Specification and Implementation of Replicated List
— The Jupiter Protocol Revisited

(Brief Announcement at PODC'2018)

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Brief Announcement

The Jupiter protocol [Nichols et al., 1995][a] for replicated list satisfies the weak list specification [Attiya et al., 2016][b].

[a] David A. Nichols et al. (1995). "High-latency, Low-bandwidth Windowing in the Jupiter Collaboration System". In: *Proceedings of the 8th Annual ACM Symposium on User Interface and Software Technology*. UIST '95. ACM, pp. 111–120.

[b] Hagit Attiya et al. (2016). "Specification and complexity of collaborative text editing". In: *Proceedings of the 2016 ACM Symposium on Principles of Distributed Computing*. PODC '16. ACM, pp. 259–268.

This was proposed as a conjecture in a PODC paper [Attiya et al., 2016].

Background

Replicated, highly available collaborative text editing systems

(a) Google Docs

(b) Apache Wave

(c) Wikipedia

(d) LaTeX Editor

Replicas are required to respond to user operations immediately.

Updates are propagated to other replicas asynchronously.

Replicated list object: to model the core functionality

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

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

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

Definition (Eventual Convergence (EC) [Ellis and Gibbs, 1989])

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

Definition (Strong Eventual Consistency (SEC) [Shapiro et al., 2011])

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.

Strong/weak list specification [Attiya et al., 2016]

Specify global properties on all states at all replicas.

Specification and Complexity of Collaborative Text Editing

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Proved: RGA [Roh et al., 2011] satisfies the strong list specification.

Conjecture: Jupiter [Nichols et al., 1995] satisfies the weak list specification.

Weak List Specification

Definition (Weak List Specification $\mathcal{A}_{\text{weak}}$ [Attiya et al., 2016])

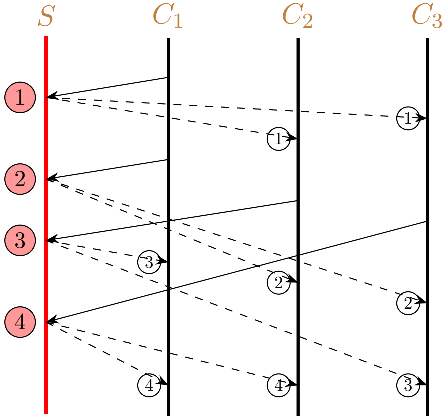
Informally, $\mathcal{A}_{\text{weak}}$ requires the ordering between elements that are not deleted to be consistent across the system.

Pairwise state compatibility property:

For any pair of list states, there cannot be two elements a and b such that a precedes b in one state but b precedes a in the other.

Jupiter

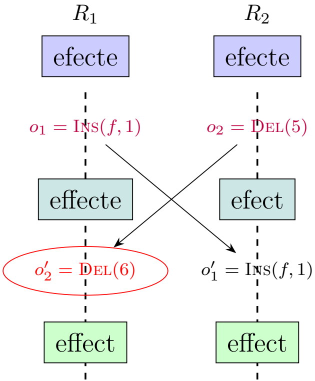
Jupiter adopts the client-server architecture [Nichols et al., 1995]:

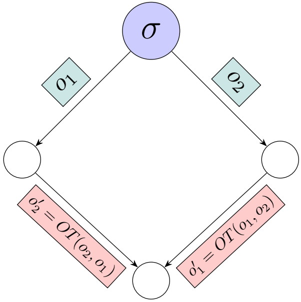


Operations are totally ordered at the server.

Client $\xrightarrow{\text{FIFO}}$ server $\xrightarrow{\text{FIFO}}$ other clients

Jupiter utilizes OT [1] [Ellis and Gibbs, 1989] to achieve convergence.

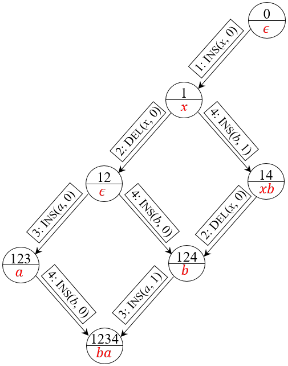




$$\sigma; o_1; o'_2 \equiv \sigma; o_2; o'_1$$

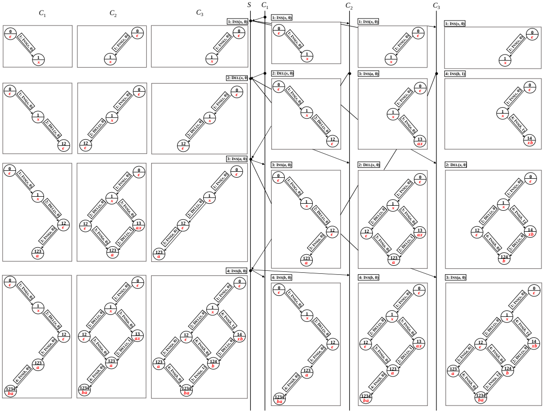
[1] OT: Operational Transformation

Jupiter uses $2D$ state spaces [Xu, Sun, and Li, 2014] to manage how and when to perform OTs.



There can be ≤ 2 edges coming from the same node (LOCAL or GLOBAL).

Each client maintains a $2D$ state space.



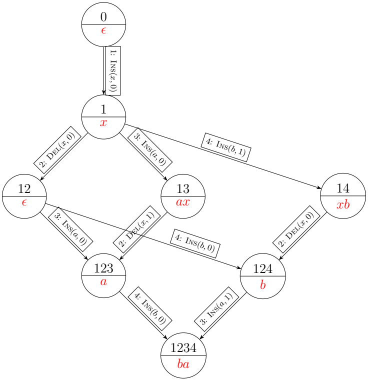
The server maintains n $(= 3)$ $2D$ state spaces, one for each client.

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.

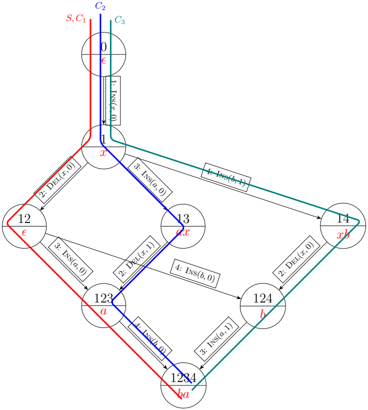


There can be more than two edges coming from the same node.

Edges from the same node are totally ordered by associated operations.

Proposition (Compactness of CJupiter (Informal))

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



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

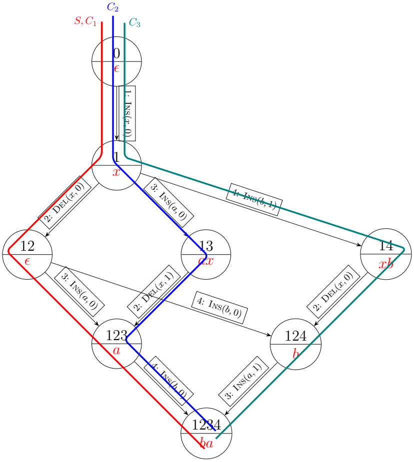
Theorem (Equivalence of CJupiter and Jupiter)

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

From the perspectives of both the server and clients.

CJupiter Satisfies the Weak List Specification

We focus on a single (compact) n-ary ordered state space.

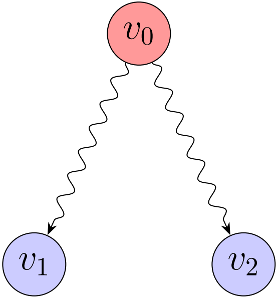


To show the pairwise state compatibility property in three steps.

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.

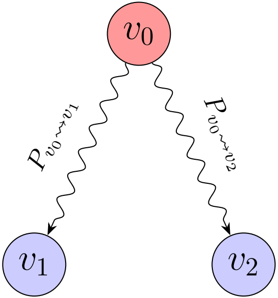


$$v_0 = \mathsf{LCA}(v_1, v_2)$$

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 $P_{v_0 \rightsquigarrow v_2}$.

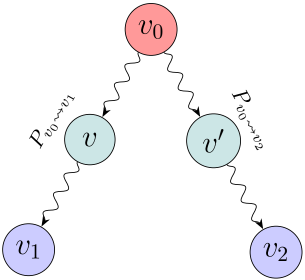


$v_0 = \mathsf{LCA}(v_1, v_2)$

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.

Brief Announcement

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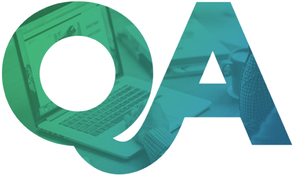
Thank You!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Attiya, Hagit et al. (2016). "Specification and complexity of collaborative text editing". In: *Proceedings of the 2016 ACM Symposium on Principles of Distributed Computing*. PODC '16. ACM, pp. 259–268.

Ellis, C. A. and S. J. Gibbs (1989). "Concurrency Control in Groupware Systems". In: *Proceedings of the 1989 ACM SIGMOD International Conference on Management of Data*. SIGMOD '89. ACM, pp. 399–407.

Nichols, David A. et al. (1995). "High-latency, Low-bandwidth Windowing in the Jupiter Collaboration System". In: *Proceedings of the 8th Annual ACM Symposium on User Interface and Software Technology*. UIST '95. ACM, pp. 111–120.

Roh, Hyun-Gul et al. (2011). "Replicated Abstract Data Types: Building Blocks for Collaborative Applications". In: *J. Parallel Distrib. Comput.* 71.3, pp. 354–368.

Shapiro, Marc et al. (2011). "Conflict-free Replicated Data Types". In: *Proceedings of the 13th International Conference on Stabilization, Safety, and Security of Distributed Systems*. SSS'11. Springer-Verlag, pp. 386–400.

Xu, Yi, Chengzheng Sun, and Mo Li (2014). "Achieving Convergence in Operational Transformation: Conditions, Mechanisms and Systems". In: *Proceedings of the 17th ACM Conference on Computer Supported Cooperative Work*. CSCW '14. ACM, pp. 505–518.

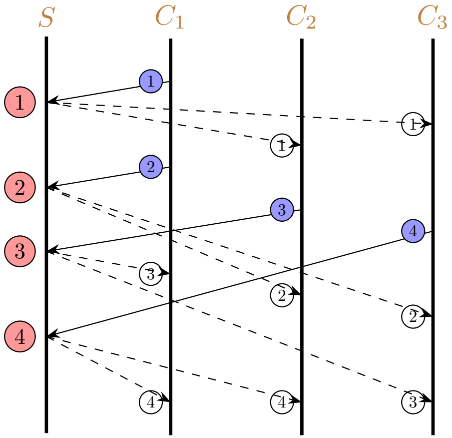
Backup

Replication (for availability)

Replicas respond to user operations immediately

Updates are propagated asynchronously

It is still challenging to achieve convergence despite the server.



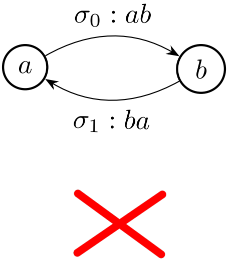
Serializability may not be desirable.

It does not imply that clients process operations in the same order.

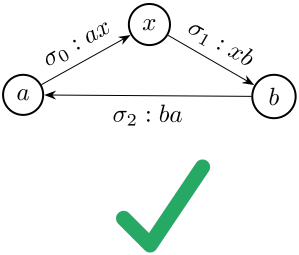
$$\forall \sigma, \sigma' : a, b \in \sigma \cap \sigma' \implies (a \prec_\sigma b \iff a \prec_{\sigma'} b)$$

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

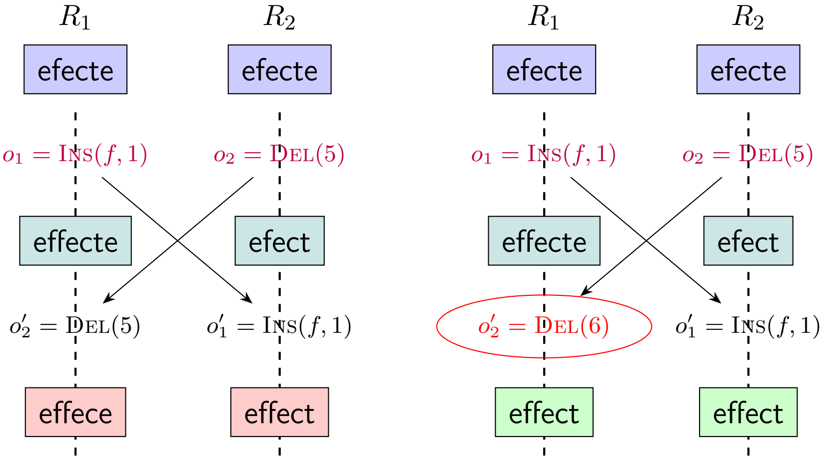
$\boxed{\sigma_0 : ab}$ $\boxed{\sigma_1 : ba}$



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



OT (Operational Transformation) [Ellis and Gibbs, 1989]



OT functions for a replicated list object [Ellis and Gibbs, 1989]

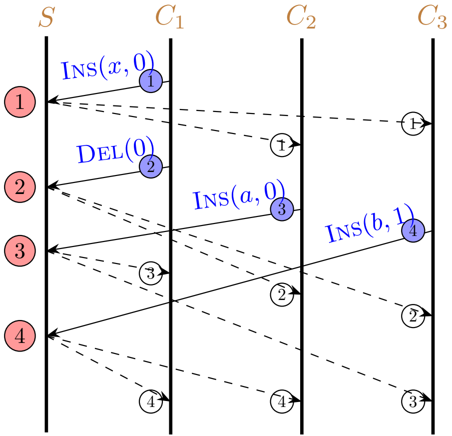
$$OT\Big(\textsc{Ins}(a_1, p_1, pr_1), \textsc{Ins}(a_2, p_2, pr_2)\Big) = \begin{cases} \textsc{Ins}(a_1, p_1, pr_1) & p_1 < p_2 \\ \textsc{Ins}(a_1, p_1 + 1, pr_1) & p_1 > p_2 \\ \text{NOP} & p_1 = p_2 \wedge a_1 = a_2 \\ \textsc{Ins}(a_1, p_1 + 1, pr_1) & p_1 = p_2 \wedge a_1 \neq a_2 \wedge pr_1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

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

$$OT\Big(\textsc{Del}(\_, p_1, pr_1), \textsc{Ins}(a_2, p_2, pr_2)\Big) = \begin{cases} \textsc{Del}(\_, p_1, pr_1) & p_1 < p_2 \\ \textsc{Del}(\_, p_1 + 1, pr_1) & p_1 \geq p_2 \end{cases}$$

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

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



Theorem (Equivalence of CJupiter and Jupiter)

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

At the server side:

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

The single n-ary ordered state space at the server side in CJupiter is a compact representation of n $2D$ state spaces at the server side in Jupiter.

At the client side:

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

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