Programming at Fast Scale: Consistency + Lock Freedom

cs378

Today

Questions?

Administrivia

- Faux Quiz
- Project Proposal Comments

Agenda:

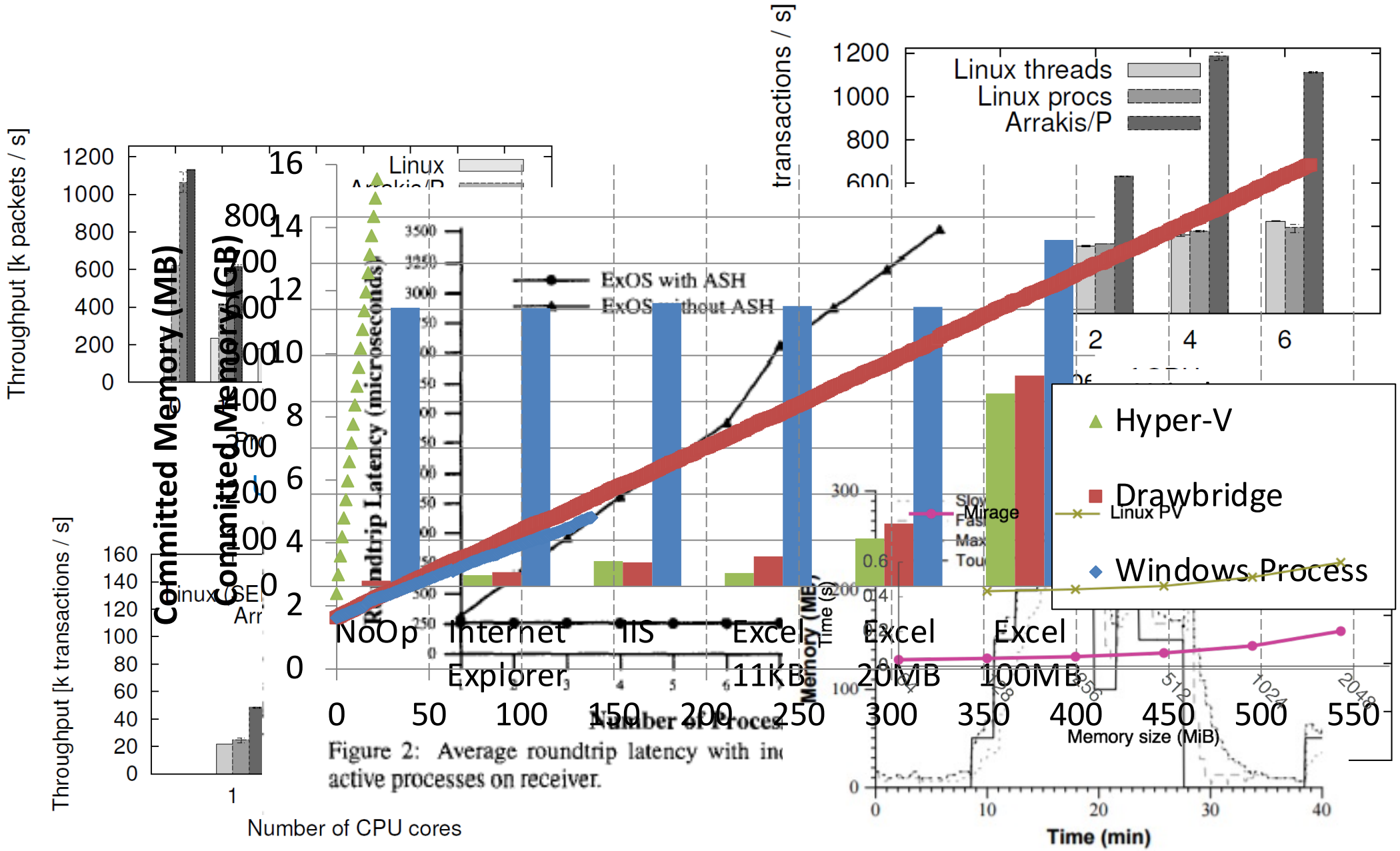
- Consistency
- Lock Freedom

Faux Quiz Questions: 5 min, pick any 2

- What is the CAP theorem? What does “PACELC” stand for and how does it relate to CAP?
- What is the difference between ACID and BASE?
- Why do NoSQL systems claim to be more horizontally scalable than RDMBSes? List some features NoSQL systems give up toward this goal?
- What is eventual consistency? Give a concrete example of how of why it causes a complex programming model (relative to a strongly consistent model).
- Define and contrast the following consistency properties:
  - strong consistency, eventual consistency, consistent prefix, monotonic reads, read-my-writes, bounded staleness
- What is causal consistency?
- What is chain replication?
- 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?

Project proposal updates

- Project foci: concurrency, and empiricism

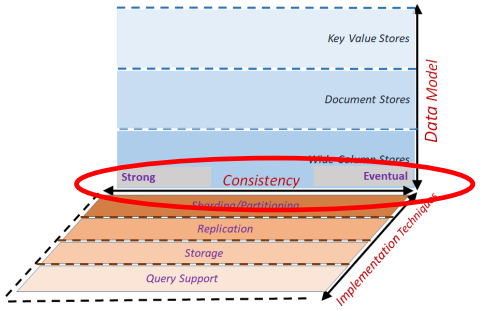

Throughput [k packets / s]
Linux
Arrakis/P
Number of CPU cores
Load balancer
Committed Memory (MB)
Committed Memory (GB)
Linux threads
Linux procs
Arrakis/P
transactions / s]
ExOS with ASH
ExOS without ASH
Roundtrip Latency (microseconds)
Number of Processes
Figure 2: Average roundtrip latency with in
active processes on receiver.
NoOp
Internet Explorer
IIS
Excel 11KB
Excel 20MB
Excel 100MB
Hyper-V
Drawbridge
Linux PV
Windows Process
Mirage
Memory (MB)
Time (s)
Memory size (MiB)
Time (min)
IP middlebox

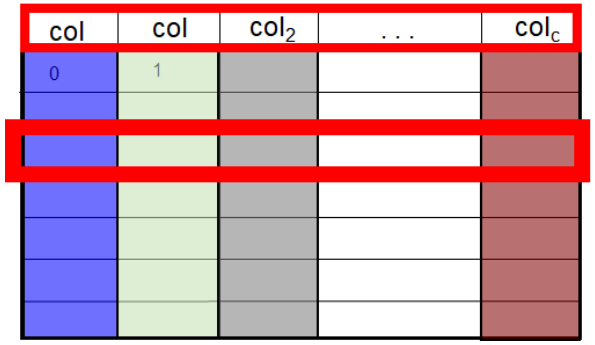
Project proposal updates

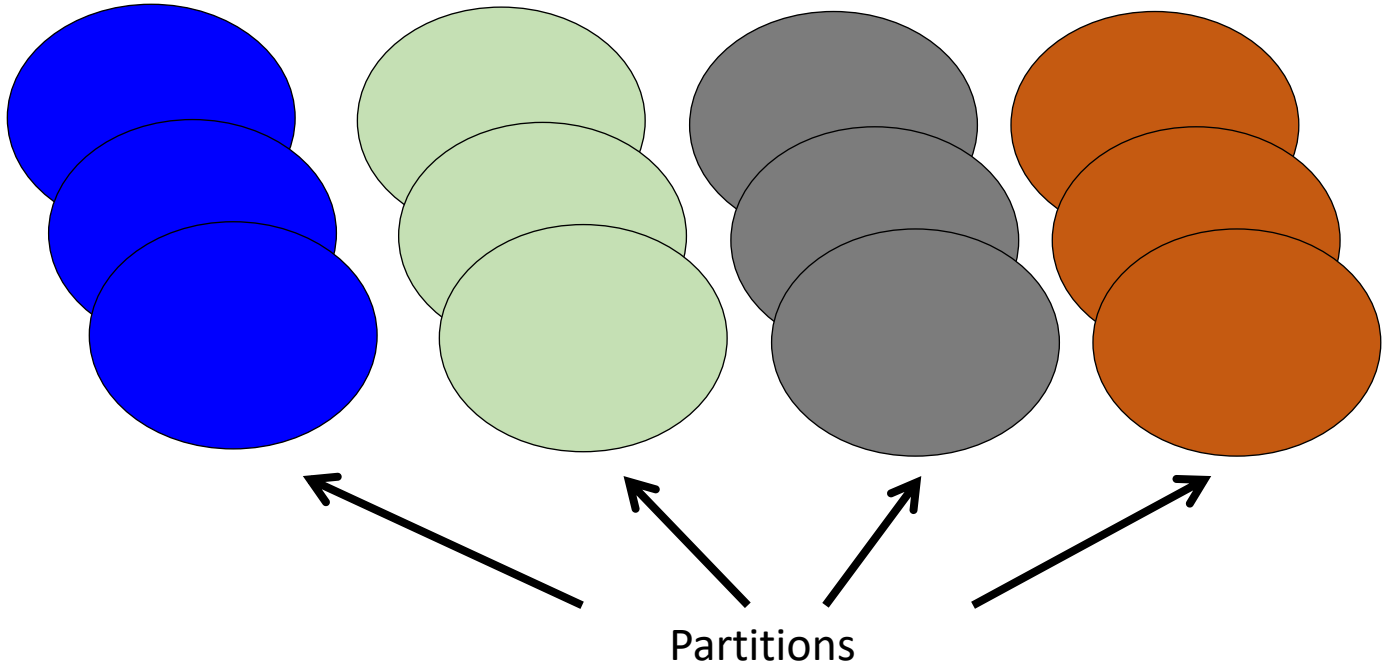
Key ask: state what the ***centerpiece data visualizations*** will be.

- It makes it clear what your hypothesis really is
- It clarifies that empirical endeavor is the point of this exercise.
- Makes it easier to judge whether you're taking on too much.

Review: Consistency



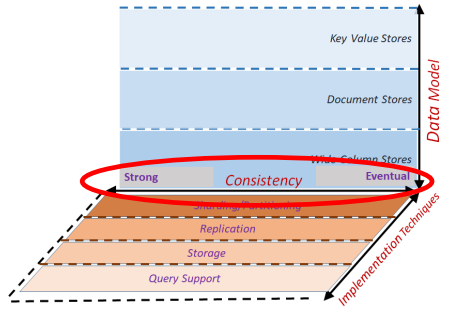


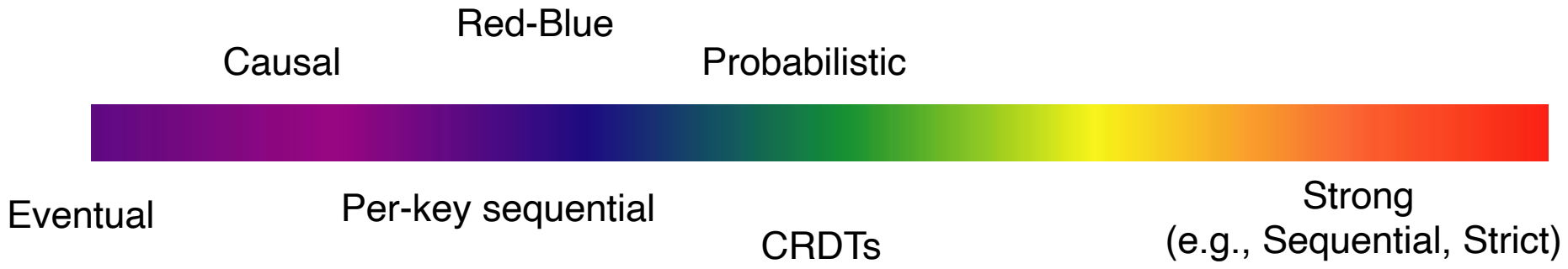


How to keep data in sync?

- Partitioning → single row spread over multiple machines
- Redundancy → single datum spread over multiple machines

Review: *Many* Consistency Models



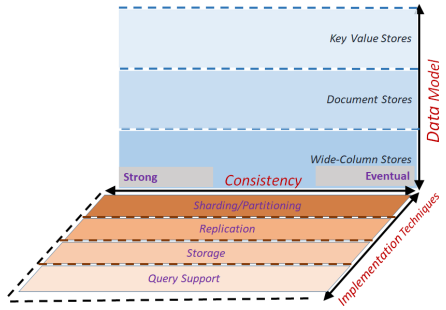


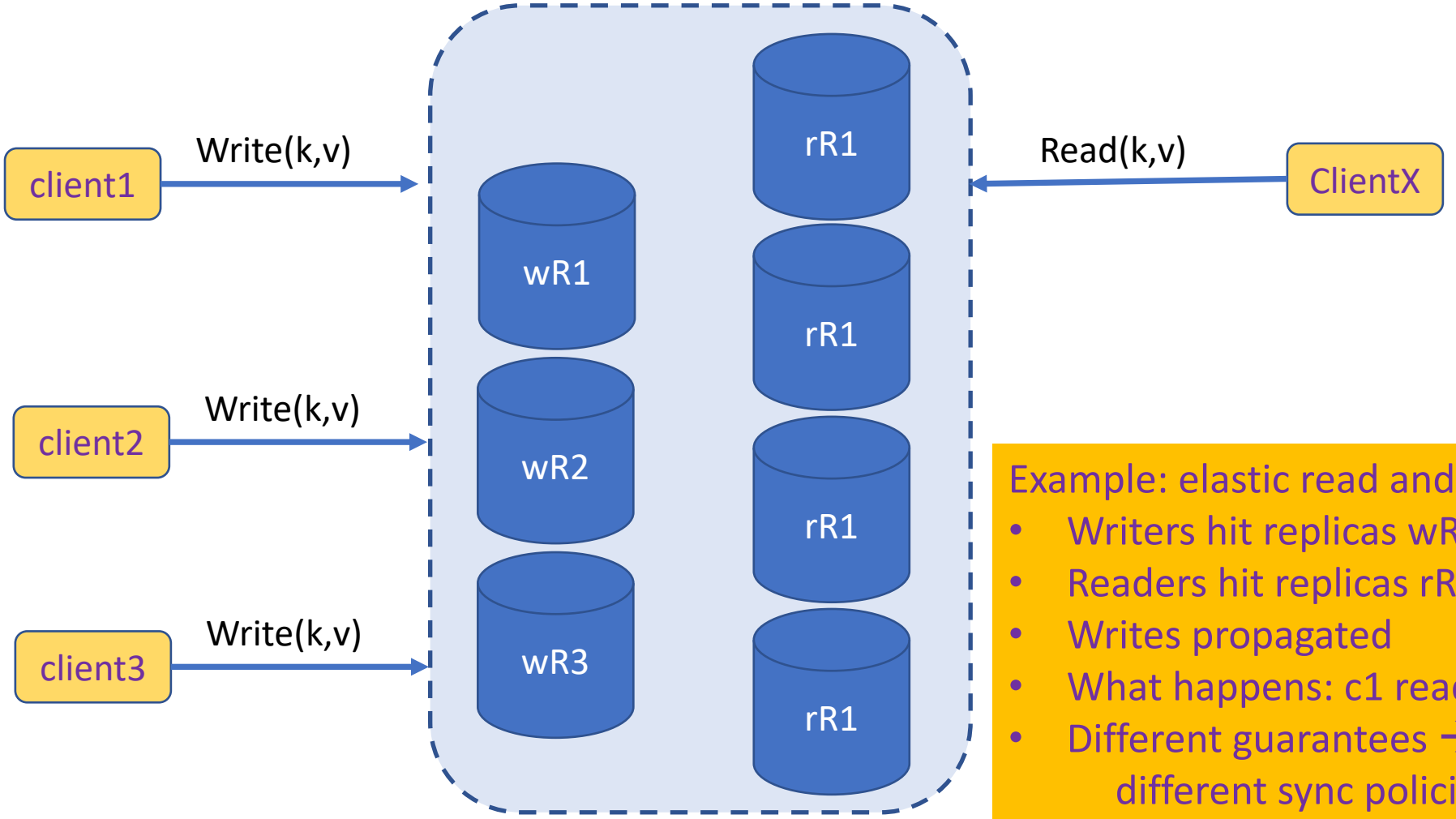
- Amazon S3 – **eventual** consistency
- Amazon Simple DB – **eventual** or strong
- Google App Engine – **strong** or eventual
- Yahoo! PNUTS – **eventual** or strong
- Windows Azure Storage – **strong** (or eventual)
- Cassandra – **eventual** or strong (if R+W > N)
- …

Question: How to choose what to use or support?

Hold the phone!

How can all these different guarantees come up?



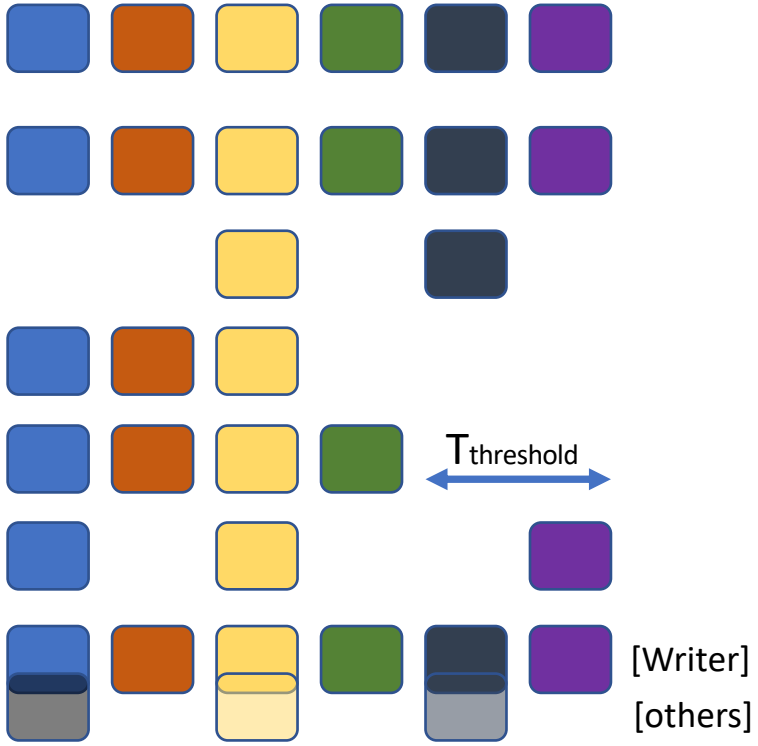


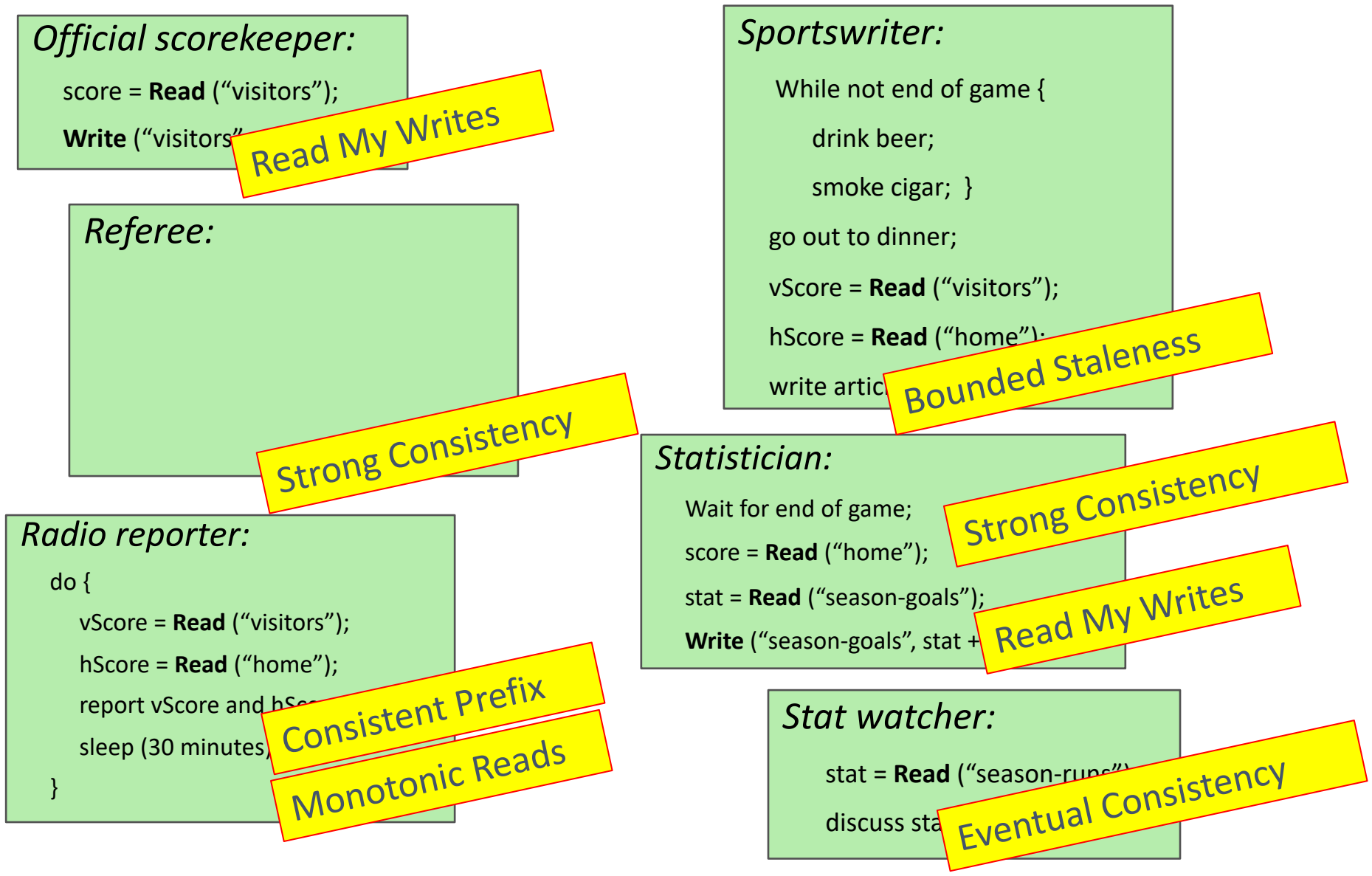
Example: elastic read and writes

- Writers hit replicas wR1..wR3
- Readers hit replicas rR1..rR4
- Writes propagated
- What happens: c1 reads own writes?
- Different guarantees →
  - different sync policies
  - different w/r routing policies

Review: Some Consistency Guarantees

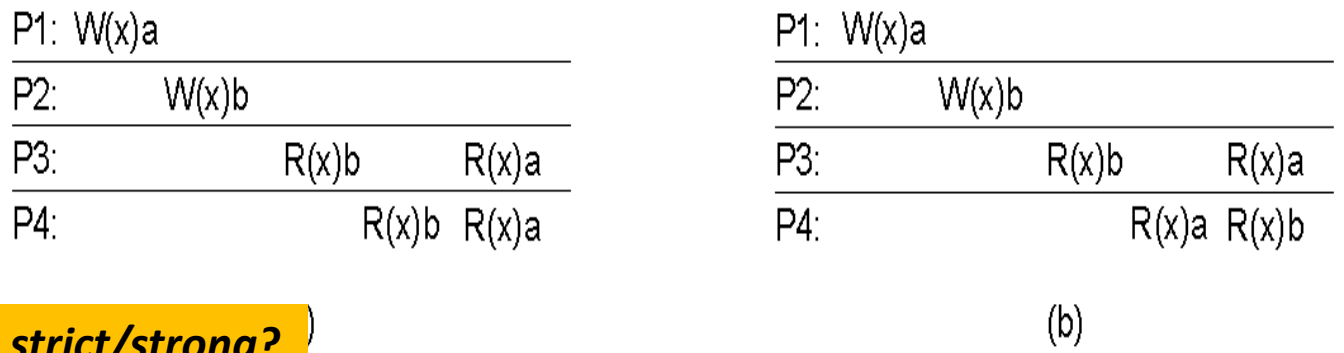
Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
Consistent Prefix	See initial sequence of writes.
Bounded Staleness	See all “old” writes.
Monotonic Reads	See increasing subset of writes.
Read My Writes	See all writes performed by reader.




Official scorekeeper:
score = Read ("visitors");
Write ("visitors"
Read My Writes
Referee:
Strong Consistency
Radio reporter:
do {
vScore = Read ("visitors");
hScore = Read ("home");
report vScore and hSc
sleep (30 minutes)
}
Consistent Prefix
Monotonic Reads
Sportswriter:
While not end of game {
drink beer;
smoke cigar; }
go out to dinner;
vScore = Read ("visitors");
hScore = Read ("home");
write artic
Bounded Staleness
Statistician:
Wait for end of game;
score = Read ("home");
stat = Read ("season-goals");
Write ("season-goals", stat +
Strong Consistency
Read My Writes
Stat watcher:
stat = Read ("season-runs")
discuss sta
Eventual Consistency

Sequential Consistency

- weaker than strict/strong consistency
  - All operations are executed in *some* sequential order
  - each process issues operations in program order
    - Any valid interleaving is allowed
    - All agree on the same interleaving
    - Each process preserves its program order



- ***Why is this weaker than strict/strong?***
- ***Nothing is said about "most recent write"***

Linearizability

- Assumes sequential consistency *and*
  - If TS(x) < TS(y) then OP(x) should precede OP(y) in the sequence
  - Stronger than sequential consistency
  - Difference between linearizability and serializability?
    - Granularity: reads/writes versus transactions
- Example:
  - Stay tuned…relevant for lock free data structures
  - Importantly: *a property of concurrent objects*

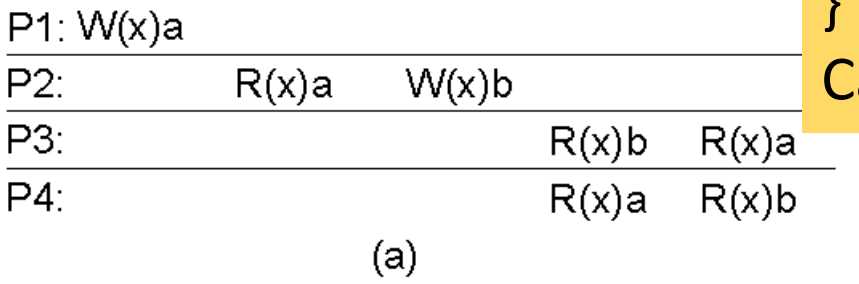
Causal consistency

- Causally related writes seer
  - *Causally?*
  - *Concurrent* writes may be se machines

Causal:
If a write produces a value that
causes another write, they are causally related

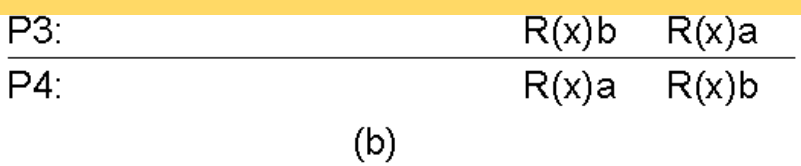
```
X = 1
if(X > 0) {
   Y = 1
}
```

Causal consistency → all see X=1, Y=1 in same order



(a)

Not permitted



(b)

Permitted

Consistency models summary

Consistency	Description
Strict	Absolute time ordering of all shared accesses matters.
Linearizability	All processes must see all shared accesses in the same order. Accesses are furthermore ordered according to a (nonunique) global timestamp
Sequential	All processes see all shared accesses in the same order. Accesses are not ordered in time
Causal	All processes see causally-related shared accesses in the same order.
FIFO	All processes see writes from each other in the order they were used. Writes from different processes may not always be seen in that order

Consistency	Description
Weak	Shared data can be counted on to be consistent only after a synchronization is done
Release	Shared data are made consistent when a critical region is exited
Entry	Shared data pertaining to a critical region are made consistent when a critical region is entered.

Non-Blocking Synchronization

Locks: a litany of problems

- Deadlock
- Priority inversion
- Convoys
- Fault Isolation
- Preemption Tolerance
- Performance

Solution: don’t use locks

Lock-free programming

- Subset of a broader class: ***Non-blocking Synchronization***
- Thread-safe access shared mutable state without mutual exclusion
- Possible without HW support
  - e.g. Lamport's Concurrent Buffer
  - …but not really practical wo HW
- 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

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

```
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;
    last->next = new_node;
}
```

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

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)
      ;
    Q_buf[h] = data;
    Q_head = next(h);
```

- 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;
};
```

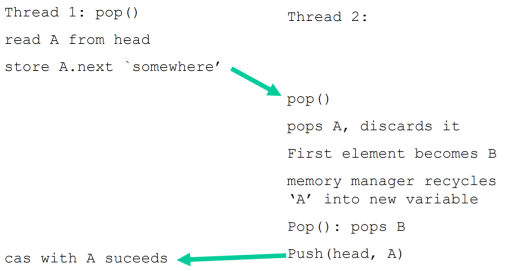
```
void push(int t) {
    Node* node = new Node(t);
    do {
        node->next = head;
    } while (!cas(&head, node, node->next));
}

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

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

Lock-Free Stack: ABA Problem

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

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



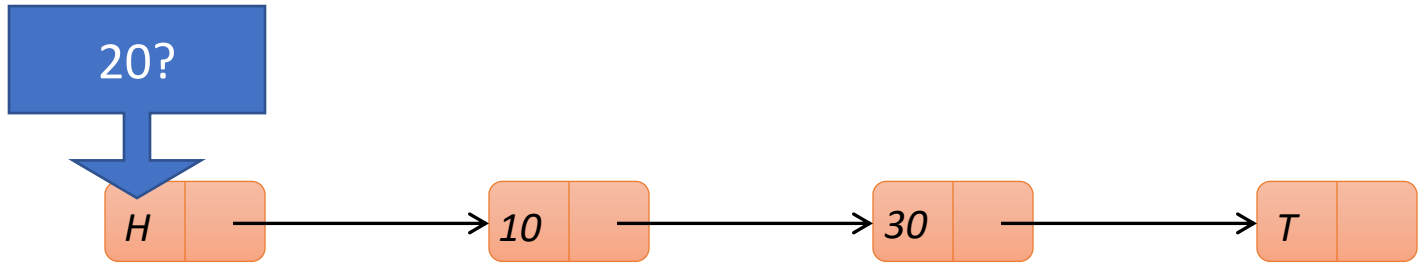
ABA Problem

- 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

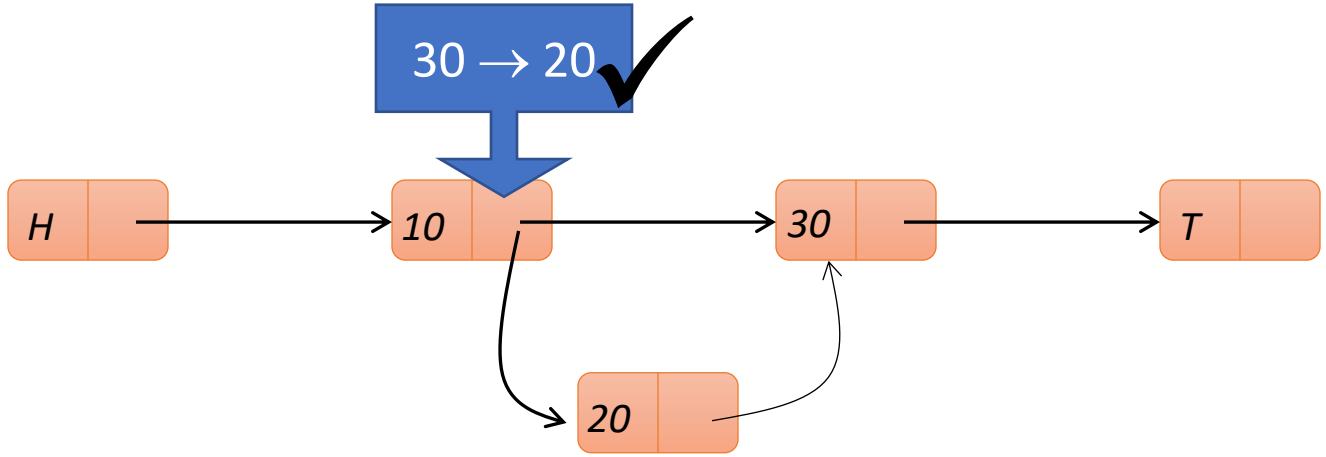
- find(20):



find(20) -> false

Inserting an item with CAS

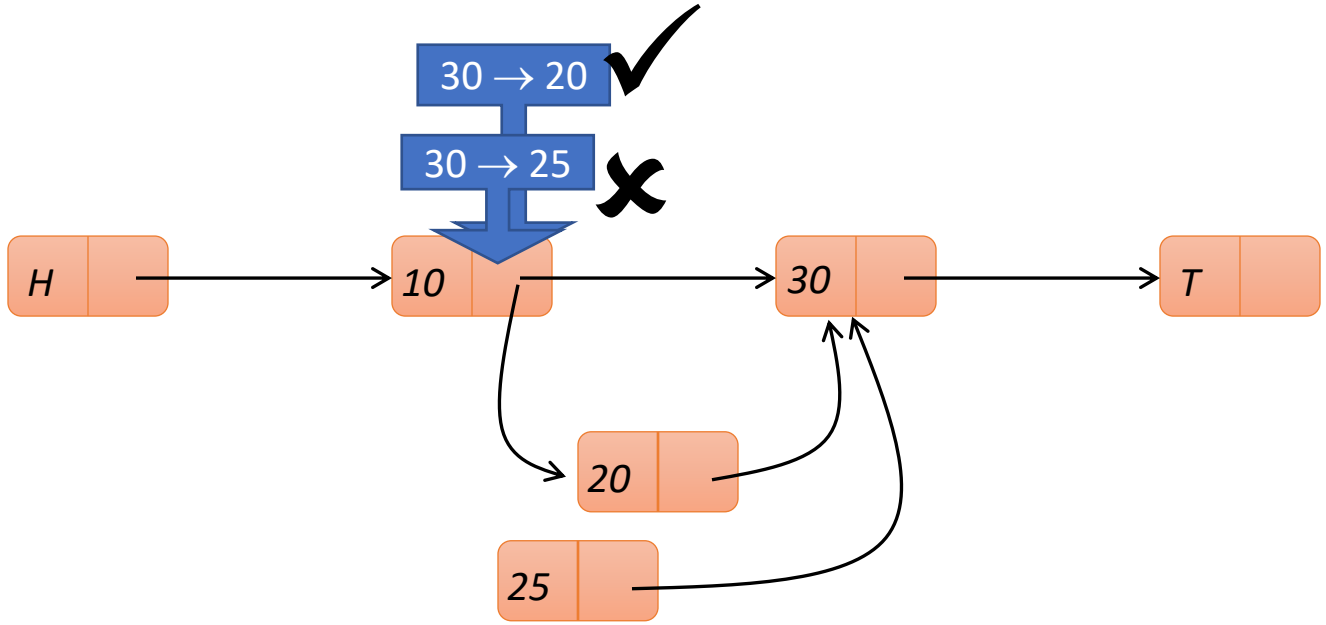
- insert(20):



insert(20) -> true

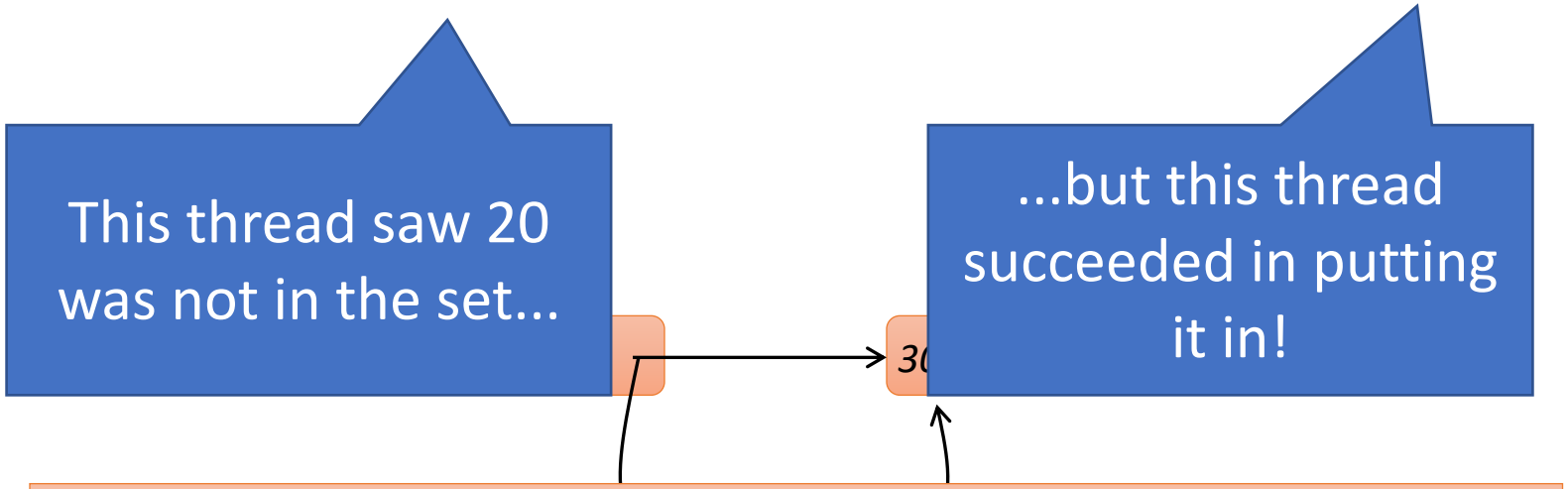
Inserting an item with CAS

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



Searching and finding together

- find(20) -> false
- insert(20) -> true



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

Correctness criteria

Informally:

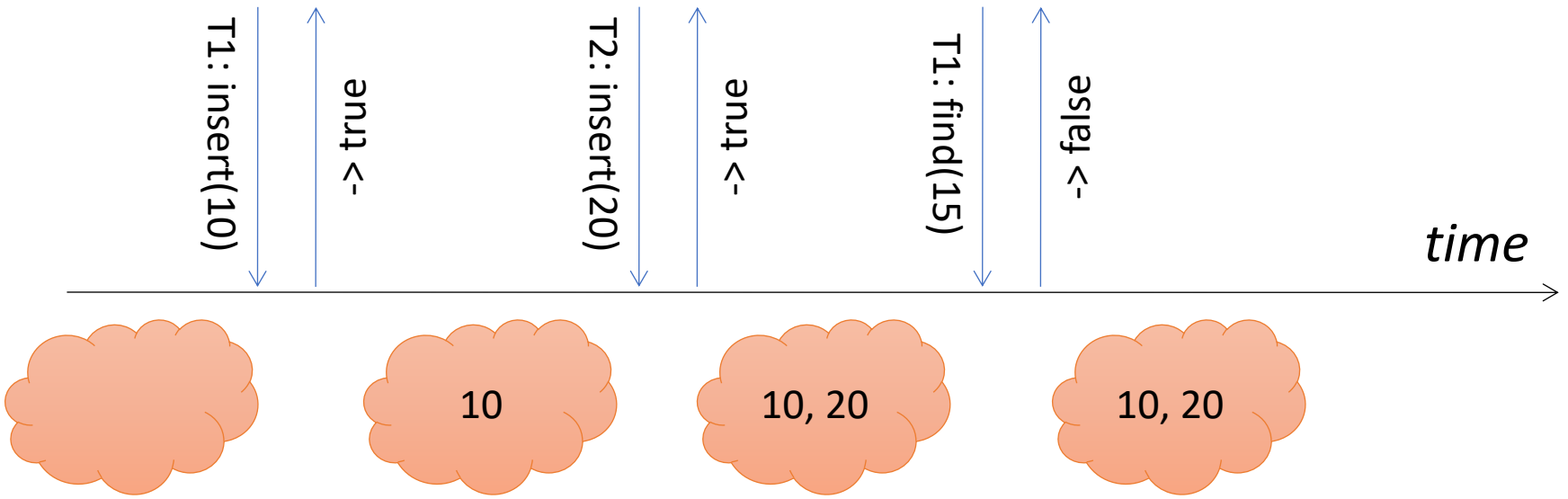
Look at the behavior of the data structure

- 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



Linearizability: concurrent behaviour should be similar

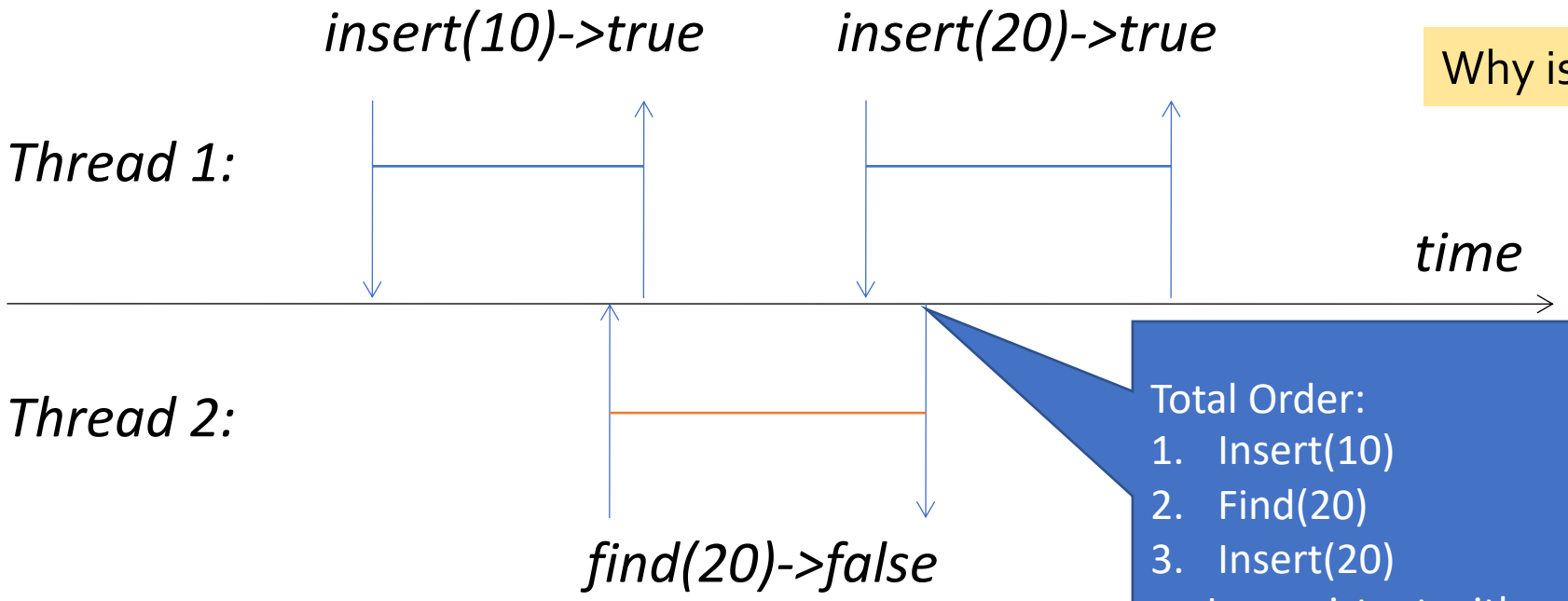
- even when threads can see intermediate state
- Recall: mutual exclusion precludes overlap

Concurrent history

Allow *overlapping* invocations

Linearizability:

- Is there a correct sequential history:
  - Same results as the concurrent one
  - Consistent with the timing of the invocations/responses?
  - Start/end impose ordering constraints



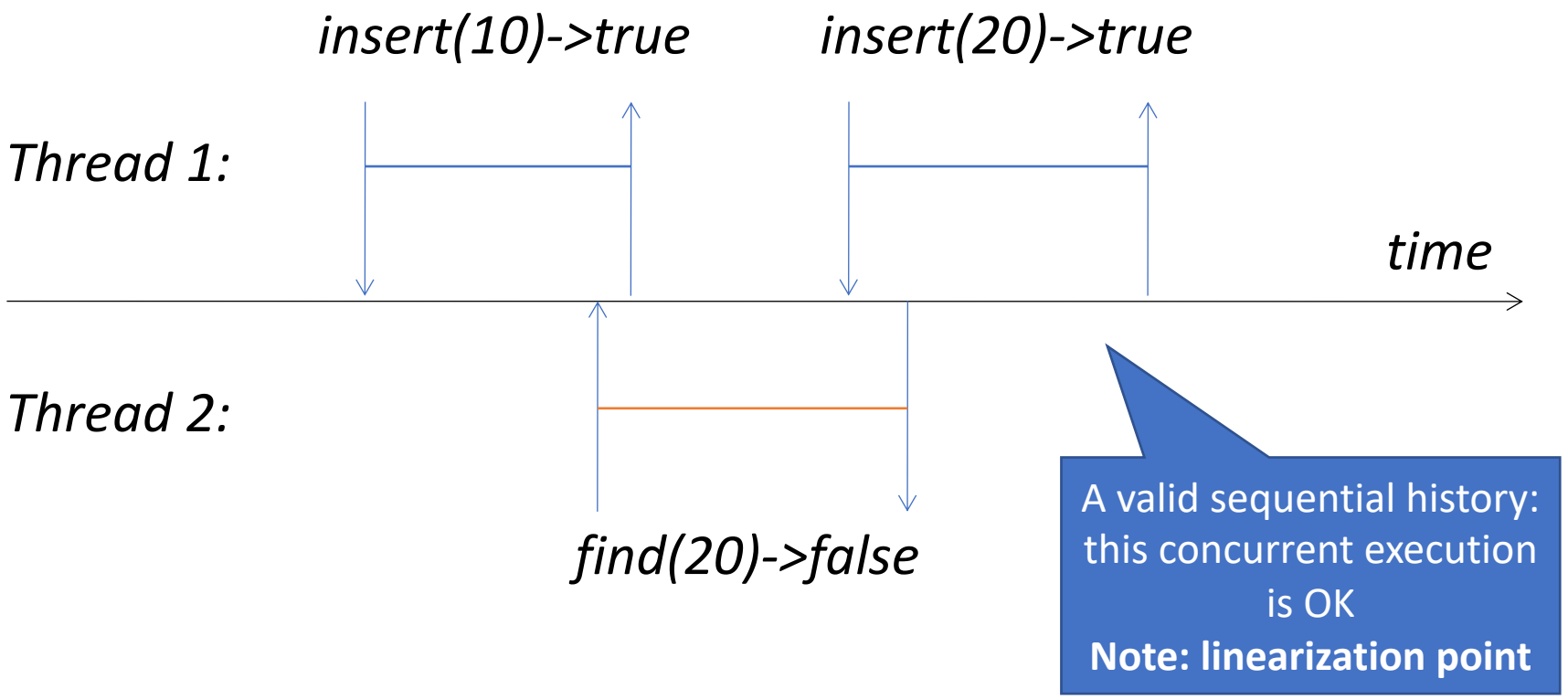
Why is this one OK?

Total Order:

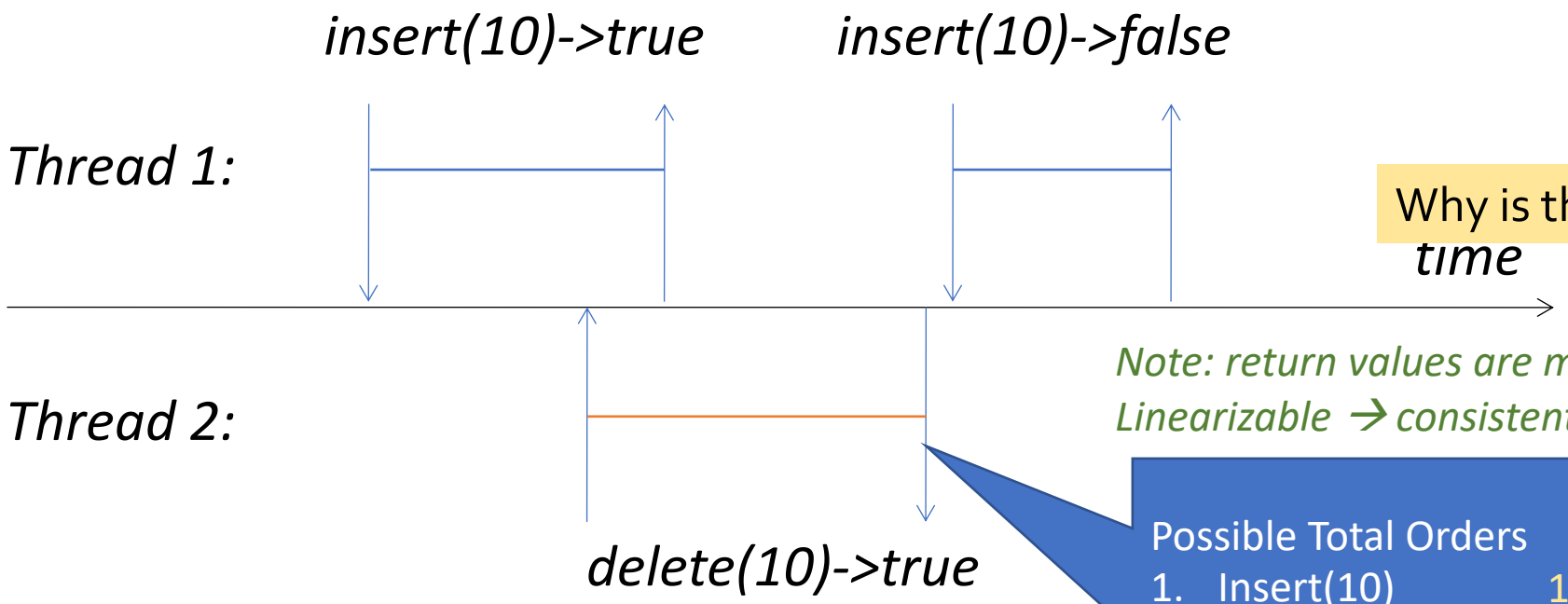
1. Insert(10)
2. Find(20)
3. Insert(20)

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

Example: linearizable



Example: not linearizable



Why is this one NOT OK?

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

Possible Total Orders

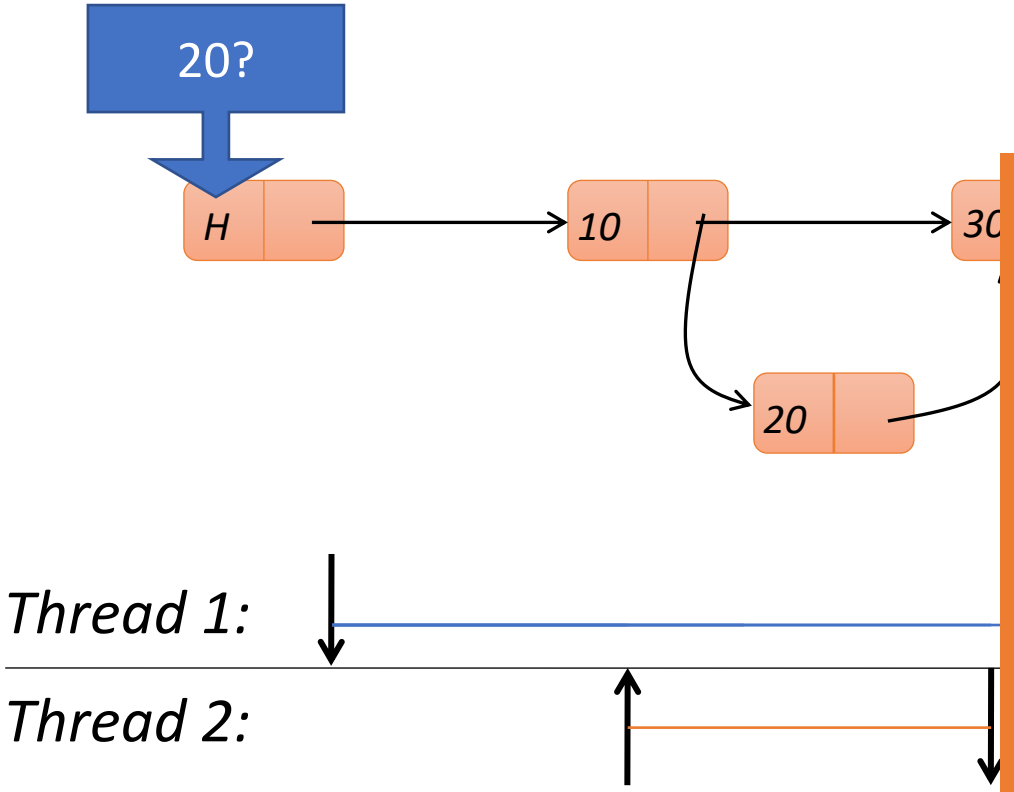
1. Insert(10)	1. Delete(10)
2. Delete(10)	2. Insert(10)
3. Insert(10)	3. Insert(10)

- Both consistent with real-time order
- 1, 2 overlap, but 3 doesn't

How can things like this happen?

Example Revisited

- find(20) -> false
- insert(20) -> true



Recurring Techniques:

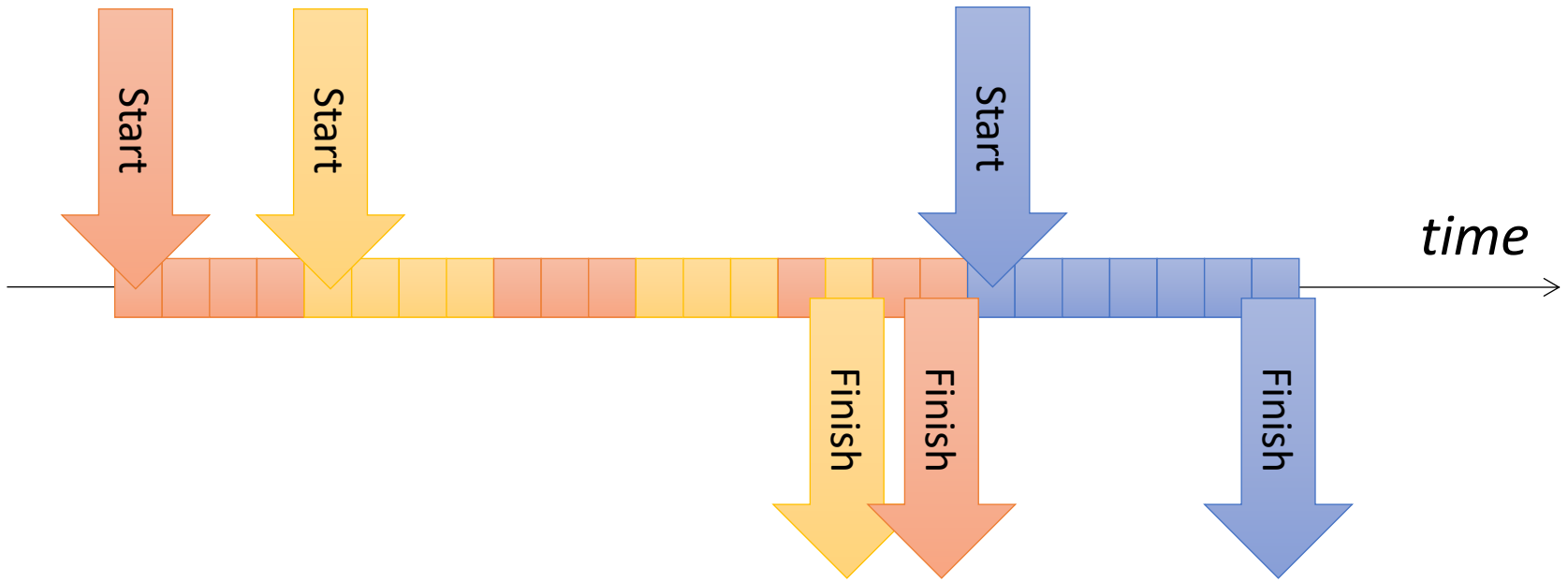
- For updates
  - Perform an essential step of an operation by a single atomic instruction
  - E.g. CAS to insert an item into a list
  - This forms a “linearization point”
- For reads
  - Identify a point during the operation’s execution when the result is valid
  - Not always a specific instruction

Formal Properties

- Wait-free
  - A thread finishes its own operation if it continues executing steps
  - Strong: everyone eventually finishes
- Lock-free
  - Some thread finishes its operation if threads continue taking steps
  - Weaker: some forward progress guaranateed, but admits unfairness, live-lock, etc.
- Obstruction-free
  - A thread finishes its own operation if it runs in isolation
  - Very weak. Means if you remove contention, someone finishes

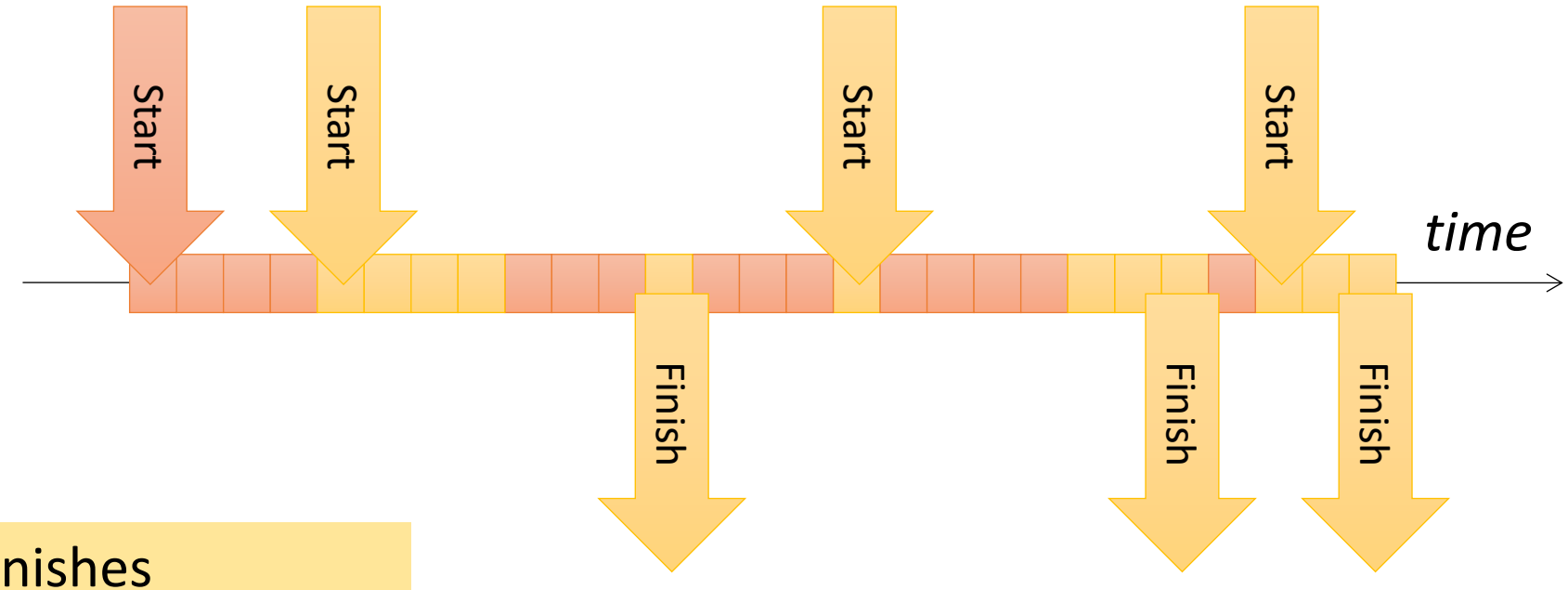
Wait-free

- A thread finishes its own operation if it continues executing steps



Lock-free

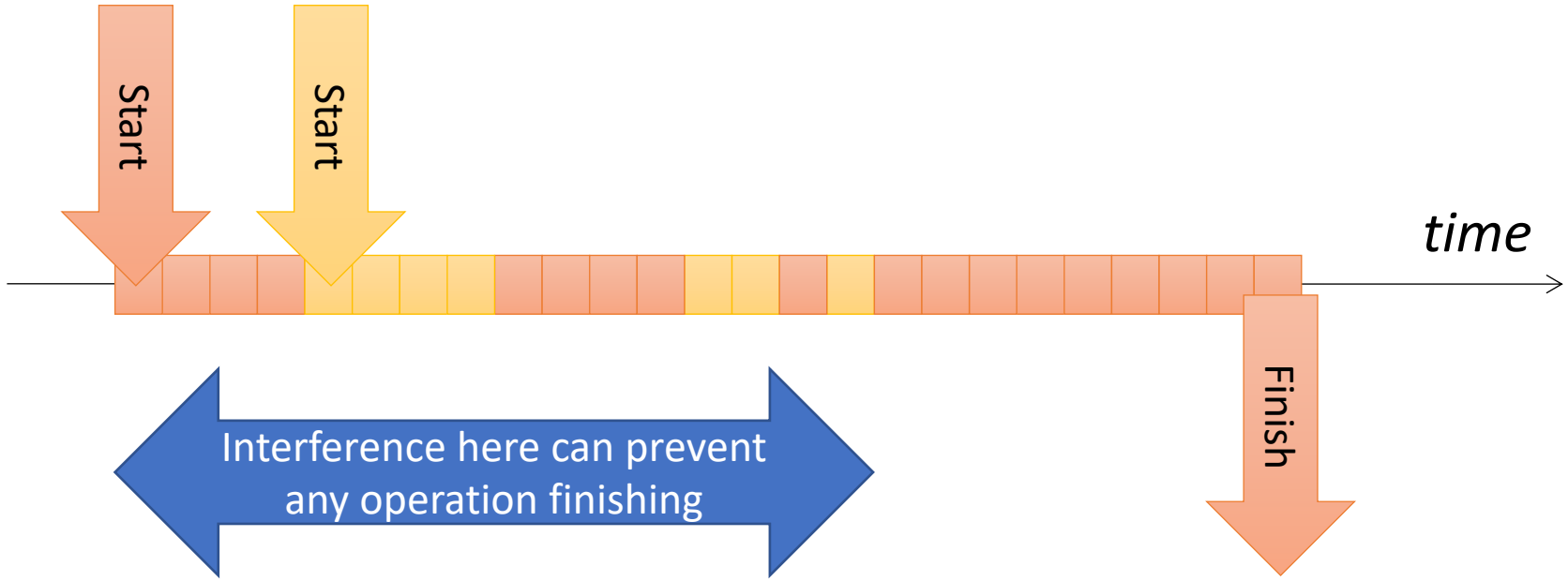
- Some thread finishes its operation if threads continue taking steps



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

Obstruction-free

- A thread finishes its own operation if it runs in isolation
- *Meaning, if you de-schedule contenders*



Formal Properties

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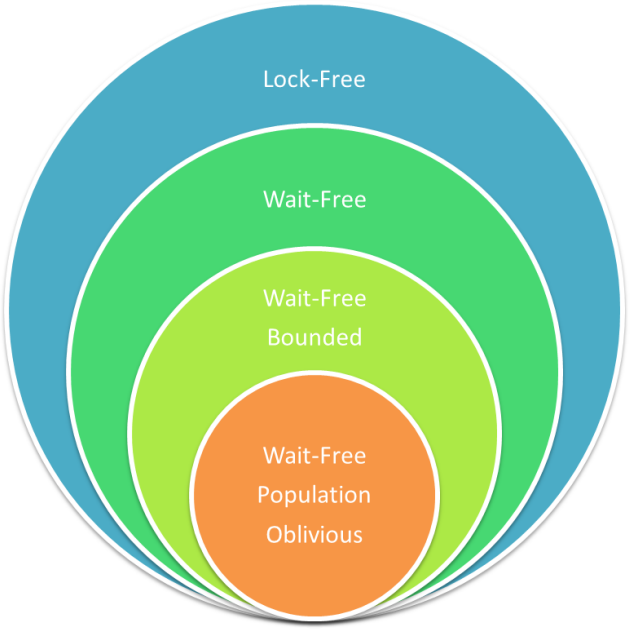
Blocking
1. Blocking
2. Starvation-Free

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

- non-blocking
  - one method is never forced to wait to sync with another.
- local property:
  - a system is linearizable iff each individual object is linearizable.
  - gives us **composability**.
- Why is it important?
  - Serializability is not composable.

Huh? Composable?

Composability

Thread-safe?

```
T * list::remove(Obj key){
  LOCK(this);
  tmp = __do_remove(key);
  UNLOCK(this);
  return tmp;
}

void list::insert(Obj key, T * val){
  LOCK(this);
  __do_insert(key, val);
  UNLOCK(this);
}
```

```
void move(list s, list d, Obj key){
  tmp = s.remove(key);
  d.insert(key, tmp);
}
void move(list s, list d, Obj key){
  LOCK(s);
  LOCK(d);
  tmp = s.remove(key);
  d.insert(key, tmp);
  UNLOCK(d);
  UNLOCK(s);
}
```

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

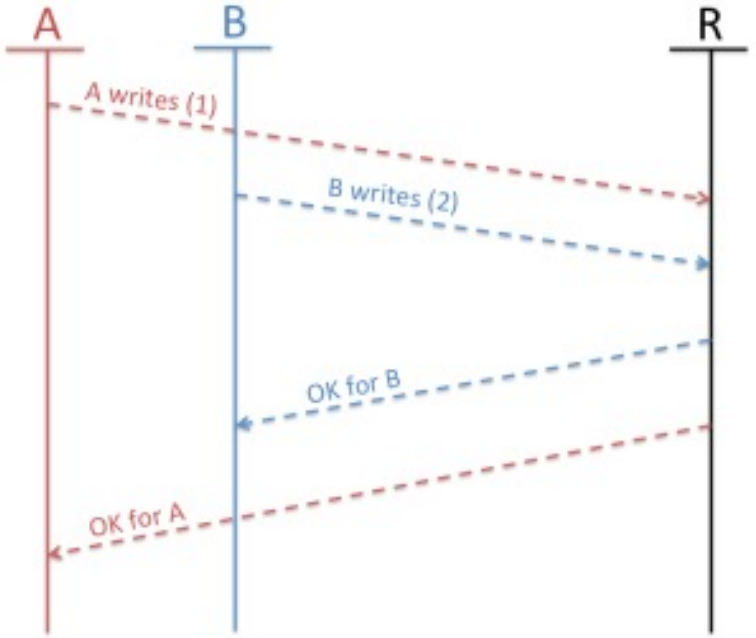
- non-blocking
  - one method is never forced to wait to sync with another.
- local property:
  - a system is linearizable iff each individual object is linearizable.
  - gives us **composability**.
- Why is it important?
  - Serializability is not composable.
  - Core hypotheses:
    - structuring all as concurrent objects buys composability
    - structuring all as concurrent objects is tractable/possible

More on Composability and Compositionality

- High level /informal meaning:
  - Can you compose codes that provide property P
  - …and expect the composition to preserve P?
- More nuanced meanings:
  - Can you compose codes
  - Can you compose schedules
- These are related but differ in subtle ways
- Non-composability of serializability is really about composing schedules

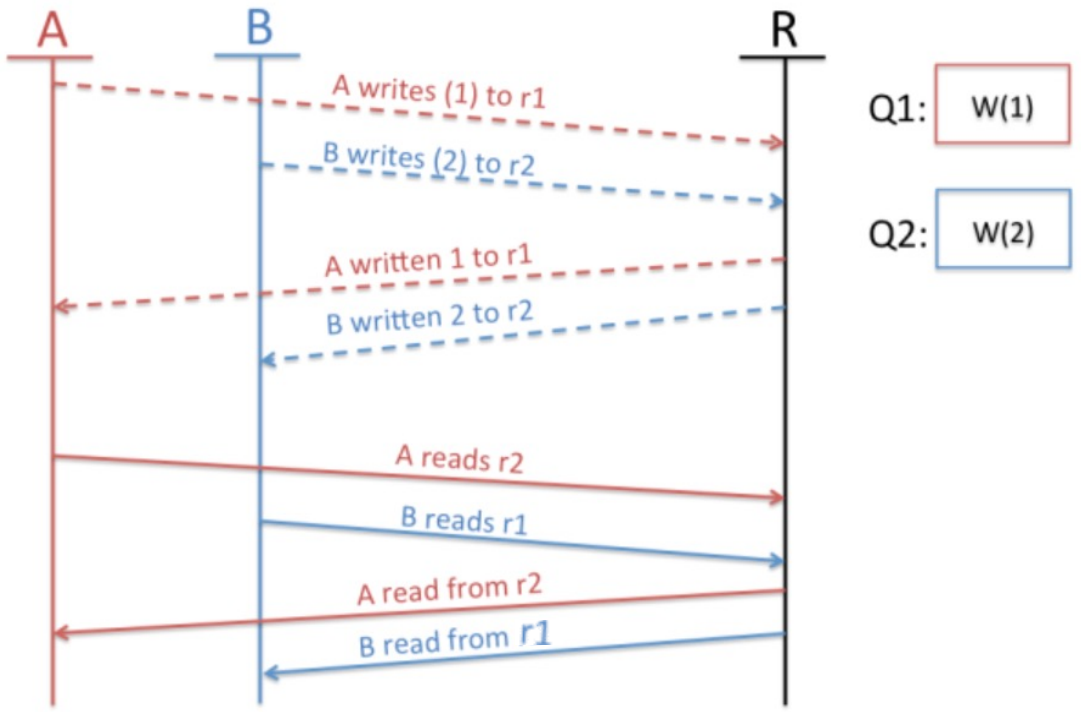
Consider A Concurrent Register

- Threads A, B write integers to a register R
- Because it’s concurrent, method invocations overlap



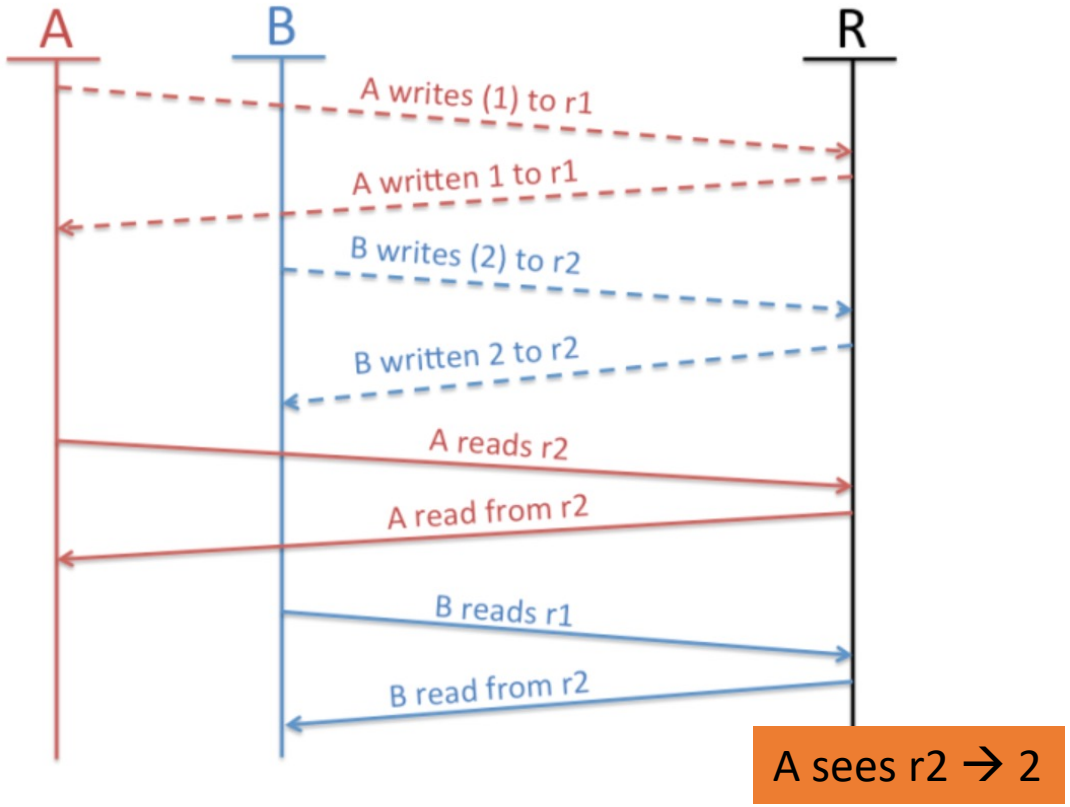
Two Concurrent Registers

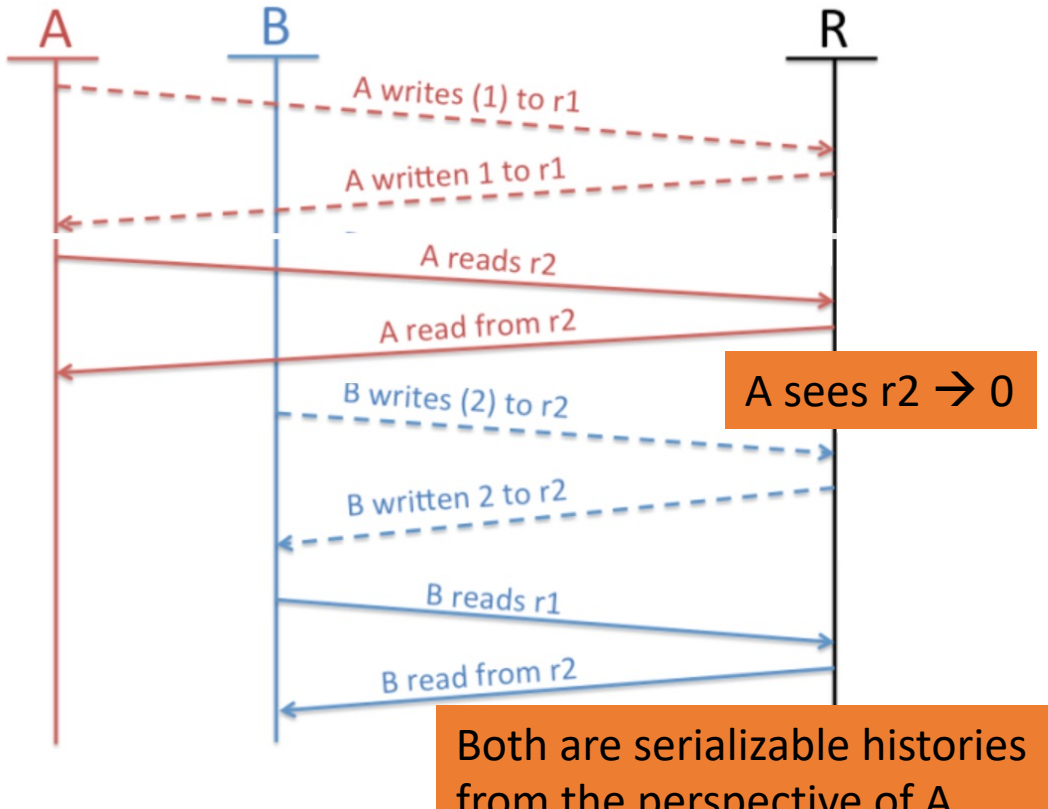
- Register value is initially zero
- The following operations occur:
  - Thread A:
    - write r1 = 1
    - read r2 → ?
  - Thread B:
    - B: write r2 -> 2
    - B: read r1 → ?
- Serializability:
  - Execution equivalent to *some serial order*
  - All see same order



Histories for multiple concurrent registers

- Consider all possible permutations of atomic invocations
  - (That respect program order)

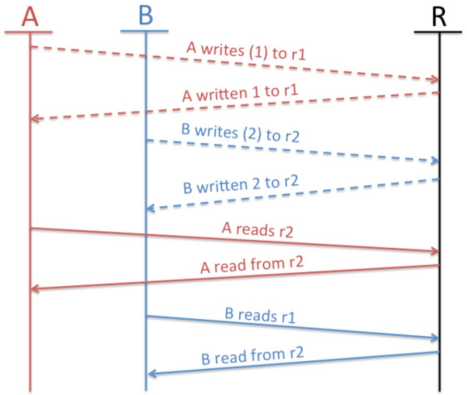


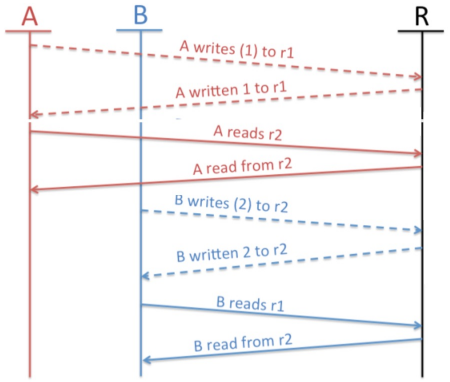


Histories for multiple concurrent registers

- Consider all possible permutations of atomic invocations
  - (That respect program order)
  - Call them “sub-histories”: from A, B “perspective”

Sub-History	Outcome
H1a	A writes r1=1, reads r2 → 0
H2a	A writes r1=1, reads r2 → 2
H1b	B writes r2=2, reads r1 → 0
H2b	B writes r2=2, reads r1 → 1





…

From the perspective 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

Histories for multiple concurrent registers

- Compose sub-histories to form all possible histories
- Composition of serializable histories → non-serializable histories
- Ex. H1ab is not serializable

Sub-History	Outcome
H1a	A writes r1=1, reads r2 → 0
H2a	A writes r1=1, reads r2 → 2
H1b	B writes r2=2, reads r1 → 0
H2b	B writes r2=2, reads r1 → 1

History	Effect
H1ab	A writes r1=1, B writes r2=2 reads r2 → 0, B reads r1 → 0
H2ab	A writes r1=1, B writes r2=2 reads r2 → 0, B reads r1 → 1
H3ab	A writes r1=1, B writes r2=2 reads r2 → 2, B reads r1 → 0
H4ab	A writes r1=1, B writes r2=2 reads r2 → 2, B reads r1 → 1

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

Linearizability Properties

- non-blocking
  - one method is never forced to wait to sync with another.
- local property:
  - a system is linearizable iff each individual object is linearizable.
  - gives us **composability**.
- Why is it important?
  - Serializability is not composable.
  - A system composed of linearizable objects remains linearizable
  - Does this mean you get txn or lock-like composition for free?
    - In general no
    - Serializability is a property of transactions, or groups of updates
    - Linearizability is a property of concurrent objects
    - The two are often conflated (e.g. because txns update only a single object)

Practical difficulties:

- Key-value ma
- Population co
- Iteration
- Resizing the h

Options to consider when implementing a "difficult" operation:

- Relax the semantics
  (e.g., non-exact count, or non-linearizable count)
- Fall back to a simple implementation if permitted
  (e.g., lock the whole table for resize)
- Design a clever implementation
  (e.g., split-ordered lists)
- Use a different data structure
  (e.g., skip lists)