Reasoning About Concurrent Data Types

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Established by the European Commission

(Sequential) Data Types

Abstractions to simplify the manipulation of high-quantity data: objects (instances) + operations

- **Queue** = **enqueue**(value) + **dequeue**( ) => value
- Stack, Set, Key-value map, …

Specifications of data types:

- API documentation

Method Summary

Methods

Modifier and Type	Method and Description
boolean	**add**(E e) Inserts the specified element into this queue if it is possible to do so immediately without violating capacity restrictions, returning `true` upon success and throwing an `IllegalStateException` if no space is currently available.
E	**element**() Retrieves, but does not remove, the head of this queue.
boolean	**offer**(E e) Inserts the specified element into this queue if it is possible to do so immediately without violating capacity restrictions.
E	**peek**() Retrieves, but does not remove, the head of this queue, or returns `null` if this queue is empty.
E	**poll**() Retrieves and removes the head of this queue, or returns `null` if this queue is empty.
E	**remove**() Retrieves and removes the head of this queue.

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Specifications of data types:

- API documentation
- Pre/Post conditions in Hoare logic (Abstract Data Types):
  - { Seq } **enqueue**(value) { Seq :: value }
  - { value :: Seq } **dequeue**() => value { Seq }

Concurrent Data Types

Basic blocks of software that needs to process data in parallel

Concurrent Data Types: operations can be invoked in parallel from different threads or sites in a network

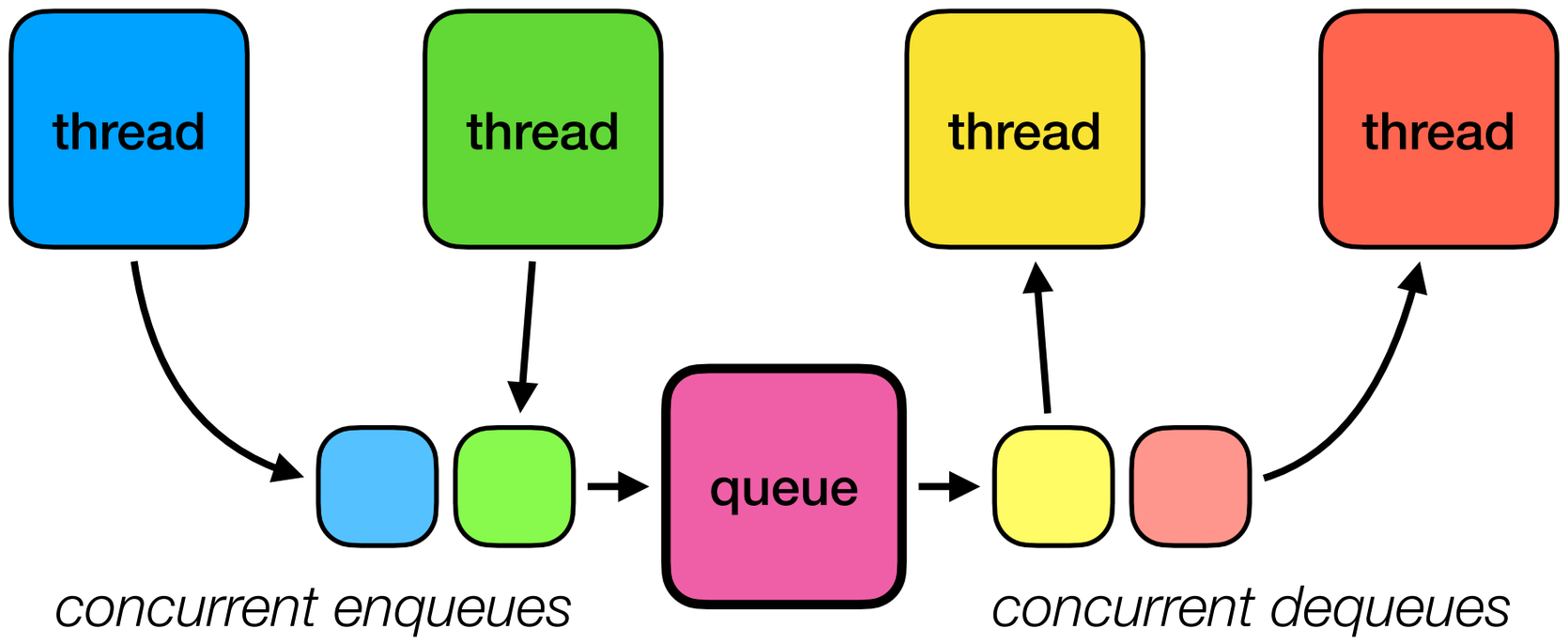
Support high-frequency parallel accesses to high-quantity data

Deployed over a shared-memory or a network

Formal specification and verification ?

Concurrent Objects

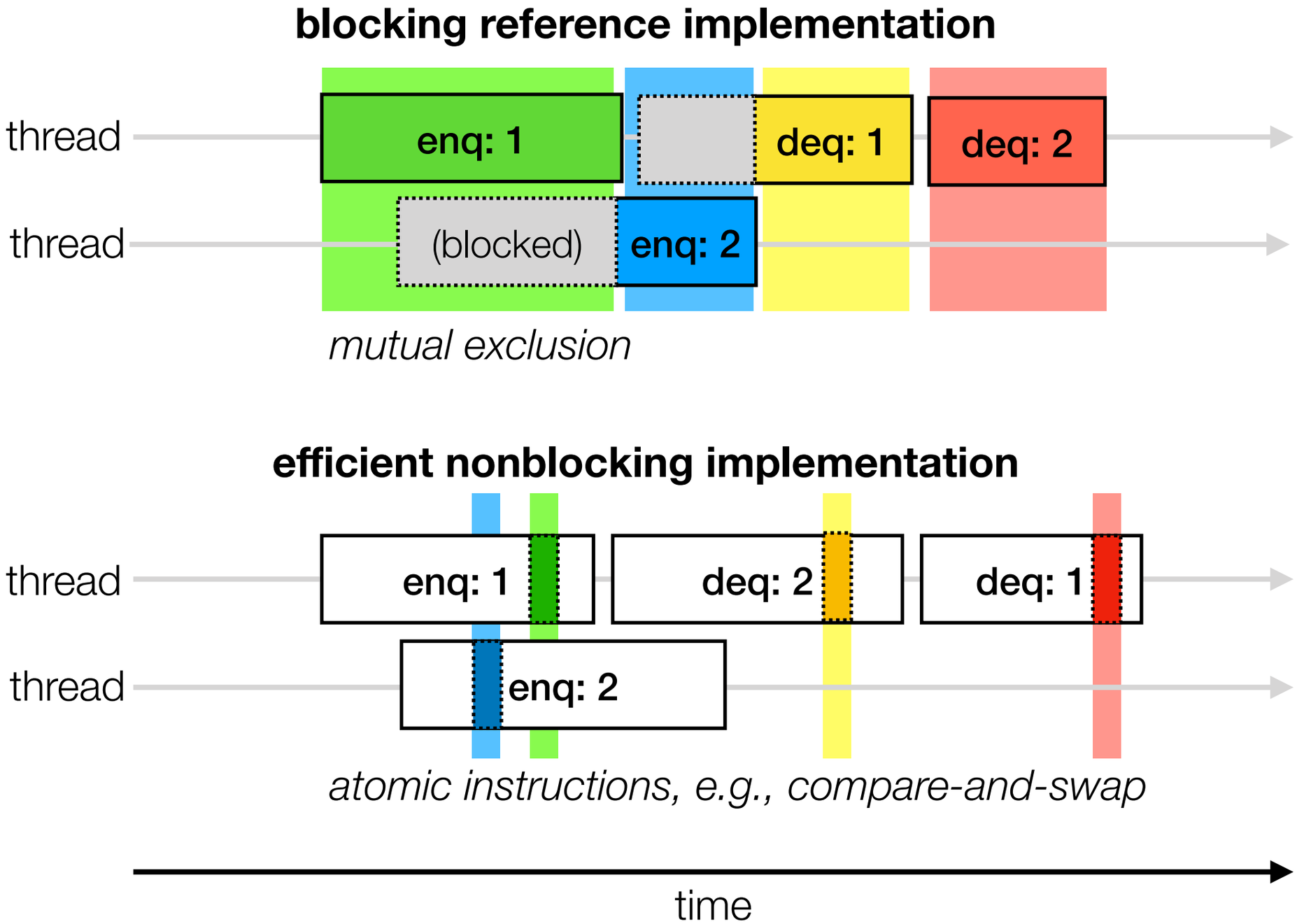
Multi-threaded programming



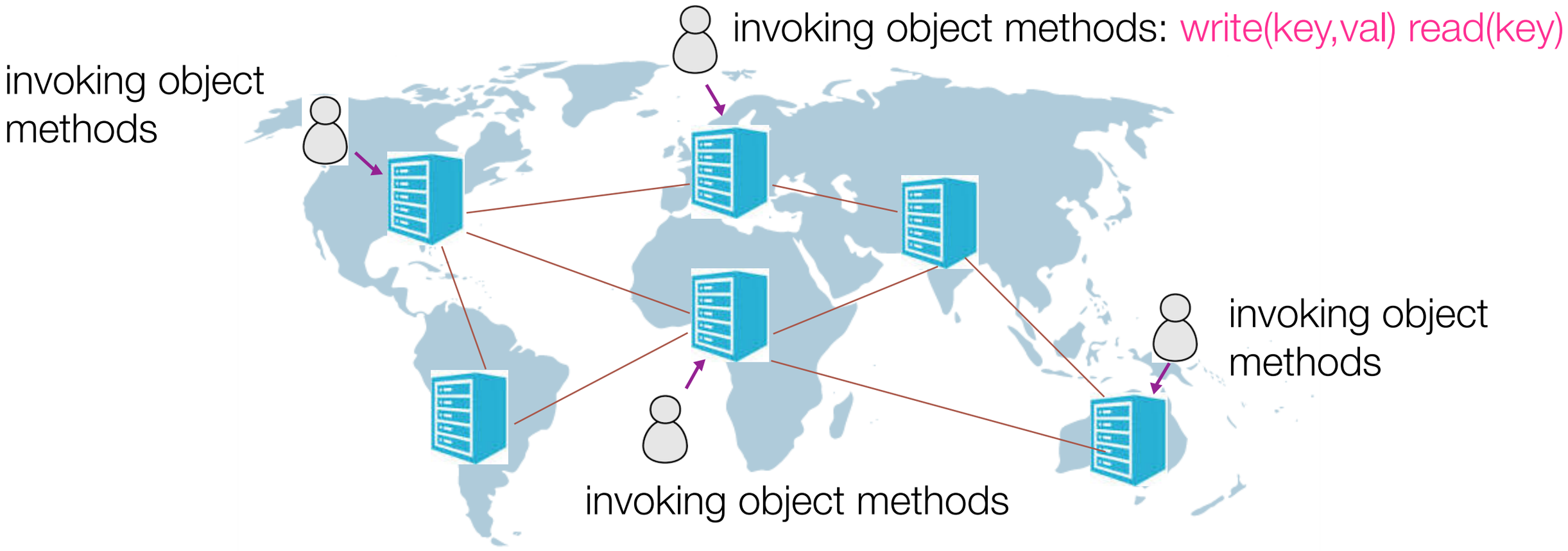
e.g. Java Development Kit SE

dozens of objects, including queues, maps, sets, lists, locks, atomic integers, …

Lock-Free Implementations



Replicated Objects (NoSQL)



To support failures, the state of the object is **replicated**

For availability, replicas may store different versions: **weak consistency**

CAP theorem: No replicated object is strongly **C**onsistent, highly-**A**vailable, and **P**artition-tolerant

Instances: key-value stores (Amazon Dynamo,Cosmos DB), CRDTs

Concurrent Data Types

Consistency model + Data type semantics

Strong Consistency:

- sequential consistency: interleaving semantics
- linearizability: interleavings are consistent with real-time

Weak Consistency:

- eventual consistency: eventual propagation of updates
- session guarantees: consistency w.r.t. previous operations in the same session
- causal consistency: causally-related operations observed in the same order

Data Type Semantics:

- the effect of an operation (return value) in function of a past history of operations
- features of the sequential semantics + conflict resolution (replication)

This Talk

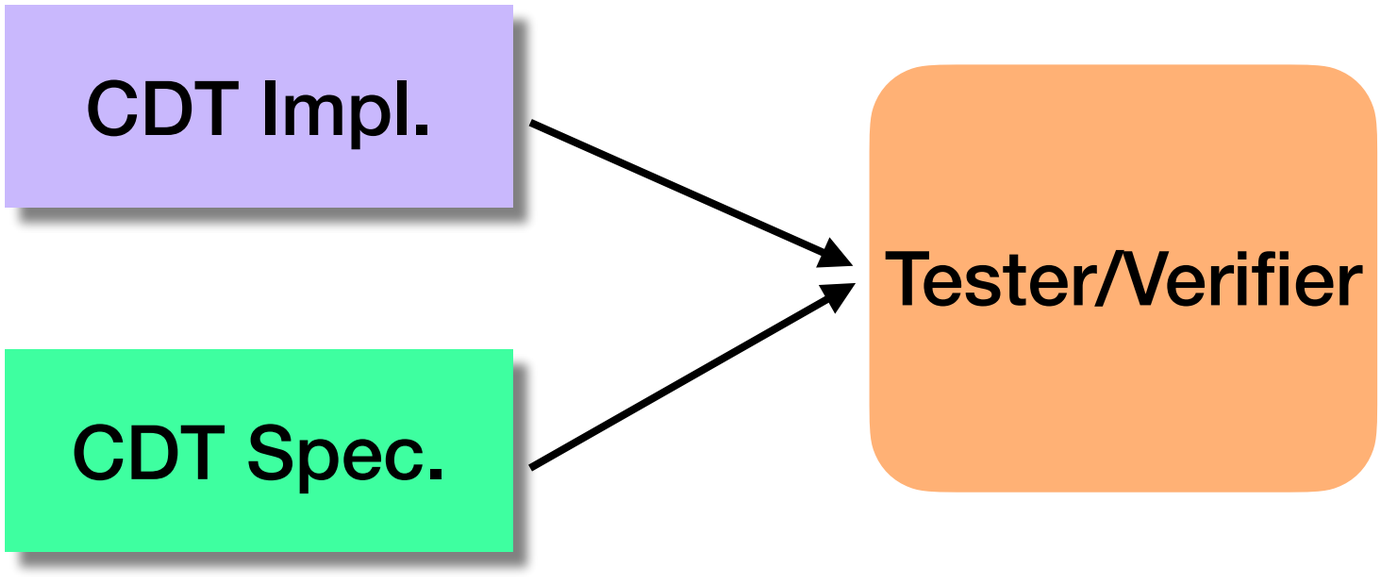
Investigating the complexity of **testing** and **verification** for CDTs

Testing is NP-complete [Gibbons.et.al.'97]: polynomial-time restrictions

Static Verification is undecidable [Alur et al.'96, ESOP'13, POPL'17]:

reductions to assertion-checking, decidable classes (complexity)

Approach: Verifiable Specs



complex logical artifacts:
e.g., second order quantification
over relations

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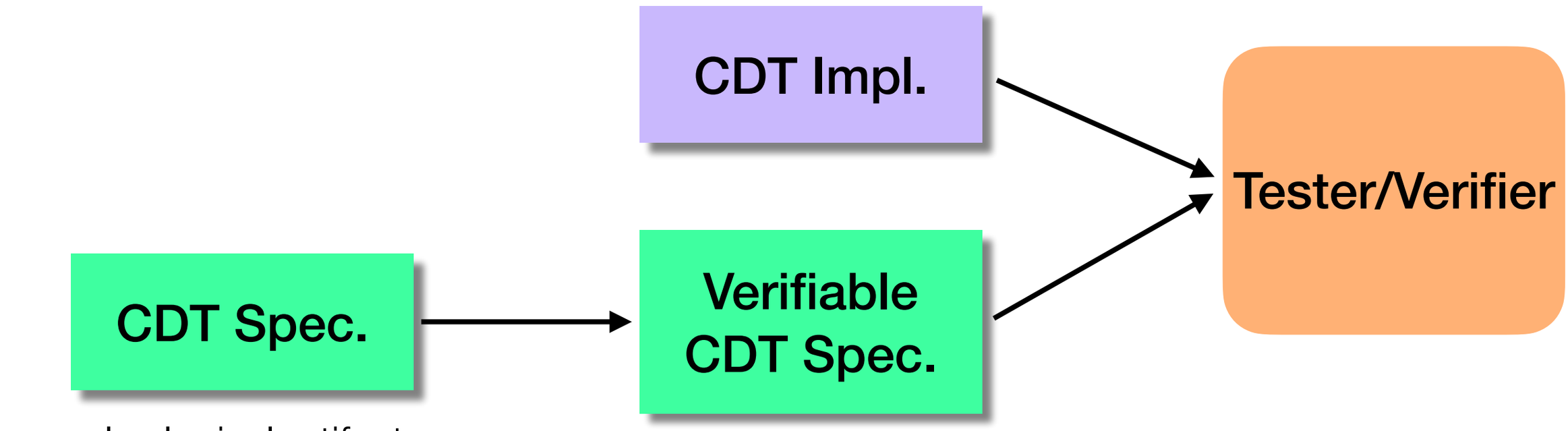

complex logical artifacts:
e.g., second order quantification over relations

e.g., acyclicity constraints
finite-state automata
reference implementations

Applied to classes of specifications and assuming mild constraints on implementations (data independence)

Approach: Verifiable Specs

Instantiations:

1. Concurrent collections (queues, stacks, etc) [ICALP'15, PLDI'15, POPL'18]
2. Replicated key-value stores [POPL'17]

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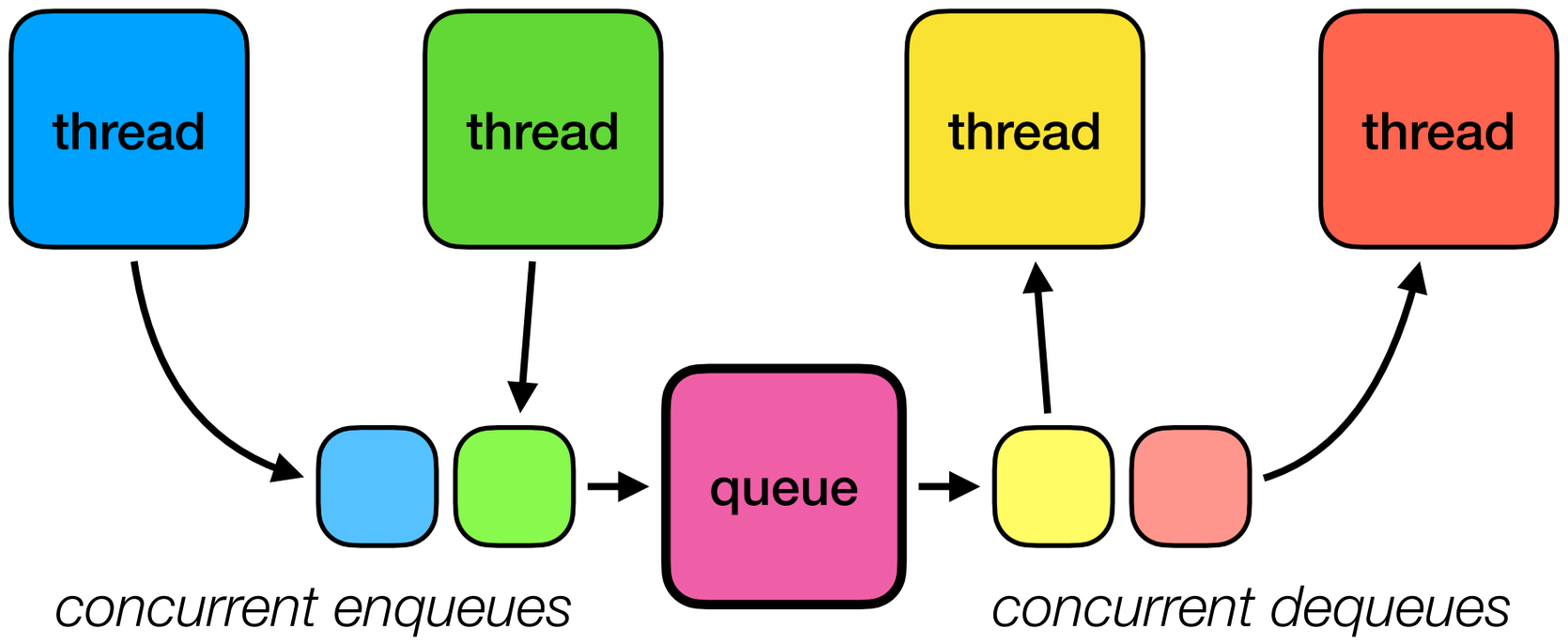

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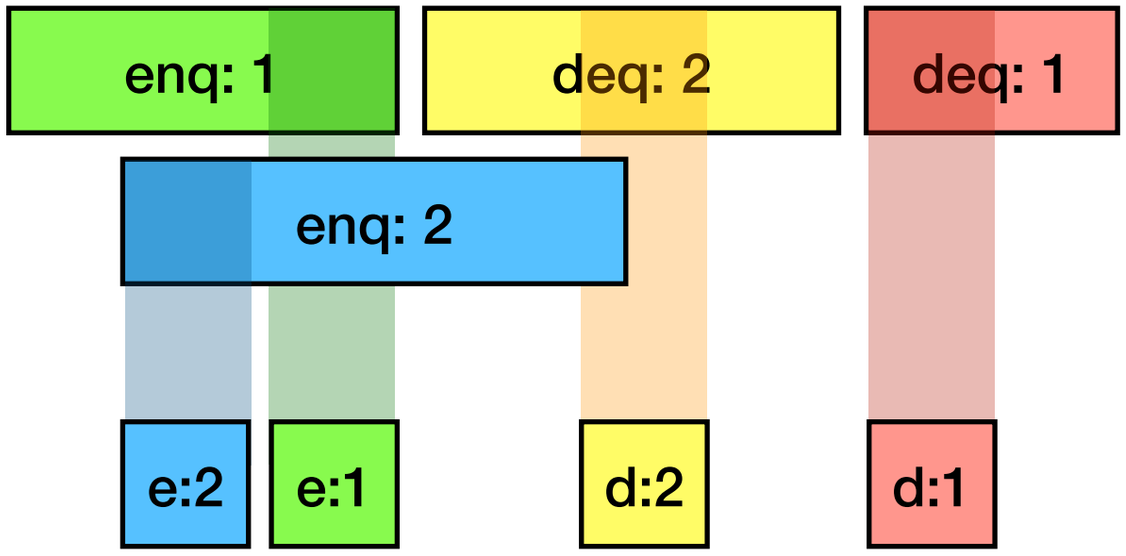
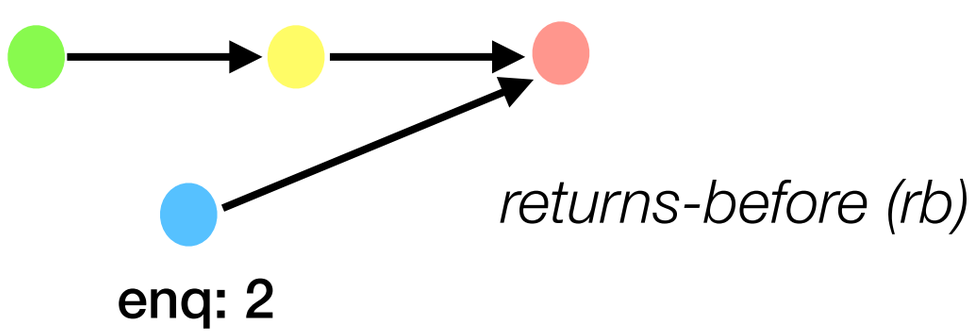
Linearizability [Herlihy&Wing'90]

Effects of each invocation appear to occur instantaneously

Execution history

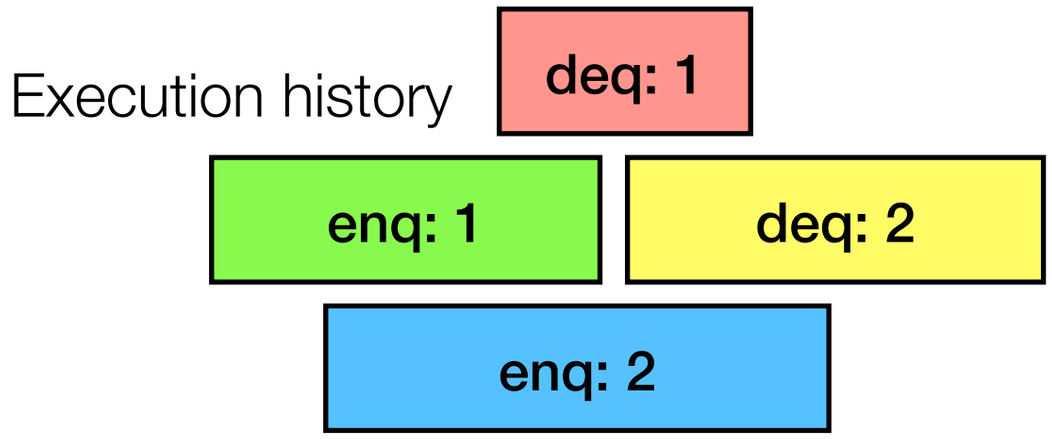


Linearization admitted by Queue ADT

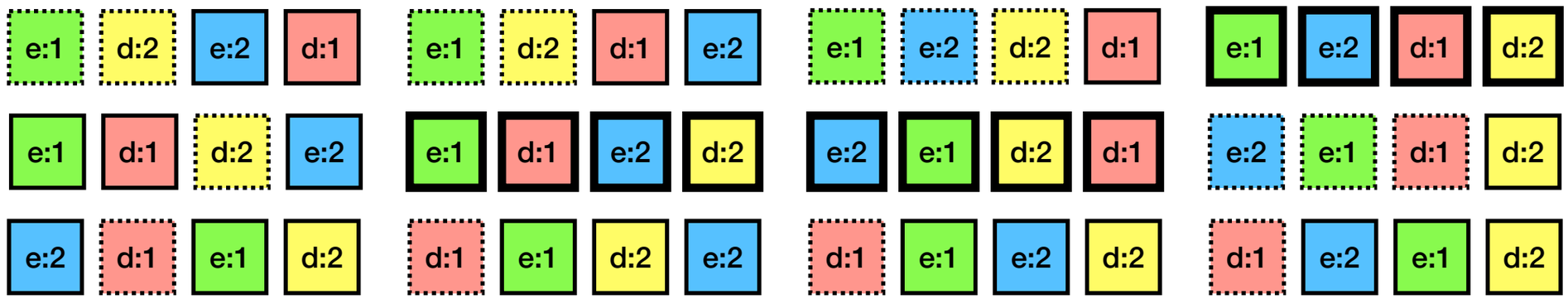


$\exists$ lin. rb $\subseteq$ lin $\wedge$ lin $\in$ Queue ADT

Complexity of Linearizability



Exponentially many linearizations to consider



Theorem [Gibbons.et.al.'97]

Checking linearizability for a fixed execution is NP-hard

Theorem [ESOP 2013]

Checking linearizability of a finite-state impl. is undecidable

Concurrent Queues [Henzinger et al'13] [ICALP'15]

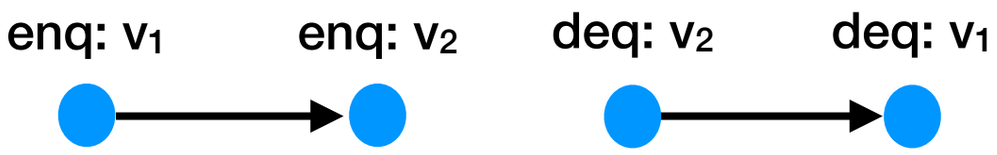
Linearizability ≡ Exclusion of **bad patterns** (assuming each value is enqueued at most once - sound under data independence)

"Value v dequeued without being enqueued"

"Value v dequeued before being enqueued"

"Value v dequeued twice"

"Values dequeued in the wrong order"



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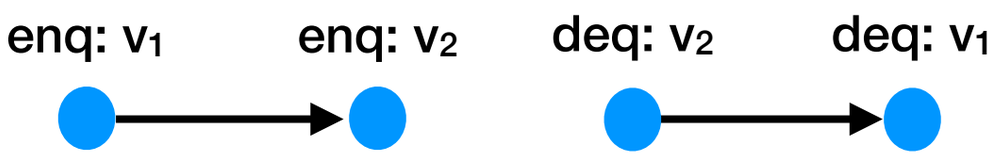

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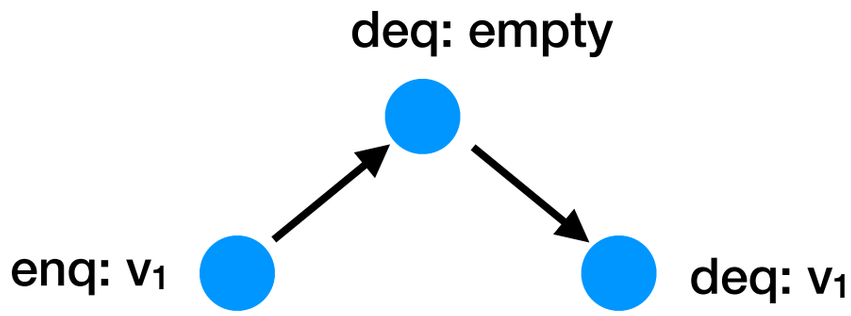

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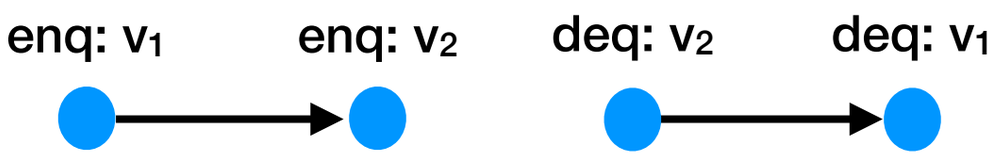

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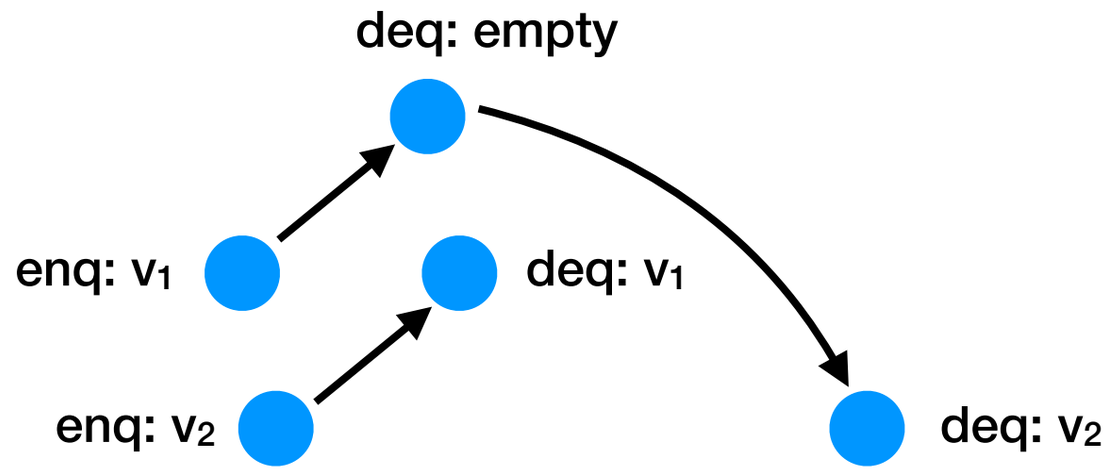

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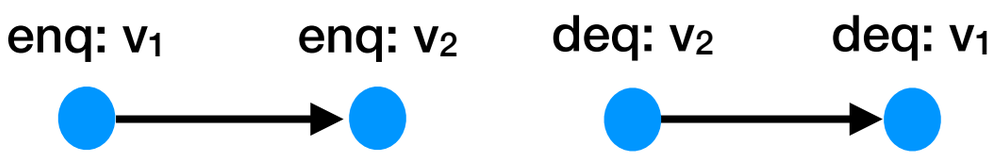

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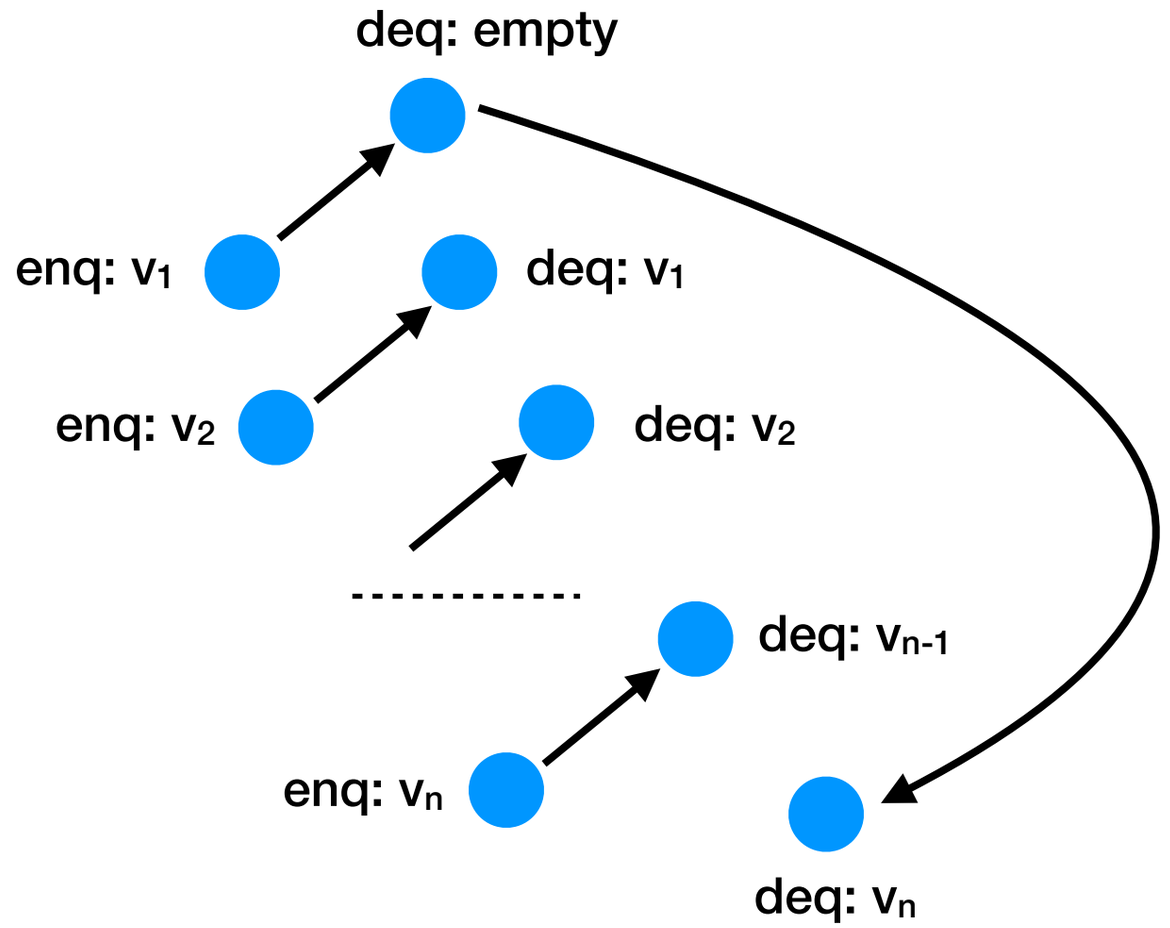

Concurrent Stacks [ICALP'15]

Linearizability ≡ Exclusion of **bad patterns** (assuming each value is enqueued at most once, which is sound under data independence)

"Pop doesn't return the top of the stack"

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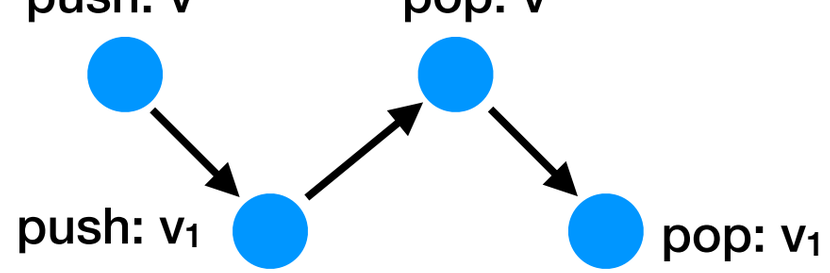

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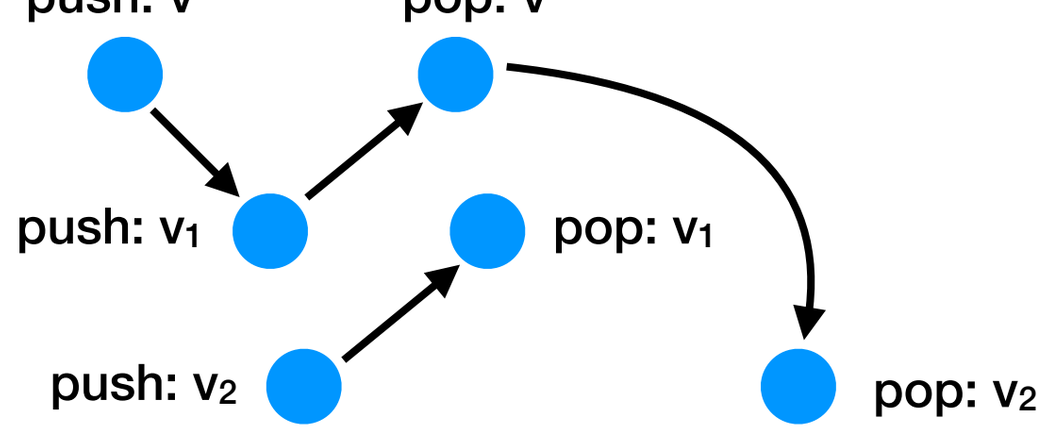

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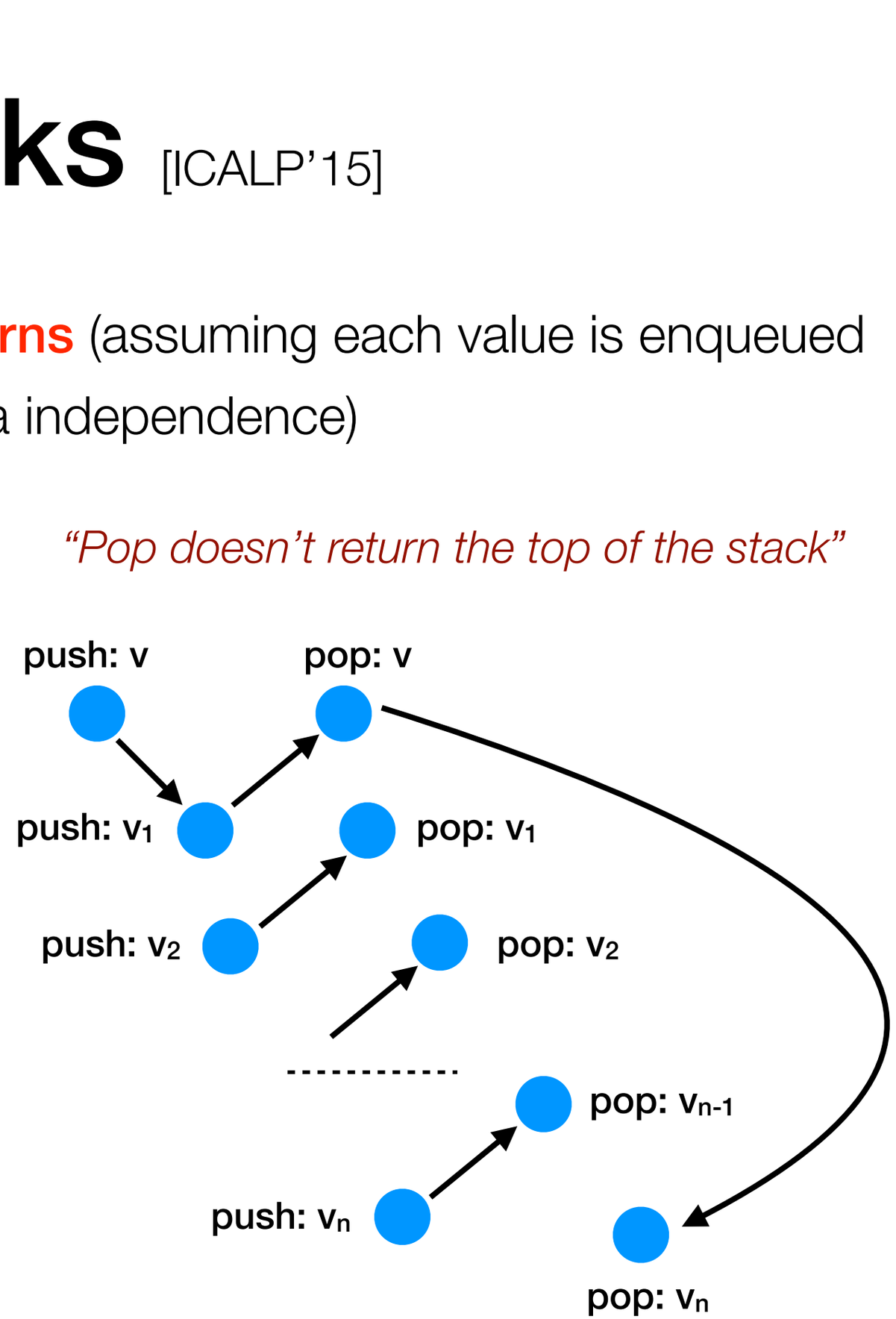
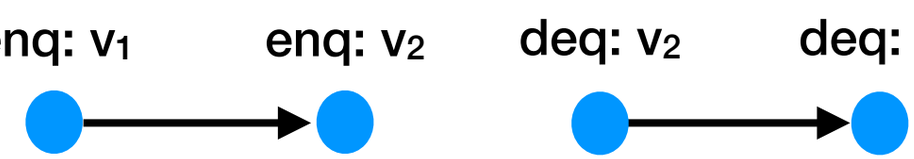


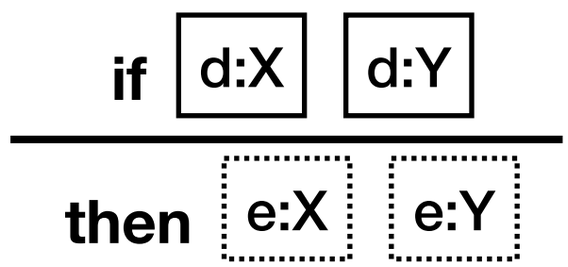
Bad Patterns - Testing

Using **bad patterns** to define inference rules for monotonic deductive inference (DATALOG)

Bad pattern



Queue ADT rule



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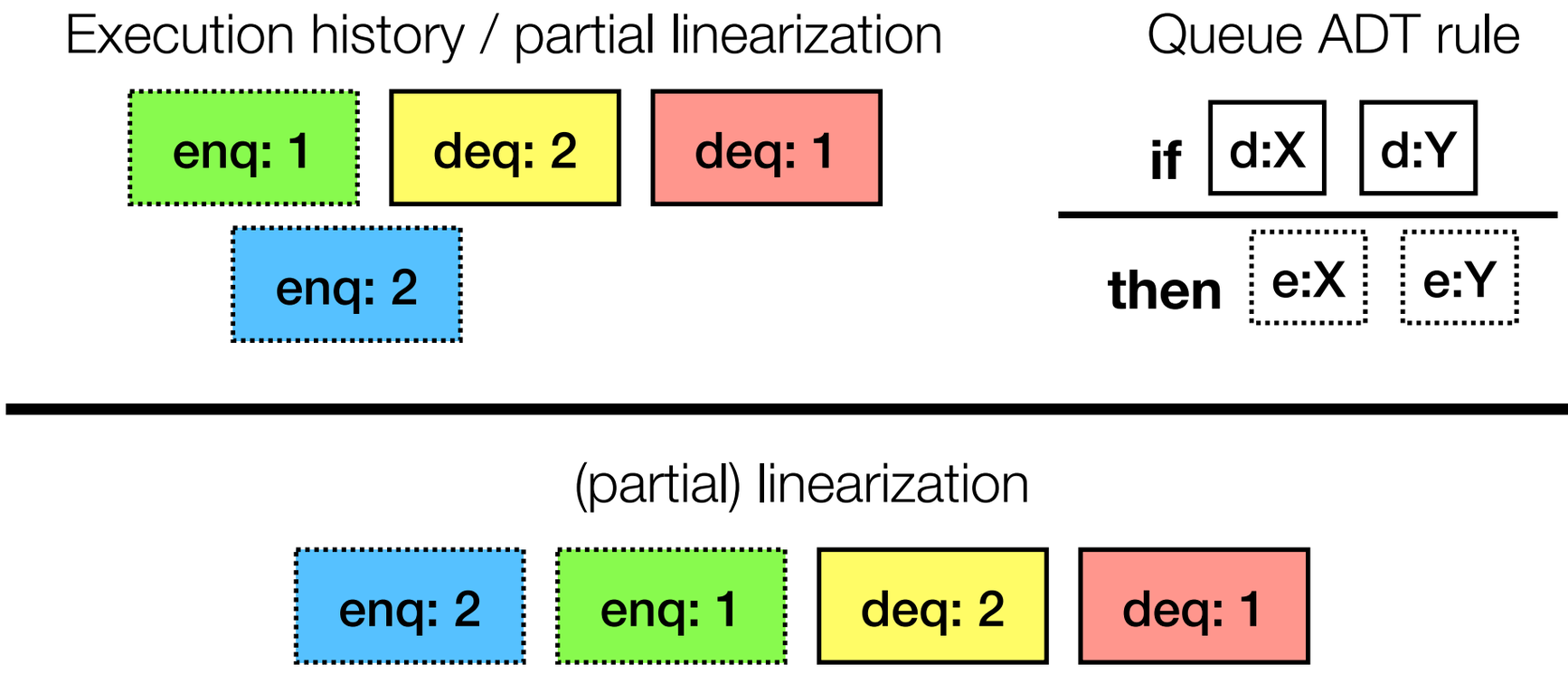


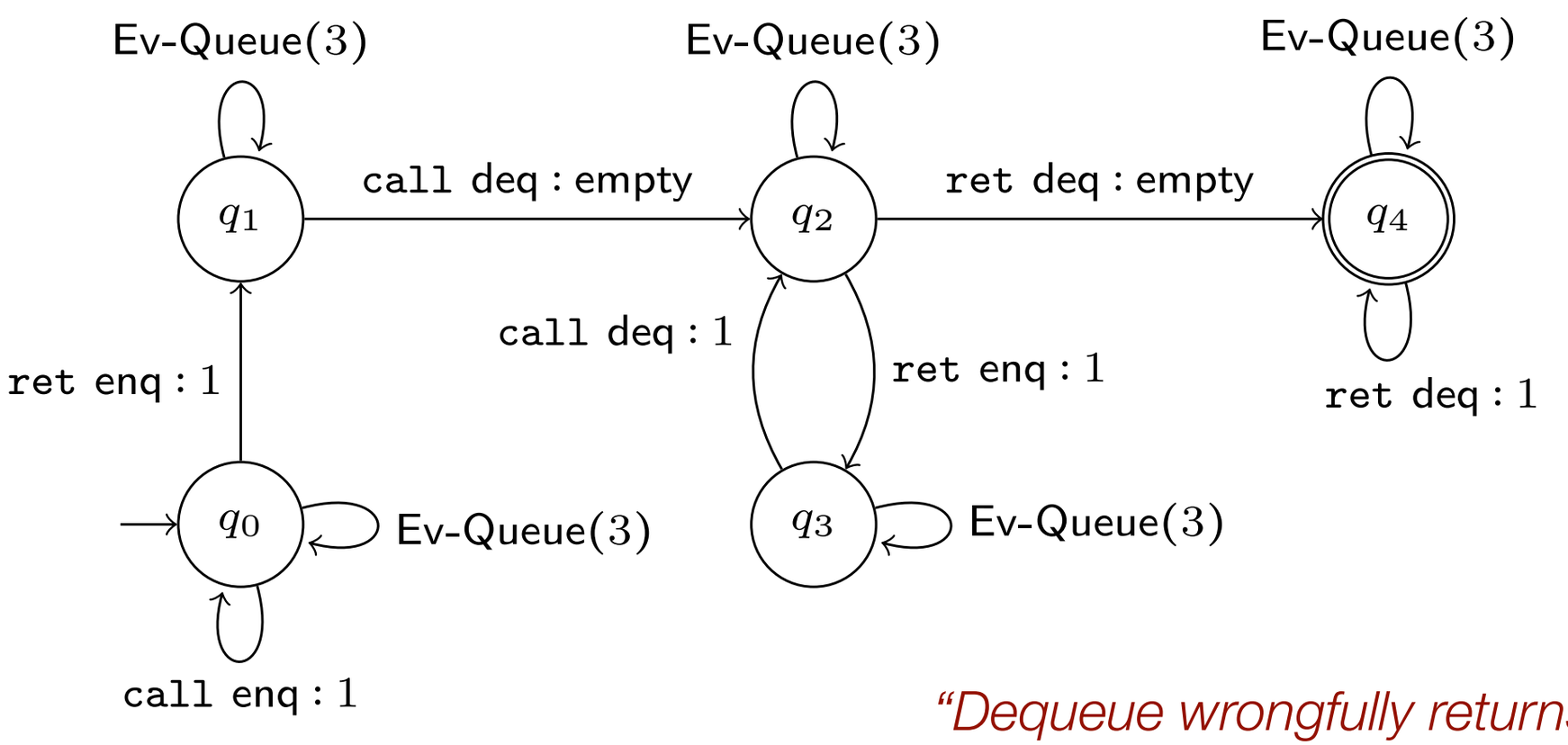
Theorem [PLDI'15, POPL'18]

Checking linearizability of an execution is polynomial-time for *collection types*

Bad Patterns - Verif. [ICALP'15]

Presence of **bad patterns** can be checked using **finite-state automata**

A **fixed** number of values suffices to expose all violations (data independence)



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Instantiations:

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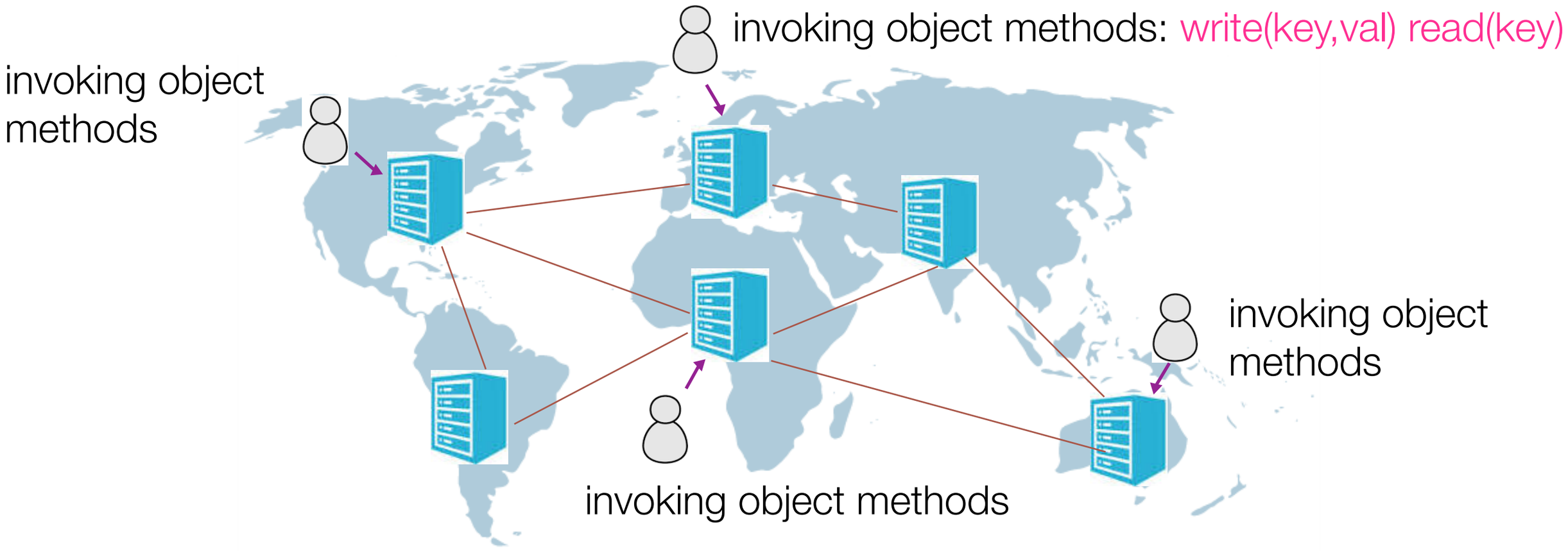
2. Replicated key-value stores [POPL'17]

Replicated Objects (NoSQL)



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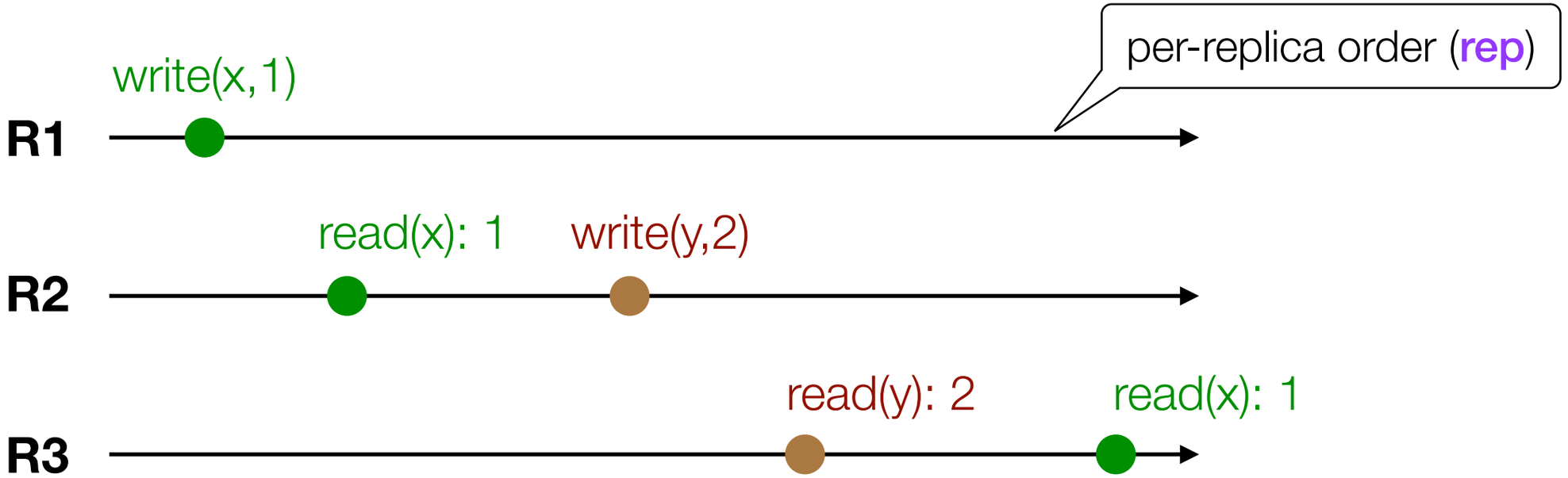
Instances: key-value stores (Amazon Dynamo,Cosmos DB), CRDTs

Weak Consistency Specs

[Burckhardt et al.'14]

Specifying executions **as observed by a client**: operations + per-replica order (**rep**) (without internal events)



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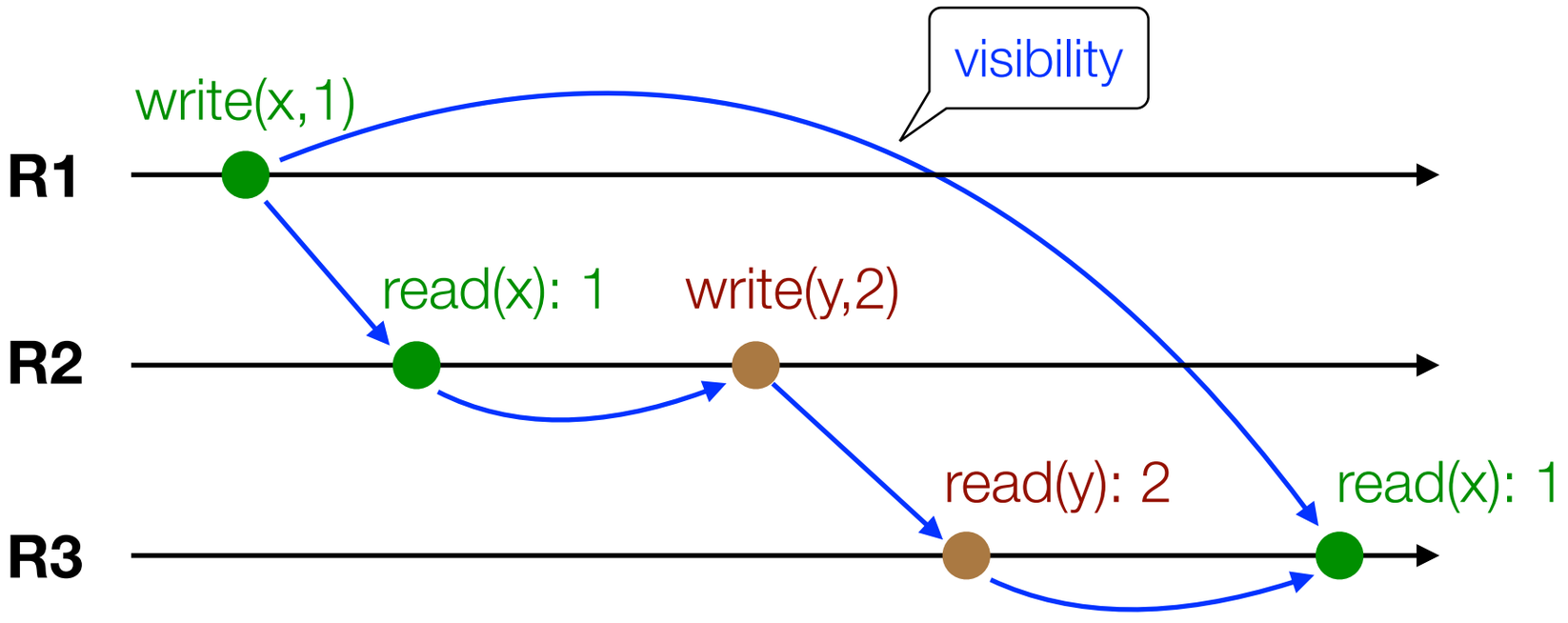


Visibility relation: acyclic relation between ops. that extends per-replica order

Exec ⊧ **ConsistencyModel** iff

∃ **vis**. ∀ op. ``**return value** is consistent with the set of visible ops"

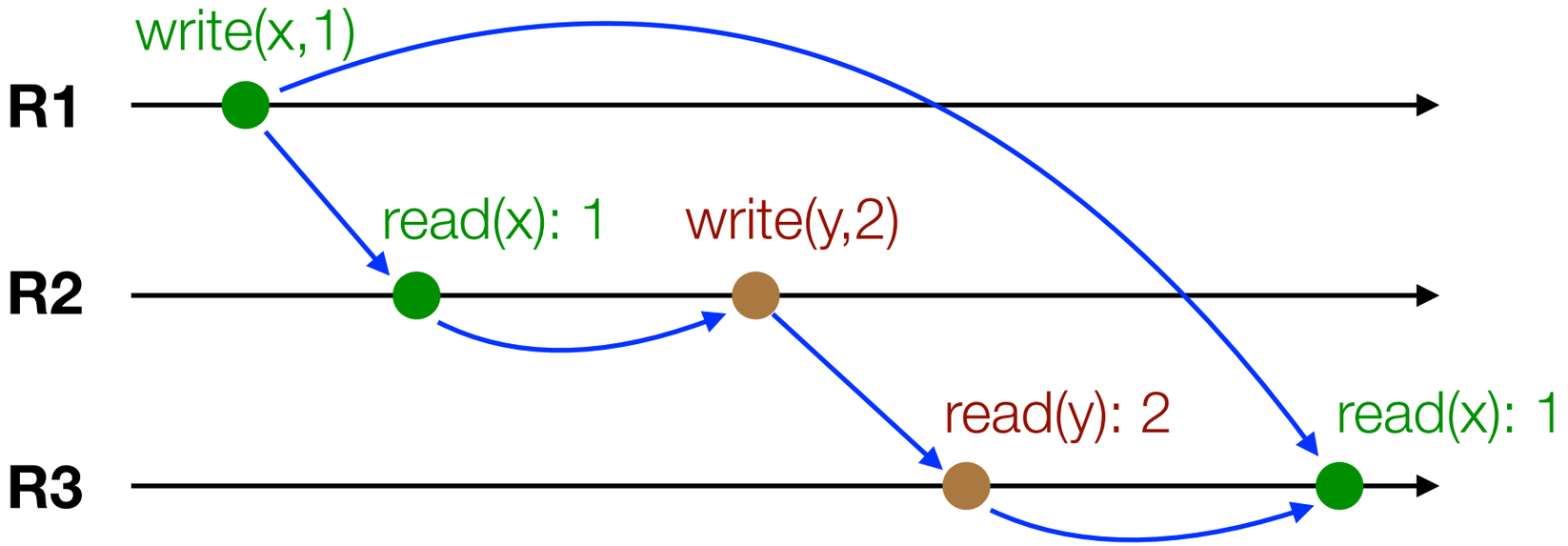
∧ **vis** ⊇ **rep** ∧ ordering properties

(ignoring the arbitration relation used to model conflict-resolution with timestamps)

Causal Consistency (CC)

[Lamport'78]

If an update is visible, then **all** the updates is **dependent** on should be also visible



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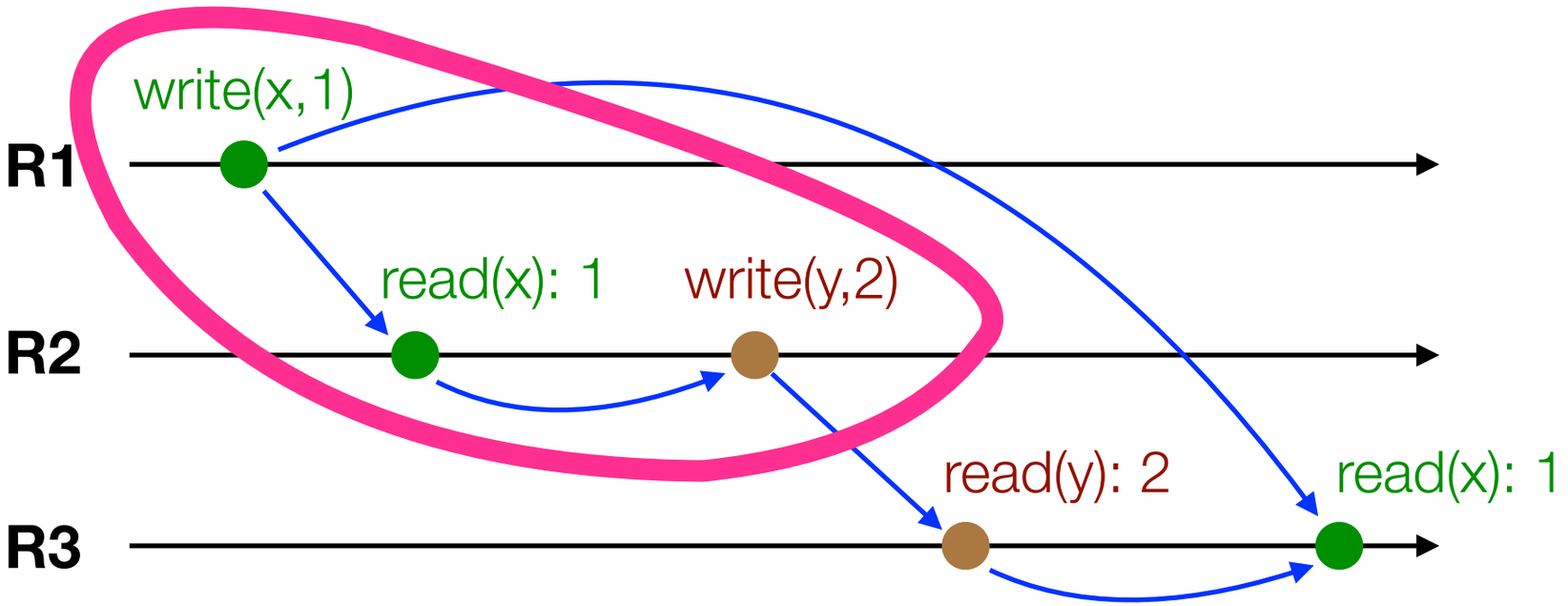

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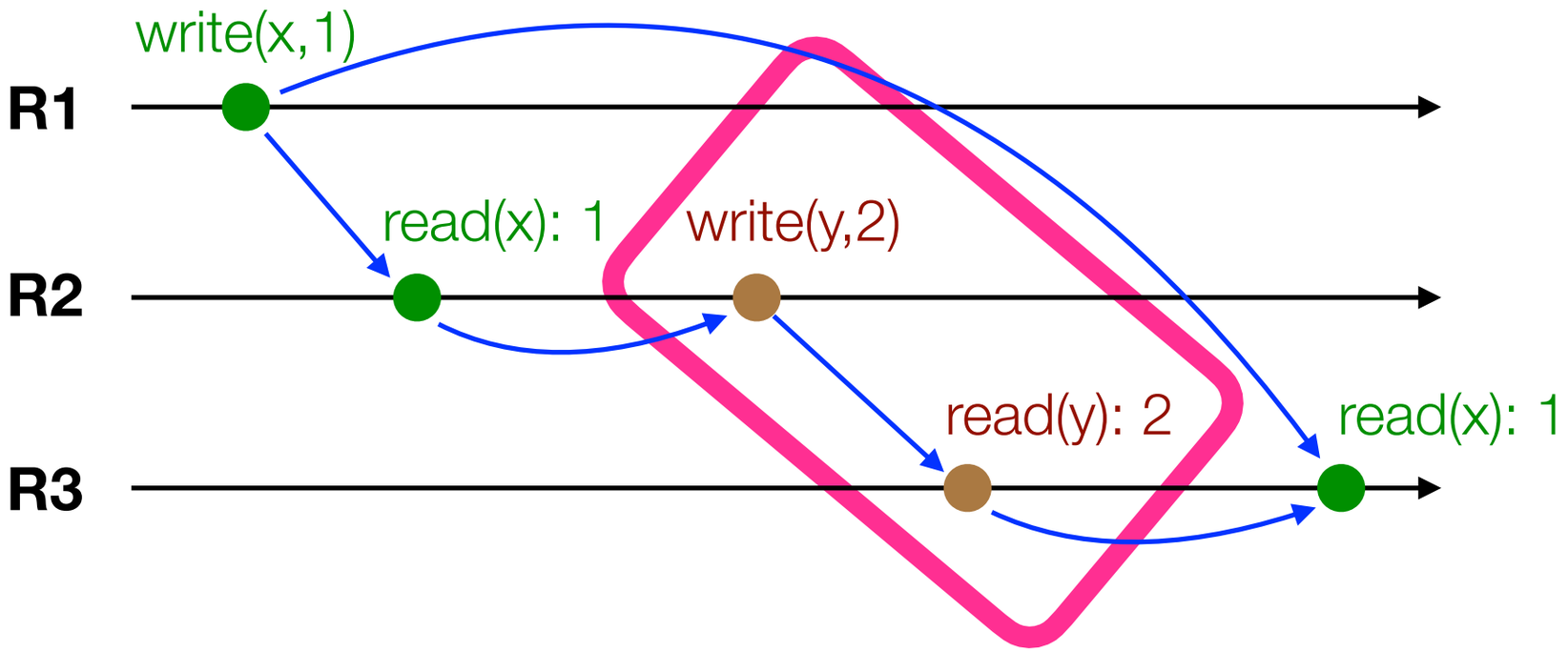

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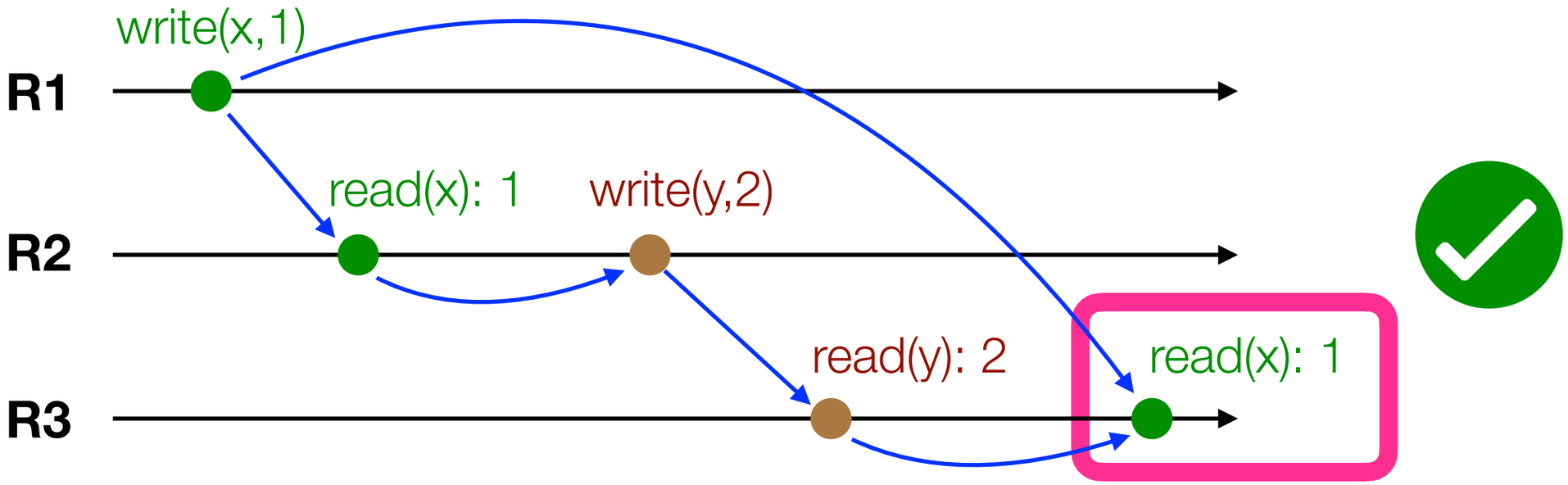

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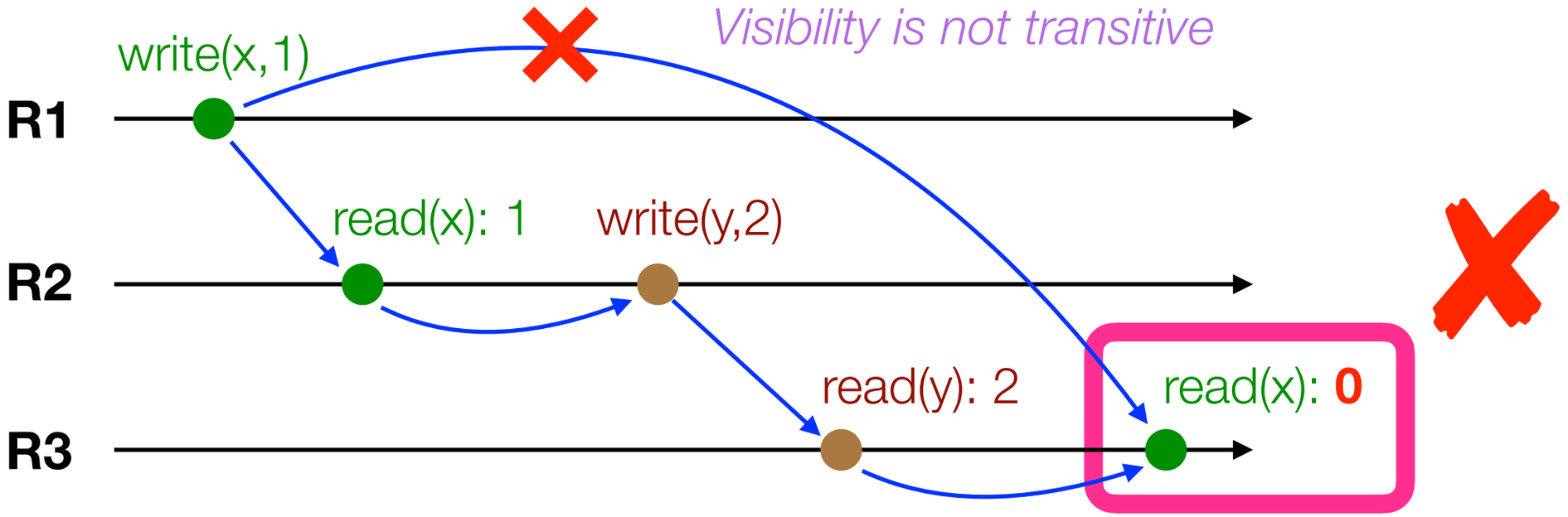

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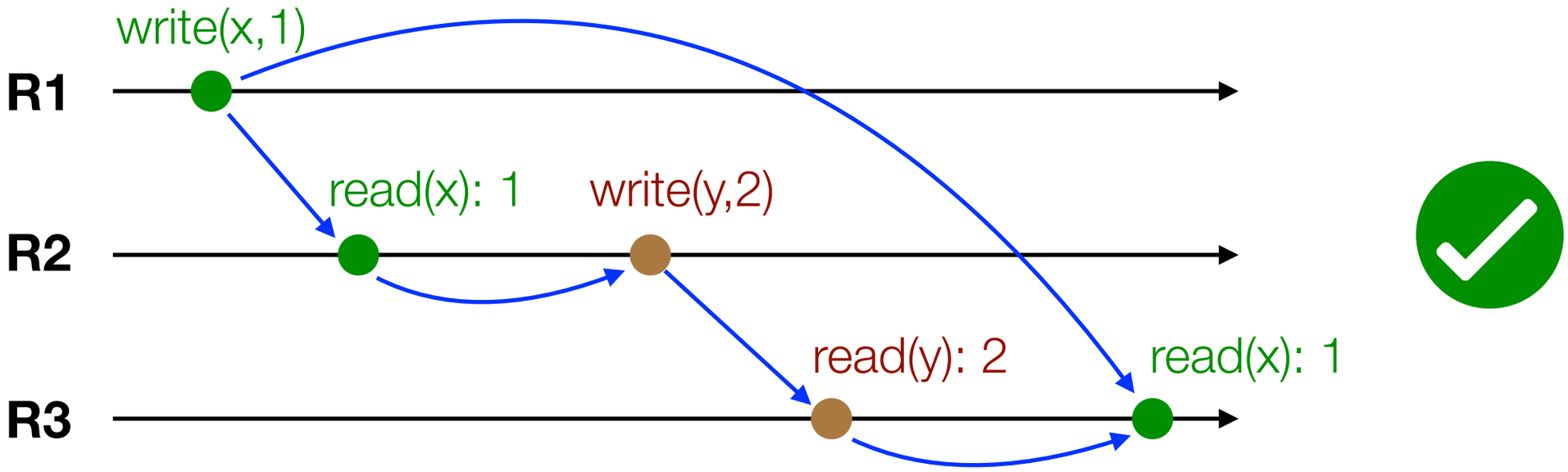

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∧ **vis** ⊇ **rep** ∧ **vis** is transitive

Causal Consistency (CC)

[Lamport'78]

If an update is visible, then **all** the updates is **dependent** on should be also visible

An instance of weak consistency: "anomalies" ≠ interleavings of operations

Empty inter-replica visibility

Possible interleavings: write(x,1); write(y,2); read(y): 2; read(x): 1

write(x,1); read(y): 0; write(y,2); read(x):1

…

(at least one read returns a non-zero value)

Checking CC: Th. Limits

Exec ⊧ CC iff

∃ **vis**. ∀ op. ``**return value** is consistent with the set of visible ops"

∧ **vis** ⊇ **rep** ∧ **vis** is transitive

Theorem. (Testing)

Checking CC for a single execution is NP-complete

Theorem. (Static verification)

Checking CC for a finite-state implementation and regular specification is undecidable

Showing that checking CC is more difficult than assertion checking.

What happens for **key-value stores** ?

CC: Key-Value Stores

∃ **vis**. ∀ read. ``**return value** → a maximal visible write”
∧ **vis** ⊇ **rep** ∧ **vis** is transitive

} original CC specification

is equivalent to

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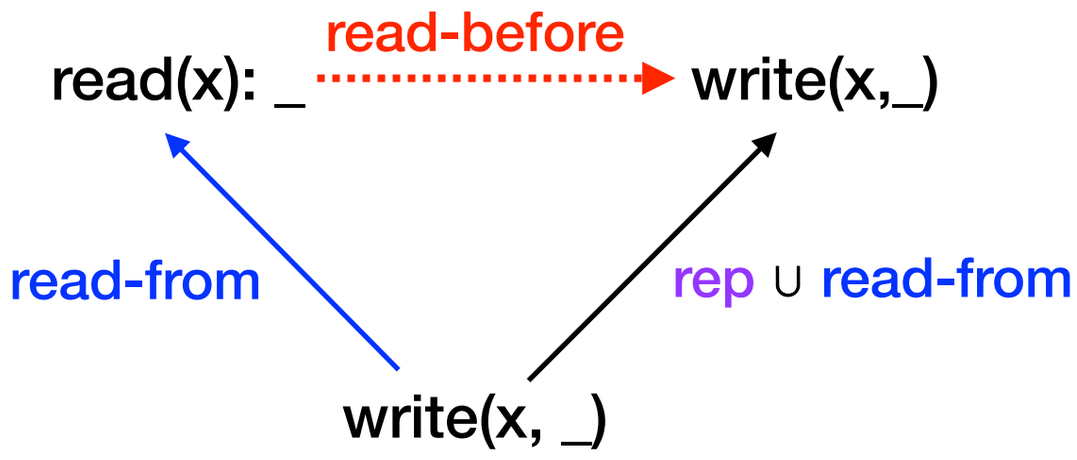

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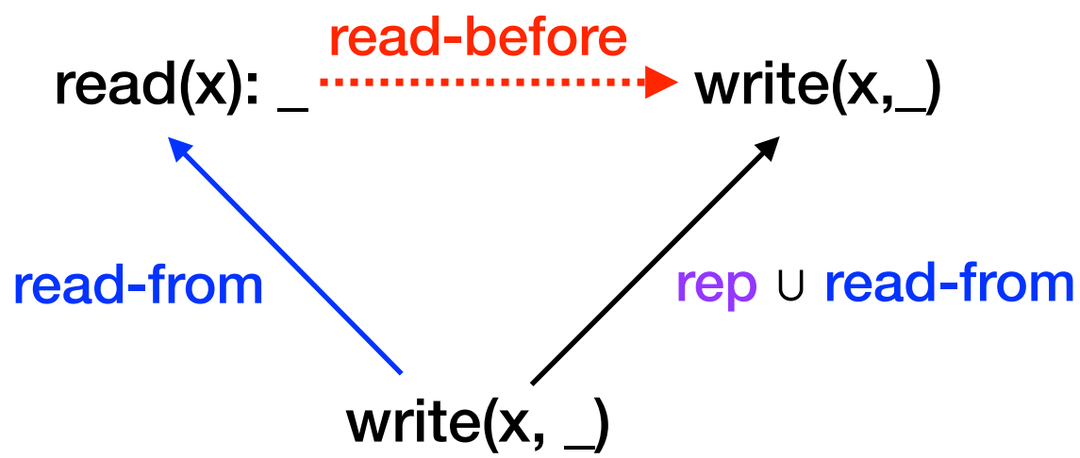

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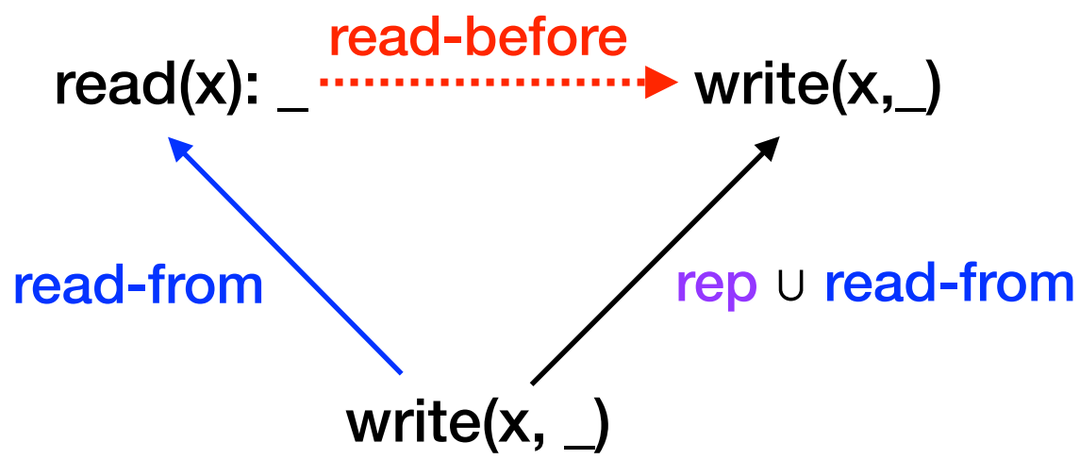

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Extended to transactions in DBCOP [OOPSLA’19]

Summary

Using verifiable specifications for

Testing: polynomial-time under reasonable assumptions

- effective tools: Java objects, key-value stores

Verification: techniques that rely on the existing technology for automation

- proof of concept implementations on paradigmatic case studies

Consistency: eventual → causal → linearizability, transactions

Data Types: key-value maps, queues, stacks, sets, CRDTs

Perspectives

CDT specifications: uniform construction of “verifiable” specifications

Root causing:

- understand the reasons behind a violation
- identify important events that invalidate an input-output behavior

Quantitative consistency: tradeoff consistency vs. performance

Programming on top of weak consistency:

- weak consistency (e.g., causal) admits “anomalies”
- understanding the impact of these anomalies on ensuring a certain functionality