What is the strongest consistency that could be achieved in a large scale distributed system?

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EPFL, INRIA

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Postdoc at EPFL/Inria

At EPFL in collaboration with:

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- **Partition** tolerance
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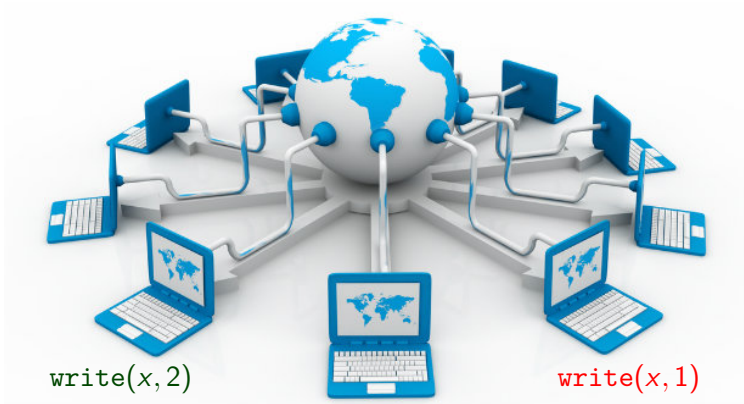

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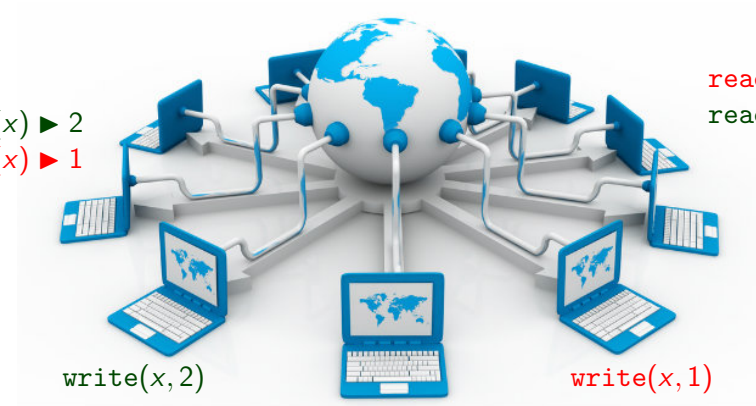

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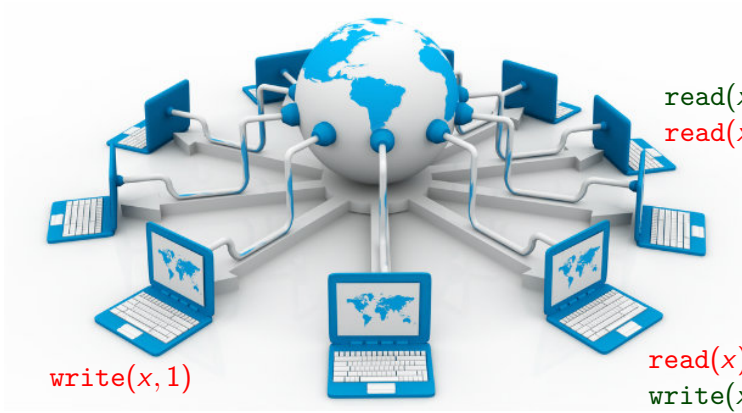

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Consistency issues

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Not possible with network failures and availability[1]

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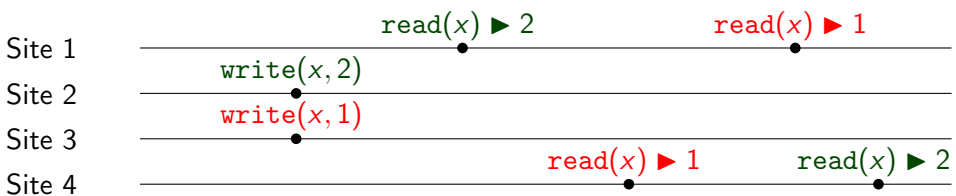

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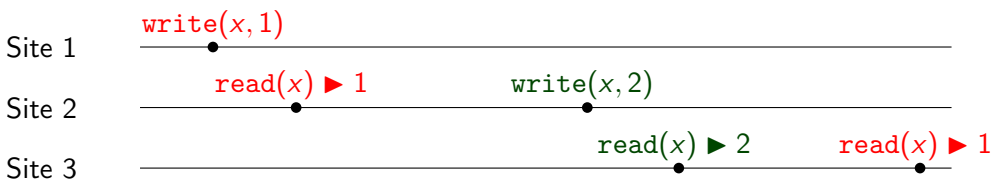

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What is the **strongest criterion** that can be implemented?

Difficulties for Implementing Distributed Data Structures

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$\Rightarrow$ Need for **verification** techniques

Two Verification Problems

- Check if **one trace** is consistent (Single-Trace Verification)
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We study these questions for **causal consistency**.

Outline

1. Strongest Consistency Criteria
2. Verification of Causal Consistency

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Constraints on the Implementations

- **Availability**: if a client makes a request, they obtain a response directly
- **Partition Tolerance**: messages between servers may be delayed/reordered/lost
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In that setting:

- Linearizable implementation is **not possible** (CAP theorem)
- Implementation where sites don't communicate: **not allowed** (not EC)
- Causal Consistency (CC) is **possible** (e.g. vector clocks)

Nothing Stronger than Causal Consistency can be Implemented

Theorem (Mahajan et al, 2011. Attiya et al, 2015.)

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What about criteria which are **not comparable** to causal consistency?

Monotonic Prefix Consistency

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All sites see increasing prefixes of the same global order

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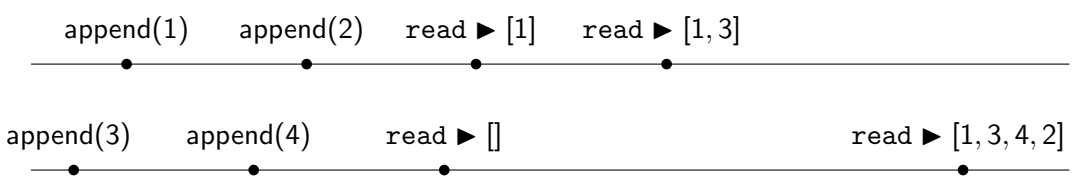
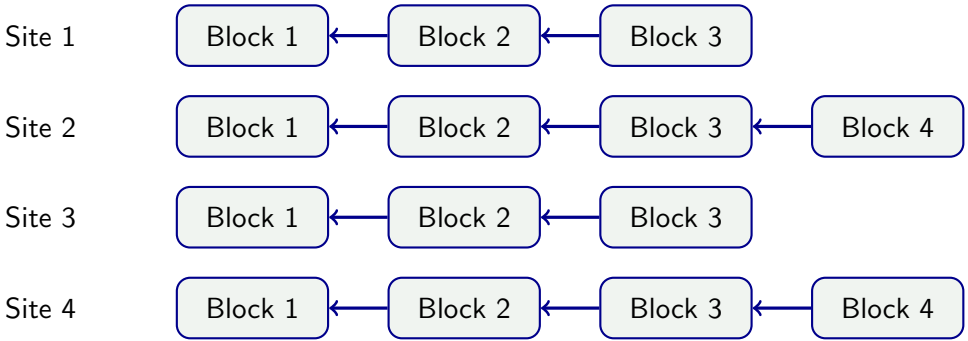


Blockchains implement Monotonic Prefix Consistency

In Bitcoin, sites maintain a **ledger** made of a chain of **blocks**



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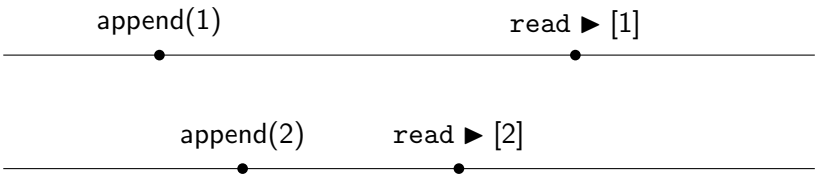

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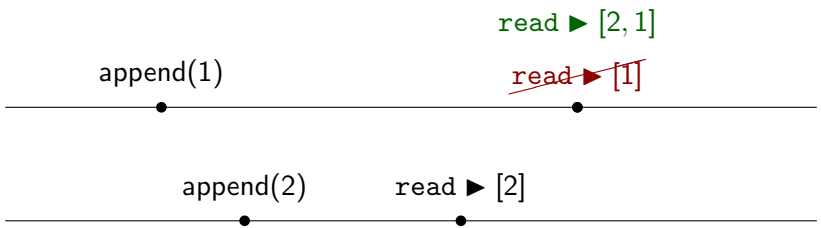

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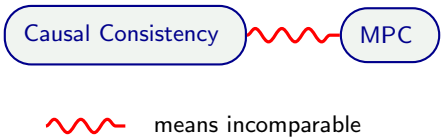
Comparison between Consistency Criteria

Diagram showing the different implementations:



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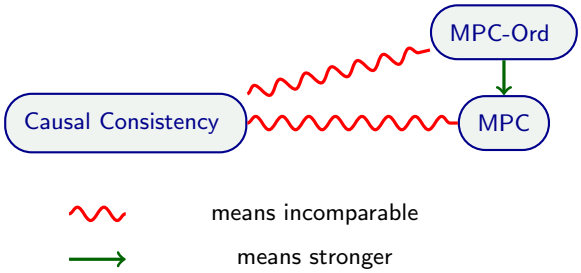

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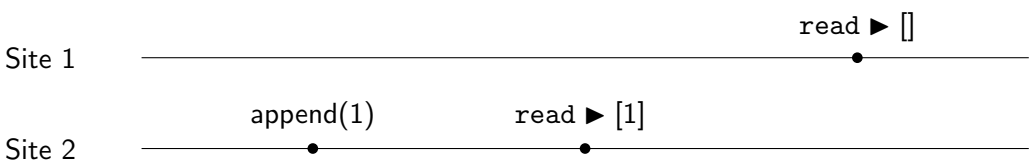

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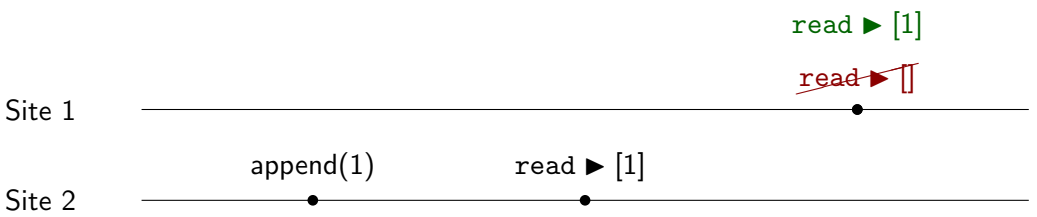

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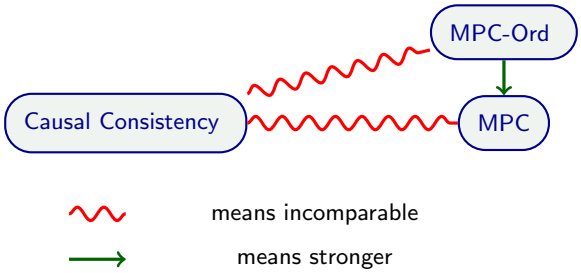

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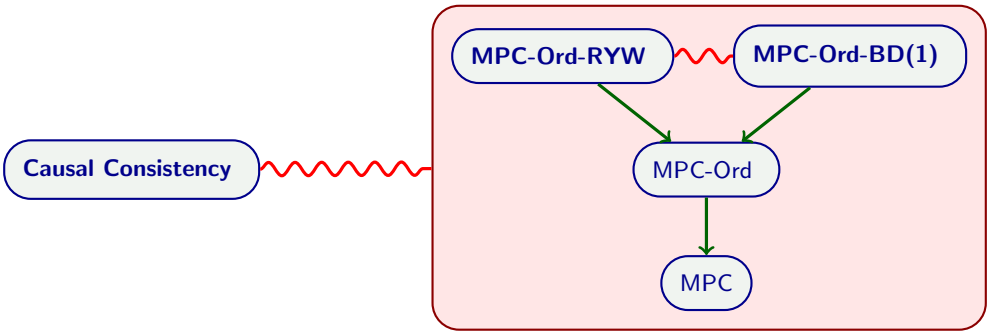

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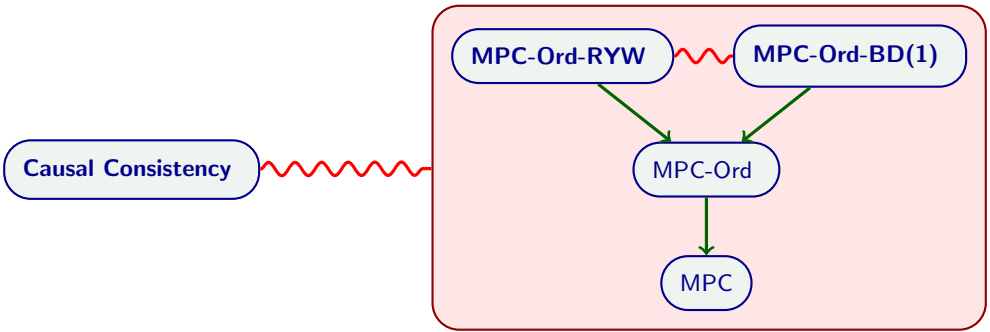

Questions:

- Can we prove nothing stronger than these criteria can be implemented?
- Are there criteria incomparable to these that can be implemented?

Outline

Existing Complexity Results for the Verification Problems

Single-Trace Verification:

- NP-**complete** for most consistency criteria[2]

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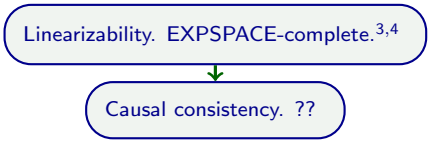

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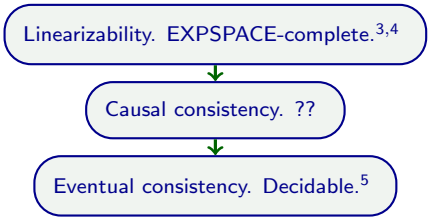

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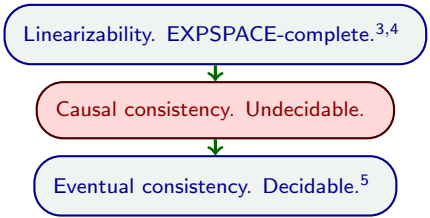

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(Input: **finite-state automaton** representing all traces)

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- Observation: Implementation are data-independent (or parametric)
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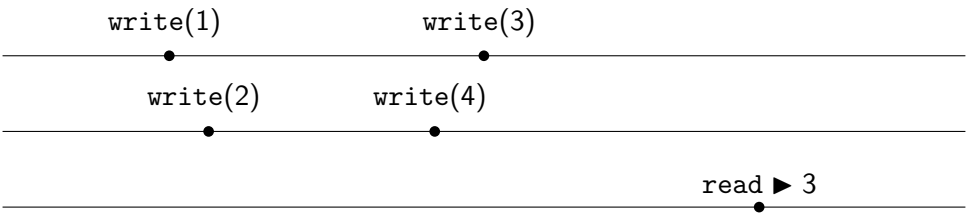

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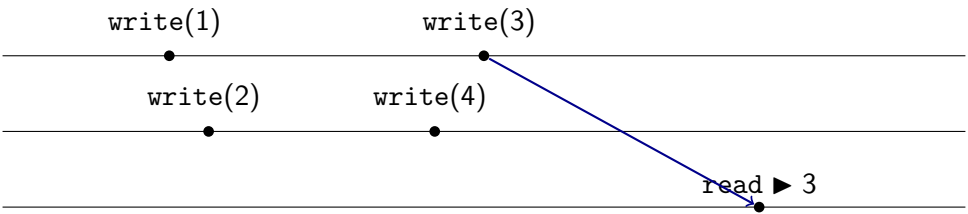

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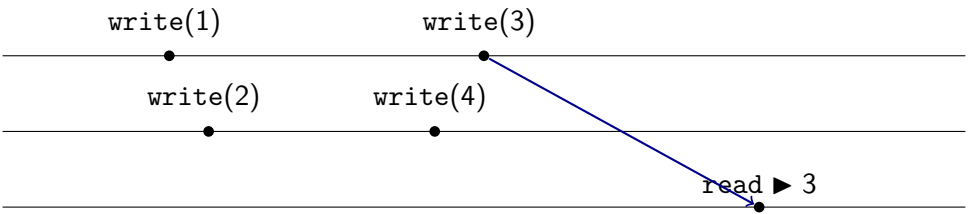

Unicity of writes automatically gives the **causality** relation.

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- CO (causal order): defined as $(PO \cup RF)^+$

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- Two `write` operations w_1 and w_2 on the same variable
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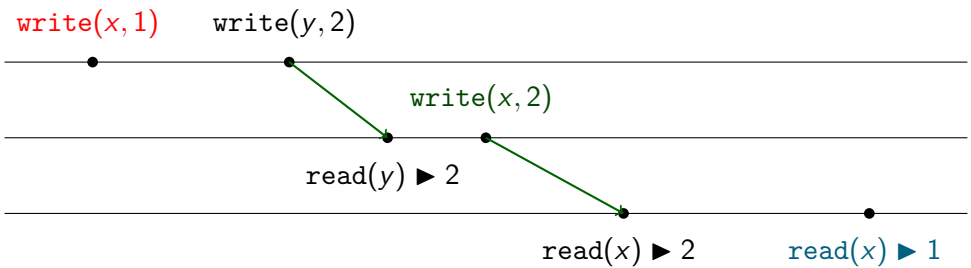

Bad Patterns for Causal Consistency Variants

Causal Consistency	Causal Memory	Causal Convergence
CyclicCO	CyclicCO	CyclicCO
WriteCOInitRead	WriteCOInitRead	WriteCOInitRead
ThinAirRead	ThinAirRead	ThinAirRead
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Bad Patterns for Causal Consistency Variants

Causal Consistency	Causal Memory	Causal Convergence
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Theorem (Bad Patterns)

A trace is **not consistent** *iff it contains a* **bad pattern**.

Outline

- Observation: Implementation are data-independent (or parametric)
  - **Bad patterns**: operations ordered in a particular way
  - Characterize **all causal consistency violations** using bad patterns
- Application of bad patterns for data-independent implementations
  - Single-Trace Verification: **polynomial time**
  - **Bad patterns** can be recognized with **state machines**
  - **Generic reduction** from causal consistency to **reachability**
  - All-Traces Verification: **decidable**

Polynomial-Time Single-Trace Verification

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Singe-Trace Verification of causal consistency is NP-**complete**.

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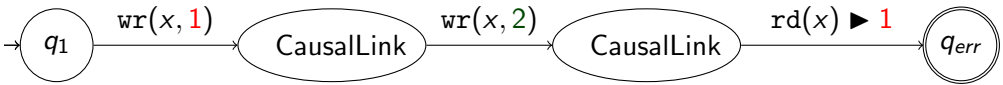
Singe-Trace Verification of causal consistency is **polynomial** *when* **writes are unique**. *(By checking the absence of bad patterns.)*

Recognizing Bad Patterns with State Machines

E.g. For one bad pattern



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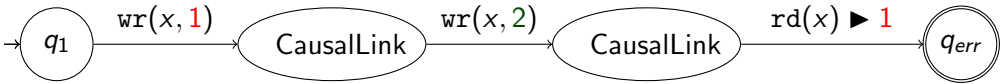
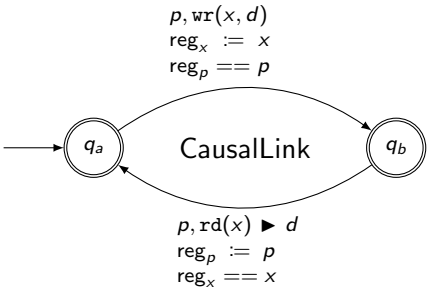


CausalLink tracks causality by alternating between the **program-order** and **read-from** relations



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Machine M tracking all bad patterns.

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Related Work

- **Single-Trace Verif.** is **NP-complete** for causal memory, and other criteria[2]
- **Data Independence**, **bad patterns** and reduction to **reachability** for linearizability[5,6,7]
- **Proof techniques** for manually proving causal consistency[8]

[5] Aspect-Oriented Linearizability Proofs. Henzinger et al. 2013.
[6] An Integrated Specification and Verification Technique for [...] Abdulla et al. 2013.
[7] On Reducing Linearizability to State Reachability. Bouajjani et al. 2015.
[8] Chapar: Certified Causally Consistent Distributed KVS. Lesani et al. 2016

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Thank you

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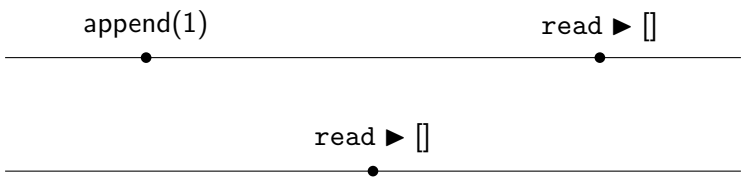

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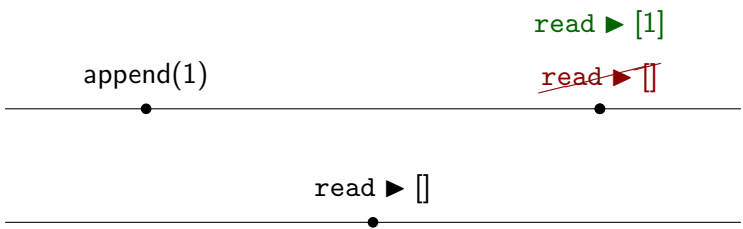

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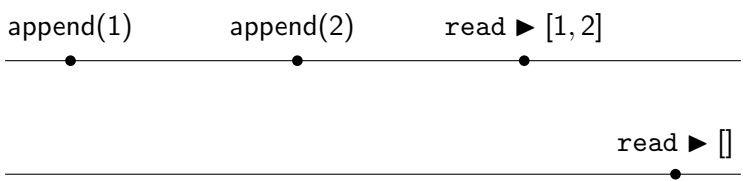

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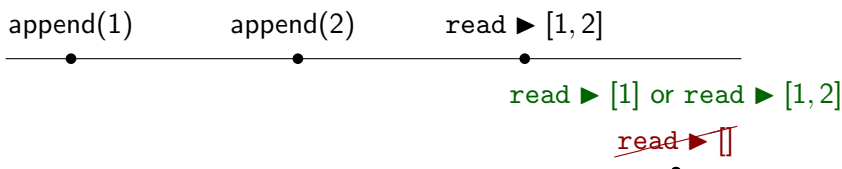

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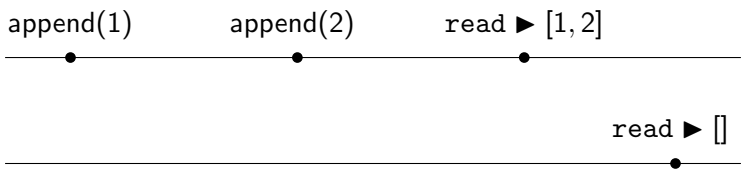

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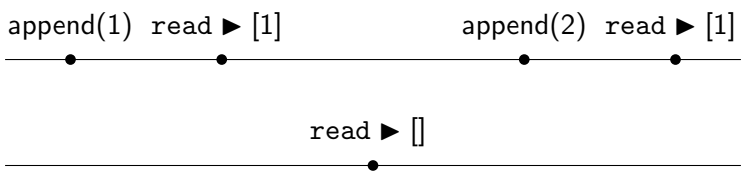
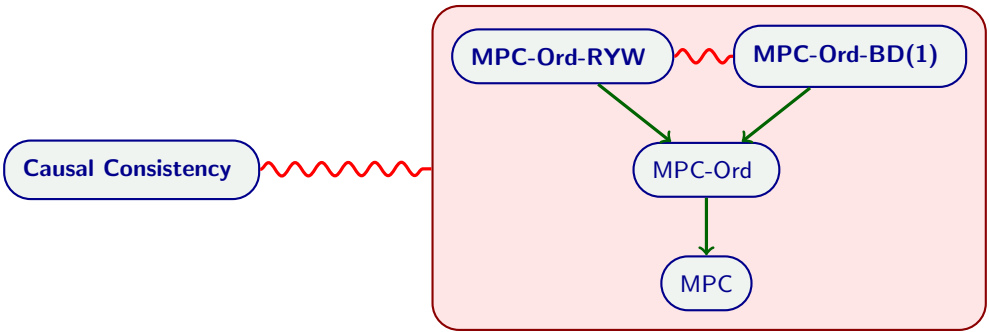


Comparison between Consistency Criteria



Blockchain Implementation: Monotonic Prefix Consistency

Using blockchains, we can implement a data-structure that ensures **Monotonic Prefix Consistency** (with good probability).

Implementation of MPC using blockchains:

- **Update request**: broadcast it and try to add it to a block
- **Query request**: ignore the last X blocks, and return the last written value in the blockchain.

Undecidability: Post Correspondence Problem

Input: a finite number of domino models $\frac{u_1}{v_1}, \frac{u_2}{v_2}, \cdots, \frac{u_n}{v_n}$
where the u_i's and v_i's are finite words.

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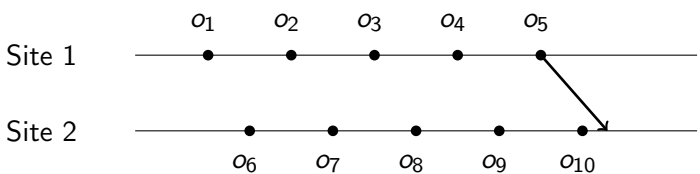
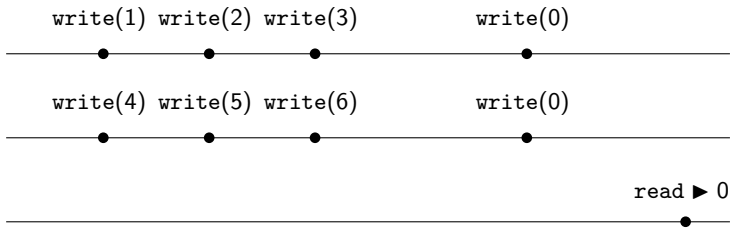


Intuition for undecidability

A verification algorithm needs to check **all possible traces**.

E.g. Traces where sites are disconnected for **arbitrarily long**.



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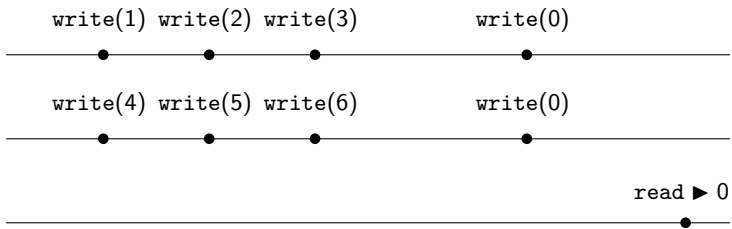

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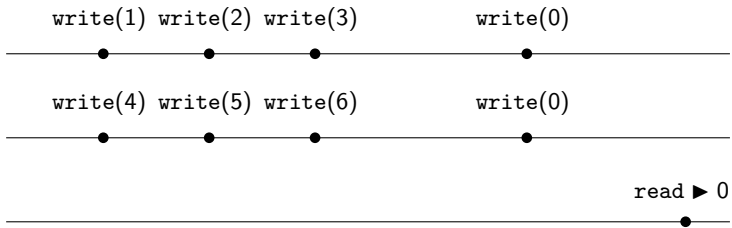

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Causal Convergence[10]

- Conflicts are resolved using a global **arbitration order**
- **Strong eventual consistency**:
  If two sites see the same writes, they are in the same state[9]

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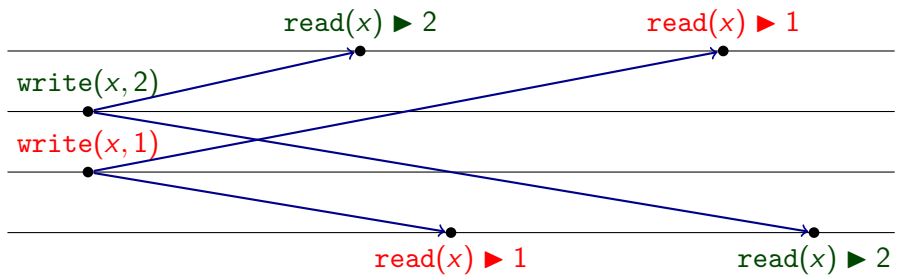

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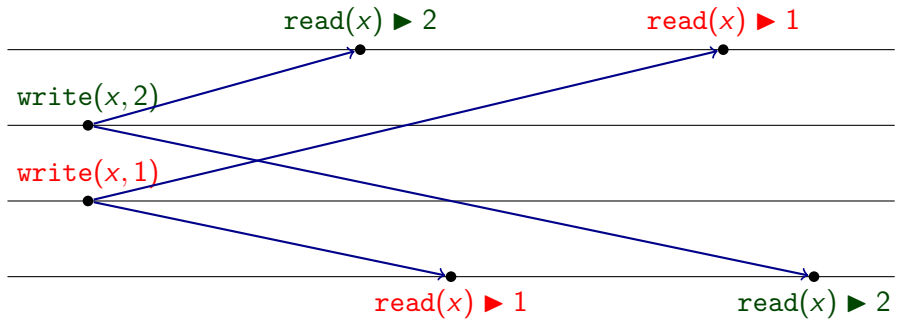

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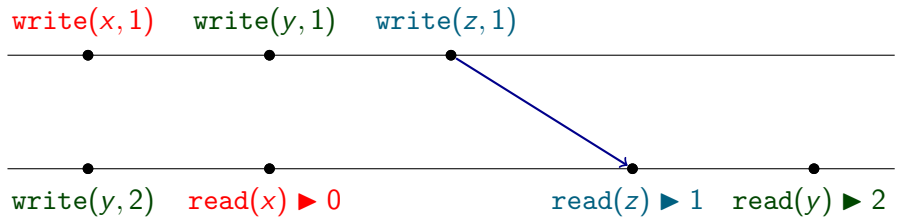

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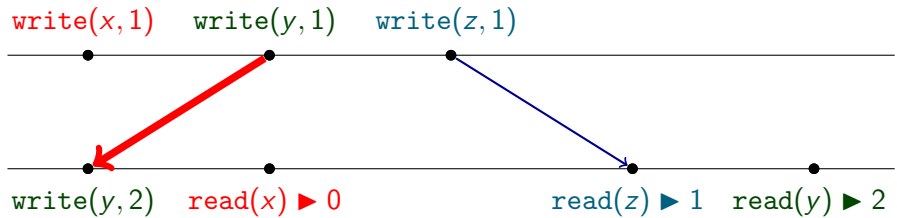

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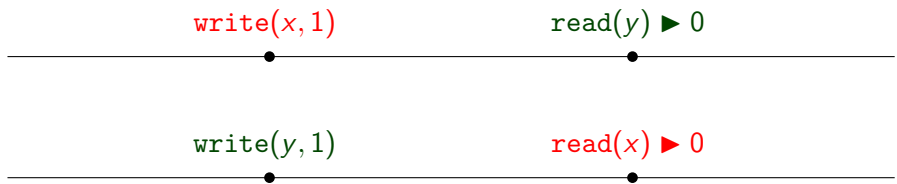
Satisfying Causal Consistency Variants but not Sequential Consistency



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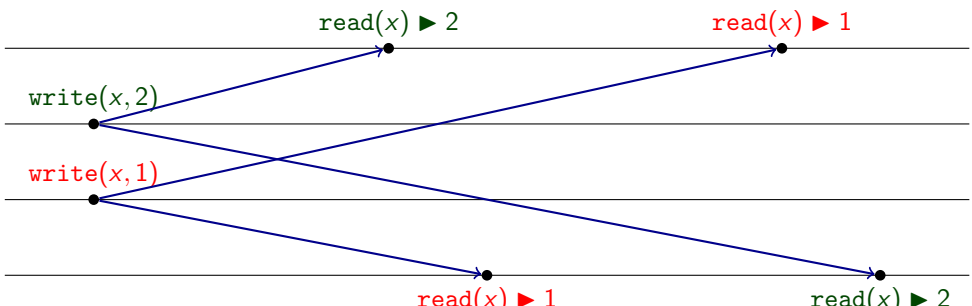

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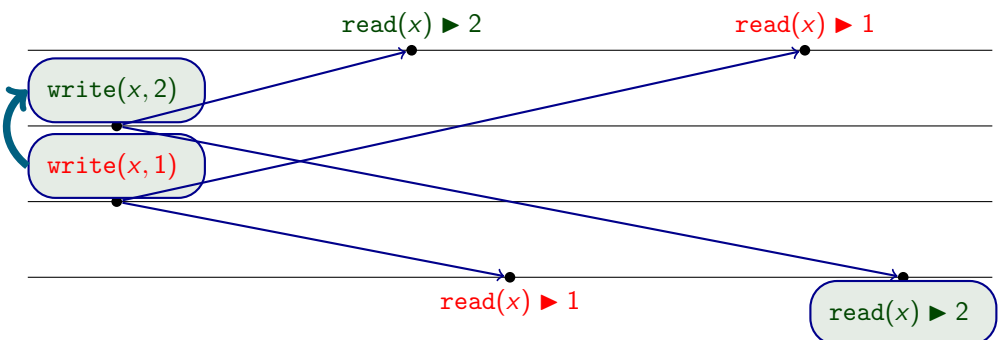

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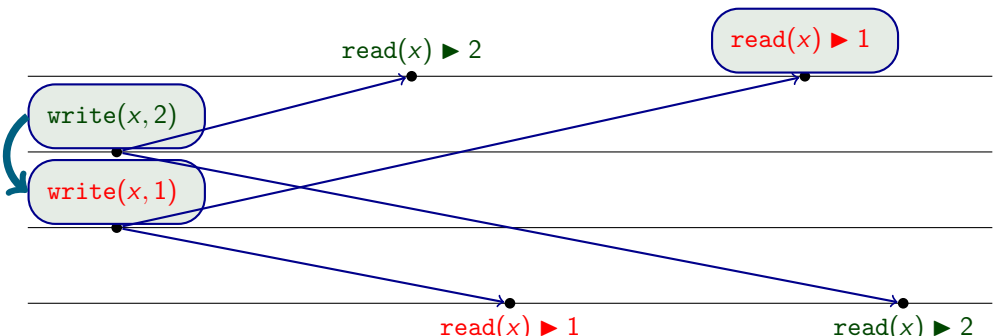

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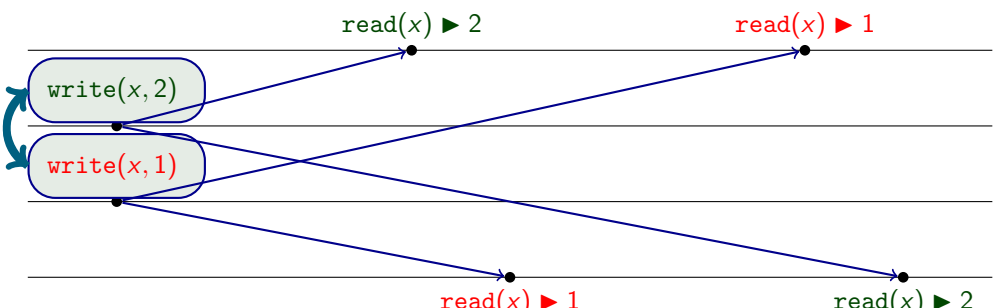

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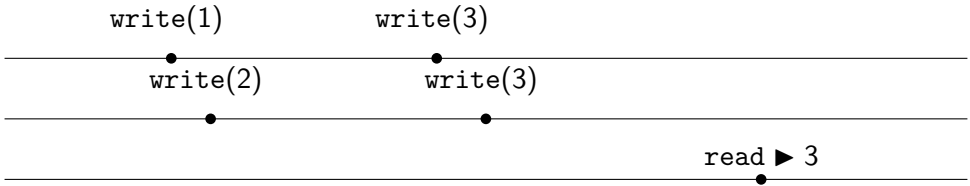
From **which** `write(3)` does `read ▶ 3` read?



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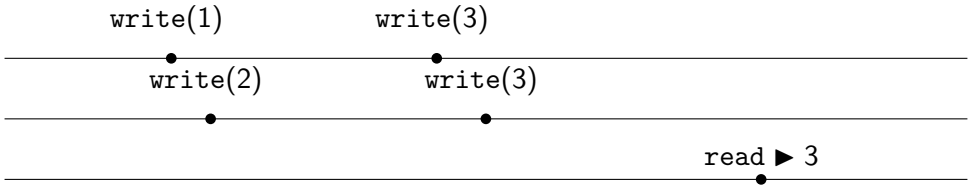

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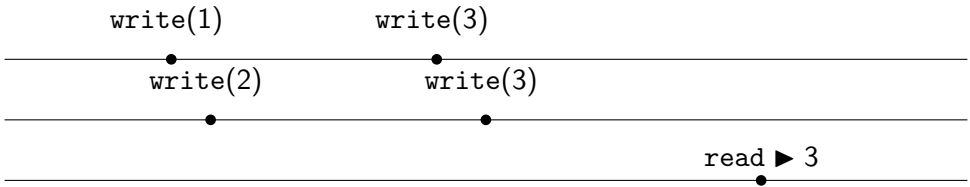

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Theorem (Testing)

Testing causal memory[13]*, causal convergence, or causal consistency is* NP-**complete**.

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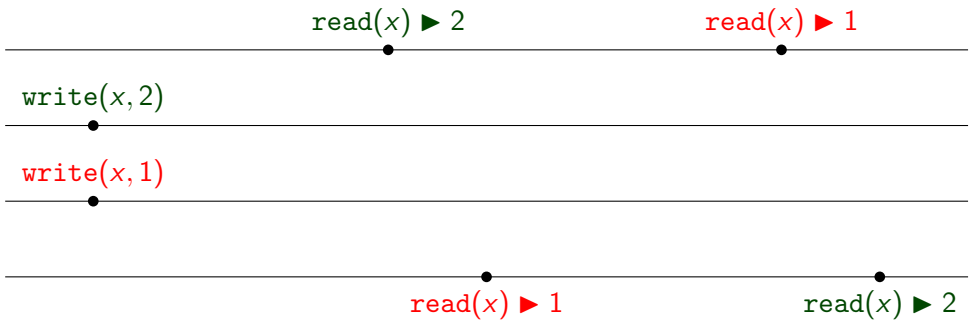

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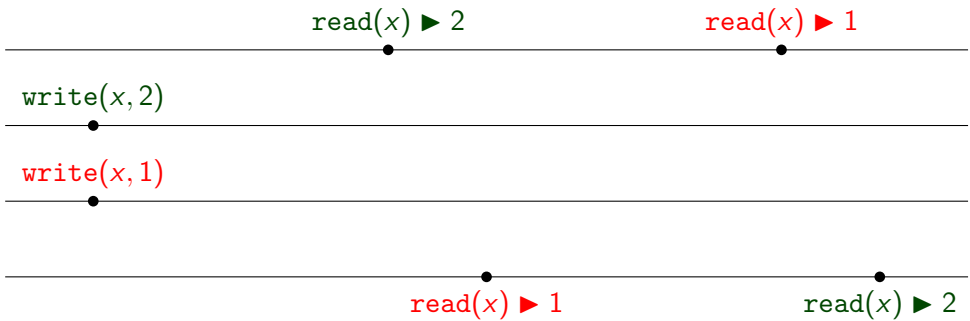

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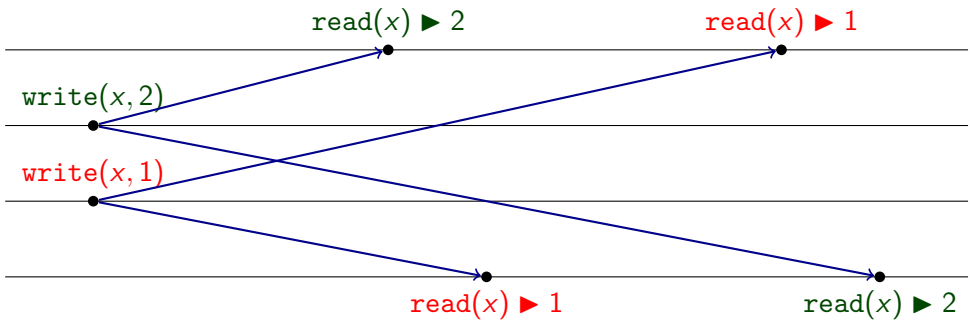

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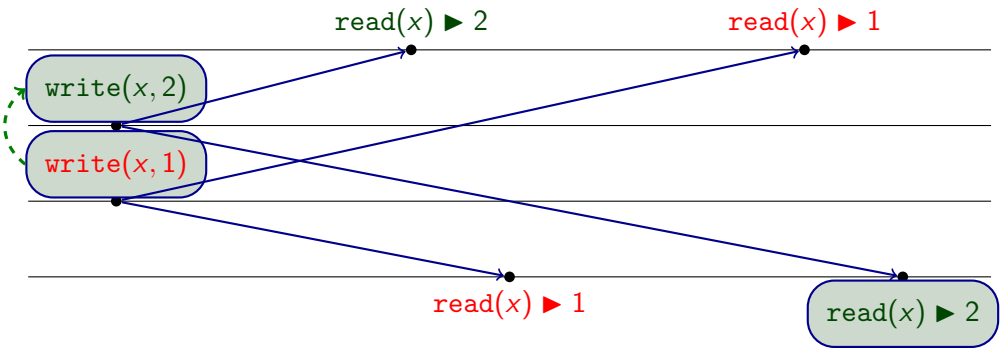

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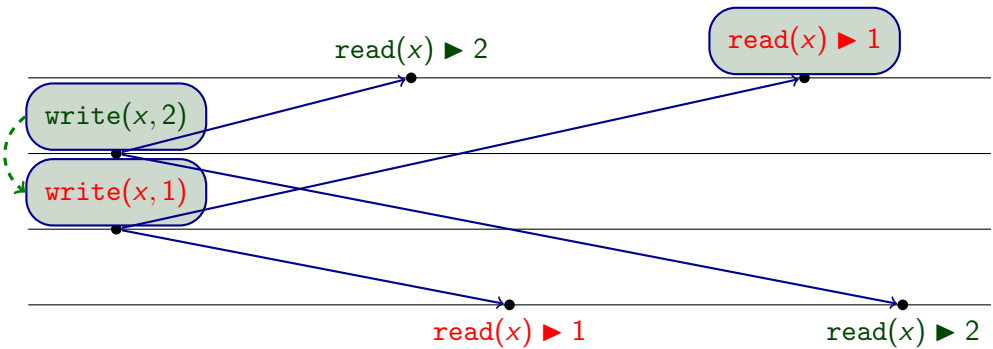

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Example of (non)-Causal Consistency

Causally related *writes must be seen by all sites in the same order.*