On Checking Correctness of Concurrent Data Structures

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Joint work with

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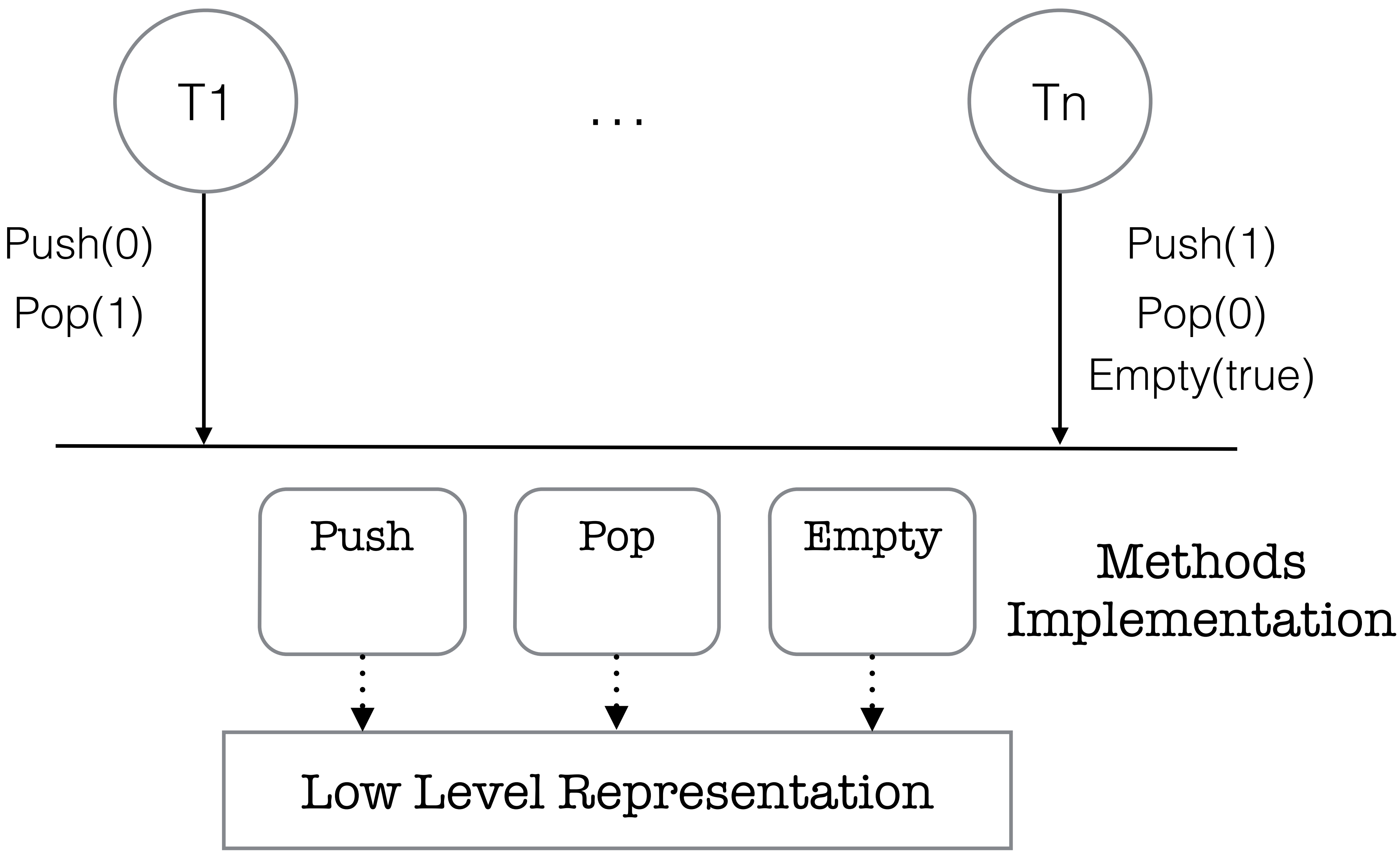
FRIDA worskhop - 23 July 2014, Vienna

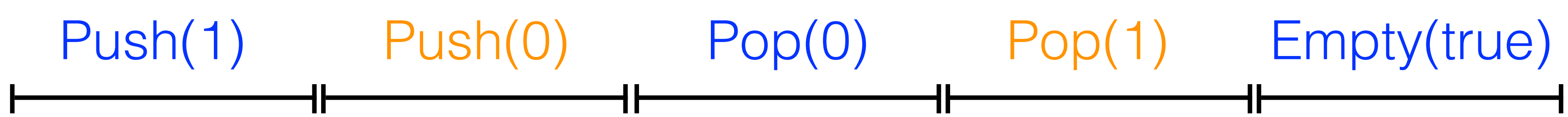
Concurrent Data Structures



Different atomicity levels

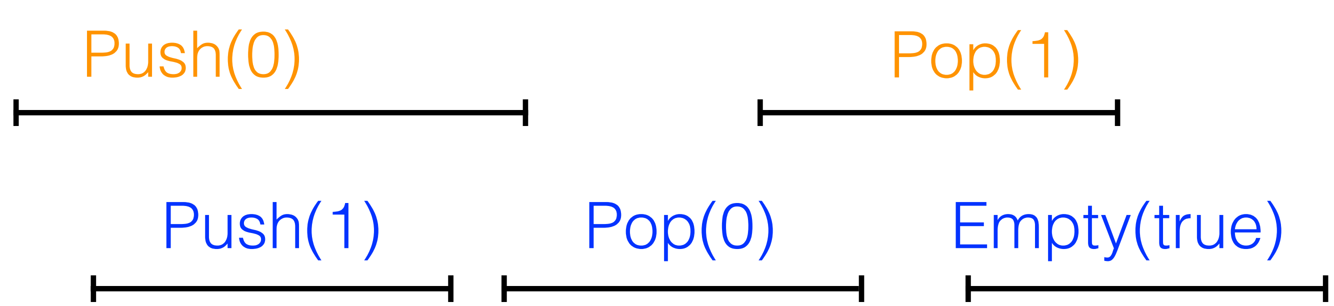
Client view:

- Operations are atomic
- Thread executions are interleaved

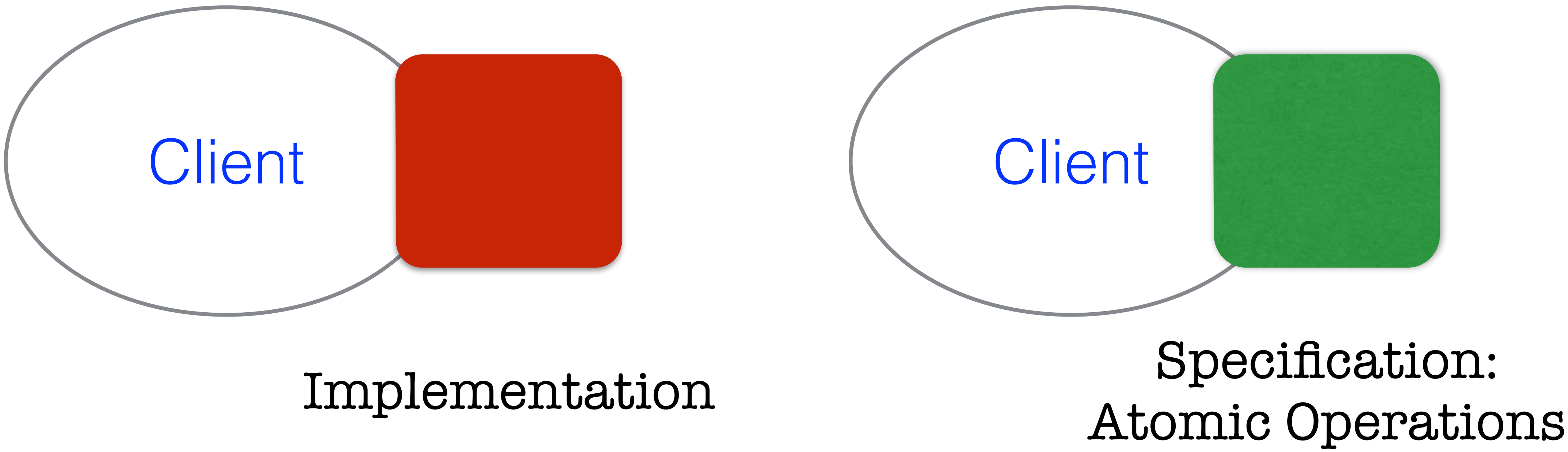


Implementation:

- Atomic operations: Coarse-grain locking
- Performances: Avoid coarse-grain locking
- => Execution intervals may overlap

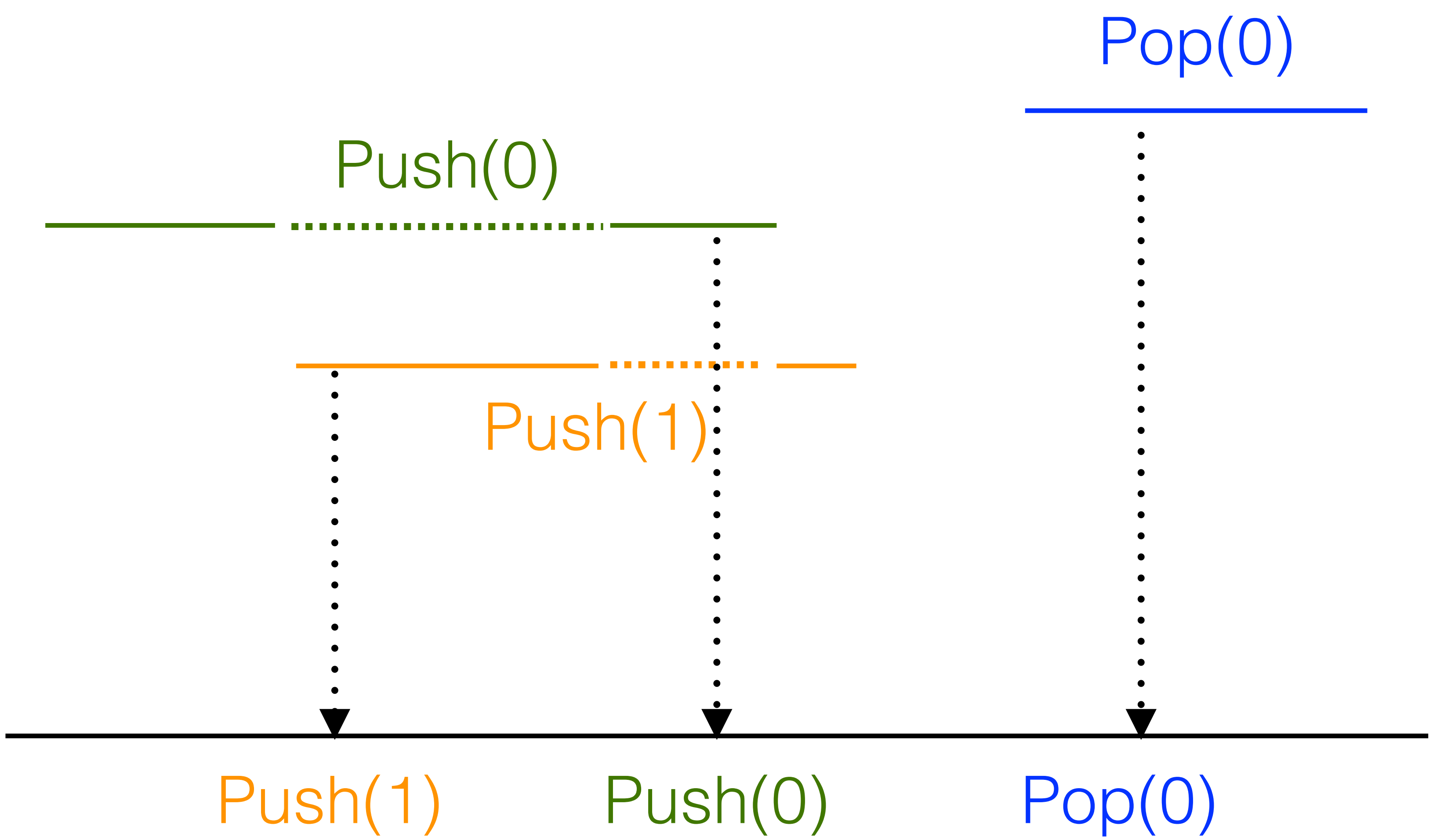


Observational Refinement



For every Client,
Client x Impl included in Client x Spec

Linearizability



Valid sequence of the specification

- history = sequence of call and return events
- reorder call/return events, while preserving returns —> calls
- find “linearization points” within execution time intervals

Linearizability implies Observational Refinement

Complexity

Finite number of threads, regular specification

- Linearizability is in EXPSPACE [Alur et al. 1996]

  - Enumeration of all possible linearizations
  - Tools for finding lineerizabiity violations (Line-up)

- Lower bound: EXSPACE-hardness [Jad Hamza '14]

Unbounded Number of Threads ?

[B, Emmi, Enea, Hamza, ESOP'13]

Finite-state threads, regular specifications

- Linearizability is undecidable

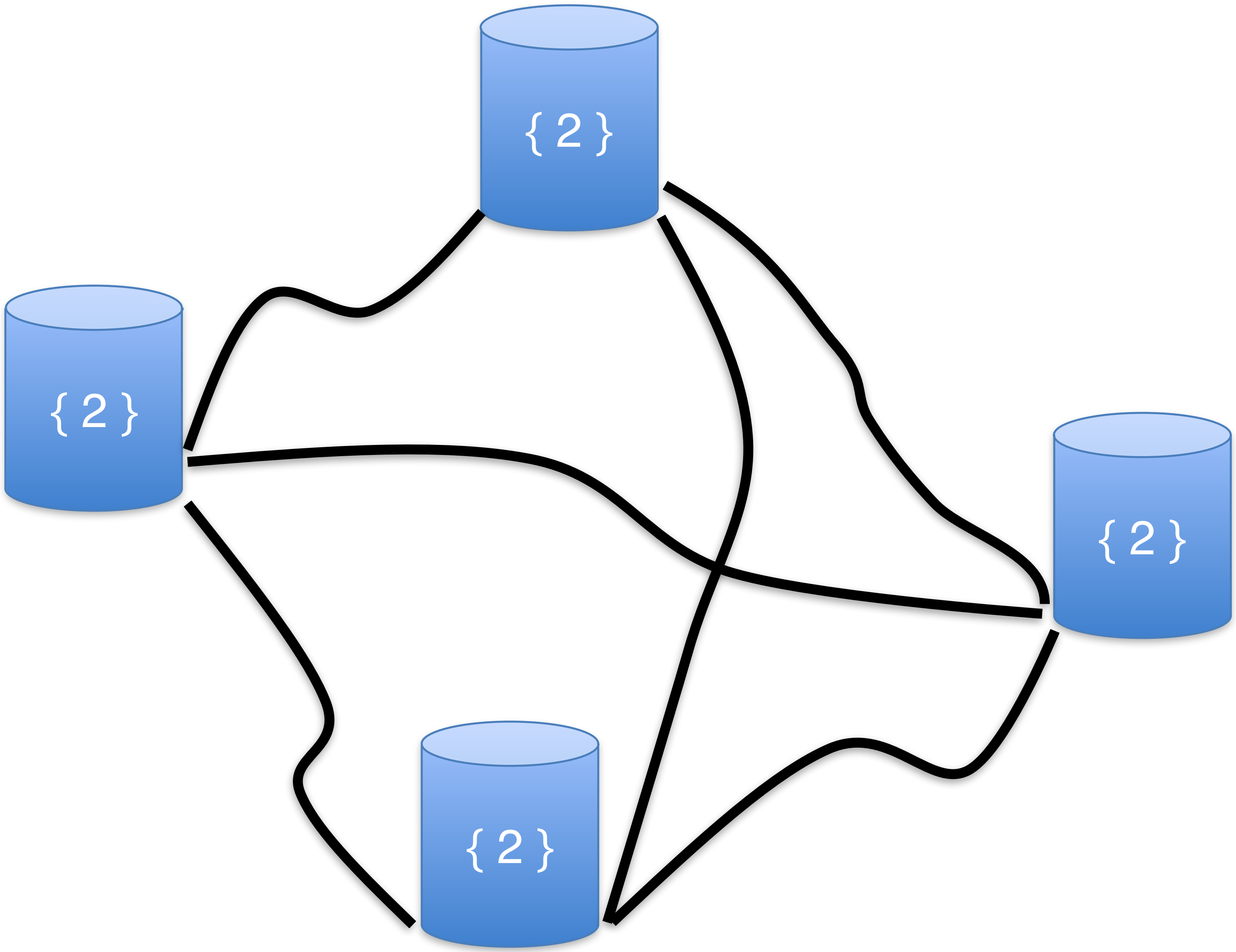
Reachability in 2-counter machines reducible to non-linearizability

- Static Linearizability:
  - Fixed linearizations points, except for read-only methods
  - Relevant for a wide class of implementations

- Static Linearizability is decidable
  - Reduction to state reachability (works for infinite-state threads)
  - Reachability in FSM/VASS for fixed/unbounded number of threads
  - P/EXP-SPACE-complete for a fixed/unbounded number of threads

Distributed, Replicated Data Structures

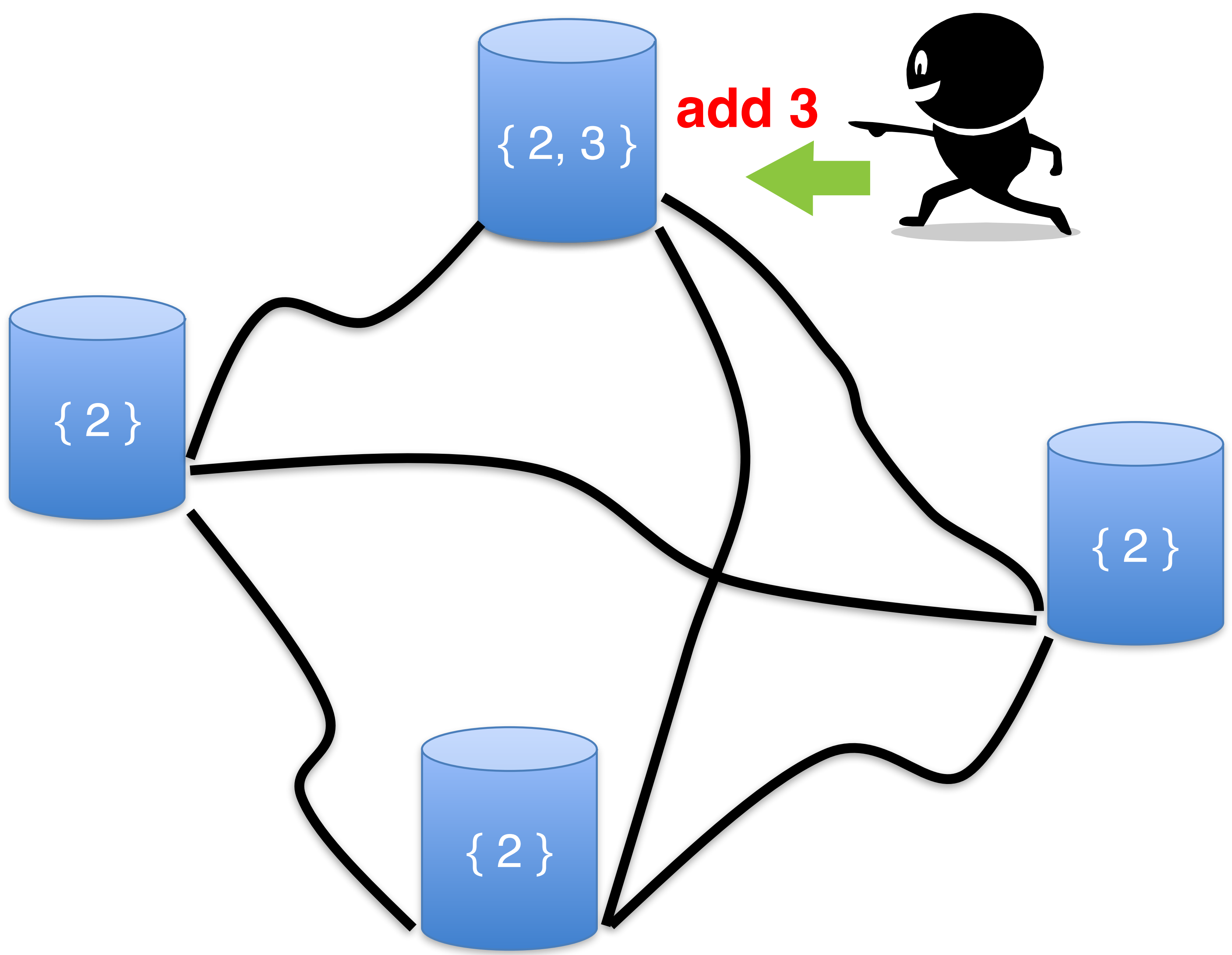
- Interactive collaborative applications (e.g., online stores)
- Replicated objects accessible at multiple sites in a network



Optimistic data replication

Optimistic replication: replicas are allowed to diverge

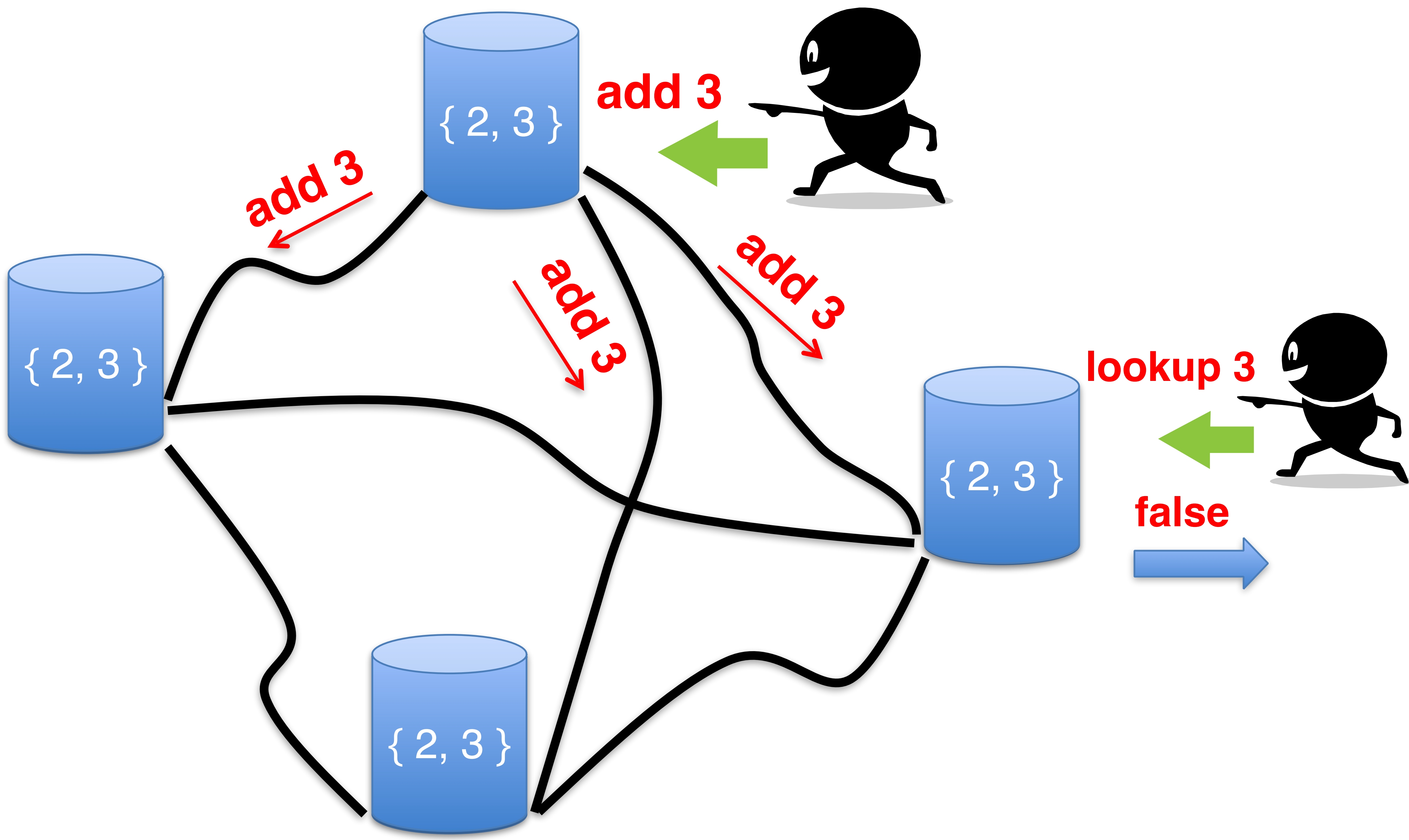
– operations are applied immediately at the submission site



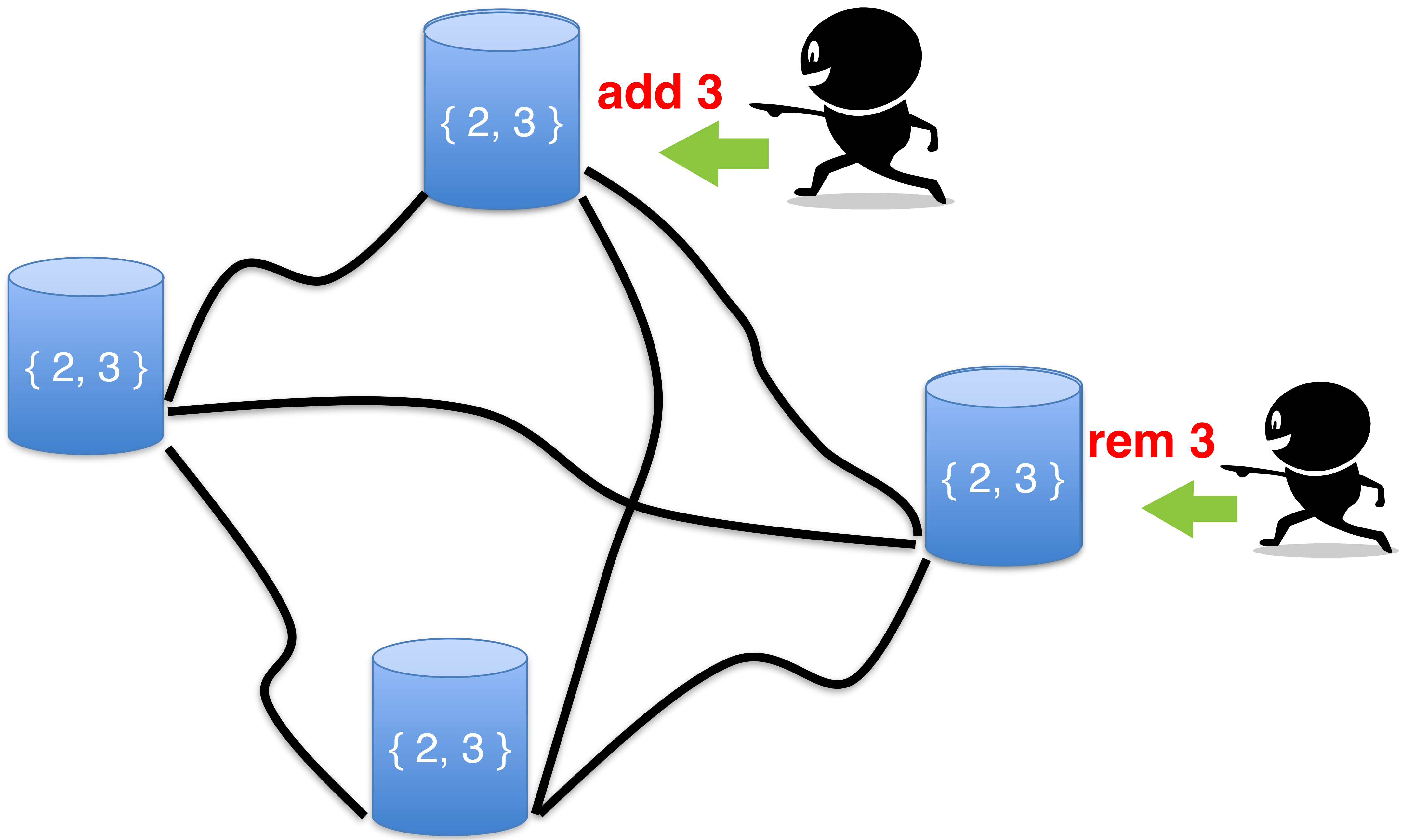
Optimistic data replication

Optimistic replication: replicas are allowed to diverge

- operations are applied immediately at the submission site
- in the background, sites exchange and apply remote operations



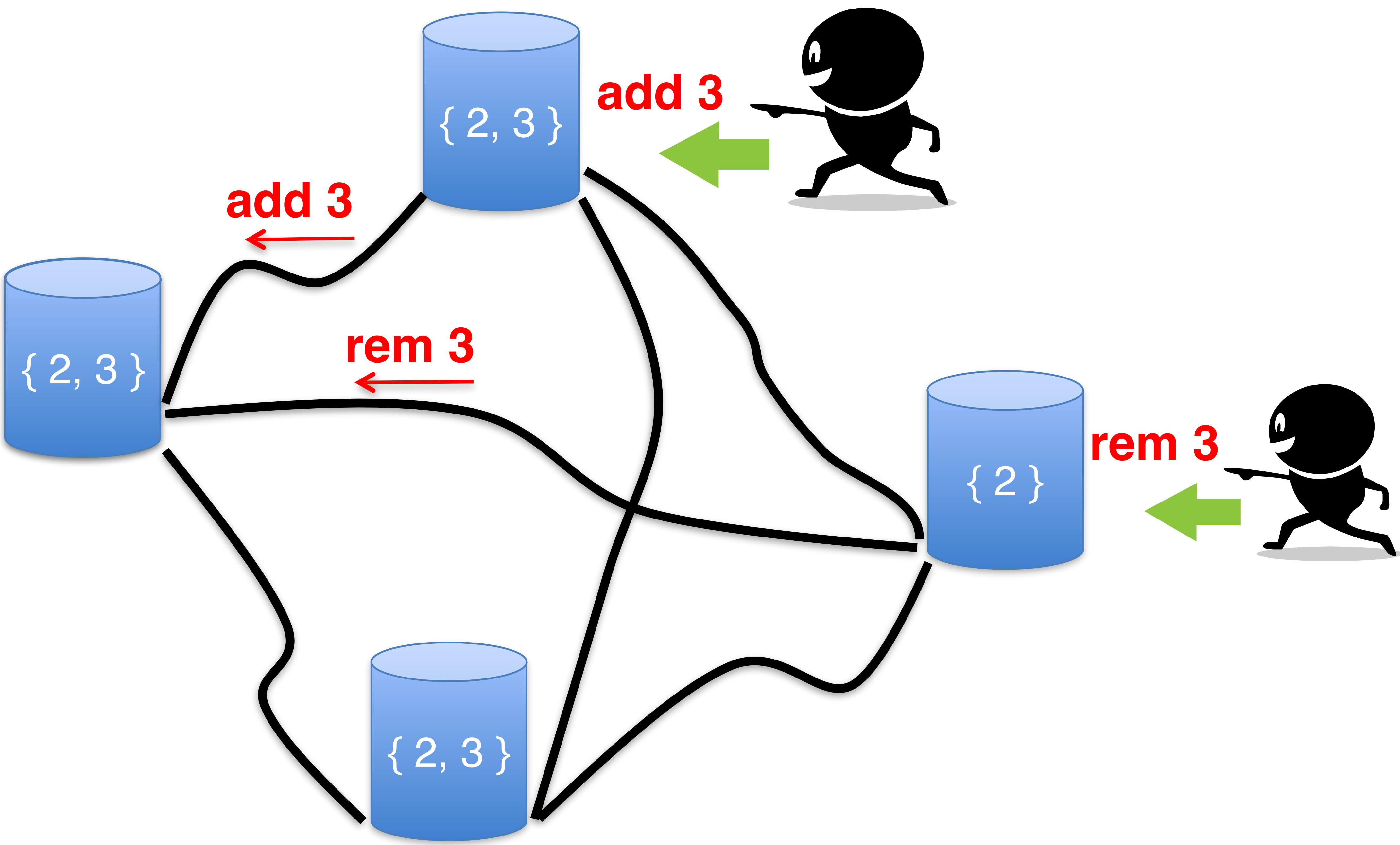
Concurrent operations



Concurrent operations

Solving conflicts between concurrent operations

- speculate and roll-back, e.g., Google App Engine Datastore



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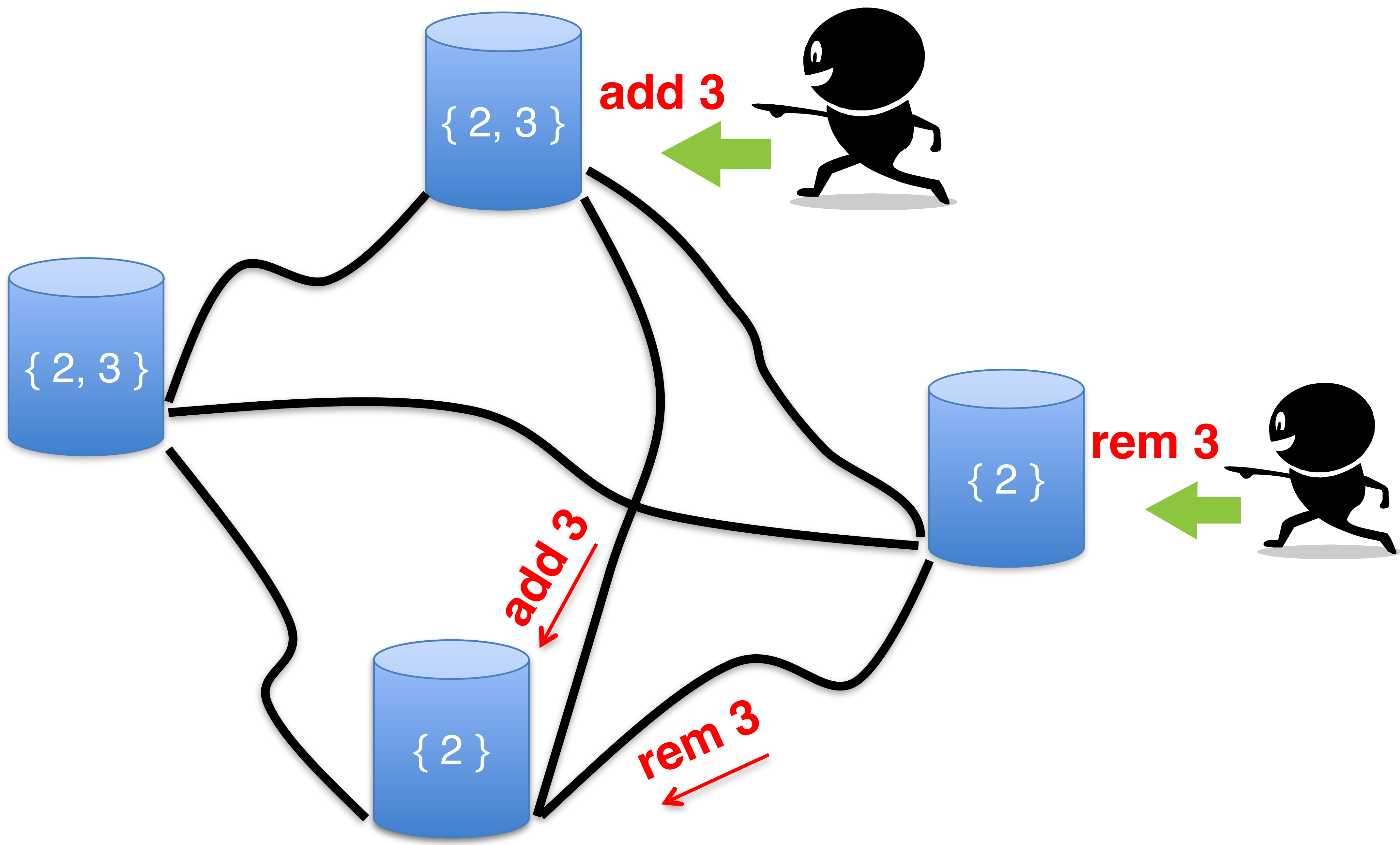

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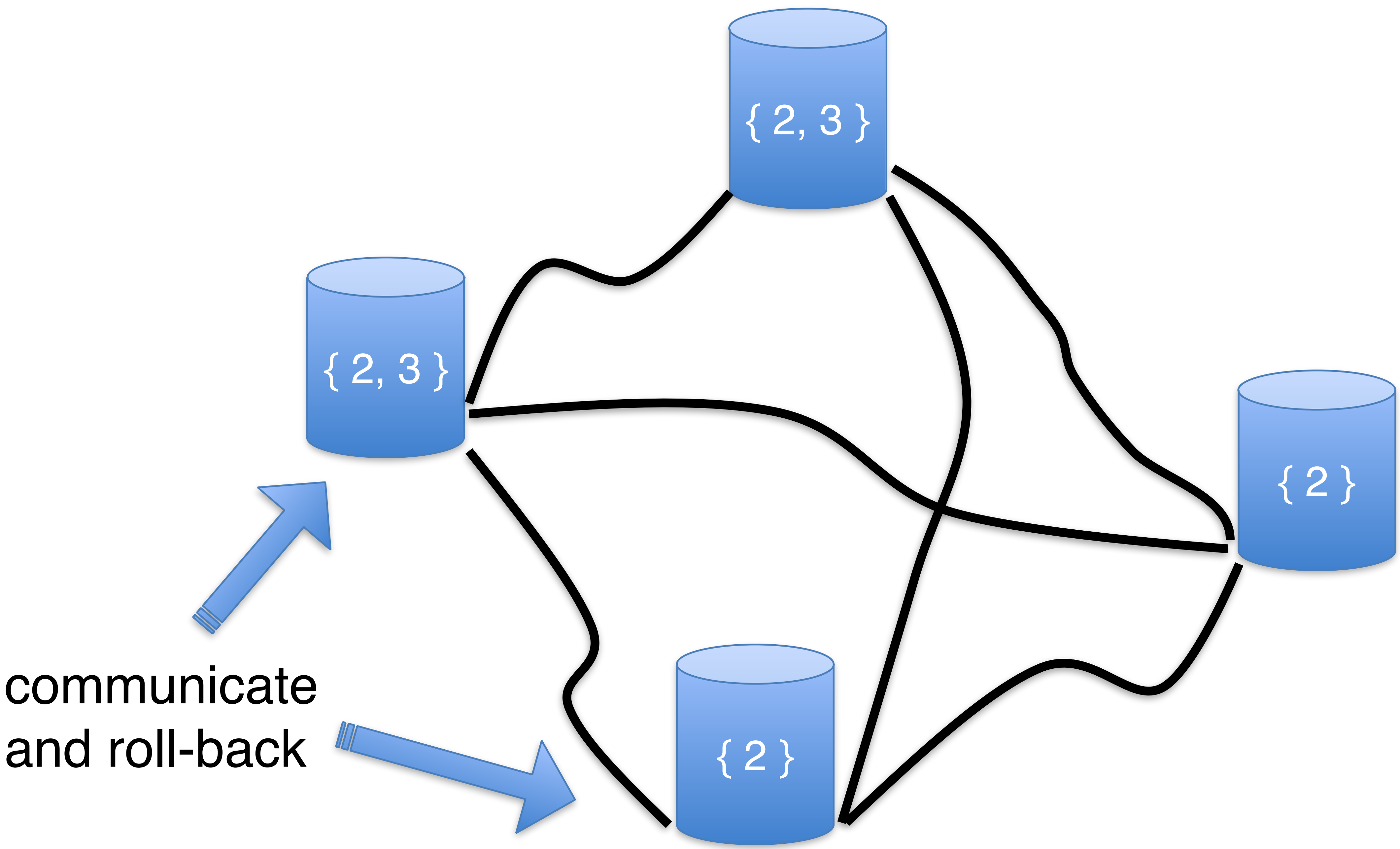
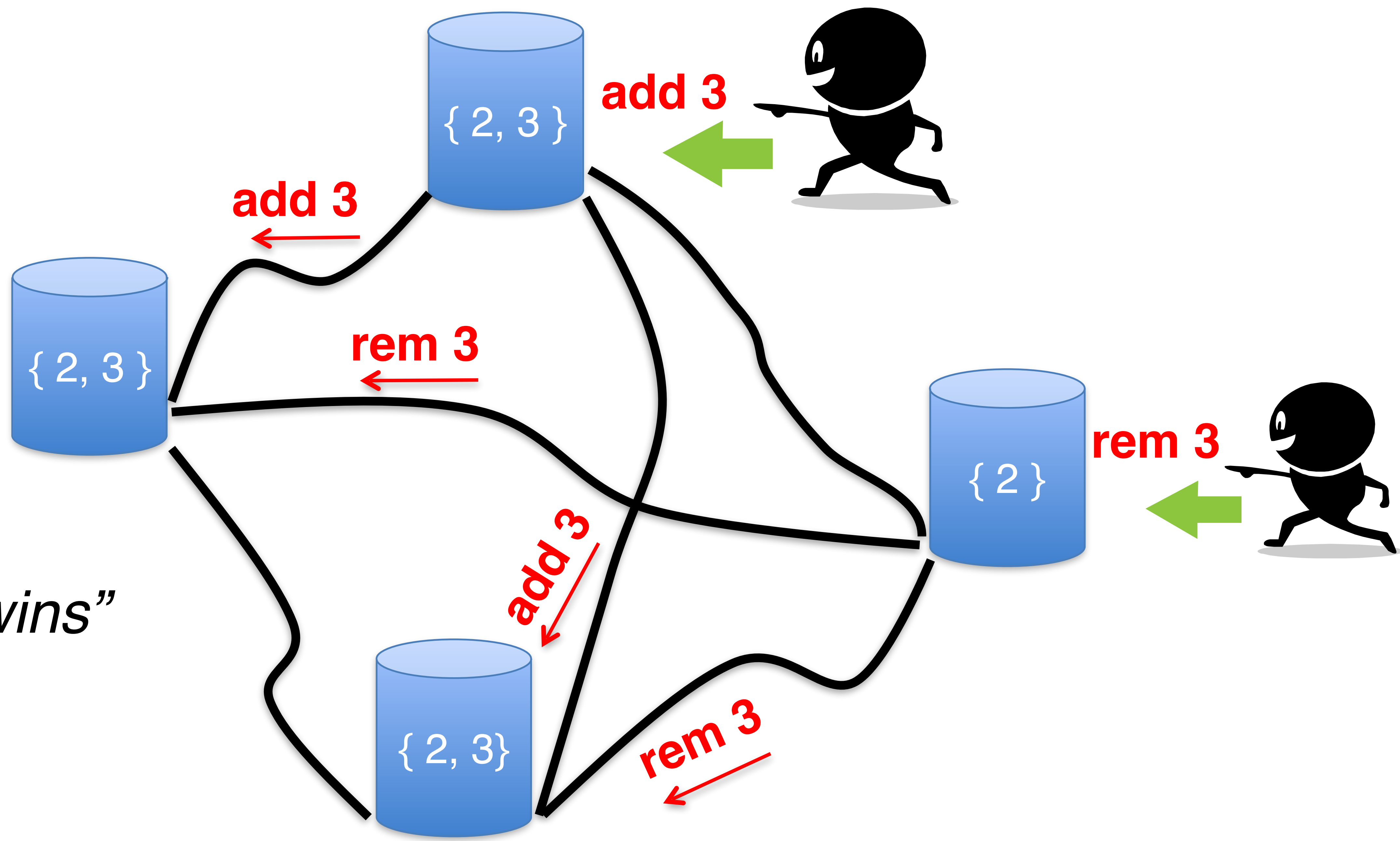


Concurrent operations

Solving conflicts between concurrent operations

- speculate and eventually, roll-back, e.g., Google App Engine Datastore
- convergent conflict resolution, e.g., CRDTs [Shapiro et al.'11]



Consistency ?

CAP (Consistency-Availability-Partition tolerance) theorem
[GL '02]
implies
Strong consistency (linearizability) is impossible

==> Other (Weaker) Correctness Criteria:
Eventual Consistency, Causal Consistency, etc.

- Formal definition ?
- Verification ?

Eventual Consistency

[B, Enea, Hamza, POPL'14]
(other formalization: Burckhardt et al. POPL'14)

- At each moment, a site has a local view: a (sub)set of the operations that have been executed in the system
- Each operation is executed in the context of a local view
- Specification: a set of (happen-before) partial order relations explaining executions of operations

- Safety Part:

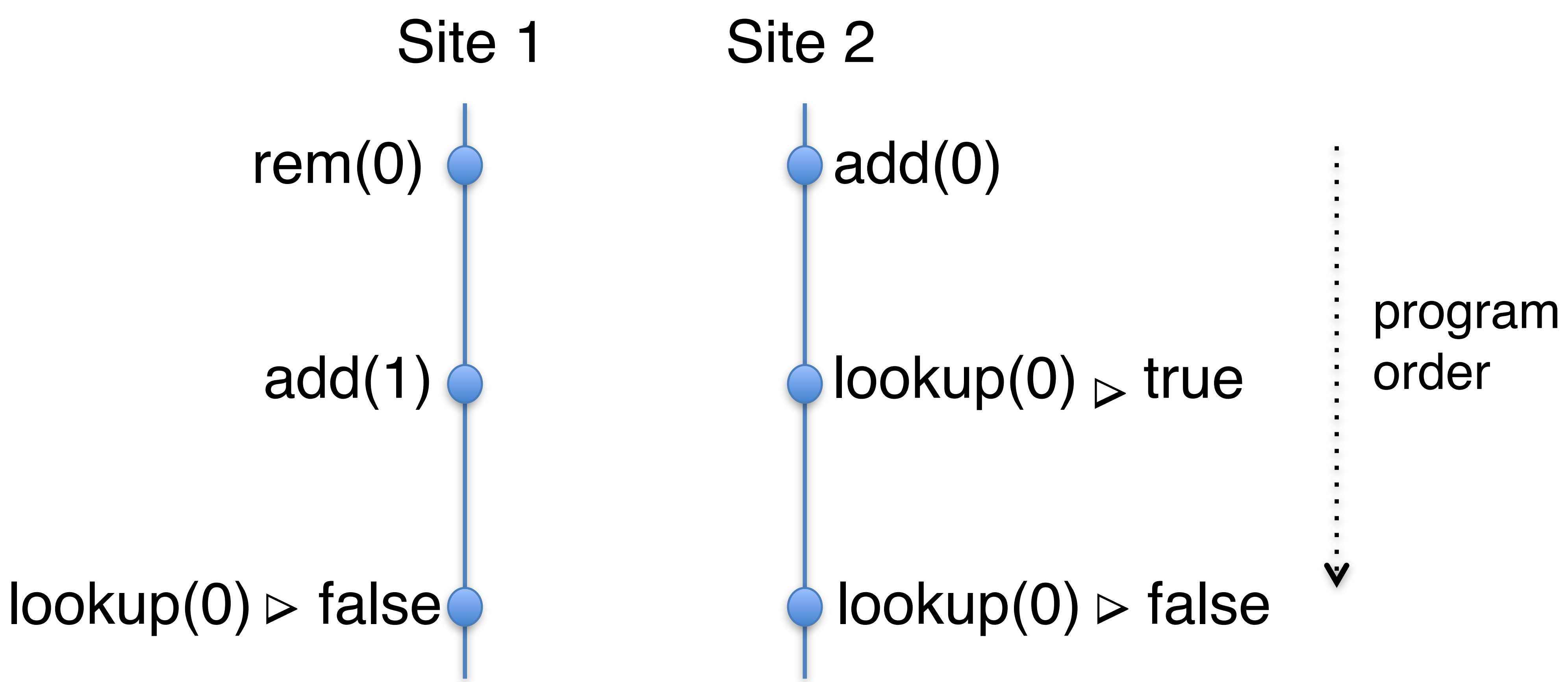
  Executions must satisfy some specification

- Liveness Part:

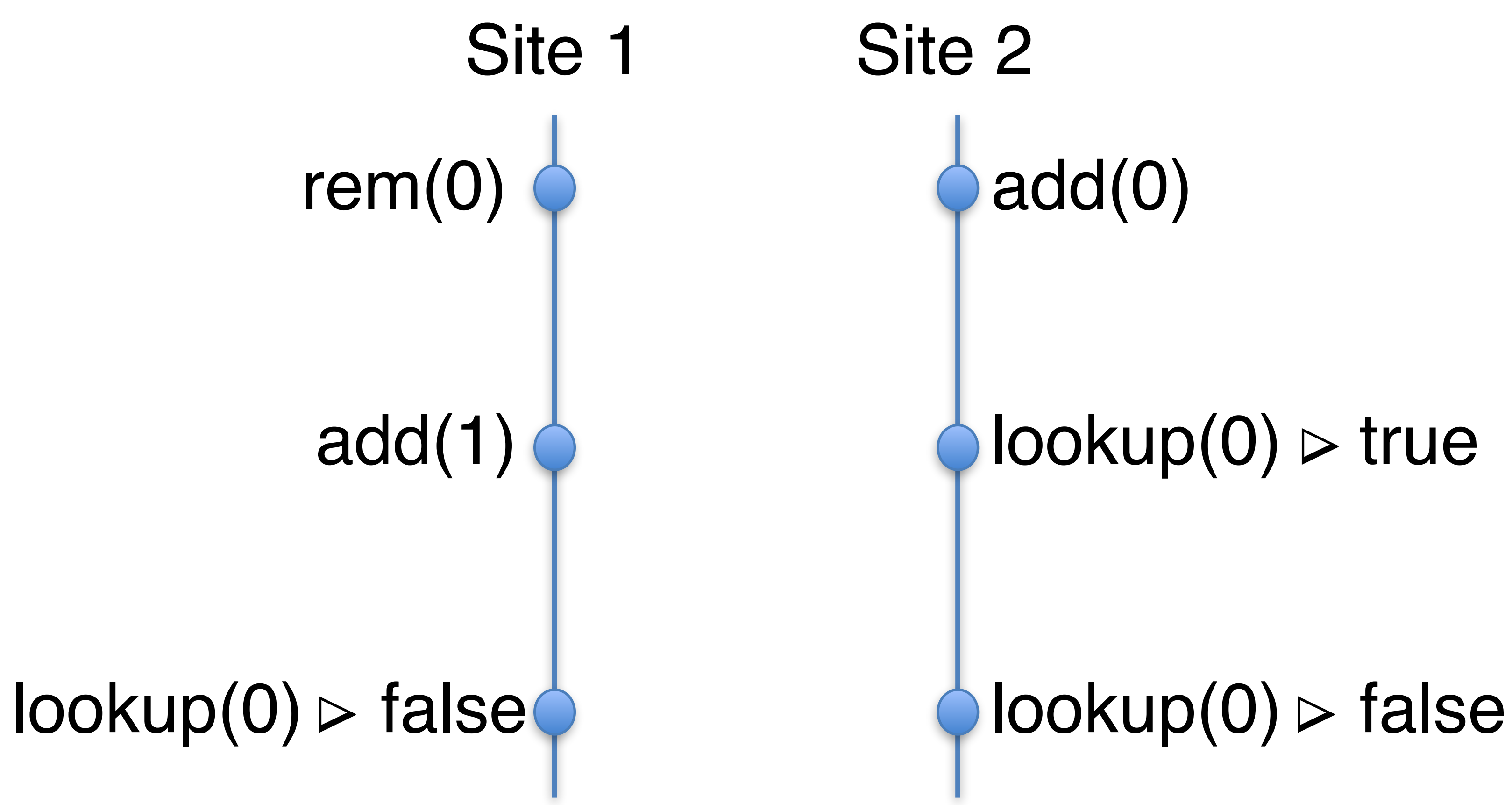
  Local views must converge toward global view

Modeling behaviors as traces

- operations are instances of a set of methods (add, rem, lookup)
- traces record the submitted operations and their return values
- trace = a partially-ordered set (poset) of operations
  - operations submitted to the same site are ordered



A trace is safe w.r.t a specification



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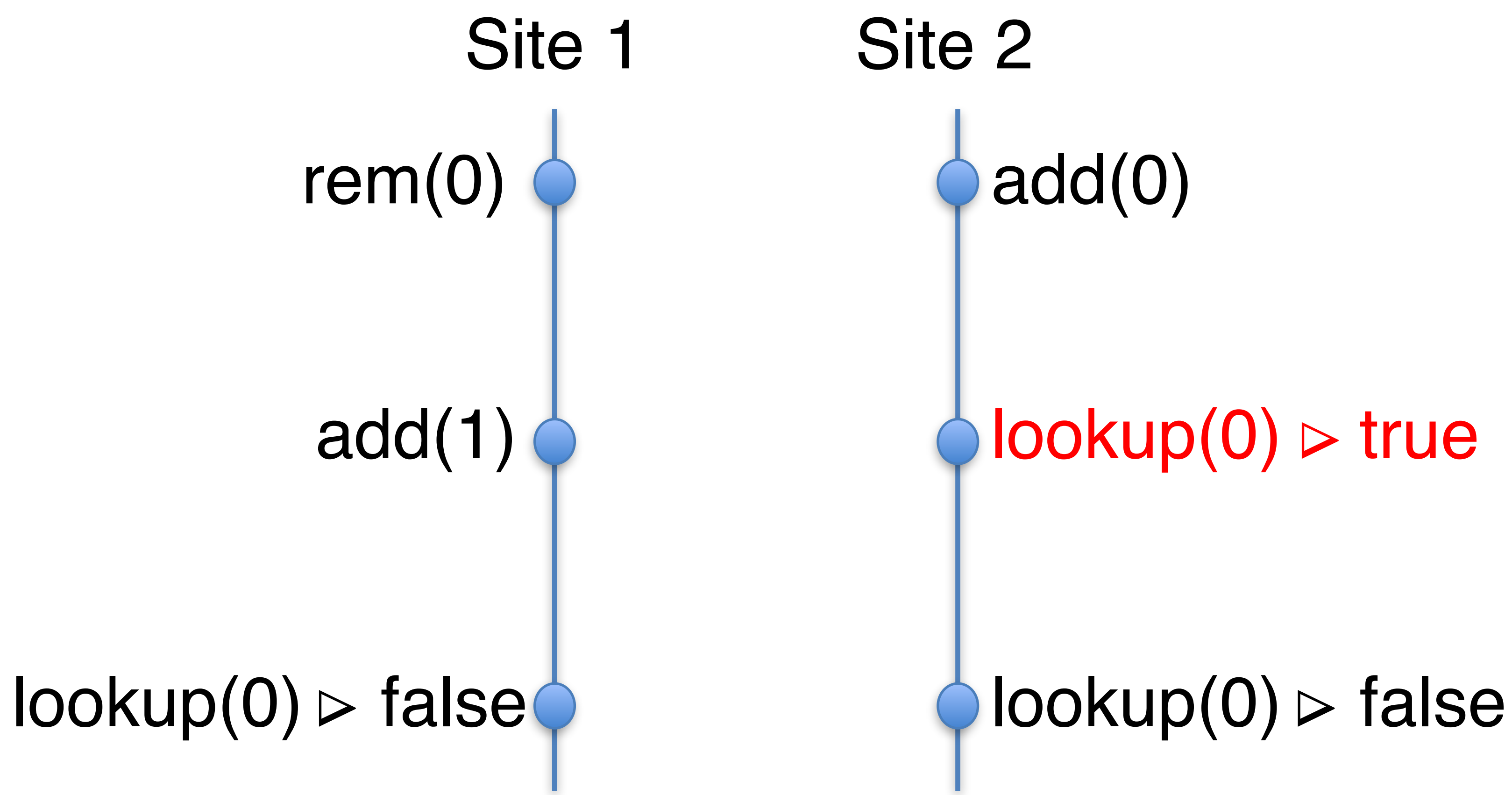

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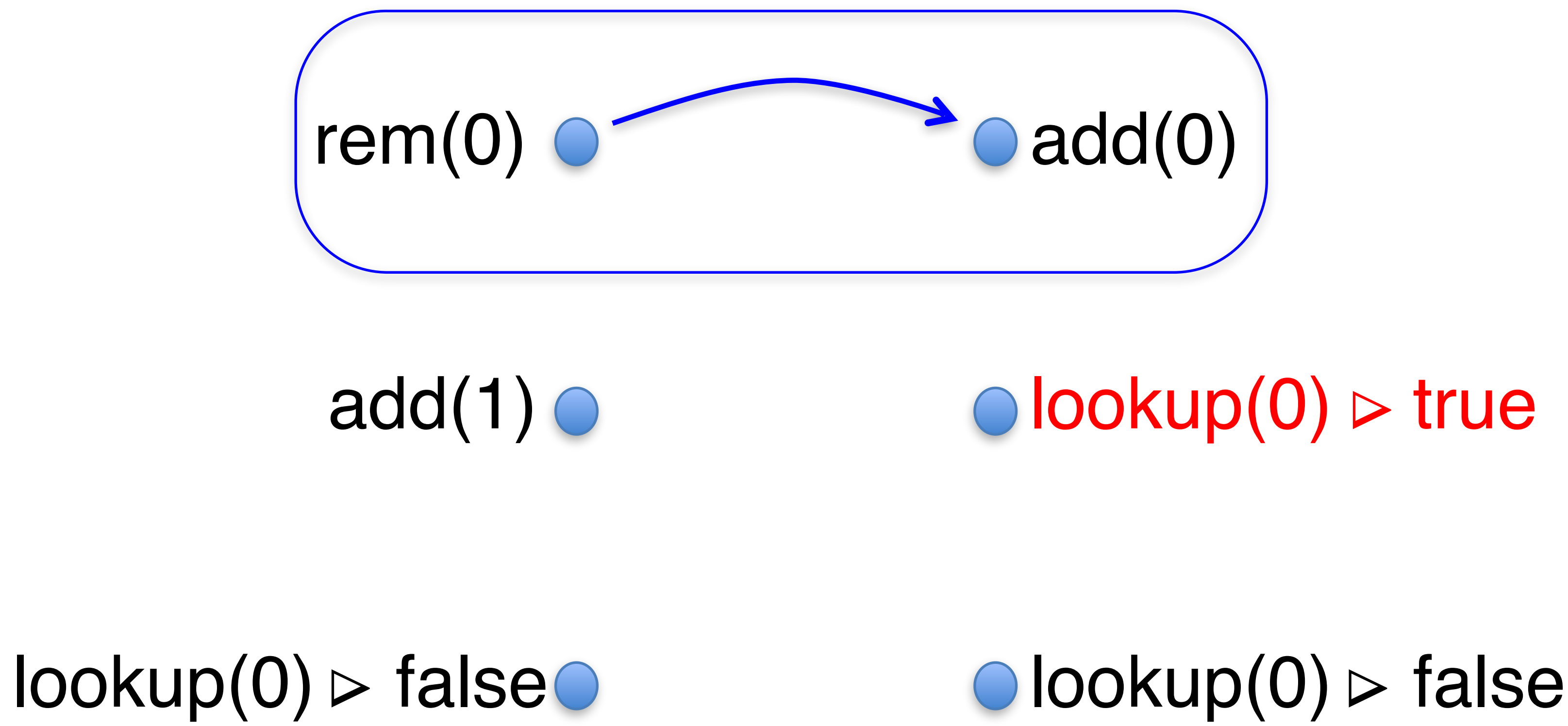

- there exists a poset in the Spec.(lookup(0)▹true)
  (posets s.t. the projection on operations with input 0 has a maximal add(0))
- this poset is called local interpretation

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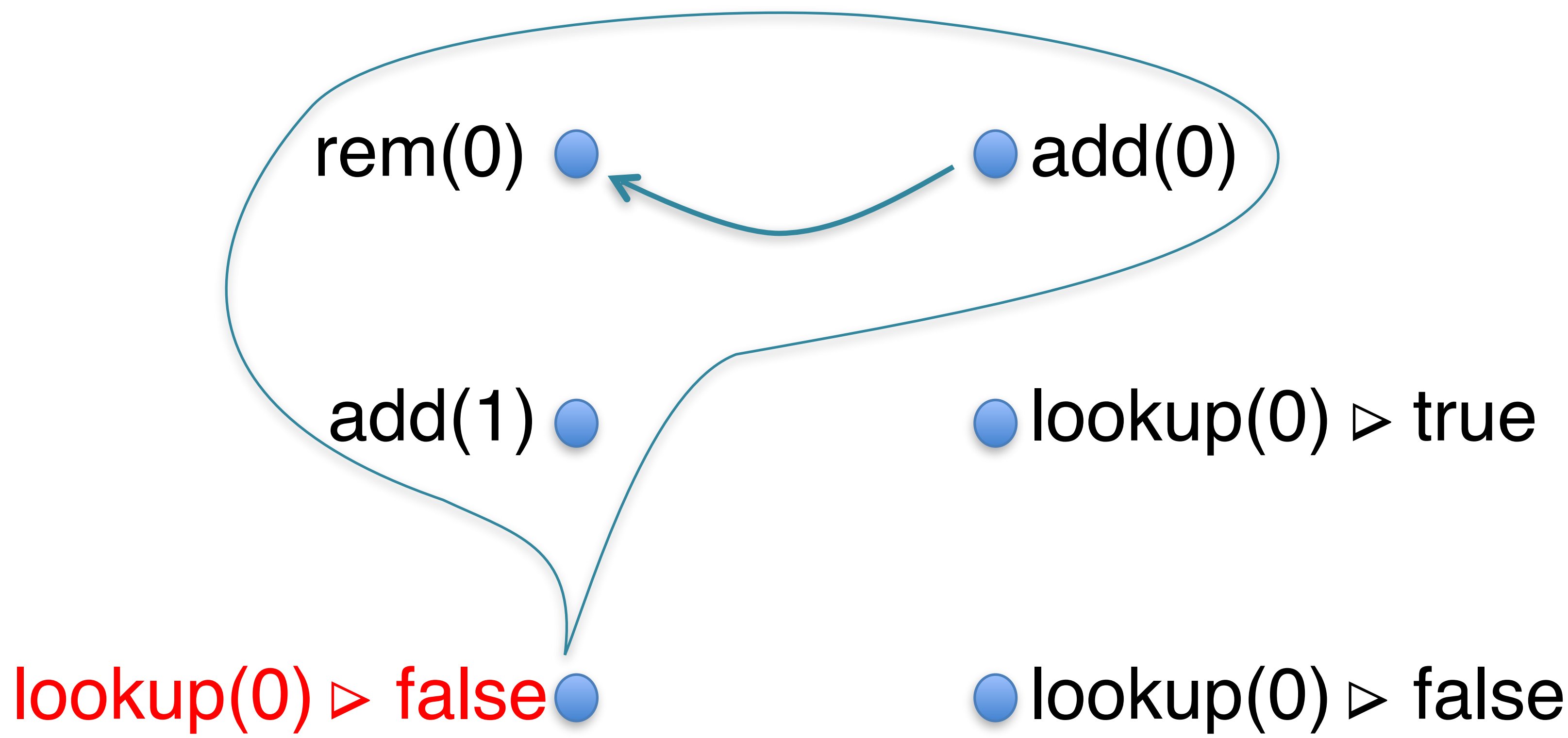

- there exists a poset in the Spec.(lookup(0) ▷ false)

  (posets s.t. the projection on operations with input 0 has **no** maximal add(0))

- this poset is called local interpretation

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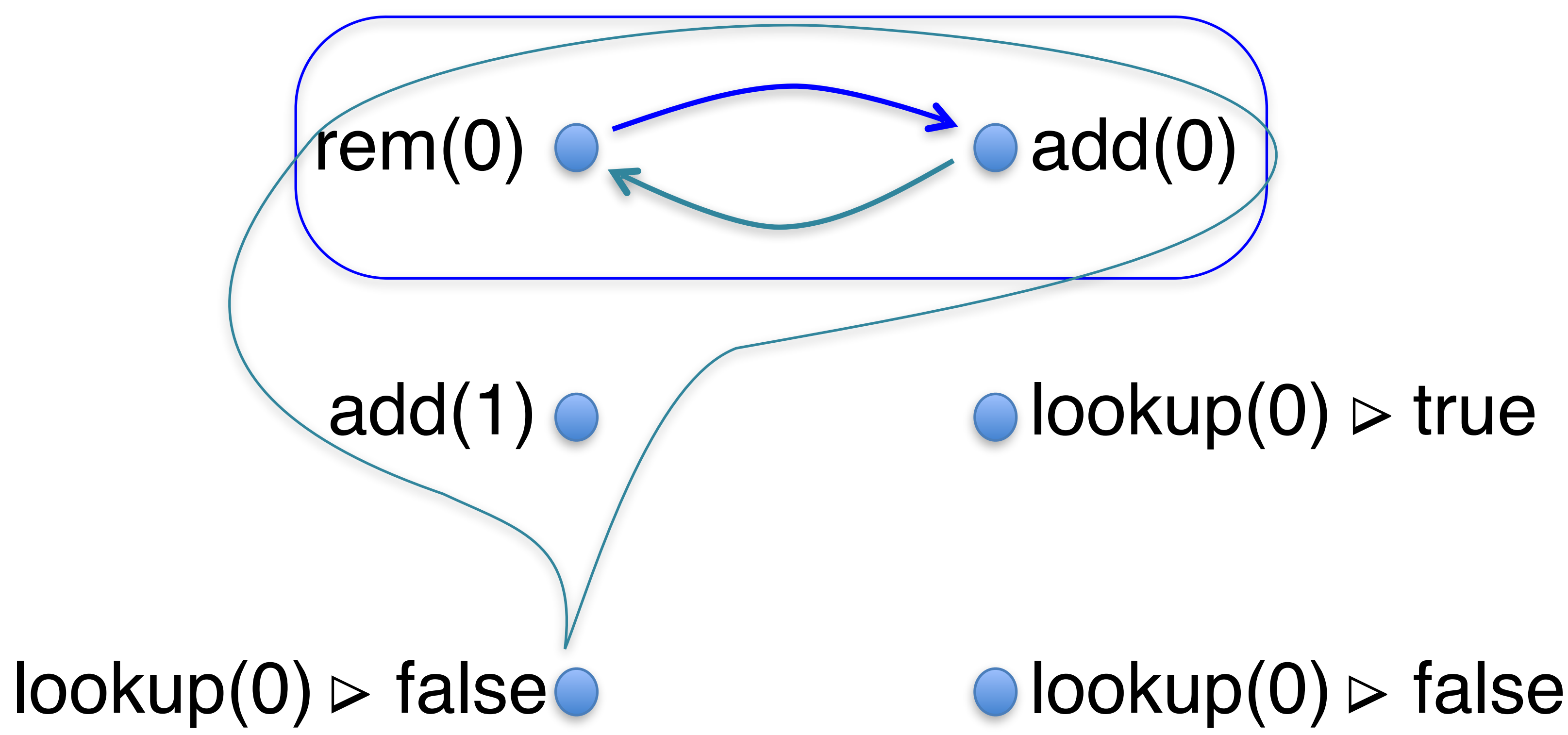
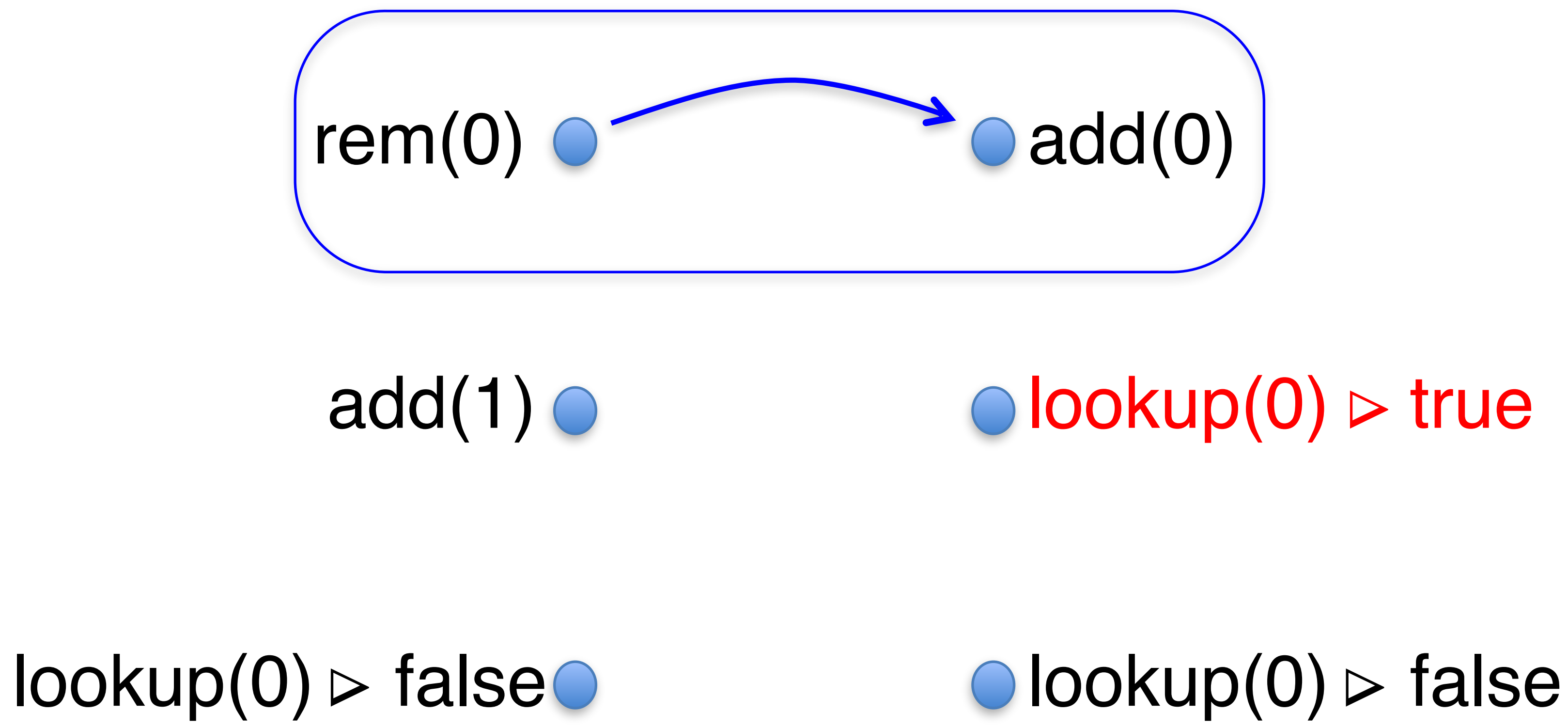


- local interpretations on different sites **do not** have to agree on the order between common operations
  - messages are received in different orders

A trace is safe w.r.t a specification



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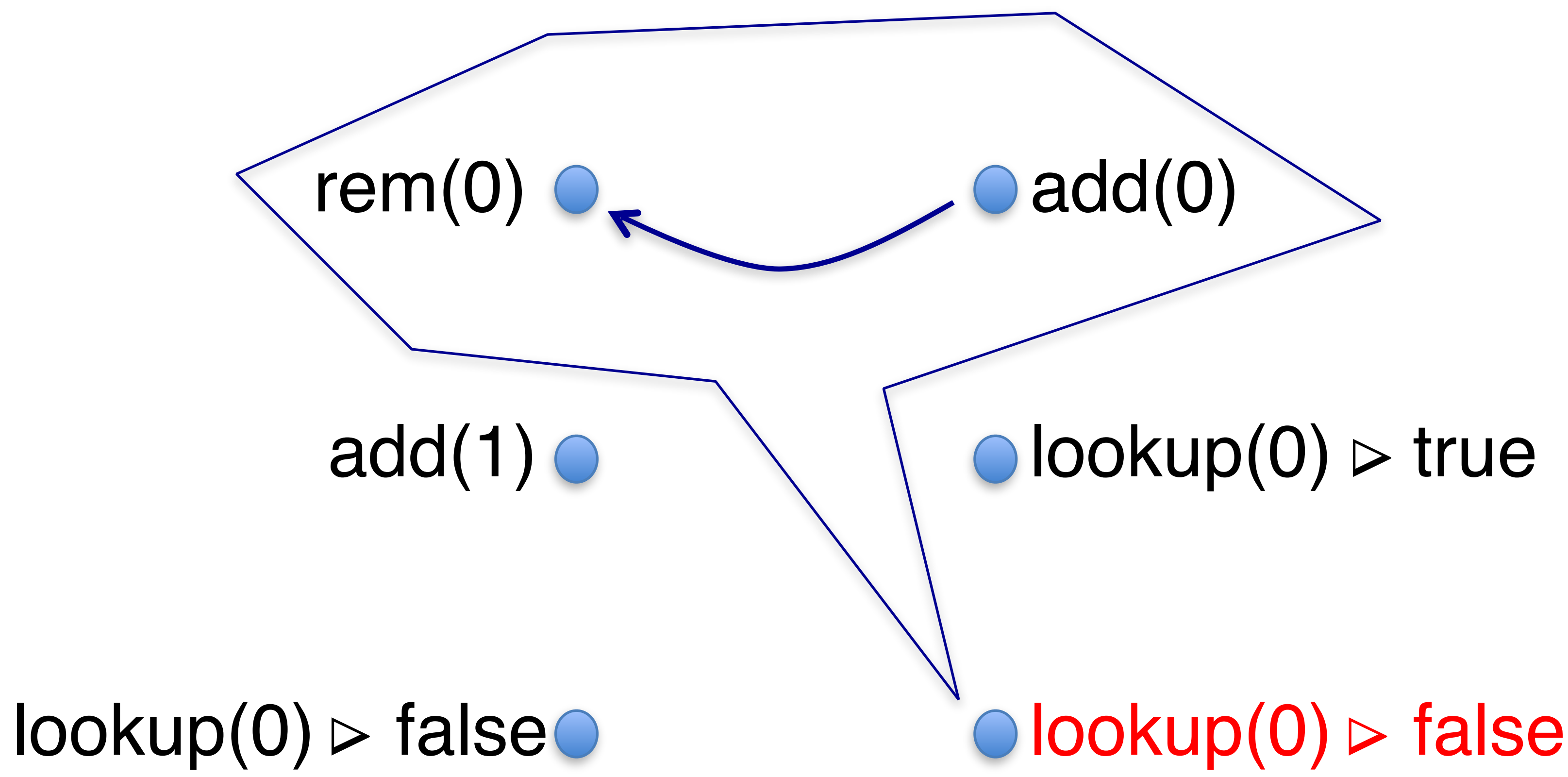

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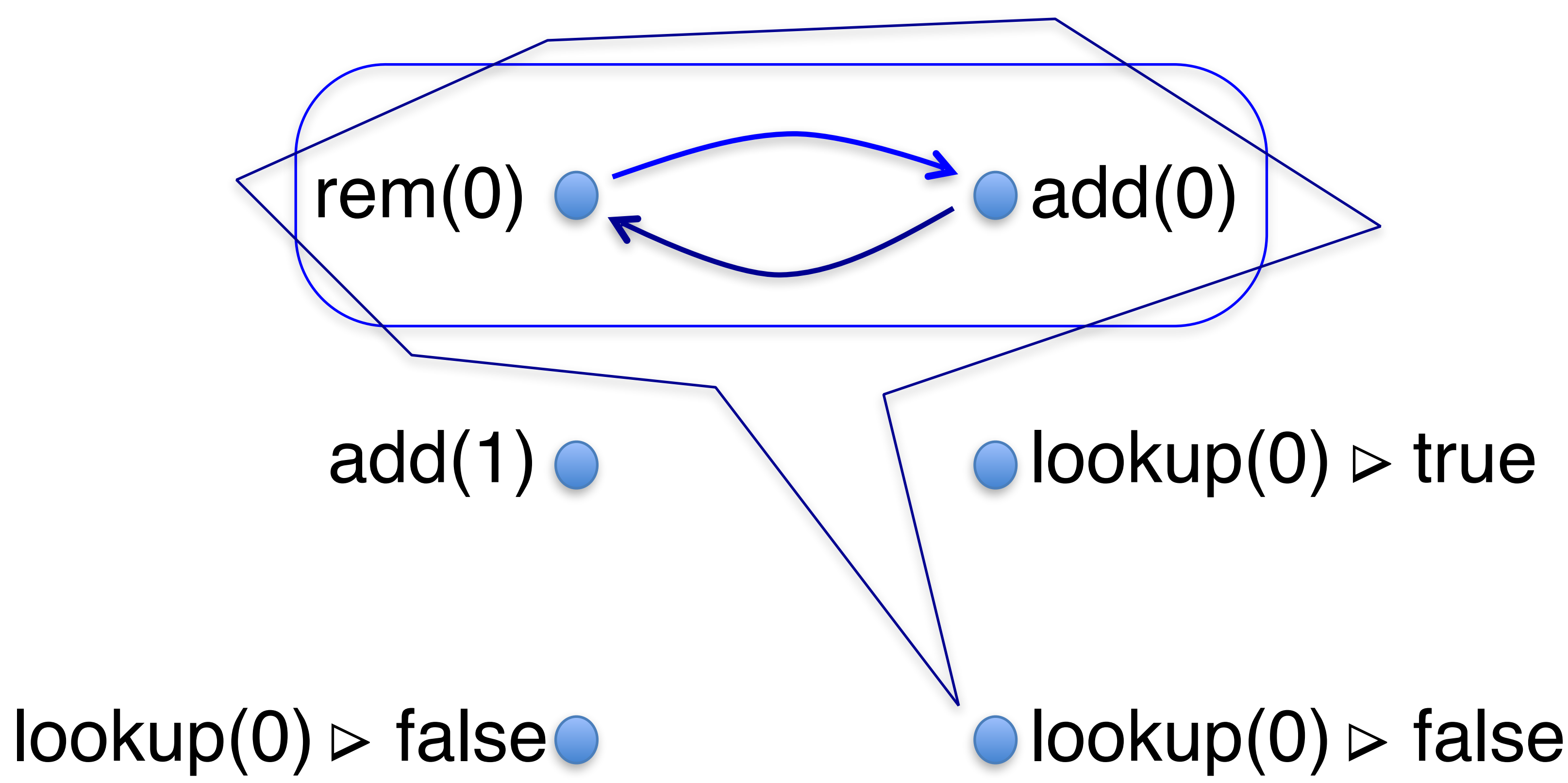
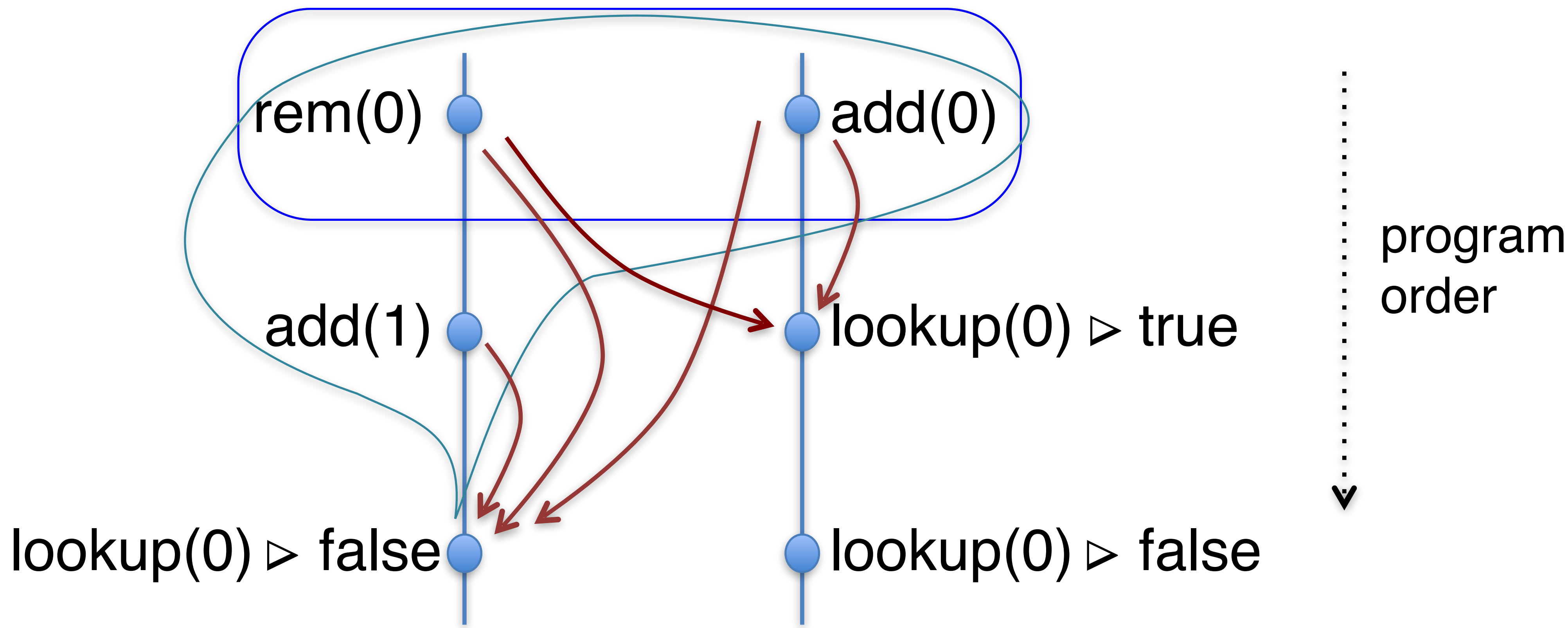


- local interpretations on the same site **do not** have to agree on the order between common operations
  – conflict resolution may be non-deterministic, e.g., speculative executions

A trace is safe w.r.t a specification

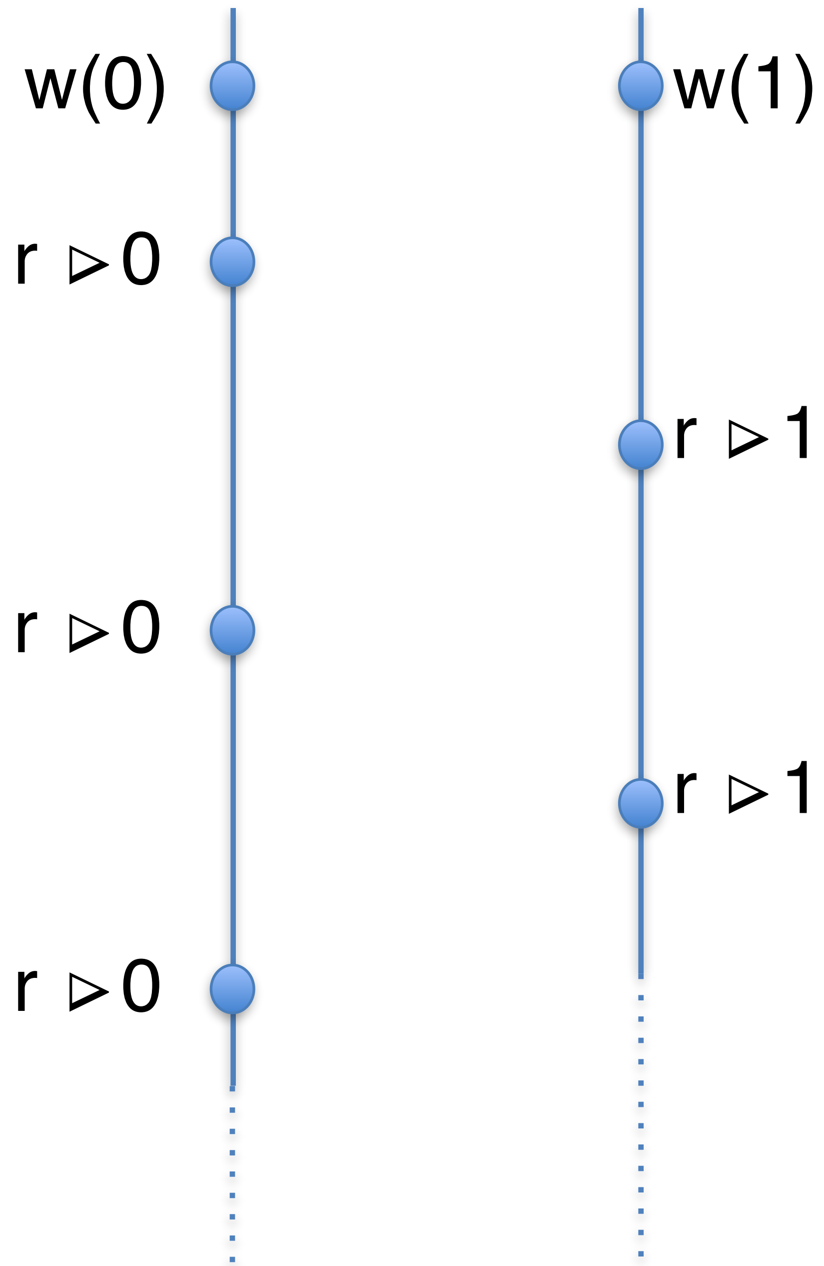


- executed-before ∪ program order is acyclic
  (aka "visibility")
  - α executed-before β iff α belongs to the local interpretation of β
  - messages that announce some operation are sent after the operation itself is submitted to a site

A trace is safe w.r.t a specification

1. For each operation O there exists a local interpretation (poset of ops.) in the specification of O
2. executed-before ∪ program order is acyclic

Violation of convergence



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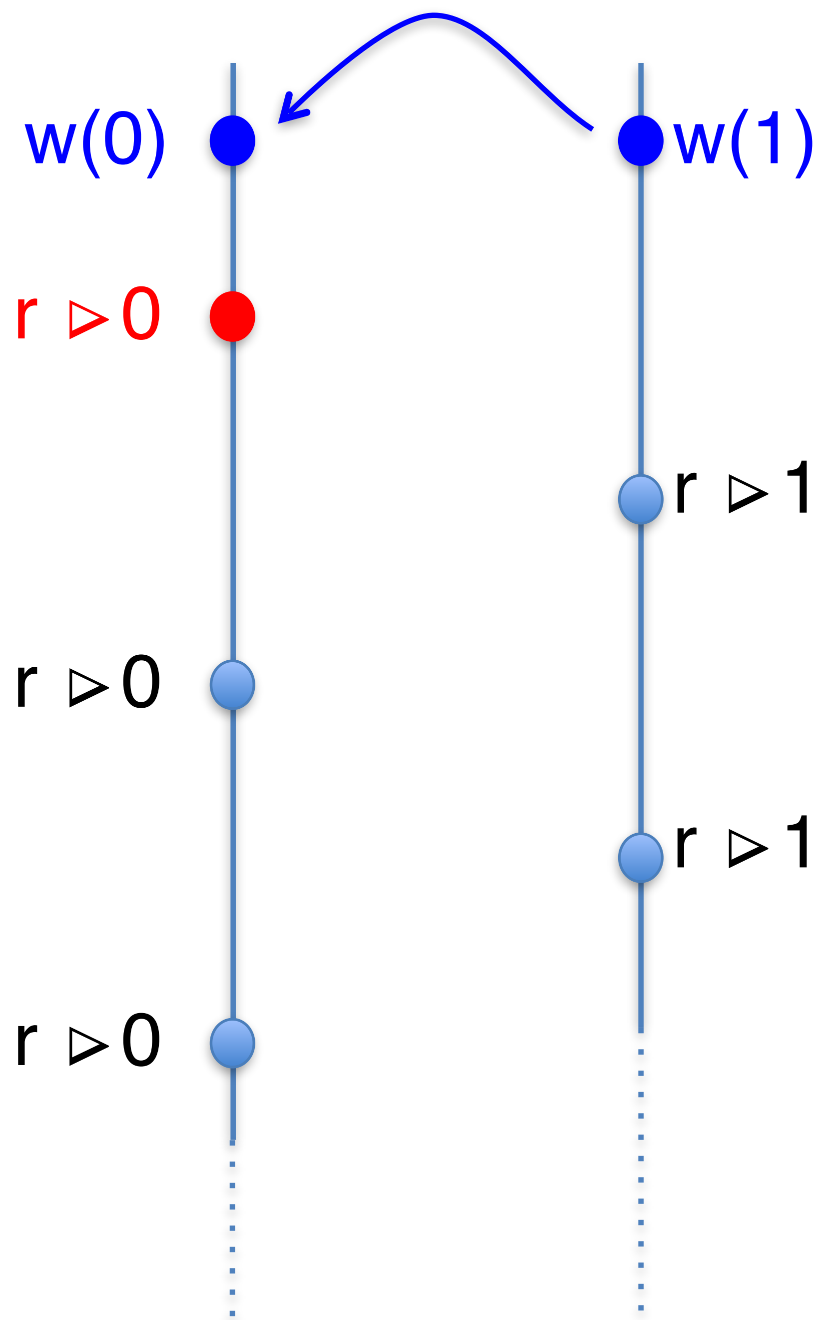

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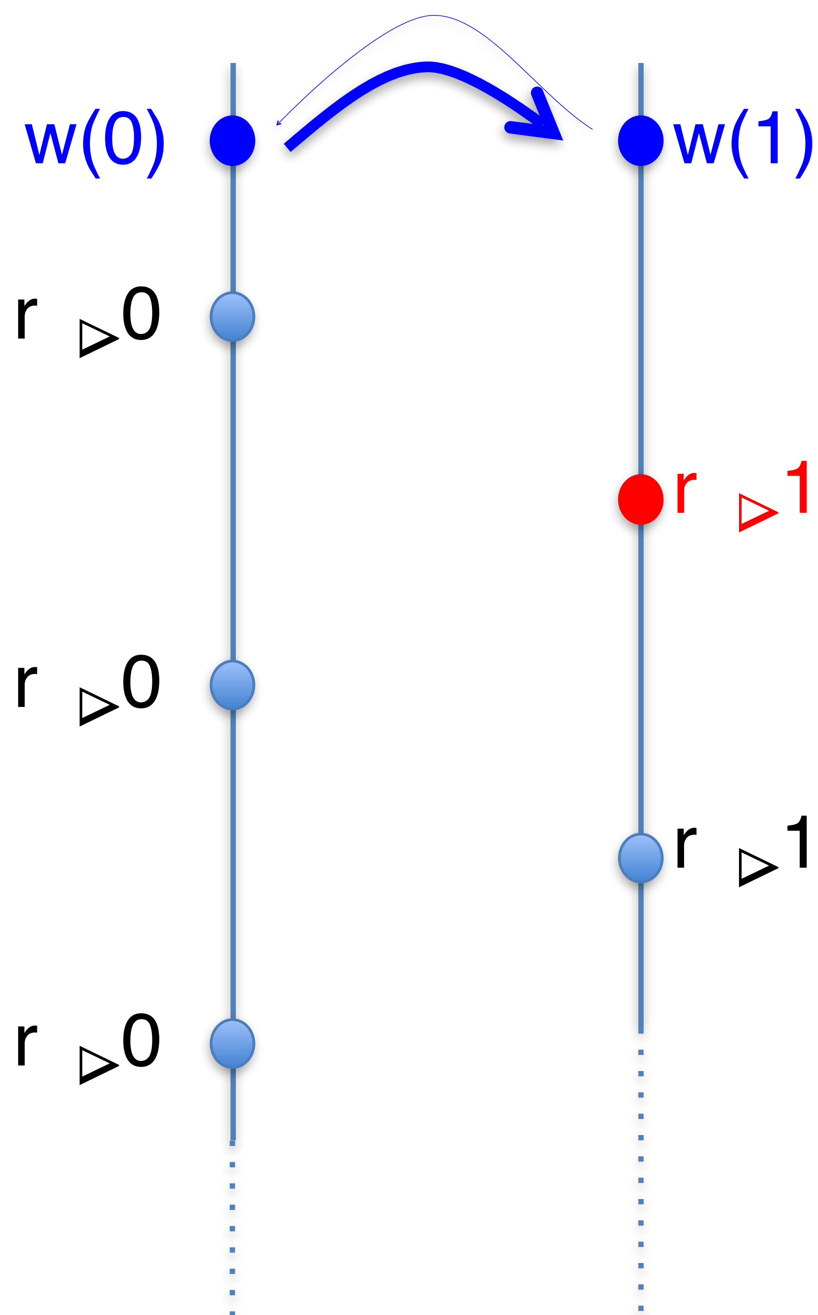

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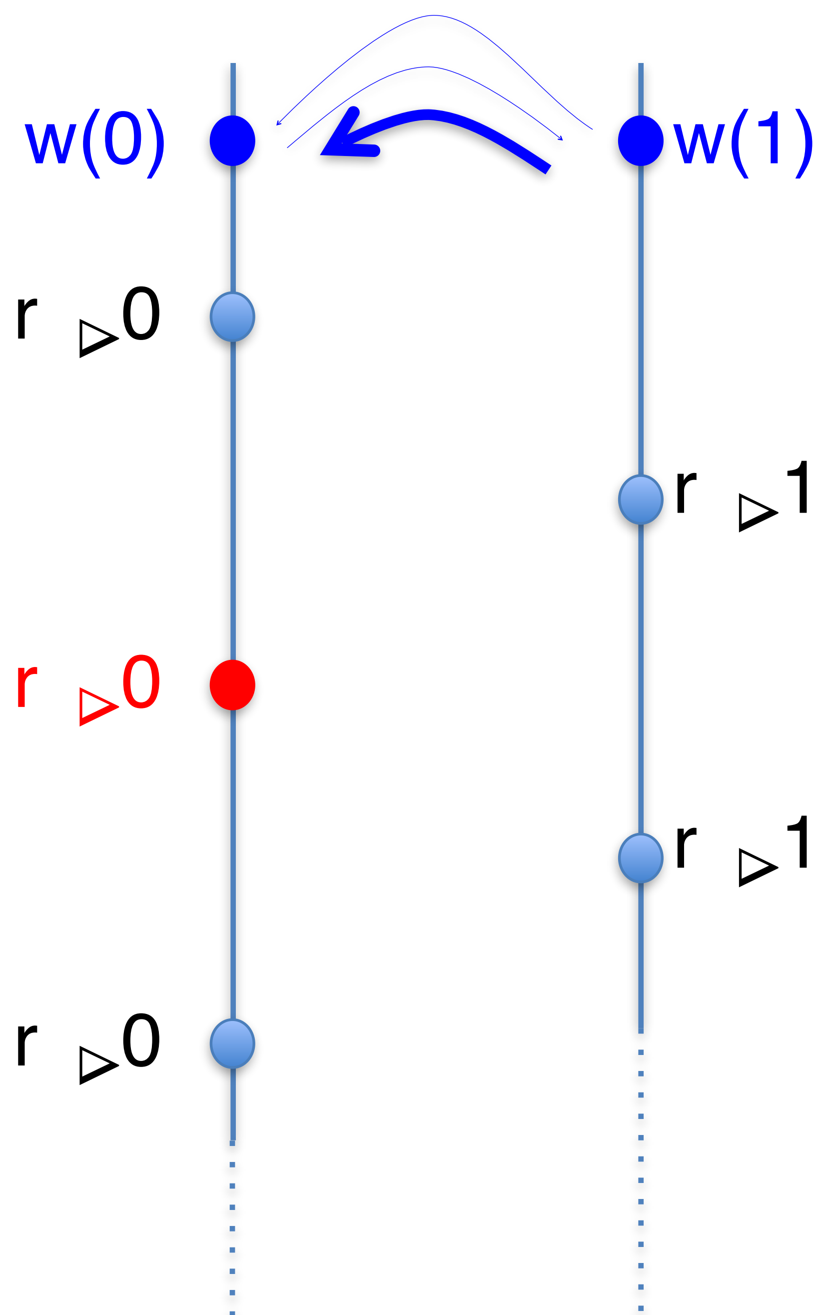

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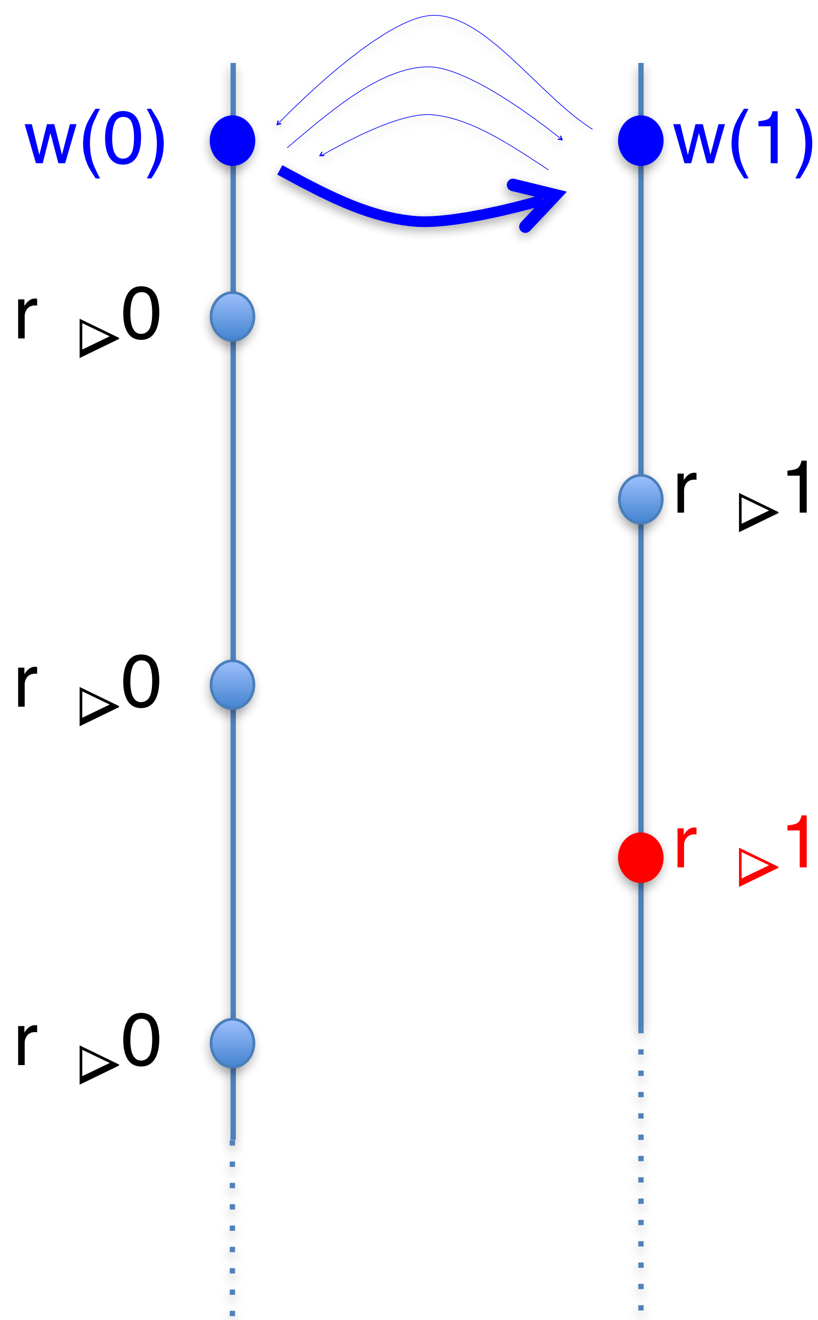

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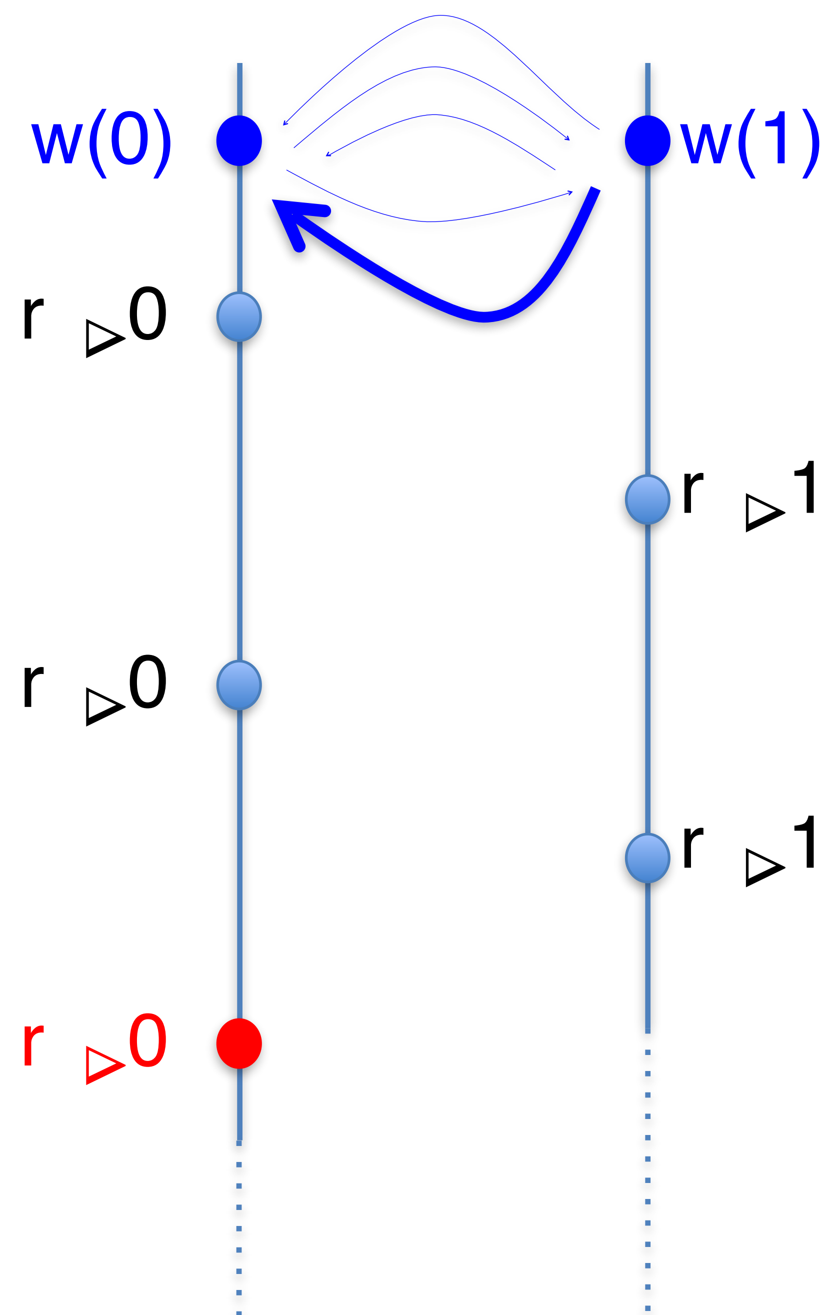

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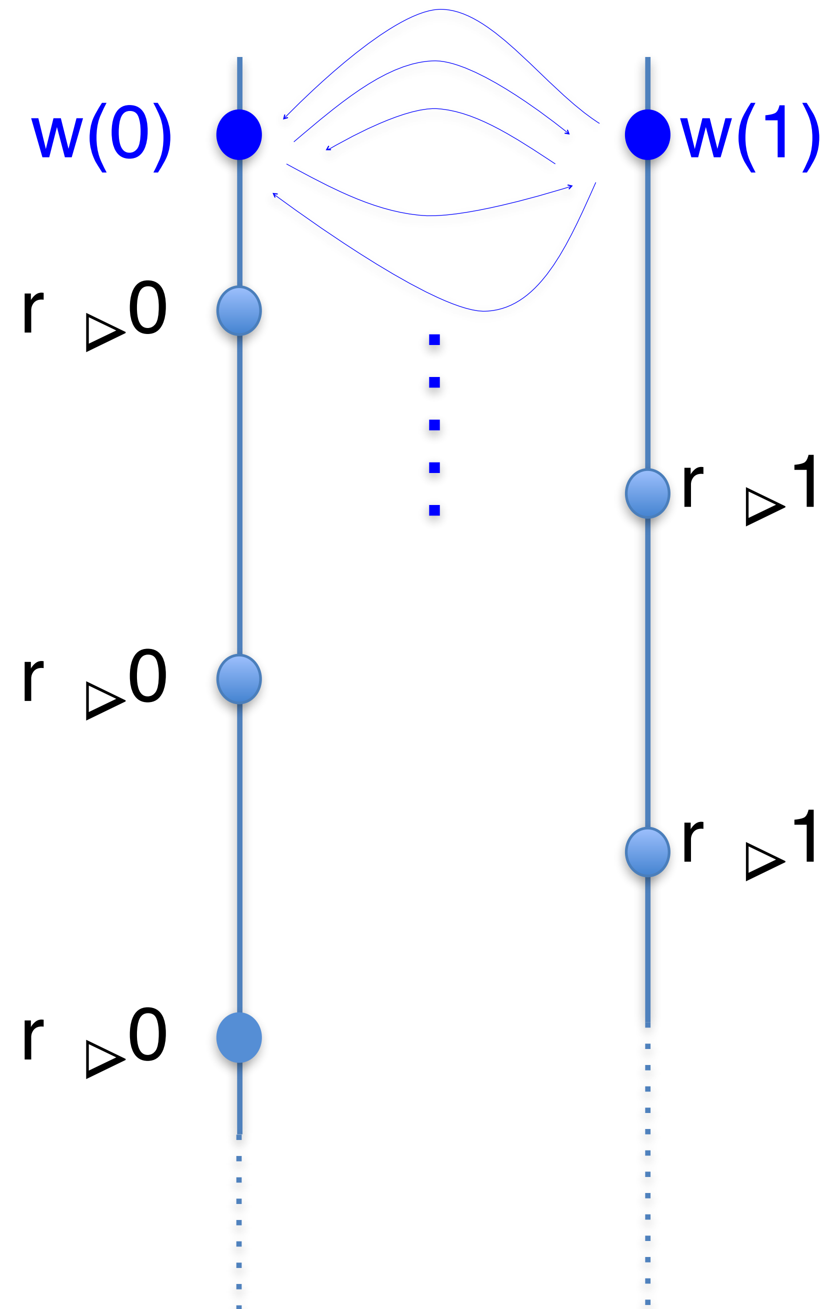

Convergence

For every infinite trace

There is a *global (infinite) interpretation* GI s.t.
For every prefix P of GI,
there is a *finite* number of local interpretations LI s.t.
P is not a prefix of LI

i.e.,

After some point,
all local interpretations have P as a prefix

Checking Eventual Consistency

- Reduction to state-reachability / model-checking
- Given a Spec, construct a monitor M[Spec] s.t.

For every Impl,

Impl is not EC wrt Spec

iff

Impl x M[Spec] can reach a specific control state

(violates some LTL formula)

Checking Eventual Consistency

Basic ingredients for the reduction

- Monitor tracks sequentializations of traces

A trace is unsafe iff all its sequentializations contain an operation that can not be explained using its past

- We only need to reason about minimal local interpretations
- We can use counting:
  - Count the number of occurrences of each operation
  - Compare with minimal posets in the specification
- Safety: Monitor checks an invariant on counters
- Convergence: Monitor checks a condition on repeating operations

Decidability, Complexity

- Class of implementations:
  - fixed number of boolean programs communicating through unbounded unordered channels
- Class of specifications:
  - new class of finite automata for representing posets
- Verifying Eventual Consistency is decidable
  - Verifying Safety is reducible to Coverability in Petri Nets (in 2EXPSPACE and EXPSPACE-hard)
  - Verifying Convergence is reducible to Reachability in Petri Nets (EXPSPACE-hard)

Conclusion/Future work

- Reductions to Invariant Checking/MC
- Decidability for Static Linearizability and Eventual Consistency
- High complexity, undecidability (linearizability in general)
- Semantical issues:
  - Formal definition of correctness criteria
  - (Weak) memory models/guarantees of the underlying infrastructure
- Decidability/Complexity issues:
  - Other criteria such as causal consistency
  - Classes of implementations/specifications
- Efficient approximate analysis:
  - Abstractions for proving correctness
  - Under-approximations for detecting violations