GSP-Calculus

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Abstract.

1 Global Sequence Protocol Language

1.1 Syntax

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

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

Let ρ and α be sequence, we write $\setminus$ as relative complement of ρ in α, 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:*

$$
\begin{array}{lll}
(\textsc{system}) & N := C \parallel S & \\
(\textsc{client}) & C := 0 \mid \{P,k,\rho,\alpha,\sigma,j\} \mid C \parallel C & \textit{where } k \textit{ and } j \in \mathbb{N} \\
(\textsc{state}) & S := \varepsilon \mid S\cdot\rho & \\
(\textsc{program}) & P := \textit{update(u);}P \mid \textit{let } x = \textit{read}(v);P \mid \textit{pull();}P \mid \textit{push();}P \mid & \\
 & \quad \textit{let } x = \textit{confirmed}();P \mid \textit{while}(\textit{cond})\ \textbf{\textit{do}}\ P &
\end{array}
$$

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^{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 ρ, a transaction buffer α, a sequence of all the updates sent by the client to the RTOB σ 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:

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

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

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

(T-PUSH)
$$\{\mathit{push}(); P,k,\rho,\alpha,\sigma,j\}_i \parallel C \parallel S \xrightarrow{\mathit{push}()} \{P,k,\rho\cdot[\alpha],\varepsilon,\sigma\cdot[\alpha],j\}_i \parallel C \parallel S$$

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

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

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

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

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

(T-PROCESS)
$$\{P,k,\rho,\alpha,[\beta]\cdot\sigma,j\} \parallel C \parallel S \xrightarrow{\tau} \{P,k,\rho,\alpha,\sigma,j\} \parallel C \parallel S\cdot\beta$$

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

Rule (T-READ) states that a client i can perform an action $\mathit{read}(r)$, 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 α. After (T-PUSH) the content of the transaction queue α is moved to the pending queue, ρ, and the sent queue, σ. 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 $\_[\_]$ such that $dom(f[g]) = dom(f) \cup dom(g)$ and

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

We write $[x_1 \mapsto y_1, \ldots, x_n \mapsto y_n]$ for the partial function f such that $dom(f) = \{x_1, \ldots, x_n\}$ 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 $Delta \times \mathcal{N} \to \mathbb{N}$, *GSPrefix* the set over sets $State \times \mathcal{N} \to \mathbb{N}$ and *Round* the set over sets $\mathcal{N} \times \mathbb{N} \times Delta$; θ 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*	: $Read \times State \to Value$
function	*apply*	: $State \times Delta^* \to State$
const	*emptydelta*	: *Delta*
function	*append*	: $Delta \times Update \to Delta$
function	*reduce*	: $Delta^* \to Delta$

Let *State* be a set of state ranged over by s, s_1, s_2, ...; We shall use δ to denote sequence of Delta ranged over by d, d_0, d_1 ...; Let ρ, σ be sequence defined:

ρ,σ := ε | [δ]· ρ

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

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

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

2.1 Auxiliar Function

$append :: GSSegment\ x\ Round^* \to State$
$append(<\delta, mr>, \varepsilon) = <\delta, mr>$
$append(<\delta, mr>, <i, n_0, \delta_0>:rs) = append(<\textbf{\textit{reduce}}(\delta \cdot \delta_0 \cdot \varepsilon), mr[b_0 \mapsto n_0]>, rs)$

$apply :: GSPrefix\ x\ GSSegment \to GSPrefix$
$apply(<ps, mr>, <\delta, mr'>) = <\textbf{\textit{apply}}(ps, \delta \cdot \varepsilon), mr[mr']>$

$receivedrounds :: (\mathcal{N} \to <\mathbb{N} \times Delta>^*) \to Round^*$
$receivedrounds(\bot) = \varepsilon$
$receivedrounds(b \to <n_0,\ \delta_0> \cdot\ f) = <b,\ n_0,\ \delta_0> \cdot receivedrounds(f)$

$curstate :: State\ x\ Round^*\ x\ Delta\ x\ Delta \to State$
$curstate(ps, p, pb, tb) = \textbf{\textit{apply}}(ps, getdeltas(p) \cdot pb \cdot tb)$

$getdeltas :: Round^* \to Delta^*$
$getdeltas(\varepsilon) = \varepsilon$
$getdeltas(<n_0, \delta_0> \cdot \delta) = \delta_0 \cdot \text{getdeltas}(\delta)$

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

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

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

(DROP_CONN)

$$\frac{b_i \in in_s \qquad b_i \in out_s}{\{ps, in_s, out_s\} \xmapsto{\dagger(b_i)} \{ps, in_s \setminus b_i, out_s \setminus b_i\}}$$

(CRASH_AND_RECOVER)

$$\{ps, in_s, out_s\} \overset{\ddagger}{\mapsto} \{ps, \bot, \bot\}$$

(BATCH)

$$\frac{ps' = apply(ps, d) \qquad d = append(\theta, rs) \qquad rs = receivedRounds(in_s)}{\{ps, in_s, out_s\} \xrightarrow{\tau} \{ps', in_s{}^p s', out_s\}}$$

(ACCEPT_CONN)

$$\frac{b_i \notin in_s \qquad b_i \notin out_s}{\{ps, in_s, out_s\} \xmapsto{\oplus(b_i)} \{ps, in_s, out_s[b_i \mapsto ps]\}}$$

COMMUNICATION

(COMM SERVER-CLIENT)

$$\frac{out_s(i) = gs \cdot gss}{\{ps, in_s, out_s\} \| \{P, E\}_i \xrightarrow{\tau} \{ps, in_s, out_s[i \mapsto gss]\} \| \{P, E[in_c \mapsto E.in_c \cup \{gs\}]\}_i}$$

(COMM CLIENT-SERVER)

$$\frac{out_c = <i, n_0, \delta_0> \cdot rs}{\{ps, in_s, out_s\} \| \{P, E\}_i \xrightarrow{\tau} \{ps, in_s[i \mapsto <i, n_0, \delta_0>], out_s\} \| \{P, E[out_c \mapsto rs]\}_i}$$

CLIENTS

(READ)

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

(UPDATE)

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

(PUSH)

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

(PULL)

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

(CONFIRMED-TRUE)

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

(CONFIRMED-FALSE)

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

(SEND)

$$\{P, E\}_i \xrightarrow{send()} \{P, E[p \mapsto E.p \cdot E.pb; pb \mapsto \varepsilon; out_c \mapsto out_c \cdot <i, E.n, E.pb>]\}_i$$

(RECEIVE)

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

(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 is 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.

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

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 vertice v, we shall write $\text{SO} \rhd_i v$ meaning that $(\mathcal{V}, \mathcal{R}) \rhd_i v = (\mathcal{V} \cup \{v\}, \mathcal{R} \cup \{(x,v)/x \in \mathbb{V}\})$. We shall refer to an update action on the queue message as $S[n]_i$.The arbitration relation AR is defined as $\{(v,w)/\{v \mapsto S[m]_h\} \in \text{OP} \wedge \{w \mapsto S[n]_i\} \in \text{OP} \wedge m < n\}$. A transition $\xrightarrow{\alpha}_i$ denotes the fact that action α is perfomed by client i.

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

(E-READ)

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

(E-UPDATE)

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

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

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 preoposition is true.
- **n=k+1**. Then $\{N, \emptyset, \emptyset, \emptyset, \emptyset\} \rightarrow^n \{N, \text{OP}, \text{SO}, \text{VIS}, \text{AR}\} \rightarrow_i \{x \mapsto update(u)_i\} \in \text{OP} \Rightarrow u^x \in S[0..k_i - 1] \cdot \rho_i \cdot [\alpha_i]$. 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 $\{x \mapsto update(u)_i\} \in$ OP, then by inductive hypothesis $u^x \in S[0..k_i-1]\cdot\rho_i\cdot[\alpha_i]$. When $N \xrightarrow{read(r)}_i N'$, k_i, ρ_i,α_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 $u^x \in S[0..k_i-1]\cdot\rho_i\cdot[\alpha_i]\cdot u_t^v$ too.
  - $x = v$. When $N \xrightarrow{update(u^v)}_i N'$, $u^v \in \alpha_i'$ (with α_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 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 $N \xrightarrow{push()}_i N'$, k_i' = k_i, ρ_i' = $\rho_i\cdot[\alpha_i]$ and α_i' = ε.
- **rule (E-PULL)**. As 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 OP, k_i, ρ_i and α_i do not change.

Theorem 3.1 (READMYWRITES).
Let SO_R *the second component of the relation* SO *and* VIS *a visibility relation, if* $\{N_0,\emptyset,\emptyset,\emptyset,\emptyset\} \to^* \{N, \text{OP}, \text{SO}, \text{VIS}, \text{AR}\}$ *then* $SO_R \cap (\mathbb{U}\times\mathbb{R}) \subseteq$ VIS

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

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

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

Theorem 3.2 (MONOTONIC READ).
Let SO_R *the second component of the relation* SO *and* VIS *a visibility relation, if* $\{N_0,\emptyset,\emptyset,\emptyset,\emptyset\} \to^* \{N, \text{OP}, \text{SO}, \text{VIS}, \text{AR}\}$ *then* $(\text{VIS};SO_R) \cap (\mathbb{U}\times\mathbb{R}) \subseteq$ VIS

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

- **n=0**. In particular SO_R and VIS are $\emptyset$, so that $\emptyset \subseteq \emptyset$.
- **n=k+1**. Then $\{N_0,\emptyset,\emptyset,\emptyset,\emptyset\} \to^n \{N, \text{OP}, \text{SO}, \text{VIS}, \text{AR}\} \xrightarrow{\alpha}_i \{N', \text{OP}', \text{SO}', \text{VIS}', \text{AR}\}$. Let R be a composition of relations. We shall say that if $(x,y) \in R$ iff $\exists y \in \mathbb{V}$ such that $(x,y) \in \text{VIS}' \wedge (y,z) \in SO_R$'. We have to prove that $(x,z) \in$ 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 $(y,z) \in \text{SO}_R$, 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 $u^x \in S[0..k_i-1] \cdot \rho_i \cdot [\alpha_i]$. 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 vertice associated an update action, then SO_R' = $\text{SO}_R \cup \{(w,v)/\{w \mapsto read(r)\} \vee \{w \mapsto update(u)_j\}\}$. As we are only interested in relations of $update \times read$, then $(\text{VIS}'; \text{SO'}_R) \cap (\mathbb{U} \times \mathbb{R}) \equiv (\text{VIS}; \text{SO}_R) \cap (\mathbb{U} \times \mathbb{R})$. By inductive hypothesis we can prove that $(\text{VIS}'; \text{SO}_R)' \cap (\mathbb{U} \times \mathbb{R}) \subseteq \text{VIS} \subseteq \text{VIS'}$. 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* $\{N_0, \emptyset, \emptyset, \emptyset, \emptyset\} \rightarrow^* \{N, \text{OP}, \text{SO}, \text{VIS}, \text{AR}\}$ *then* ***acyclic***$(\text{SO}_R \cup \text{VIS})^+$.

Proof. Since VIS is acyclic and $\text{SO}_R \cap (\mathbb{U} \times \mathbb{R}) \subseteq$ 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.

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

$$E = \{C_1 \parallel C_2 \parallel S, \emptyset, \emptyset, \emptyset, \emptyset\}$$

$$C_1 = \{\textit{add(aList,'hello');push();send();}, 0, \varepsilon, \varepsilon, \varepsilon, \varepsilon\}$$
$$C_2 = \{\textit{add(aList,'world');push();send();let v = read(x);}, 0, \varepsilon, \varepsilon, \varepsilon, \varepsilon\}$$
$$S = \varepsilon$$

Enviroment has a system N with two clients and a message queue S without updates. Relation sets OP,SO,VIS,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*. In this state, C_1 and C_2 can perform their update actions. Considerer the following execution:

$$E \xrightarrow{update(add(aList,'hello')^v)}_1 \{C_1' \parallel C_2 \parallel S, v_0 \mapsto add(aList,'hello'), \emptyset, \emptyset, \emptyset\}$$

$$C_1' = \{push(); send();, 0, \varepsilon, \varepsilon, \varepsilon, \varepsilon\}$$
$$C_2 = \{\textit{update(aList,'world');push();send();let v = read(x);}, 0, \varepsilon, \varepsilon, \varepsilon, \varepsilon\}$$
$$S = \varepsilon$$