Convergence is Half Way to Consensus

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CU Programming Languages
& Verification

Distributed Convergence is Half Way to Distributed Consensus

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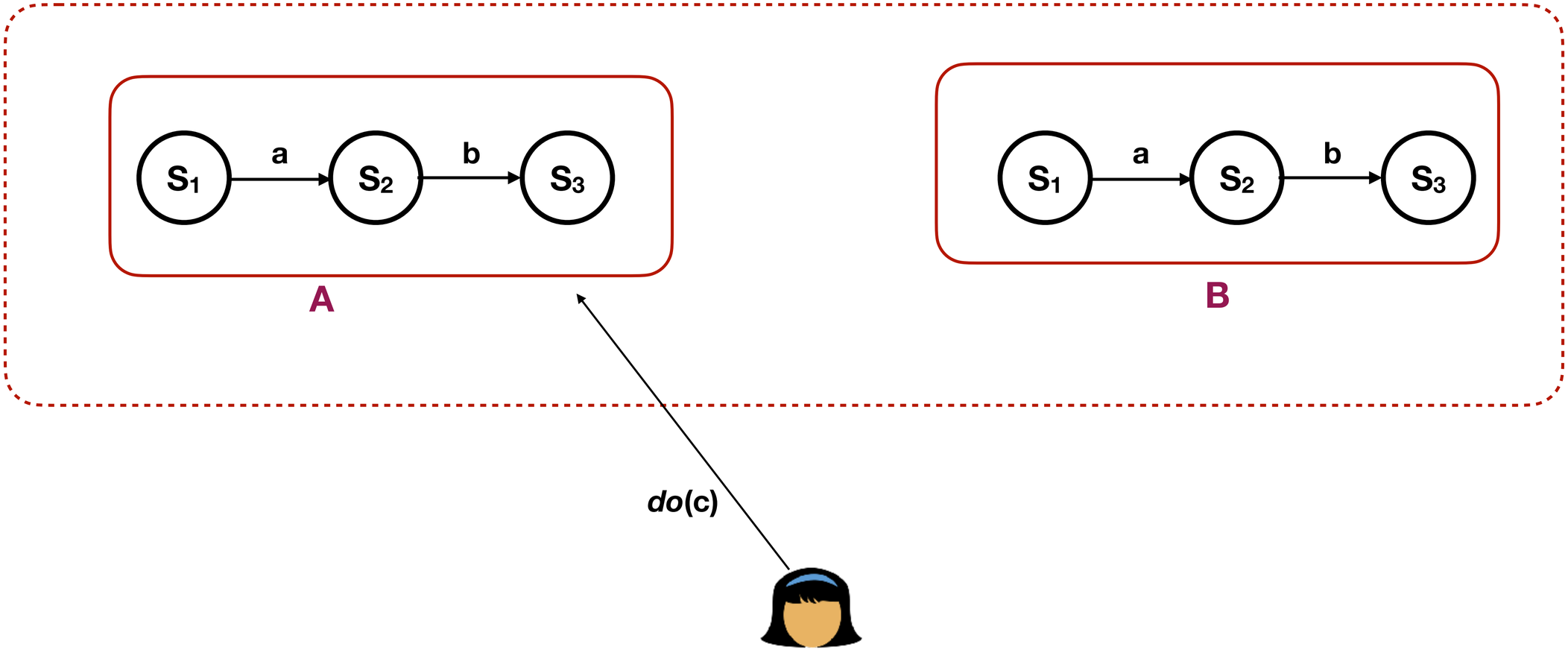
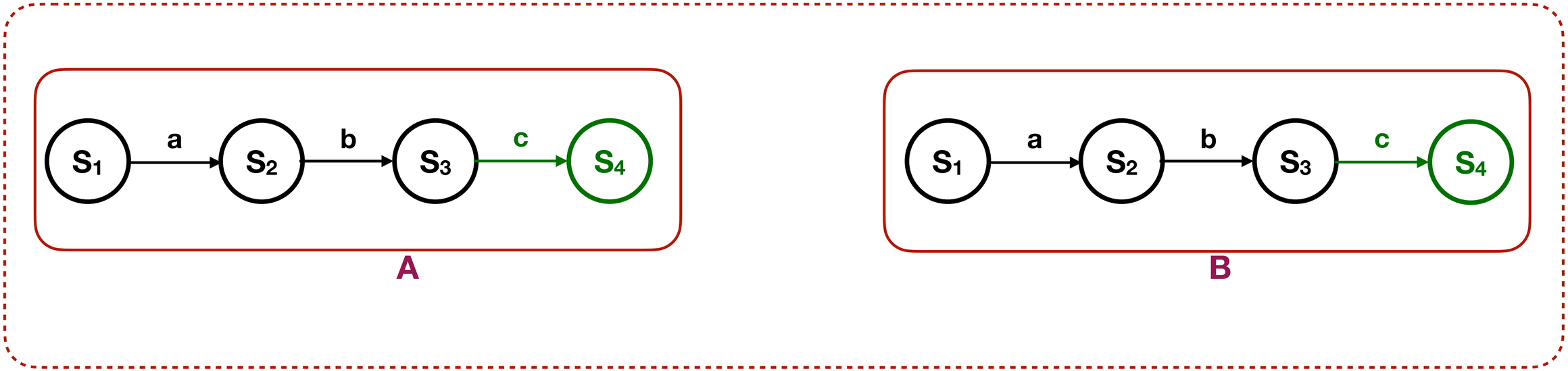
CU Programming Languages
& Verification

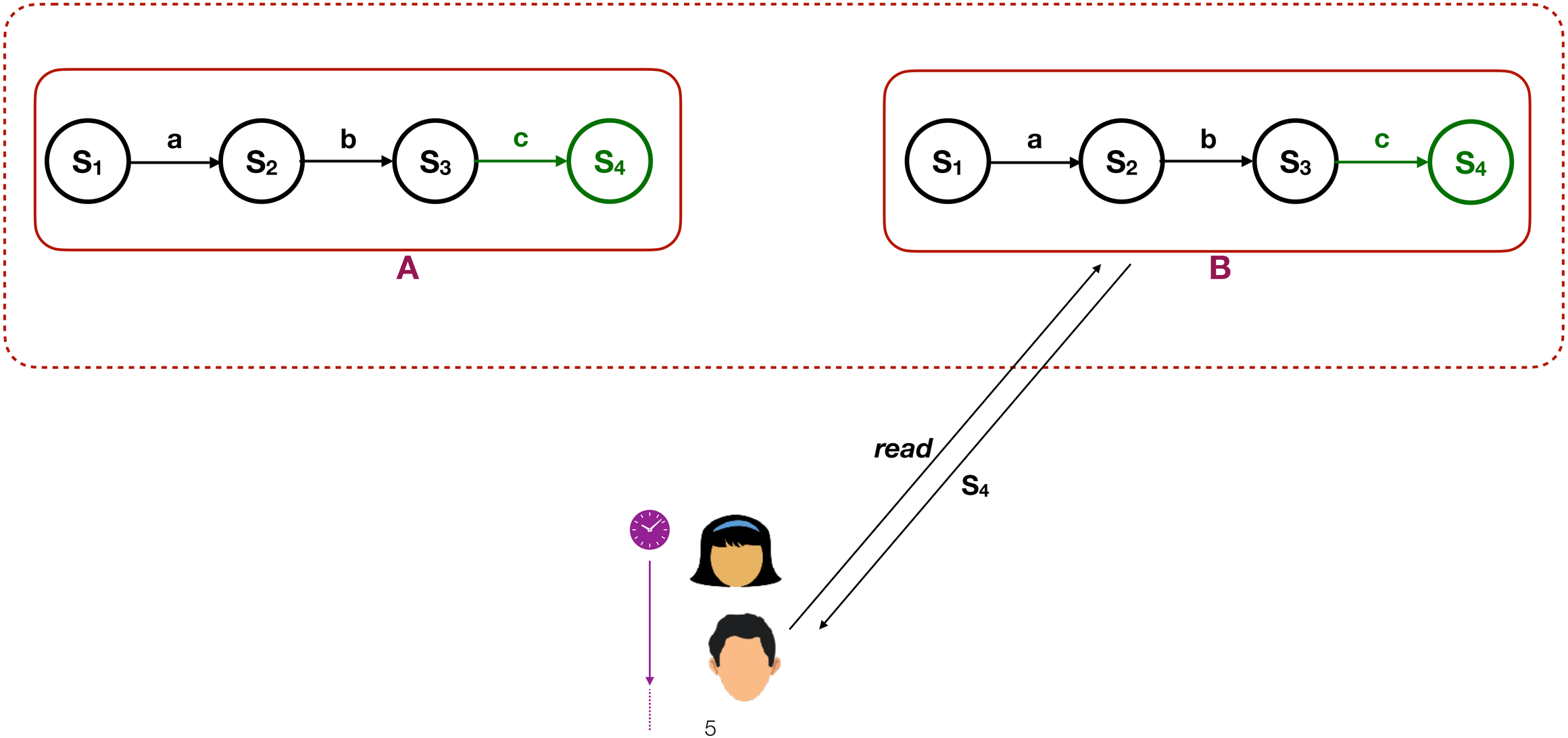
Replicated State Machines



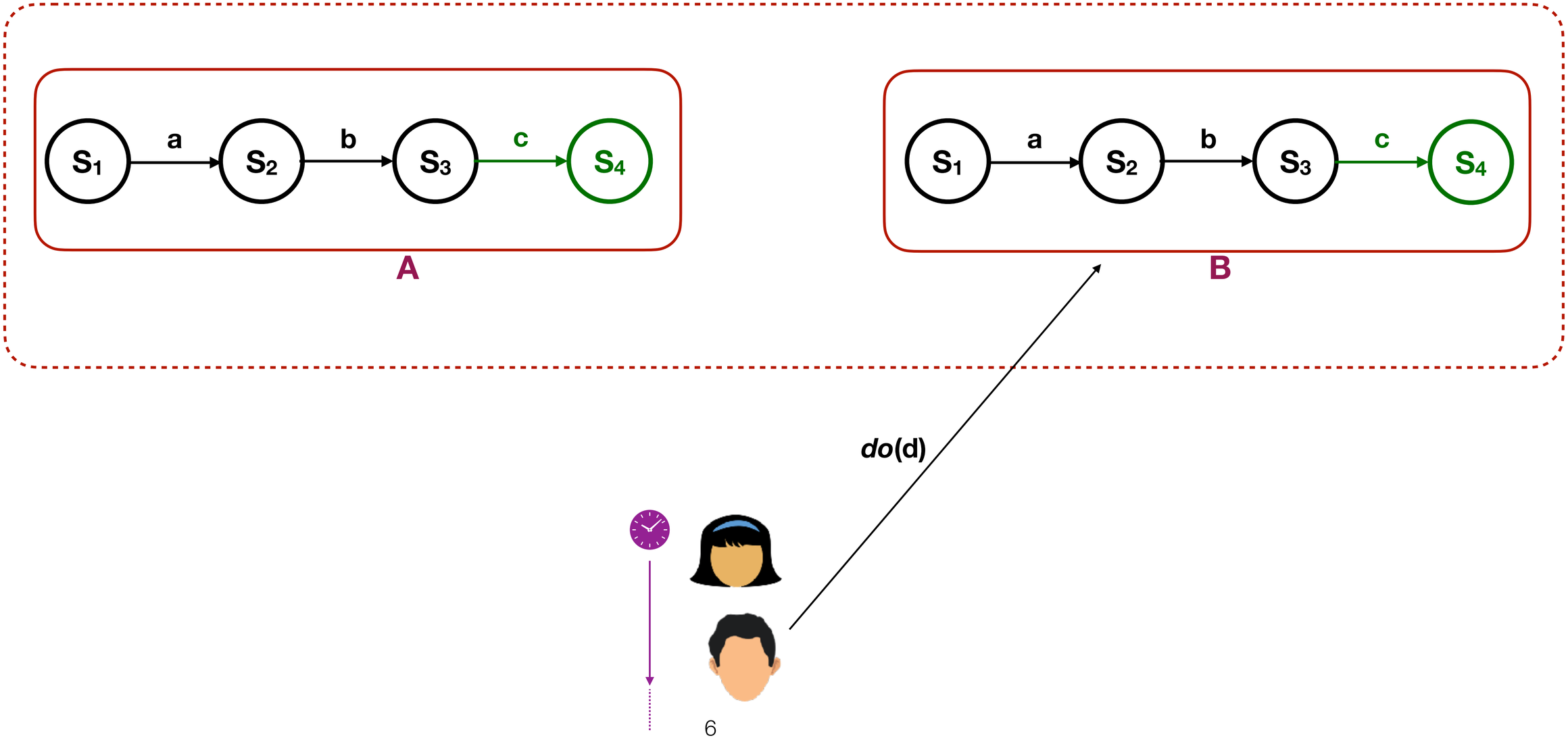
Replicated State Machines



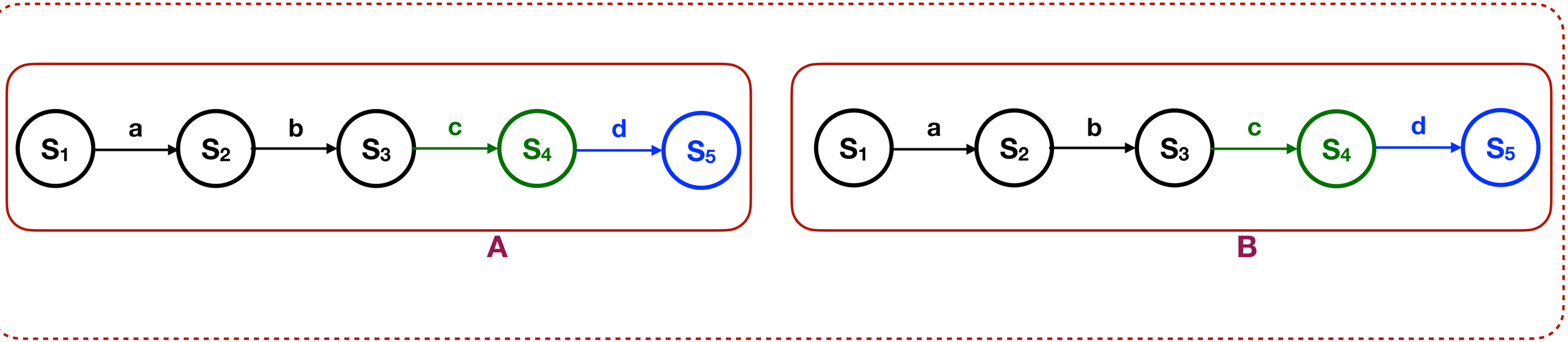
Replicated State Machines

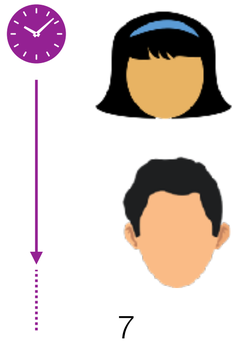


Replicated State Machines



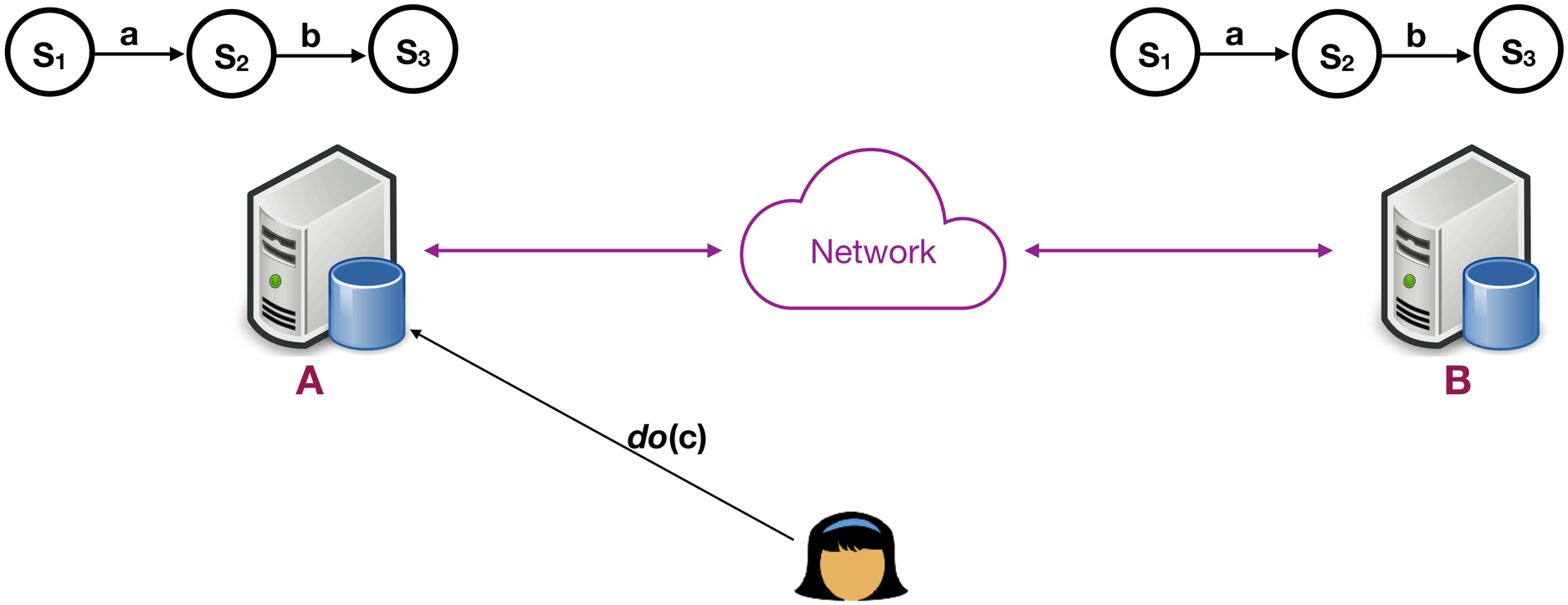
Replicated State Machines



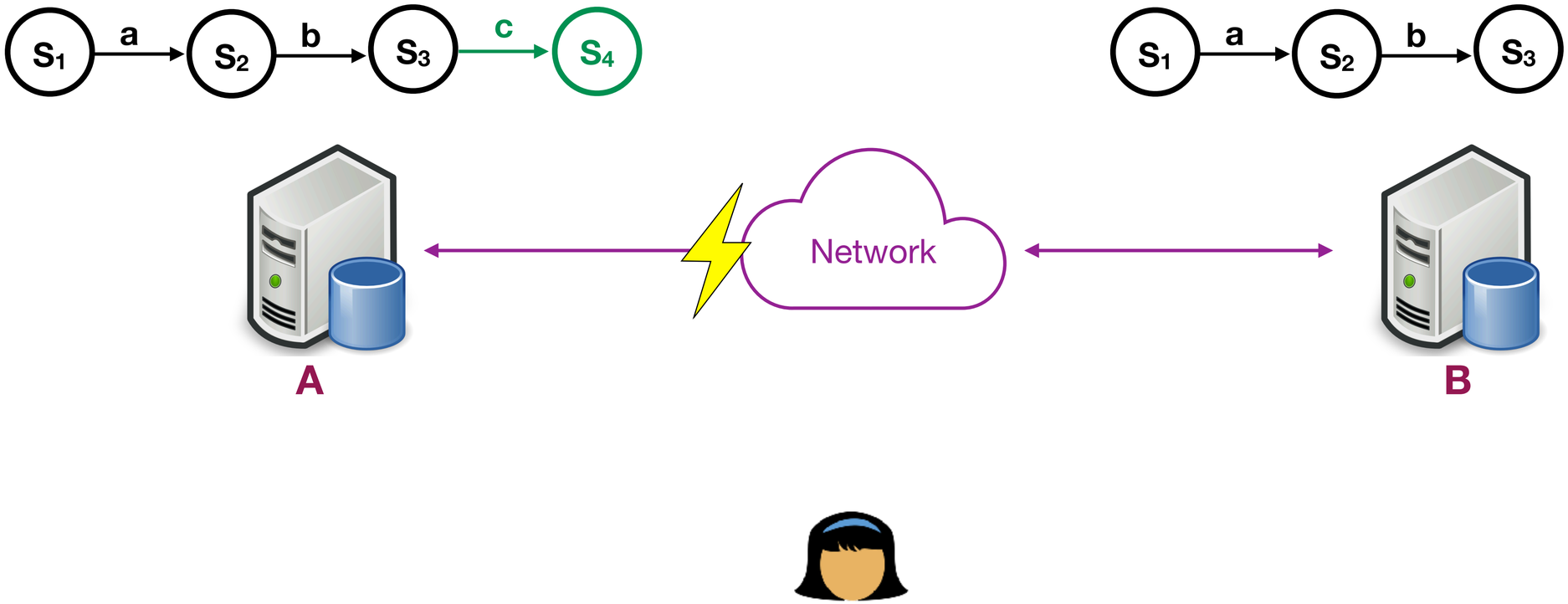


“Strong Consistency”

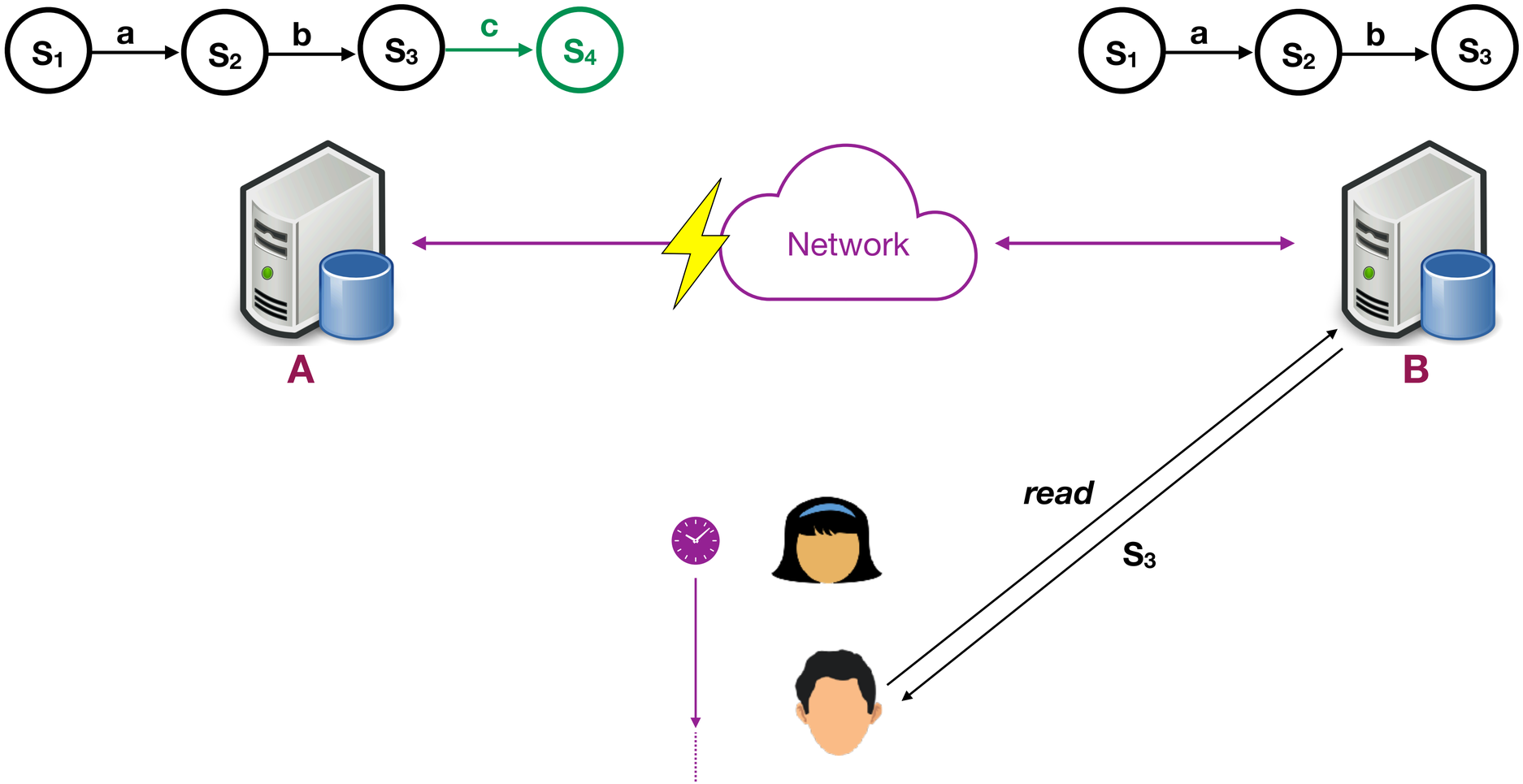
Replicated State Machines: In Practice



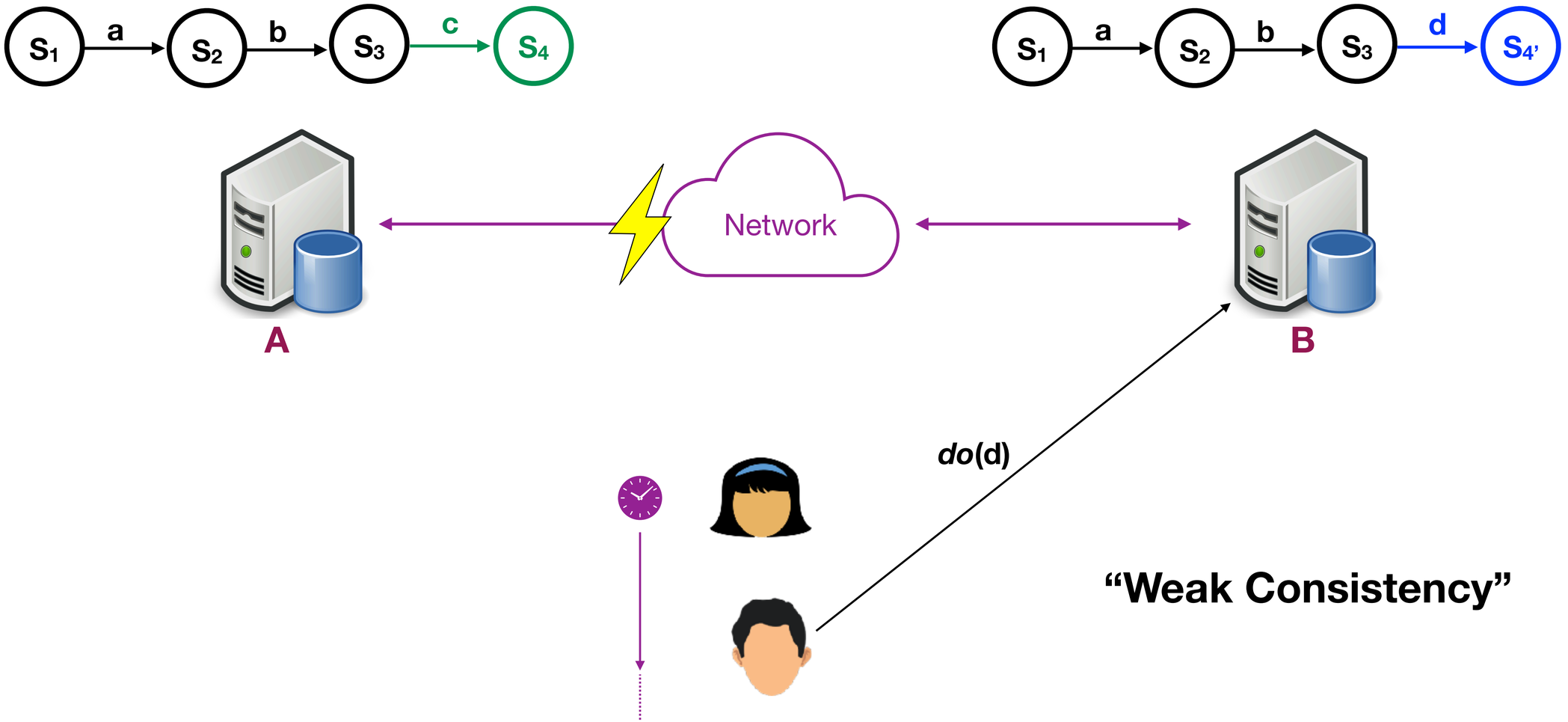
Replicated State Machines: In Practice



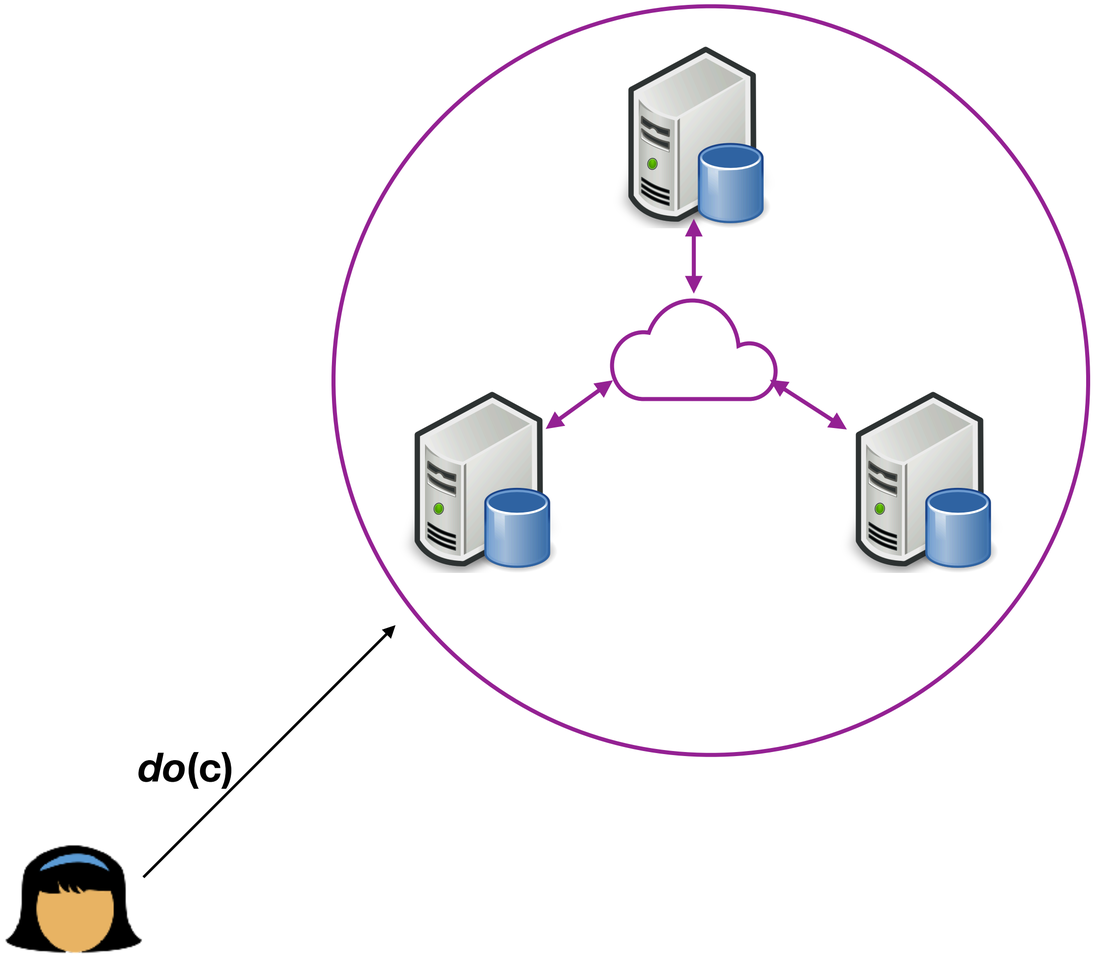
Replicated State Machines: In Practice

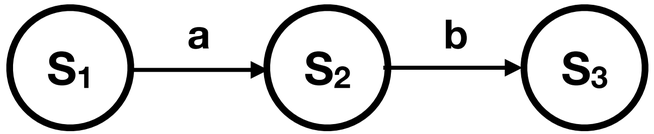


Replicated State Machines: In Practice

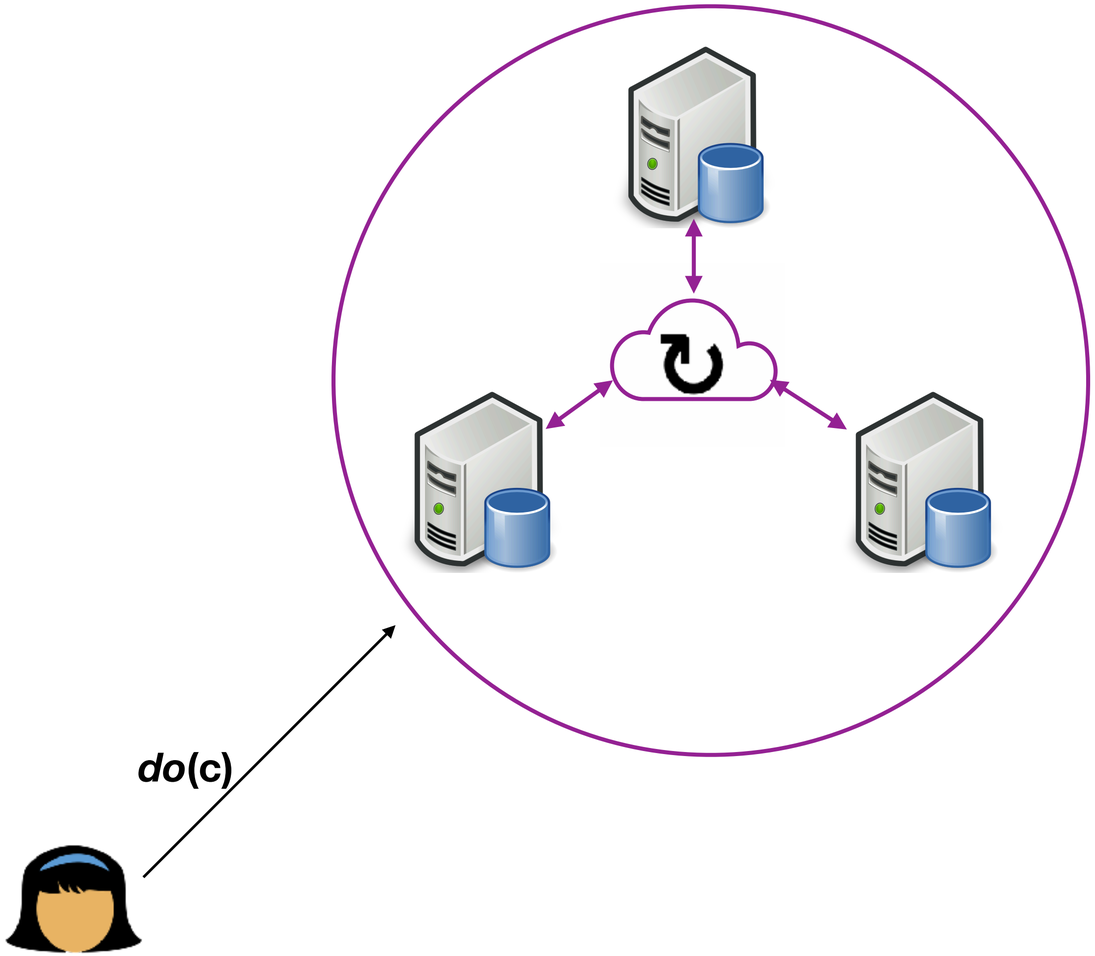


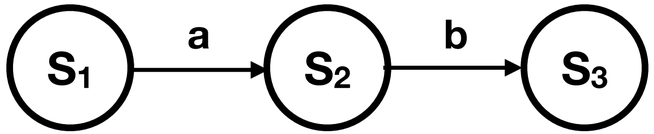
Consensus in Replicated State Machines





Consensus in Replicated State Machines





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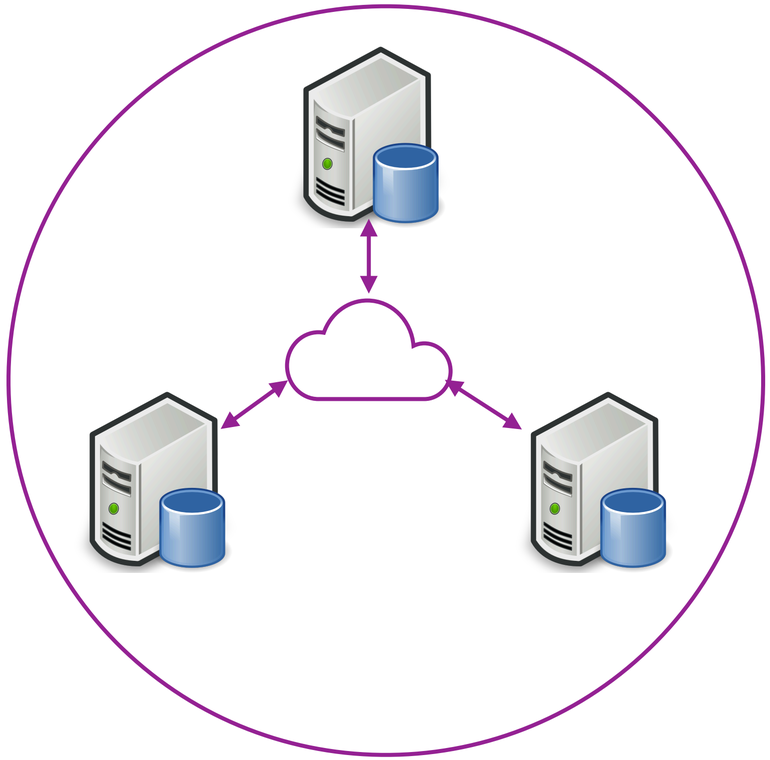

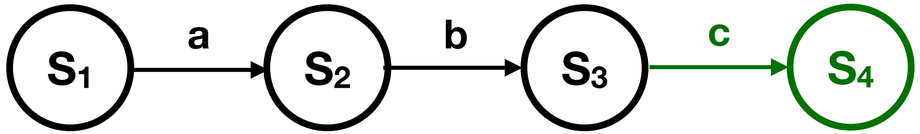

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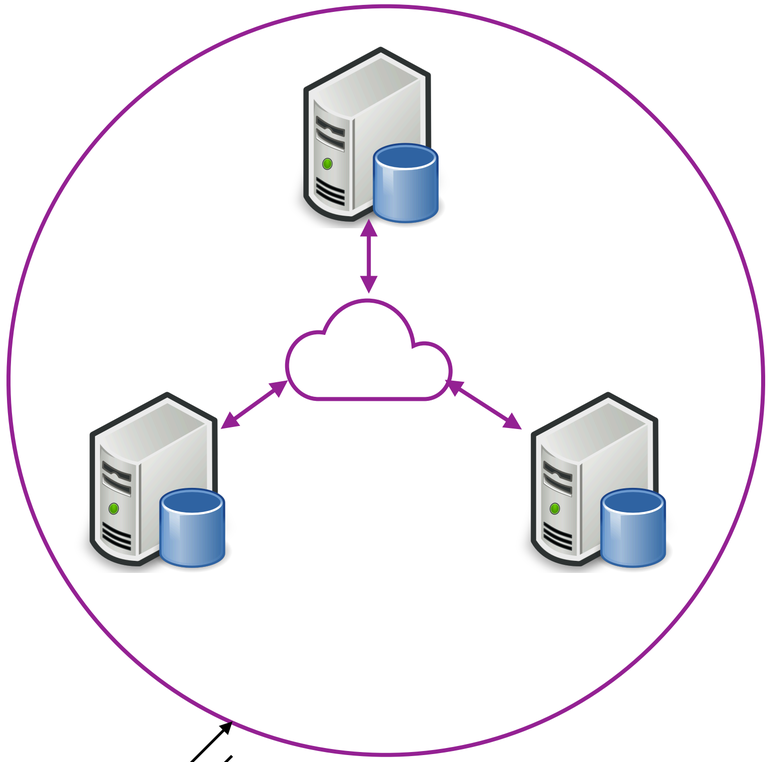

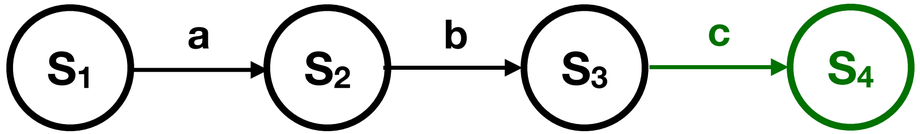

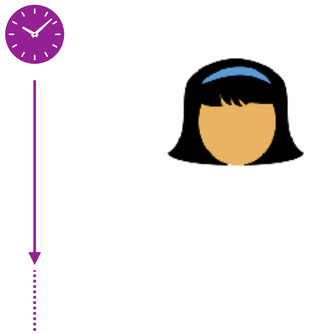

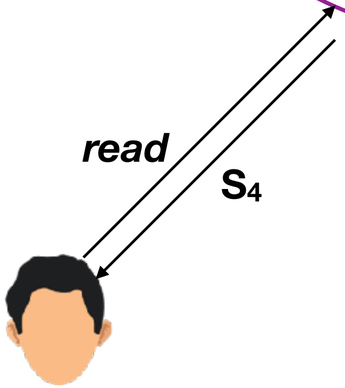

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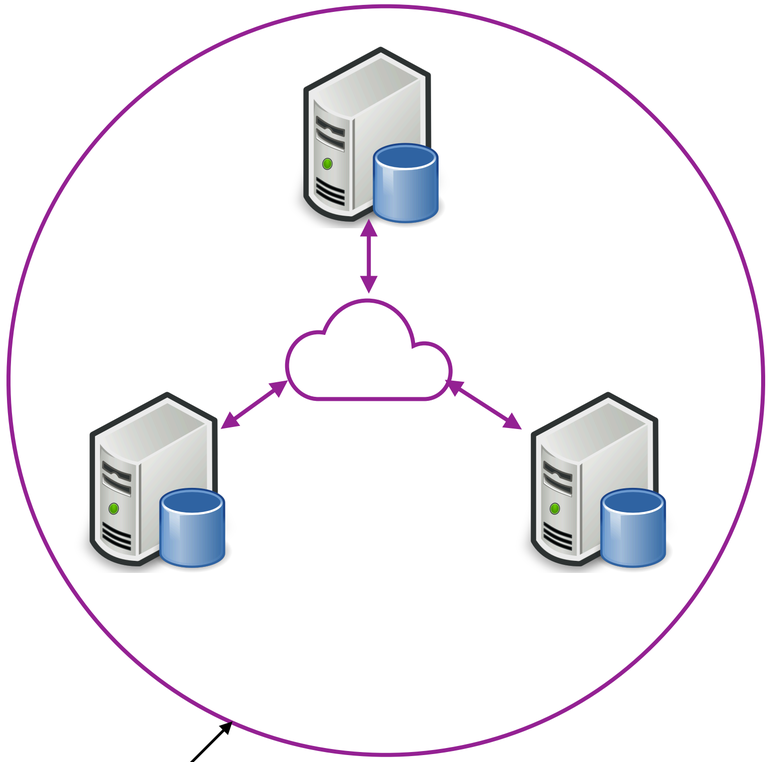

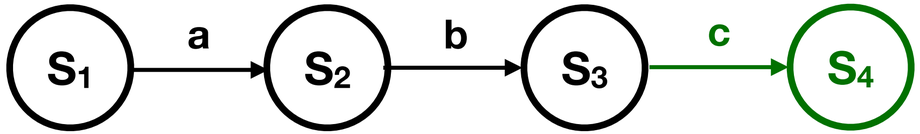

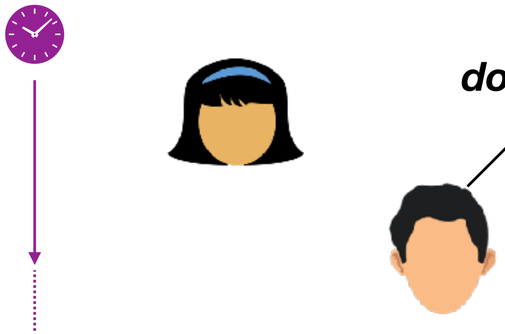

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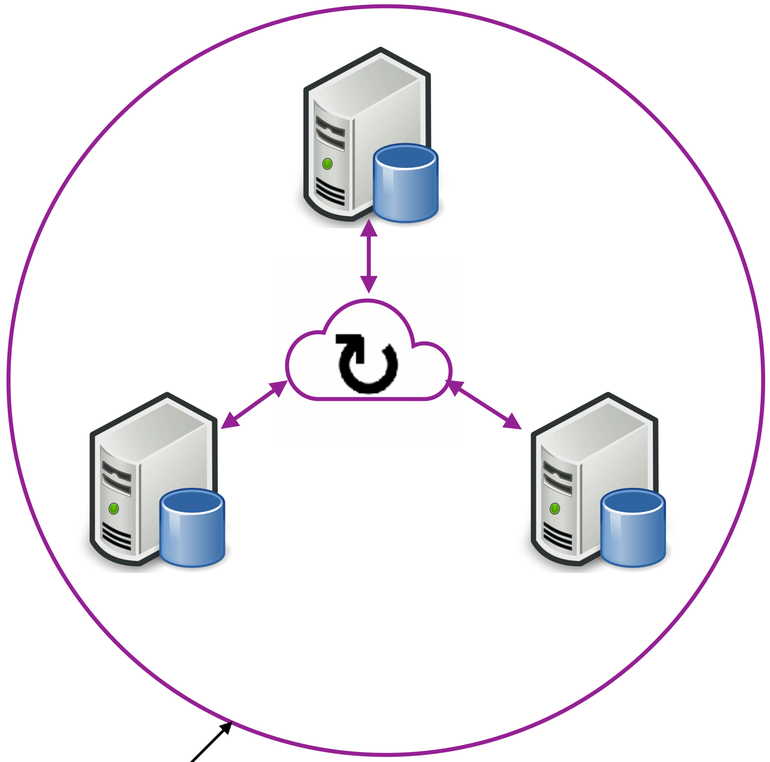
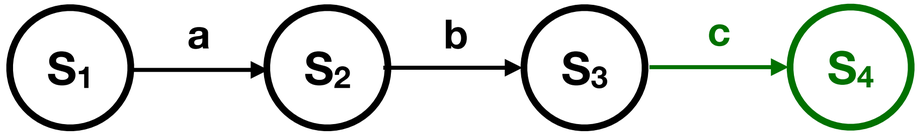
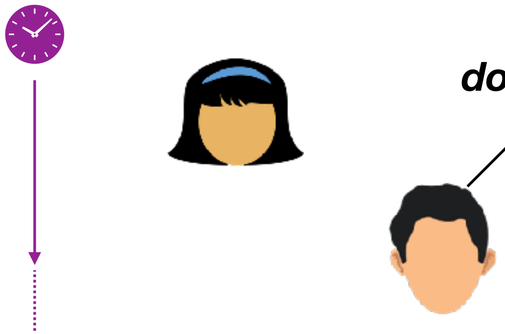
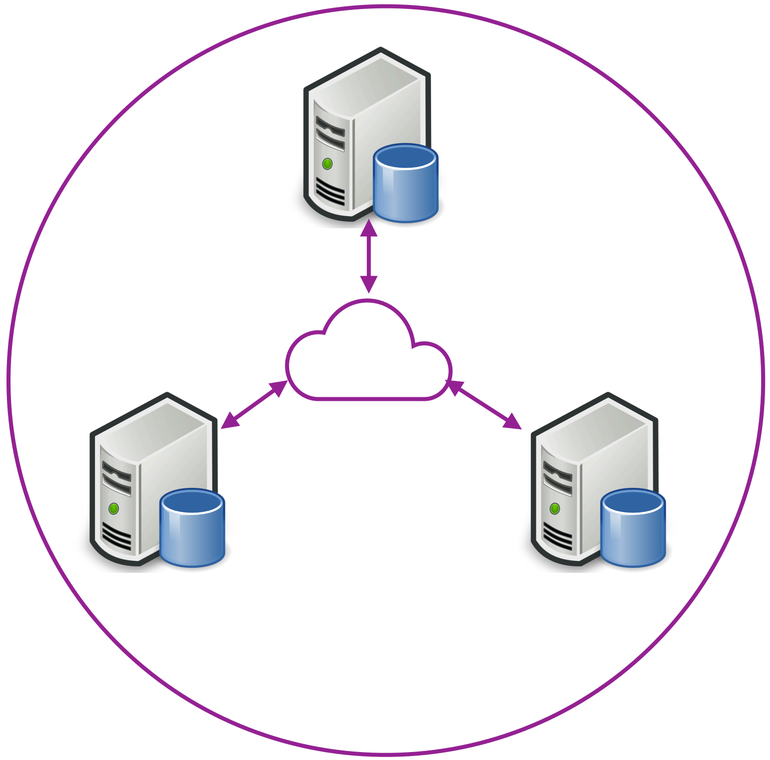
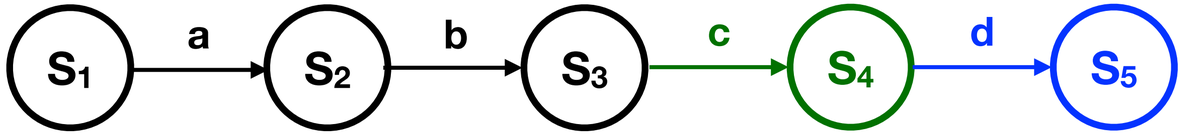


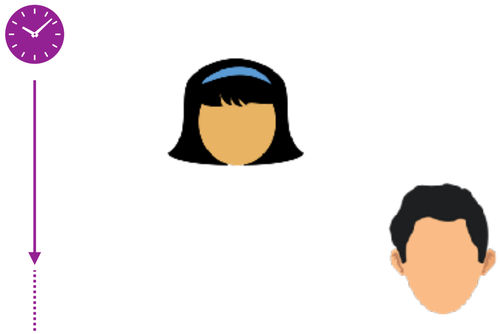




Consensus in Replicated State Machines







Consensus Algorithms

- Paxos [Lamport 1998]
  - Multi-Paxos [Lamport 2001]
  - Disk Paxos [Gafni et al 2002]
  - Fast Paxos [Lamport 2006]
  - Stoppable Paxos [Malkhi et al 2008]
  - …
- Raft [Ongaro et al 2014]
  - Muti-Region Raft [Cockroach DB, TikV DB]
  - FlexiRaft [Yadav et al 2023]
- Viewstamped Replication [Oki et al 1988]
- Zookeeper [Junqueira et al 2011]
- Chubby [2006]
- …

- Impossible to guarantee availability (CAP)
- Hard to guarantee correctness

Via formal verification

Problem with Formal Verification: Too Much Work!

- Hawblitzel et al. 2015 *IronFleet: Proving Practical Distributed Systems Correct.*
  "…developing IronFleet and applying it to two real systems required approximately 3.7 person-years"
- Wilcox et al. 2015 *Verdi: A Framework for Implementing and Formally Verifying Distributed Systems.*
- Woos et al. 2016 *Planning for Change in a Formal Verification of the Raft Consensus Protocol.*
  "…required iteratively discovering and proving 90 system invariants"
  "…530 lines of code and 50,000 lines of proof."
- Padon et al. 2017 *Paxos made EPR: Decidable Reasoning about Distributed Protocols.*
- Taube et al. 2018 *Modularity for Decidability of Deductive Verification with Applications to Distributed Systems.*
  "…took approximately 3 person-months …300 [lines] of invariants and ghost code."
- Gleissenthall et al. 2019. *Pretend Synchrony: Synchronous Verification of Asynchronous Distributed Systems.*

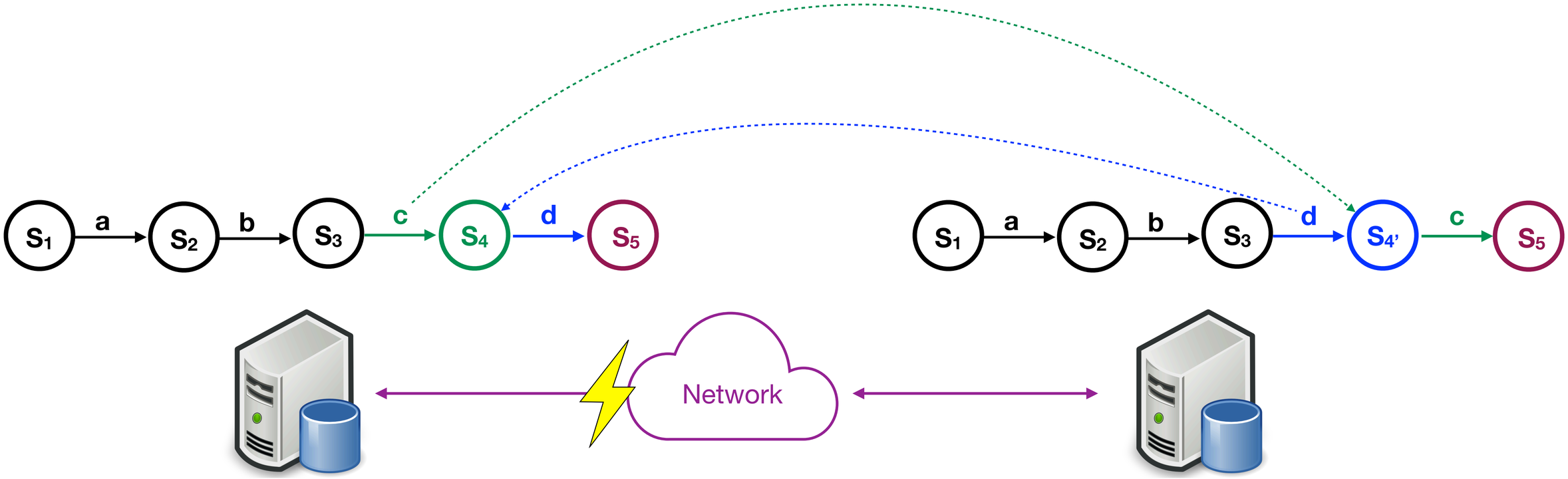
Key Questions

Can we avoid strong consistency/consensus?

- Impossible to guarantee availability (CAP)
- Hard to guarantee correctness

Can we make formal verification easier?

Eventual Consistency, i.e., Convergence



Operations `f` and `g` on data type `T` are commutative iff:

$$\forall s : T,\ \ f(g(s)) = g(f(s))$$

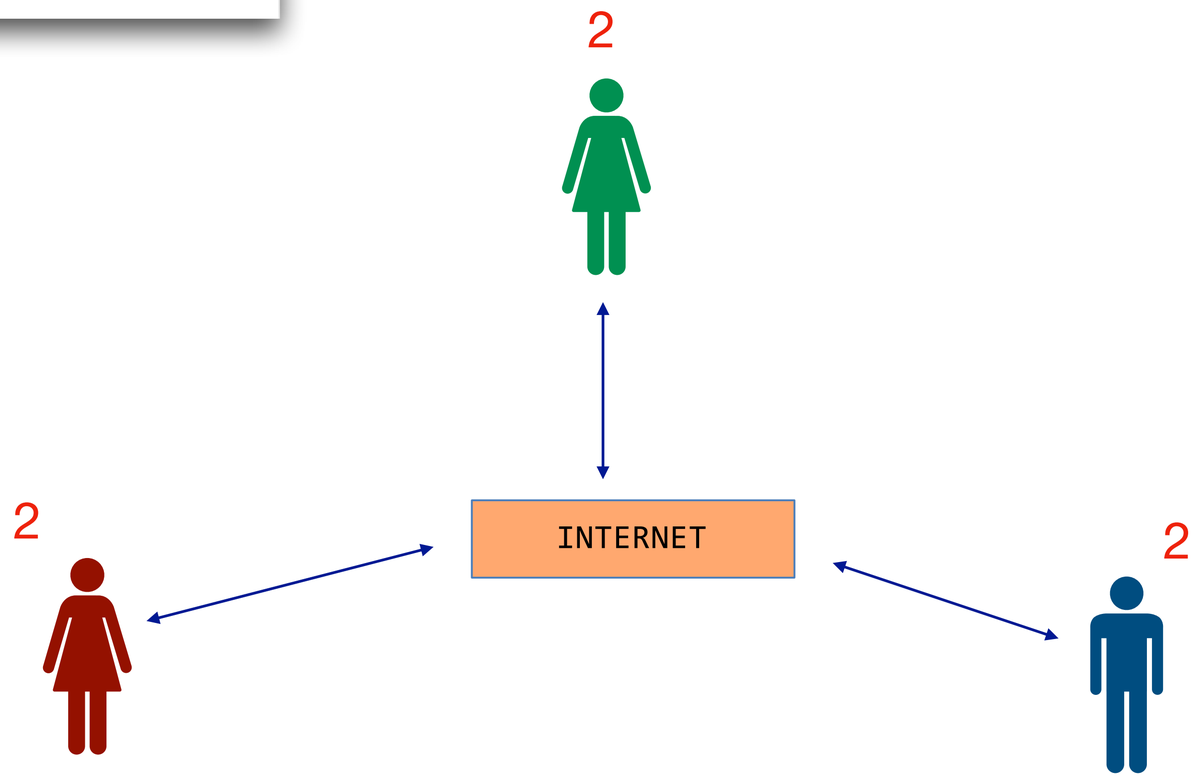
If all operations on `T` are commutative then `T` is a conflict-free replicated data type (CRDT)

CRDTs

Conflict-free Replicated Data Types *

Marc Shapiro, INRIA & LIP6, Paris, France
Nuno Preguiça, CITI, Universidade Nova de Lisboa, Portugal
Carlos Baquero, Universidade do Minho, Portugal
Marek Zawirski, INRIA & UPMC, Paris, France

- Define data types in terms of commutative operations
- E.g., an Integer Counter CRDT with `add` and `sub`:



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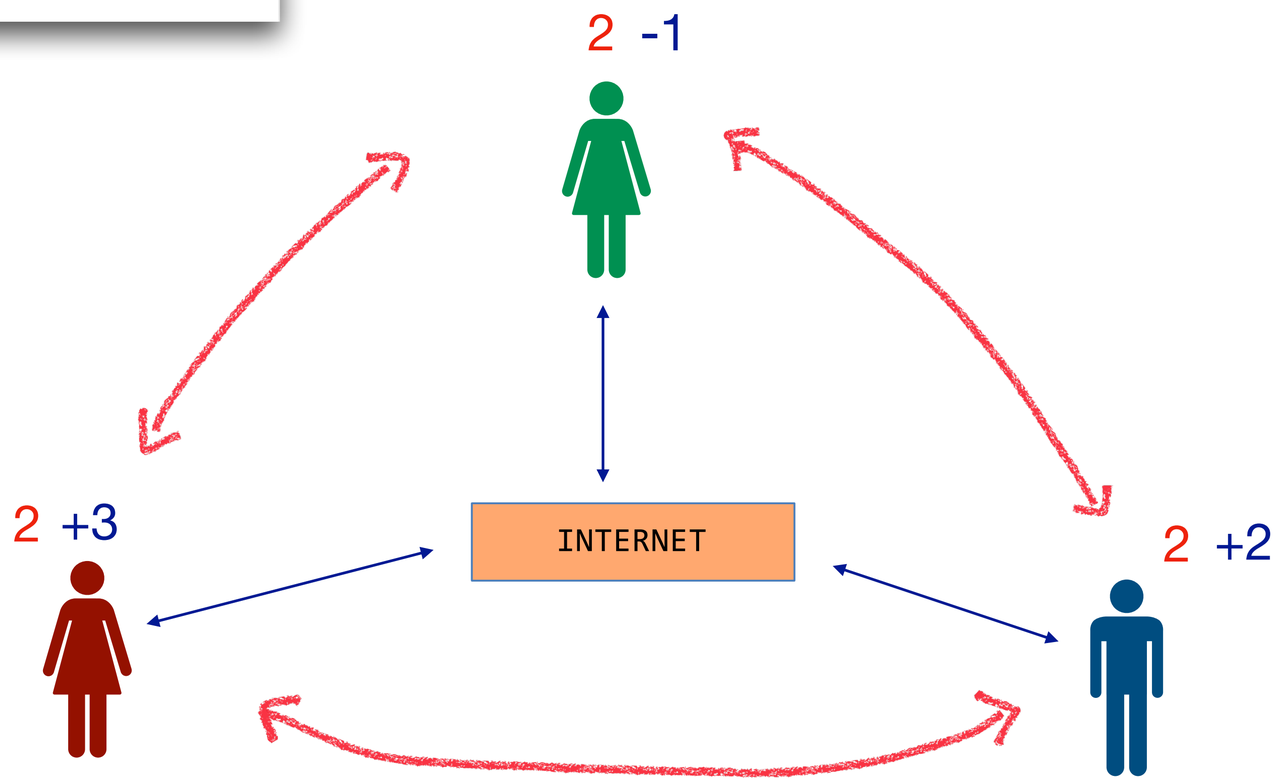

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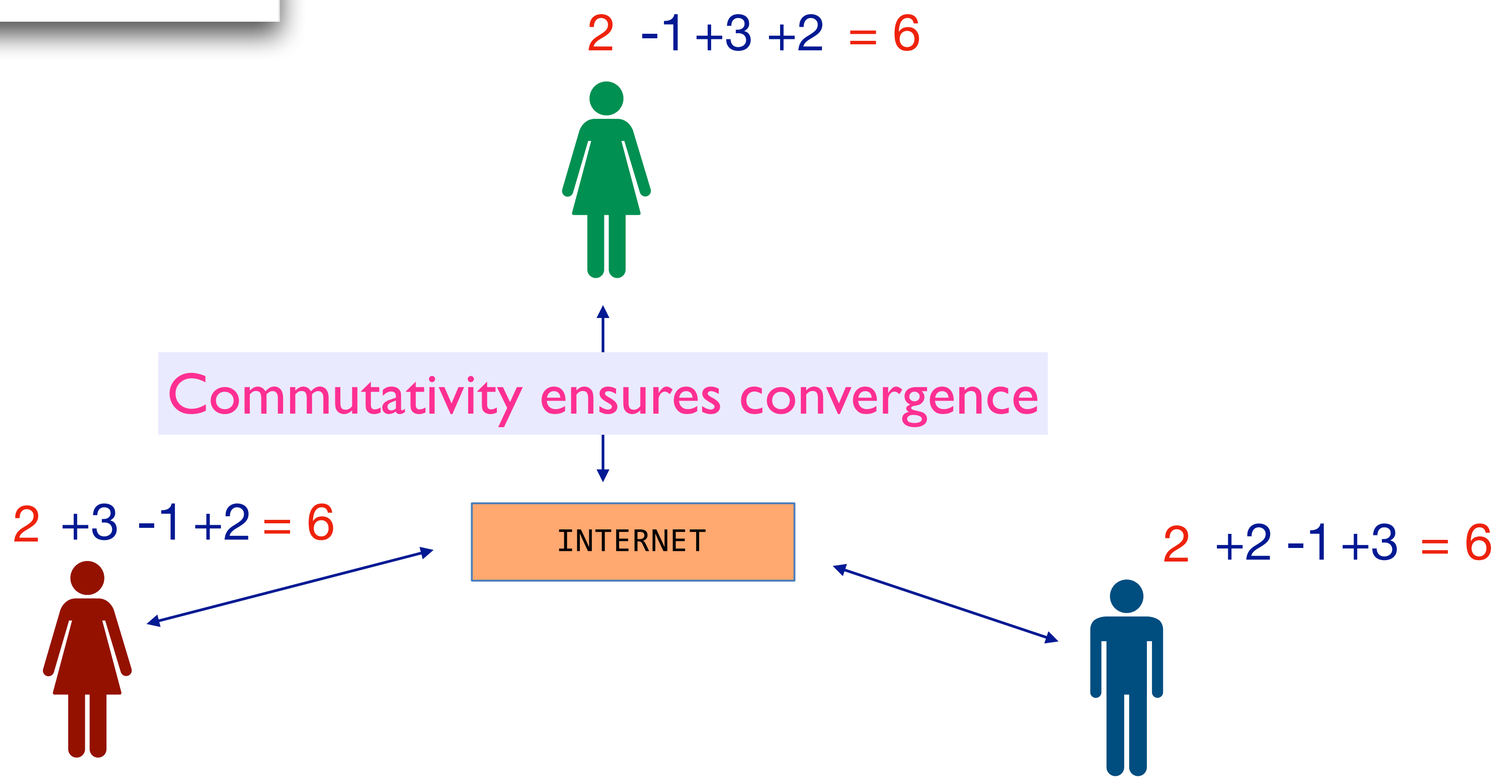
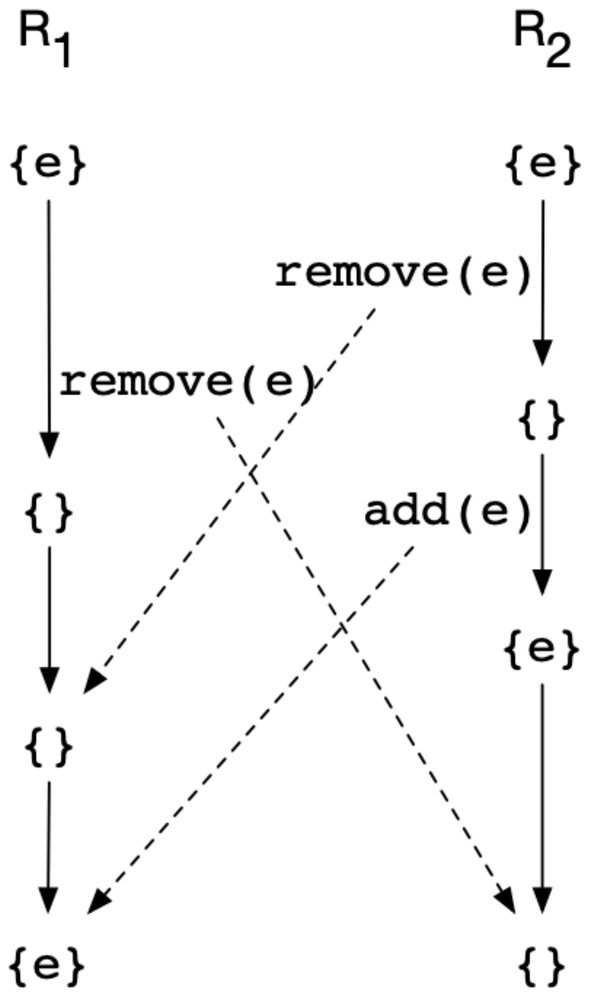


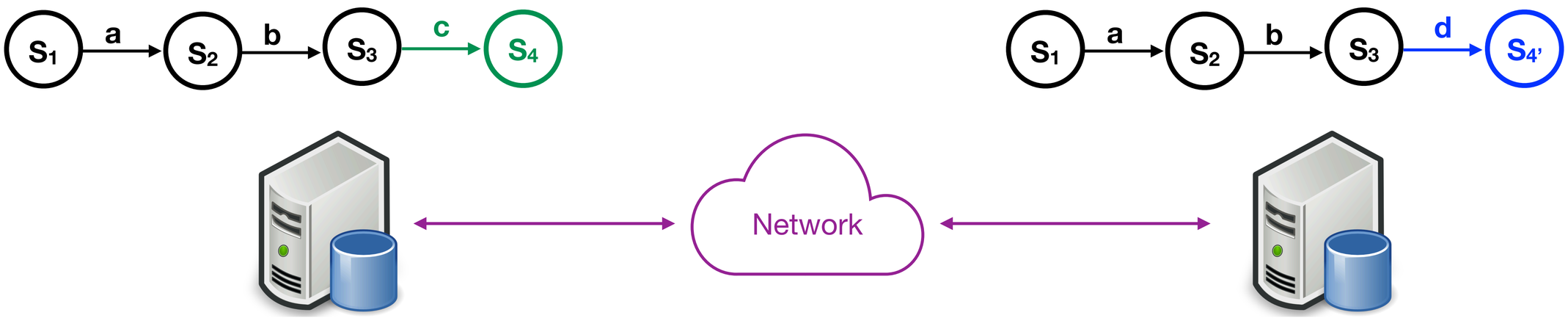
Commutativity is not common

E.g., a set data type with `add` and `remove`

- R_1 and R_2 start with a singleton set `{e}`
- Both execute `remove(e)`
- R_2 executes `add(e)`
- Eventually all operations are delivered to both replicas
- Since R_1's `remove` and R_2's `add` are concurrent, they are executed in different orders at R_1 and R_2
- Divergence!
- Solution: let one of `add` or `remove` "win" in case of concurrency (*add-wins* set or *remove-wins* set)
- Works for set but has limitations in general.

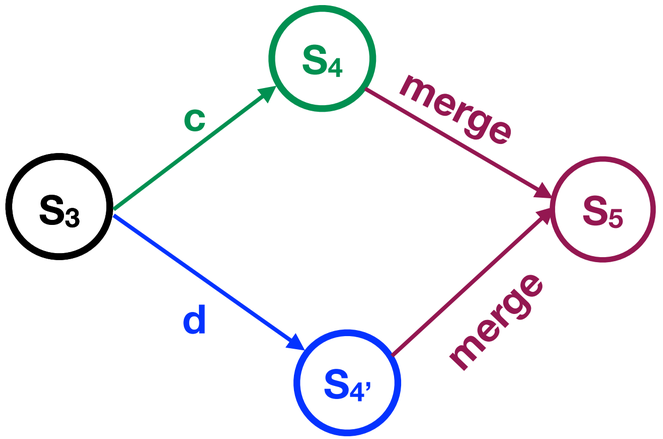


Divergence

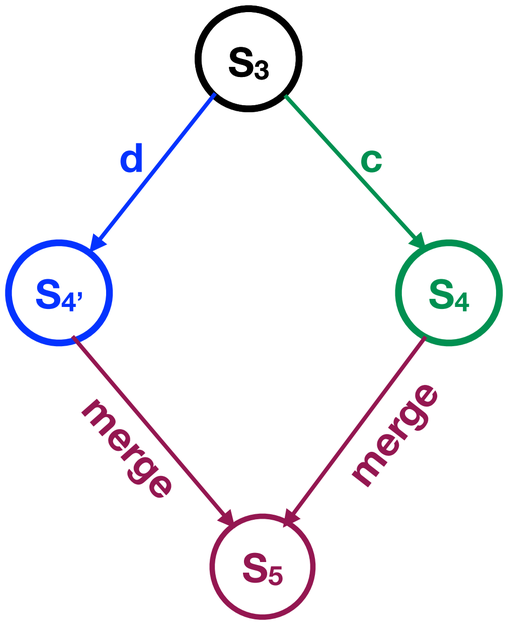


Qn: What to do If `c` & `d` are not commutative?

Divergence: Zoomed In

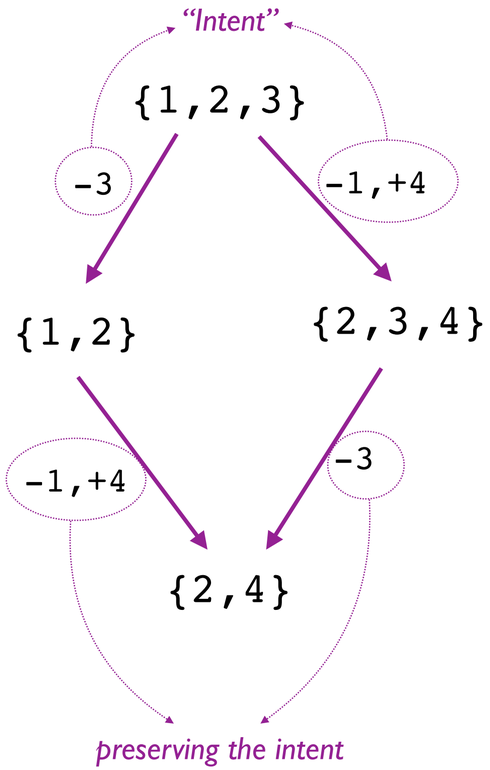


Merge



merge(S3 , S4' , S4) = S5

Set Merge



$$set\_merge(s, s_1, s_2) = (s \cap s_1 \cap s_2) \cup (s_1 - s) \cup (s_2 - s)$$

★ Merged set contains:

- ★ Elements in s that are not deleted in s_1 and s_2
- ★ Elements newly added in s_1
- ★ Elements newly added in s_2

Generality & Practicality of MRDTs

Mergeable Replicated Data Types

GOWTHAM KAKI, Purdue University, USA
SWARN PRIYA, Purdue University, USA
KC SIVARAMAKRISHNAN, IIT Madras, India
SURESH JAGANNATHAN, Purdue University, USA

[OOPSLA 2019]

Table 1. Characteristic relations for various data types

Data Type	Characteristic Relations
Binary Heap	Membership (R_{mem}), Ancestor ($R_{ans} \subseteq R_{mem} \times R_{mem}$)
Priority Queue	Membership (R_{mem})
Set	Membership (R_{mem})
Graph	Vertex (R_V), Edge (R_E)
Functional Map	Key-Value (R_{kv})
List	Membership (R_{mem}), Order (R_{ob})
Binary Tree	Membership (R_{mem}), Tree-order ($R_{to} \subseteq R_{mem} \times \texttt{label} \times R_{mem}$)
Binary Search Tree	Membership (R_{mem})

Generality & Practicality of MRDTs

RunTime-Assisted Convergence in Replicated Data Types

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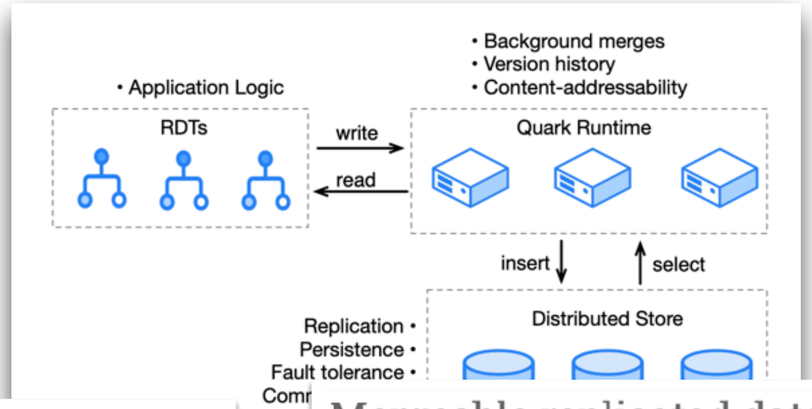
[PLDI 2022]



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Mergeable replicated data types – Part I (acolyer.org)

104 points by telotortium 75 days ago | hide | past | web | un-favorite | 21 comments

Mergeable replicated data types – Part I

NOVEMBER 25, 2019

Mergeable replicated data types Kaki et al., *OOPSLA'19*

This paper was published at OOPSLA, but perhaps it's amongst the distributed systems community that I expect there to be the greatest interest.

Mergeable Replicated Data Types

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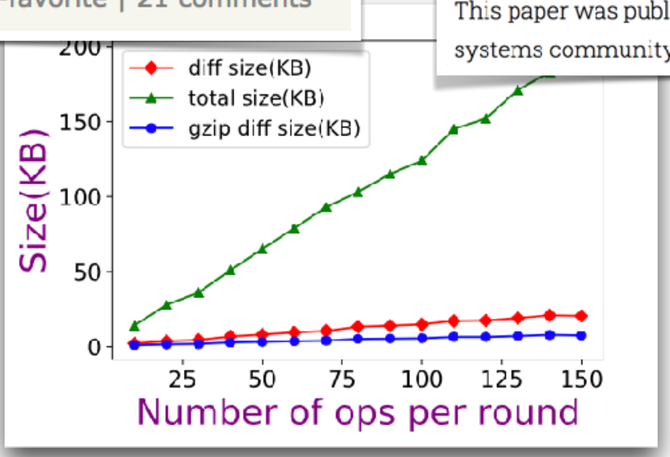
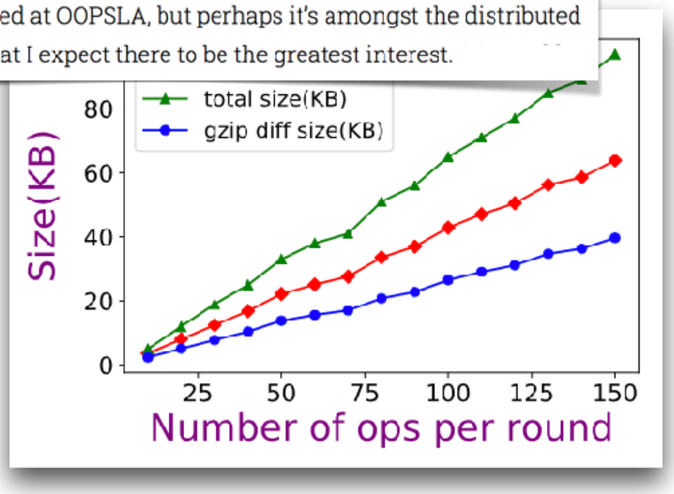
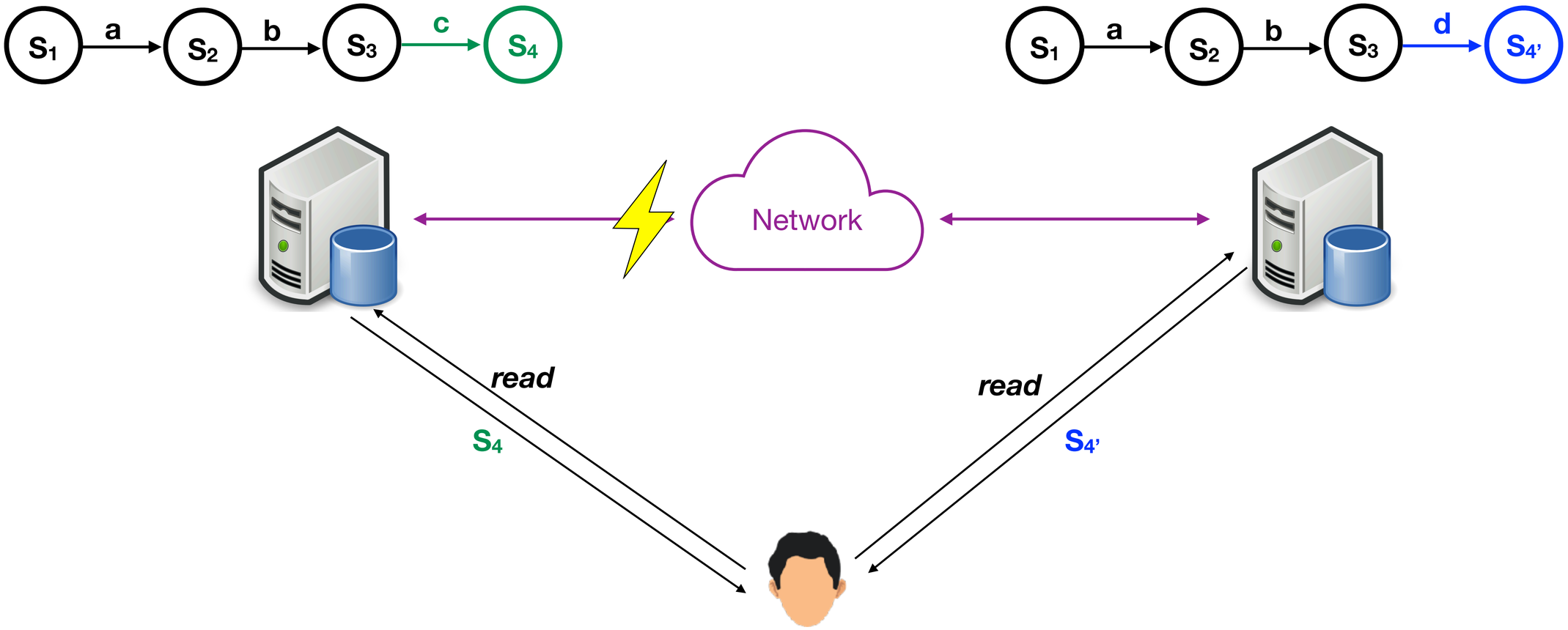
[OOPSLA 2019]

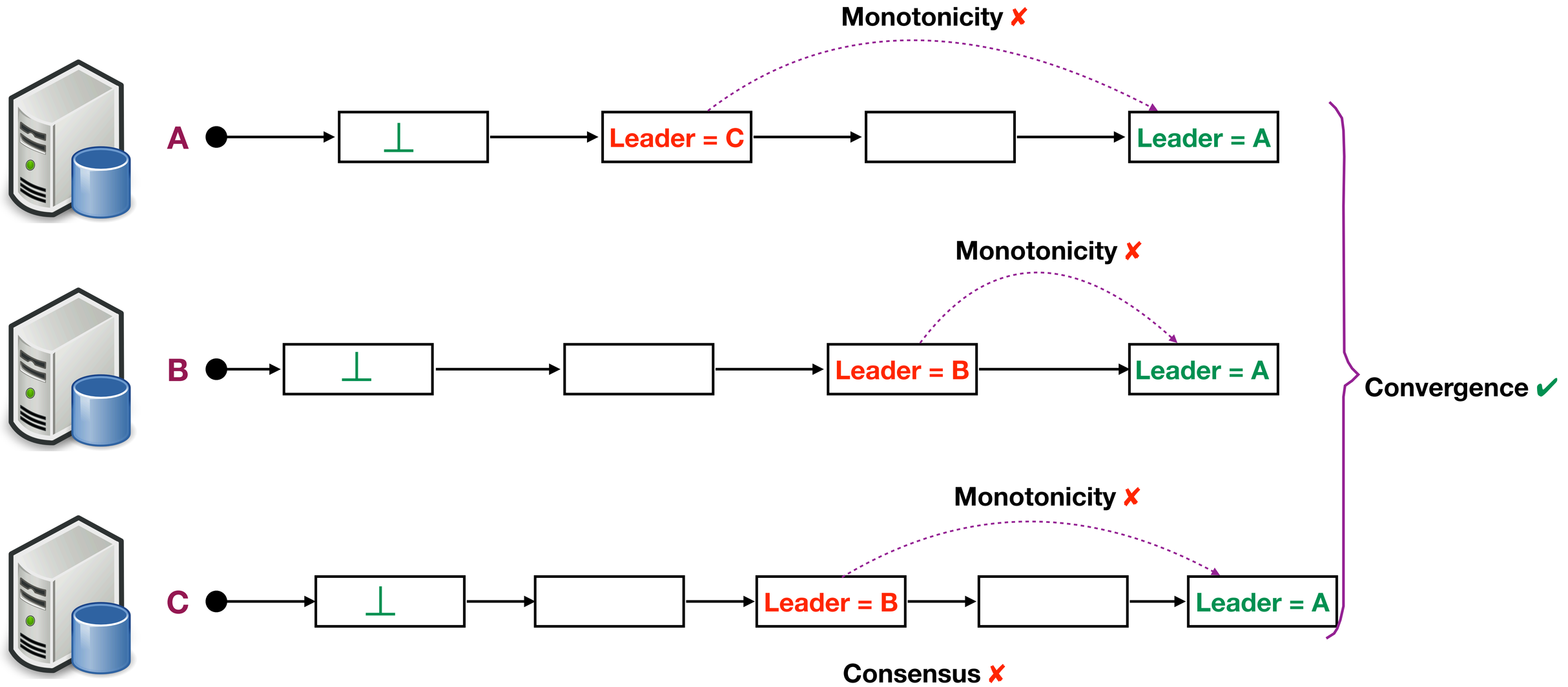




Convergence ≠ Consensus



Example: Leader Election



Convergence is half-way to consensus

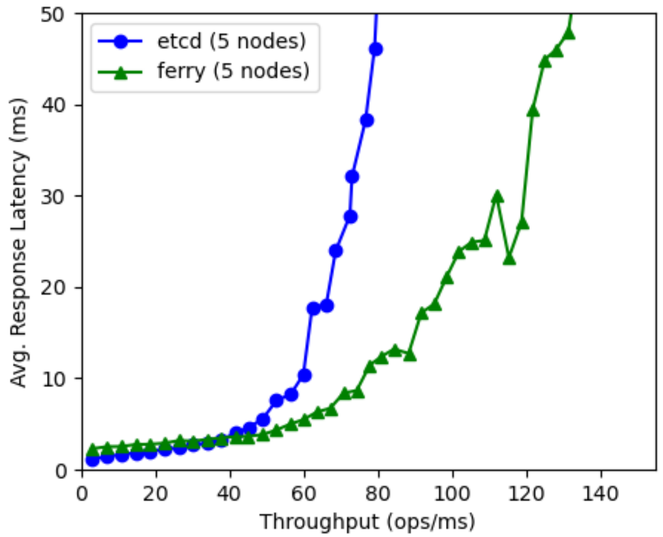
Convergence + Monotonicity ⇒ Consensus

Bolt-On Strong Consistency: Specification, Implementation, and Verification

NICHOLAS V. LEWCHENKO, University of Colorado Boulder, USA
GOWTHAM KAKI, University of Colorado Boulder, USA
BOR-YUH EVAN CHANG*, University of Colorado Boulder, USA and Amazon, USA

[OOPSLA 2025]

- Super-V: A Haskell DSL to implement and formally verify distributed protocols.



- Automated formal verification of Paxos and Raft Implementations with flexible quorum optimization.
- Raft implementation in Super-V performs similarly or better than `etcd-raft`

Conclusion

- Distributed consensus is expensive and hard to get right.
- Convergence is weaker than consensus, but cheap and easy to implement. It can substitute consensus in surprisingly many use cases.
  - Mergeable Replicated Data Types (MRDTs)
  - Quark: https://github.com/cuplv/Quark
- When consensus is unavoidable, it can be implemented *on top of* convergence. This approach results in efficient implementations that can be formally verified with little effort.
  - Super-V: https://github.com/cuplv/super-v