Safety, Liveness, and Consistency

How Do We Specify Distributed Systems?

Execution: Sequence of events (i.e., steps taken by the system), potentially infinite.

Property: A predicate on executions.

Safety property: Specifies the "bad things" that shouldn't happen in any execution.

Liveness property: Specifies the "good things" that should happen in every execution.

(See paper for formal definitions.)

Theorem: Every property is expressible as the conjunction of a safety property and a liveness property.

Neat automata theory!

[Alpern and Schneider. 1987]

Some Properties

The system never deadlocks.

Every client that sends a request eventually gets a reply.

Both generals attack simultaneously.

More Properties: Consensus

n processes, all of which have an input value from some domain. Processes output a value by calling *decide*(v).

Non-faulty processes continue correctly executing protocol steps forever. We usually denote the number of faulty processes f.

Agreement: No two correct processes decide different values.

Integrity: Every correct process decides at most one value, and if a correct process decides a value v, some process had v as its input.

Termination: Every correct process eventually decides a value.

Consistency is Key!

Consistency: *the allowed semantics (return values) of a set of operations to a data store or shared object.*

Consistency properties specify the **interface**, not the **implementation**. The data might be replicated, cached, disaggregated, etc. "Weird" consistency semantics happen all over the stack!

Anomaly: violation of the consistency semantics

Terminology

Strong consistency: the system behaves as if there's just a single copy of the data (or almost behaves that way).

The intuition is that things like caching and sharding are implementation decisions and shouldn't be visible to clients.

Weak consistency: allows behaviors significantly different from the single store model.

Eventual consistency: the aberrant behaviors are only temporary.

Why the Difference?

Performance

Consistency requires synchronization/coordination when data is replicated

Often slower to make sure you always return right answer

Availability

What if client is offline, or network is not working?

Weak/eventual consistency may be only option

Programmability

Weaker models are harder to reason against

Lamport's Register Semantics

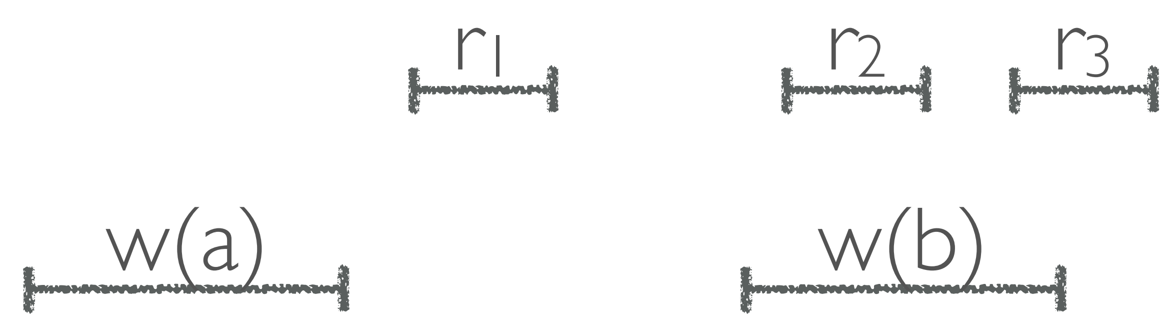
Registers hold a single value. Here, we consider single-writer registers only supporting `write` and `read`.

Semantics defined in terms of the *real-time* beginnings and ends of operations to the object.

safe: a read not concurrent with any write obtains the previously written value

regular: safe + a read that overlaps a write obtains either the old or new value

atomic: safe + reads and writes behave as if they occur in some definite order



safe $\Rightarrow r_1 \rightarrow a$

regular $\Rightarrow r_1 \rightarrow a \wedge (r_2 \rightarrow a \vee r_2 \rightarrow b) \wedge$
$(r_3 \rightarrow a \vee r_3 \rightarrow b)$

atomic $\Rightarrow r_1 \rightarrow a \wedge (r_2 \rightarrow a \vee r_2 \rightarrow b) \wedge$
$(r_3 \rightarrow a \vee r_3 \rightarrow b) \wedge$
$(r_2 \rightarrow b \Rightarrow r_3 \rightarrow b)$

Sequential Consistency

Applies to arbitrary shared objects.

Requires that a history of operations be *equivalent to a legal sequential history*, where a legal sequential history is one that respects the local ordering at each node.

Called **serializability** when applied to transactions

Is It Sequential?

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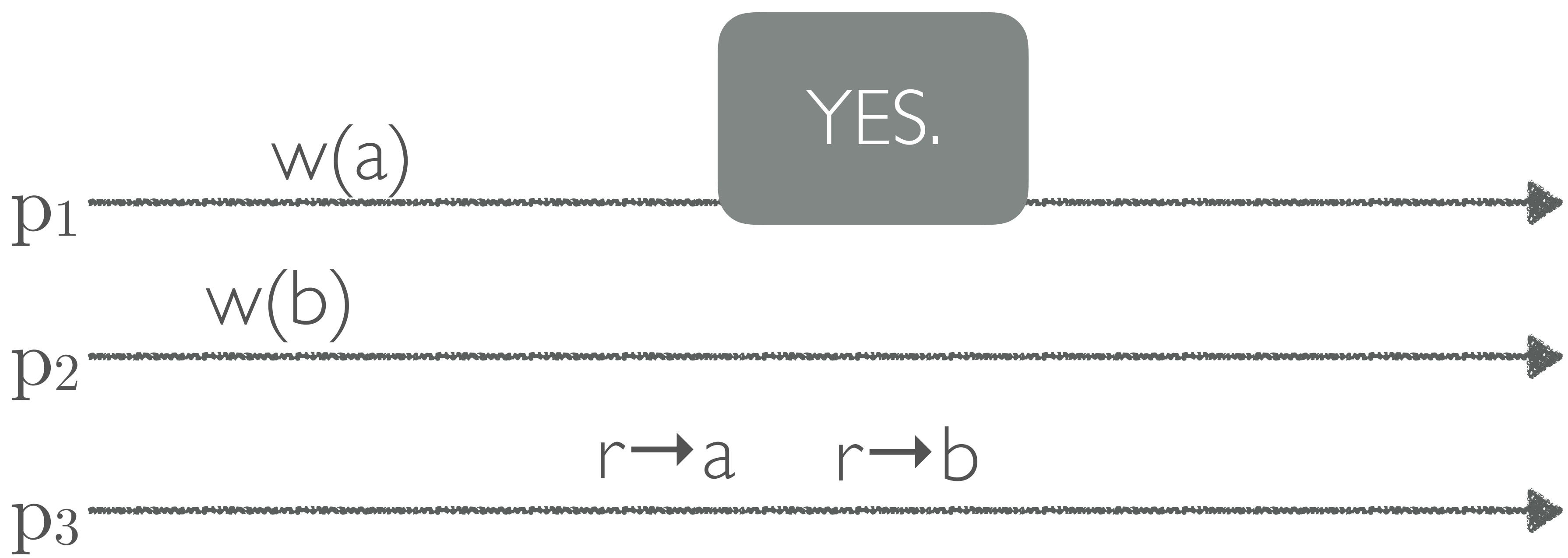

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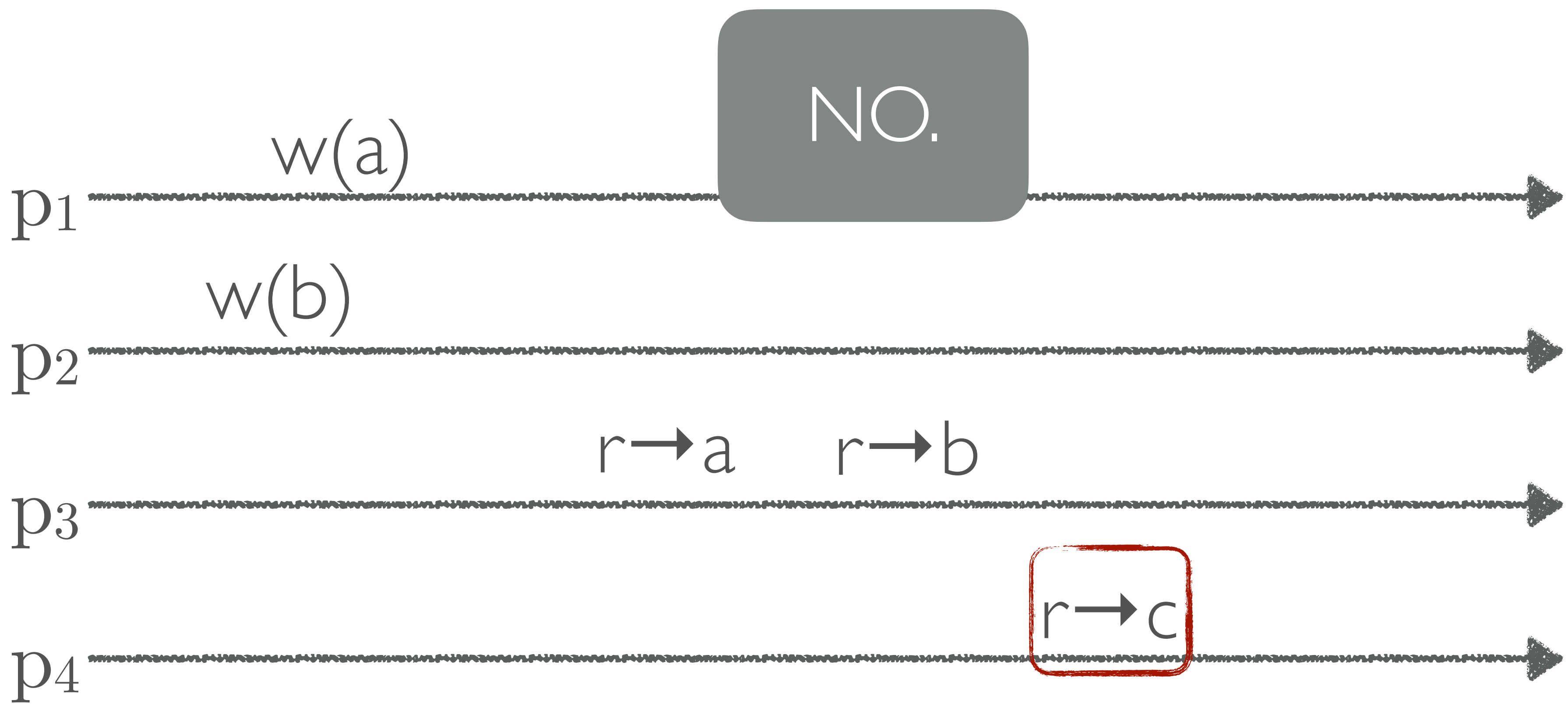

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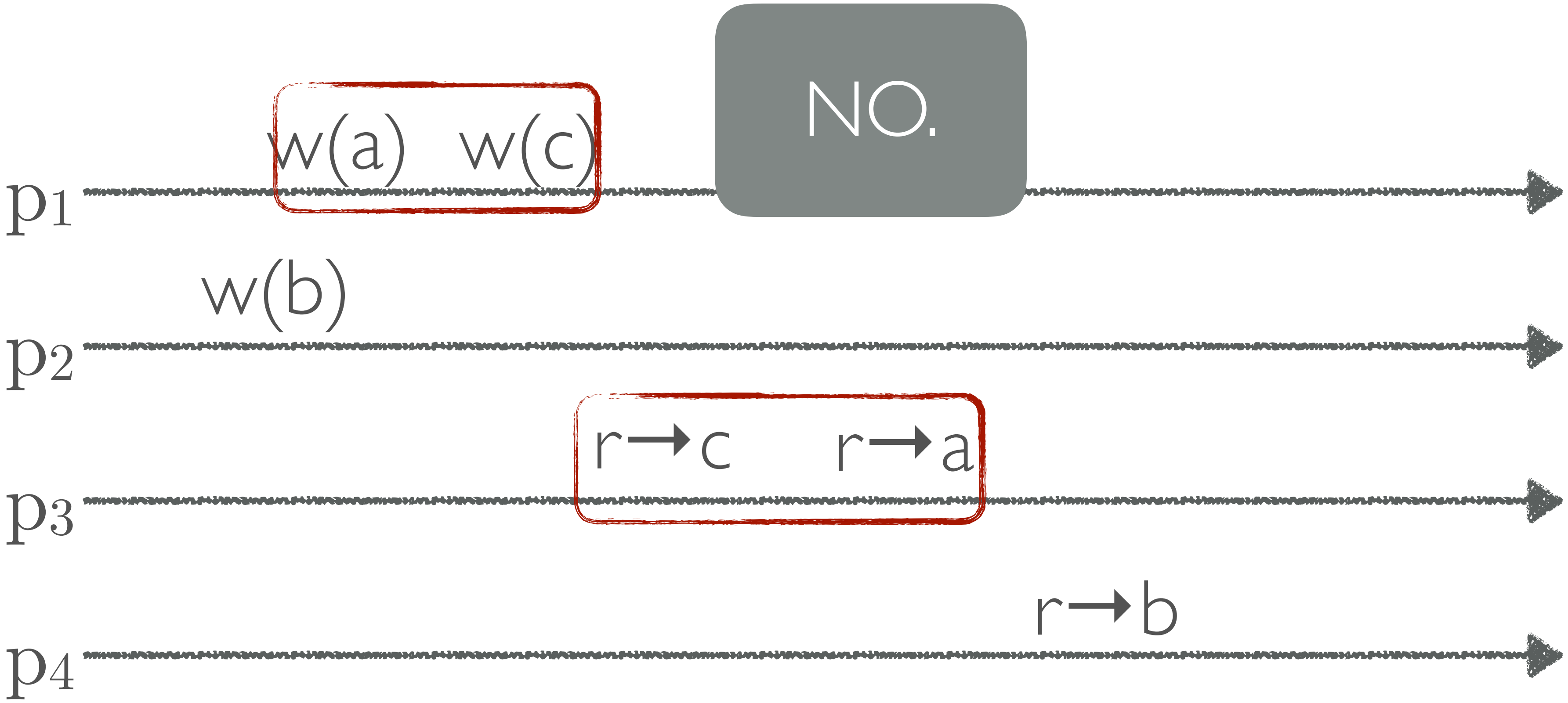

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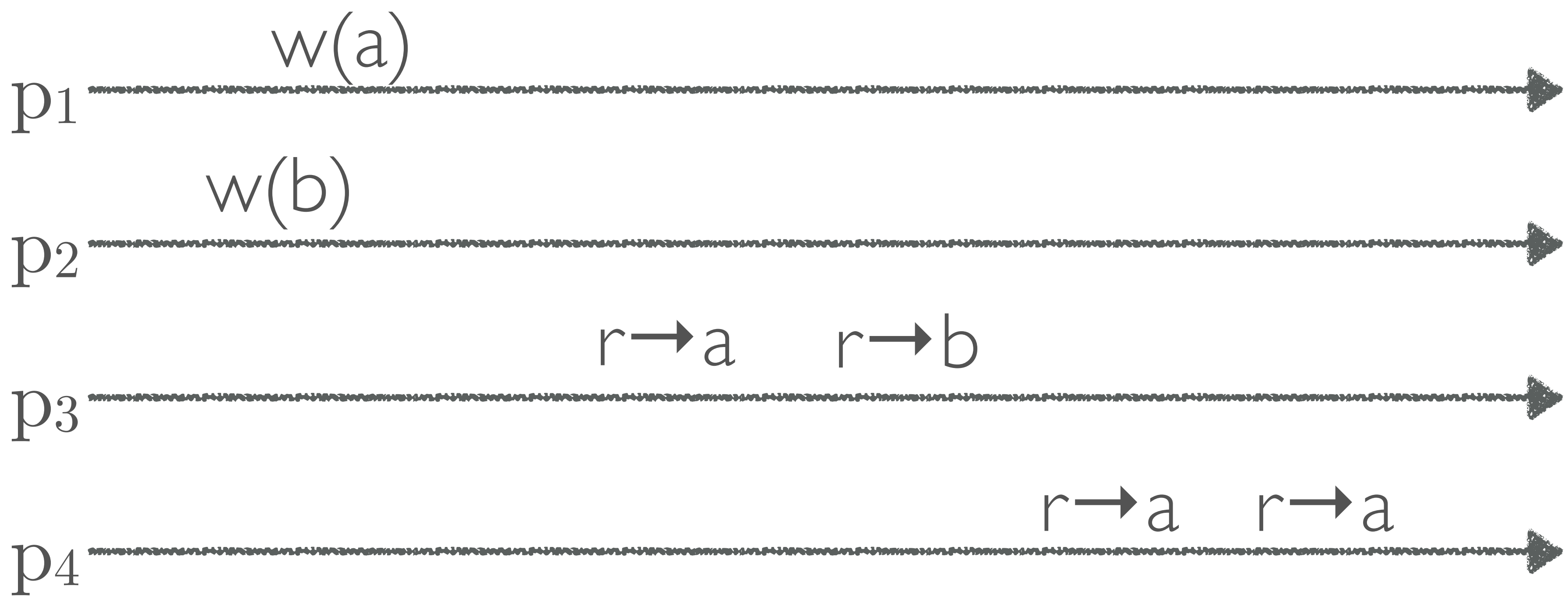
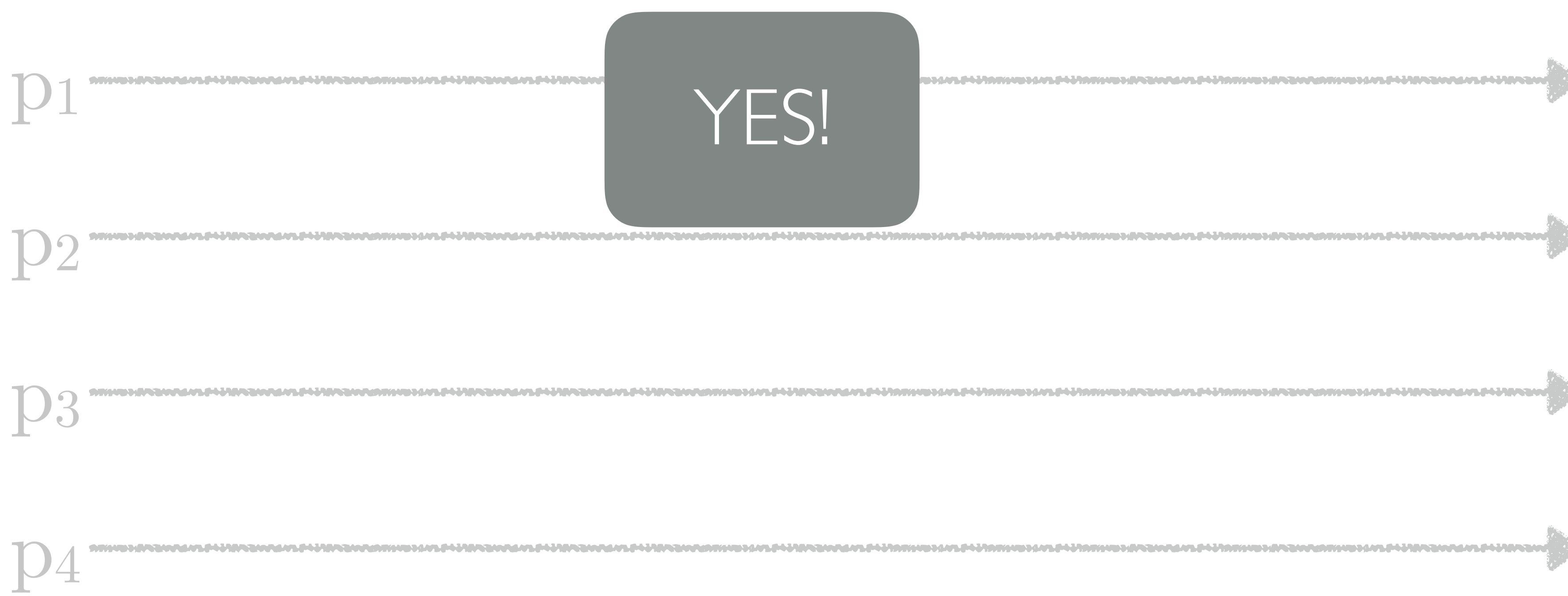
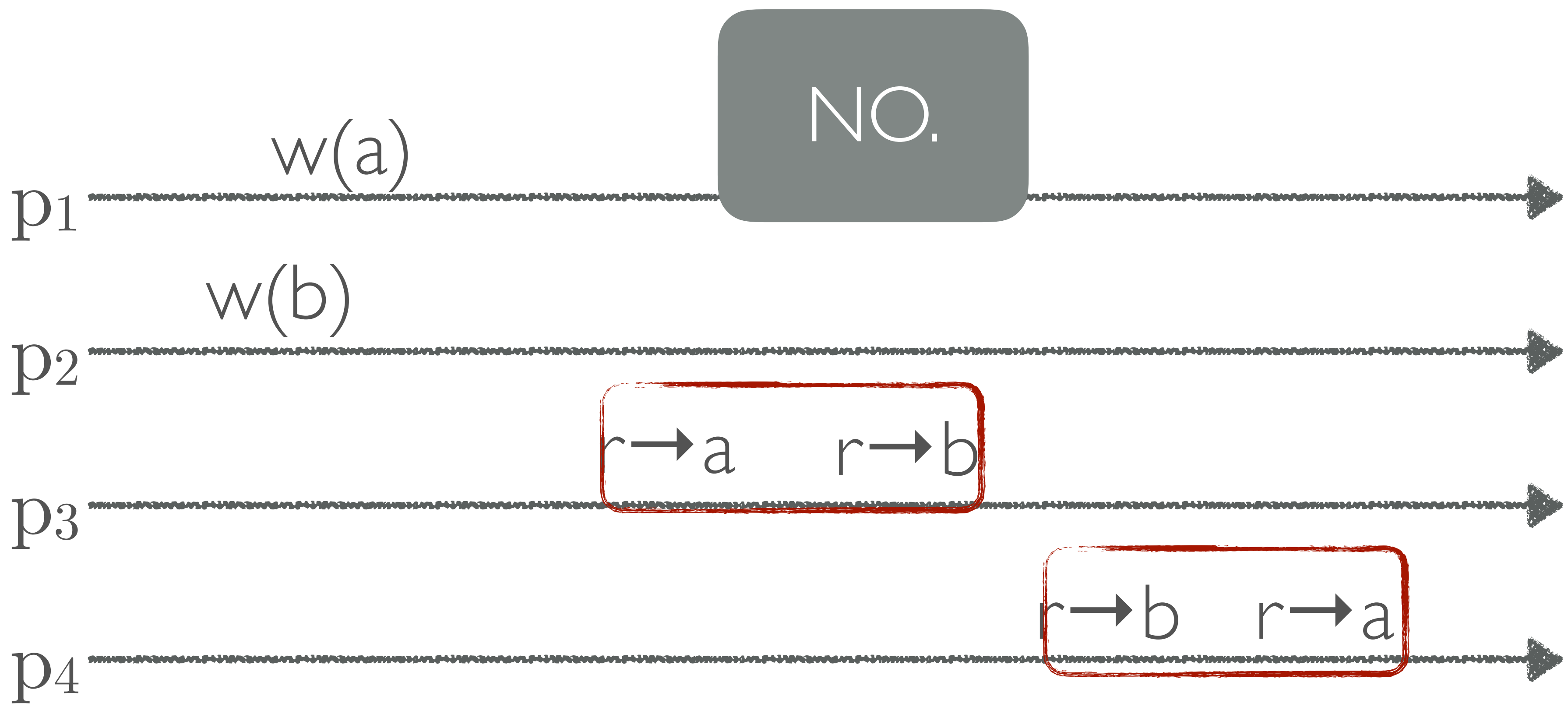


Is It Sequential?

w(a) r→a r→a r→a w(b) r→b



Is It Sequential?



Linearizability

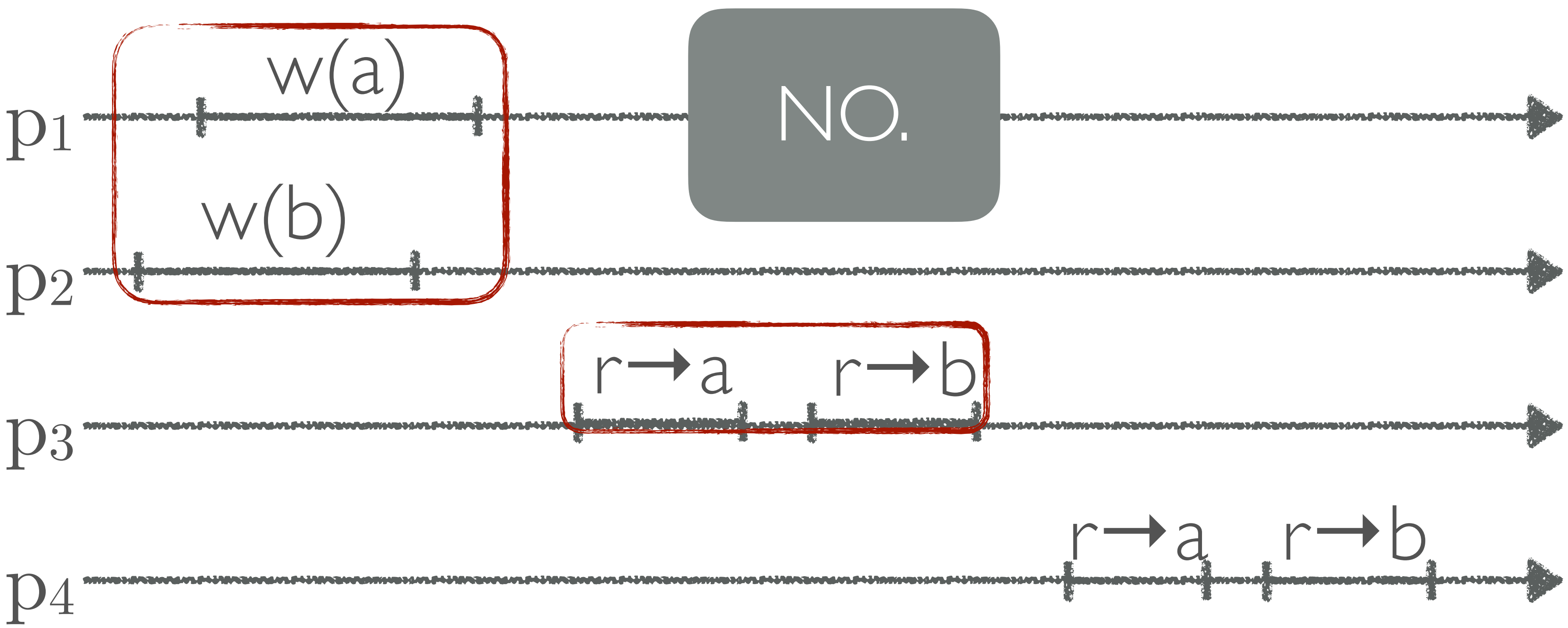
Linearizability = sequential consistency + respects real-time ordering.

If e_1 **ends** before e_2 **begins**, *then* e_1 *appears before* e_2 *in the sequential history.*

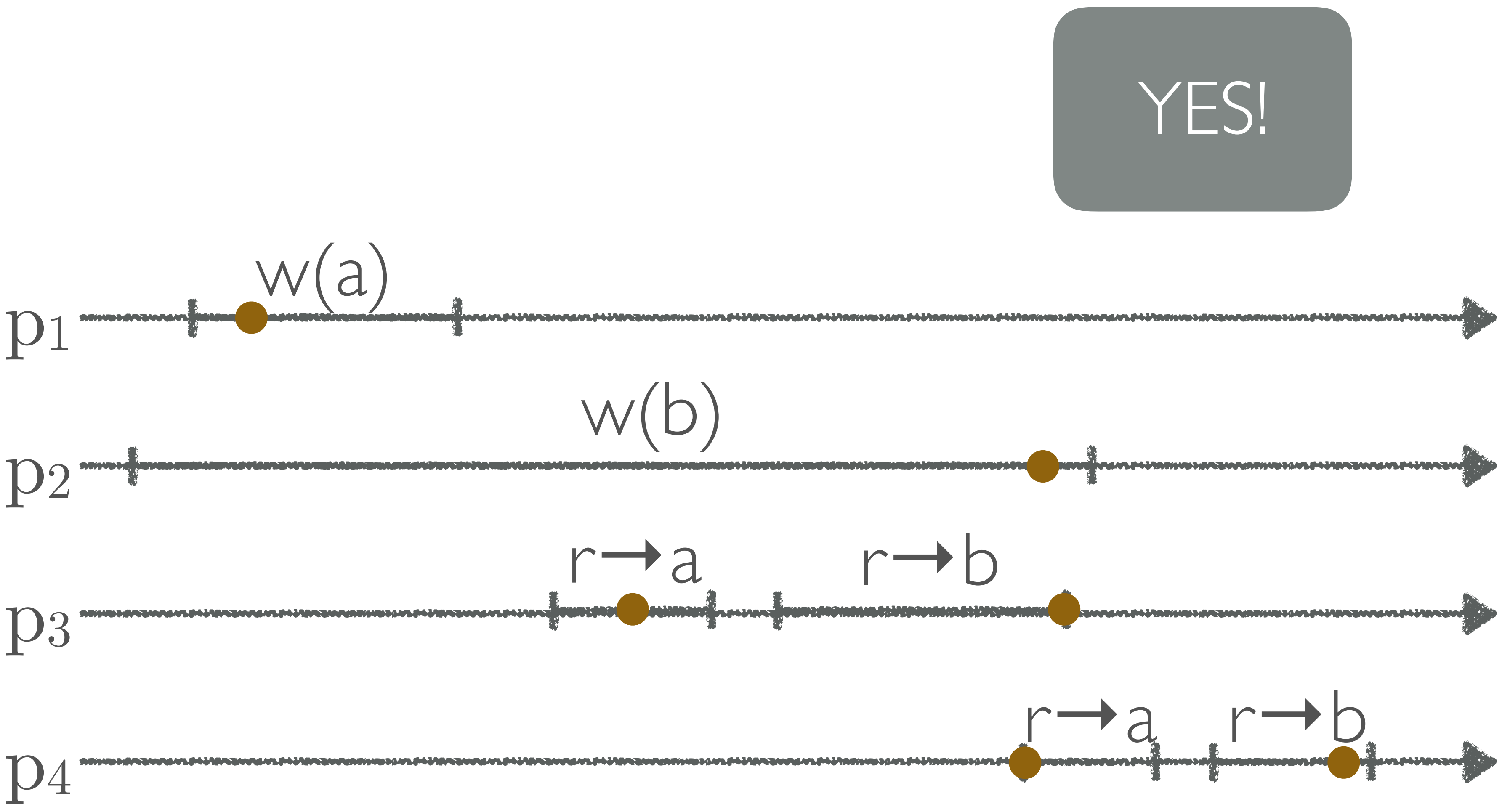
Linearizable data structures behave as if there's a single, correct copy.

Atomic registers are linearizable.

Is It Linearizable?



Is It Linearizable?

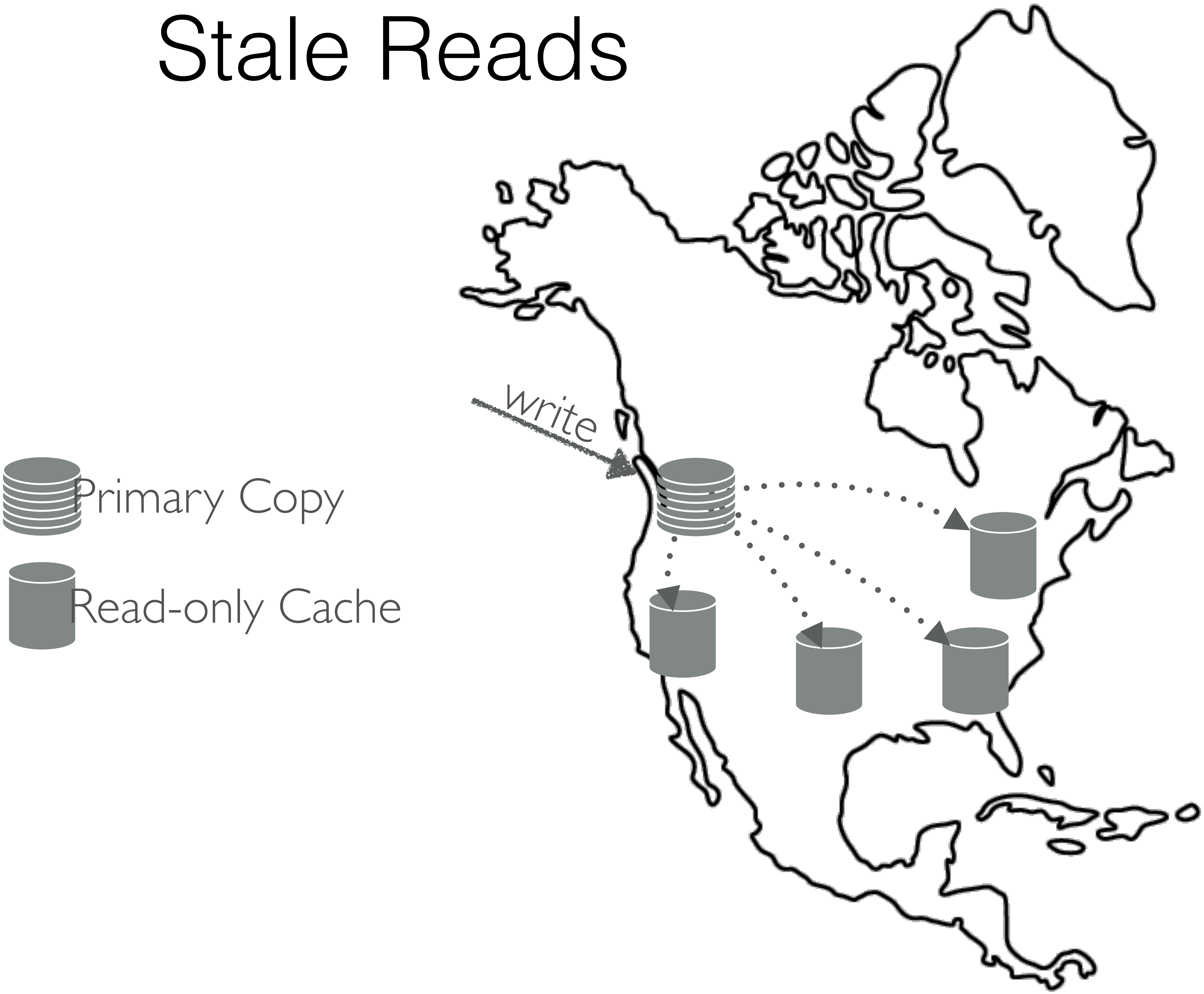


Linearizability vs. Sequential Consistency

Sequential consistency allows operations to appear out of real-time order. How could that happen in reality?

The most common way systems are sequentially consistency but not linearizability is that they allow read-only operations to return **stale data**.

Stale Reads

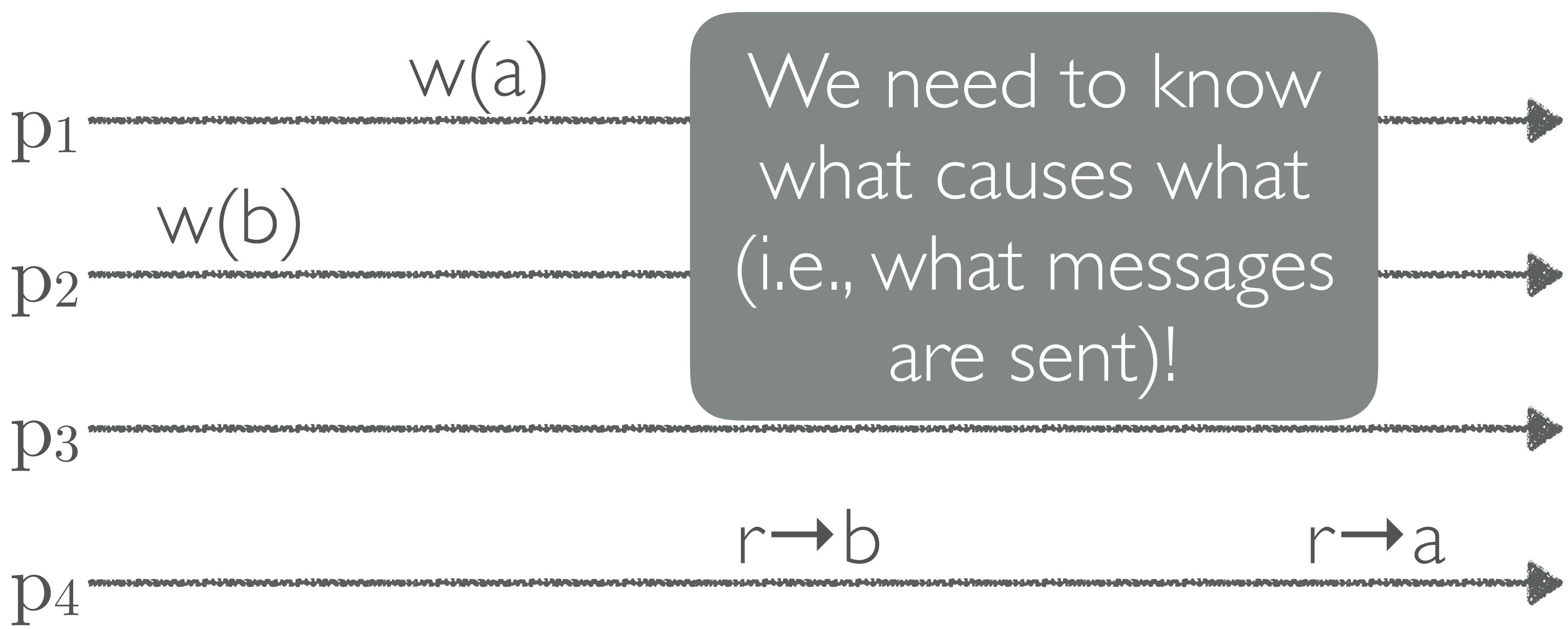


Causal Consistency

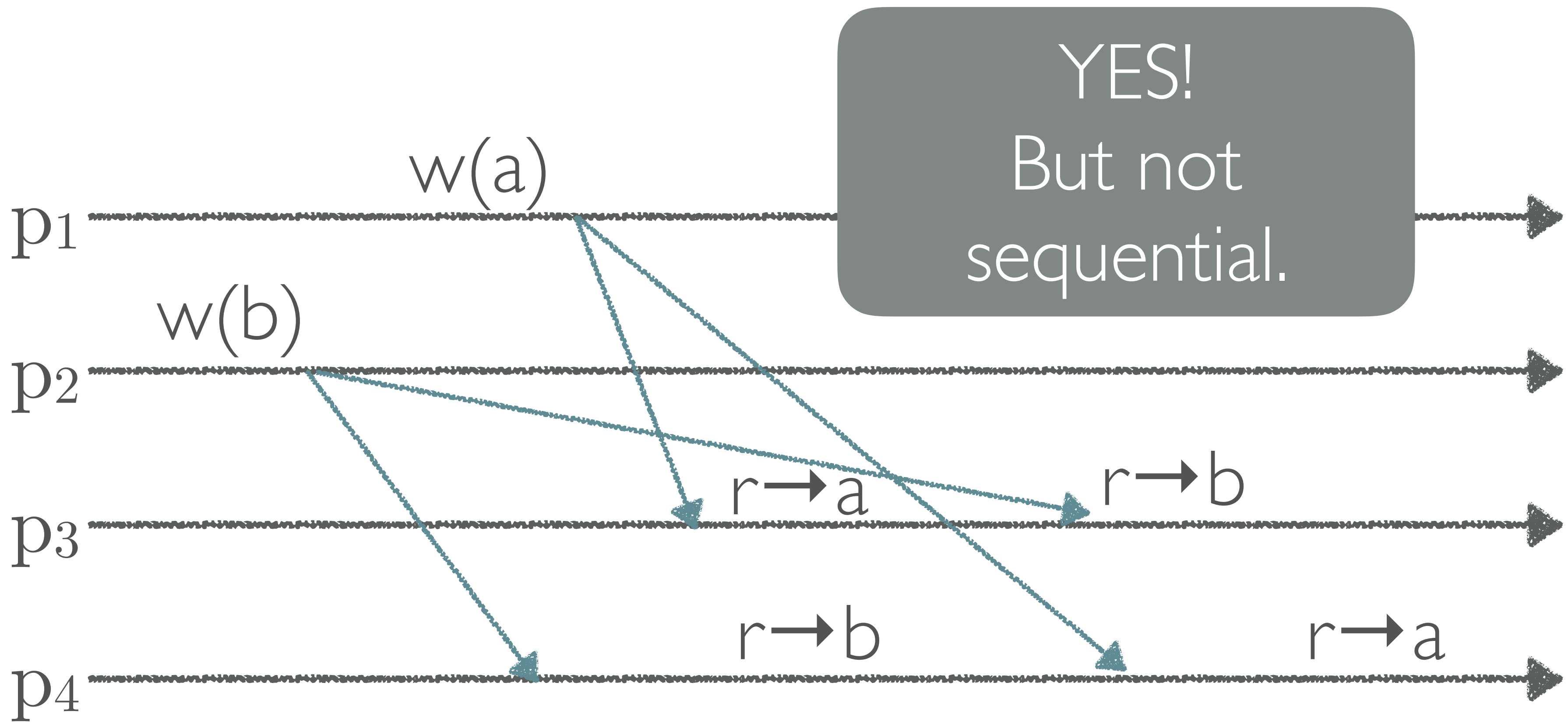
Writes that are not concurrent (i.e., writes related by the happens-before relation) must be seen in that order. Concurrent writes can be seen in different orders on different nodes.

Linearizability implies causal consistency.

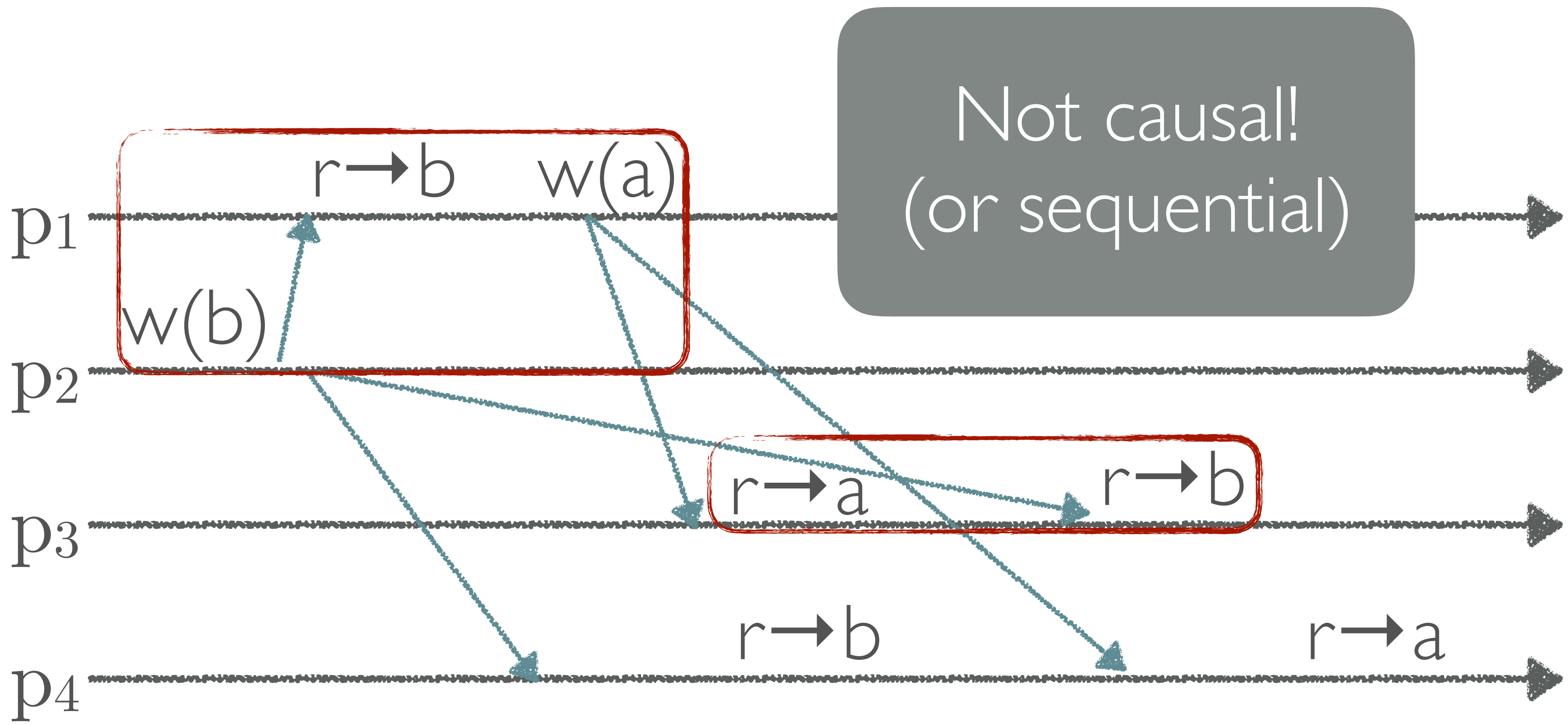
Is It Causal?


w(a)
w(b)
p1
p2
p3
p4
We need to know what causes what (i.e., what messages are sent)!
r→b
r→a

Is It Causal?



Is It Causal?



Cool Theorem: Causal consistency* is the strongest form of consistency that can be provided in an always-available convergent system.

Basically, if you want to process writes even in the presence of network partitions and failures, causal consistency is the best you can do.

[Mahajan et al. UTCS TR-11-22]

*real-time causal consistency

We Can Get Weaker!

FIFO Consistency: writes done by the same process are seen in that order; writes to different processes can be seen in different orders. Equivalent to the PRAM model.

Eventual Consistency ≈ if all writes to an object stop, eventually all processes read the same value. (Not even a safety property! "Eventual consistency is no consistency.")

Lamport's register semantics, sequential consistency, linearizability, and causal consistency, and FIFO consistency are all *safety properties*.

Using Consistency Guarantees

Depends on memory consistency!

Thread 1	**Thread 2**
`a = 1`	`b = 1`
`print("b:" + b)`	`print("a:" + a)`

Initially, both a and b are 0.

What are the possible outputs of this program?

Using Consistency Guarantees

Thread 1

```
a = 1
print("b:" + b)
```

Thread 2

```
b = 1
print("a:" + a)
```

Suppose both `prints` output 0.

Then there's a cycle in the happens-before graph.
Not sequential!

Aside: Java's Memory Model

Java is **not** sequentially consistent!

It guarantees sequential consistency only when the program is *data-race free*.

A **data-race** occurs when two threads access the same memory location concurrently, one of the accesses is a write, and the accesses are not protected by locks (or monitors etc.).

How to Use Weak Consistency?

Separate operations with stronger semantics, weak consistency (and high performance) by default

Application-level protocols, either using separate communication, or extra synchronization variables in the data store (not always possible)

Main Takeaways

The weaker the consistency model, the harder it is to program against (usually).

The stronger the model, the harder it is to enforce (again, usually).