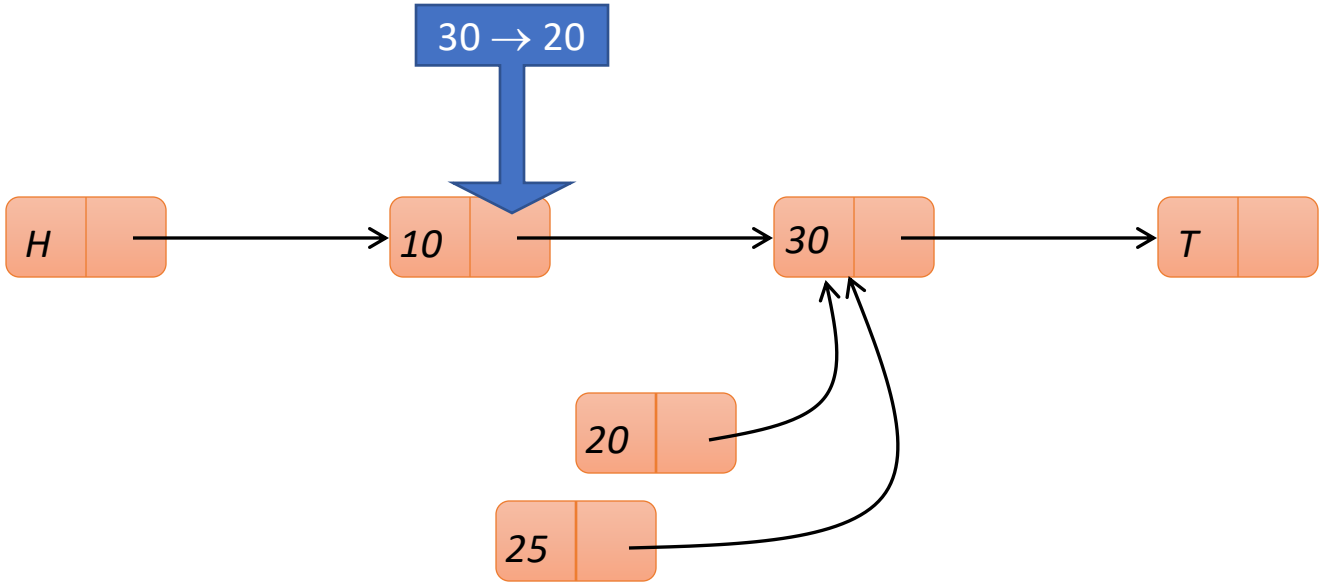


Inserting an item with CAS

- insert(20):
- insert(25):



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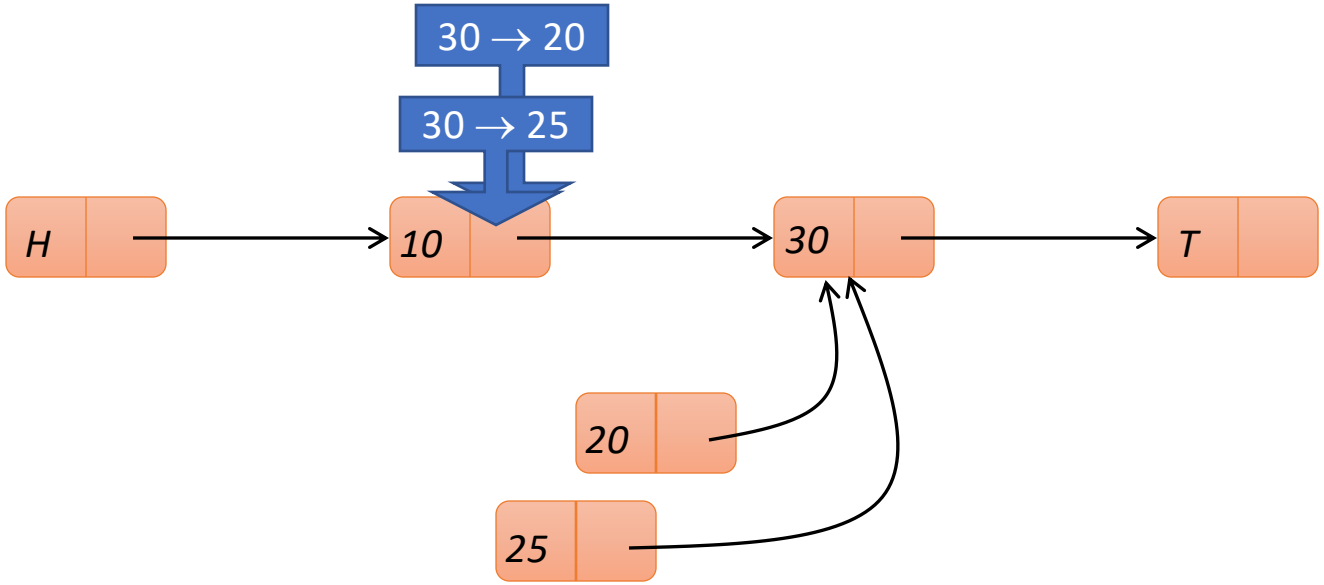

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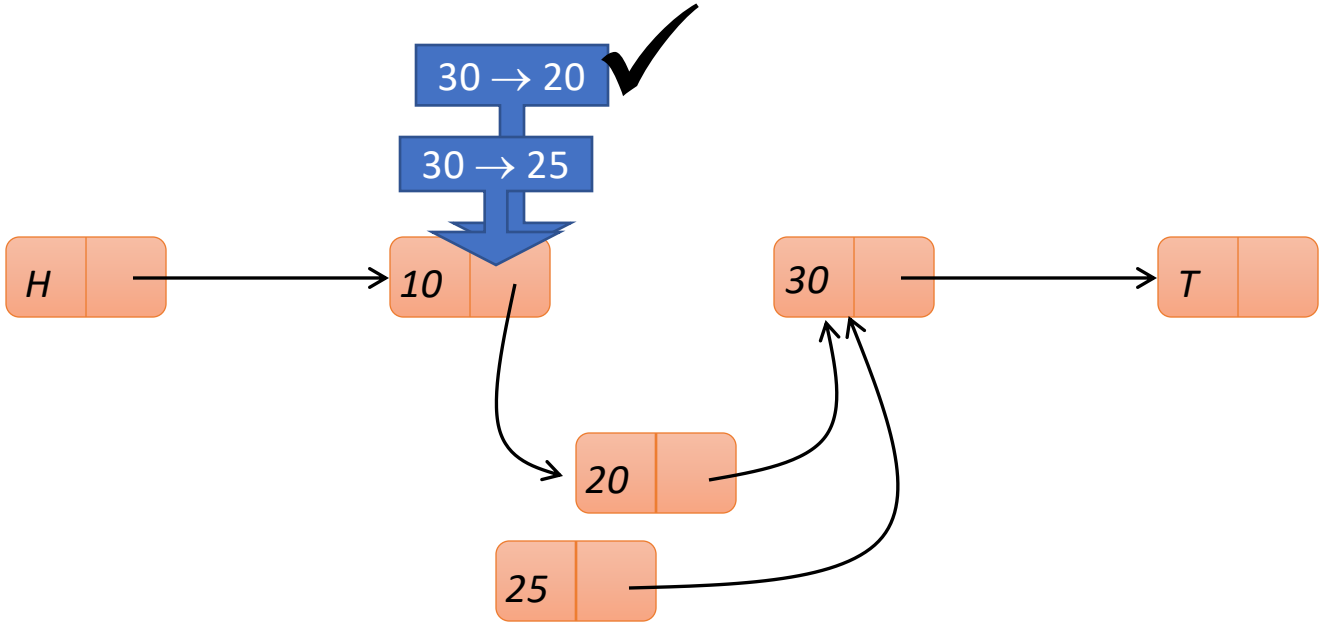

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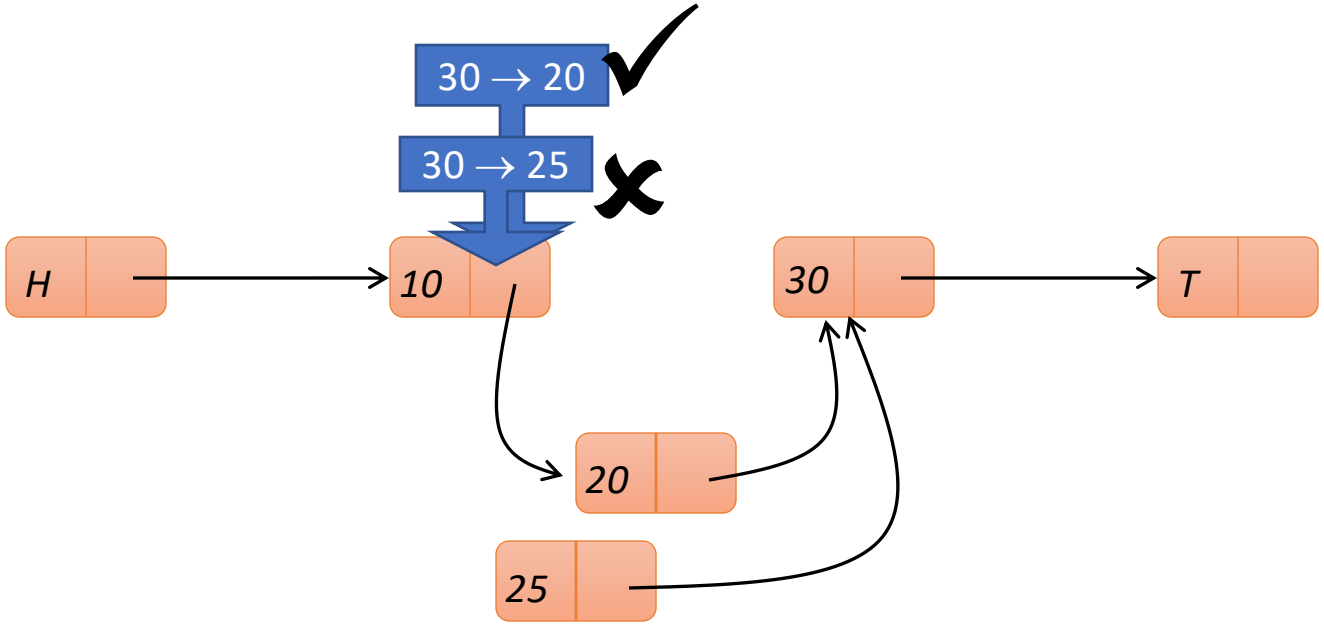

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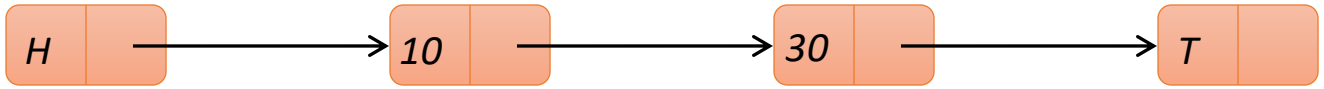

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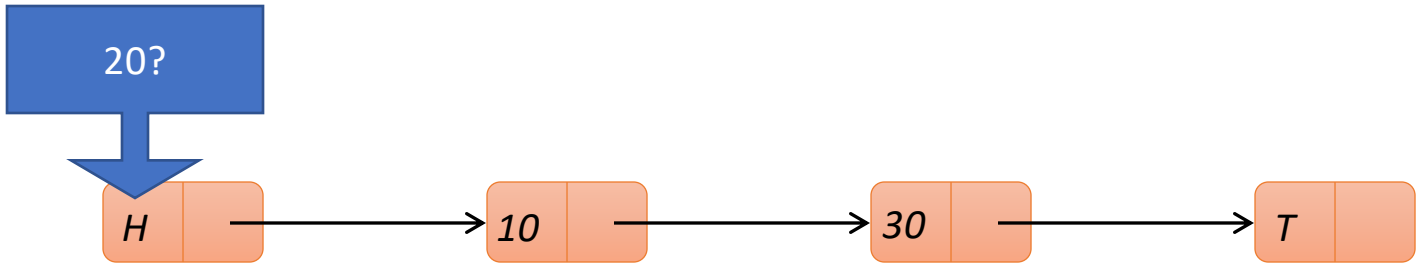

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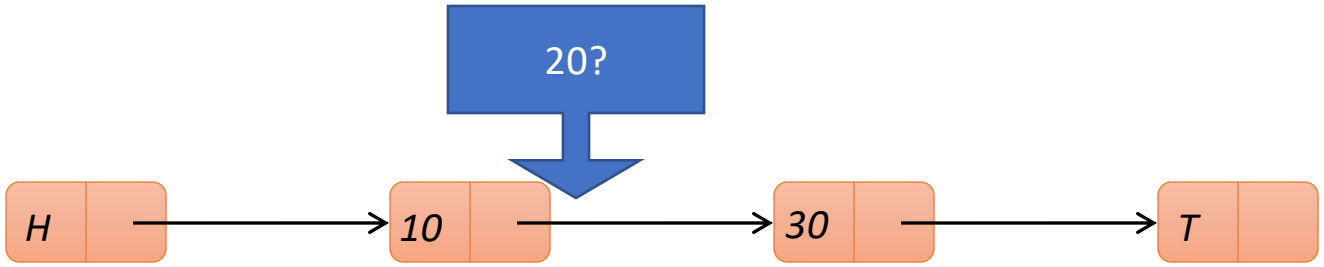

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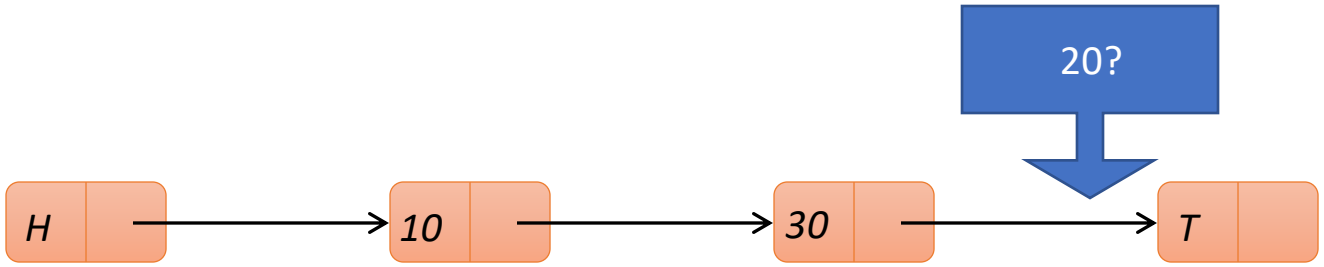

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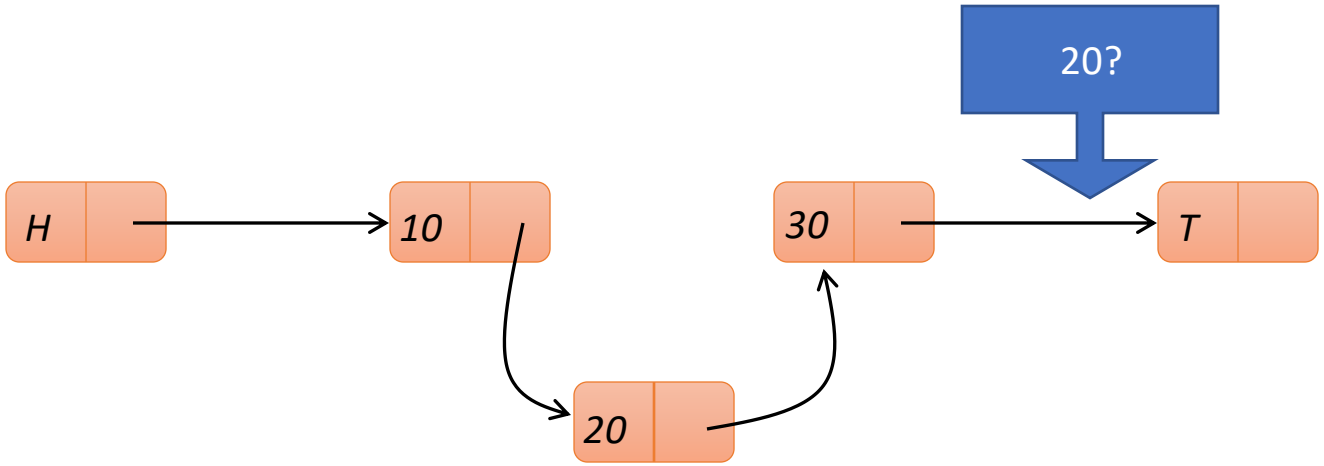

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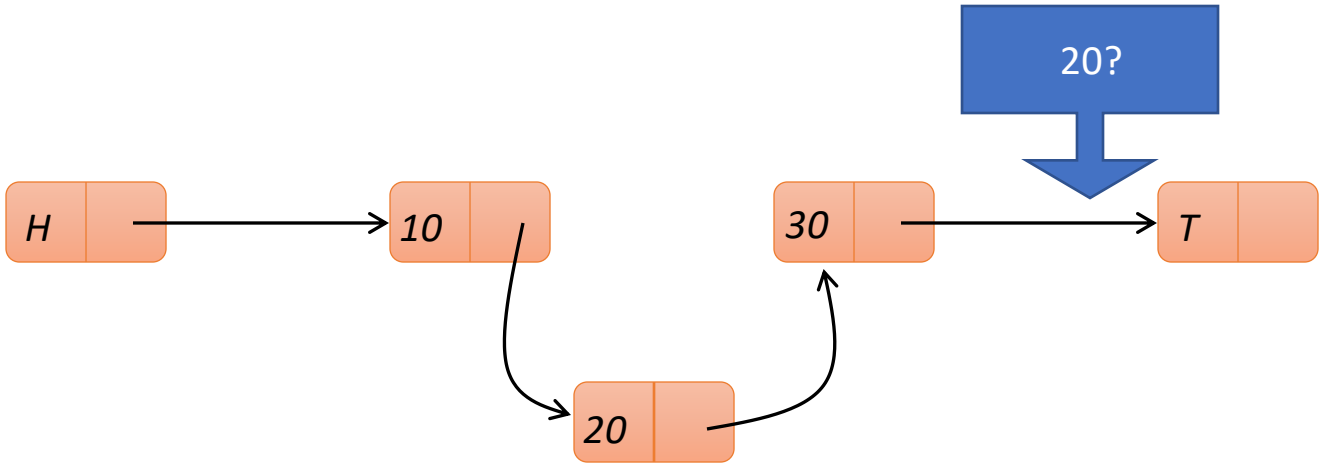

Searching and inserting together

- find(20) -> false

This thread saw 20 was not in the set...

- insert(20) -> true

...but this thread succeeded in putting it in!

- Is this a correct implementation?
- Should the programmer be surprised if this happens?
- What about more complicated mixes of operations?

Correctness criteria

Informally:

Look at the behavior of the data structure

- what operations are called on it
- what their results are

If behavior is indistinguishable from atomic calls to a sequential implementation then the concurrent implementation is correct.

Sequential history

- No overlapping invocations

Sequential history

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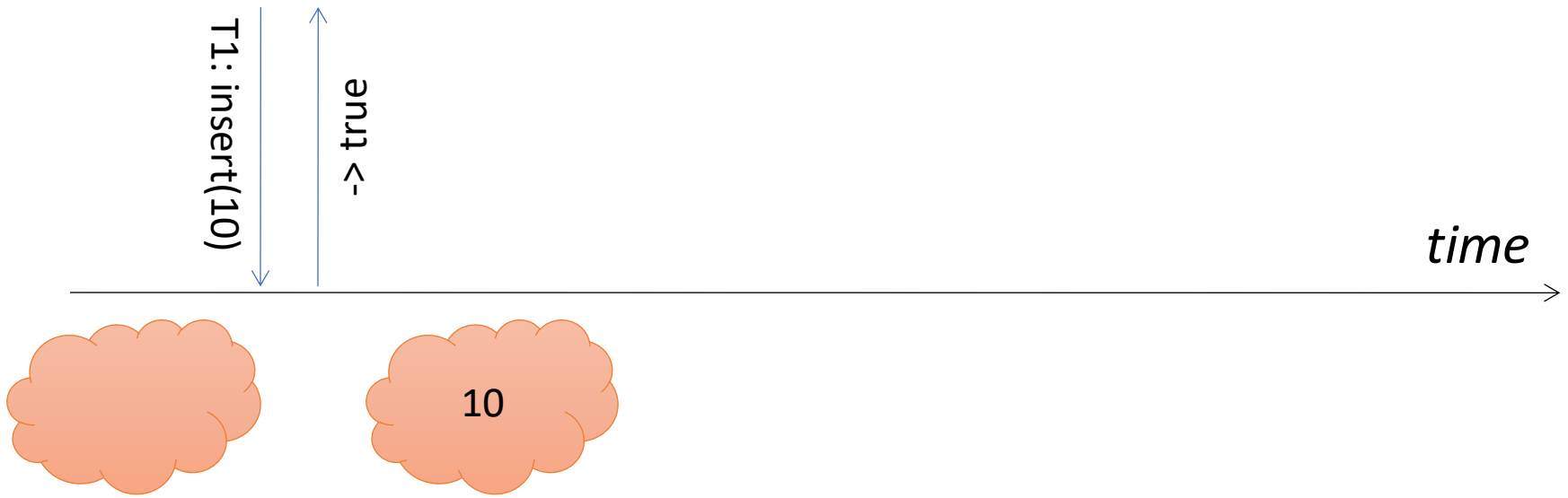

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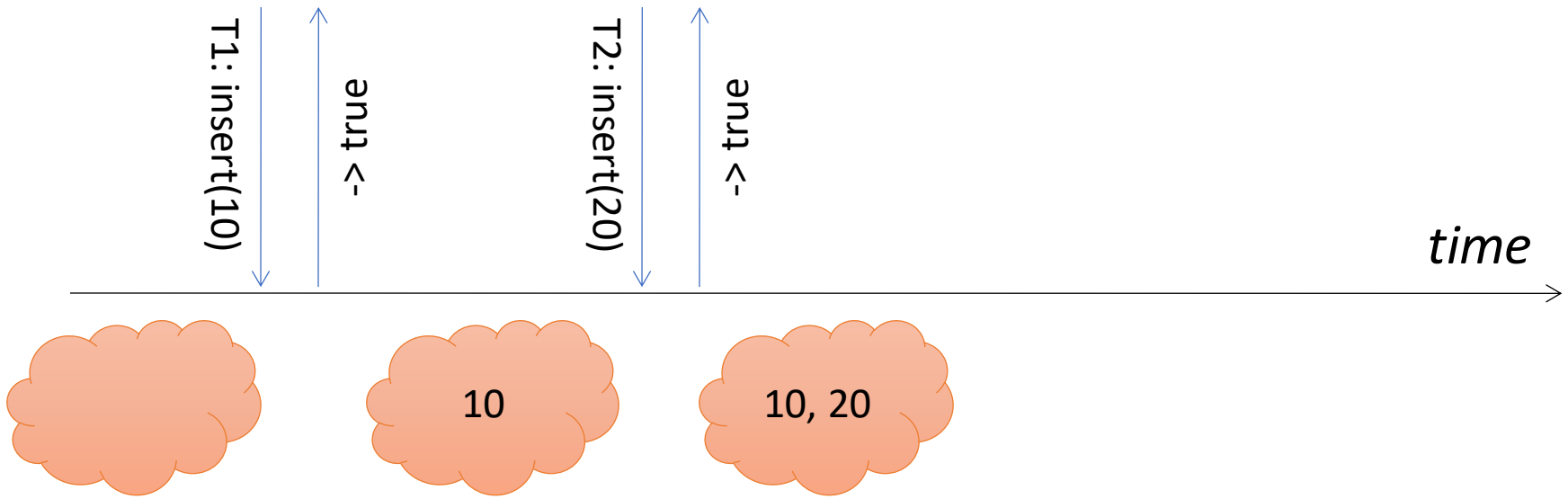

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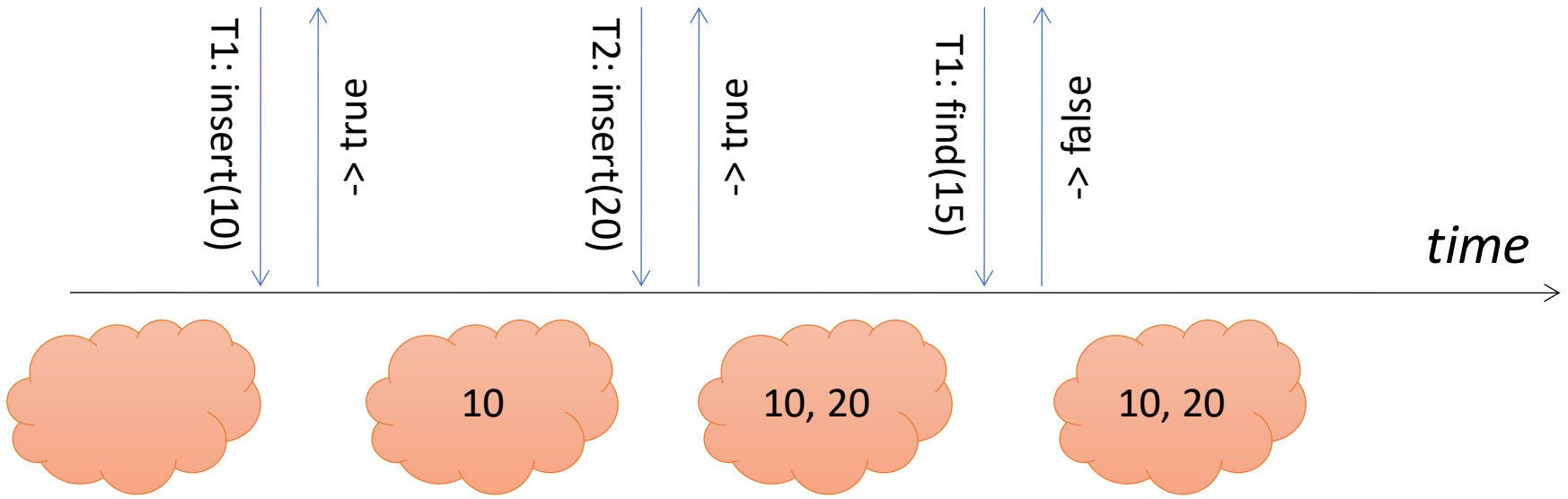

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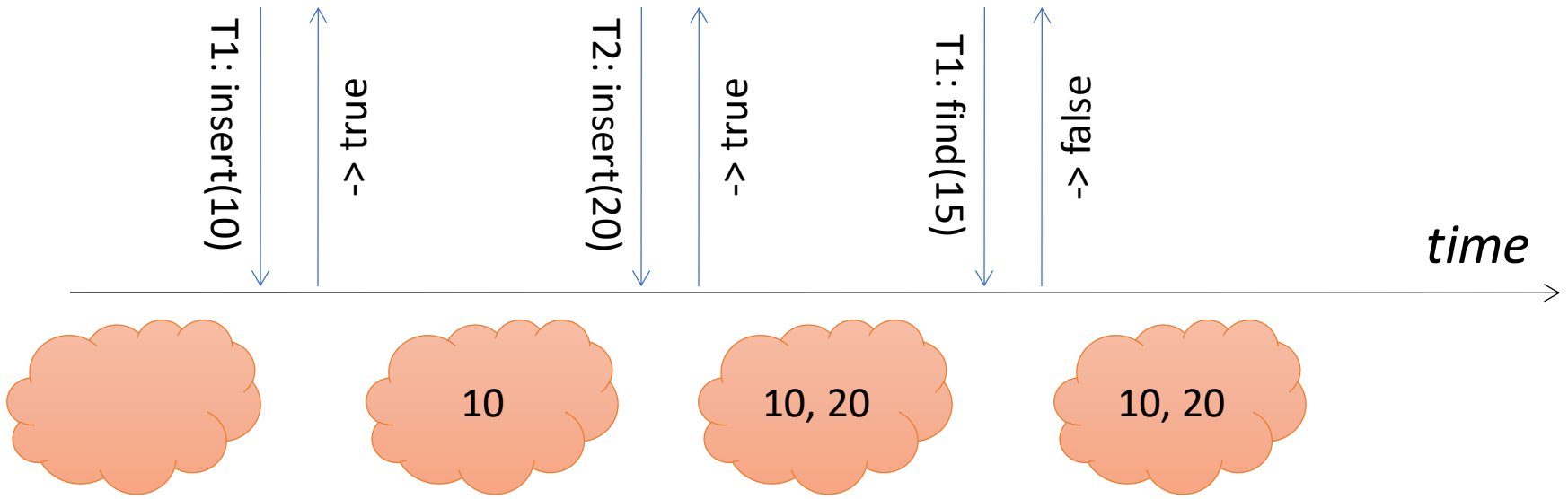
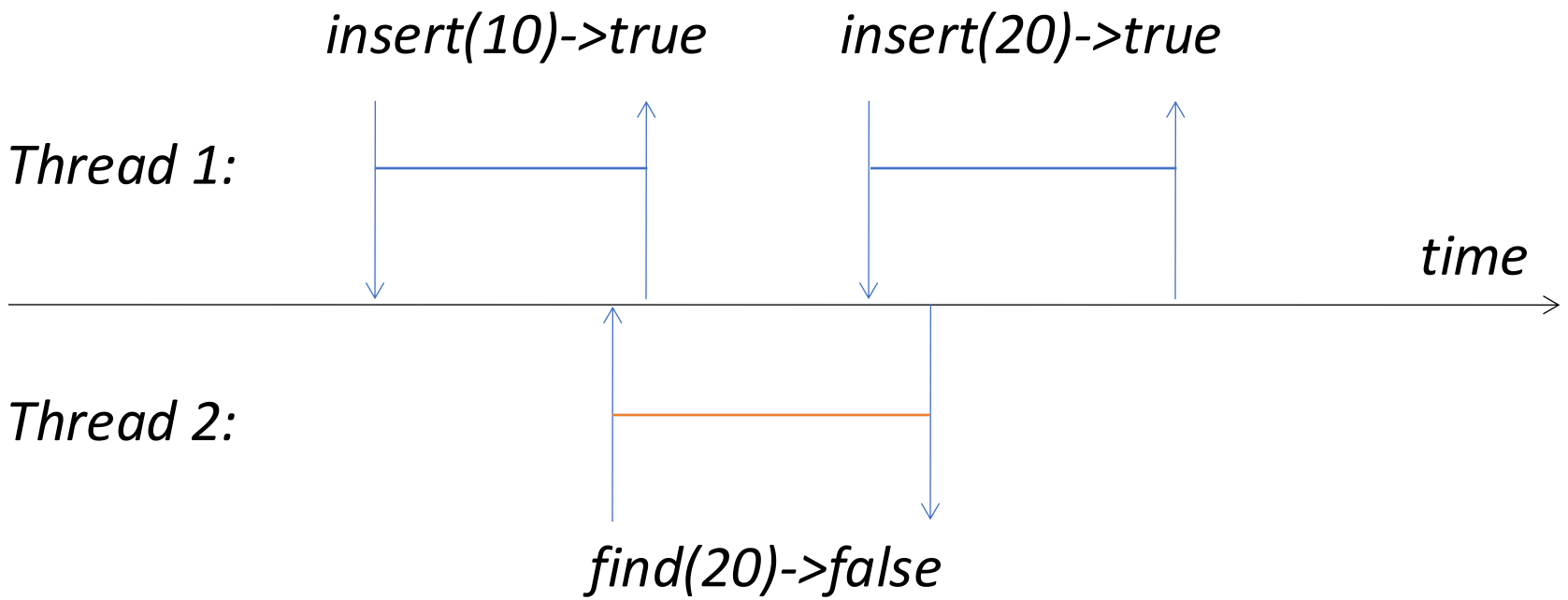


Linearizability: concurrent behaviour should be similar

- even when threads can see intermediate state
- Recall: mutual exclusion precludes overlap

Concurrent history

Allow *overlapping* invocations



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- Is there a correct sequential history:
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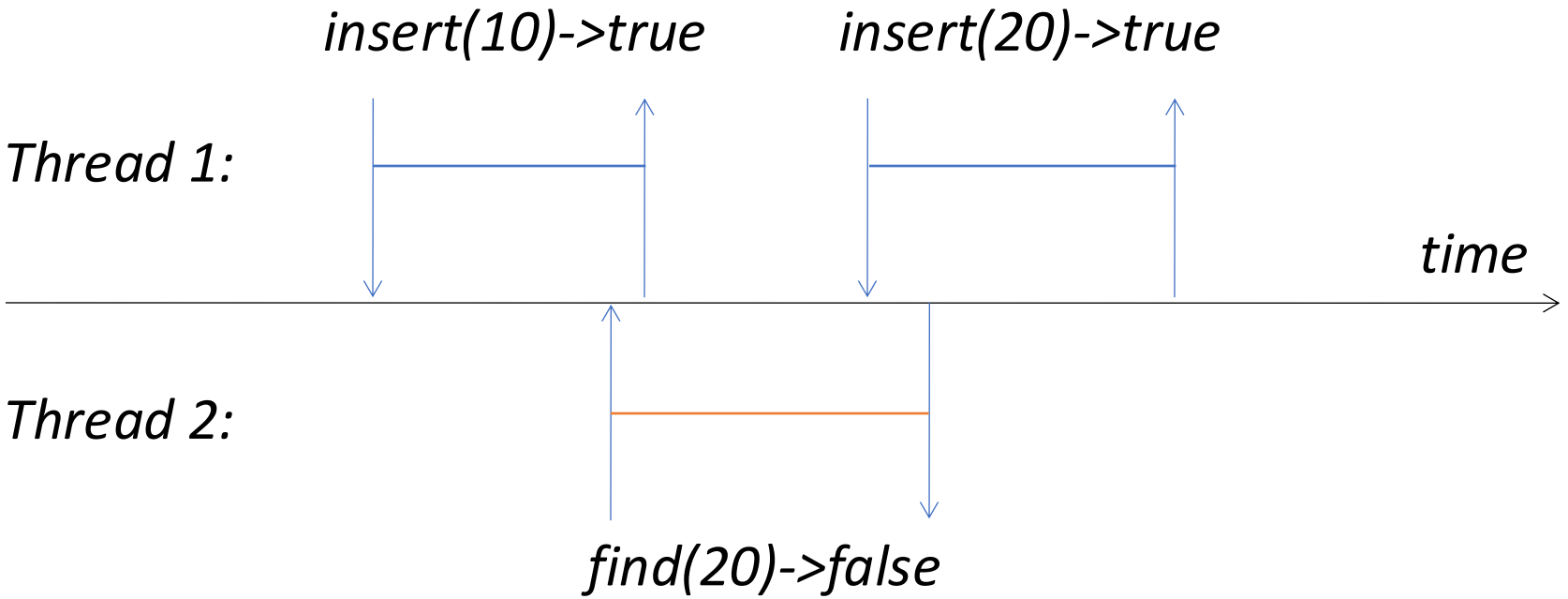

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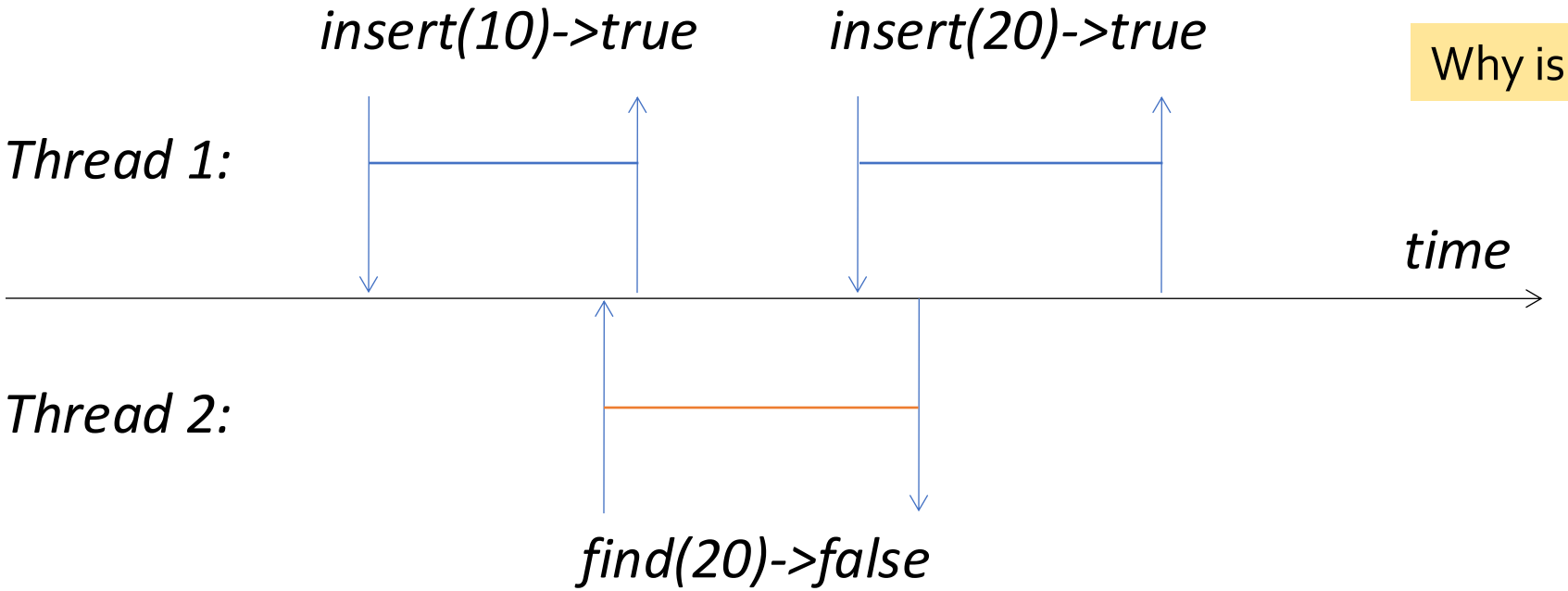

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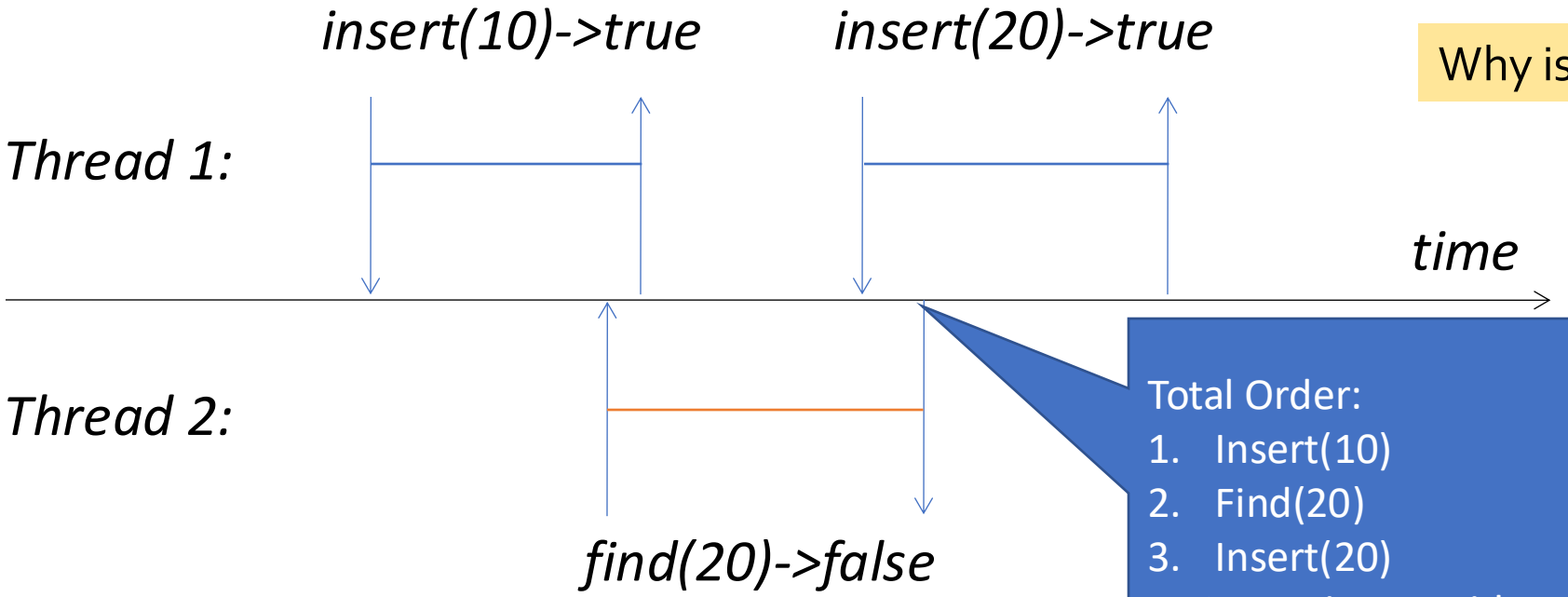


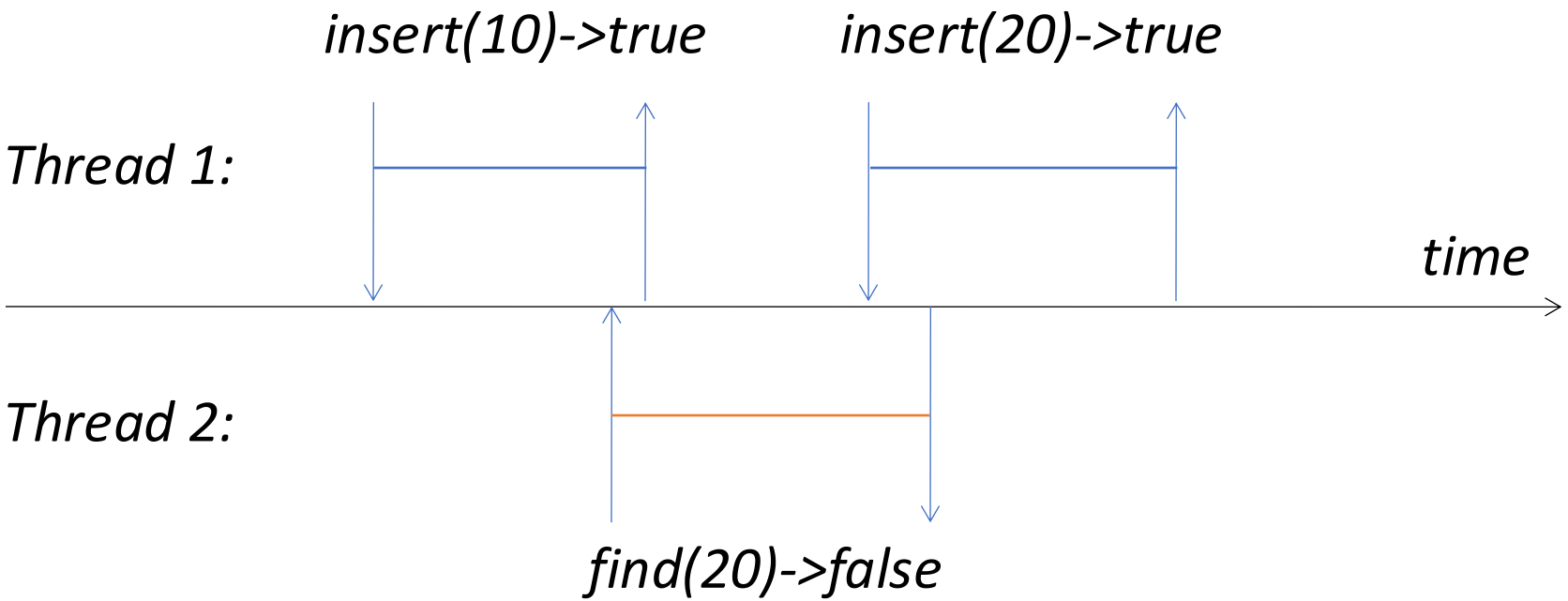
Why is this one OK?

Total Order:

1. Insert(10)
2. Find(20)
3. Insert(20)

- Is consistent with real-time order
- 2, 3 overlap, but return order OK

Example: linearizable



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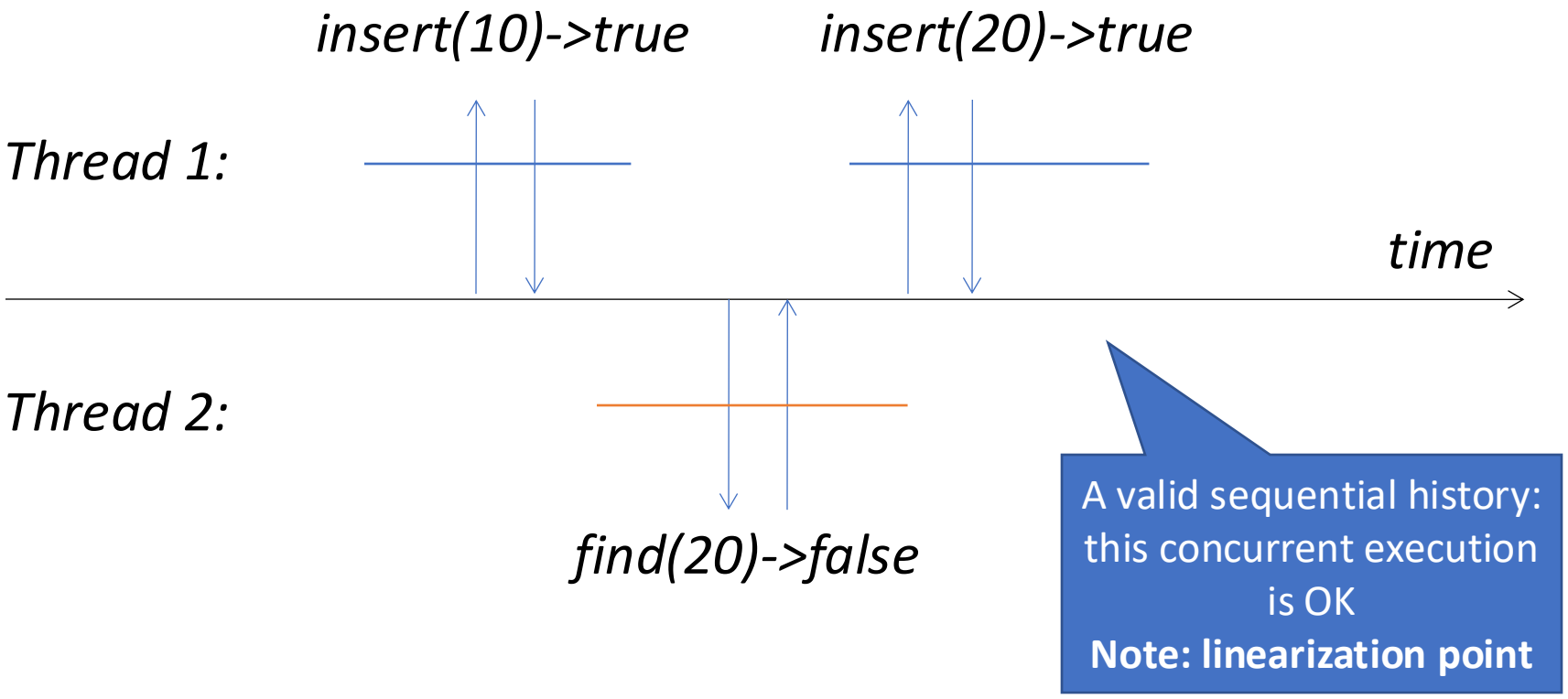

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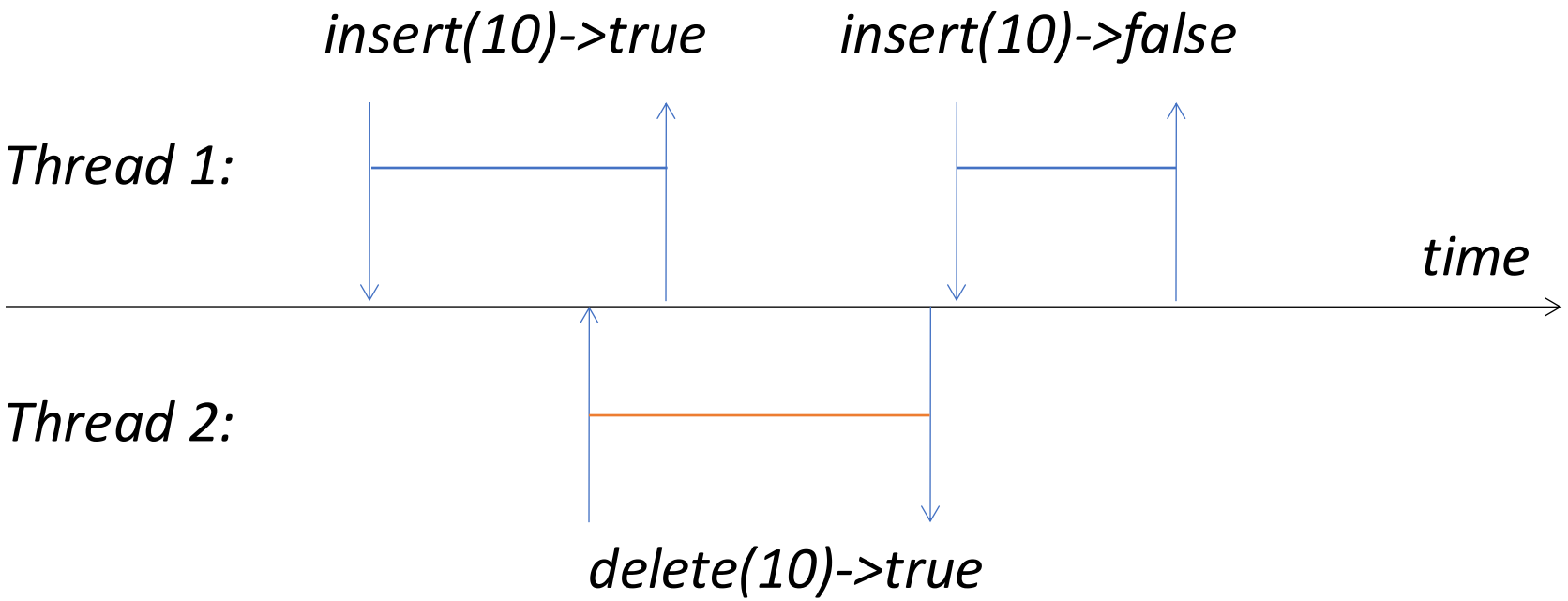

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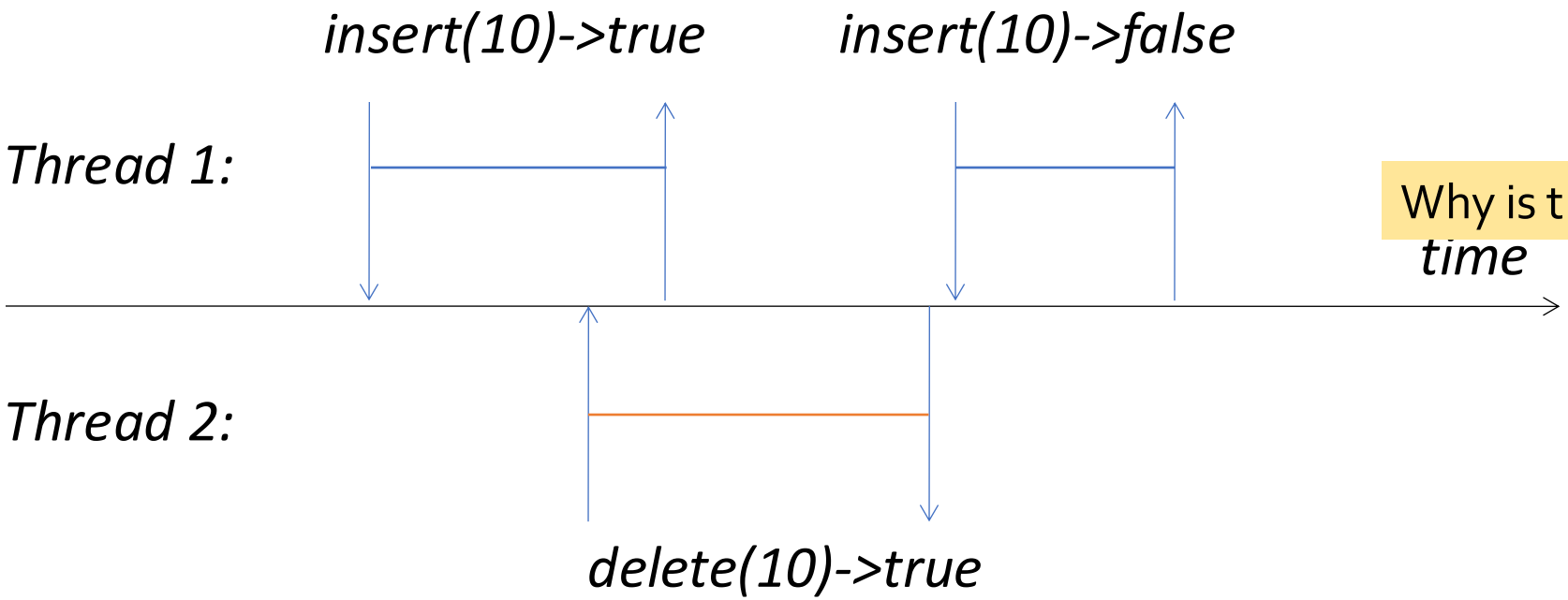

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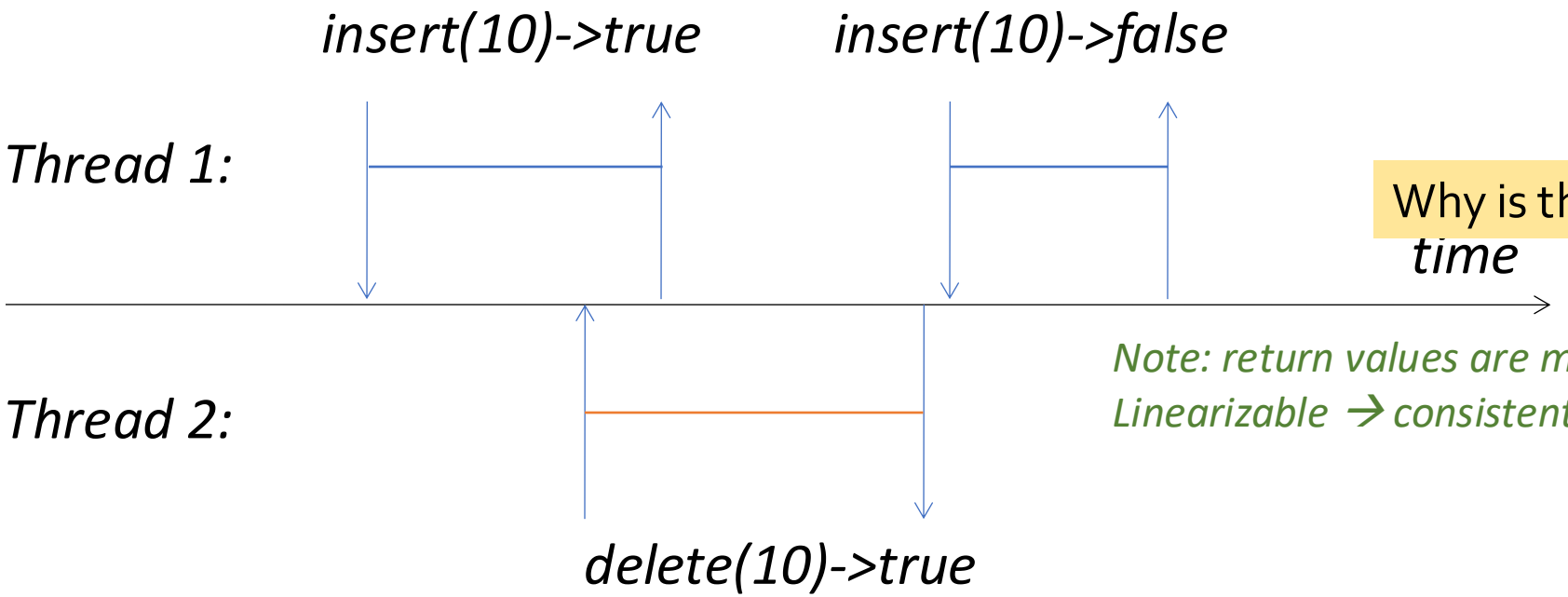

Why is this one NOT OK?

Note: return values are meaningful!
Linearizable → consistent with return values

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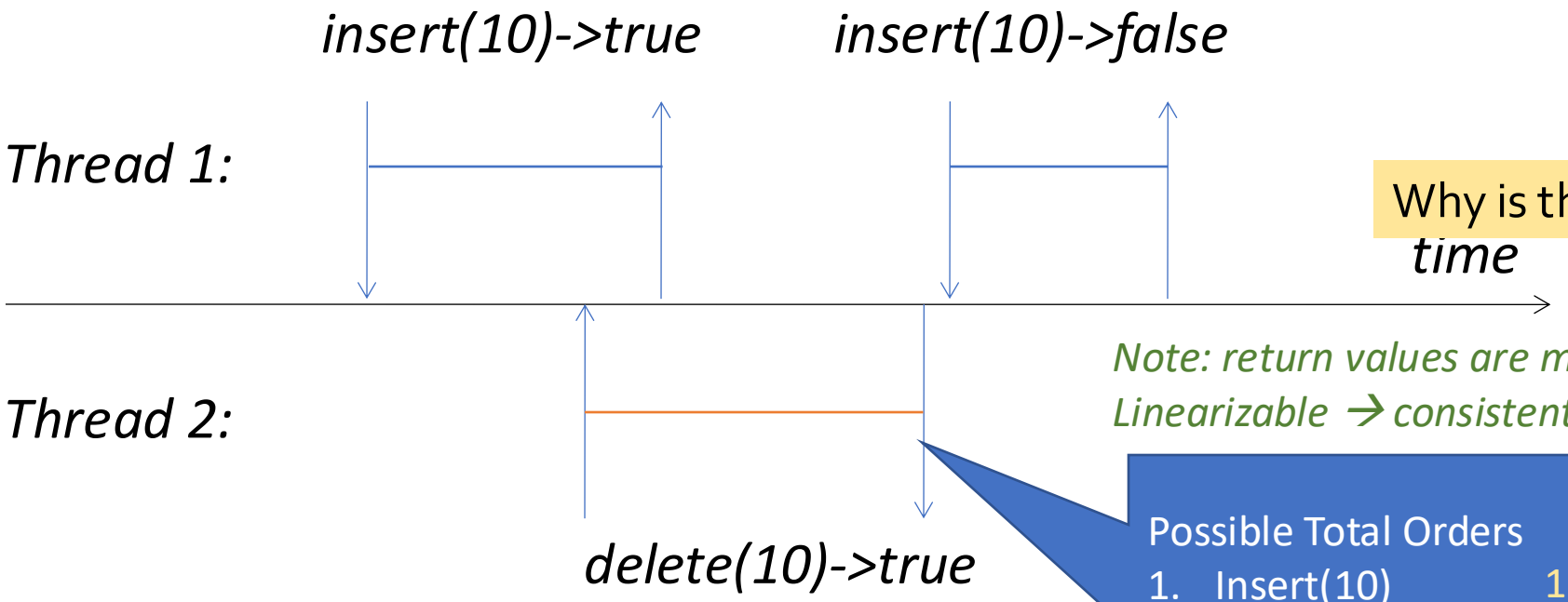

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Possible Total Orders

1. Insert(10)	1. Delete(10)
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- Both consistent with real-time order
- 1, 2 overlap, but 3 doesn't

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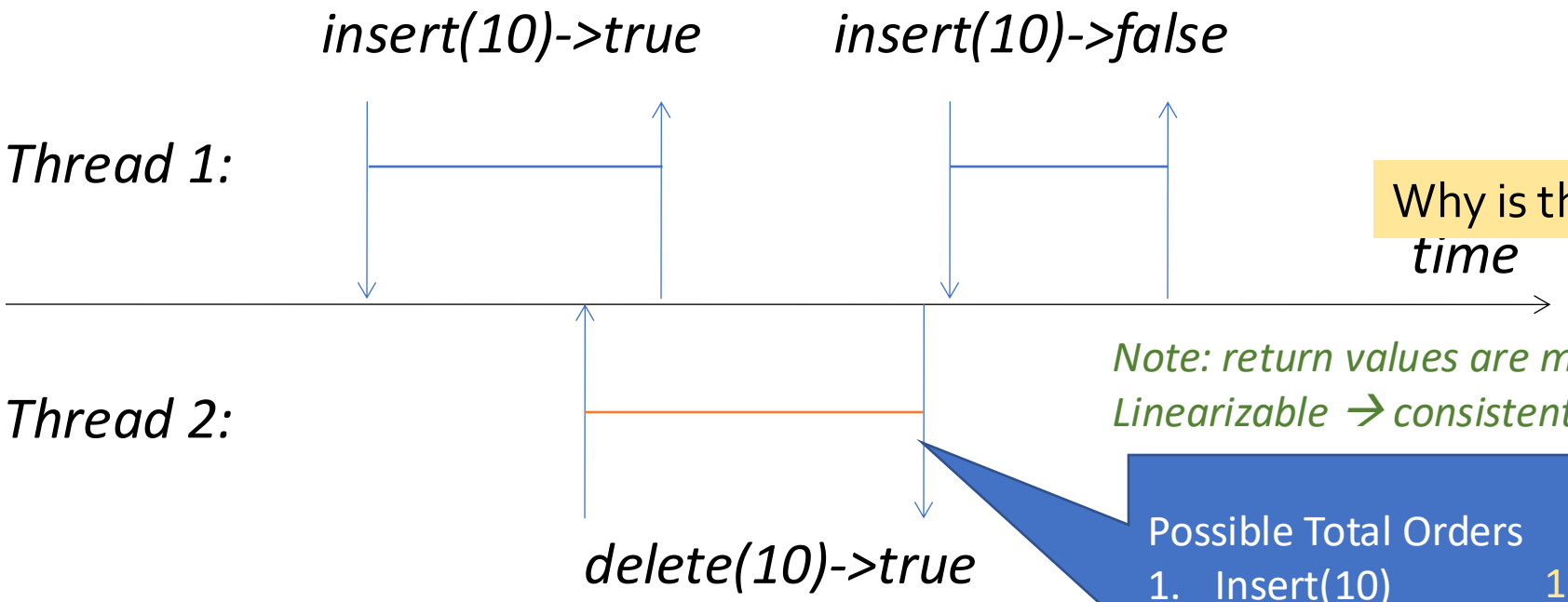

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How can things like this happen?

Example Revisited

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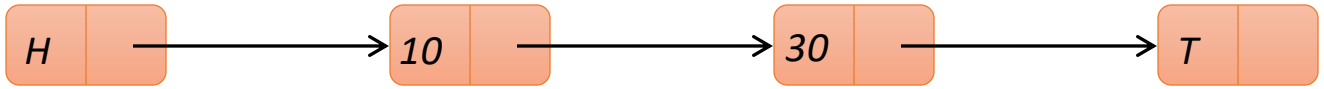

Thread 1:

Thread 2:

Example Revisited

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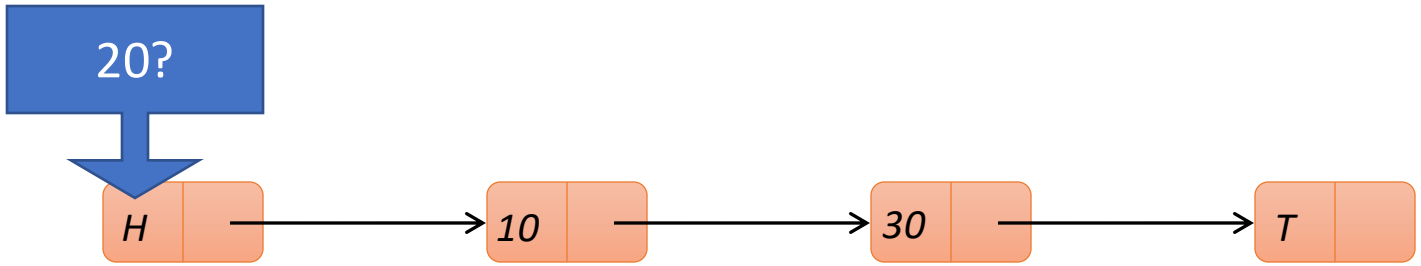

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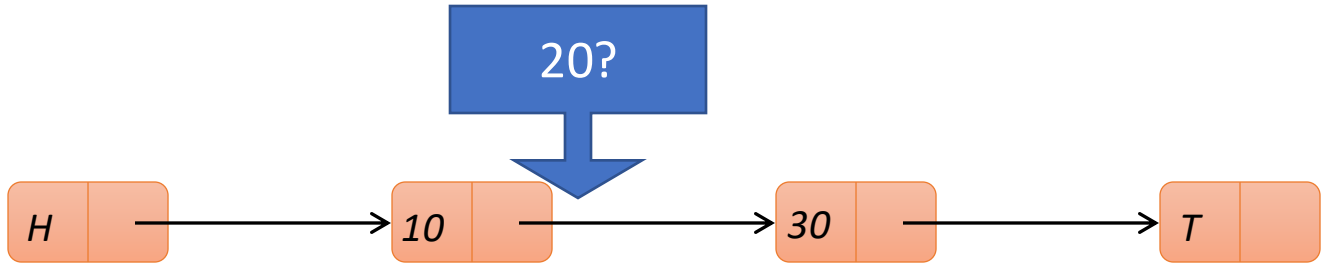

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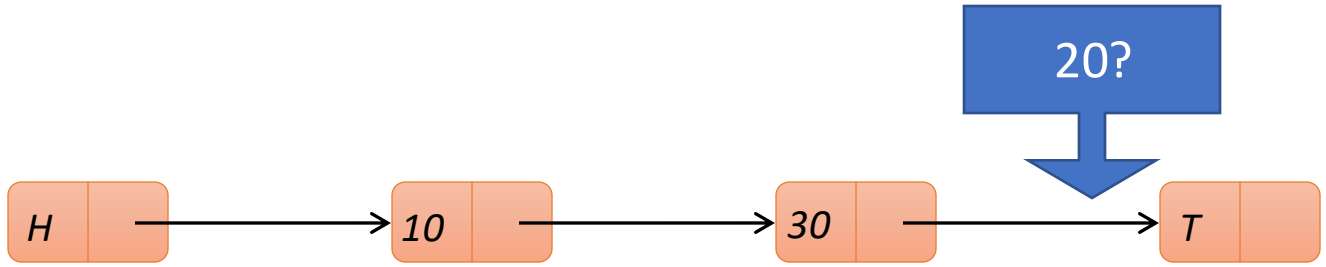

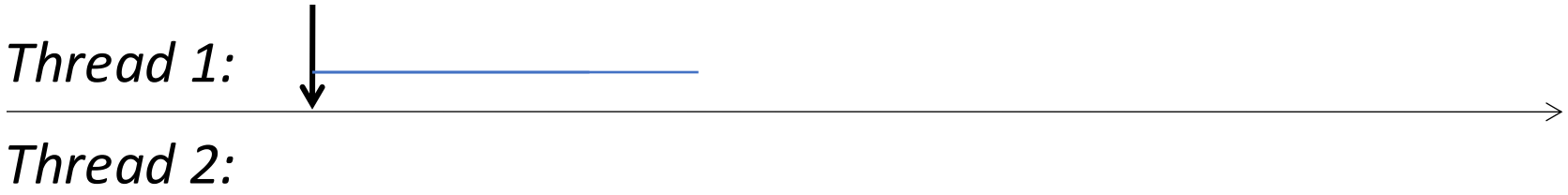

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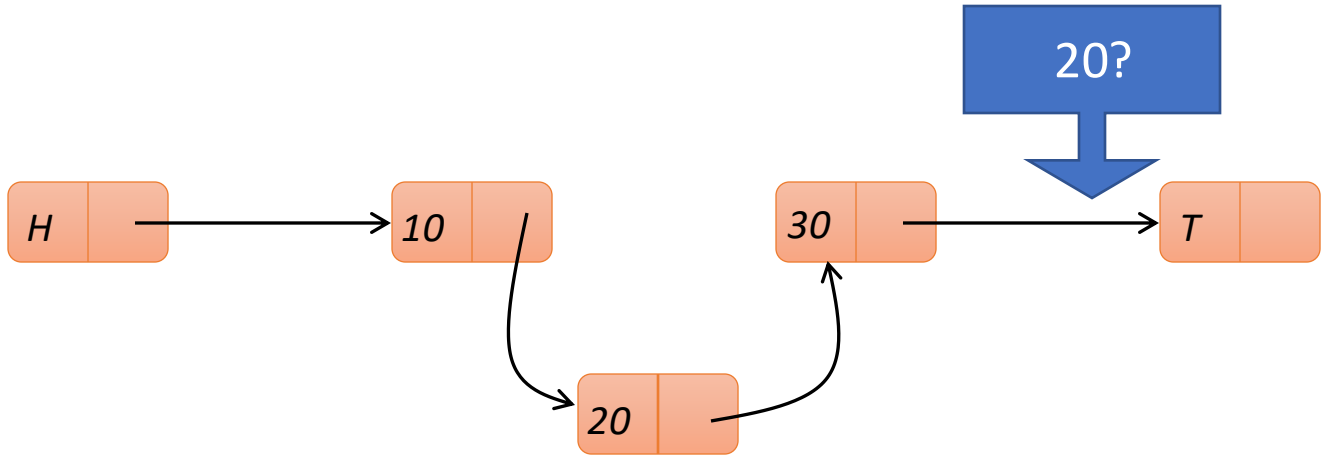

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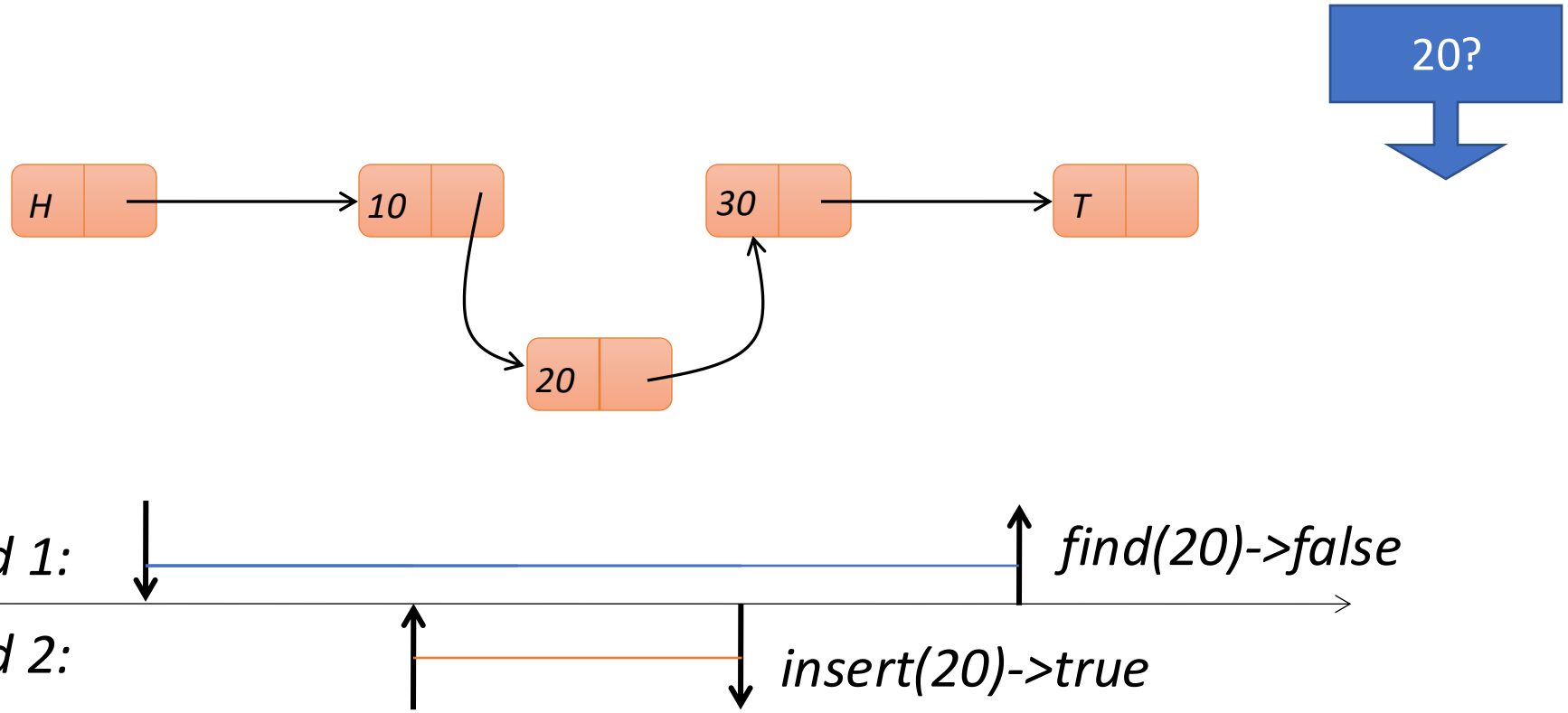

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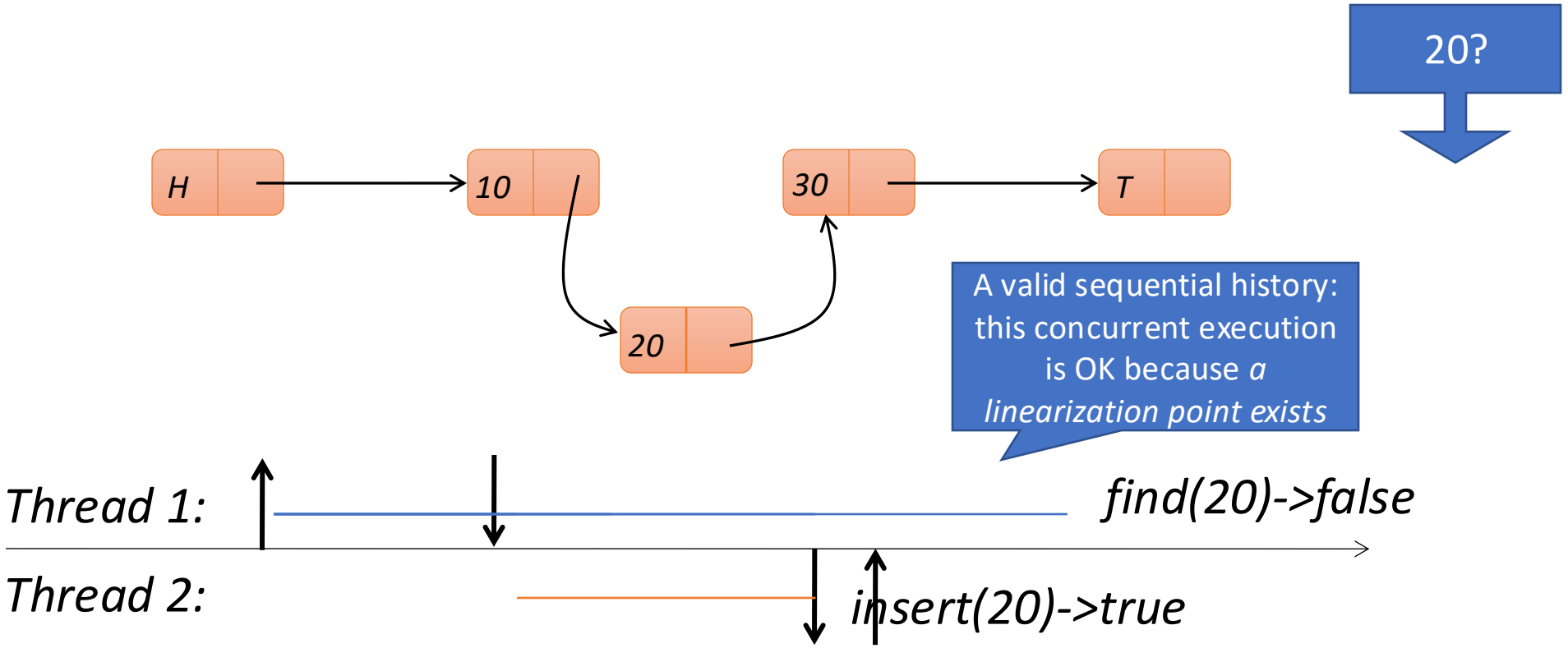

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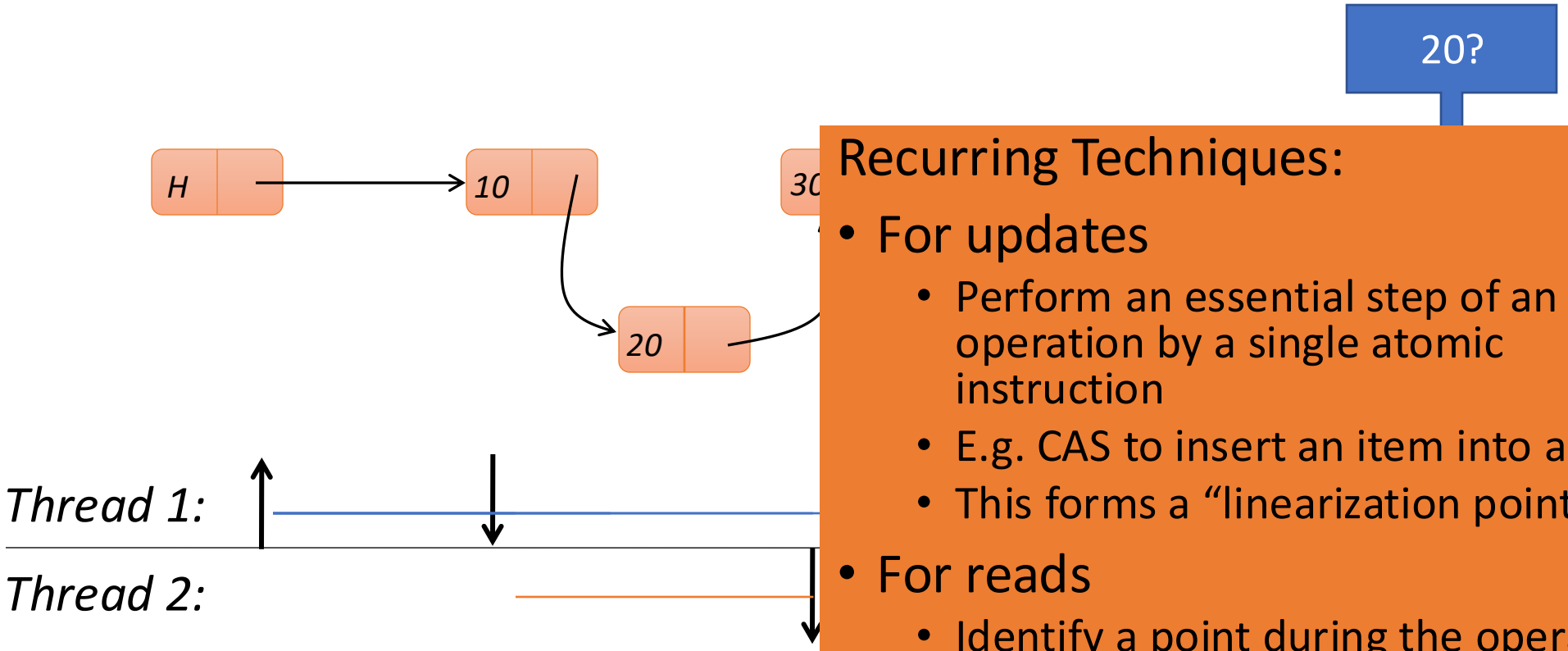

Recurring Techniques:

- For updates
  - Perform an essential step of an operation by a single atomic instruction
  - E.g. CAS to insert an item into a list
  - This forms a “linearization point”
- For reads
  - Identify a point during the operation’s execution when the result is valid
  - Not always a specific instruction

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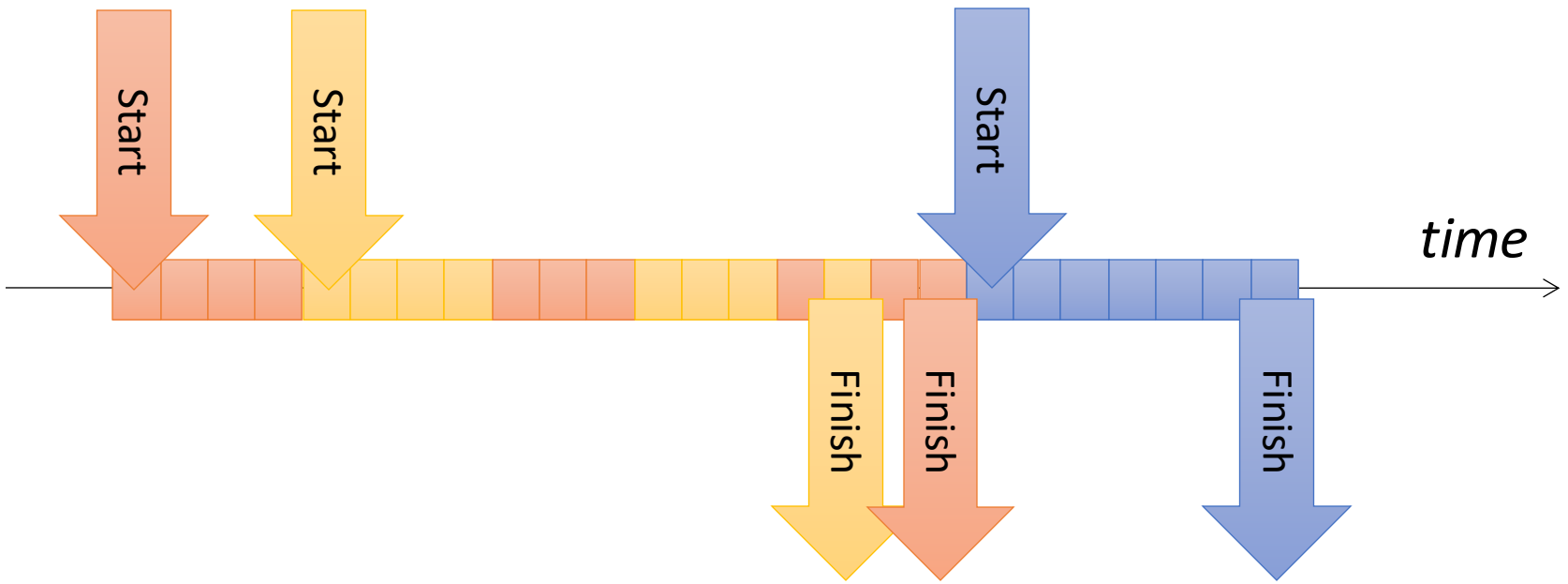

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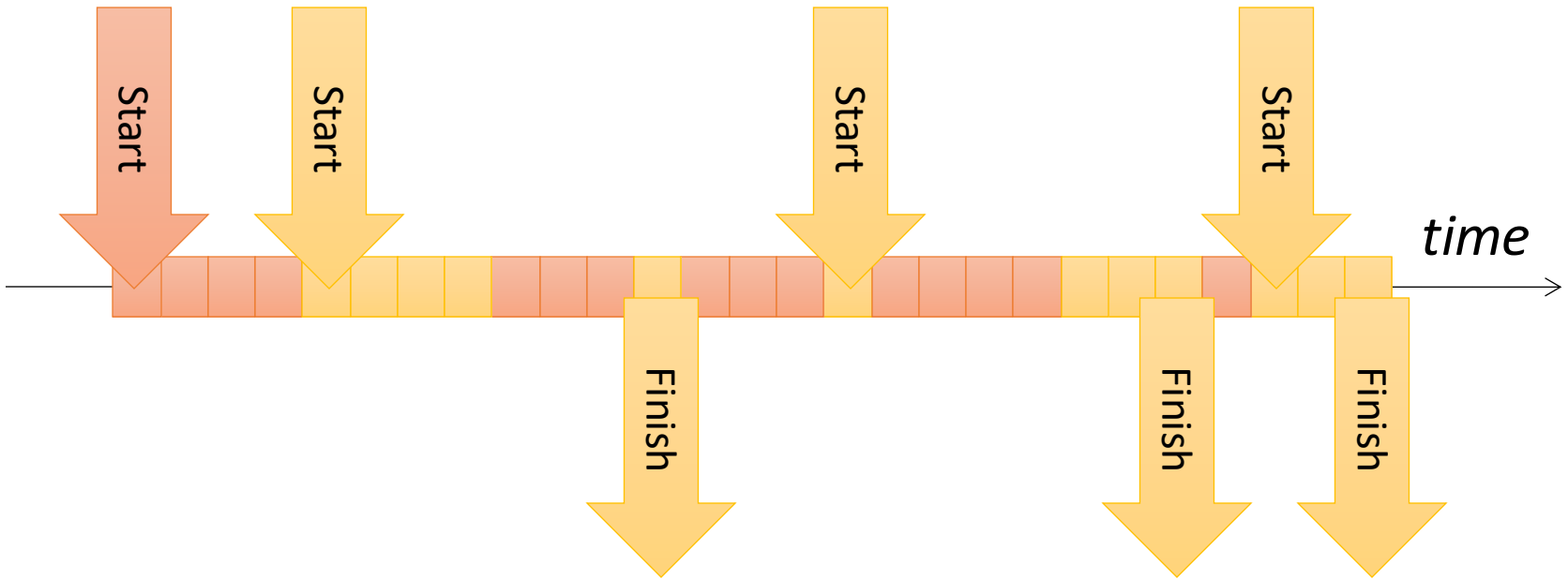

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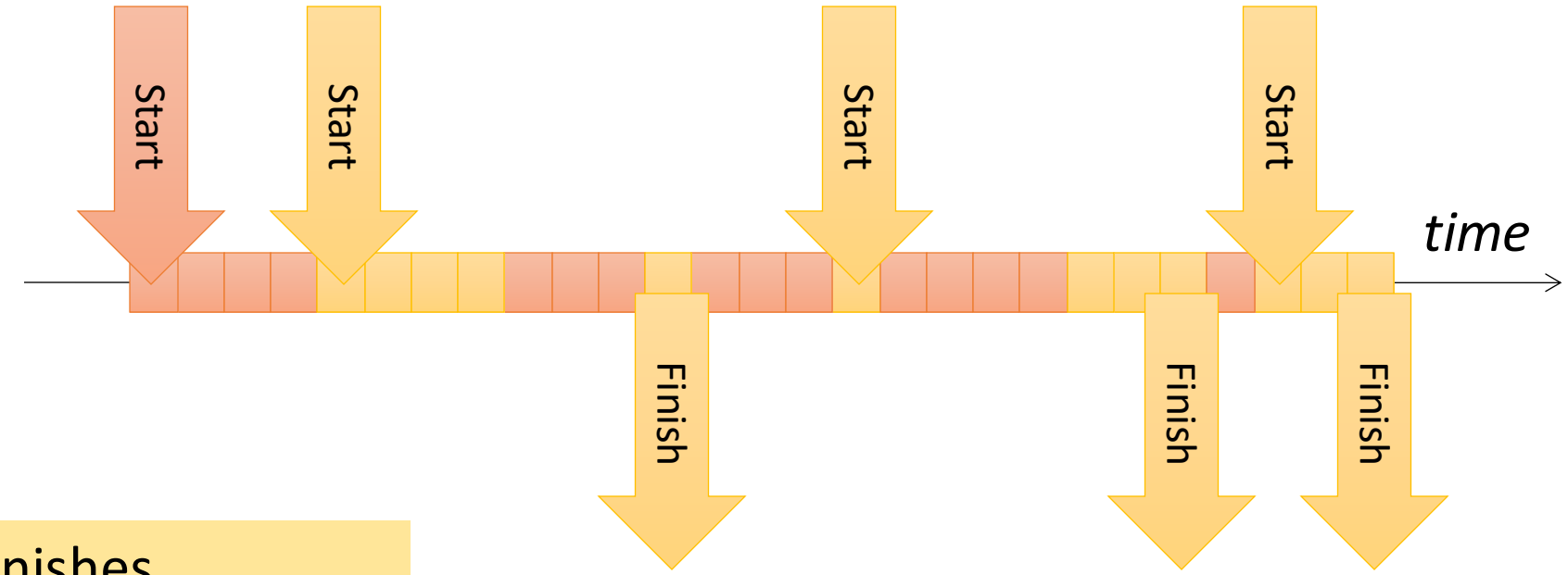

- Red never finishes
- Orange does
- Still lock-free

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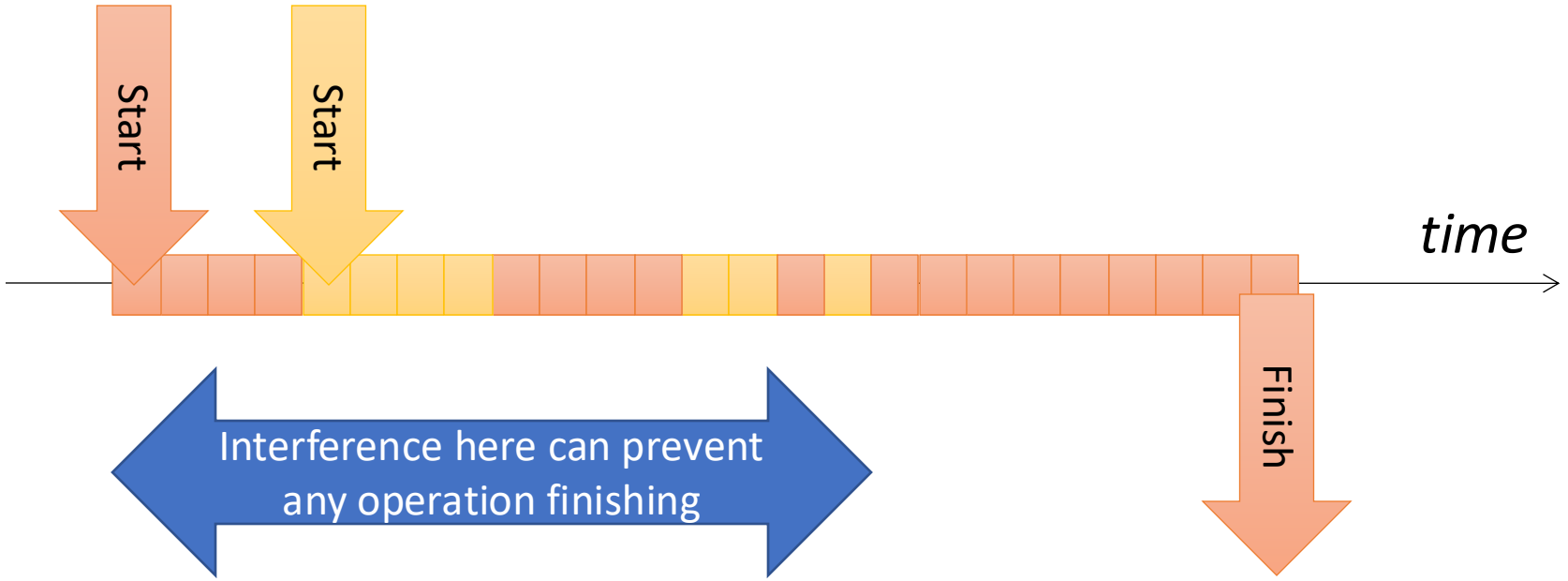

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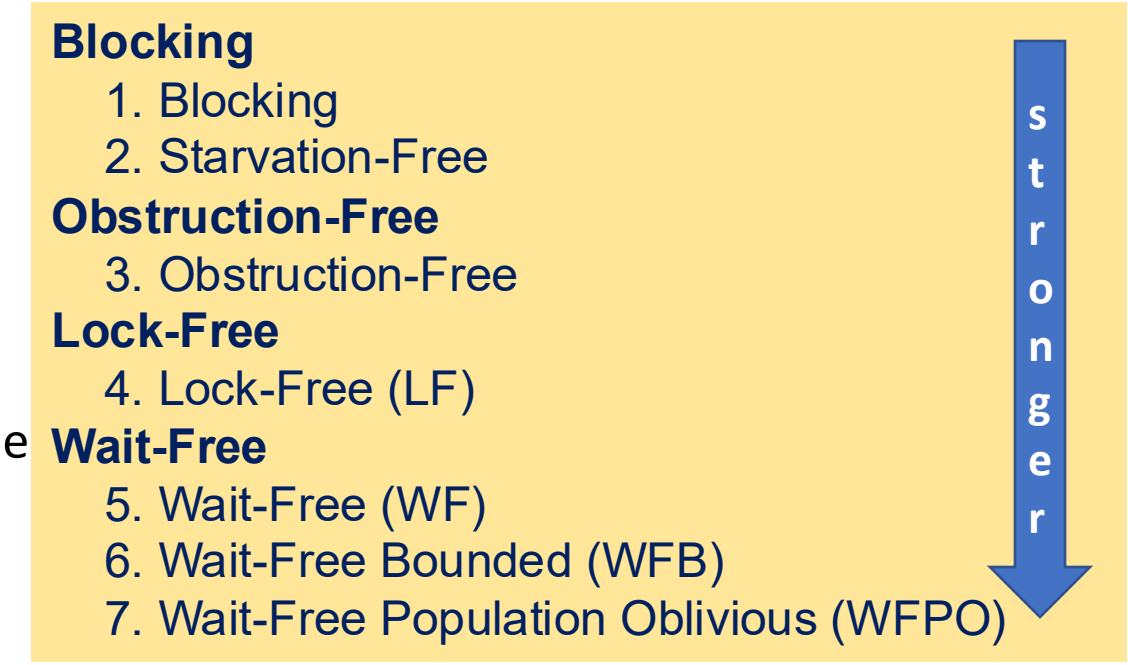

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Blocking
1. Blocking
2. Starvation-Free

Obstruction-Free
3. Obstruction-Free

Lock-Free
4. Lock-Free (LF)

Wait-Free
5. Wait-Free (WF)
6. Wait-Free Bounded (WFB)
7. Wait-Free Population Oblivious (WFPO)

stronger

Linearizability Properties

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Huh? Composable?

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T * list::remove(Obj key){
  LOCK(this);
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```
void move(list s, list d, Obj key){
  tmp = s.remove(key);
  d.insert(key, tmp);
}
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Composability

Thread-safe?

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Painting with a very broad brush
Composition with linearizability is really about composed schedules

- Lock-based code doesn't compose
- If list were a linearizable concurrent data structure, composition OK?

Linearizability Properties

- non-blocking
  - one method is never forced to wait to sync with another.
- applies to histories *and* objects *and* systems:
  - a history can be linearizable
  - an object is linearizable if all valid histories of its use are linearizable
- local property:
  - a system is linearizable iff each individual object is linearizable.
  - gives us **composability**.
- Why is it important?
  - Serializability is not composable.
  - Core hypotheses:
    - structuring all as concurrent objects buys composability
    - structuring all as concurrent objects is tractable/possible

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- Non-composability of serializability is really about composing schedules

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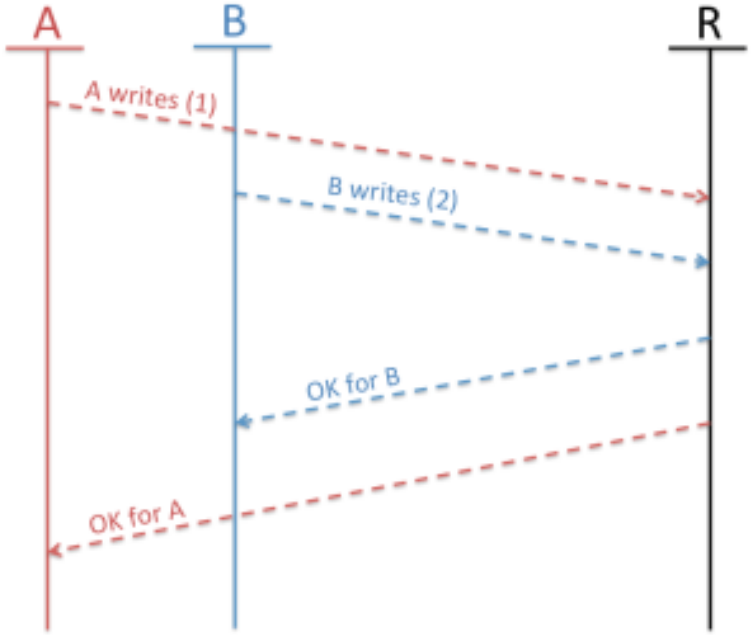

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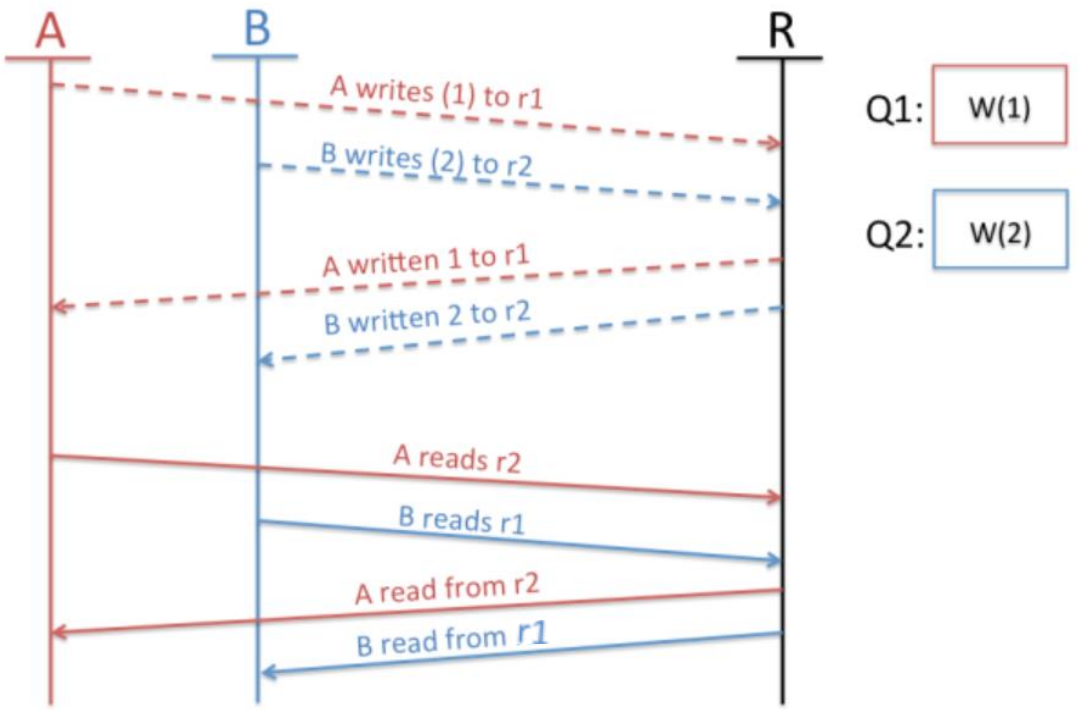

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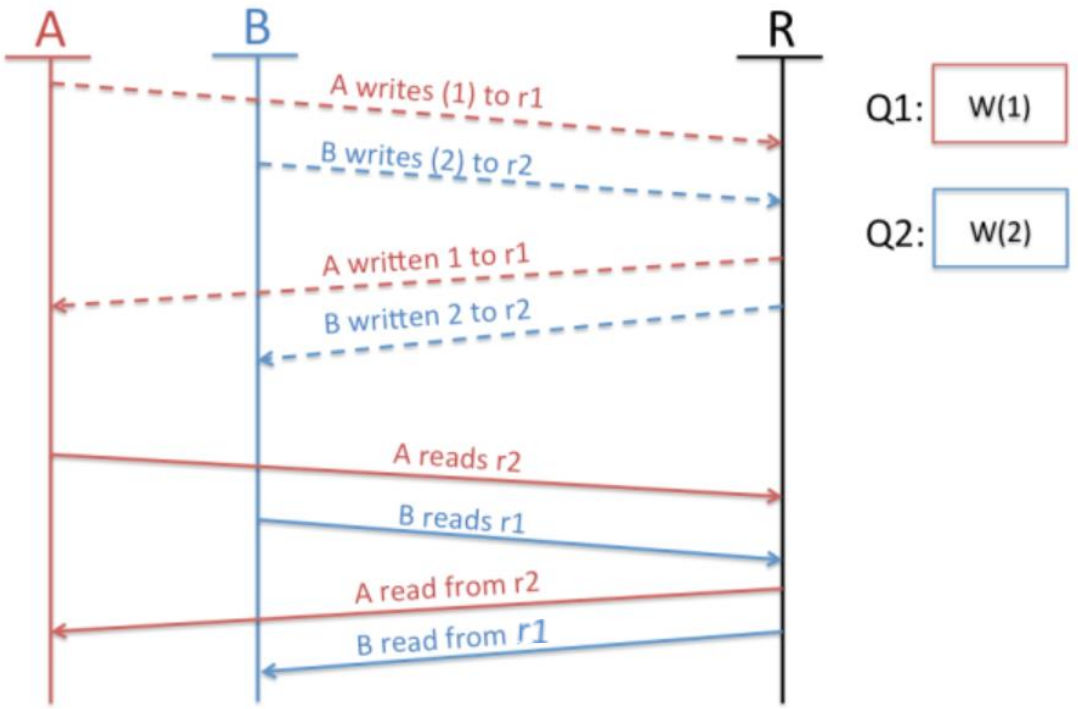
- Serializability:
  - Execution equivalent to *some serial order*
  - All see same order



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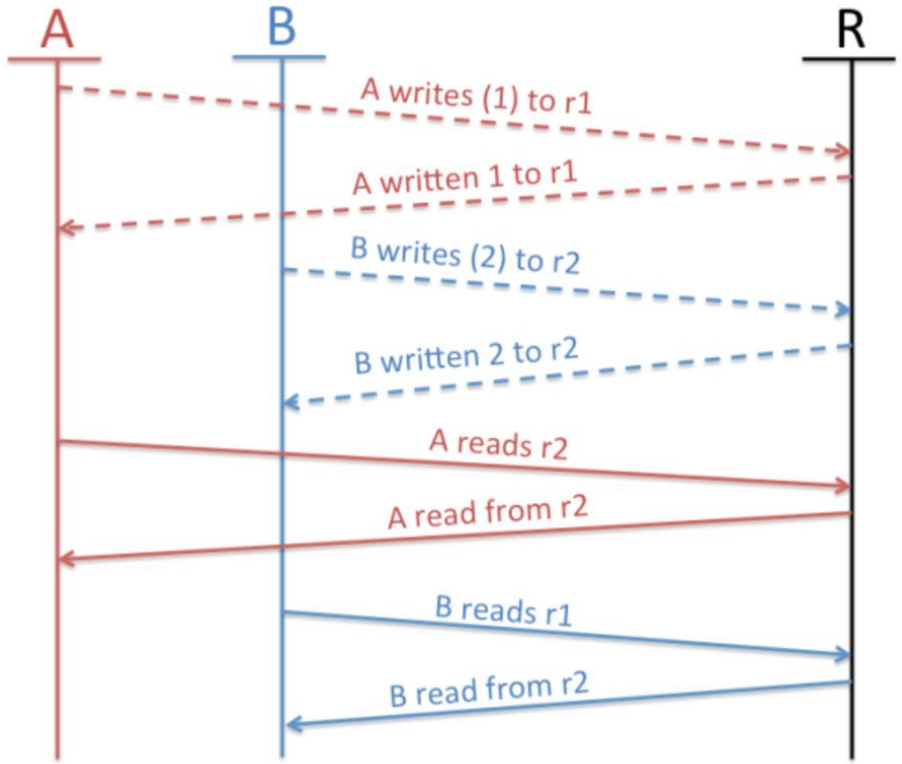

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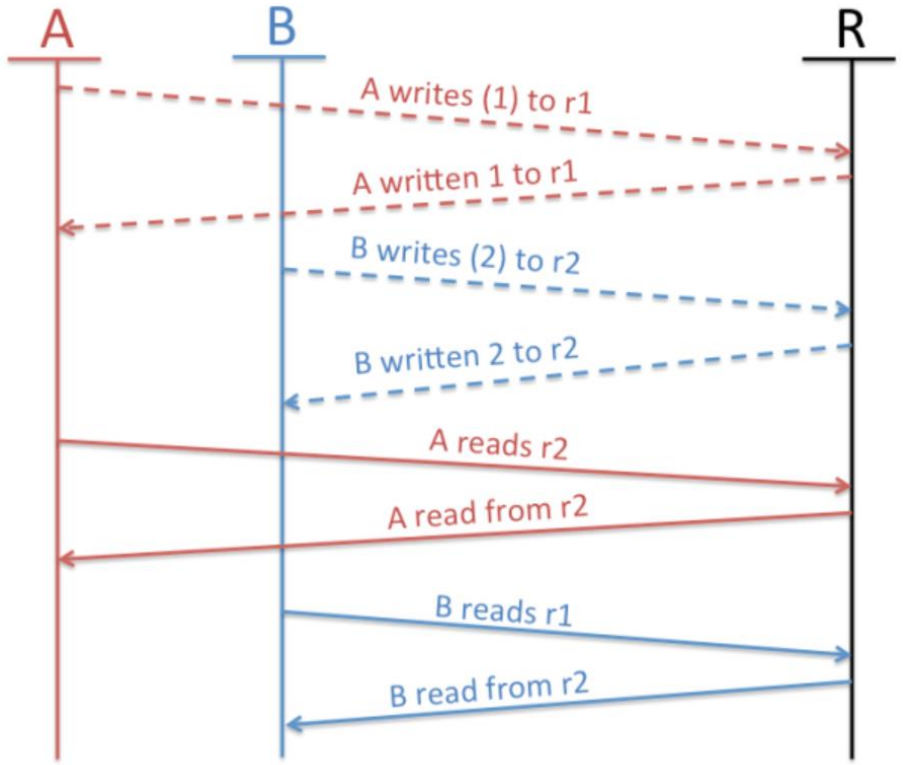

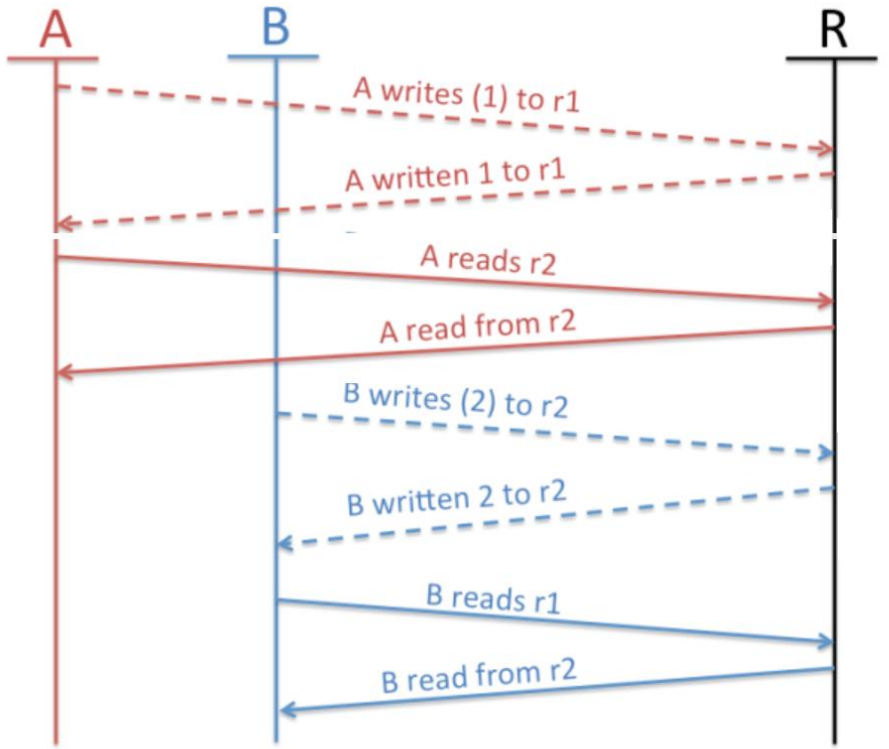

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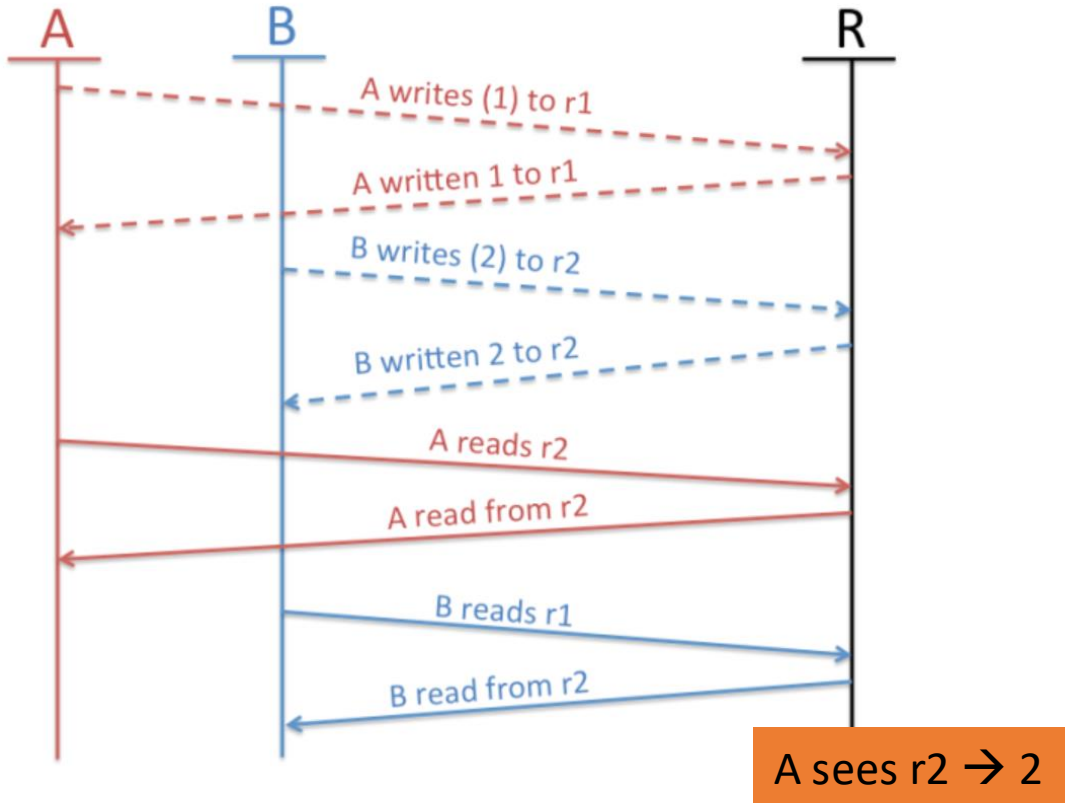

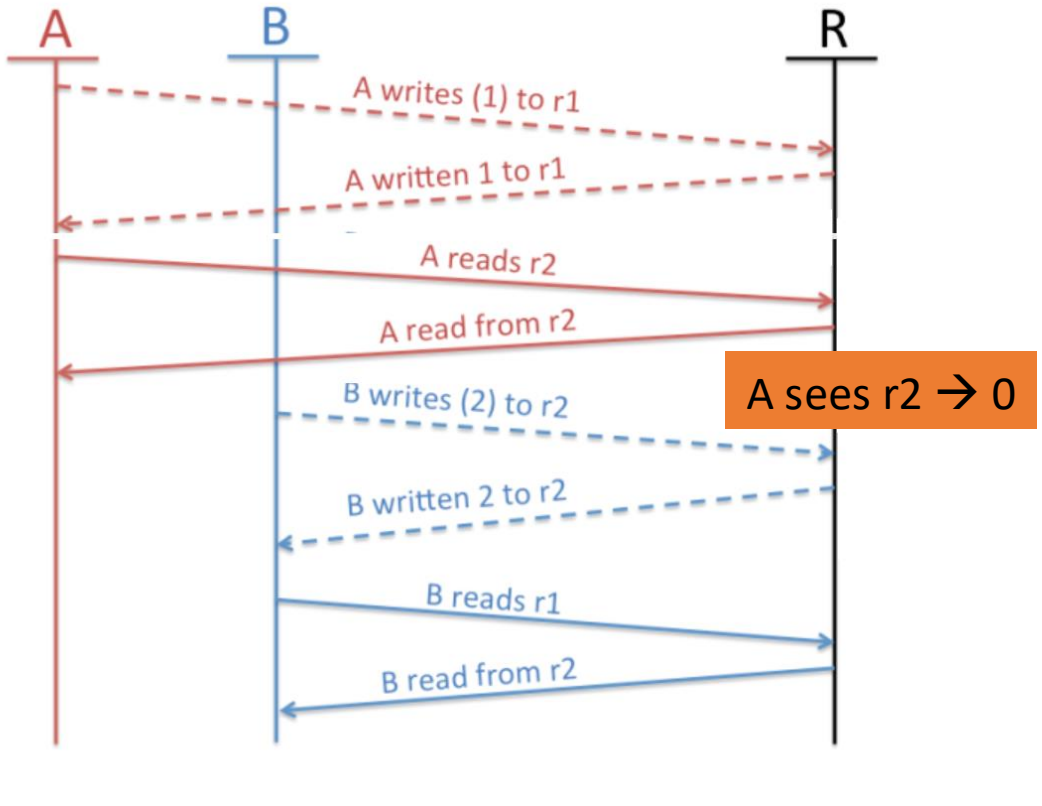

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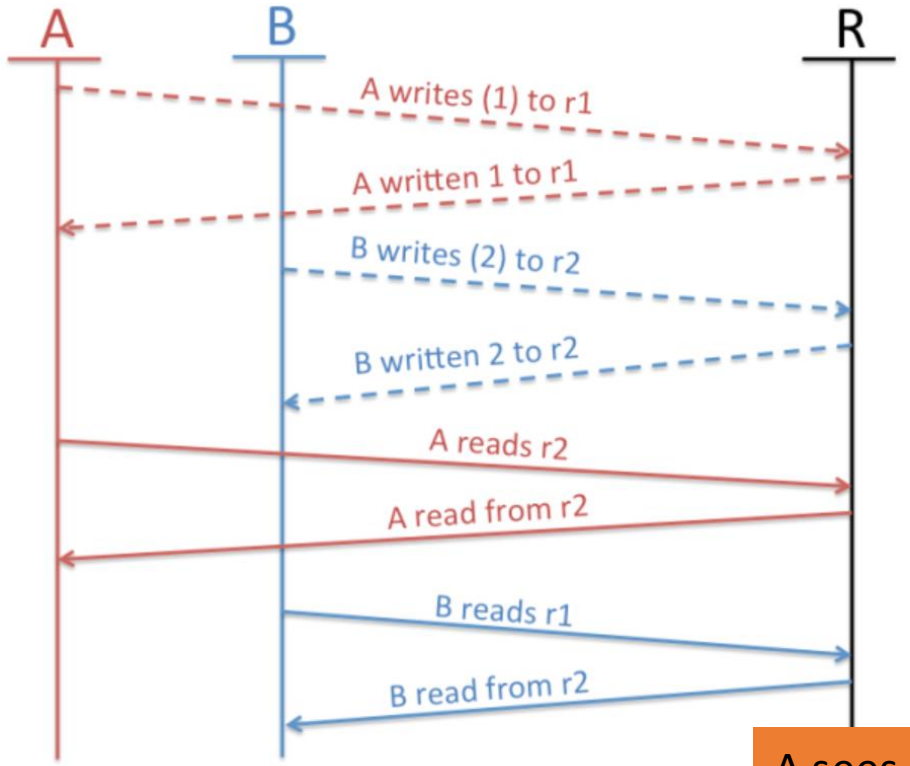
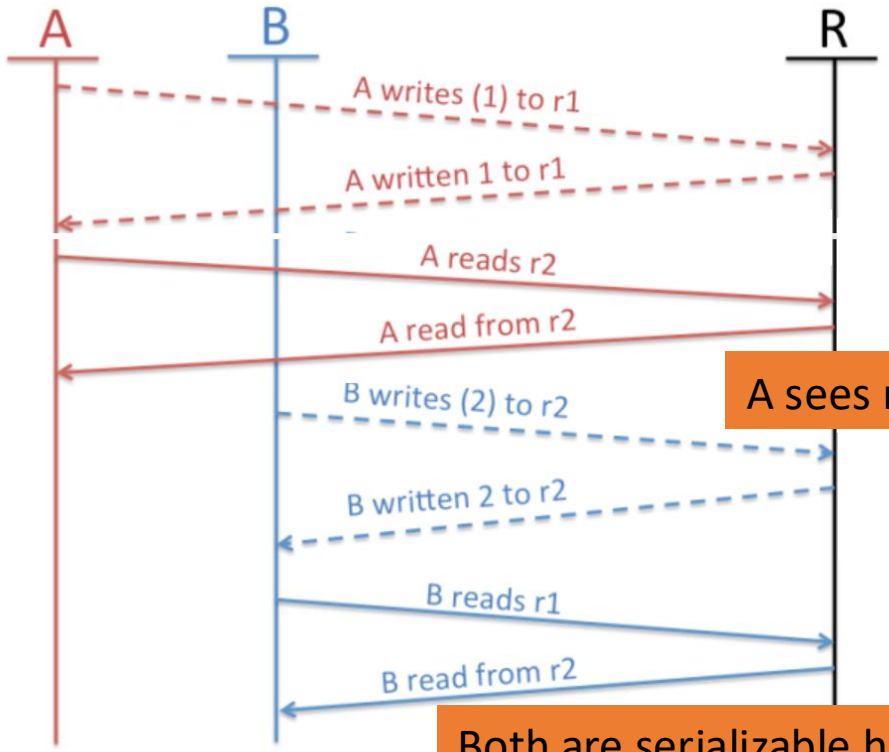


A sees r2 → 2



A sees r2 → 0

Both are serializable histories from the perspective of A

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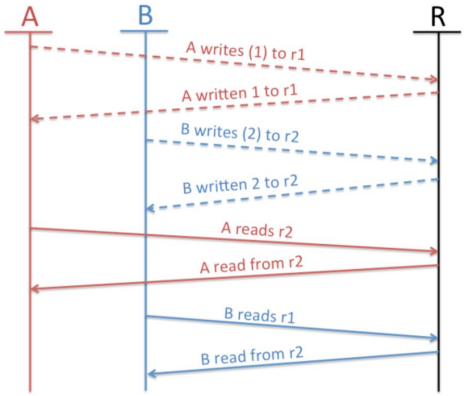

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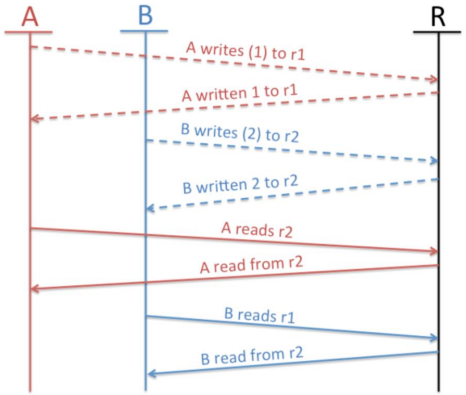

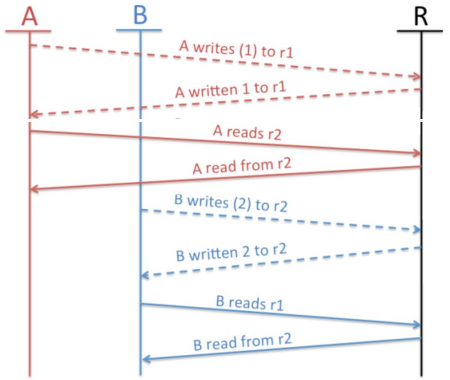

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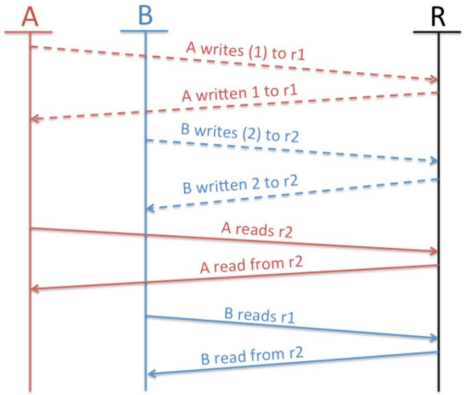

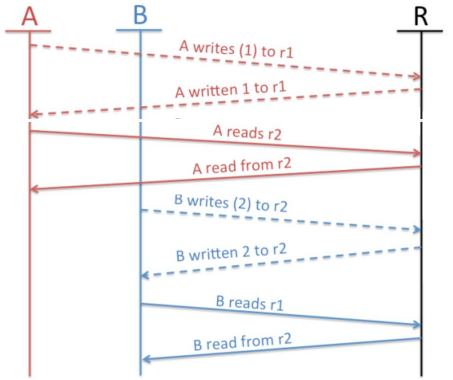

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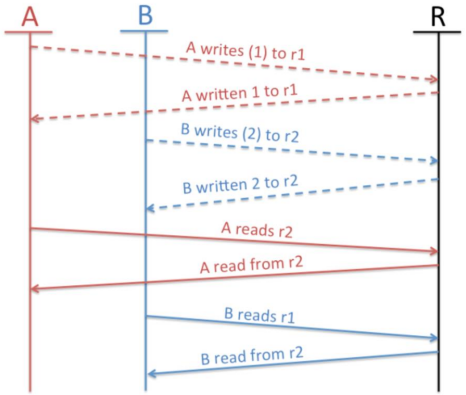

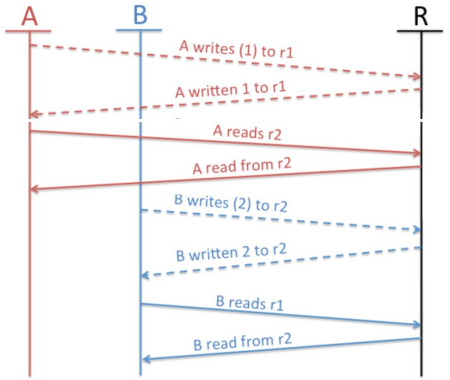

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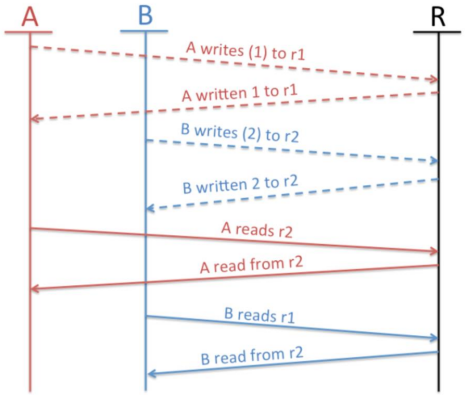

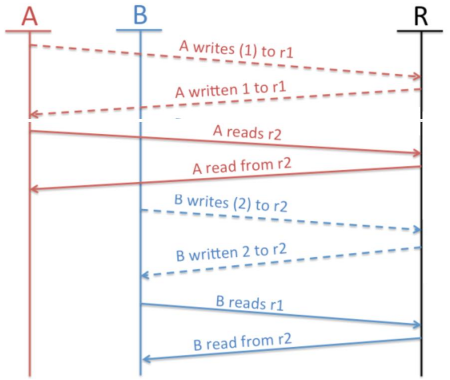

…

From the perspective of threads A, B, all sub-histories are serializable

- They respect program order for each of A, B
- And are equivalent to *some* serial execution
- If we “compose” these histories, some composed histories not serializable

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4 serializable sub-histories composed
To form 4 complete histories,
Only H4ab is actually serializable

…Now back to Linearizability

- A concurrent register implementation that allows H1ab, H2ab, H3ab is not linearizable
- To be linearizable its implementation must disallow those histories
- Simplest technique to achieve this: make writes atomic (CAS)
  - such that overlapping reads cannot be reordered (e.g. A reads r2->0 after B writes r2=2
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Another Perspective

Serializability
invocations and responses can be reordered to yield a sequential history
the sequential history is correct according to the sequential definition of the object

Linearizability
invocations and responses can be reordered to yield a sequential history
the sequential history is correct according to the sequential definition of the/each object
if a response preceded an invocation in the original history, it must still precede it in the sequential reordering

Linearizability Redux

- non-blocking
  - one method is never forced to wait to sync with another.
- applies to histories *and* objects *and* systems:
  - a history can be linearizable
  - an object is linearizable if all valid histories of its use are linearizable
- local property:
  - a system is linearizable iff each individual object is linearizable.
  - gives us **composability**.

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- Key-value mapping
- Population count
- Iteration
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- Use a different data structure
  (e.g., skip lists)