Specification and Implementation of Replicated List

— The Jupiter Protocol Revisited

(Brief Announcement at PODC'2018)

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July 24, 2018

The Jupiter protocol [] for replicated list satisfies the weak list specification [**?**].

This has been proposed as a conjecture in a PODC'16 paper [**?**].

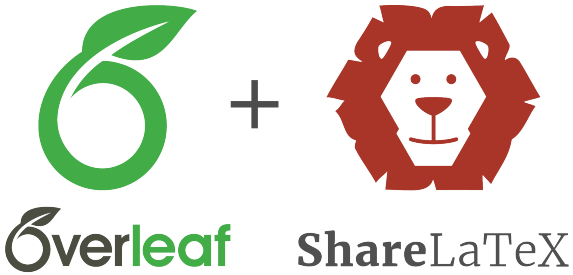
Background for the Conjecture

Collaborative Text Editing Systems

(a) Google Docs

(b) Apache Wave

(c) Wikipedia



(d) LaTeX Editor

Replication (for availability)

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- Replicas respond to user operations immediately
  - Updates are propagated asynchronously

List: to model the core functionality

$\textsc{Ins}(a, p)$: Insert a at position p.

$\textsc{Del}(p)$: Delete an element at position p.

$\textsc{Read}$: Return the list.

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To implement a highly available replicated list object.

Definition (Eventual Convergence (EC) [])

The lists at all replicas are identical *at quiescence*.

Definition (Strong Eventual Consistency (SEC) [])

The lists at the replicas that *have executed the same set of user operations* are identical.

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The lists at the replicas that *have executed the same set of user operations* are identical.

Specify little on *intermediate states* going through by replicas.

Specification and Complexity of Collaborative Text Editing

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Sebastian Burckhardt
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Alexey Gotsman
IMDEA Software Institute

Adam Morrison
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Strong/Weak List Specification []

Specify global properties on all (intermediate) states at all replicas.

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Strong/Weak List Specification []

Specify global properties on all (intermediate) states at all replicas.

Proved: RGA [**?**] satisfies the strong list spec.

Conjecture: *Jupiter* [**?**] satisfies the weak list spec.

Does Jupiter satisfy the weak list specification?

Yes, it does.

Weak List Specification

Definition (Weak List Specification $\mathcal{A}_{\text{weak}}$ [?])

Informally, $\mathcal{A}_{\text{weak}}$ requires the ordering between elements that are not deleted to be consistent across the system.

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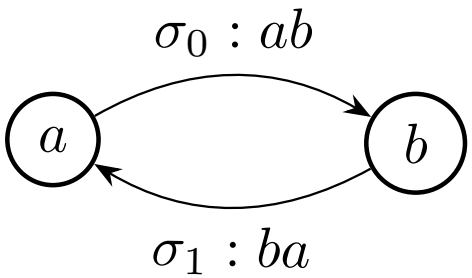
Pairwise state compatibility property:

$$\forall \sigma, \sigma' : a, b \in \sigma \cap \sigma' \implies (a \prec_\sigma b \iff a \prec_{\sigma'} b)$$

$(\sigma, \sigma' :$ list; $\quad a, b :$ element; $\quad \prec_\sigma :$ precedes$)$

$$\forall \sigma, \sigma' : a, b \in \sigma \cap \sigma' \implies (a \prec_{\sigma} b \iff a \prec_{\sigma'} b)$$

$\boxed{\sigma_0 : ab}$ $\boxed{\sigma_1 : ba}$



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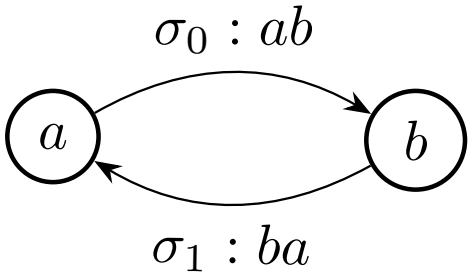
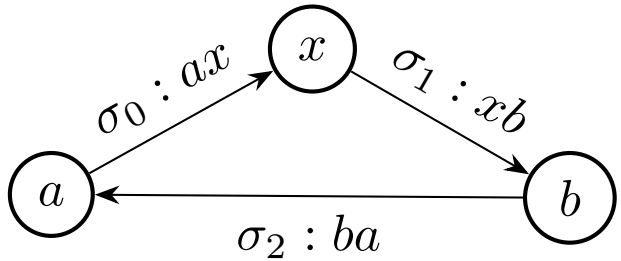
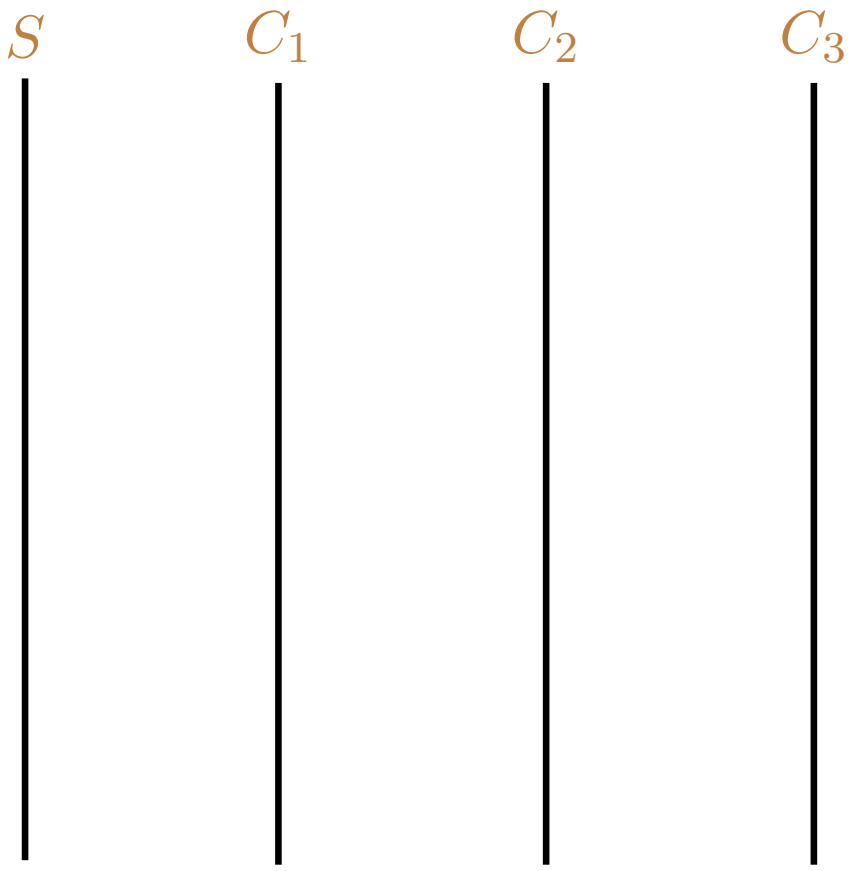


$\boxed{\sigma_0 : ax}$ $\boxed{\sigma_1 : xb}$ $\boxed{\sigma_2 : ba}$

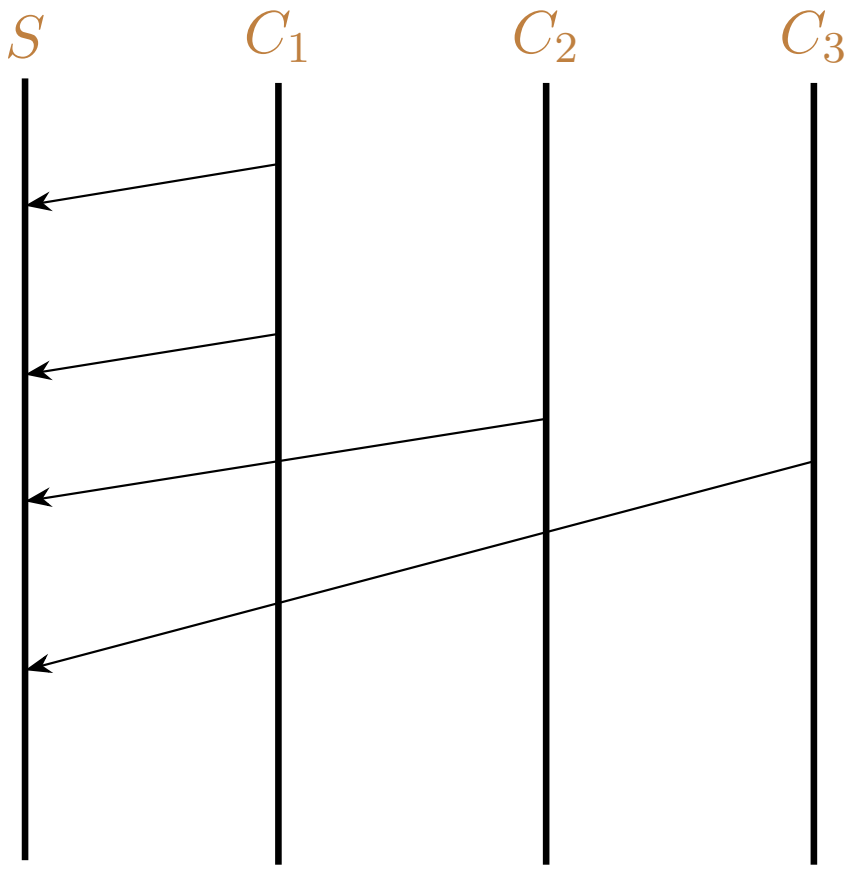


Jupiter



System model of Jupiter:

- client-server architecture



System model of Jupiter:

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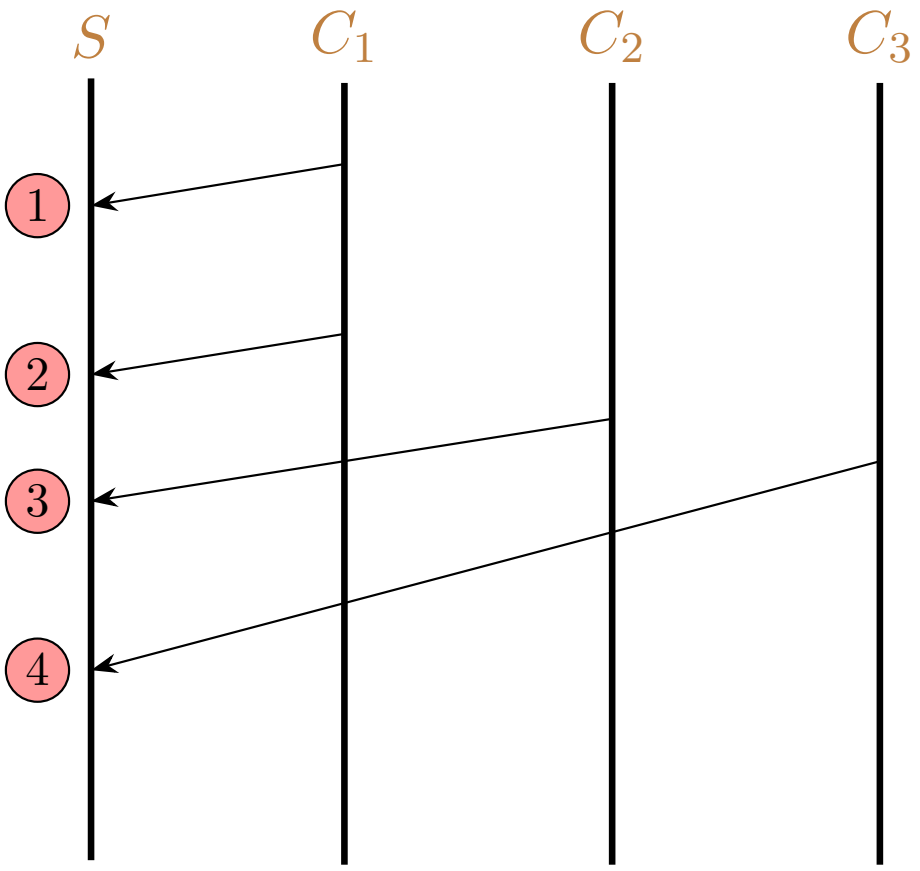

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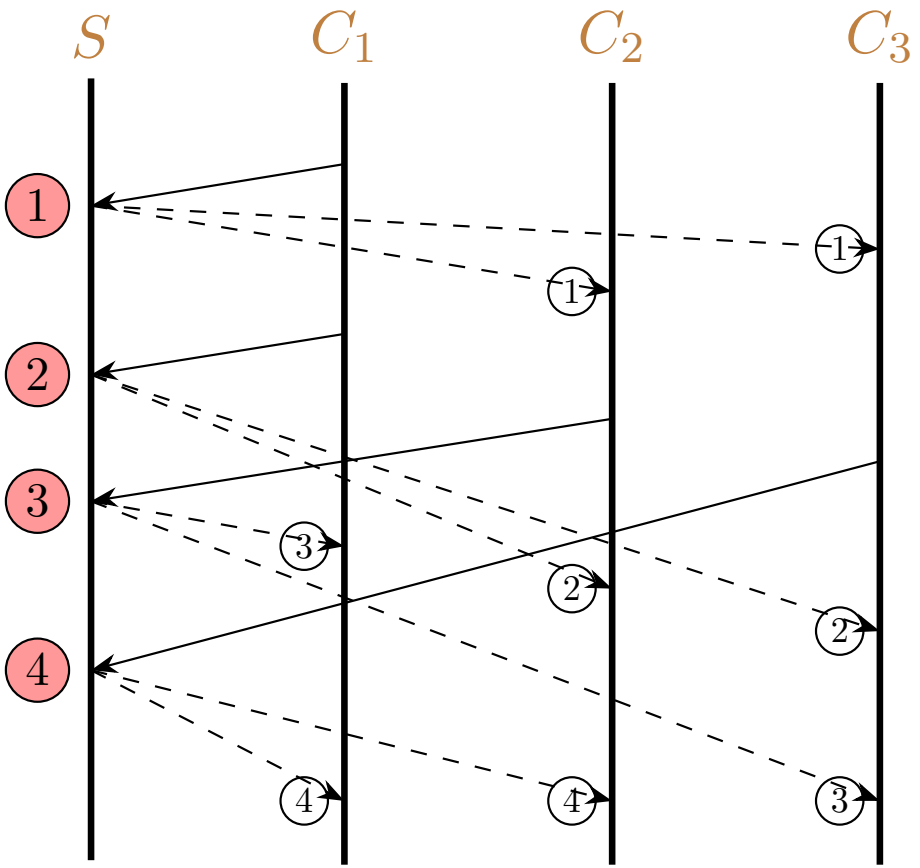

System model of Jupiter:

- client-server architecture
- client $\xrightarrow{\text{FIFO}}$ server
- totally ordered at the server
- server $\xrightarrow{\text{FIFO}}$ client

OT (Operational Transformation) []

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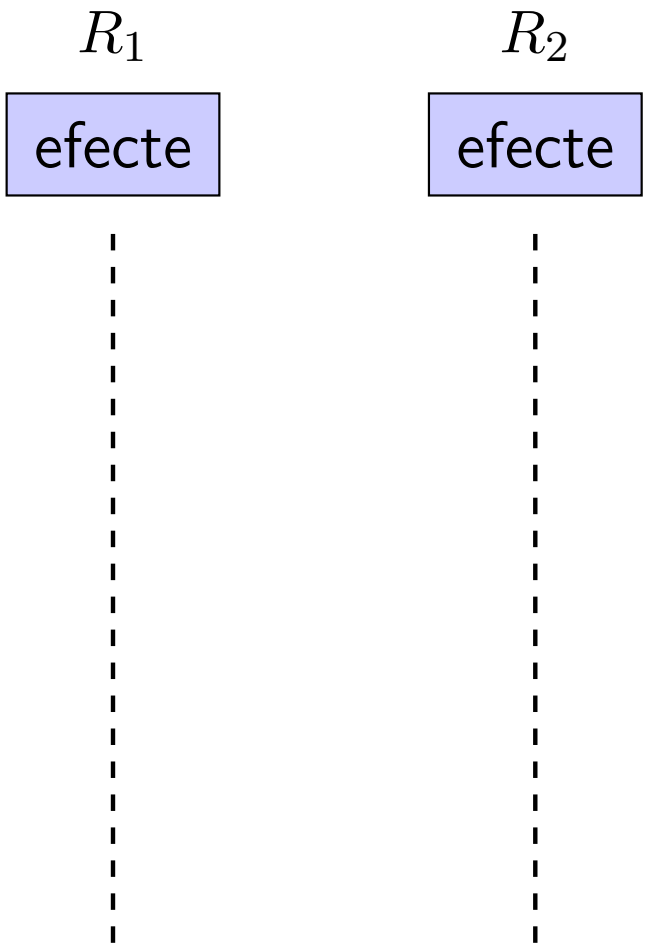

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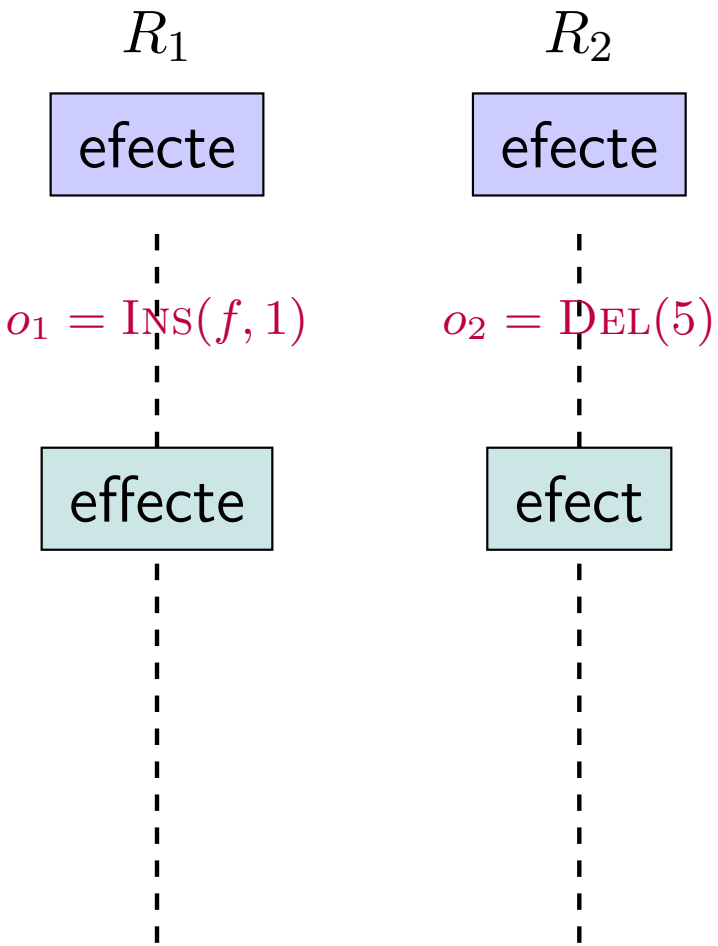

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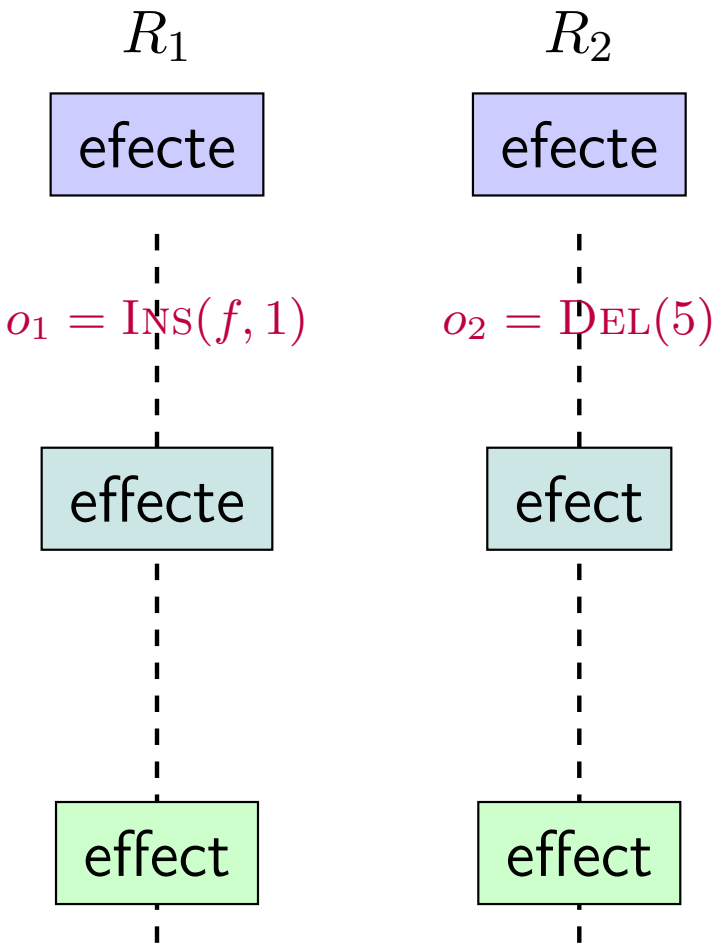

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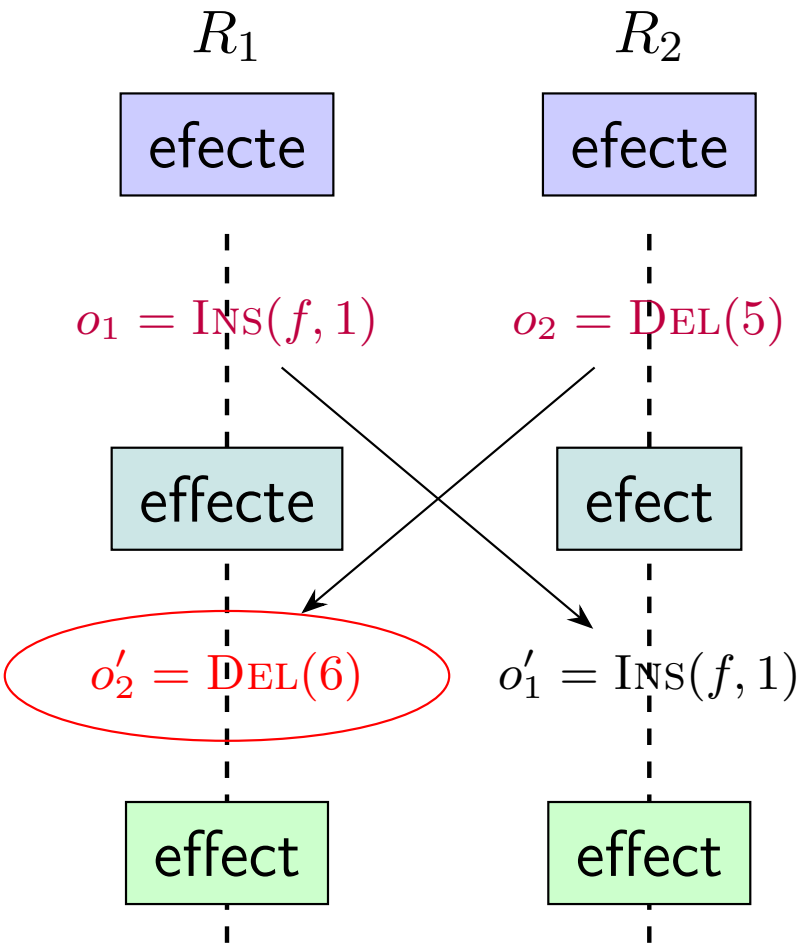

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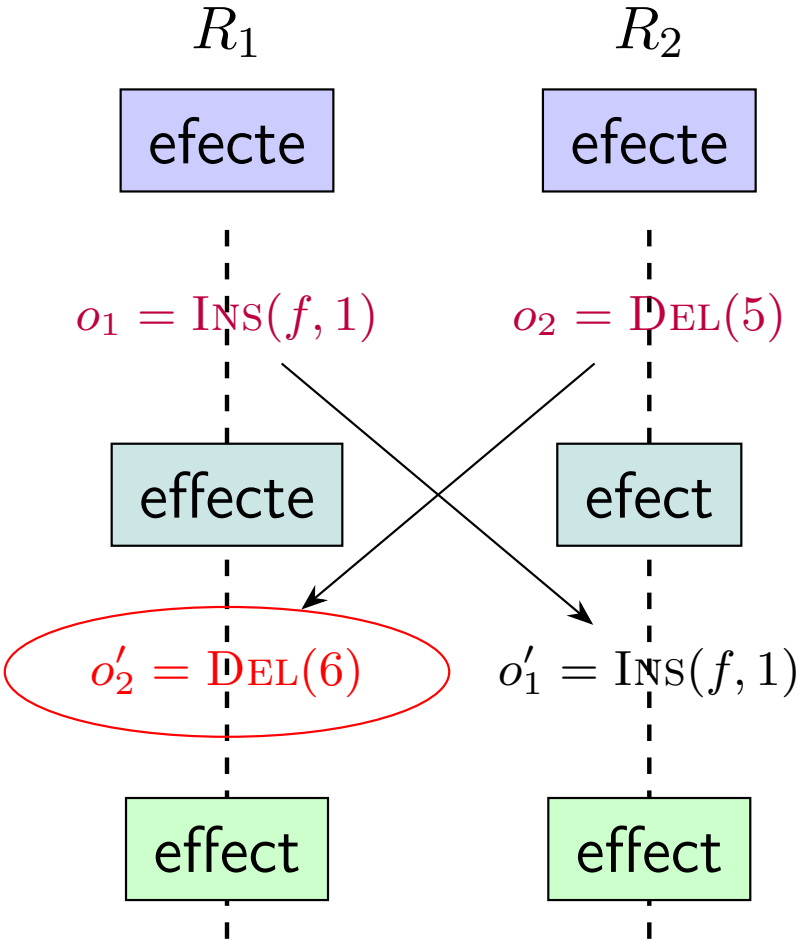
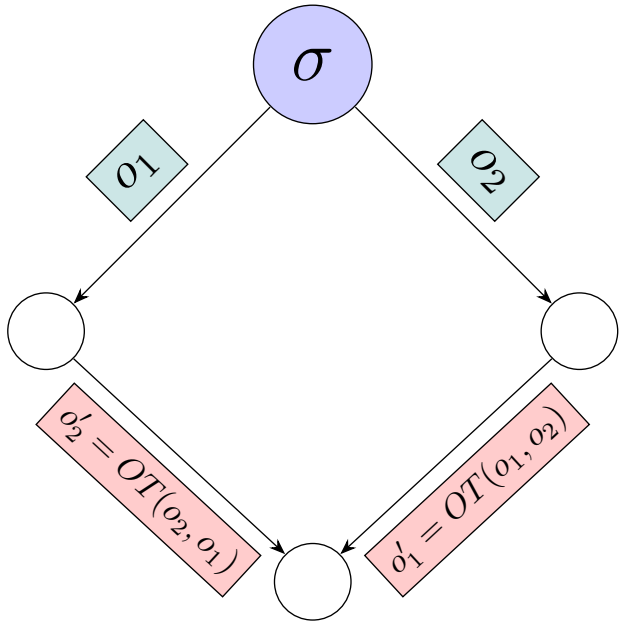
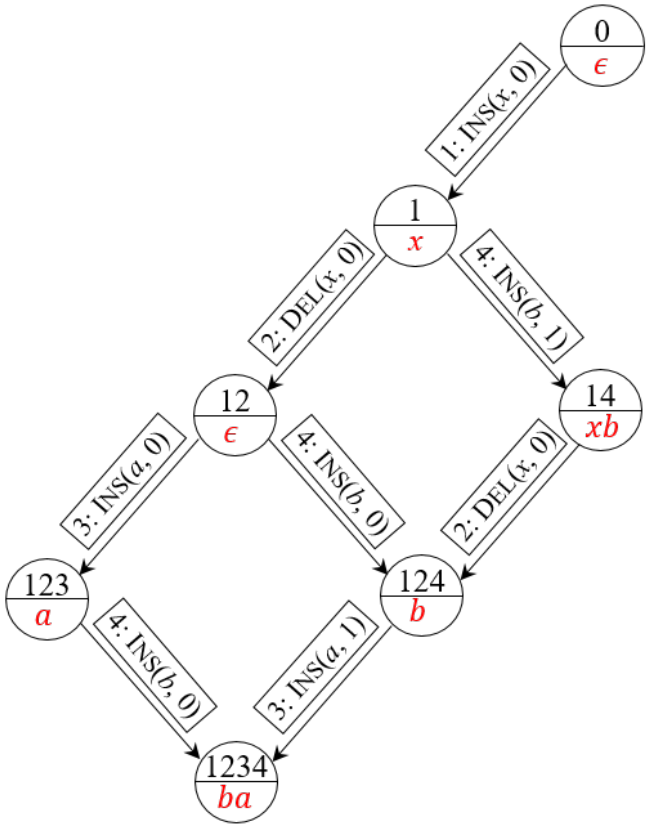




$$\sigma; o_1; o_2' \equiv \sigma; o_2; o_1'$$

Jupiter uses $2D$ state spaces []
to manage how and when to perform OTs.



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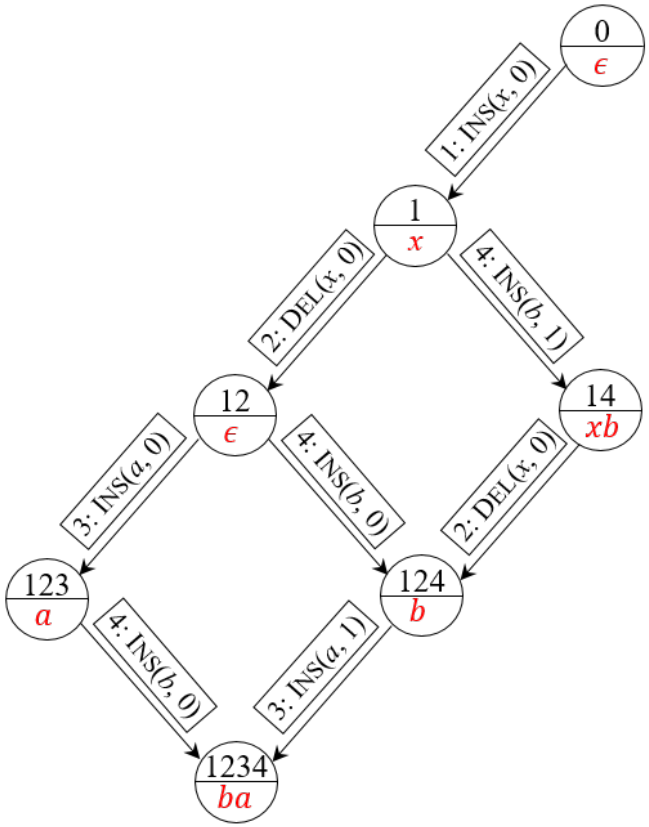

Nodes represent states. Edges are labeled with operations.

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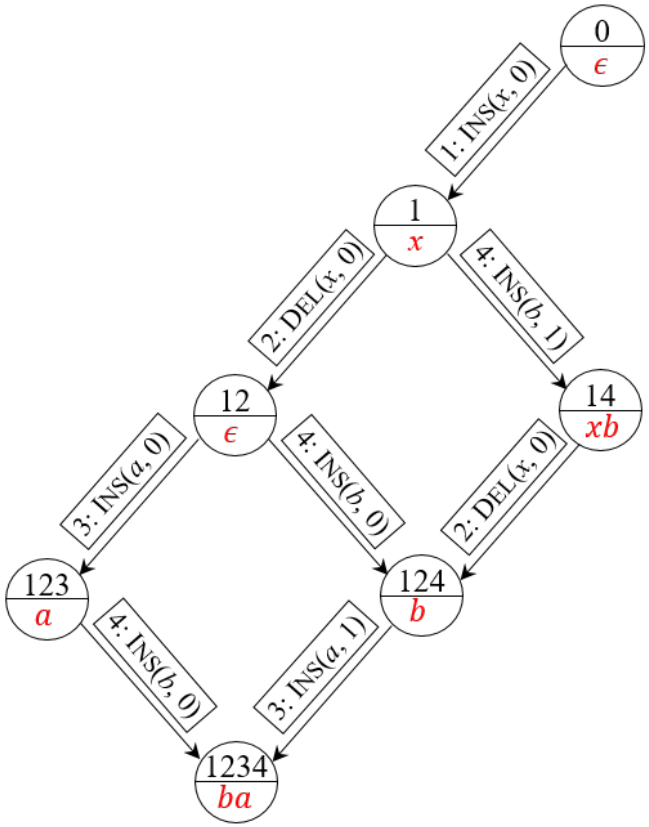
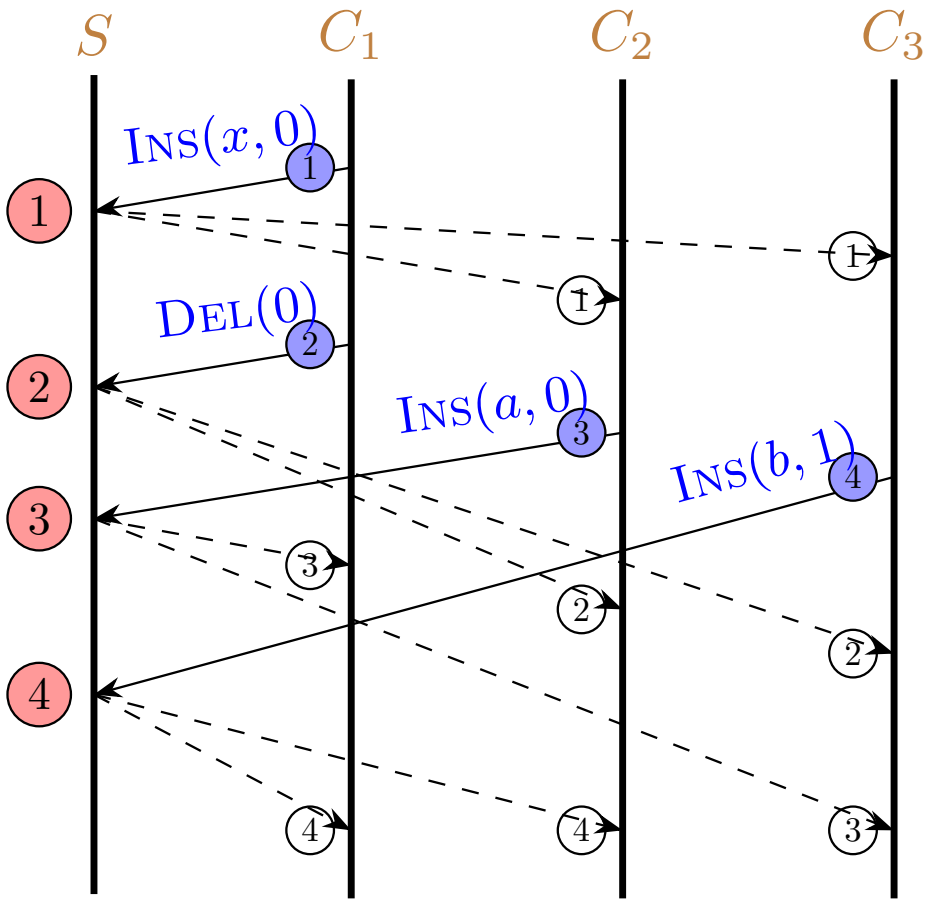


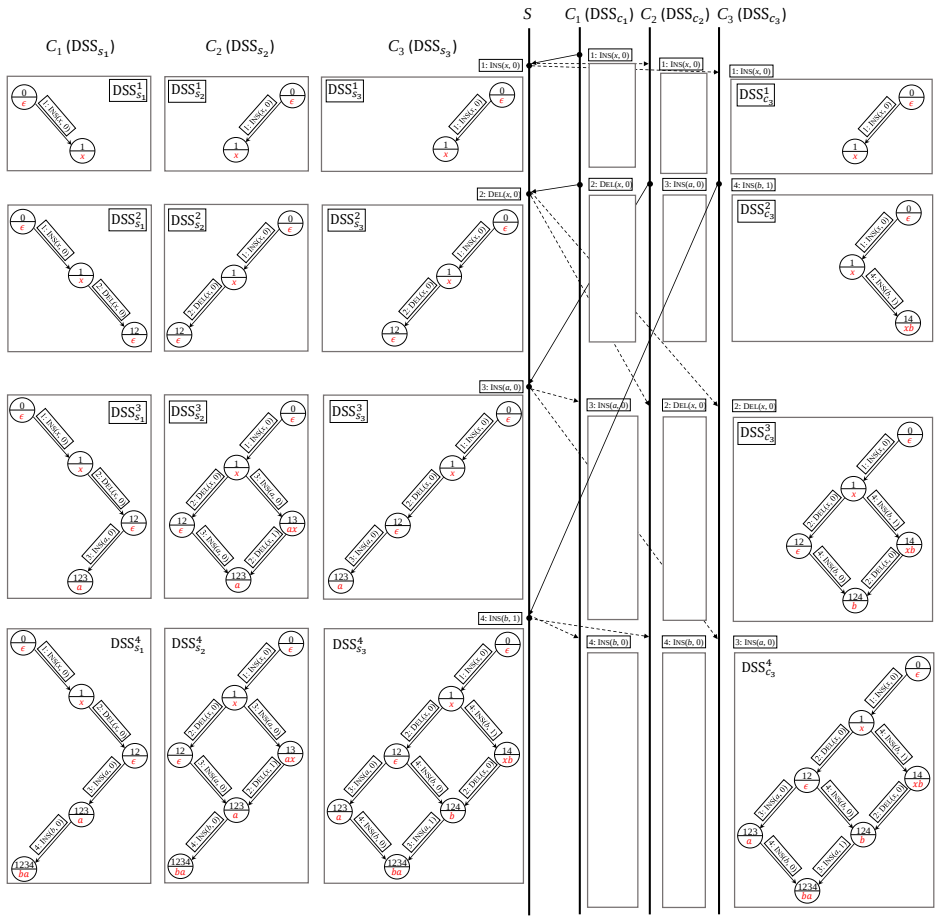
Nodes represent states. Edges are labeled with operations.

$2D$: An operation from the same node is either LOCAL or GLOBAL.

Consider a replicated system with $n\ (=3)$ clients.



Each client maintains a $2D$ state space.



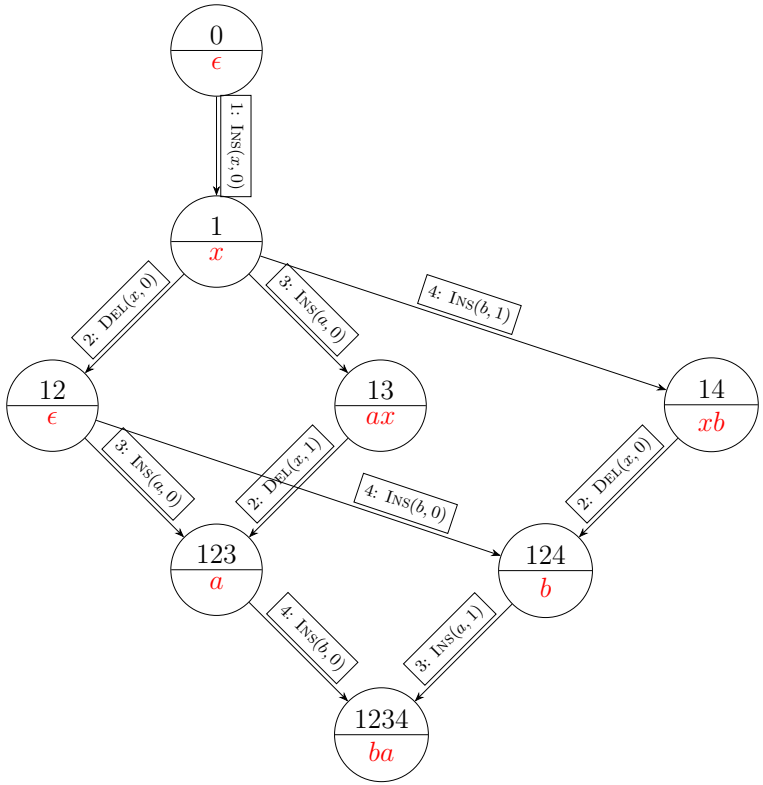
The server maintains $n\ (=3)$ $2D$ state spaces, one for each client.

Global property on all replica states
specified by the weak list specification

Local view each replica maintains in Jupiter

CJupiter (Compact Jupiter)

CJupiter maintains an n-ary ordered state space for each replica.



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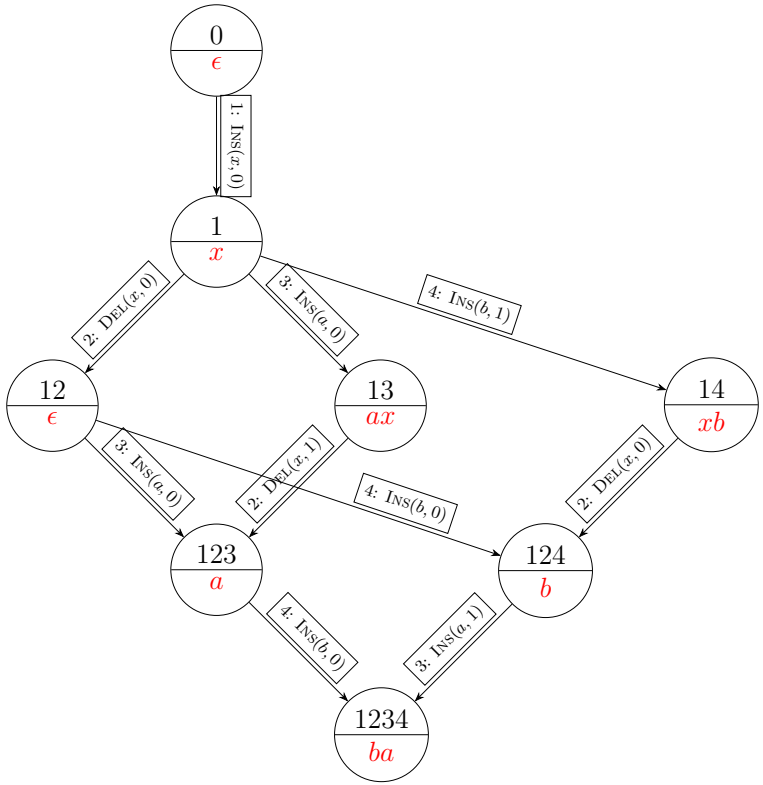

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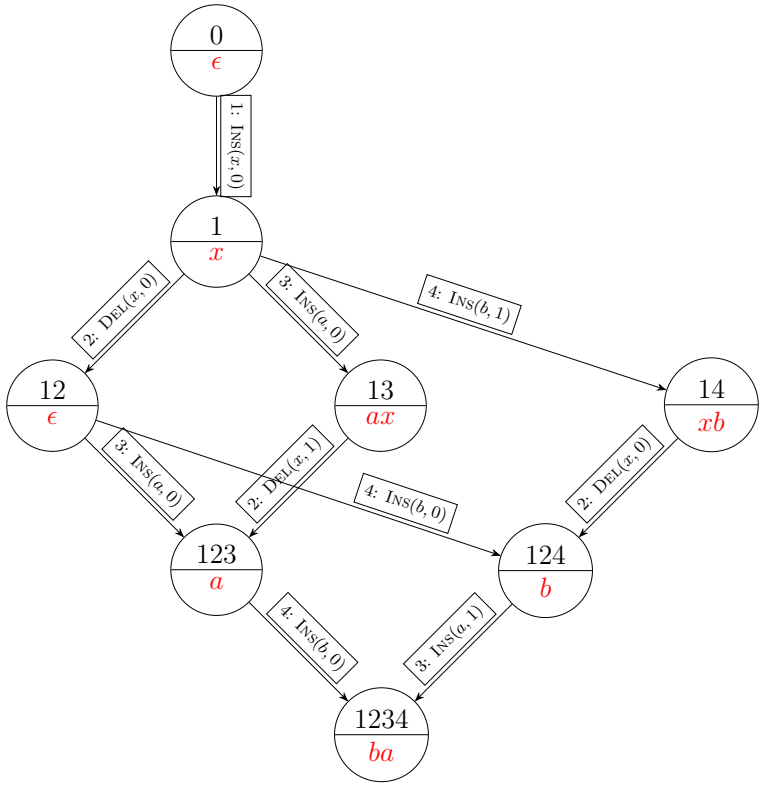
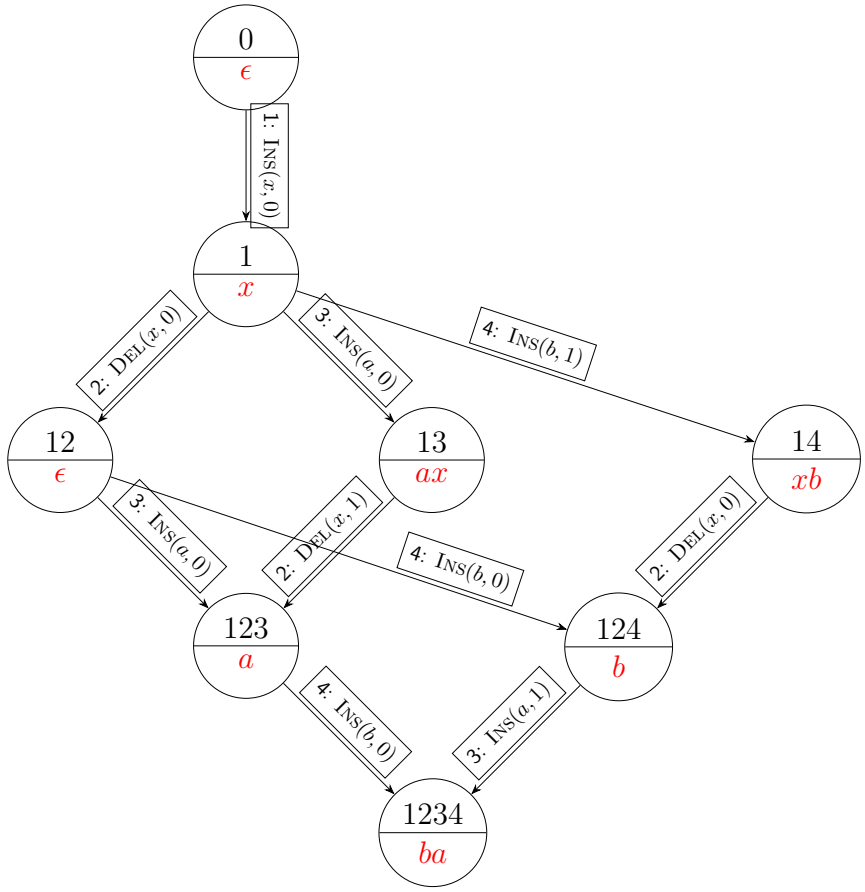


Nodes represent states. Edges are labeled with operations.
Edges from the same node are totally ordered by associated operations.

Proposition ($n + 1 \to 1$ (Informal))

At a high level, CJupiter maintains only one n-ary ordered state space.



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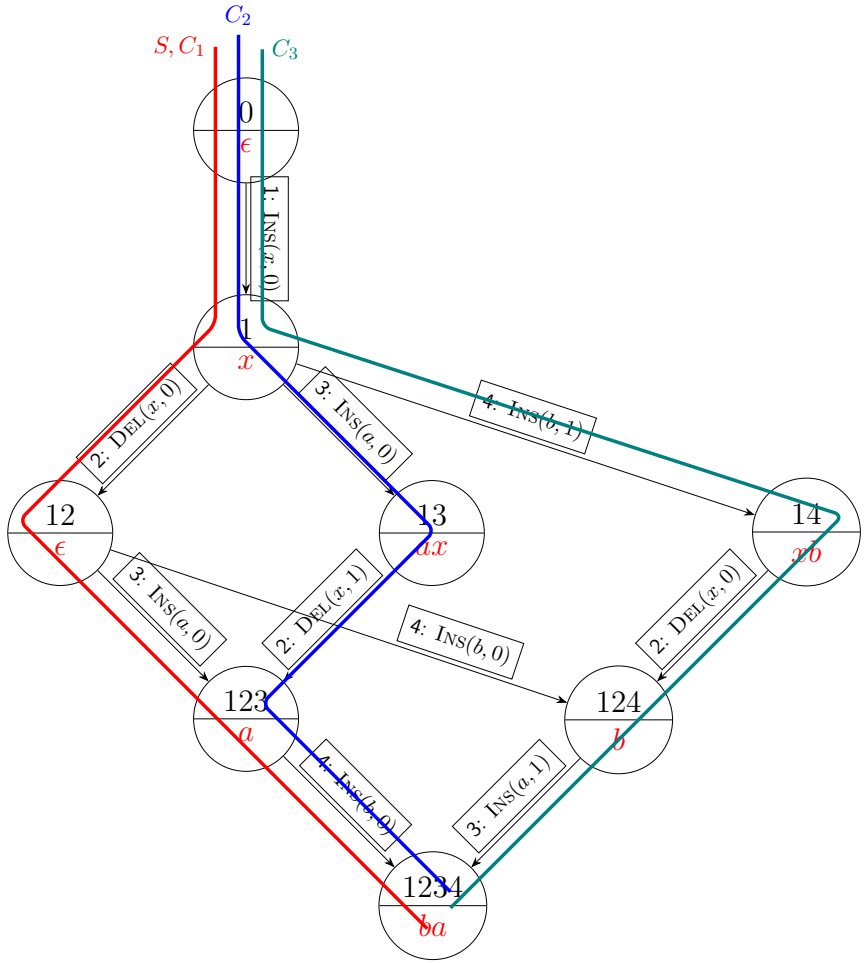

Each replica behavior corresponds to a path going through this state space.

Theorem (Equivalence)

Under the same schedule, the behaviors of corresponding replicas in CJupiter and Jupiter are the same.

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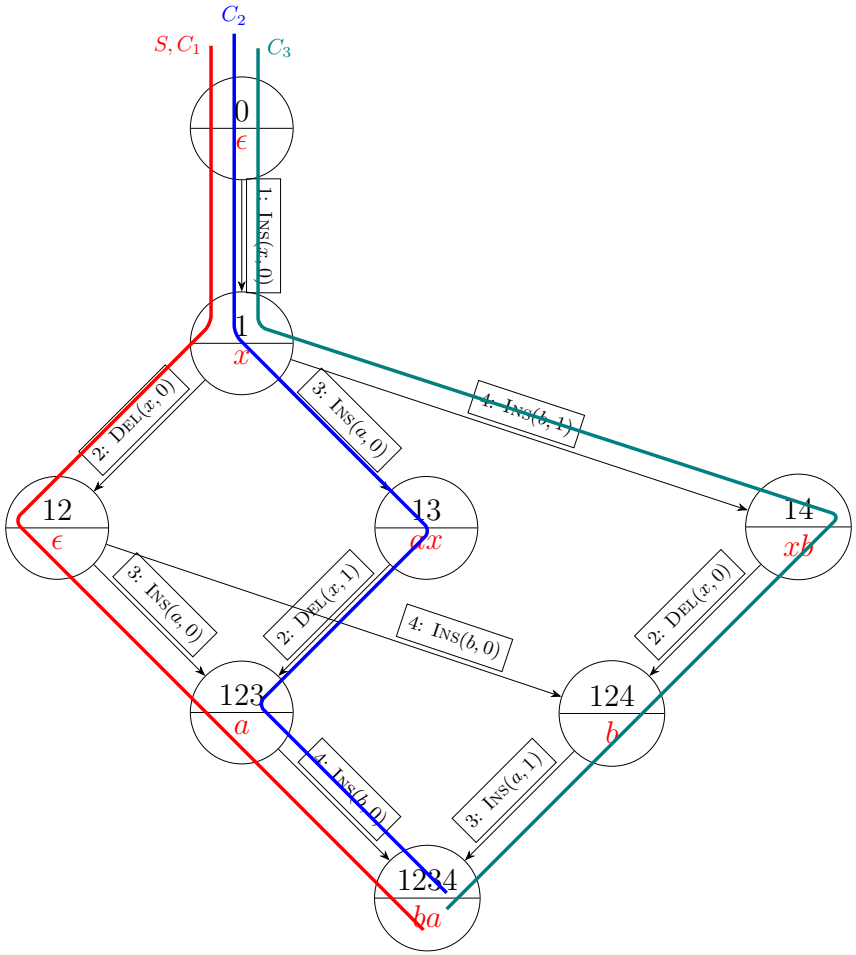
At the client side:

Proposition ($1 \leftrightarrow 1$ (Informal))

Jupiter is slightly optimized in implementation at clients by eliminating redundant OTs than CJupiter.

CJupiter satisfies the weak list specification.

We study a single n-ary ordered state space CSS_s at the server which provides a global view of all possible replica states.



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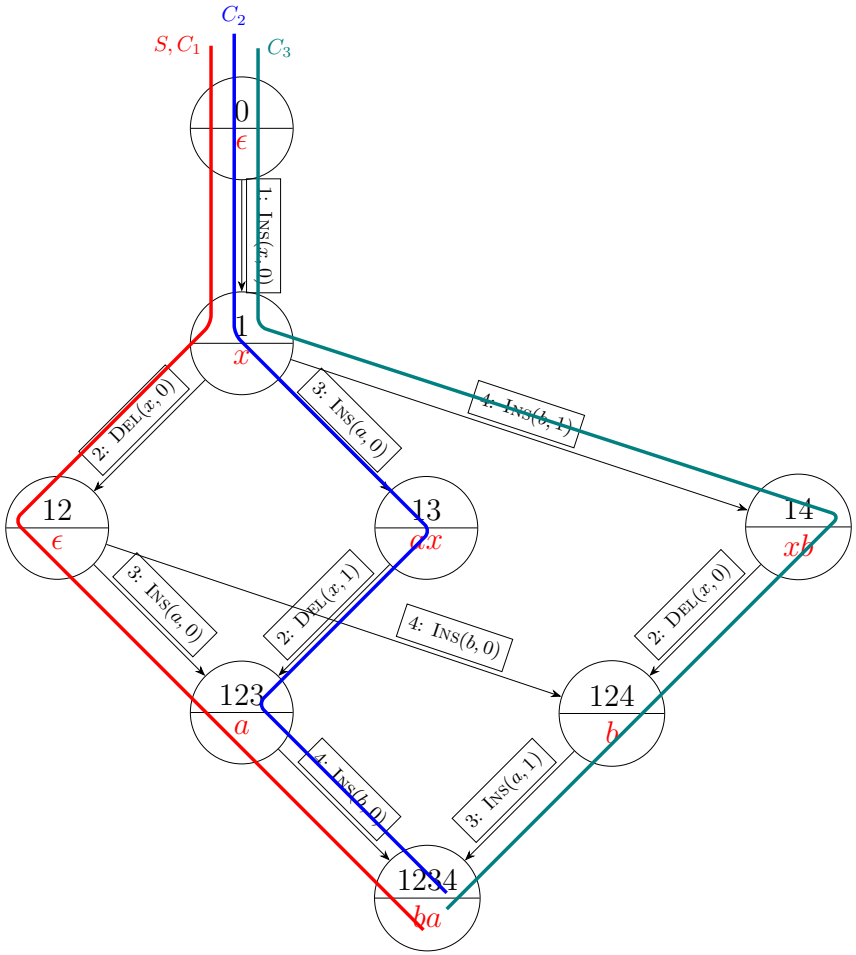
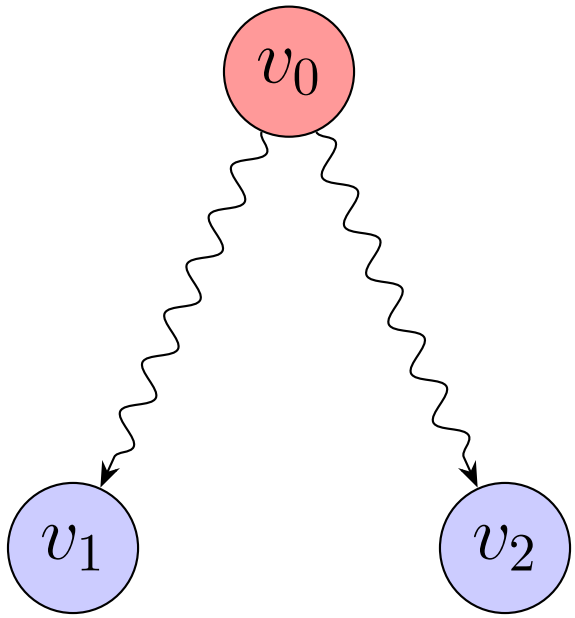


To show the pairwise state compatibility property in three steps.

1. Take any two nodes/states v_1 and v_2.

Lemma (LCA (Lowest Common Ancestor))

Each pair of states in the n-ary ordered state space has a unique LCA.

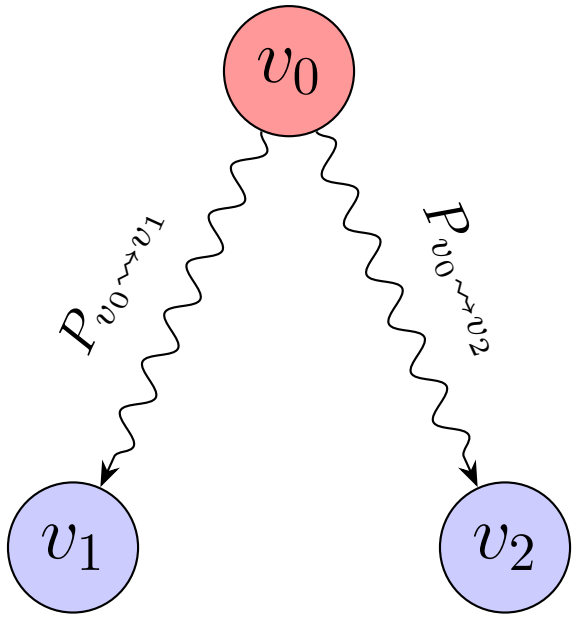


$$v_0 = \mathsf{LCA}(v_1, v_2)$$

2 Consider the paths to v_1 and v_2 from their LCA v_0.

Lemma (Disjoint Paths)

The set of operations $O_{v_0 \rightsquigarrow v_1}$ along $P_{v_0 \rightsquigarrow v_1}$ is disjoint from the set of operations $O_{v_0 \rightsquigarrow v_2}$ along $P_{v_0 \rightsquigarrow v_2}$.

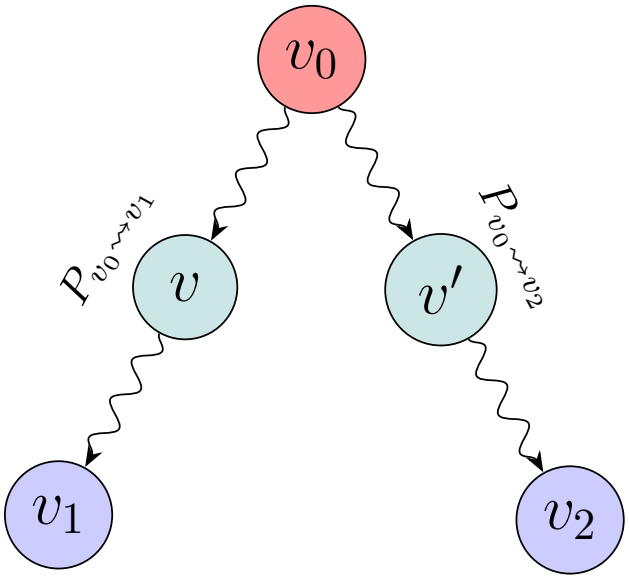


$$v_0 = \mathsf{LCA}(v_1, v_2)$$

3 Consider the states in these two paths.

Lemma (Compatible Paths)

Each pair of states consisting of one state v in $P_{v_0 \rightsquigarrow v_1}$ and the other v' in $P_{v_0 \rightsquigarrow v_2}$ are compatible.



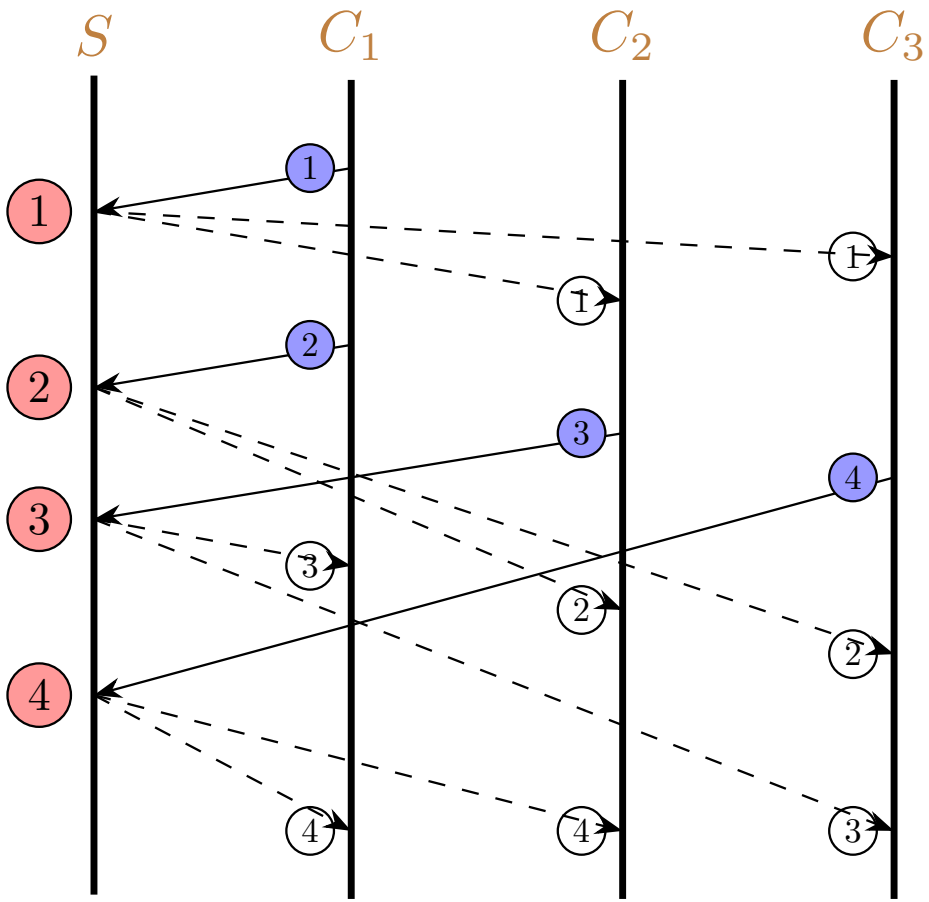
$$v_0 = \mathsf{LCA}(v_1, v_2)$$

In particular,
v_1 and v_2 are compatible.


Thank
You!

Backup

It is still challenging to achieve convergence despite the server.



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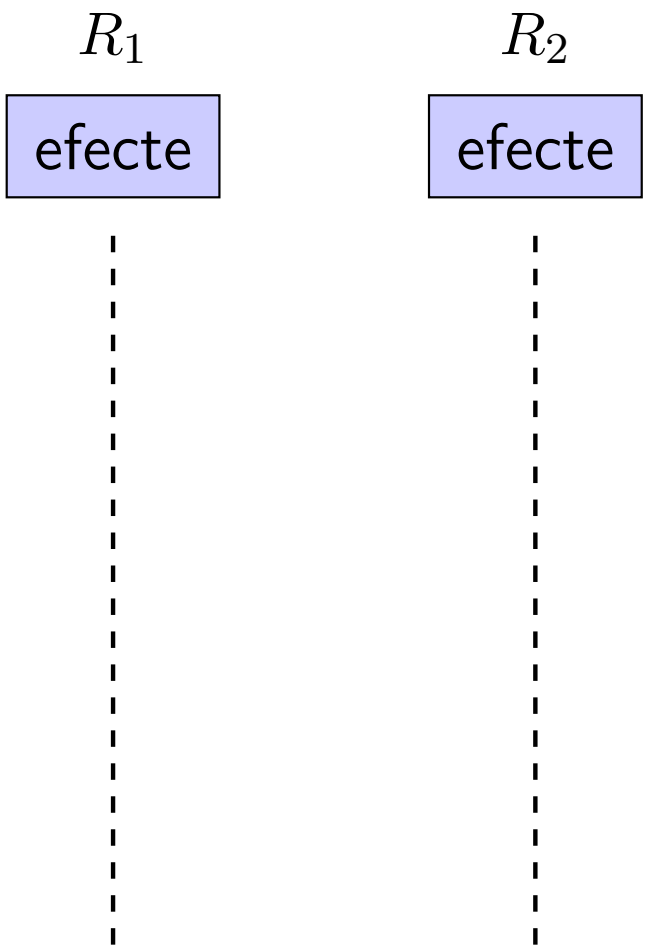

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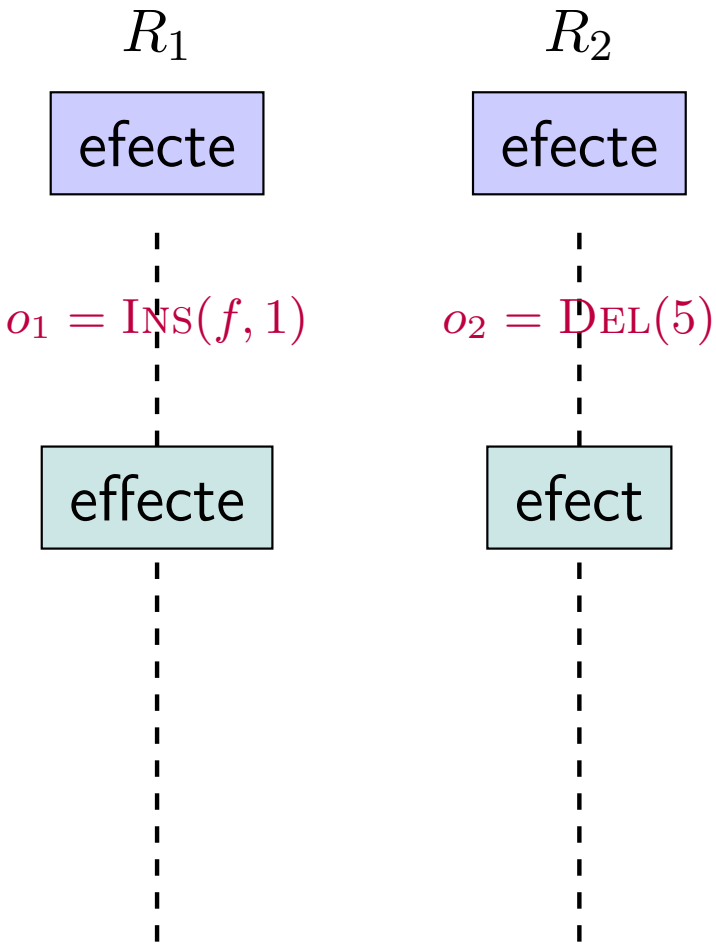

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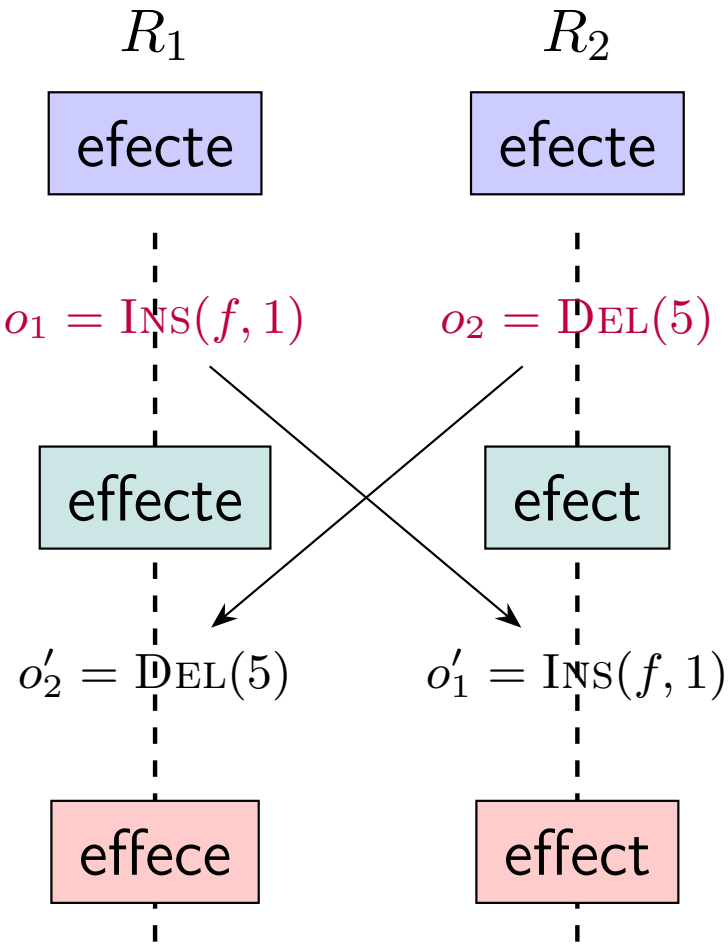

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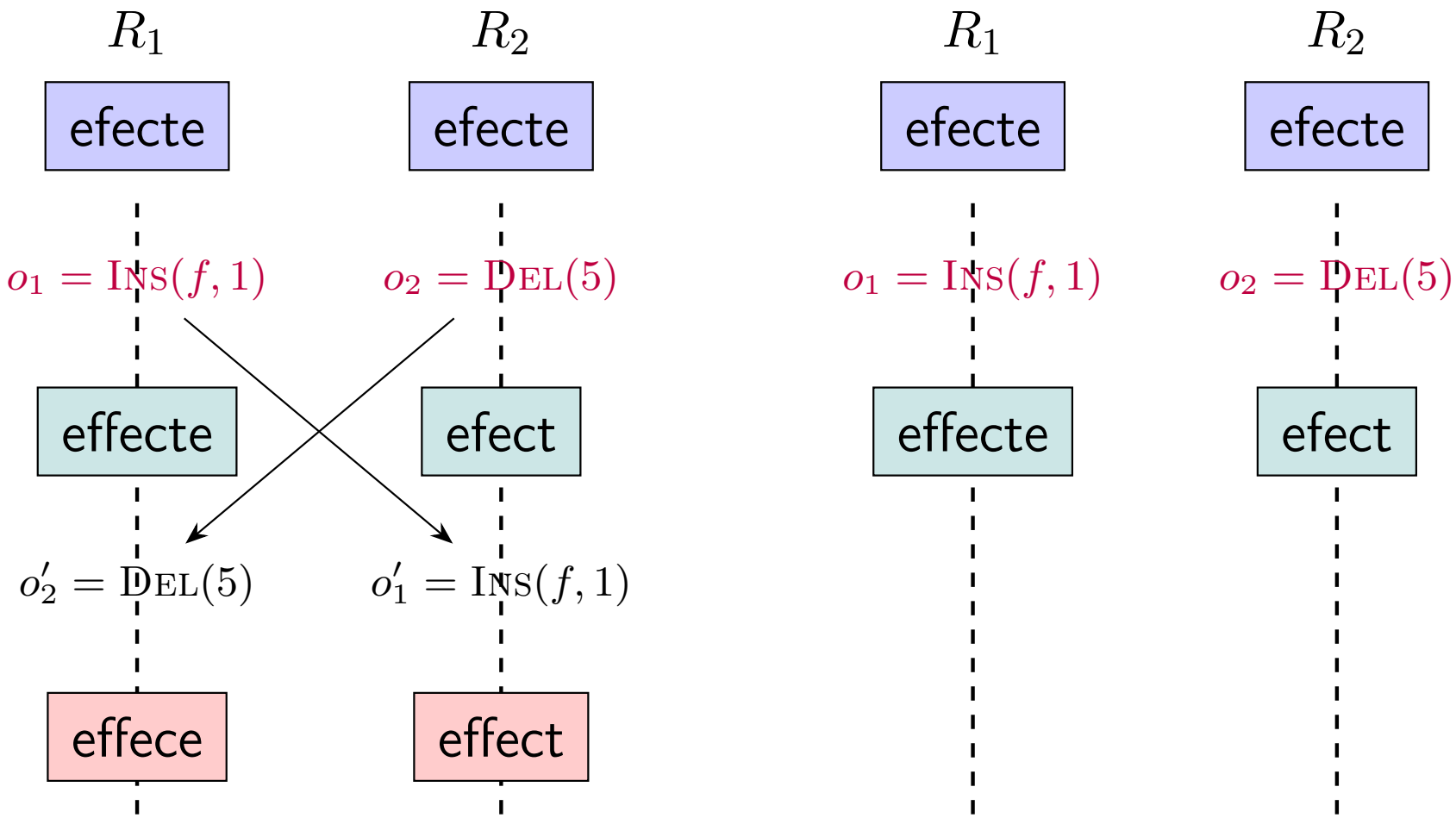

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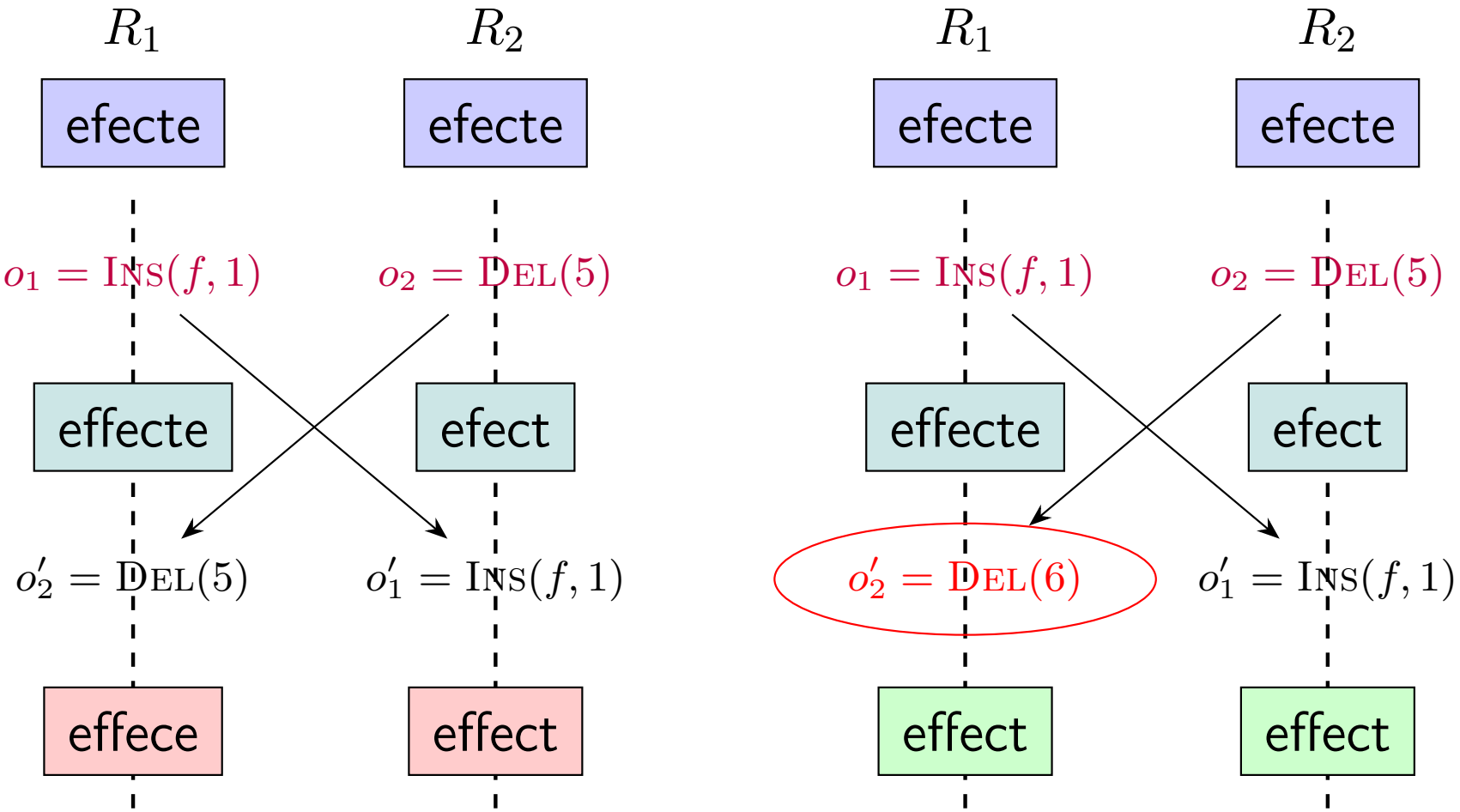

OT functions for a replicated list object [?, ?]

$$OT\Big(\textsc{Ins}(a_1,p_1,pr_1),\textsc{Ins}(a_2,p_2,pr_2)\Big)=\begin{cases}\textsc{Ins}(a_1,p_1,pr_1) & p_1<p_2\\ \textsc{Ins}(a_1,p_1+1,pr_1) & p_1>p_2\\ \text{NOP} & p_1=p_2\wedge a_1=a_2\\ \textsc{Ins}(a_1,p_1+1,pr_1) & p_1=p_2\wedge a_1\neq a_2\wedge pr_1>pr_2\\ \textsc{Ins}(a_1,p_1,pr_1) & p_1=p_2\wedge a_1\neq a_2\wedge pr_1\leq pr_2\end{cases}$$

$$OT\Big(\textsc{Ins}(a_1,p_1,pr_1),\textsc{Del}(\_,p_2,pr_2)\Big)=\begin{cases}\textsc{Ins}(a_1,p_1,pr_1) & p_1\leq p_2\\ \textsc{Ins}(a_1,p_1-1,pr_1) & p_1>p_2\end{cases}$$

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