Specification and Implementation of Replicated List: The Jupiter Protocol Revisited

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Abstract

The replicated list object is frequently used to model the core functionality of replicated collaborative text editing systems. Since 1989, the convergence property has been a common specification of a replicated list object. Recently, Attiya et al. proposed the strong/weak list specification and conjectured that the well-known Jupiter protocol satisfies the weak list specification. The major obstacle to proving this conjecture is the mismatch between the global property on all replica states prescribed by the specification and the local view each replica maintains in Jupiter using data structures like 1D buffer or 2D state space. To address this issue, we propose CJupiter (Compact Jupiter) based on a novel data structure called \( n \)-ary ordered state space for a replicated client/server system with \( n \) clients. At a high level, CJupiter maintains only a single \( n \)-ary ordered state space which encompasses exactly all states of each replica. We prove that CJupiter and Jupiter are equivalent and that CJupiter satisfies the weak list specification, thus solving the conjecture above.

2012 ACM Subject Classification
Computing methodologies → Distributed computing methodologies, Software and its engineering → Correctness, Human-centered computing → Collaborative and social computing systems and tools

Keywords and phrases
Collaborative text editing systems, Replicated list, Concurrency control, Strong/weak list specification, Operational transformation, Jupiter protocol

Digital Object Identifier 10.4230/LIPIcs.OPODIS.2018.0

Related Version
A full version is available at https://arxiv.org/abs/1708.04754 [25].

Funding
This work is supported by the National 973 Program of China (No. 2015CB352202) and the National Natural Science Foundation of China (No. 61690204, 61702253).

1 Introduction

Collaborative text editing systems, like Google Docs [2], Apache Wave [1], or wikis [11], allows multiple users to concurrently edit the same document. For availability, such systems often replicate the document at several replicas. For low latency, replicas are required to
respond to user operations immediately without any communication with others and updates are propagated asynchronously.

The replicated list object has been frequently used to model the core functionality (e.g., insertion and deletion) of replicated collaborative text editing systems [8, 13, 26, 5]. A common specification of a replicated list object is the convergence property, proposed by Ellis et al. [8]. It requires the final lists at all replicas be identical after executing the same set of user operations. Recently, Attiya et al. [5] proposed the strong/weak list specification. Beyond the convergence property, the strong/weak list specification specifies global properties on intermediate states going through by replicas. Attiya et al. [5] have proved that the existing RGA protocol [16] satisfies the strong list specification. Meanwhile, it is conjectured that the well-known Jupiter protocol [13, 26], which is behind Google Docs [3] and Apache Wave [4], satisfies the weak list specification.

Jupiter adopts a centralized server replica for propagating updates 2, and client replicas are connected to the server replica via FIFO channels; see Figure 1. Jupiter relies on the technique of operational transformations (OT) [8, 20] to achieve convergence. The basic idea of OT is for each replica to execute any local operation immediately and to transform a remote operation so that it takes into account the concurrent operations previously executed at the replica. Consider a replicated list system consisting of replicas $R_1$ and $R_2$ which initially hold the same list (Figure 2). Suppose that user 1 invokes $o_1 = \text{Ins}(f, 1)$ at $R_1$ and concurrently user 2 invokes $o_2 = \text{Del}(5)$ at $R_2$. After being executed locally, each operation is sent to the other replica. Without OT (Figure 2a), the states of two replicas diverge. With the OT of $o_1$ and $o_2$ (Figure 2b), $o_2$ is transformed to $o_2' = \text{Del}(6)$ at $R_1$, taking into account the fact that $o_1$ has inserted an element at position 1. Meanwhile, $o_1$ remains unchanged. As a result, two replicas converge to the same list. We note that although the idea of OT is straightforward, many OT-based protocols for replicated list are hard to understand and some of them have even been shown incorrect with respect to convergence [8, 20, 22].

The major obstacle to proving that Jupiter satisfies the weak list specification is the mismatch between the global property on all states prescribed by such a specification and the local view each replica maintains in the protocol. On the one hand, the weak list specification requires that states across the system are pairwise compatible [5]. That is, 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. On the other hand, Jupiter uses data structures like 1D buffer [18] or 2D state space [13, 26] which are not “compact” enough to capture all replica states in one. In particular, Jupiter maintains $2n$ 2D state spaces for a system with $n$ clients [26]: Each client maintains a single state space which is synchronized with those of other clients via its counterpart state space maintained by the server. Each 2D state space of a client (as well as its counterpart at the server) consists of a local dimension and a global dimension, keeping track of the operations processed by the client itself and the others, respectively. In this way, replica states of Jupiter are dispersed in multiple 2D state spaces maintained locally at individual replicas.

To resolve the mismatch, we propose CJupiter (Compact Jupiter), a variant of Jupiter, which uses a novel data structure called $n$-ary ordered state space for a system with $n$ clients. CJupiter is compact in the sense that at a high level, it maintains only a single $n$-ary ordered state space which encompasses exactly all states of each replica. Each replica behavior

\[\text{Since replicas are required to respond to user operations immediately, the client/server architecture does not imply that clients process operations in the same order.}\]

\[\text{The details about Figure 1 will be described in Examples 4 and 13.}\]
corresponds to a path going through this state space. This makes it feasible for us to reason about global properties and finally prove that Jupiter satisfies the weak list specification, thus solving the conjecture of Attiya et al. The roadmap is as follows:

- (Section 3) We propose C-Jupiter based on the \( n \)-ary ordered state space data structure.
- (Section 4) We prove that C-Jupiter is equivalent to Jupiter in the sense that the behaviors of corresponding replicas of these two protocols are the same under the same schedule of operations. Jupiter is slightly optimized in implementation at clients (but not at the server) by eliminating redundant OTs, which, however, has obscured the similarities among clients and led to the mismatch discussed above.
- (Section 5) We prove that C-Jupiter satisfies the weak list specification. Thanks to the “compactness” of C-Jupiter, we are able to focus on a single \( n \)-ary ordered state space which provides a global view of all possible replica states.

Section 2 presents preliminaries on specifying replicated list data type and OT. Section 6 describes related work. Section 7 concludes the paper. The full paper [25] contains proofs and pseudocode.

2 Preliminaries: Replicated List and Operational Transformation

We describe the system model and specifications of replicated list in the framework for specifying replicated data types [7, 6, 5].

2.1 System Model

A highly-available replicated data store consists of replicas that process user operations on the replicated objects and communicate updates to each other with messages. To be highly-available, replicas are required to respond to user operations immediately without any communication with others. A replica is defined as a state machine \( R = (\Sigma, \sigma_0, E, \Delta) \), where 1) \( \Sigma \) is a set of states; 2) \( \sigma_0 \in \Sigma \) is the initial state; 3) \( E \) is a set of possible events; and 4) \( \Delta : \Sigma \times E \rightarrow \Sigma \) is a transition function. The state transitions determined by \( \Delta \) are local
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steps of a replica, describing how it interacts with the following three kinds of events from users and other replicas:

- \texttt{do(o, v)}: a user invokes an operation \( o \in \mathcal{O} \) on the replicated object and immediately receives a response \( v \in \text{Val} \). We leave the users unspecified and say that the replica generates the operation \( o \).
- \texttt{send(m)}: the replica sends a message \( m \) to some replicas; and
- receive\( (m) \): the replica receives a message \( m \).

A protocol is a collection \( \mathcal{R} \) of replicas. An execution \( \alpha \) of a protocol \( \mathcal{R} \) is a sequence of all events occurring at the replicas in \( \mathcal{R} \). We denote by \( R(e) \) the replica at which an event \( e \) occurs. For an execution (or generally, an event sequence) \( \alpha \), we denote by \( e \prec_\alpha e' \) (or \( e \prec e' \)) that \( e \) precedes \( e' \) in \( \alpha \). An execution \( \alpha \) is \textit{well-formed} if for every replica \( R \): 1) the subsequence of events \( \langle e_1, e_2, \ldots \rangle \) at \( R \), denoted \( \alpha|_R \), is well-formed, namely there is a sequence of states \( \langle \sigma_1, \sigma_2, \ldots \rangle \), such that \( \sigma_i = \Delta(\sigma_{i-1}, e_i) \) for all \( i \); and 2) every receive\( (m) \) event at \( R \) is preceded by a send\( (m) \) event in \( \alpha \). We consider only well-formed executions.

We are often concerned with replica behaviors and states when studying a protocol. The \textit{behavior} of replica \( R \) in \( \alpha \) is a sequence of the form: \( \sigma_0, e_1, \sigma_1, e_2, \ldots \), where \( \langle e_1, e_2, \ldots \rangle = \alpha|_R \) and \( \sigma_i = \Delta(\sigma_{i-1}, e_i) \) for all \( i \). A replica state \( \sigma \) of \( R \) in \( \alpha \) can be represented by the events in a prefix of \( \alpha|_R \) it has processed. Specifically, \( \sigma_0 = \emptyset \) and \( \sigma_i = \sigma_{i-1} \circ e_i = \langle e_1, e_2, \ldots, e_i \rangle \).

We now define the causally-before, concurrent, and totally-before relations on events in an execution. When restricted to the do events only, they define relations on user operations. In an execution \( \alpha \), event \( e \) is \textit{causally before} \( e' \), denoted \( e \hbox{hbox} e' \) (or \( e \hbox{hb} e' \)), if one of the following conditions holds \cite{10}: 1) Thread of execution: \( R(e) = R(e') \land e \prec_\alpha e' \); 2) Message delivery: \( e = \text{send}(m) \land e' = \text{receive}(m) \); 3) Transitivity: \( \exists e'' \in \alpha: e \hbox{hb} e'' \land e'' \hbox{hb} e' \).

Events \( e, e' \in \alpha \) are \textit{concurrent}, denoted \( e \parallel \alpha e' \) (or \( e \parallel e' \)), if it is neither \( e \hbox{hb} e' \) nor \( e' \hbox{hb} e \). A relation on events in an execution \( \alpha \), denoted \( e \hbox{tb} e' \) (or \( e \hbox{tb} e' \)), is a \textit{totally-before} relation consistent with the causally-before relation \( e \hbox{hb} e' \) on events in \( \alpha \) if it is total: \( \forall e, e' \in \alpha: e \hbox{hb} e' \lor e' \hbox{hb} e \), and it is consistent: \( \forall e, e' \in \alpha: e \hbox{hb} e' \Longrightarrow e \hbox{tb} e' \).

2.2 Specifying Replicated Objects

A replicated object is specified by a set of abstract executions which record user operations (corresponding to do events) and visibility relations on them \cite{7}. An abstract execution is a pair \( A = (H, \text{vis}) \), where \( H \) is a sequence of do events and \( \text{vis} \subseteq H \times H \) is an acyclic \textit{visibility} relation such that 1) if \( e_1 \prec_H e_2 \) and \( R(e_1) = R(e_2) \), then \( e_1 \hbox{vis} e_2 \); 2) if \( e_1 \hbox{vis} e_2 \), then \( e_1 \prec_H e_2 \); and 3) \( \text{vis} \) is transitive: \( e_1 \hbox{vis} e_2 \land e_2 \hbox{vis} e_3 \Longrightarrow e_1 \hbox{vis} e_3 \).

An abstract execution \( A' = (H', \text{vis}') \) is a prefix of another abstract execution \( A = (H, \text{vis}) \) if \( H' \) is a prefix of \( H \) and \( \text{vis}' = \text{vis} \cap (H' \times H') \). A specification \( \mathcal{S} \) of a replicated object is a prefix-closed set of abstract executions, namely if \( A \in \mathcal{S} \), then \( A' \in \mathcal{S} \) for every prefix \( A' \) of \( A \). A protocol \( \mathcal{R} \) \textit{satisfies} a specification \( \mathcal{S} \), denoted \( \mathcal{R} \models \mathcal{S} \), if any (concrete) execution \( \alpha \) of \( \mathcal{R} \) \textit{complies with} some abstract execution \( A = (H, \text{vis}) \) in \( \mathcal{S} \), namely \( \forall R \in \mathcal{R}: H|_R = \alpha|_{\mathcal{R}} \), where \( \alpha|_{\mathcal{R}} \) is the subsequence of do events of replica \( R \) in \( \alpha \).

2.3 Replicated List Specification

A replicated list object supports three types of user operations \cite{5} (\( U \) for some universe):

- \texttt{INS(a, p)}: inserts \( a \in U \) at position \( p \in \mathbb{N} \) and returns the updated list. For \( p \) larger than the list size, we assume an insertion at the end. We assume that all inserted elements are unique, which can be achieved by attaching replica identifiers and sequence numbers.
We also write \( \sigma \) ensure the convergence property, OT functions are required to satisfy CP1 (Convergence Property) \([8]\). Given two operations \( o_1 \) and \( o_2 \), if \( o_1 \cdot o_2 = \sigma \), then \( \sigma; o_1; o_2 = o_2; o_1 \) should hold, meaning that the same state is obtained by applying \( o_1 \) and \( o_2 \) in sequence, and applying \( o_1 \) and \( o_2 \) in sequence, on the same initial state \( \sigma \). A set of OT functions satisfying CP1 for a replicated list object \([8, 9, 22]\) can be found in Figure A.1 of \([25]\).

Example 2 (Weak List Specification). In the execution depicted in Figure 1 (produced by CJupiter), there exist three states with list contents \( w_1 = ba \), \( w_2 = ax \), and \( w_3 = xb \), respectively. This is allowed by the weak list specification with the list order \( lo \): \( b \xrightarrow{l} a \) on \( w_1 \), \( a \xrightarrow{l} x \) on \( w_2 \), and \( x \xrightarrow{l} b \) on \( w_3 \). However, an execution is not allowed by the weak list specification if it contained two states with, say \( w = ab \) and \( w' = ba \).
3 The CJupiter Protocol

In this section we propose CJupiter (Compact Jupiter) for a replicated list based on the data structure called n-ary ordered state space. Like Jupiter, CJupiter also adopts a client/server architecture. For convenience, we assume that the server does not generate operations [26, 5]. It mainly serializes operations and propagates them from one client to others. We denote by ‘≺s’ the total order on the set of operations established by the server. Note that ‘≺s’ is consistent with the causally-before relation ‘hb≺’. To facilitate the comparison of Jupiter and CJupiter, we refer to ‘hb≺’ and ‘≺s’ together as the schedule of operations.

3.1 Data Structure: n-ary Ordered State Space

For a client/server system with n clients, CJupiter maintains (n + 1) n-ary ordered state spaces, one per replica (CSS, for the server and CSSci, for client ci). Each CSS is a directed graph whose vertices represent states and edges are labeled with operations; see Appendix B.1 of [25].

An operation op of type Op is a tuple op = (o, oid, ctx, sctx), where 1) o is the signature of type O described in Section 2.3; 2) oid is a globally unique operation identifier which is a pair (oid, seq) consisting of the client id and a sequence number; 3) ctx is an operation context which is a set of oids, denoting the operations that are causally before op; and 4) sctx is a set of oids, denoting the operations that, as far as op knows, have been executed before op at the server. At a given replica, sctx is used to determine the total order ‘≺s’ relation between two operations as in Algorithm B.1 of [25].

The OT function of two operations op, op’ ∈ Op, denoted (op(opp) : Op, op′(opp) : Op) = OT(op, op′), is defined based on that of op, op′, o ∈ O, denoted (o, o′) = OT(op, op′, o), such that op(opp) = (o, op.oid, op.ctx ∪ {op’.oid}, op.sctx) and op′(opp) = (o′, op’.oid, op’.ctx ∪ {op.oid}, op’.sctx).

A vertex v of type Vertex is a pair v = (oids, edges), where oids is the set of operations (represented by their identifiers) that have been executed, and edges is an ordered set of edges of type Edge from v to other vertices, labeled with operations. That is, each edge is a pair (op : Op, v : Vertex). Edges from the same vertex are totally ordered by their op components. For each vertex v and each edge e = (op, u) from v to u, it is required that
- the ctx of op associated with e matches the oids of v: op.ctx = v.oids;
- the oids of u consists of the oids of v and the oid of op: u.oids = v.oids ∪ {op.oid}.

Definition 3 (n-ary Ordered State Space). An n-ary ordered state space is a set of vertices such that
1. Vertices are uniquely identified by their oids.
2. For each vertex u with |u.edges| ≥ 2, let u’ be its child vertex along the first edge euv = (op’, u’) and v another child vertex along ewv = (op, v). There exist (Figure 3)
   - a vertex v’ with v’.oids = u.oids ∪ {op’.oid, op.oid};
   - two edges euv’ = (op(op’), v’) from u’ to v’ and ewv’ = (op(op), v’) from v to v’.

The second condition models OTs in CJupiter described in Section 3.2, and the choice of the “first” edge is justified in Lemmas 5 and 7.

3.2 The CJupiter Protocol

Each replica in CJupiter maintains an n-ary ordered state space S and keeps the most recent vertex cur (initially (0, 0)) of S. Following [26], we describe CJupiter in three parts; see
Figure 3 Illustration of an OT of two operations op, op′ in both the n-ary ordered state space of CJupiter and the 2D state space of Jupiter: (op(op′), op′(op)) = OT(op, op′). In the CJupiter and Jupiter protocols (and Examples 4 and 13), op corresponds to the new incoming operation to be transformed.

Figure 4 The same final n-ary ordered state space (thus for CSS, and each CSSc) constructed by CJupiter for each replica under the schedule of Figure 1. Each replica behavior (i.e., the sequence of state transitions) corresponds to a path going through this state space.

Appendix B.2 of [25] for pseudocode.

Local Processing Part. When a client receives an operation o ∈ O from a user, it
1. applies o locally, obtaining a new list val ∈ Val;
2. generates op ∈ Op by attaching to o a unique operation identifier and the operation context S.cur.oids, representing the set of operations that are causally before op;
3. creates a vertex v with v.oids = S.cur.oids ∪ {op.oid}, appends v to S by linking it to S.cur via an edge labeled with op, and updates cur to be v;
4. sends op to the server asynchronously and returns val to the user.

Server Processing Part. To establish the total order ‘≺’ on operations, the server maintains the set soids of operations it has executed. When the server receives an operation op ∈ Op from client ci, it
1. updates op.sctx to be soids and updates soids to include op.oid;
2. transforms op with an operation sequence in S to obtain op′ by calling S.xForm(op) (see below), and applies op′ (specifically, op′.o) locally;
3. sends op (instead of op′) to other clients asynchronously.

Remote Processing Part. When a client receives an operation op ∈ Op from the server, it transforms op with an operation sequence in S to obtain op′ by calling S.xForm(op) (see below), and applies op′ (specifically, op′.o) locally.

OTs in CJupiter. The procedure S.xForm(op : Op) transforms op with an operation sequence in an n-ary ordered state space S. Specifically, it
1. locates the vertex u whose oids matches the ctx of op, i.e., u.oids = op.ctx 4, and creates a vertex v with v.oids = u.oids ∪ {op.oid};

4 The vertex u exists due to the FIFO communication between the clients and the server.
2. **first** edges from $u$ to the final vertex $cur$ of $S$ (Figure 3):
   a. obtains the vertex $u'$ and the operation $op'$ associated with the first edge of $u$;
   b. transforms $op$ with $op'$ to obtain $op(op')$ and $op'(op)$;
   c. creates a vertex $v'$ with $v'.oids = v.oids \cup \{op'.oid\}$;
   d. links $v'$ to $v$ via an edge labeled with $op'(op)$ and $v$ to $u$ via an edge labeled with $op$;
   e. updates $u$, $v$, and $op$ to be $u'$, $v'$, and $op(op')$, respectively;
3. when $u$ is the final vertex $cur$ of $S$, links $v$ to $u$ via an edge labeled with $op$, updates $cur$ to be $v$, and returns the last transformed operation $op$.

To keep track of the construction of the $n$-ary ordered state spaces in C Jupiter, for each state space, we introduce a superscript $k$ to refer to the one after the $k$-th step (i.e., after processing $k$ operations), counting from 0. For instance, the state space CSS$_{c_1}$ (resp. CSS$_s$) after the $k$-th step maintained by client $c_i$ (resp. the server $s$) is denoted by CSS$_{c_i}^k$ (resp. CSS$_s^k$). This notational convention also applies to Jupiter (reviewed in Section 4.1).

**Example 4 (Illustration of C Jupiter).** Figure 5 illustrates client $c_3$ in C Jupiter under the schedule of Figure 1. For convenience, we denote, for instance, a vertex $v$ with $v.oids = \{o_1, o_2\}$ by $v_{14}$ and an operation $o_3$ with $o_3.ctx = \{o_1, o_2\}$ by $o_3\{o_1, o_2\}$. We have also mixed the notations of operations of types $\mathcal{O}$ and $\mathcal{Op}$ when no confusion arises. We map various vertices and operations in this example to the ones (i.e., $u$, $u'$, $v$, $v'$, $op$, $op'$) used in the description of the C Jupiter protocol.

After receiving and applying $o_1 = \text{Ins}(x, 0)$ of client $c_1$ from the server, client $c_3$ generates $o_4 = \text{Ins}(b, 1)$. It applies $o_4$ locally, creates a new vertex $v_{14}$, and appends it to CSS$_{c_3}^1$ via an edge from $v_1$ labeled with $o_4\{o_1\}$. Then, $o_4\{o_1\}$ is propagated to the server.

Next, client $c_3$ receives $o_2 = \text{Del}(x, 0)$ of client $c_1$ from the server. The operation context of $o_2$ is $\{o_1\}$, matching the $oids$ of $v_1$ ($u$). By $\text{XFORM}$, $o_2\{o_1\}(op)$ is transformed with $o_4\{o_1\}(op')$: $\text{OT}(o_2\{o_1\} = \text{Del}(x, 0), o_4\{o_1\} = \text{Ins}(b, 1)) = \left(\left(o_2\{o_1, o_4\} = \text{Del}(x, 0), o_4\{o_1, o_2\} = \text{Ins}(b, 0)\right)\right)$. As a result, $v_{24}'(v')$ is created and is linked to $v_{12}'(v)$ and $v_{14}'(u')$ via the edges labeled with $o_4\{o_1, o_2\}$ and $o_2\{o_1, o_4\}$, respectively. Because $o_2$ is unaware of $o_4$ at the server...
\((o_4. setx = \emptyset \) now), the edge from \( v_1 \) to \( v_{12} \) is ordered before (to the left of) that from \( v_1 \) to \( v_{14} \) in CSS\(_3^s\).

Finally, client \( c_3 \) receives \( o_3\{o_1\} = \text{Ins}(a, 0) \) of client \( c_2 \) from the server. The operation context of \( o_3 \) is \( \{o_1\} \), matching the \( \text{oids} \) of \( v_1 \) (\( u \)). By \text{XFORM}, \( o_3\{o_1\} \) will be transformed with the operation sequence consisting of operations along the first edges from \( v_1 \) to the final vertex \( v_{124} \) of CSS\(_3^s\), namely \( o_2\{o_1\} \) from \( v_1 \) and \( o_4\{o_1, o_2\} \) from \( v_{12} \). Specifically, \( o_3\{o_1\} \) (\( \text{op} \)) is first transformed with \( o_2\{o_1\} \) (\( \text{op}' \)): \( \text{OT}(o_3\{o_1\}) = \text{Ins}(a, 0), o_2\{o_1\} = \text{Del}(x, 0) \) = \( \left(o_3\{o_1, o_2\} = \text{Ins}(a, 0), o_2\{o_1, o_3\} = \text{Del}(x, 1)\right)\). Since \( o_3 \) is aware of \( o_2 \) but unaware of \( o_4 \) at the server, the new edge from \( v_1 \) labeled with \( o_3\{o_1\} \) is placed before that with \( o_4\{o_1\} \) but after that with \( o_2\{o_1\} \). Then, \( o_3\{o_1, o_2\} \) (\( \text{op} \)) is transformed with \( o_4\{o_1, o_2\} \) (\( \text{op}' \)), yielding \( v_{1234} \) and \( o_3\{o_1, o_2, o_4\} \). Client \( c_3 \) applies \( o_3\{o_1, o_2, o_4\} \), obtaining the list context \( ba \).

The choice of the “first” edges in OTs is necessary to establish equivalence between CJupiter and Jupiter, particularly at the server side. First, the operation sequence along the first edges from a vertex of CSS at the server admits a simple characterization.

\[ \text{Lemma 5} \; (\text{CJupiter’s “First” Rule}). \; \text{Let } OP = (o_{p_1}, o_{p_2}, \ldots, o_{p_m}) \; (o_i \in Op) \text{ be the operation sequence the server has currently processed in total order } \prec_s \text{. For any vertex } v \text{ in the current CSS}_s, \text{ the path along the first edges from } v \text{ to the final vertex of } CSS_s \text{ consists of the operations of } OP \setminus v \text{ in total order } \prec_s \text{ (may be empty if } v \text{ is the final vertex of } CSS_s), \text{ where} \]

\[ OP \setminus v = \{ op \in OP \mid op.oid \in \{o_{p_1}.oid, o_{p_2}.oid, \ldots, o_{p_m}.oid\} \setminus v.oids \}. \]

\[ \text{Example 6} \; (\text{CJupiter’s “First” Rule}). \; \text{Consider CSS}_s \text{ at the server shown in Figure 4 under the schedule of Figure 1; see Figure B.1a of [25] for its construction. Suppose that the server has processed all four operations. That is, we take } OP = \{o_1, o_2, o_3, o_4\} \text{ in Lemma 5 (we mix operations of types } O \text{ and } OP). \text{ Then, the path along the first edges from vertex } v_1 \text{ (resp. } v_{13} \text{) consists of the operations } OP \setminus v_1 = \{o_2, o_3, o_4\} \text{ (resp. } OP \setminus v_{13} = \{o_2, o_4\} \text{) in total order } \prec_s \text{.} \]

Based on Lemma 5, the operation sequence with which an operation transforms at the server can be characterized as follows, which is exactly the same with that for Jupiter [26].

\[ \text{Lemma 7} \; (\text{CJupiter’s OT Sequence}). \; \text{In } \text{XFORM} \text{ of CJupiter, the operation sequence } L \text{ (may be empty) with which an operation } op \text{ transforms at the server consists of the operations that are both totally ordered by } \prec_s \text{ before and concurrent by } \parallel \text{ with } op. \text{ Furthermore, the operations in } L \text{ are totally ordered by } \prec_s \text{.} \]

\[ \text{Example 8} \; (\text{CJupiter’s OT Sequence}). \; \text{Consider the behavior of the server summarized in Figure 4 under the schedule of Figure 1. According to Lemma 5, the operation sequence with which } op = o_1 \text{ transforms consists of operations } o_2 \text{ (i.e., } o_2\{o_1\}) \text{ from vertex } v_1 \text{ and } o_3 \text{ (i.e., } o_3\{o_1, o_2\}) \text{ from vertex } v_{12} \text{ in total order } \prec_s \text{, which are both totally ordered by } \prec_s \text{ before and concurrent by } \parallel \text{ with } o_4. \]

### 3.3 CJupiter is Compact

Although \( (n + 1) \)-ary ordered state spaces are maintained by CJupiter for a system with \( n \) clients, they are all the same. That is, at a high level, CJupiter maintains only a single \( n \)-ary ordered state space.
Proposition 9 \((n + 1 \Rightarrow 1)\). In CJupiter, the replicas that have processed the same set of operations (in terms of their oids) have the same \(n\)-ary ordered state space.

Informally, this proposition holds because we have kept all “by-product” states/vertices of OTs in the \(n\)-ary ordered state spaces, and each client is “synchronized” with the server. Since all replicas will eventually process all operations, the final \(n\)-ary ordered state spaces at all replicas are the same. The construction order may differ replica by replica.

Example 10 (CJupiter is Compact). Figure 4 shows the same final \(n\)-ary ordered state space constructed by CJupiter for each replica under the schedule of Figure 1. (Figure B.1 of [25] shows the step-by-step construction for each replica.) Each replica behavior (i.e., the sequence of state transitions) corresponds to a path going through this state space. As illustrated, the server \(s\) and client \(c_1\) go along the path \(v_0 \overset{a_1}{\rightarrow} v_1 \overset{a_2}{\rightarrow} v_{12} \overset{a_3}{\rightarrow} v_{123} \overset{a_4}{\rightarrow} v_{1234}\), client \(c_2\) goes along the path \(v_0 \overset{a_1}{\rightarrow} v_1 \overset{a_3}{\rightarrow} v_{13} \overset{a_2}{\rightarrow} v_{123} \overset{a_4}{\rightarrow} v_{1234}\), and client \(c_3\) goes along the path \(v_0 \overset{a_1}{\rightarrow} v_1 \overset{a_4}{\rightarrow} v_{14} \overset{a_2}{\rightarrow} v_{124} \overset{a_3}{\rightarrow} v_{1234}\).

Together with the fact that the OT functions satisfy CP1, Proposition 9 implies that

Theorem 11 (CJupiter \(= \mathcal{A}_{cp}\)). CJupiter satisfies the convergence property \(\mathcal{A}_{cp}\).

CJupiter is Equivalent to Jupiter

We now prove that CJupiter is equivalent to Jupiter (reviewed in Section 4.1) from perspectives of both the server and clients. Specifically, we prove that the behaviors of the servers are the same (Section 4.2), and that the behaviors of each pair of corresponding clients are the same (Section 4.3). Consequently, we have that

Theorem 12 (Equivalence). Under the same schedule, the behaviors (Section 2.1) of corresponding replicas in CJupiter and Jupiter are the same.

4 Review of Jupiter

We review the Jupiter protocol in [26], a multi-client description of Jupiter first proposed in [13] \(^5\). Consider a client/server system with \(n\) clients. Jupiter [26] maintains \(2n\) 2D state spaces (Appendix C.1 of [25]), each consisting of a local dimension and a global dimension. Specifically, each client \(c_i\) maintains a 2D state space, denoted \(\text{DSS}_{c_i}\), with the local dimension for operations generated by the client and the global dimension by others. The server maintains \(n\) 2D state spaces, one for each client. The state space for client \(c_i\), denoted \(\text{DSS}_{si}\), consists of the local dimension for operations from client \(c_i\) and the global dimension from others.

Jupiter is similar to CJupiter with two major differences: First, in \(\text{XFORM}(op : Op, d \in \{\text{LOCAL}, \text{GLOBAL}\})\) of Jupiter, the operation sequence with which \(op\) transforms is determined by the parameter \(d\), indicating the local/global dimension described above (instead of following the first edges as in CJupiter). Second, in Jupiter, the server propagates the transformed operation (instead of the original one it receives) to other clients. As with CJupiter, we describe Jupiter in three parts. We omit the details that are in common with and have been explained in CJupiter; see Appendix C.2 of [25] for pseudocode.

\(^5\) The Jupiter protocol in [13] uses 1D buffers, but does not explicitly describe the multi-client scenario.
As shown in [26] (see the “Jupiter” section and Definition 8 of [26]), the operation sequence with which an incoming operation transforms while Jupiter does. Third, because the transformed operations are propagated by the server, Jupiter is slightly optimized in implementation due to the operation sequence consisting of OTs in Jupiter. In the procedure XFORM(op, GLOBAL) (see below), and applies op’ locally. 

Remote Processing Part. When client \( c_3 \) receives an operation \( op \in Op \) from client \( c_i \), it first transforms \( op \) with an operation sequence along the global dimension in \( DSS_{s_i} \). For each \( j \neq i \), it saves \( op' \) at the end of \( DSS_{s_j} \) along the global dimension. Finally, \( op' \) (instead of \( op \)) is sent to other clients asynchronously.

We highlight three differences between CJupiter and Jupiter, by comparing the behaviors of \( c_3 \) in this example and Example 4. First, the fourth operation the server \( s \) transforms \( c_3 \) and \( c_2 \) are the same with those in CJupiter; see CSS\(^3\), CSS\(^2\), and CSS\(^1\) of Figure 5 and \( DSS_{s_2} \), \( DSS_{s_3} \), and \( DSS_{s_4} \) of Figure 6.

We now elaborate on the fourth state transition of client \( c_3 \) in Jupiter. First, client \( c_2 \) propagates its operation \( o_3 \{ o_1 \} = \text{INS}(a, 0) \) to the server \( s \). At the server, \( o_3 \{ o_1 \} \) is stored in \( DSS_{s_2} \), obtaining \( o_3 \{ o_1, o_2 \} = \text{INS}(a, 0) \). In addition to being stored, the transformed operation \( o_3 \{ o_1, o_2 \} \) is then redirected by the server to clients \( c_1 \) and \( c_3 \). At client \( c_3 \), the operation context of \( o_3 \{ o_1, o_2 \} \) (i.e., \( o_3 \{ o_1, o_2 \} \)) matches the operation context \( op' \) of \( op \), and then iteratively transforms \( op \) with an operation sequence along the \( d \) dimension from \( u \) to the final vertex of this 2D state space.

Example 13 (Illustration of Jupiter). Figure 6 illustrates client \( c_3 \), as well as the server \( s \), in Jupiter under the schedule of Figure 1. The first three state transitions made by client \( c_3 \) in Jupiter due to the operation sequence consisting of \( o_1 \) from client \( c_1 \), \( o_4 \) generated by itself, and \( o_2 \) from client \( c_1 \) are the same with those in CJupiter; see CSS\(^3\), CSS\(^2\), and CSS\(^1\) of Figure 5 and \( DSS_{s_2} \), \( DSS_{s_3} \), and \( DSS_{s_4} \) of Figure 6.

4.2 The Servers Established Equivalent

As shown in [26] (see the “Jupiter” section and Definition 8 of [26]), the operation sequence with which an incoming operation transforms at the server in XFORM of Jupiter can be characterized exactly as in XFORM of CJupiter (Lemma 7). By mathematical induction on

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\( \text{\footnotesize \(^6 \)} \) Although they happen to have the same signature \( \text{INS}(a, 0) \), they have different operation contexts.
the operation sequence the server processes, we can prove that the state spaces of Jupiter and CJupiter at the server are essentially the same. Formally, the \(n\)-ary ordered state space \(CSS_s\) of CJupiter equals the union \(^7\) of all 2D state spaces \(DSS_{ci}\) maintained at the server for each client \(c_i\) in Jupiter. For example, \(CSS_s\) of Figure 4 is the union of the three \(DSS_{ci}\)'s of Figure 6. More specifically, we have

\[CSS_s = \bigcup_{i=1}^{k} DSS_{ci(op)} = \bigcup_{c_i \in c(O)} \bigcup_{j=1}^{k} DSS_{ci}^j, \quad 1 \leq k \leq m,\]

where \(c(op)\) denotes the client that generates the operation \(op\) (more specifically, \(op_i.o\) and

\(^7\) The union is taken on state spaces which are (directed) graphs as sets of vertices and edges. The order of edges of \(n\)-ary ordered state spaces should be respected when \(DSS_{ci}\)'s are unioned to obtain \(CSS_s\).
\( c(O) = \{c(op_1), c(op_2), \ldots, c(op_m)\}. \)

The equivalence of servers are thus established.

\textbf{Theorem 15 (Equivalence of Servers).} Under the same schedule, the behaviors (i.e., the sequence of (list) state transitions, defined in Section 2.1) of the servers in CJupiter and Jupiter are the same.

4.3 The Clients Established Equivalent

As discussed in Example 13, Jupiter is slightly optimized in implementation at clients by eliminating redundant OTs. Formally, by mathematical induction on the operation sequence client \( c_i \) processes, we can prove that \( DSS_{c_i}^k \) of Jupiter is a part (i.e., subgraph) of \( CSS_{c_i}^k \) of CJupiter. The equivalence of clients follows since the final transformed operations (for an original one) executed at \( c_i \) in Jupiter and CJupiter are the same, regardless of the optimization adopted by Jupiter at clients.

\textbf{Proposition 16 (1↔1).} Under the same schedule, we have that

\[
DSS_{c_i}^k \subseteq CSS_{c_i}^k, \quad 1 \leq i \leq n, \quad k \geq 1.
\]

\textbf{Theorem 17 (Equivalence of Clients).} Under the same schedule, the behaviors (Section 2.1) of each pair of corresponding clients in CJupiter and Jupiter are the same.

5 CJupiter Satisfies the Weak List Specification

The following theorem, together with Theorem 12, solves the conjecture of Attiya et al. [5].

\textbf{Theorem 18 (CJupiter |= A_{\text{weak}}).} CJupiter satisfies the weak list specification \( A_{\text{weak}} \).

\textbf{Proof.} For each execution \( \alpha \) of CJupiter, we construct an abstract execution \( A = (H, \text{vis}) \) with \( \text{vis} = \frac{h}{\text{do}} \) (Section 2.1). We then prove the conditions of \( A_{\text{weak}} \) (Definition 1) in the order 1(c), 1(a), 1(b), and 2.

Condition 1(c) follows from the local processing of CJupiter. Condition 1(a) holds due to the FIFO communication and the property of OTs that when transformed in CJupiter, the type and effect of an \( \text{Ins}(a,p) \) (resp. a \( \text{Del}(a,p) \)) remains unchanged (with a trivial exception of being transformed to be NOP), namely to insert (resp. delete) the element \( a \) (possibly at a different position than \( p \)).

To show that \( A = (H, \text{vis}) \) belongs to \( A_{\text{weak}} \), we define the list order relation \( \text{lo} \) in Definition 19 below, and then prove that \( \text{lo} \) satisfies conditions 1(b) and 2 of Definition 1.

\textbf{Definition 19 (List Order ‘lo’).} Let \( \alpha \) be an execution. For \( a, b \in \text{elems}(A) \), \( a \xrightarrow{\text{lo}} b \) if and only if there exists an event \( e \in \alpha \) with returned list \( w \) such that \( a \) precedes \( b \) in \( w \).

By definition, 1) \( \text{lo} \) is transitive and total on \( \{a \mid a \in w\} \) for all events \( e = \text{do}(o, w) \in H; \) and 2) \( \text{lo} \) satisfies 1(b) of Definition 1. The irreflexivity of \( \text{lo} \) can be rephrased in terms of the pairwise state compatibility property.

\textbf{Definition 20 (State Compatibility).} Two list states \( w_1 \) and \( w_2 \) are compatible, if and only if for any two common elements \( a \) and \( b \) of \( w_1 \) and \( w_2 \), their relative orderings are the same in \( w_1 \) and \( w_2 \).
Lemma 21 (Irreflexivity). Let \( \alpha \) be an execution and \( A = (H, vis) \) the abstract execution constructed from \( \alpha \) as described in the proof of Theorem 18. The list order \( \preceq \) based on \( \alpha \) is irreflexive if and only if the list states (i.e., returned lists) in \( A \) are pairwise compatible.

The proof relies on the following lemma about paths in \( n \)-ary ordered state spaces.

Lemma 22 (Simple Path). Let \( P_{v_1\to v_2} \) be a path from vertex \( v_1 \) to vertex \( v_2 \) in an \( n \)-ary ordered state space. Then, there are no duplicate operations (in terms of their oids) along the path \( P_{v_1\to v_2} \). We call such a path a simple path.

Therefore, it remains to prove that all list states in an execution of CJupiter are pairwise compatible, which concludes the proof of Theorem 18. By Proposition 9, we can focus on the state space \( CSS_s \) at the server. We first prove several properties about vertex pairs and paths of \( CSS_s \), which serve as building blocks for the proof of the main result (Theorem 26).

By mathematical induction on the operation sequence processed in the total order \( '\prec_s' \) at the server and by contradiction (in the inductive step), we can show that

Lemma 23 (LCA). In CJupiter, each pair of vertices in the \( n \)-ary ordered state space \( CSS_s \) (as a rooted directed acyclic graph) has a unique LCA (Lowest Common Ancestor).\(^8\)

In the following, we are concerned with the paths to a pair of vertices from their LCA.

Lemma 24 (Disjoint Paths). Let \( v_0 \) be the unique LCA of a pair of vertices \( v_1 \) and \( v_2 \) in the \( n \)-ary ordered state space \( CSS_s \), denoted \( v_0 = LCA(v_1, v_2) \). Then, the set of operations \( O_{v_0\to v_1} \) along a simple path \( P_{v_0\to v_1} \) is disjoint in terms of the operation oids from the set of operations \( O_{v_0\to v_2} \) along a simple path \( P_{v_0\to v_2} \).

The next lemma gives a sufficient condition for two states (vertices) being compatible in terms of disjoint simple paths to them from a common vertex.

Lemma 25 (Compatible Paths). Let \( P_{v_0\to v_1} \) and \( P_{v_0\to v_2} \) be two paths from vertex \( v_0 \) to vertices \( v_1 \) and \( v_2 \), respectively in the \( n \)-ary ordered state space \( CSS_s \). If they are disjoint simple paths, then the list states of \( v_1 \) and \( v_2 \) are compatible.

The desired pairwise state compatibility property follows, when we take the common vertex \( v_0 \) in Lemma 25 as the LCA of the two vertices \( v_1 \) and \( v_2 \) under consideration.

Theorem 26 (Pairwise State Compatibility). Every pair of list states in the state space \( CSS_s \) are compatible.

Proof. Consider vertices \( v_1 \) and \( v_2 \) in \( CSS_s \). 1) By Lemma 23, they have a unique LCA, denoted \( v_0 \); 2) By Lemma 22, \( P_{v_0\to v_1} \) and \( P_{v_0\to v_2} \) are simple paths; 3) By Lemma 24, \( P_{v_0\to v_1} \) and \( P_{v_0\to v_2} \) are disjoint; and 4) By Lemma 25, the list states of \( v_1 \) and \( v_2 \) are compatible.

6 Related Work

Convergence is the main property for implementing a highly-available replicated list object [8, 26]. Since 1989 [8], a number of OT [8]-based protocols have been proposed. These protocols can be classified according to whether they rely on a total order on operations [26]. Various

\(^8\) The LCAs of two vertices \( v_1 \) and \( v_2 \) in a rooted directed acyclic graph is a set of vertices \( V \) such that 1) Each vertex in \( V \) has both \( v_1 \) and \( v_2 \) as descendants; 2) In \( V \), no vertex is an ancestor of another. The uniqueness further requires \( |V| = 1 \).
protocols like Jupiter [13, 26] establish a total order via a central server, a sequencer, or a distributed timestamping scheme [1, 24, 18, 12, 23]. By contrast, protocols like adOPTed [15] rely only on a partial (causal) order on operations [8, 14, 21, 20, 19].

In 2016, Attiya et al. [5] propose the strong/weak list specification of a replicated list object. They prove that the existing CRDT (Conflict-free Replicated Data Types) [17]-based RGA protocol [16] satisfies the strong list specification, and conjecture that the well-known OT-based Jupiter protocol [13, 26] satisfies the weak list specification.

The OT-based protocols typically use data structures like 1D buffer [18], 2D state space [13, 26], or \(N\)-dimensional interaction model [15] to keep track of OTs or choose correct OTs to perform. As a generalization of 2D state space, our \(n\)-ary ordered state space is similar to the \(N\)-dimensional interaction model. However, they are proposed for different system models. In an \(n\)-ary ordered state space, edges from the same vertex are ordered, utilizing the existence of a total order on operations. By contrast, the \(N\)-dimensional interaction model relies only on a partial order on operations. Consequently, the simple characterization of OTs in xForm of CJupiter does not apply in the \(N\)-dimensional interaction model.

7 Conclusion and Future Work

We prove that the Jupiter protocol [13, 26] satisfies the weak list specification [5], thus solving the conjecture recently proposed by Attiya et al. [5]. To this end, we have designed CJupiter based on a novel data structure called \(n\)-ary ordered state space. In the future, we will explore how to algebraically manipulate and reason about \(n\)-ary ordered state spaces. We also plan to generalize this data structure to the scenarios without a central server and study whether the distributed adOPTed protocol [15] satisfies the strong/weak list specification.

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