

# GSP-Calculus

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**Abstract.**

## 1 Global Sequence Protocol Language

### 1.1 Syntax

We assume the following countable sets of vertex names  $\mathbb{V}$  ranged over by  $v; v_0; v_1, \dots$ ; We shall use  $\alpha, \beta$  to denote sequence of updates  $\mathbb{U}$  ranged over by  $u^v, u_0^{v_0}, u_1^{v_1}, \dots$ ; Let  $\mathcal{U} = u_0^{v_0} \cdot u_1^{v_1} \cdot \dots \cdot u_n^{v_n}$ . For the sake of clarity, we shall only use vertices as update's decoration whenever it would be necessary.

Let  $\rho, \sigma$  be sequence defined as  $\varepsilon \mid [\alpha] \cdot \rho$ . We use  $\varepsilon$  to denote the empty sequence, i.e., the sequence of length 0.

Let  $\rho$  and  $\alpha$  be sequence, we write  $\setminus$  as relative complement of  $\rho$  in  $\alpha$ , i.e.  $\rho \setminus \alpha = [u_i \mid u_i \in \rho \wedge u_i \notin \alpha]$ .

**Definition 1.1 (Global Sequence Protocol Language).** *The set of tgsp-calculus expressions is defined by the following syntax:*

$$\begin{array}{ll}
 \text{(SYSTEM)} & N := C \parallel S \\
 \text{(CLIENT)} & C := 0 \mid \{P, k, \rho, \alpha, \sigma, j\} \mid C \parallel C \quad \text{where } k \text{ and } j \in \mathbb{N} \\
 \text{(STATE)} & S := \varepsilon \mid S \cdot \rho \\
 \text{(PROGRAM)} & P := \text{update}(u); P \mid \text{let } x = \text{read}(v); P \mid \text{pull}(); P \mid \text{push}(); P \mid \\
 & \quad \text{let } x = \text{confirmed}(); P \mid \text{while}(\text{cond}) \text{ do } P
 \end{array}$$

We model the system  $N$  as several clients interacting with a message queue  $S$ . This message queue will represent the program state. We formalize an  $i^{\text{th}}$  client as a tuple  $\{P, k, \rho, \alpha, \sigma, j\}_i$  where  $P$ , called Program, is a set of programming primitives that allow programmer to interact with the distributed store by invoking of actions on objects, a index  $k$  which denotes the maximum index of update that reading in  $S$ , a sequence of updates sent but unconfirmed their reception  $\rho$ , a transaction buffer  $\alpha$ , a sequence of all the updates sent by the client to the RTOB  $\sigma$  and finally  $j$  which represents a amount of received updates.

## 1.2 Operational Semantics

The operational semantics of *tgsp-calculus* is defined by a labeled transition system over well-formed terms, up-to the structural congruence.

The labeled transition system considers the following actions:

$$\alpha ::= \tau \mid read(r) \mid update(u) \mid pull() \mid push() \mid confirmed()$$

(T-READ)

$$\frac{rvalue(r, flatten(S[0..k-1] \cdot \rho) \cdot \alpha) = v}{\{let\ x = read(r); P, k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S \xrightarrow{read(r)} \{P[x \mapsto v], k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S}$$

(T-UPDATE)

$$\{update(u); P, k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S \xrightarrow{update(u)} \{P, k, \rho, \alpha \cdot u, \sigma, j\}_i \parallel C \parallel S$$

(T-PUSH)

$$\{push(); P, k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S \xrightarrow{push()} \{P, k, \rho \cdot [\alpha], \epsilon, \sigma \cdot [\alpha], j\}_i \parallel C \parallel S$$

(T-PULL)

$$\{pull(); P, k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S \xrightarrow{pull()} \{P, k+j, \rho \setminus S[k..k+j], \alpha, \sigma, 0\}_i \parallel C \parallel S$$

(T-CONFIRMED)

$$\{let\ x = confirmed(); P, k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S \xrightarrow{confirmed()} \{P[x \mapsto \rho \neq [] \vee \alpha \neq \epsilon], k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S$$

(T-WHILE-TRUE)

$$\frac{\neg(cond \downarrow) = false}{\{while(cond)\ \mathbf{do}\ P, k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S \xrightarrow{\tau} \{P; while(cond)\ \mathbf{do}\ P, k, \rho, \alpha, \sigma, j+1\}_i \parallel C \parallel S}$$

(T-WHILE-FALSE)

$$\frac{\neg(cond \downarrow) = true}{\{while(cond)\ \mathbf{do}\ P, k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S \xrightarrow{\tau} \{0, k, \rho, \alpha, \sigma, j+1\}_i \parallel C \parallel S}$$

(T-RECEIVE)

$$\frac{k+j+1 \leq |S|}{\{P, k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S \xrightarrow{\tau} \{P, k, \rho, \alpha, \sigma, j+1\}_i \parallel C \parallel S}$$

(T-PROCESS)

$$\{P, k, \rho, \alpha, [\beta] \cdot \sigma, j\}_i \parallel C \parallel S \xrightarrow{\tau} \{P, k, \rho, \alpha, \sigma, j\}_i \parallel C \parallel S \cdot \beta$$

The meaning of  $\tau$  is standard. A *tgsp-calculus* program is given by a Labeled Transition System (LTS) before introducing. Transitions for systems are labeled by actions  $\alpha$  as usual.

Rule (T-READ) states that a client  $i$  can perform an action  $read(r)$ , substituting each occurrence of  $x$  in  $P$  with the value  $v$ . Notice that  $v$  is got from the queue message and the client's internal queues. Rule (T-UPDATE) describes effects performed by an

update operation. The update  $u$  is saving in the temporal queue  $\alpha$ . After (T-PUSH) the content of the transaction queue  $\alpha$  is moved to the pending queue,  $\rho$ , and the sent queue,  $\sigma$ . Rule (T-PULL) increases the amount of updates that client  $i$  can read in the message queue  $S$ . This increase is given by the amount of update receiving. The pending queue removes those updates which belong between index  $k$  and the amount of update receiving  $j$  in  $S$ . Besides,  $j$  is restarted in 0. (T-CONFIRMED) sets  $x$  in false whether updates are in pending queue or transaction queue, true in otherwise. Rule (T-WHILE-TRUE) and (T-WHILE-FALSE) are standard. Rule (T-RECEIVE) states that a counter  $j$  is incremented (by 1). Finally, the last one rule, (T-PROCESS), moves updates from sent queue to the message queue.

*Notation.* Let  $f$  and  $g$  be a partial function, we define the update operator  $_{\cdot}[\cdot]$  such that  $dom(f[g]) = dom(f) \cup dom(g)$  and

$$f[g](x) = \begin{cases} f(x) & \text{if } x \notin dom(g) \wedge x \in dom(f) \\ g(x) & \text{if } x \in dom(g) \\ \perp & \text{Otherwise} \end{cases}$$

We write  $[x_1 \mapsto y_1, \dots, x_n \mapsto y_n]$  for the partial function  $f$  such that  $dom(f) = \{x_1, \dots, x_n\}$  and  $f(x_i) = y_i$ ;  $A \setminus B$  to denote the usual difference of sets.

## 2 Robust Streaming

Let *State* and *Delta* be abstract types, *GSSegment* the set operation over sets  $Delta \times \mathbb{N} \rightarrow \mathbb{N}$ , *GSPrefix* the set over sets  $State \times \mathbb{N} \rightarrow \mathbb{N}$  and *Round* the set over sets  $\mathbb{N} \times \mathbb{N} \times Delta$ ;  $\theta$  is a fresh element of *GSSegment*.

Furthermore, we assume the following parametric functions defined over the abstract data types above borrowed from[1]:

```

const    initialstate : State
function read          : Read  $\times$  State  $\rightarrow$  Value
function apply         : State  $\times$  Delta*  $\rightarrow$  State
const    emptydelta : Delta
function append        : Delta  $\times$  Update  $\rightarrow$  Delta
function reduce        : Delta*  $\rightarrow$  Delta

```

Let *State* be a set of state ranged over by  $s, s_1, s_2, \dots$ ; We shall use  $\delta$  to denote sequence of Delta ranged over by  $d, d_0, d_1 \dots$ ; Let  $\rho, \sigma$  be sequence defined:

$$\rho, \sigma := \varepsilon \mid [\delta] \cdot \rho$$

We assume the following countable sets of persisted state *GSPrefix* ranged over by  $ps, ps_1, \dots$ ;

Let  $in_s$  be a partial function in  $\mathbb{N} \rightarrow \mathbb{N} \times Delta$

Let  $out_s$  be a partial function in  $\mathbb{N} \rightarrow GSSegment^* \cup GSPrefix$

## 2.1 Auxiliar Function

$append :: GSSegment \times Round^* \rightarrow State$   
 $append(<\delta, mr>, \epsilon) = <\delta, mr>$   
 $append(<\delta, mr>, <i, n_0, \delta_0>:rs) = append(<\mathbf{reduce}(\delta \cdot \delta_0 \cdot \epsilon), mr[b_0 \mapsto n_0]>, rs)$

$apply :: GSPrefix \times GSSegment \rightarrow GSPrefix$   
 $apply(<ps, mr>, <\delta, mr'>) = <\mathbf{apply}(ps, \delta \cdot \epsilon), mr[mr']>$

$receivedrounds :: (\mathbb{N} \rightarrow <\mathbb{N} \times Delta>^*) \rightarrow Round^*$   
 $receivedrounds(\perp) = \epsilon$   
 $receivedrounds(b \rightarrow <n_0, \delta_0> \cdot f) = <b, n_0, \delta_0> \cdot receivedrounds(f)$

$curstate :: State \times Round^* \times Delta \times Delta \rightarrow State$   
 $curstate(ps, p, pb, tb) = \mathbf{apply}(ps, getdeltas(p) \cdot pb \cdot tb)$

$getdeltas :: Round^* \rightarrow Delta^*$   
 $getdeltas(\epsilon) = \epsilon$   
 $getdeltas(<n_0, \delta_0> \cdot \delta) = \delta_0 \cdot getdeltas(\delta)$

**Definition 2.1 (GSP).** *The syntax of clients and server is given by the following grammar*

(SYSTEM)  $N ::= 0 \mid S \parallel C$   
 (SERVER)  $S ::= 0 \mid \{ps, in_s, out_s\}$   
 (CLIENTS)  $C ::= \emptyset \mid \{P, <State, \rho, \delta, \delta, GSSegment \cup GSPrefix, \mathbb{N}, in_c, out_c>\} \mid C \parallel C$   
 (PROGRAM)  $P ::= 0 \mid let\ x = read(r); P \mid update(u); P \mid push(); P \mid pull(); P$

$E.k \in State; E.p \in \rho; E.pb, E.tb \in \delta; E.n \in \mathbb{N}.$

## 2.2 Operational Semantics

The operational semantics of *gsp-calculus* is defined by a labeled transition system over well-formed terms, up-to the structural congruence.

The labeled transition system considers the following actions:

$\alpha ::= \tau \mid read(r) \mid update(u) \mid pull() \mid push() \mid confirmed()$

## SERVER

$$\begin{array}{c}
\text{(DROP\_CONN)} \\
\frac{b_i \in in_s \quad b_i \in out_s}{\{ps, in_s, out_s\} \xrightarrow{\dagger(b_i)} \{ps, in_s \setminus b_i, out_s \setminus b_i\}} \\
\\
\text{(CRASH\_AND\_RECOVER)} \\
\{ps, in_s, out_s\} \xrightarrow{\ddagger} \{ps, \perp, \perp\} \\
\\
\text{(BATCH)} \\
\frac{ps' = apply(ps, d) \quad d = append(\theta, rs) \quad rs = receivedRounds(in_s)}{\{ps, in_s, out_s\} \xrightarrow{\tau} \{ps', in_s^p s', out_s\}} \\
\\
\text{(ACCEPT\_CONN)} \\
\frac{b_i \notin in_s \quad b_i \notin out_s}{\{ps, in_s, out_s\} \xrightarrow{\oplus(b_i)} \{ps, in_s, out_s[b_i \mapsto ps]\}}
\end{array}$$

## COMMUNICATION

$$\begin{array}{c}
\text{(COMM SERVER-CLIENT)} \\
\frac{out_s(i) = gs \cdot gss}{\{ps, in_s, out_s\} \parallel \{P, E\}_i \xrightarrow{\tau} \{ps, in_s, out_s[i \mapsto gss]\} \parallel \{P, E[in_c \mapsto E.in_c \cup \{gs\}]\}_i} \\
\\
\text{(COMM CLIENT-SERVER)} \\
\frac{out_c = \langle i, n_0, \delta_0 \rangle \cdot rs}{\{ps, in_s, out_s\} \parallel \{P, E\}_i \xrightarrow{\tau} \{ps, in_s[i \mapsto \langle i, n_0, \delta_0 \rangle], out_s\} \parallel \{P, E[out_c \mapsto rs]\}_i}
\end{array}$$

## CLIENTS

(READ)

$$\frac{\text{read}(r, \text{curstate}(k, p, pb, tb)) = v}{\{\text{let } x = \text{read}(r); P, E\}_i \xrightarrow{\text{read}(r)} \{P[x \mapsto v], E\}_i}$$

(UPDATE)

$$\{\text{update}(u); P, E\}_i \xrightarrow{\text{update}(u)} \{P, E[tb \mapsto \text{append}(E.tb, u)]\}_i$$

(PUSH)

$$\{\text{push}(); P, E\}_i \xrightarrow{\text{push}()} \{P, E[pb \mapsto \text{reduce}(E.pb \cdot E.tb); tb \mapsto \epsilon; n \mapsto E.n + 1]\}_i$$

(PULL)

$$\frac{E.in_c \neq \emptyset \quad E.out_c \neq \emptyset \quad |E.rb| > 0}{\{\text{pull}(); P, E\}_i \xrightarrow{\text{pull}()} \{P, E[k \mapsto \text{reducestate}(E.k, E.rb); rb \mapsto \epsilon]\}_i}$$

(CONFIRMED-TRUE)

$$\frac{E.p = \epsilon \quad E.pb = \epsilon \quad E.tb = \epsilon}{\{\text{let } x = \text{confirmed}(); P, E\}_i \xrightarrow{\text{confirmed}()} \{P[x \mapsto \text{true}], E\}_i}$$

(CONFIRMED-FALSE)

$$\frac{E.p \neq \epsilon \parallel E.pb \neq \epsilon \parallel E.tb \neq \epsilon}{\{\text{let } x = \text{confirmed}(); P, E\}_i \xrightarrow{\text{confirmed}()} \{P[x \mapsto \text{false}], E\}_i}$$

(SEND)

$$\{P, E\}_i \xrightarrow{\text{send}()} \{P, E[p \mapsto E.p \cdot E.pb; pb \mapsto \epsilon; out_c \mapsto out_c \cdot \langle i, E.n, E.pb \rangle]\}_i$$

(RECEIVE)

$$\frac{E.in_c = gs_0 \cdot gs_t}{\{P, E\}_i \xrightarrow{\text{receive}()} \{P, E[rb \mapsto E.rb \cdot gs_0.gssegment; in_c \mapsto gs_t]\}_i}$$

(DROP\_CONNECTION)

$$\{P, k\}_i E \xrightarrow{\dagger} \{P, E[in_c \mapsto \emptyset; out_c \mapsto \emptyset]\}_i$$

### 3 Consistency Guarantees

We shall introduce a series of store-level consistency guarantees and then we shall show which are captured by application written in GSP. We start identifying three kinds of relations between actions of update and read:

*Session Order* relates whatever pair of actions from the same client, indicating the program order. It is a total order on actions.

*Visibility* relates Updates with Reads. It is used to indicate if an action of Update is visible for an action of Read.

*Arbitration* relates Updates with Updates. It is used to resolve update conflicts. It is a total order on actions of update.

We extend the GSP language with a new term which capture the relations amount operation in our system.

$$(ENVIRONMENT) \quad E ::= \{N, OP, SO, VIS, AR\}$$

Let  $E$ , a new term, where  $N$  represents our system introduced in Definition 1.1,  $OP$  is a mapping of vertices to actions,  $SO$  is a session order relation defined from vertices to relations of vertices  $\mathbb{V} \times (\mathbb{V} \times \mathbb{V})$  and  $VIS, AR$  are visibility and arbitration relation.

*Notation.* Given a session order relation  $so$  from client  $i$  and a vertex  $v$ , we shall write  $so \triangleright_i v$  meaning that  $(\mathcal{V}, \mathcal{R}) \triangleright_i v = (\mathcal{V} \cup \{v\}, \mathcal{R} \cup \{(x, v)/x \in \mathbb{V}\})$ . We shall refer to an update action on the queue message as  $S[n]_i$ . The arbitration relation  $AR$  is defined as  $\{(v, w)/\{v \mapsto S[m]_h\} \in OP \wedge \{w \mapsto S[n]_i\} \in OP \wedge m < n\}$ . A transition  $\xrightarrow{\alpha}_i$  denotes the fact that action  $\alpha$  is performed by client  $i$ .

The following operational semantic allow to understand how working the environment when the actions are executed.

(E-READ)

$$\frac{N \xrightarrow{read(r)}_i N' \quad v \notin dom(OP) \quad VIS' = VIS \cup \{(x, v)/\{x \mapsto update(u)_h\} \in OP \wedge u^x \in S[0..k-1] \cdot p \cdot [\alpha]\}}{\{N, OP, SO, VIS, AR\} \xrightarrow{read(r)}_i \{N', OP \cup \{v \mapsto read(r)\}, SO \triangleright_i v, VIS', AR\}}$$

(E-UPDATE)

$$\frac{N \xrightarrow{update(u^v)}_i N' \quad v \notin dom(OP)}{\{N, OP, SO, VIS, AR\} \xrightarrow{update(u^v)}_i \{N', OP \cup \{v \mapsto update(u)\}, SO \triangleright_i v, VIS, AR\}}$$

### 3.1 Ordering Guarantees

We now prove what ordering guarantees are assured by GSP language and what do not.

First, we prove a useful lemma:

**Lemma 3.1.** *Let  $u$  an update action,  $S$  a message queue,  $p_i$  and  $\alpha_i$  a pending queue and transaction queue from the client  $i$ , if  $\{N, \emptyset, \emptyset, \emptyset\} \rightarrow^* \{N, OP, SO, VIS, AR\}$  then  $\{x \mapsto update(u)_i\} \in OP \Rightarrow u^x \in S[0..k_i-1] \cdot p_i \cdot [\alpha_i]$*

*Proof.* The proof follows by induction on the length of the derivation  $\rightarrow^*$ .

- **n=0.** Then  $OP$  is  $\emptyset$ , so that antecedent is false, then the preposition is true.
- **n=k+1.** Then  $\{N, \emptyset, \emptyset, \emptyset\} \rightarrow^n \{N, OP, SO, VIS, AR\} \rightarrow_i \{x \mapsto update(u)_i\} \in OP \Rightarrow u^x \in S[0..k_i-1] \cdot p_i \cdot [\alpha_i]$ . We proceed by case analysis on the last transition:

- **rule (E-READ).** As  $x$  is an update operation then it must not be  $v$ , so that  $\{x \mapsto \text{update}(u)_i\} \in \text{op}$ , then by inductive hypothesis  $u^x \in S[0..k_i - 1] \cdot \rho_i \cdot [\alpha_i]$ .  
When  $N \xrightarrow{\text{read}(r)}_i N'$ ,  $k_i, \rho_i, \alpha_i$  do not change.
- **rule (E-UPDATE).** There are two possibilities:
  - \*  $x \neq v$ . Then we can use inductive hypothesis, so that it is easy to see that if  $u^x \in S[0..k_i - 1] \cdot \rho_i \cdot [\alpha_i]$  then  $u^x \in S[0..k_i - 1] \cdot \rho_i \cdot [\alpha_i] \cdot u_i^v$  too.
  - \*  $x = v$ . When  $N \xrightarrow{\text{update}(u^v)}_i N'$ ,  $u^v \in \alpha'_i$  (with  $\alpha'_i$  transaction queue in  $N'$ ) because  $\alpha'_i = \alpha_i \cdot u^v$ . It is immediate to note that  $u^x \in S[0..k'_i - 1] \cdot \rho'_i \cdot [\alpha'_i]$ .
- **rule (E-PUSH).** As  $\text{op}$  do not change, then by inductive hypothesis,  $u^x \in S[0..k_i - 1] \cdot \rho_i \cdot [\alpha_i] \equiv u^x \in S[0..k_i - 1] \cdot (\rho_i \cdot [\alpha_i]) \cdot \varepsilon$ . When  $N \xrightarrow{\text{push}()}_i N'$ ,  $k_i' = k_i, \rho_i' = \rho_i \cdot [\alpha_i]$  and  $\alpha_i' = \varepsilon$ .
- **rule (E-PULL).** As  $\text{op}$  do not change, then by inductive hypothesis,  $u^x \in S[0..k_i - 1] \cdot \rho_i \cdot [\alpha_i]$ . We should prove that it is equivalent to  $u^x \in S[0..k_i - 1 + j_i] \cdot \rho_i \setminus S[k_i..k_i + j_i] \cdot [\alpha_i]$ . There are two interesting cases to consider:
  - \* If  $u^x \in \rho_i \wedge u^x \notin S[k_i..k_i + j_i]$ , then  $u^x \in \rho_i'$ .
  - \* If  $u^x \in \rho_i \wedge u^x \in S[k_i..k_i + j_i]$ , then  $u^x \notin \rho_i'$  but  $u^x \in S[k_i..k_i + j_i]$ .

The proof for the remaining cases is by inductive hypothesis because  $\text{op}$ ,  $k_i$ ,  $\rho_i$  and  $\alpha_i$  do not change.

**Theorem 3.1 (READ MY WRITES).**

Let  $\text{SO}_R$  the second component of the relation  $\text{SO}$  and  $\text{VIS}$  a visibility relation, if  $\{N_0, \emptyset, \emptyset, \emptyset, \emptyset\} \rightarrow^* \{N, \text{op}, \text{so}, \text{vis}, \text{ar}\}$  then  $\text{SO}_R \cap (\mathbb{U} \times \mathbb{R}) \subseteq \text{VIS}$

*Proof.* The proof follows by induction on the length of the derivation  $\rightarrow^*$ .

- **n=0.** In particular  $\text{op}$  and  $\text{vis}$  are  $\emptyset$ , so that  $\emptyset \subseteq \emptyset$ .
- **n=k+1.** Then  $\{N_0, \emptyset, \emptyset, \emptyset, \emptyset\} \rightarrow^n \{N, \text{op}, \text{so}, \text{vis}, \text{ar}\} \xrightarrow{\alpha}_i \{N', \text{op}', \text{so}', \text{vis}', \text{ar}\}$ . We proceed by definition:
  - $\text{SO}_R' = \text{SO}_R \cup \{(w, v) / \{w \mapsto \text{read}(r)\} \vee \{w \mapsto \text{update}(u)_j\}\}$ . Applying the intersection  $(\mathbb{U} \times \mathbb{R})$ , we shall obtain  $\text{SO}_R \cup \{(w, v) / \{w \mapsto \text{update}(u)_j\}\}$ .
  - $\text{vis}' = \text{vis} \cup \{(x, v) / \{x \mapsto \text{update}(u)_h\} \in \text{op} \wedge u^x \in S[0..k - 1] \cdot \rho \cdot [\alpha]\}$ .

By inductive hypothesis,  $\text{SO}_R \cup (\mathbb{U} \times \mathbb{R}) \subseteq \text{vis}$ . We only have to prove that  $\{(w, v) / \{w \mapsto \text{update}(u)_j\} \in \text{op}\} \subseteq \{(x, v) / \{x \mapsto \text{update}(u)_h\} \in \text{op} \wedge u^x \in S[0..k - 1] \cdot \rho \cdot [\alpha]\}$ . When  $j = h$  and  $w = x$ , we can use Lemma 3.1. So that, we have proved that  $\text{SO}_R' \cap (\mathbb{U} \times \mathbb{R}) \subseteq \text{vis}'$ .

**Theorem 3.2 (MONOTONIC READ).** Let  $\text{SO}_R$  the second component of the relation  $\text{SO}$  and  $\text{VIS}$  a visibility relation, if  $\{N_0, \emptyset, \emptyset, \emptyset, \emptyset\} \rightarrow^* \{N, \text{op}, \text{so}, \text{vis}, \text{ar}\}$  then  $(\text{vis}; \text{SO}_R) \cap (\mathbb{U} \times \mathbb{R}) \subseteq \text{vis}$

*Proof.* The proof follows by induction on the length of the derivation  $\rightarrow^*$ .

- **n=0.** In particular  $\text{SO}_R$  and  $\text{vis}$  are  $\emptyset$ , so that  $\emptyset \subseteq \emptyset$ .
- **n=k+1.** Then  $\{N_0, \emptyset, \emptyset, \emptyset, \emptyset\} \rightarrow^n \{N, \text{op}, \text{so}, \text{vis}, \text{ar}\} \xrightarrow{\alpha}_i \{N', \text{op}', \text{so}', \text{vis}', \text{ar}\}$ . Let  $R$  be a composition of relations. We shall say that if  $(x, y) \in R$  iff  $\exists y \in \mathbb{V}$  such that  $(x, y) \in \text{vis}' \wedge (y, z) \in \text{SO}_R'$ . We have to prove that  $(x, z) \in \text{vis}'$ . We proceed by case analysis on the last transition:



- **rule (E-READ).** We know that  $v$  is fresh, therefore,  $v$  have not be neither  $x$  nor  $y$  because there exists  $z$  such that,  $z$  happens after from  $x$  and  $y$ . There are only two possibilities:
  - \*  $z = v$ . As  $(y, z) \in SO_R$ , then  $y$  and  $z$  are from the same client, called  $i$ . We are only interested in relations of  $update \times read$ . We know that  $v$  is associated to an read action besides  $x$  have to be an update action. As  $(x, y) \in VIS'$  then  $y$  is an read action, i.e.,  $\{y \mapsto read(r)_i\} \in op$ . By Lemma xx, there exists an update  $u$  such that  $u^x \in S[0..k_i - 1] \cdot p_i \cdot [\alpha_i]$ . Substituting  $w$  by  $v$  in  $VIS'$ , we prove that  $(x, z) \in VIS'$ . item  $z \neq v$ . This case follows immediately by inductive hypothesis.
- **rule (E-UPDATE).** Visibility relation does not change, i.e.,  $VIS = VIS'$ . Let  $v$  be a vertex associated an update action, then  $SO_R' = SO_R \cup \{(w, v) / \{w \mapsto read(r)\} \vee \{w \mapsto update(u)_j\}\}$ . As we are only interested in relations of  $update \times read$ , then  $(VIS'; SO_R') \cap (\mathbb{U} \times \mathbb{R}) \equiv (VIS; SO_R) \cap (\mathbb{U} \times \mathbb{R})$ . By inductive hypothesis we can prove that  $(VIS'; SO_R') \cap (\mathbb{U} \times \mathbb{R}) \subseteq VIS \subseteq VIS'$ . The proof for the remaining cases follow are not interesting because the relations does not change.

**Theorem 3.3 (NO CIRCULAR CAUSALITY).**

Let  $SO_R$  the second component of the relation  $SO$  and  $VIS$  a visibility relation, if  $\{N_0, \emptyset, \emptyset, \emptyset, \emptyset\} \rightarrow^* \{N, op, SO, VIS, AR\}$  then **acyclic** $(SO_R \cup VIS)^+$ .

*Proof.* Since  $VIS$  is acyclic and  $SO_R \cap (\mathbb{U} \times \mathbb{R}) \subseteq VIS$  by Theorem 3.1, we have to prove that  $VIS^+$  is acyclic. In particular, the transitive closure of an acyclic graph is the reachability relation of the directed acyclic graph and a strict partial order.

**Theorem 3.4 (CAUSAL VISIBILITY).**

Let  $SO_R$  the second component of the relation  $SO$  and  $VIS$  a visibility relation,  $(SO_R \cup VIS)^+ \cap (\mathbb{U} \times \mathbb{R}) \subseteq VIS$ .

*Proof.* The proof follows by induction on the number of union sets between  $SO_R$  and  $VIS$ . Then,  $\bigcup_{n=1}^{\infty} (SO_R \cup VIS)^n \cap (\mathbb{U} \times \mathbb{R}) \subseteq VIS$ .

- **n=0.** This means that  $SO_R$  and  $VIS$  are  $\emptyset$ , so that  $\emptyset \subseteq \emptyset$ .
- **n=k+1.** Suppose that we have proved that the number of union sets  $< k+1$ . Now, we have to prove that:  $\forall (a, b) \mid (a, b \in \mathbb{V} \Rightarrow (a, b) \in (SO_R \cup VIS)^{k+1} \cap (\mathbb{U} \times \mathbb{R})) \Rightarrow (a, b) \in VIS$ .  
 Assume  $(a, x_1), (x_1, x_2), \dots, (x_{k-1}, x_k), (x_k, b)$  are relations from  $(SO_R \cup VIS)^{k+1}$ . Then  $(a, x_1), (x_1, x_2), \dots, (x_{k-1}, x_k)$  are relations from  $(SO_R \cup VIS)^k$ . By the induction hypothesis,  $(a, x_k) \in (SO_R \cup VIS)^k$ , and we also have  $(x_k, b) \in (SO_R \cup VIS)$ . Thus by the definition of  $(SO_R \cup VIS)^{k+1}$ ,  $(a, b) \in (SO_R \cup VIS)^{k+1}$ . Conversely, assume  $(a, b) \in (SO_R \cup VIS)^{k+1} = (SO_R \cup VIS)^k \circ (SO_R \cup VIS)$ . Then there is a vertex  $c \in \mathbb{V}$  such that  $(a, c) \in (SO_R \cup VIS)^k$  and  $(c, b) \in (SO_R \cup VIS)$ . We are only interested when  $a$  is an update action and  $b$  a read action. It is because of the intersection with  $(Update \times Read)$ . We have two possible cases:
  - $c$  is a read action. It means that  $(c, b)$  only can be in  $SO_R$  because  $VIS$  requires that  $c$  will be an update action. In particular, if  $(c, b) \in SO_R$ , they belong to the same client.

- \* if  $(a, c) \in \text{VIS}$  and  $(c, b) \in \text{SO}_R$ , by Theorem 3.2,  $(a, b) \in \text{VIS}$ .
- \* if  $(a, c) \in \text{SO}_R$  then by Theorem 3.1,  $(a, c) \in \text{VIS}$ . Then, it is analogous to the previous case.
- $c$  is an update action. It means that  $(a, c)$  only can be in  $\text{SO}_R$  because  $\text{VIS}$  requires that  $c$  will be an read action. In particular, if  $(a, c) \in \text{SO}_R$ , they belong to the same client.
  - \* if  $(a, c) \in \text{SO}_R$  and  $(c, b) \in \text{VIS}$ , by Theorem Monotonic Writes (Falta probar!),  $(a, b) \in \text{VIS}$ .
  - \* if  $(a, c) \in \text{VIS} \dots \text{VER}$ .

**Theorem 3.5 (CAUSAL ARBITRATION).**

Let  $\text{SO}_R$  the second component of the relation  $\text{SO}$ ,  $\text{VIS}$  a visibility relation and  $\text{AR}$  an arbitration relation then  $(\mathbb{U} \times \mathbb{U}) \cap (\text{SO}_R \cup \text{VIS})^+ - \text{SO}_R \subseteq \text{AR}$ .

*Proof.* The proof follows by induction on the number of union sets between  $\text{SO}_R$  and  $\text{VIS}$ . Then,  $(\mathbb{U} \times \mathbb{U}) \cap \bigcup_{n=1}^{\infty} (\text{SO}_R \cup \text{VIS})^n - \text{SO}_R \subseteq \text{AR}$ .

- $n=0$ . This means that  $\text{SO}_R$ ,  $\text{VIS}$  and  $\text{AR}$  are  $\emptyset$ , so that  $\emptyset \subseteq \emptyset$ .
- $n=k+1$ . Suppose that we have proved that the number of union sets  $< k+1$ . Now, we have to prove that:  $\forall (a, b) \mid (a, b \in \mathbb{V} \Rightarrow (a, b) \in (\mathbb{U} \times \mathbb{U}) \cap \bigcup_{n=1}^{\infty} (\text{SO}_R \cup \text{VIS})^{k+1} - \text{SO}_R \Rightarrow (a, b) \in \text{AR}$ .  
 Assume  $(a, b) \in (\text{SO}_R \cup \text{VIS})^{k+1} = (\text{SO}_R \cup \text{VIS})^k \circ (\text{SO}_R \cup \text{VIS})$ . Then there is a vertice  $c \in \mathbb{V}$  such that  $(a, c) \in (\text{SO}_R \cup \text{VIS})^k$  and  $(c, b) \in (\text{SO}_R \cup \text{VIS})$ .  
 We are only interested when  $a$  and  $b$  are an update actions. It is because of the intersection with  $(\text{Update} \times \text{Update})$ . We have two possible cases:
  - $c$  is a read action. It means that  $(c, b)$  only can be in  $\text{SO}_R$  because  $\text{VIS}$  requires that  $c$  will be an update action. In particular, if  $(c, b) \in \text{SO}_R$ , they belong to the same client. COMPLETAR
  - $c$  is an update action. COMPLETAR

*Example 3.1 (Consistent Prefix).* Consider the following system built-up from two different client:

$$E = \{ \{ \text{update}(aList.add('a')); \text{push}(); 0, \epsilon, \epsilon, \epsilon, 0 \}_1 \parallel \{ \text{update}(aList.add('b')); \text{push}(); \text{let } v = \text{read}(x); 0, \epsilon, \epsilon, \epsilon, 0 \}_2 \parallel \epsilon, \emptyset, \emptyset, \emptyset, \emptyset \}$$

Environment has a system  $N$  with two clients and a message queue  $S$  without updates. Relation sets  $\text{OP}, \text{SO}, \text{VIS}, \text{AR}$  are empty, i.e., there were not an execution in  $N$  captured by the relation sets. The update action add a string to an object called  $aList$  which has not elements. In this state,  $C_1$  and  $C_2$  can perform their update actions.  $E$  may non-deterministically choose to do  $\text{update}(aList.add('a'))$  or  $\text{update}(aList.add('b'))$ . If the first communication takes place over  $\text{update}(aList.add('a'))$ , then the system evolves as follows:

$$E \xrightarrow{\text{update}(aList.add('a'))v_0} \{ \{ \text{push}(); 0, \epsilon, [aList.add('a')], \epsilon, 0 \}_1 \parallel \{ \text{update}(aList.add('b')); \text{push}(); \text{let } x = \text{read}(aList); 0, \epsilon, \epsilon, \epsilon, 0 \}_2 \parallel \epsilon, \emptyset, \{ \{ v_0 \}, \emptyset \}, \emptyset, \emptyset \}$$

The action  $update(aList.add('a'))$  of the client 1 will be identified by vertice  $v_0$  by rule E-UPDATE. In particular, the update action will be left into the transactional queue of Client 1 besides the new vertice will be added to vertices in so. Now, Client 1 performs  $push()$ :

$$\begin{aligned} E & \xrightarrow{push()}_1 \{ \{0, 0, [aList.add('a')], \epsilon, [aList.add('a')], 0 \}_1 \parallel \\ & \{ update(aList.add('b')); push(); let x = read(aList);, 0, \epsilon, \epsilon, 0 \}_2 \parallel \epsilon, \\ & \emptyset, \{ (\{v_0\}, \emptyset) \}, \emptyset, \emptyset \} \end{aligned}$$

When it happens,  $aList.add('a')$  is moved to the sent queue and pending queue. At this moment, Client 2 can perform an update action however Client 1 will realize an internal action which is given by E-PROCESS.

$$\begin{aligned} E & \xrightarrow{\tau}_1 \{ \{0, 0, [aList.add('a')], \epsilon, \epsilon, 0 \}_1 \parallel \\ & \{ update(aList.add('b')); push(); let x = read(aList);, 0, \epsilon, \epsilon, 0 \}_2 \parallel \\ & aList.add('a'), \emptyset, \{ (\{v_0\}, \emptyset) \}, \emptyset, \emptyset \} \end{aligned}$$

Analogously, Client 2 realize its actions leaving to environment evolves as below:

$$\begin{aligned} E & \xrightarrow{update(aList.add('b'))}_2 \{ \{0, 0, [aList.add('a')], \epsilon, \epsilon, 0 \}_1 \parallel \\ & \{ push(); let x = read(aList);, 0, \epsilon, [aList.add('b')], \epsilon, 0 \}_2 \parallel \\ & aList.add('a'), \emptyset, \{ (\{v_0, v_1\}, \{ (v_0, v_1) \}) \}, \emptyset, \emptyset \} \\ & \xrightarrow{push()}_2 \{ \{0, 0, [aList.add('a')], \epsilon, \epsilon, 0 \}_1 \parallel \\ & \{ let x = read(aList);, 0, [aList.add('b')], \epsilon, [aList.add('b')], 0 \}_2 \parallel \\ & aList.add('a'), \emptyset, \{ (\{v_0, v_1\}, \{ (v_0, v_1) \}) \}, \emptyset, \emptyset \} \\ & \xrightarrow{\tau}_2 \{ \{0, 0, [aList.add('a')], \epsilon, \epsilon, 0 \}_1 \parallel \\ & \{ let x = read(aList);, 0, [aList.add('b')], \epsilon, \epsilon, 0 \}_2 \parallel \\ & aList.add('a') \cdot [aList.add('b')], \emptyset, \{ (\{v_0, v_1\}, \{ (v_0, v_1) \}) \}, \emptyset, \{ (v_0, v_1) \} \} \\ & \xrightarrow{read(aList)}_2 \{ \{0, 0, [aList.add('a')], \epsilon, \epsilon, 0 \}_1 \parallel \\ & \{ 0[x \mapsto ['b']], 0, [aList.add('b')], \epsilon, \epsilon, 0 \}_2 \parallel aList.add('a') \cdot [aList.add('b')], \\ & \emptyset, \emptyset, \emptyset \} \end{aligned}$$

Note that AR is modified because the message queue has two elements. The value returned will be the list with a only element, ['b'], because of the internal action associated to the rule E-RECEIVE did not perform it. Then, if the rule E-RECEIVE were performed, the value of the list would be ['a', 'b']. It is because the content of the pending queue is removed when the server left their message.

The guarantee Consistent Prefix, which rules is  $(AR; VIS) \subseteq AR; VIS$ , states that if we see an result from a client in a particular order, we will never see this result in a different order.

## 4 Extending GSP

As illustrated in above examples, there are situations in which a environment does not ensures consistency guarantees from the literature, as Consistent Prefix or Single Order. The nature of such cases is caused by having no transactions as the usual databases.

The remaining of this section is proposing a environment that ensures these consistency guarantees. We start by refining the syntax of GSP distinguishing two relations:

*Return Before* identified as RB. It is used to indicate is if an action of Update is visible for an action of Read.

RB and Tx.