A framework for establishing Strong Eventual Consistency for Conflict-free Replicated Data types

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Abstract

In this work, we focus on the correctness of Conflict-free Replicated Data Types (CRDTs), a class of algorithm that provides strong eventual consistency guarantees for replicated data. We develop a modular and reusable framework for verifying the correctness of CRDT algorithms. We avoid correctness issues that have dogged previous mechanised proofs in this area by including a network model in our formalisation, and proving that our theorems hold in all possible network behaviours. Our axiomatic network model is a standard abstraction that accurately reflects the behaviour of real-world computer networks. Moreover, we identify an abstract convergence theorem, a property of order relations, which provides a formal definition of strong eventual consistency. We then obtain the first machine-checked correctness theorems for three concrete CRDTs: the Replicated Growable Array, the Observed-Remove Set, and an Increment-Decrement Counter.

Contents

1 Introduction

Strong eventual consistency (SEC) is a model that strikes a compromise between strong and eventual consistency [12]. Informally, it guarantees that whenever two nodes have received the same set of messages—possibly in a different order—their view of the shared state is identical, and any conflicting concurrent updates must be merged automatically. Large-scale deployments of SEC algorithms include datacentre-based applications using the Riak distributed database [3], and collaborative editing applications such as Google Docs [5]. Unlike strong consistency models, it is possible to implement SEC in decentralised settings without any central server or leader, and it allows local execution at each node to proceed without waiting for communication with other nodes. However, algorithms for achieving decentralised SEC are currently poorly understood: several such algorithms, published in peer-reviewed venues, were subsequently shown to violate their supposed guarantees [6, 7, 9]. Informal reasoning has repeatedly produced plausible-looking but incorrect algorithms, and there have even been examples of mechanised formal proofs of SEC algorithm correctness later being shown to be flawed. These mechanised proofs failed because, in formalising the algorithm, they made false assumptions about the execution environment.

In this work we use the Isabelle/HOL proof assistant [13] to create a framework for reliably reasoning about the correctness of a particular class of decentralised replication algorithms. We do this by formalising not only the replication algorithms, but also the network in which they execute, allowing us to prove that the algorithm's assumptions hold in all possible network behaviours. We model the network using the axioms of *asynchronous unreliable causal broadcast*, a well-understood abstraction that is commonly implemented by network protocols, and which can run on almost any computer network, including large-scale networks that delay, reorder, or drop messages, and in which nodes may fail.

We then use this framework to produce machine-checked proofs of correctness for three Conflict-Free Replicated Data Types (CRDTs), a class of replication algorithms that ensure strong eventual consistency [11, 12]. To our knowledge, this is the first machine-checked verification of SEC algorithms that explicitly models the network and reasons about all possible network behaviours. The framework is modular and reusable, making it easy to formulate proofs for new algorithms. We provide the first mechanised proofs of the Replicated Growable Array, the operation-based Observed-Remove Set, and the operation-based counter CRDT.

2 Technical Lemmas

This section contains a list of helper definitions and lemmas about sets, lists and the option monad.

theory
Util
imports
Main
HOL−Library.Monad-Syntax

begin

2.1 Kleisli arrow composition

definition *kleisli* :: $('b \Rightarrow 'b\ option) \Rightarrow ('b \Rightarrow 'b\ option) \Rightarrow ('b \Rightarrow 'b\ option)$ (**infixr** $\rhd$ *65*) **where**
$f \rhd g \equiv \lambda x.\ (f\ x \gg= (\lambda y.\ g\ y))$

lemma *kleisli-comm-cong*:
assumes $x \rhd y = y \rhd x$
shows $z \rhd x \rhd y = z \rhd y \rhd x$
⟨*proof*⟩

lemma *kleisli-assoc*:
shows $(z \rhd x) \rhd y = z \rhd (x \rhd y)$
⟨*proof*⟩

2.2 Lemmas about sets

lemma *distinct-set-notin* [*dest*]:
assumes *distinct* $(x\#xs)$
shows $x \notin set\ xs$
⟨*proof*⟩

lemma *set-membership-equality-technicalD* [*dest*]:
assumes $\{x\} \cup (set\ xs) = \{y\} \cup (set\ ys)$
shows $x = y \lor y \in set\ xs$
⟨*proof*⟩

lemma *set-equality-technical*:
assumes $\{x\} \cup (set\ xs) = \{y\} \cup (set\ ys)$
and $x \notin set\ xs$
and $y \notin set\ ys$
and $y \in set\ xs$
shows $\{x\} \cup (set\ xs - \{y\}) = set\ ys$
⟨*proof*⟩

lemma *set-elem-nth*:
assumes $x \in set\ xs$
shows $\exists\, m.\ m < length\ xs \land xs\ !\ m = x$
⟨*proof*⟩

2.3 Lemmas about list

lemma *list-nil-or-snoc*:
shows $xs = [] \lor (\exists\, y\ ys.\ xs = ys@[y])$
⟨*proof*⟩

lemma *suffix-eq-distinct-list*:
assumes *distinct xs*
and $ys@suf1 = xs$
and $ys@suf2 = xs$
shows $suf1 = suf2$
⟨*proof*⟩

lemma *pre-suf-eq-distinct-list*:
assumes *distinct xs*
and $ys \neq []$
and $pre1@ys@suf1 = xs$

and $pre2@ys@suf2 = xs$
shows $pre1 = pre2 \wedge suf1 = suf2$
$\langle proof \rangle$

lemma *list-head-unaffected*:
assumes $hd\ (x\ @\ [y,\ z]) = v$
shows $hd\ (x\ @\ [y\quad]) = v$
$\langle proof \rangle$

lemma *list-head-butlast*:
assumes $hd\ xs = v$
and $length\ xs > 1$
shows $hd\ (butlast\ xs) = v$
$\langle proof \rangle$

lemma *list-head-length-one*:
assumes $hd\ xs = x$
and $length\ xs = 1$
shows $xs = [x]$
$\langle proof \rangle$

lemma *list-two-at-end*:
assumes $length\ xs > 1$
shows $\exists\, xs'\ x\ y.\ xs = xs'\ @\ [x,\ y]$
$\langle proof \rangle$

lemma *list-nth-split-technical*:
assumes $m < length\ cs$
and $cs \neq []$
shows $\exists\, xs\ ys.\ cs = xs@(cs!m)\#ys$
$\langle proof \rangle$

lemma *list-nth-split*:
assumes $m < length\ cs$
and $n < m$
and $1 < length\ cs$
shows $\exists\, xs\ ys\ zs.\ cs = xs@(cs!n)\#ys@(cs!m)\#zs$
$\langle proof \rangle$

lemma *list-split-two-elems*:
assumes $distinct\ cs$
and $x \in set\ cs$
and $y \in set\ cs$
and $x \neq y$
shows $\exists\, pre\ mid\ suf.\ cs = pre\ @\ x\ \#\ mid\ @\ y\ \#\ suf \vee cs = pre\ @\ y\ \#\ mid\ @\ x\ \#\ suf$
$\langle proof \rangle$

lemma *split-list-unique-prefix*:
assumes $x \in set\ xs$
shows $\exists\, pre\ suf.\ xs = pre\ @\ x\ \#\ suf \wedge (\forall\, y \in set\ pre.\ x \neq y)$
$\langle proof \rangle$

lemma *map-filter-append*:
shows $List.map\text{-}filter\ P\ (xs\ @\ ys) = List.map\text{-}filter\ P\ xs\ @\ List.map\text{-}filter\ P\ ys$
$\langle proof \rangle$

end

3 Strong Eventual Consistency

In this section we formalise the notion of strong eventual consistency. We do not make any assumptions about networks or data structures; instead, we use an abstract model of operations that may be reordered, and we reason about the properties that those operations must satisfy. We then provide concrete implementations of that abstract model in later sections.

theory
  Convergence
imports
  Util
begin

The *happens-before* relation, as introduced by [8], captures causal dependencies between operations. It can be defined in terms of sending and receiving messages on a network. However, for now, we keep it abstract, our only restriction on the happens-before relation is that it must be a *strict partial order*, that is, it must be irreflexive and transitive, which implies that it is also antisymmetric. We describe the state of a node using an abstract type variable. To model state changes, we assume the existence of an *interpretation* function *interp* which lifts an operation into a *state transformer*—a function that either maps an old state to a new state, or fails.

locale *happens-before* = *preorder hb-weak hb*
  for *hb-weak* :: $'a \Rightarrow 'a \Rightarrow bool$ (**infix** $\preceq$ *50*)
  and *hb* :: $'a \Rightarrow 'a \Rightarrow bool$ (**infix** $\prec$ *50*) +
  fixes *interp* :: $'a \Rightarrow 'b \rightharpoonup 'b$ (⟨-⟩ [*0*] *1000*)
begin

3.1 Concurrent operations

We say that two operations x and y are *concurrent*, written $x \| y$, whenever one does not happen before the other: $\neg(x \prec y)$ and $\neg(y \prec x)$.

definition *concurrent* :: $'a \Rightarrow 'a \Rightarrow bool$ (**infix** $\|$ *50*) **where**
  $s1 \parallel s2 \equiv \neg (s1 \prec s2) \wedge \neg (s2 \prec s1)$

lemma *concurrentI* [*intro*!]: $\neg (s1 \prec s2) \Longrightarrow \neg (s2 \prec s1) \Longrightarrow s1 \parallel s2$
  ⟨*proof*⟩

lemma *concurrentD1* [*dest*]: $s1 \parallel s2 \Longrightarrow \neg (s1 \prec s2)$
  ⟨*proof*⟩

lemma *concurrentD2* [*dest*]: $s1 \parallel s2 \Longrightarrow \neg (s2 \prec s1)$
  ⟨*proof*⟩

lemma *concurrent-refl* [*intro*!, *simp*]: $s \parallel s$
  ⟨*proof*⟩

lemma *concurrent-comm*: $s1 \parallel s2 \longleftrightarrow s2 \parallel s1$
  ⟨*proof*⟩

definition *concurrent-set* :: $'a \Rightarrow 'a$ *list* $\Rightarrow bool$ **where**
  concurrent-set x xs $\equiv \forall y \in$ *set xs*. $x \parallel y$

lemma *concurrent-set-empty* [*simp*, *intro*!]:
  concurrent-set x []
  ⟨*proof*⟩

lemma *concurrent-set-ConsE* [*elim*!]:

assumes *concurrent-set a* $(x\#xs)$
and *concurrent-set a xs* $\Longrightarrow$ *concurrent x a* $\Longrightarrow$ G
shows G
⟨*proof*⟩

lemma *concurrent-set-ConsI* [*intro*!]:
concurrent-set a xs $\Longrightarrow$ *concurrent a x* $\Longrightarrow$ *concurrent-set a* $(x\#xs)$
⟨*proof*⟩

lemma *concurrent-set-appendI* [*intro*!]:
concurrent-set a xs $\Longrightarrow$ *concurrent-set a ys* $\Longrightarrow$ *concurrent-set a* $(xs@ys)$
⟨*proof*⟩

lemma *concurrent-set-Cons-Snoc* [*simp*]:
concurrent-set a $(xs@[x])$ = *concurrent-set a* $(x\#xs)$
⟨*proof*⟩

3.2 Happens-before consistency

The purpose of the happens-before relation is to require that some operations must be applied in a particular order, while allowing concurrent operations to be reordered with respect to each other. We assume that each node applies operations in some sequential order (a standard assumption for distributed algorithms), and so we can model the execution history of a node as a list of operations.

inductive *hb-consistent* :: *'a list* $\Rightarrow$ *bool* **where**
[*intro*!]: *hb-consistent* [] |
[*intro*!]: ⟦ *hb-consistent xs*; $\forall x \in$ *set xs*. $\neg\, y \prec x$ ⟧ $\Longrightarrow$ *hb-consistent* $(xs\ @\ [y])$

As a result, whenever two operations x and y appear in a hb-consistent list, and $x \prec y$, then x must appear before y in the list. However, if $x \parallel y$, the operations can appear in the list in either order.

lemma $(x \prec y \lor$ *concurrent x y*$) = (\neg\, y \prec x)$
⟨*proof*⟩

lemma *consistentI* [*intro*!]:
assumes *hb-consistent* $(xs\ @\ ys)$
and $\forall x \in$ *set* $(xs\ @\ ys)$. $\neg\, z \prec x$
shows *hb-consistent* $(xs\ @\ ys\ @\ [z])$
⟨*proof*⟩

inductive-cases *hb-consistent-elim* [*elim*]:
hb-consistent []
hb-consistent $(xs@[y])$
hb-consistent $(xs@ys)$
hb-consistent $(xs@ys@[z])$

inductive-cases *hb-consistent-elim-gen*:
hb-consistent zs

lemma *hb-consistent-append-D1* [*dest*]:
assumes *hb-consistent* $(xs\ @\ ys)$
shows *hb-consistent xs*
⟨*proof*⟩

lemma *hb-consistent-append-D2* [*dest*]:
assumes *hb-consistent* $(xs\ @\ ys)$
shows *hb-consistent ys*

⟨*proof*⟩

lemma *hb-consistent-append-elim-ConsD* [*elim*]:
assumes *hb-consistent* $(y\#ys)$
shows *hb-consistent ys*
⟨*proof*⟩

lemma *hb-consistent-remove1* [*intro*]:
assumes *hb-consistent xs*
shows *hb-consistent* (*remove1 x xs*)
⟨*proof*⟩

lemma *hb-consistent-singleton* [*intro*!]:
shows *hb-consistent* $[x]$
⟨*proof*⟩

lemma *hb-consistent-prefix-suffix-exists*:
assumes *hb-consistent ys*
hb-consistent $(xs @ [x])$
$\{x\} \cup set\ xs = set\ ys$
distinct $(x\#xs)$
distinct ys
shows $\exists\, prefix\ suffix.\ ys = prefix\ @\ x\ \#\ suffix \wedge concurrent\text{-}set\ x\ suffix$
⟨*proof*⟩

lemma *hb-consistent-append* [*intro*!]:
assumes *hb-consistent suffix*
hb-consistent prefix
$\bigwedge s\ p.\ s \in set\ suffix \Longrightarrow p \in set\ prefix \Longrightarrow \neg\ s \prec p$
shows *hb-consistent* (*prefix* @ *suffix*)
⟨*proof*⟩

lemma *hb-consistent-append-porder*:
assumes *hb-consistent* $(xs @ ys)$
$x \in set\ xs$
$y \in set\ ys$
shows $\neg\ y \prec x$
⟨*proof*⟩

3.3 Apply operations

We can now define a function *apply-operations* that composes an arbitrary list of operations into a state transformer. We first map *interp* across the list to obtain a state transformer for each operation, and then collectively compose them using the Kleisli arrow composition combinator.

definition *apply-operations* :: $'a\ list \Rightarrow 'b \rightharpoonup 'b$ **where**
$apply\text{-}operations\ es \equiv foldl\ (\triangleright)\ Some\ (map\ interp\ es)$

lemma *apply-operations-empty* [*simp*]: $apply\text{-}operations\ []\ s = Some\ s$
⟨*proof*⟩

lemma *apply-operations-Snoc* [*simp*]:
$apply\text{-}operations\ (xs@[x]) = (apply\text{-}operations\ xs) \triangleright \langle x \rangle$
⟨*proof*⟩

3.4 Concurrent operations commute

We say that two operations x and y *commute* whenever $\langle x\rangle \rhd \langle y\rangle = \langle y\rangle \rhd \langle x\rangle$, i.e. when we can swap the order of the composition of their interpretations without changing the resulting state transformer. For our purposes, requiring that this property holds for *all* pairs of operations is too strong. Rather, the commutation property is only required to hold for operations that are concurrent.

definition *concurrent-ops-commute* :: *'a list* ⇒ *bool* **where**
  concurrent-ops-commute xs ≡
    $\forall x\ y.\ \{x,\ y\} \subseteq set\ xs \longrightarrow concurrent\ x\ y \longrightarrow \langle x\rangle\rhd\langle y\rangle = \langle y\rangle\rhd\langle x\rangle$

lemma *concurrent-ops-commute-empty* [*intro*!]: *concurrent-ops-commute* []
  ⟨*proof*⟩

lemma *concurrent-ops-commute-singleton* [*intro*!]: *concurrent-ops-commute* [*x*]
  ⟨*proof*⟩

lemma *concurrent-ops-commute-appendD* [*dest*]:
  assumes *concurrent-ops-commute* (*xs*@*ys*)
    shows *concurrent-ops-commute xs*
⟨*proof*⟩

lemma *concurrent-ops-commute-rearrange*:
  concurrent-ops-commute (*xs*@*x*#*ys*) = *concurrent-ops-commute* (*xs*@*ys*@[*x*])
  ⟨*proof*⟩

lemma *concurrent-ops-commute-concurrent-set*:
  assumes *concurrent-ops-commute* (*prefix*@*suffix*@[*x*])
      concurrent-set x suffix
      distinct (*prefix* @ *x* # *suffix*)
  shows *apply-operations* (*prefix* @ *suffix* @ [*x*]) = *apply-operations* (*prefix* @ *x* # *suffix*)
⟨*proof*⟩

3.5 Abstract convergence theorem

We can now state and prove our main theorem, *convergence*. This theorem states that two hb-consistent lists of distinct operations, which are permutations of each other and in which concurrent operations commute, have the same interpretation.

theorem *convergence*:
  assumes *set xs* = *set ys*
      concurrent-ops-commute xs
      concurrent-ops-commute ys
      distinct xs
      distinct ys
      hb-consistent xs
      hb-consistent ys
  shows *apply-operations xs* = *apply-operations ys*
⟨*proof*⟩

corollary *convergence-ext*:
  assumes *set xs* = *set ys*
      concurrent-ops-commute xs
      concurrent-ops-commute ys
      distinct xs
      distinct ys
      hb-consistent xs

hb-consistent ys
shows *apply-operations xs s = apply-operations ys s*
⟨*proof*⟩
end

3.6 Convergence and progress

Besides convergence, another required property of SEC is *progress*: if a valid operation was issued on one node, then applying that operation on other nodes must also succeed—that is, the execution must not become stuck in an error state. Although the type signature of the interpretation function allows operations to fail, we need to prove that in all *hb-consistent* network behaviours such failure never actually occurs. We capture the combined requirements in the *strong-eventual-consistency* locale, which extends *happens-before*.

locale *strong-eventual-consistency = happens-before +*
fixes *op-history* :: *'a list ⇒ bool*
and *initial-state* :: *'b*
assumes *causality*: *op-history xs ⟹ hb-consistent xs*
assumes *distinctness*: *op-history xs ⟹ distinct xs*
assumes *commutativity*: *op-history xs ⟹ concurrent-ops-commute xs*
assumes *no-failure*: *op-history(xs@[x]) ⟹ apply-operations xs initial-state = Some state ⟹ ⟨x⟩ state ≠ None*
assumes *trunc-history*: *op-history(xs@[x]) ⟹ op-history xs*
begin

theorem *sec-convergence*:
assumes *set xs = set ys*
op-history xs
op-history ys
shows *apply-operations xs = apply-operations ys*
⟨*proof*⟩

theorem *sec-progress*:
assumes *op-history xs*
shows *apply-operations xs initial-state ≠ None*
⟨*proof*⟩

end
end

4 Axiomatic network models

In this section we develop a formal definition of an *asynchronous unreliable causal broadcast network*. We choose this model because it satisfies the causal delivery requirements of many operation-based CRDTs [1, 2]. Moreover, it is suitable for use in decentralised settings, as motivated in the introduction, since it does not require waiting for communication with a central server or a quorum of nodes.

theory
Network
imports
Convergence
begin

4.1 Node histories

We model a distributed system as an unbounded number of communicating nodes. We assume nothing about the communication pattern of nodes—we assume only that each node is uniquely identified by a natural number, and that the flow of execution at each node consists of a finite, totally ordered sequence of execution steps (events). We call that sequence of events at node i the *history* of that node. For convenience, we assume that every event or execution step is unique within a node's history.

locale *node-histories* =
  fixes *history* :: *nat* ⇒ *'evt list*
  assumes *histories-distinct* [*intro*!, *simp*]: *distinct* (*history i*)

lemma (**in** *node-histories*) *history-finite*:
  shows *finite* (*set* (*history i*))
⟨*proof*⟩

definition (**in** *node-histories*) *history-order* :: *'evt* ⇒ *nat* ⇒ *'evt* ⇒ *bool* (-/ ⊏⁻/ - [*50*,*1000*,*50*]*50*)
where
  $x \sqsubset^i z \equiv \exists xs\ ys\ zs.\ xs@x\#ys@z\#zs = history\ i$

lemma (**in** *node-histories*) *node-total-order-trans*:
  assumes $e1 \sqsubset^i e2$
    and $e2 \sqsubset^i e3$
  shows $e1 \sqsubset^i e3$
⟨*proof*⟩

lemma (**in** *node-histories*) *local-order-carrier-closed*:
  assumes $e1 \sqsubset^i e2$
  shows $\{e1,e2\} \subseteq set\ (history\ i)$
  ⟨*proof*⟩

lemma (**in** *node-histories*) *node-total-order-irrefl*:
  shows $\neg\ (e \sqsubset^i e)$
  ⟨*proof*⟩

lemma (**in** *node-histories*) *node-total-order-antisym*:
  assumes $e1 \sqsubset^i e2$
    and $e2 \sqsubset^i e1$
  shows *False*
  ⟨*proof*⟩

lemma (**in** *node-histories*) *node-order-is-total*:
  assumes $e1 \in set\ (history\ i)$
    and $e2 \in set\ (history\ i)$
    and $e1 \neq e2$
  shows $e1 \sqsubset^i e2 \vee e2 \sqsubset^i e1$
  ⟨*proof*⟩

definition (**in** *node-histories*) *prefix-of-node-history* :: *'evt list* ⇒ *nat* ⇒ *bool* (**infix** *prefix of 50*) **where**
  xs prefix of i ≡ ∃ *ys*. *xs*@*ys* = *history i*

lemma (**in** *node-histories*) *carriers-head-lt*:
  assumes *y*#*ys* = *history i*
  shows $\neg(x \sqsubset^i y)$
⟨*proof*⟩

lemma (**in** *node-histories*) *prefix-of-ConsD* [*dest*]:

assumes $x \# xs$ *prefix of* i
shows $[x]$ *prefix of* i
⟨*proof*⟩

lemma (**in** *node-histories*) *prefix-of-appendD* [*dest*]:
assumes xs @ ys *prefix of* i
shows xs *prefix of* i
⟨*proof*⟩

lemma (**in** *node-histories*) *prefix-distinct*:
assumes xs *prefix of* i
shows *distinct* xs
⟨*proof*⟩

lemma (**in** *node-histories*) *prefix-to-carriers* [*intro*]:
assumes xs *prefix of* i
shows *set* $xs \subseteq$ *set* (*history* i)
⟨*proof*⟩

lemma (**in** *node-histories*) *prefix-elem-to-carriers*:
assumes xs *prefix of* i
and $x \in$ *set* xs
shows $x \in$ *set* (*history* i)
⟨*proof*⟩

lemma (**in** *node-histories*) *local-order-prefix-closed*:
assumes $x \sqsubset^i y$
and xs *prefix of* i
and $y \in$ *set* xs
shows $x \in$ *set* xs
⟨*proof*⟩

lemma (**in** *node-histories*) *local-order-prefix-closed-last*:
assumes $x \sqsubset^i y$
and xs@$[y]$ *prefix of* i
shows $x \in$ *set* xs
⟨*proof*⟩

lemma (**in** *node-histories*) *events-before-exist*:
assumes $x \in$ *set* (*history* i)
shows $\exists$ *pre*. *pre* @ $[x]$ *prefix of* i
⟨*proof*⟩

lemma (**in** *node-histories*) *events-in-local-order*:
assumes *pre* @ $[e2]$ *prefix of* i
and $e1 \in$ *set pre*
shows $e1 \sqsubset^i e2$
⟨*proof*⟩

4.2 Asynchronous broadcast networks

We define a new locale *network* containing three axioms that define how broadcast and deliver events may interact, with these axioms defining the properties of our network model.

datatype *'msg event*
= *Broadcast 'msg*
| *Deliver 'msg*

locale *network* = *node-histories history* **for** *history* :: *nat* ⇒ *'msg event list* +
fixes *msg-id* :: *'msg* ⇒ *'msgid*

assumes *delivery-has-a-cause*: ⟦ *Deliver m* ∈ *set* (*history i*) ⟧ ⟹
∃ *j*. *Broadcast m* ∈ *set* (*history j*)
and *deliver-locally*: ⟦ *Broadcast m* ∈ *set* (*history i*) ⟧ ⟹
Broadcast m $\sqsubset^i$ *Deliver m*
and *msg-id-unique*: ⟦ *Broadcast m1* ∈ *set* (*history i*);
Broadcast m2 ∈ *set* (*history j*);
msg-id m1 = *msg-id m2* ⟧ ⟹ *i* = *j* ∧ *m1* = *m2*

The axioms can be understood as follows:

delivery-has-a-cause: If some message *m* was delivered at some node, then there exists some node on which *m* was broadcast. With this axiom, we assert that messages are not created "out of thin air" by the network itself, and that the only source of messages are the nodes.

deliver-locally: If a node broadcasts some message *m*, then the same node must subsequently also deliver *m* to itself. Since *m* does not actually travel over the network, this local delivery is always possible, even if the network is interrupted. Local delivery may seem redundant, since the effect of the delivery could also be implemented by the broadcast event itself; however, it is standard practice in the description of broadcast protocols that the sender of a message also sends it to itself, since this property simplifies the definition of algorithms built on top of the broadcast abstraction [4].

msg-id-unique: We do not assume that the message type *'msg* has any particular structure; we only assume the existence of a function *msg-id*::*'msg*⇒*'msgid* that maps every message to some globally unique identifier of type *'msgid*. We assert this uniqueness by stating that if *m1* and *m2* are any two messages broadcast by any two nodes, and their *msg-id*s are the same, then they were in fact broadcast by the same node and the two messages are identical. In practice, these globally unique IDs can by implemented using unique node identifiers, sequence numbers or timestamps.

lemma (**in** *network*) *broadcast-before-delivery*:
assumes *Deliver m* ∈ *set* (*history i*)
shows ∃ *j*. *Broadcast m* $\sqsubset^j$ *Deliver m*
⟨*proof*⟩

lemma (**in** *network*) *broadcasts-unique*:
assumes *i* ≠ *j*
and *Broadcast m* ∈ *set* (*history i*)
shows *Broadcast m* ∉ *set* (*history j*)
⟨*proof*⟩

Based on the well-known definition by [8], we say that *m1* ≺ *m2* if any of the following is true:

1. *m1* and *m2* were broadcast by the same node, and *m1* was broadcast before *m2*.
2. The node that broadcast *m2* had delivered *m1* before it broadcast *m2*.
3. There exists some operation *m3* such that *m1* ≺ *m3* and *m3* ≺ *m2*.

inductive (**in** *network*) *hb* :: *'msg* ⇒ *'msg* ⇒ *bool* **where**
hb-broadcast: ⟦ *Broadcast m1* $\sqsubset^i$ *Broadcast m2* ⟧ ⟹ *hb m1 m2* |
hb-deliver: ⟦ *Deliver m1* $\sqsubset^i$ *Broadcast m2* ⟧ ⟹ *hb m1 m2* |
hb-trans: ⟦ *hb m1 m2*; *hb m2 m3* ⟧ ⟹ *hb m1 m3*

inductive-cases (**in** *network*) *hb-elim*: *hb x y*

definition (**in** *network*) *weak-hb* :: $'msg \Rightarrow 'msg \Rightarrow bool$ **where**
weak-hb m1 m2 $\equiv$ *hb m1 m2* $\vee$ *m1* $=$ *m2*

locale *causal-network* = *network* +
assumes *causal-delivery*: *Deliver m2* $\in$ *set* (*history j*) $\Longrightarrow$ *hb m1 m2* $\Longrightarrow$ *Deliver m1* $\sqsubset^j$ *Deliver m2*

lemma (**in** *causal-network*) *causal-broadcast*:
assumes *Deliver m2* $\in$ *set* (*history j*)
and *Deliver m1* $\sqsubset^i$ *Broadcast m2*
shows *Deliver m1* $\sqsubset^j$ *Deliver m2*
⟨*proof*⟩

lemma (**in** *network*) *hb-broadcast-exists1*:
assumes *hb m1 m2*
shows $\exists$ *i*. *Broadcast m1* $\in$ *set* (*history i*)
⟨*proof*⟩

lemma (**in** *network*) *hb-broadcast-exists2*:
assumes *hb m1 m2*
shows $\exists$ *i*. *Broadcast m2* $\in$ *set* (*history i*)
⟨*proof*⟩

4.3 Causal networks

lemma (**in** *causal-network*) *hb-has-a-reason*:
assumes *hb m1 m2*
and *Broadcast m2* $\in$ *set* (*history i*)
shows *Deliver m1* $\in$ *set* (*history i*) $\vee$ *Broadcast m1* $\in$ *set* (*history i*)
⟨*proof*⟩

lemma (**in** *causal-network*) *hb-cross-node-delivery*:
assumes *hb m1 m2*
and *Broadcast m1* $\in$ *set* (*history i*)
and *Broadcast m2* $\in$ *set* (*history j*)
and $i \neq j$
shows *Deliver m1* $\in$ *set* (*history j*)
⟨*proof*⟩

lemma (**in** *causal-network*) *hb-irrefl*:
assumes *hb m1 m2*
shows *m1* $\neq$ *m2*
⟨*proof*⟩

lemma (**in** *causal-network*) *hb-broadcast-broadcast-order*:
assumes *hb m1 m2*
and *Broadcast m1* $\in$ *set* (*history i*)
and *Broadcast m2* $\in$ *set* (*history i*)
shows *Broadcast m1* $\sqsubset^i$ *Broadcast m2*
⟨*proof*⟩

lemma (**in** *causal-network*) *hb-antisym*:
assumes *hb x y*
and *hb y x*
shows *False*
⟨*proof*⟩

definition (**in** *network*) *node-deliver-messages* :: *'msg event list* ⇒ *'msg list* **where**
node-deliver-messages cs ≡ *List.map-filter* (*λe. case e of Deliver m* ⇒ *Some m* | - ⇒ *None*) *cs*

lemma (**in** *network*) *node-deliver-messages-empty* [*simp*]:
shows *node-deliver-messages* [] = []
⟨*proof*⟩

lemma (**in** *network*) *node-deliver-messages-Cons*:
shows *node-deliver-messages* (*x*#*xs*) = (*node-deliver-messages* [*x*])@(*node-deliver-messages xs*)
⟨*proof*⟩

lemma (**in** *network*) *node-deliver-messages-append*:
shows *node-deliver-messages* (*xs*@*ys*) = (*node-deliver-messages xs*)@(*node-deliver-messages ys*)
⟨*proof*⟩

lemma (**in** *network*) *node-deliver-messages-Broadcast* [*simp*]:
shows *node-deliver-messages* [*Broadcast m*] = []
⟨*proof*⟩

lemma (**in** *network*) *node-deliver-messages-Deliver* [*simp*]:
shows *node-deliver-messages* [*Deliver m*] = [*m*]
⟨*proof*⟩

lemma (**in** *network*) *prefix-msg-in-history*:
assumes *es prefix of i*
and *m* ∈ *set* (*node-deliver-messages es*)
shows *Deliver m* ∈ *set* (*history i*)
⟨*proof*⟩

lemma (**in** *network*) *prefix-contains-msg*:
assumes *es prefix of i*
and *m* ∈ *set* (*node-deliver-messages es*)
shows *Deliver m* ∈ *set es*
⟨*proof*⟩

lemma (**in** *network*) *node-deliver-messages-distinct*:
assumes *xs prefix of i*
shows *distinct* (*node-deliver-messages xs*)
⟨*proof*⟩

lemma (**in** *network*) *drop-last-message*:
assumes *evts prefix of i*
and *node-deliver-messages evts* = *msgs* @ [*last-msg*]
shows ∃ *pre. pre prefix of i* ∧ *node-deliver-messages pre* = *msgs*
⟨*proof*⟩

locale *network-with-ops* = *causal-network history fst*
for *history* :: *nat* ⇒ (*'msgid* × *'op*) *event list* +
fixes *interp* :: *'op* ⇒ *'state* ⇀ *'state*
and *initial-state* :: *'state*

context *network-with-ops* **begin**

definition *interp-msg* :: *'msgid* × *'op* ⇒ *'state* ⇀ *'state* **where**
interp-msg msg state ≡ *interp* (*snd msg*) *state*

sublocale *hb*: *happens-before weak-hb hb interp-msg*
⟨*proof*⟩

end

definition (**in** *network-with-ops*) *apply-operations* :: $('msgid \times 'op)$ *event list* $\rightharpoonup$ *'state* **where**
apply-operations es $\equiv$ *hb.apply-operations* (*node-deliver-messages es*) *initial-state*

definition (**in** *network-with-ops*) *node-deliver-ops* :: $('msgid \times 'op)$ *event list* $\Rightarrow$ *'op list* **where**
node-deliver-ops cs $\equiv$ *map snd* (*node-deliver-messages cs*)

lemma (**in** *network-with-ops*) *apply-operations-empty* [*simp*]:
shows *apply-operations* [] = *Some initial-state*
⟨*proof*⟩

lemma (**in** *network-with-ops*) *apply-operations-Broadcast* [*simp*]:
shows *apply-operations* (*xs* @ [*Broadcast m*]) = *apply-operations xs*
⟨*proof*⟩

lemma (**in** *network-with-ops*) *apply-operations-Deliver* [*simp*]:
shows *apply-operations* (*xs* @ [*Deliver m*]) = (*apply-operations xs* $\gg=$ *interp-msg m*)
⟨*proof*⟩

lemma (**in** *network-with-ops*) *hb-consistent-technical*:
assumes $\bigwedge m\ n.\ m < \mathit{length}\ cs \Longrightarrow n < m \Longrightarrow cs\ !\ n \sqsubset^i cs\ !\ m$
shows *hb.hb-consistent* (*node-deliver-messages cs*)
⟨*proof*⟩

corollary (**in** *network-with-ops*)
shows *hb.hb-consistent* (*node-deliver-messages* (*history i*))
⟨*proof*⟩

lemma (**in** *network-with-ops*) *hb-consistent-prefix*:
assumes *xs prefix of i*
shows *hb.hb-consistent* (*node-deliver-messages xs*)
⟨*proof*⟩

locale *network-with-constrained-ops* = *network-with-ops* +
fixes *valid-msg* :: $'c \Rightarrow ('a \times 'b) \Rightarrow \mathit{bool}$
assumes *broadcast-only-valid-msgs*: *pre* @ [*Broadcast m*] *prefix of i* $\Longrightarrow$
$\exists$ *state. apply-operations pre* = *Some state* $\wedge$ *valid-msg state m*

lemma (**in** *network-with-constrained-ops*) *broadcast-is-valid*:
assumes *Broadcast m* $\in$ *set* (*history i*)
shows $\exists$ *state. valid-msg state m*
⟨*proof*⟩

lemma (**in** *network-with-constrained-ops*) *deliver-is-valid*:
assumes *Deliver m* $\in$ *set* (*history i*)
shows $\exists$ *j pre state. pre* @ [*Broadcast m*] *prefix of j* $\wedge$ *apply-operations pre* = *Some state* $\wedge$ *valid-msg state m*
⟨*proof*⟩

lemma (**in** *network-with-constrained-ops*) *deliver-in-prefix-is-valid*:
assumes *xs prefix of i*
and *Deliver m* $\in$ *set xs*
shows $\exists$ *state. valid-msg state m*
⟨*proof*⟩

4.4 Dummy network models

interpretation *trivial-node-histories*: *node-histories* $\lambda m.$ []
⟨*proof*⟩

interpretation *trivial-network*: *network* $\lambda m.$ [] *id*
⟨*proof*⟩

interpretation *trivial-causal-network*: *causal-network* $\lambda m.$ [] *id*
⟨*proof*⟩

interpretation *trivial-network-with-ops*: *network-with-ops* $\lambda m.$ [] $(\lambda x\ y.\ Some\ y)\ 0$
⟨*proof*⟩

interpretation *trivial-network-with-constrained-ops*: *network-with-constrained-ops* $\lambda m.$ [] $(\lambda x\ y.\ Some\ y)\ 0\ \lambda x\ y.\ True$
⟨*proof*⟩

end

5 Replicated Growable Array

The RGA, introduced by [10], is a replicated ordered list (sequence) datatype that supports *insert* and *delete* operations.

theory
Ordered-List
imports
Util
begin

type-synonym $('id, 'v)\ elt = 'id \times 'v \times bool$

5.1 Insert and delete operations

Insertion operations place the new element *after* an existing list element with a given ID, or at the head of the list if no ID is given. Deletion operations refer to the ID of the list element that is to be deleted. However, it is not safe for a deletion operation to completely remove a list element, because then a concurrent insertion after the deleted element would not be able to locate the insertion position. Instead, the list retains so-called *tombstones*: a deletion operation merely sets a flag on a list element to mark it as deleted, but the element actually remains in the list. A separate garbage collection process can be used to eventually purge tombstones [10], but we do not consider tombstone removal here.

hide-const *insert*

fun *insert-body* :: $('id::\{linorder\}, 'v)\ elt\ list \Rightarrow ('id, 'v)\ elt \Rightarrow ('id, 'v)\ elt\ list$ **where**
insert-body [] $e = [e]$ |
insert-body $(x\#xs)\ e =$
$($*if fst* $x <$ *fst* e *then*
$e\#x\#xs$
else $x\#$*insert-body* $xs\ e)$

fun *insert* :: $('id::\{linorder\}, 'v)\ elt\ list \Rightarrow ('id, 'v)\ elt \Rightarrow 'id\ option \Rightarrow ('id, 'v)\ elt\ list\ option$ **where**
insert $xs\ e\ None = Some\ ($*insert-body* $xs\ e)$ |
insert [] $e\ (Some\ i) = None$ |
insert $(x\#xs)\ e\ (Some\ i) =$
$($*if fst* $x = i$ *then*

$\quad Some\ (x\#insert\text{-}body\ xs\ e)$
$\ \ else$
$\quad insert\ xs\ e\ (Some\ i) \ggg= (\lambda t.\ Some\ (x\#t)))$

fun $delete :: ('id::\{linorder\},\ 'v)\ elt\ list \Rightarrow 'id \Rightarrow ('id,\ 'v)\ elt\ list\ option$ **where**
$delete\ []\qquad i = None\ |$
$delete\ ((i',\ v,\ flag)\#xs)\ i =$
$(if\ i' = i\ then$
$\quad Some\ ((i',\ v,\ True)\#xs)$
$\ \ else$
$\quad delete\ xs\ i \ggg= (\lambda t.\ Some\ ((i',v,flag)\#t)))$

5.2 Well-definedness of insert and delete

lemma *insert-no-failure*:
assumes $i = None \lor (\exists i'.\ i = Some\ i' \land i' \in fst\ `\ set\ xs)$
shows $\exists xs'.\ insert\ xs\ e\ i = Some\ xs'$
$\langle proof \rangle$

lemma *insert-None-index-neq-None* [*dest*]:
assumes $insert\ xs\ e\ i = None$
shows $i \neq None$
$\langle proof \rangle$

lemma *insert-Some-None-index-not-in* [*dest*]:
assumes $insert\ xs\ e\ (Some\ i) = None$
shows $i \notin fst\ `\ set\ xs$
$\langle proof \rangle$

lemma *index-not-in-insert-Some-None* [*simp*]:
assumes $i \notin fst\ `\ set\ xs$
shows $insert\ xs\ e\ (Some\ i) = None$
$\langle proof \rangle$

lemma *delete-no-failure*:
assumes $i \in fst\ `\ set\ xs$
shows $\exists xs'.\ delete\ xs\ i = Some\ xs'$
$\langle proof \rangle$

lemma *delete-None-index-not-in* [*dest*]:
assumes $delete\ xs\ i = None$
shows $i \notin fst\ `\ set\ xs$
$\langle proof \rangle$

lemma *index-not-in-delete-None* [*simp*]:
assumes $i \notin fst\ `\ set\ xs$
shows $delete\ xs\ i = None$
$\langle proof \rangle$

5.3 Preservation of element indices

lemma *insert-body-preserve-indices* [*simp*]:
shows $fst\ `\ set\ (insert\text{-}body\ xs\ e) = fst\ `\ set\ xs \cup \{fst\ e\}$
$\langle proof \rangle$

lemma *insert-preserve-indices*:
assumes $\exists ys.\ insert\ xs\ e\ i = Some\ ys$
shows $fst\ `\ set\ (the\ (insert\ xs\ e\ i)) = fst\ `\ set\ xs \cup \{fst\ e\}$

⟨*proof*⟩

corollary *insert-preserve-indices′*:
assumes $insert\ xs\ e\ i = Some\ ys$
shows $fst\ `\ set\ (the\ (insert\ xs\ e\ i)) = fst\ `\ set\ xs \cup \{fst\ e\}$
⟨*proof*⟩

lemma *delete-preserve-indices*:
assumes $delete\ xs\ i = Some\ ys$
shows $fst\ `\ set\ xs = fst\ `\ set\ ys$
⟨*proof*⟩

5.4 Commutativity of concurrent operations

lemma *insert-body-commutes*:
assumes $fst\ e1 \neq fst\ e2$
shows $insert\text{-}body\ (insert\text{-}body\ xs\ e1)\ e2 = insert\text{-}body\ (insert\text{-}body\ xs\ e2)\ e1$
⟨*proof*⟩

lemma *insert-insert-body*:
assumes $fst\ e1 \neq fst\ e2$
and $i2 \neq Some\ (fst\ e1)$
shows $insert\ (insert\text{-}body\ xs\ e1)\ e2\ i2 = insert\ xs\ e2\ i2 \gg= (\lambda ys.\ Some\ (insert\text{-}body\ ys\ e1))$
⟨*proof*⟩

lemma *insert-Nil-None*:
assumes $fst\ e1 \neq fst\ e2$
and $i \neq fst\ e2$
and $i2 \neq Some\ (fst\ e1)$
shows $insert\ []\ e2\ i2 \gg= (\lambda ys.\ insert\ ys\ e1\ (Some\ i)) = None$
⟨*proof*⟩

lemma *insert-insert-body-commute*:
assumes $i \neq fst\ e1$
and $fst\ e1 \neq fst\ e2$
shows $insert\ (insert\text{-}body\ xs\ e1)\ e2\ (Some\ i) =$
$insert\ xs\ e2\ (Some\ i) \gg= (\lambda y.\ Some\ (insert\text{-}body\ y\ e1))$
⟨*proof*⟩

lemma *insert-commutes*:
assumes $fst\ e1 \neq fst\ e2$
$i1 = None \vee i1 \neq Some\ (fst\ e2)$
$i2 = None \vee i2 \neq Some\ (fst\ e1)$
shows $insert\ xs\ e1\ i1 \gg= (\lambda ys.\ insert\ ys\ e2\ i2) =$
$insert\ xs\ e2\ i2 \gg= (\lambda ys.\ insert\ ys\ e1\ i1)$
⟨*proof*⟩

lemma *delete-commutes*:
shows $delete\ xs\ i1 \gg= (\lambda ys.\ delete\ ys\ i2) = delete\ xs\ i2 \gg= (\lambda ys.\ delete\ ys\ i1)$
⟨*proof*⟩

lemma *insert-body-delete-commute*:
assumes $i2 \neq fst\ e$
shows $delete\ (insert\text{-}body\ xs\ e)\ i2 \gg= (\lambda t.\ Some\ (x\#t)) =$
$delete\ xs\ i2 \gg= (\lambda y.\ Some\ (x\#insert\text{-}body\ y\ e))$
⟨*proof*⟩

lemma *insert-delete-commute*:

assumes $i2 \neq fst\ e$
shows $insert\ xs\ e\ i1 \ggg (\lambda ys.\ delete\ ys\ i2) = delete\ xs\ i2 \ggg (\lambda ys.\ insert\ ys\ e\ i1)$
⟨*proof*⟩

5.5 Alternative definition of insert

fun $insert' :: ('id::\{linorder\}, 'v)\ elt\ list \Rightarrow ('id, 'v)\ elt \Rightarrow 'id\ option \rightharpoonup ('id::\{linorder\}, 'v)\ elt\ list$
where

$insert'\ []\ e\ \ \ None\ \ \ = Some\ [e]\ |$
$insert'\ []\ e\ \ \ (Some\ i) = None\ |$
$insert'\ (x\#xs)\ e\ None\ \ =$
$\quad(if\ fst\ x < fst\ e\ then$
$\quad\quad Some\ (e\#x\#xs)$
$\quad else$
$\quad\quad case\ insert'\ xs\ e\ None\ of$
$\quad\quad\quad None\ \ \Rightarrow None$
$\quad\quad |\ Some\ t \Rightarrow Some\ (x\#t))\ |$
$insert'\ (x\#xs)\ e\ (Some\ i) =$
$\quad(if\ fst\ x = i\ then$
$\quad\quad case\ insert'\ xs\ e\ None\ of$
$\quad\quad\quad None\ \ \Rightarrow None$
$\quad\quad |\ Some\ t \Rightarrow Some\ (x\#t)$
$\quad else$
$\quad\quad case\ insert'\ xs\ e\ (Some\ i)\ of$
$\quad\quad\quad None\ \ \Rightarrow None$
$\quad\quad |\ Some\ t \Rightarrow Some\ (x\#t))$

lemma [*elim!*, *dest*]:
assumes $insert'\ xs\ e\ None = None$
shows $False$
⟨*proof*⟩

lemma *insert-body-insert′*:
shows $insert'\ xs\ e\ None = Some\ (insert\text{-}body\ xs\ e)$
⟨*proof*⟩

lemma *insert-insert′*:
shows $insert\ xs\ e\ i = insert'\ xs\ e\ i$
⟨*proof*⟩

lemma *insert-body-stop-iteration*:
assumes $fst\ e > fst\ x$
shows $insert\text{-}body\ (x\#xs)\ e = e\#x\#xs$
⟨*proof*⟩

lemma *insert-body-contains-new-elem*:
shows $\exists\, p\ s.\ xs = p\ @\ s \wedge insert\text{-}body\ xs\ e = p\ @\ e\ \#\ s$
⟨*proof*⟩

lemma *insert-between-elements*:
assumes $xs = pre@ref\#suf$
and $distinct\ (map\ fst\ xs)$
and $\bigwedge i'.\ i' \in fst\ `\ set\ xs \Longrightarrow i' < fst\ e$
shows $insert\ xs\ e\ (Some\ (fst\ ref)) = Some\ (pre\ @\ ref\ \#\ e\ \#\ suf)$
⟨*proof*⟩

lemma *insert-position-element-technical*:
assumes $\forall\, x{\in}set\ as.\ a \neq fst\ x$

```
    and insert-body (cs @ ds) e = cs @ e # ds
  shows insert (as @ (a, aa, b) # cs @ ds) e (Some a) = Some (as @ (a, aa, b) # cs @ e # ds)
⟨proof⟩

lemma split-tuple-list-by-id:
  assumes (a,b,c) ∈ set xs
    and distinct (map fst xs)
  shows ∃ pre suf. xs = pre @ (a,b,c) # suf ∧ (∀ y ∈ set pre. fst y ≠ a)
⟨proof⟩

lemma insert-preserves-order:
  assumes i = None ∨ (∃ i′. i = Some i′ ∧ i′ ∈ fst ‘ set xs)
      and distinct (map fst xs)
    shows ∃ pre suf. xs = pre@suf ∧ insert xs e i = Some (pre @ e # suf)
  ⟨proof⟩
end
```

5.6 Network

```
theory
  RGA
imports
  Network
  Ordered-List
begin

datatype (′id, ′v) operation =
  Insert (′id, ′v) elt ′id option |
  Delete ′id

fun interpret-opers :: (′id::linorder, ′v) operation ⇒ (′id, ′v) elt list ⇀ (′id, ′v) elt list (⟨-⟩ [0] 1000)
where
  interpret-opers (Insert e n) xs  = insert xs e n |
  interpret-opers (Delete n)    xs  = delete xs n

definition element-ids :: (′id, ′v) elt list ⇒ ′id set where
 element-ids list ≡ set (map fst list)

definition valid-rga-msg :: (′id, ′v) elt list ⇒ ′id × (′id::linorder, ′v) operation ⇒ bool where
 valid-rga-msg list msg ≡ case msg of
    (i, Insert e  None      ) ⇒ fst e = i |
    (i, Insert e (Some pos)) ⇒ fst e = i ∧ pos ∈ element-ids list |
    (i, Delete           pos ) ⇒ pos ∈ element-ids list


locale rga = network-with-constrained-ops - interpret-opers [] valid-rga-msg

definition indices :: (′id × (′id, ′v) operation) event list ⇒ ′id list where
  indices xs ≡
     List.map-filter (λx. case x of Deliver (i, Insert e n) ⇒ Some (fst e) | - ⇒ None) xs

lemma indices-Nil [simp]:
  shows indices [] = []
⟨proof⟩

lemma indices-append [simp]:
  shows indices (xs@ys) = indices xs @ indices ys
⟨proof⟩
```

lemma *indices-Broadcast-singleton* [*simp*]:
  shows *indices* [*Broadcast b*] = []
⟨*proof*⟩

lemma *indices-Deliver-Insert* [*simp*]:
  shows *indices* [*Deliver* (*i*, *Insert e n*)] = [*fst e*]
⟨*proof*⟩

lemma *indices-Deliver-Delete* [*simp*]:
  shows *indices* [*Deliver* (*i*, *Delete n*)] = []
⟨*proof*⟩

lemma (**in** *rga*) *idx-in-elem-inserted* [*intro*]:
  assumes *Deliver* (*i*, *Insert e n*) ∈ *set xs*
  shows *fst e* ∈ *set* (*indices xs*)
⟨*proof*⟩

lemma (**in** *rga*) *apply-opers-idx-elems*:
  assumes *es prefix of i*
    and *apply-operations es* = *Some xs*
   shows *element-ids xs* = *set* (*indices es*)
⟨*proof*⟩

lemma (**in** *rga*) *delete-does-not-change-element-ids*:
  assumes *es* @ [*Deliver* (*i*, *Delete n*)] *prefix of j*
  and *apply-operations es* = *Some xs1*
  and *apply-operations* (*es* @ [*Deliver* (*i*, *Delete n*)]) = *Some xs2*
  shows *element-ids xs1* = *element-ids xs2*
⟨*proof*⟩

lemma (**in** *rga*) *someone-inserted-id*:
  assumes *es* @ [*Deliver* (*i*, *Insert* (*k*, *v*, *f*) *n*)] *prefix of j*
  and *apply-operations es* = *Some xs1*
  and *apply-operations* (*es* @ [*Deliver* (*i*, *Insert* (*k*, *v*, *f*) *n*)]) = *Some xs2*
  and *a* ∈ *element-ids xs2*
  and $a \neq k$
  shows *a* ∈ *element-ids xs1*
⟨*proof*⟩

lemma (**in** *rga*) *deliver-insert-exists*:
  assumes *es prefix of j*
    and *apply-operations es* = *Some xs*
    and *a* ∈ *element-ids xs*
   shows ∃ *i v f n*. *Deliver* (*i*, *Insert* (*a*, *v*, *f*) *n*) ∈ *set es*
⟨*proof*⟩

lemma (**in** *rga*) *insert-in-apply-set*:
  assumes *es* @ [*Deliver* (*i*, *Insert e* (*Some a*))] *prefix of j*
    and *Deliver* (*i*′, *Insert e*′ *n*) ∈ *set es*
    and *apply-operations es* = *Some s*
   shows *fst e*′ ∈ *element-ids s*
⟨*proof*⟩

lemma (**in** *rga*) *insert-msg-id*:
  assumes *Broadcast* (*i*, *Insert e n*) ∈ *set* (*history j*)
  shows *fst e* = *i*
⟨*proof*⟩

lemma (**in** *rga*) *allowed-insert*:
  assumes $Broadcast\ (i,\ Insert\ e\ n) \in set\ (history\ j)$
  shows $n = None \vee (\exists\, i'\ e'\ n'.\ n = Some\ (fst\ e') \wedge Deliver\ (i',\ Insert\ e'\ n') \sqsubset^j Broadcast\ (i,\ Insert\ e\ n))$
$\langle proof \rangle$

lemma (**in** *rga*) *allowed-delete*:
  assumes $Broadcast\ (i,\ Delete\ x) \in set\ (history\ j)$
  shows $\exists\, i'\ n'\ v\ b.\ Deliver\ (i',\ Insert\ (x,\ v,\ b)\ n') \sqsubset^j Broadcast\ (i,\ Delete\ x)$
$\langle proof \rangle$

lemma (**in** *rga*) *insert-id-unique*:
  assumes $fst\ e1 = fst\ e2$
  and $Broadcast\ (i1,\ Insert\ e1\ n1) \in set\ (history\ i)$
  and $Broadcast\ (i2,\ Insert\ e2\ n2) \in set\ (history\ j)$
  shows $Insert\ e1\ n1 = Insert\ e2\ n2$
$\langle proof \rangle$

lemma (**in** *rga*) *allowed-delete-deliver*:
  assumes $Deliver\ (i,\ Delete\ x) \in set\ (history\ j)$
    shows $\exists\, i'\ n'\ v\ b.\ Deliver\ (i',\ Insert\ (x,\ v,\ b)\ n') \sqsubset^j Deliver\ (i,\ Delete\ x)$
  $\langle proof \rangle$

lemma (**in** *rga*) *allowed-delete-deliver-in-set*:
  assumes $(es@[Deliver\ (i,\ Delete\ m)])$ *prefix of* j
  shows $\exists\, i'\ n\ v\ b.\ Deliver\ (i',\ Insert\ (m,\ v,\ b)\ n) \in set\ es$
$\langle proof \rangle$

lemma (**in** *rga*) *allowed-insert-deliver*:
  assumes $Deliver\ (i,\ Insert\ e\ n) \in set\ (history\ j)$
  shows $n = None \vee (\exists\, i'\ n'\ n''\ v\ b.\ n = Some\ n' \wedge Deliver\ (i',\ Insert\ (n',\ v,\ b)\ n'') \sqsubset^j Deliver\ (i,\ Insert\ e\ n))$
$\langle proof \rangle$

lemma (**in** *rga*) *allowed-insert-deliver-in-set*:
  assumes $(es@[Deliver\ (i,\ Insert\ e\ m)])$ *prefix of* j
  shows $m = None \vee (\exists\, i'\ m'\ n\ v\ b.\ m = Some\ m' \wedge Deliver\ (i',\ Insert\ (m',\ v,\ b)\ n) \in set\ es)$
$\langle proof \rangle$

lemma (**in** *rga*) *Insert-no-failure*:
  assumes $es\ @\ [Deliver\ (i,\ Insert\ e\ n)]$ *prefix of* j
    and $apply\text{-}operations\ es = Some\ s$
    shows $\exists\, ys.\ insert\ s\ e\ n = Some\ ys$
$\langle proof \rangle$

lemma (**in** *rga*) *delete-no-failure*:
  assumes $es\ @\ [Deliver\ (i,\ Delete\ n)]$ *prefix of* j
    and $apply\text{-}operations\ es = Some\ s$
    shows $\exists\, ys.\ delete\ s\ n = Some\ ys$
$\langle proof \rangle$

lemma (**in** *rga*) *Insert-equal*:
  assumes $fst\ e1 = fst\ e2$
    and $Broadcast\ (i1,\ Insert\ e1\ n1) \in set\ (history\ i)$
    and $Broadcast\ (i2,\ Insert\ e2\ n2) \in set\ (history\ j)$
    shows $Insert\ e1\ n1 = Insert\ e2\ n2$
$\langle proof \rangle$

lemma (**in** *rga*) *same-insert*:
assumes *fst e1* = *fst e2*
and *xs prefix of i*
and (*i1*, *Insert e1 n1*) ∈ *set* (*node-deliver-messages xs*)
and (*i2*, *Insert e2 n2*) ∈ *set* (*node-deliver-messages xs*)
shows *Insert e1 n1* = *Insert e2 n2*
⟨*proof*⟩

lemma (**in** *rga*) *insert-commute-assms*:
assumes {*Deliver* (*i*, *Insert e n*), *Deliver* (*i'*, *Insert e' n'*)} ⊆ *set* (*history j*)
and *hb.concurrent* (*i*, *Insert e n*) (*i'*, *Insert e' n'*)
shows *n* = *None* ∨ *n* ≠ *Some* (*fst e'*)
⟨*proof*⟩

lemma *subset-reorder*:
assumes {*a*, *b*} ⊆ *c*
shows {*b*, *a*} ⊆ *c*
⟨*proof*⟩

lemma (**in** *rga*) *Insert-Insert-concurrent*:
assumes {*Deliver* (*i*, *Insert e k*), *Deliver* (*i'*, *Insert e'* (*Some m*))} ⊆ *set* (*history j*)
and *hb.concurrent* (*i*, *Insert e k*) (*i'*, *Insert e'* (*Some m*))
shows *fst e* ≠ *m*
⟨*proof*⟩

lemma (**in** *rga*) *insert-valid-assms*:
assumes *Deliver* (*i*, *Insert e n*) ∈ *set* (*history j*)
shows *n* = *None* ∨ *n* ≠ *Some* (*fst e*)
⟨*proof*⟩

lemma (**in** *rga*) *Insert-Delete-concurrent*:
assumes {*Deliver* (*i*, *Insert e n*), *Deliver* (*i'*, *Delete n'*)} ⊆ *set* (*history j*)
and *hb.concurrent* (*i*, *Insert e n*) (*i'*, *Delete n'*)
shows *n'* ≠ *fst e*
⟨*proof*⟩

lemma (**in** *rga*) *concurrent-operations-commute*:
assumes *xs prefix of i*
shows *hb.concurrent-ops-commute* (*node-deliver-messages xs*)
⟨*proof*⟩

corollary (**in** *rga*) *concurrent-operations-commute'*:
shows *hb.concurrent-ops-commute* (*node-deliver-messages* (*history i*))
⟨*proof*⟩

lemma (**in** *rga*) *apply-operations-never-fails*:
assumes *xs prefix of i*
shows *apply-operations xs* ≠ *None*
⟨*proof*⟩

lemma (**in** *rga*) *apply-operations-never-fails'*:
shows *apply-operations* (*history i*) ≠ *None*
⟨*proof*⟩

corollary (**in** *rga*) *rga-convergence*:
assumes *set* (*node-deliver-messages xs*) = *set* (*node-deliver-messages ys*)
and *xs prefix of i*

and *ys prefix of j*
shows *apply-operations xs* = *apply-operations ys*
⟨*proof*⟩

5.7 Strong eventual consistency

context *rga* **begin**

sublocale *sec*: *strong-eventual-consistency weak-hb hb interp-msg*
λ*ops.*$\exists$ *xs i. xs prefix of i* $\wedge$ *node-deliver-messages xs* = *ops* []
⟨*proof*⟩

end

interpretation *trivial-rga-implementation*: *rga* $\lambda x.$ []
⟨*proof*⟩

end

6 Increment-Decrement Counter

The Increment-Decrement Counter is perhaps the simplest CRDT, and a paradigmatic example of a replicated data structure with commutative operations.

theory
Counter
imports
Network
begin

datatype *operation* = *Increment* | *Decrement*

fun *counter-op* :: *operation* $\Rightarrow$ *int* $\rightharpoonup$ *int* **where**
counter-op Increment x = *Some* (*x* + *1*) |
counter-op Decrement x = *Some* (*x* − *1*)

locale *counter* = *network-with-ops* - *counter-op 0*

lemma (**in** *counter*) *counter-op x* $\rhd$ *counter-op y* = *counter-op y* $\rhd$ *counter-op x*
⟨*proof*⟩

lemma (**in** *counter*) *concurrent-operations-commute*:
assumes *xs prefix of i*
shows *hb.concurrent-ops-commute* (*node-deliver-messages xs*)
⟨*proof*⟩

corollary (**in** *counter*) *counter-convergence*:
assumes *set* (*node-deliver-messages xs*) = *set* (*node-deliver-messages ys*)
and *xs prefix of i*
and *ys prefix of j*
shows *apply-operations xs* = *apply-operations ys*
⟨*proof*⟩

context *counter* **begin**

sublocale *sec*: *strong-eventual-consistency weak-hb hb interp-msg*
λ*ops.* $\exists$ *xs i. xs prefix of i* $\wedge$ *node-deliver-messages xs* = *ops 0*
⟨*proof*⟩

end
end

7 Observed-Remove Set

The ORSet is a well-known CRDT for implementing replicated sets, supporting two operations: the *insertion* and *deletion* of an arbitrary element in the shared set.

theory
  ORSet
imports
  Network
begin

datatype $('id, 'a)$ *operation* $=$ *Add* $'id$ $'a$ $|$ *Rem* $'id$ *set* $'a$

type-synonym $('id, 'a)$ *state* $= 'a \Rightarrow 'id$ *set*

definition *op-elem* :: $('id, 'a)$ *operation* $\Rightarrow 'a$ **where**
  op-elem oper $\equiv$ *case oper of Add i e* $\Rightarrow$ *e* $|$ *Rem is e* $\Rightarrow$ *e*

definition *interpret-op* :: $('id, 'a)$ *operation* $\Rightarrow ('id, 'a)$ *state* $\rightharpoonup ('id, 'a)$ *state* $(\langle\text{-}\rangle\ [0]\ 1000)$ **where**
  interpret-op oper state $\equiv$
    let before $=$ *state* (*op-elem oper*);
        after $=$ *case oper of Add i e* $\Rightarrow$ *before* $\cup \{i\}$ $|$ *Rem is e* $\Rightarrow$ *before* $-$ *is*
    in Some (*state* ((*op-elem oper*) := *after*))

definition *valid-behaviours* :: $('id, 'a)$ *state* $\Rightarrow 'id \times ('id, 'a)$ *operation* $\Rightarrow$ *bool* **where**
  valid-behaviours state msg $\equiv$
    case msg of
      $(i,$ *Add j e*$) \Rightarrow i = j$ $|$
      $(i,$ *Rem is e*$) \Rightarrow$ *is* $=$ *state e*

locale *orset* $=$ *network-with-constrained-ops* - *interpret-op* $\lambda x.\ \{\}$ *valid-behaviours*

lemma (**in** *orset*) *add-add-commute*:
  shows $\langle$*Add i1 e1*$\rangle \rhd \langle$*Add i2 e2*$\rangle = \langle$*Add i2 e2*$\rangle \rhd \langle$*Add i1 e1*$\rangle$
  $\langle$*proof*$\rangle$

lemma (**in** *orset*) *add-rem-commute*:
  assumes $i \notin$ *is*
  shows $\langle$*Add i e1*$\rangle \rhd \langle$*Rem is e2*$\rangle = \langle$*Rem is e2*$\rangle \rhd \langle$*Add i e1*$\rangle$
  $\langle$*proof*$\rangle$

lemma (**in** *orset*) *apply-operations-never-fails*:
  assumes *xs prefix of i*
  shows *apply-operations xs* $\neq$ *None*
$\langle$*proof*$\rangle$

lemma (**in** *orset*) *add-id-valid*:
  assumes *xs prefix of j*
    and *Deliver* (*i1*, *Add i2 e*) $\in$ *set xs*
  shows *i1* $=$ *i2*
$\langle$*proof*$\rangle$

definition (**in** *orset*) *added-ids* :: $('id \times ('id, 'b)$ *operation*$)$ *event list* $\Rightarrow 'b \Rightarrow 'id$ *list* **where**
  added-ids es p $\equiv$ *List.map-filter* ($\lambda x.$ *case x of Deliver* (i, *Add j e*) $\Rightarrow$ *if e* $=$ *p then Some j else None*

| - ⇒ *None*) *es*

lemma (**in** *orset*) [*simp*]:
shows *added-ids* [] e = []
⟨*proof*⟩

lemma (**in** *orset*) [*simp*]:
shows *added-ids* (*xs* @ *ys*) e = *added-ids xs e* @ *added-ids ys e*
⟨*proof*⟩

lemma (**in** *orset*) *added-ids-Broadcast-collapse* [*simp*]:
shows *added-ids* ([*Broadcast e*]) e' = []
⟨*proof*⟩

lemma (**in** *orset*) *added-ids-Deliver-Rem-collapse* [*simp*]:
shows *added-ids* ([*Deliver* (*i*, *Rem is e*)]) e' = []
⟨*proof*⟩

lemma (**in** *orset*) *added-ids-Deliver-Add-diff-collapse* [*simp*]:
shows $e \neq e' \Longrightarrow$ *added-ids* ([*Deliver* (*i*, *Add j e*)]) e' = []
⟨*proof*⟩

lemma (**in** *orset*) *added-ids-Deliver-Add-same-collapse* [*simp*]:
shows *added-ids* ([*Deliver* (*i*, *Add j e*)]) e = [*j*]
⟨*proof*⟩

lemma (**in** *orset*) *added-id-not-in-set*:
assumes *i1* ∉ *set* (*added-ids* [*Deliver* (*i*, *Add i2 e*)] *e*)
shows *i1* ≠ *i2*
⟨*proof*⟩

lemma (**in** *orset*) *apply-operations-added-ids*:
assumes *es prefix of j*
and *apply-operations es* = *Some f*
shows *f x* ⊆ *set* (*added-ids es x*)
⟨*proof*⟩

lemma (**in** *orset*) *Deliver-added-ids*:
assumes *xs prefix of j*
and *i* ∈ *set* (*added-ids xs e*)
shows *Deliver* (*i*, *Add i e*) ∈ *set xs*
⟨*proof*⟩

lemma (**in** *orset*) *Broadcast-Deliver-prefix-closed*:
assumes *xs* @ [*Broadcast* (*r*, *Rem ix e*)] *prefix of j*
and *i* ∈ *ix*
shows *Deliver* (*i*, *Add i e*) ∈ *set xs*
⟨*proof*⟩

lemma (**in** *orset*) *Broadcast-Deliver-prefix-closed2*:
assumes *xs prefix of j*
and *Broadcast* (*r*, *Rem ix e*) ∈ *set xs*
and *i* ∈ *ix*
shows *Deliver* (*i*, *Add i e*) ∈ *set xs*
⟨*proof*⟩

lemma (**in** *orset*) *concurrent-add-remove-independent-technical*:
assumes *i* ∈ *is*

and *xs prefix of j*
and (*i*, *Add i e*) ∈ *set* (*node-deliver-messages xs*) **and** (*ir*, *Rem is e*) ∈ *set* (*node-deliver-messages xs*)
shows *hb* (*i*, *Add i e*) (*ir*, *Rem is e*)
⟨*proof*⟩

lemma (**in** *orset*) *Deliver-Add-same-id-same-message*:
assumes *Deliver* (*i*, *Add i e1*) ∈ *set* (*history j*) **and** *Deliver* (*i*, *Add i e2*) ∈ *set* (*history j*)
shows $e1 = e2$
⟨*proof*⟩

lemma (**in** *orset*) *ids-imply-messages-same*:
assumes $i \in is$
and *xs prefix of j*
and (*i*, *Add i e1*) ∈ *set* (*node-deliver-messages xs*) **and** (*ir*, *Rem is e2*) ∈ *set* (*node-deliver-messages xs*)
shows $e1 = e2$
⟨*proof*⟩

corollary (**in** *orset*) *concurrent-add-remove-independent*:
assumes ¬ *hb* (*i*, *Add i e1*) (*ir*, *Rem is e2*) **and** ¬ *hb* (*ir*, *Rem is e2*) (*i*, *Add i e1*)
and *xs prefix of j*
and (*i*, *Add i e1*) ∈ *set* (*node-deliver-messages xs*) **and** (*ir*, *Rem is e2*) ∈ *set* (*node-deliver-messages xs*)
shows $i \notin is$
⟨*proof*⟩

lemma (**in** *orset*) *rem-rem-commute*:
shows ⟨*Rem i1 e1*⟩ ▷ ⟨*Rem i2 e2*⟩ = ⟨*Rem i2 e2*⟩ ▷ ⟨*Rem i1 e1*⟩
⟨*proof*⟩

lemma (**in** *orset*) *concurrent-operations-commute*:
assumes *xs prefix of i*
shows *hb.concurrent-ops-commute* (*node-deliver-messages xs*)
⟨*proof*⟩

theorem (**in** *orset*) *convergence*:
assumes *set* (*node-deliver-messages xs*) = *set* (*node-deliver-messages ys*)
and *xs prefix of i* **and** *ys prefix of j*
shows *apply-operations xs* = *apply-operations ys*
⟨*proof*⟩

context *orset* **begin**

sublocale *sec*: *strong-eventual-consistency weak-hb hb interp-msg*
$\lambda ops.\exists\, xs\ i.\ xs\ prefix\ of\ i \wedge node\text{-}deliver\text{-}messages\ xs = ops\ \lambda x.\{\}$
⟨*proof*⟩

end
end

References

[1] P. S. Almeida, A. Shoker, and C. Baquero. Efficient state-based CRDTs by delta-mutation. In *International Conference on Networked Systems (NETYS)*, May 2015.

[2] C. Baquero, P. S. Almeida, and A. Shoker. Making operation-based CRDTs operation-

based. In *14th IFIP International Conference on Distributed Applications and Interoperable Systems (DAIS)*, pages 126–140, June 2014.

[3] R. Brown, S. Cribbs, C. Meiklejohn, and S. Elliott. Riak DT map: a composable, convergent replicated dictionary. In *1st Workshop on Principles and Practice of Eventual Consistency (PaPEC)*, Apr. 2014.

[4] C. Cachin, R. Guerraoui, and L. Rodrigues. *Introduction to Reliable and Secure Distributed Programming*. Springer, second edition, Feb. 2011.

[5] J. Day-Richter. What's different about the new Google Docs: Making collaboration fast, Sept. 2010.

[6] A. Imine, P. Molli, G. Oster, and M. Rusinowitch. Proving correctness of transformation functions in real-time groupware. In *8th European Conference on Computer-Supported Cooperative Work (ECSCW)*, pages 277–293, Sept. 2003.

[7] A. Imine, M. Rusinowitch, G. Oster, and P. Molli. Formal design and verification of operational transformation algorithms for copies convergence. *Theoretical Computer Science*, 351(2):167–183, Feb. 2006.

[8] L. Lamport. Time, clocks, and the ordering of events in a distributed system. *Communications of the ACM*, 21(7):558–565, July 1978.

[9] G. Oster, P. Urso, P. Molli, and A. Imine. Proving correctness of transformation functions in collaborative editing systems. Technical Report RR-5795, Dec. 2005.

[10] H.-G. Roh, M. Jeon, J.-S. Kim, and J. Lee. Replicated abstract data types: Building blocks for collaborative applications. *Journal of Parallel and Distributed Computing*, 71(3):354–368, 2011.

[11] M. Shapiro, N. Preguiça, C. Baquero, and M. Zawirski. A comprehensive study of convergent and commutative replicated data types. Technical Report 7506, INRIA, 2011.

[12] M. Shapiro, N. Preguiça, C. Baquero, and M. Zawirski. Conflict-free replicated data types. In *13th International Symposium on Stabilization, Safety, and Security of Distributed Systems (SSS)*, pages 386–400, Oct. 2011.

[13] M. Wenzel, L. C. Paulson, and T. Nipkow. The Isabelle framework. In *Theorem Proving in Higher Order Logics, 21st International Conference, TPHOLs 2008, Montreal, Canada, August 18-21, 2008. Proceedings*, pages 33–38, 2008.