Refinement Calculus of Reactive Systems: Isabelle Theories

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Abstract

This document contains the Isabelle theories of the Refinement Calculus of Reactive Systems (RCRS). It has been automatically generated by Isabelle from the corresponding theories. For an overview of RCRS, the reader is referred primarily to [1, 2]. Additional papers about RCRS are [3, 4, 5, 6, 7, 8]. A precursor of RCRS is the theory of relational interfaces [9].

- Section 1 formalizes the Refinement Calculus [10] and auxiliary concepts needed for RCRS.
- Section 2 formalizes complete distributive lattices.
- Section 3 formalizes linear temporal logic.
- Section 4 formalizes monotonic property transformers, which form the semantic foundation of RCRS.
- Section 5 gives an overview of RCRS following closely the paper [1]. The section numbers in the subsections/subsubsections of Section 5 in the table of contents below refer to the sections of paper [1].
- Section 6 formalizes instantaneous feedback as presented in [4].
- Section 7 formalizes Simulink in RCRS [6, 3].
- Section 8 formalizes list operations and proves properties used in Section 9.
- Section 9 formalizes the hierarchical block diagram translation algorithms presented in [6] and proves that these algorithms yield semantically equivalent results, as presented in [5].

Contents

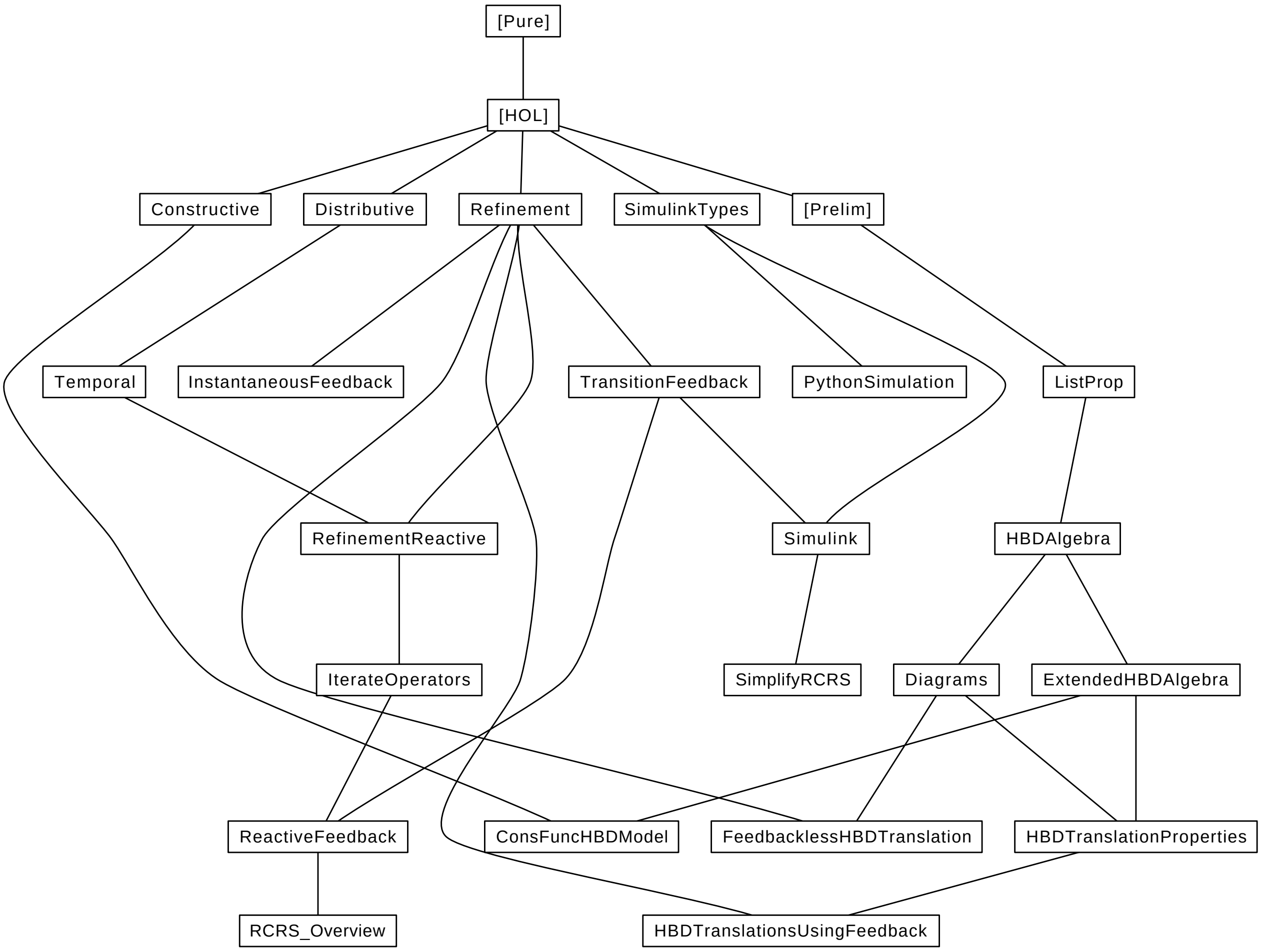

Figure 1: Dependency graph of RCRS Isabelle theories.

1 Refinement Calculus and Monotonic Predicate Transformers

theory *Refinement* **imports** *Main*
begin

In this section we introduce the basics of refinement calculus [10]. Part of this theory is a reformulation of some definitions from [11], but here they are given for predicates, while [11] uses sets.

notation
bot ($\bot$) **and**
top ($\top$) **and**
inf (**infixl** $\sqcap$ *70*)
and *sup* (**infixl** $\sqcup$ *65*)

1.1 Basic predicate transformers

definition
demonic :: ('a => 'b::lattice) => 'b => 'a ⇒ bool ([: - :] [0] 1000) **where**
$[:Q:]\ p\ s = (Q\ s \leq p)$

definition
assert::'a::semilattice-inf => 'a => 'a ({. - .} [0] 1000) **where**
$\{.p.\}\ q \equiv\ p \sqcap q$

definition
assume::('a::boolean-algebra) => 'a => 'a ([. - .] [0] 1000) **where**
$[.p.]\ q \equiv\ (-p \sqcup q)$

definition
angelic :: ('a ⇒ 'b::{semilattice-inf,order-bot}) ⇒ 'b ⇒ 'a ⇒ bool ({: - :} [0] 1000) **where**
$\{:Q:\}\ p\ s = (Q\ s \sqcap p \neq \bot)$

syntax

-assert :: *patterns* => *logic* => *logic* $((1\{.\text{-}.\text{-}.\}))$
translations
-assert x P == *CONST assert* (*-abs* x P)

syntax
-demonic :: *patterns* => *patterns* => *logic* => *logic* $(([:\text{-}\leadsto\text{-}.\text{-}:]))$
translations
-demonic x y t == (*CONST demonic* (*-abs* x (*-abs* y t)))

syntax
-angelic :: *patterns* => *patterns* => *logic* => *logic* $((\{:\text{-} \leadsto \text{-}.\text{-}:\}))$
translations
-angelic x y t == (*CONST angelic* (*-abs* x (*-abs* y t)))

lemma *assert-o-def*: $\{.f\ o\ g.\} = \{.(\lambda\ x\ .\ f\ (g\ x)).\}$

lemma *demonic-demonic*: $[:r:]\ o\ [:r':] = [:r\ OO\ r':]$

lemma *assert-demonic-comp*: $\{.p.\}\ o\ [:r:]\ o\ \{.p'.\}\ o\ [:r':] =$
$\{.x\ .\ p\ x \wedge (\forall\ y\ .\ r\ x\ y \longrightarrow p'\ y).\}\ o\ [:r\ OO\ r':]$

lemma *demonic-assert-comp*: $[:r:]\ o\ \{.p.\} = \{.x.(\forall\ y\ .\ r\ x\ y \longrightarrow p\ y).\}\ o\ [:r:]$

lemma *assert-assert-comp*: $\{.p{::}'a{::}lattice.\}\ o\ \{.p'.\} = \{.p \sqcap p'.\}$

lemma *assert-assert-comp-pred*: $\{.p.\}\ o\ \{.p'.\} = \{.x\ .\ p\ x \wedge p'\ x.\}$

lemma *demonic-refinement*: $r' \leq r \Longrightarrow [:r:] \leq [:r':]$

definition *inpt* $r\ x = (\exists\ y\ .\ r\ x\ y)$

definition *trs* :: $('a => 'b \Rightarrow bool) => ('b \Rightarrow bool) => 'a \Rightarrow bool$ $(\{:\ \text{-}\ :]\ [0]\ 1000)$ **where**
trs $r = \{.\ inpt\ r.\}\ o\ [:r:]$

syntax
-trs :: *patterns* => *patterns* => *logic* => *logic* $((\{:\text{-}\leadsto\text{-}.\text{-}:]))$
translations
-trs x y t == (*CONST trs* (*-abs* x (*-abs* y t)))

lemma *assert-demonic-prop*: $\{.p.\}\ o\ [:r:] = \{.p.\}\ o\ [:(\lambda\ x\ y\ .\ p\ x) \sqcap r:]$

lemma *trs-trs*: $(trs\ r)\ o\ (trs\ r')$
$= trs\ ((\lambda\ s\ t.\ (\forall\ s'\ .\ r\ s\ s' \longrightarrow (inpt\ r'\ s'))) \sqcap (r\ OO\ r'))$ (**is** $?S = ?T$)

lemma *prec-inpt-equiv*: $p \leq inpt\ r \Longrightarrow r' = (\lambda\ x\ y\ .\ p\ x \wedge r\ x\ y) \Longrightarrow \{.p.\}\ o\ [:r:] = \{:r':]$

lemma *assert-demonic-refinement*: $(\{.p.\}\ o\ [:r:] \leq \{.p'.\}\ o\ [:r':]) = (p \leq p' \wedge (\forall\ x\ .\ p\ x \longrightarrow r'\ x \leq r\ x))$

lemma *spec-demonic-refinement*: $(\{.p.\}\ o\ [:r:] \leq [:r':]) = (\forall\ x\ .\ p\ x \longrightarrow r'\ x \leq r\ x)$

lemma *trs-refinement*: $(trs\ r \le trs\ r') = ((\forall\ x\ .\ inpt\ r\ x \longrightarrow inpt\ r'\ x) \wedge (\forall\ x\ .\ inpt\ r\ x \longrightarrow r'\ x \le r\ x))$

lemma *demonic-choice*: $[:r:] \sqcap [:r':] = [:r \sqcup r':]$

lemma *spec-demonic-choice*: $(\{.p.\}\ o\ [:r:]) \sqcap (\{.p'.\}\ o\ [:r':]) = (\{.p \sqcap p'.\}\ o\ [:r \sqcup r':])$

lemma *trs-demonic-choice*: $trs\ r \sqcap trs\ r' = trs\ ((\lambda\ x\ y\ .\ inpt\ r\ x \wedge inpt\ r'\ x) \sqcap (r \sqcup r'))$

lemma *spec-angelic*: $p \sqcap p' = \bot \Longrightarrow (\{.p.\}\ o\ [:r:]) \sqcup (\{.p'.\}\ o\ [:r':])$
$= \{.p \sqcup p'.\}\ o\ [:(\lambda\ x\ y\ .\ p\ x \longrightarrow r\ x\ y) \sqcap ((\lambda\ x\ y\ .\ p'\ x \longrightarrow r'\ x\ y)):]$

1.2 Conjunctive predicate transformers

definition *conjunctive* $(S::'a::complete\text{-}lattice \Rightarrow 'b::complete\text{-}lattice) = (\forall\ Q\ .\ S\ (Inf\ Q) = INFIMUM\ Q\ S)$

definition *sconjunctive* $(S::'a::complete\text{-}lattice \Rightarrow 'b::complete\text{-}lattice) = (\forall\ Q\ .\ (\exists\ x\ .\ x \in Q) \longrightarrow S\ (Inf\ Q) = INFIMUM\ Q\ S)$

lemma *conjunctive-sconjunctive*[*simp*]: *conjunctive* $S \Longrightarrow$ *sconjunctive* S

lemma [*simp*]: *conjunctive* $\top$

lemma *conjuncive-demonic* [*simp*]: *conjunctive* $[:r:]$

lemma *sconjunctive-assert* [*simp*]: *sconjunctive* $\{.p.\}$

lemma *sconjunctive-simp*: $x \in Q \Longrightarrow$ *sconjunctive* $S \Longrightarrow S\ (Inf\ Q) = INFIMUM\ Q\ S$

lemma *sconjunctive-INF-simp*: $x \in X \Longrightarrow$ *sconjunctive* $S \Longrightarrow S\ (INFIMUM\ X\ Q) = INFIMUM\ (Q`X)\ S$

lemma *demonic-comp* [*simp*]: *sconjunctive* $S \Longrightarrow$ *sconjunctive* $S' \Longrightarrow$ *sconjunctive* $(S\ o\ S')$

lemma *conjunctive-INF*[*simp*]:*conjunctive* $S \Longrightarrow S\ (INFIMUM\ X\ Q) = (INFIMUM\ X\ (S\ o\ Q))$

lemma *conjunctive-simp*: *conjunctive* $S \Longrightarrow S\ (Inf\ Q) = INFIMUM\ Q\ S$

lemma *conjunctive-monotonic* [*simp*]: *sconjunctive* $S \Longrightarrow$ *mono* S

definition $grd\ S = -\ S\ \bot$

lemma *grd-demonic*: $grd\ [:r:] = inpt\ r$

lemma $(S::'a::bot \Rightarrow 'b::boolean\text{-}algebra) \le S' \Longrightarrow grd\ S' \le grd\ S$

lemma [*simp*]: $inpt\ (\lambda x\ y.\ p\ x \wedge r\ x\ y) = p \sqcap inpt\ r$

lemma [*simp*]: $p \le inpt\ r \Longrightarrow p \sqcap inpt\ r = p$

lemma *grd-spec*: $grd\ (\{.p.\}\ o\ [:r:]) = -p \sqcup inpt\ r$

definition $\mathit{fail}\ S = -(S\ \top)$
definition $\mathit{term}\ S = (S\ \top)$
definition $\mathit{prec}\ S = -\ (\mathit{fail}\ S)$
definition $\mathit{rel}\ S = (\lambda\ x\ y\ .\ \neg\ S\ (\lambda\ z\ .\ y \neq z)\ x)$

lemma $\mathit{rel\text{-}spec}$: $\mathit{rel}\ (\{.p.\}\ o\ [:r:])\ x\ y = (p\ x \longrightarrow r\ x\ y)$

lemma $\mathit{prec\text{-}spec}$: $\mathit{prec}\ (\{.p.\}\ o\ [:r::'a \Rightarrow 'b \Rightarrow \mathit{bool}:]) = p$

lemma $\mathit{fail\text{-}spec}$: $\mathit{fail}\ (\{.p.\}\ o\ [:(r::'a \Rightarrow 'b::\mathit{boolean\text{-}algebra}):]) = -p$

lemma $[\mathit{simp}]$: $\mathit{prec}\ (\{.p.\}\ o\ [:(r::'a \Rightarrow 'b::\mathit{boolean\text{-}algebra}):]) = p$

lemma $[\mathit{simp}]$: $\mathit{prec}\ (T::('a::\mathit{boolean\text{-}algebra} \Rightarrow\ 'b::\mathit{boolean\text{-}algebra})) = \top \Longrightarrow \mathit{prec}\ (S\ o\ T) = \mathit{prec}\ S$

lemma $[\mathit{simp}]$: $\mathit{prec}\ [:r::'a \Rightarrow\ 'b::\mathit{boolean\text{-}algebra}:] = \top$

lemma $\mathit{prec\text{-}rel}$: $\{.\ p\ .\} \circ [:\ \lambda x\ y.\ p\ x \wedge r\ x\ y\ :] = \{.p.\}\ o\ [:r:]$

definition $\mathit{Fail} = \bot$

lemma $\mathit{Fail\text{-}assert\text{-}demonic}$: $\mathit{Fail} = \{.\bot.\}\ o\ [:r:]$

lemma $\mathit{Fail\text{-}assert}$: $\mathit{Fail} = \{.\bot.\}\ o\ [:\bot:]$

lemma $\mathit{fail\text{-}comp}[\mathit{simp}]$: $\bot\ o\ S = \bot$

lemma $\mathit{Fail\text{-}fail}$: $\mathit{mono}\ (S::'a::\mathit{boolean\text{-}algebra} \Rightarrow\ 'b::\mathit{boolean\text{-}algebra}) \Longrightarrow (S = \mathit{Fail}) = (\mathit{fail}\ S = \top)$

lemma $\mathit{sconjunctive\text{-}spec}$: $\mathit{sconjunctive}\ S \Longrightarrow S = \{.\mathit{prec}\ S.\}\ o\ [:\mathit{rel}\ S:]$

definition $\mathit{non\text{-}magic}\ S = (S\ \bot = \bot)$

lemma $\mathit{non\text{-}magic\text{-}spec}$: $\mathit{non\text{-}magic}\ (\{.p.\}\ o\ [:r:]) = (p \leq \mathit{inpt}\ r)$

lemma $\mathit{sconjunctive\text{-}non\text{-}magic}$: $\mathit{sconjunctive}\ S \Longrightarrow \mathit{non\text{-}magic}\ S = (\mathit{prec}\ S \leq \mathit{inpt}\ (\mathit{rel}\ S))$

definition $\mathit{implementable}\ S = (\mathit{sconjunctive}\ S \wedge \mathit{non\text{-}magic}\ S)$

lemma $\mathit{implementable\text{-}spec}$: $\mathit{implementable}\ S \Longrightarrow \exists\ p\ r\ .\ S = \{.p.\}\ o\ [:r:] \wedge p \leq \mathit{inpt}\ r$

definition $\mathit{Skip} = (\mathit{id}::\ ('a \Rightarrow \mathit{bool}) \Rightarrow ('a \Rightarrow \mathit{bool}))$

lemma $\mathit{assert\text{-}true\text{-}skip}$: $\{.\top::'a \Rightarrow \mathit{bool}.\} = \mathit{Skip}$

lemma $\mathit{skip\text{-}comp}\ [\mathit{simp}]$: $\mathit{Skip}\ o\ S = S$

lemma $\mathit{comp\text{-}skip}[\mathit{simp}]$:$S\ o\ \mathit{Skip} = S$

lemma $\mathit{assert\text{-}rel\text{-}skip}[\mathit{simp}]$: $\{.\ \lambda\ (x,\ y)\ .\ \mathit{True}\ .\} = \mathit{Skip}$

lemma [*simp*]: $mono\ S \Longrightarrow mono\ S' \Longrightarrow mono\ (S\ o\ S')$

lemma [*simp*]: $mono\ \{.p::('a \Rightarrow bool).\}$

lemma [*simp*]: $mono\ [:r::('a \Rightarrow 'b \Rightarrow bool):]$

lemma *assert-true-skip-a*: $\{.\ x\ .\ True\ .\} = Skip$

lemma *assert-false-fail*: $\{.\bot::'a::boolean\text{-}algebra.\} = \bot$

lemma *magoc-comp*[*simp*]: $\top\ o\ S = \top$

lemma *left-comp*: $T\ o\ U = T'\ o\ U' \Longrightarrow S\ o\ T\ o\ U = S\ o\ T'\ o\ U'$

lemma *assert-demonic*: $\{.p.\}\ o\ [:r:] = \{.p.\}\ o\ [:x \ \rightsquigarrow y\ .\ p\ x \wedge r\ x\ y:]$

lemma $trs\ r \sqcap trs\ r' = trs\ (\lambda\ x\ y\ .\ inpt\ r\ x \wedge inpt\ r'\ x \wedge (r\ x\ y \vee r'\ x\ y))$

lemma *mono-assert*[*simp*]: $mono\ \{.p.\}$

lemma *mono-assume*[*simp*]: $mono\ [.p.]$

lemma *mono-demonic*[*simp*]: $mono\ [:r:]$

lemma *mono-comp-a*[*simp*]: $mono\ S \Longrightarrow mono\ T \Longrightarrow mono\ (S\ o\ T)$

lemma *mono-demonic-choice*[*simp*]: $mono\ S \Longrightarrow mono\ T \Longrightarrow mono\ (S \sqcap T)$

lemma *mono-Skip*[*simp*]: $mono\ Skip$

lemma *mono-comp*: $mono\ S \Longrightarrow S \le S' \Longrightarrow T \le T' \Longrightarrow S\ o\ T \le S'\ o\ T'$

lemma *sconjunctive-simp-a*: $sconjunctive\ S \Longrightarrow prec\ S = p \Longrightarrow rel\ S = r \Longrightarrow S = \{.p.\}\ o\ [:r:]$

lemma *sconjunctive-simp-b*: $sconjunctive\ S \Longrightarrow prec\ S = \top \Longrightarrow rel\ S = r \Longrightarrow S = [:r:]$

lemma *sconj-Fail*[*simp*]: $sconjunctive\ Fail$

lemma *sconjunctive-simp-c*: $sconjunctive\ (S::('a \Rightarrow bool) \Rightarrow 'b \Rightarrow bool) \Longrightarrow prec\ S = \bot \Longrightarrow S = Fail$

lemma *demonic-eq-skip*: $[:\ op = :] = Skip$

definition $Havoc = [:\top:]$

definition $Magic = [:\bot::'a \Rightarrow 'b::boolean\text{-}algebra:]$

lemma *Magic-top*: $Magic = \top$

lemma [*simp*]: $Magic \neq Fail$

lemma *Havoc-Fail*[*simp*]: $Havoc\ o\ (Fail::'a \Rightarrow 'b \Rightarrow bool) = Fail$

lemma *demonic-havoc*: $[:\ \lambda x\ (x',\ y).\ True\ :] = Havoc$

lemma [*simp*]: *mono Magic*

lemma *demonic-false-magic*: $[: \lambda(x,\ y)\ (u,\ v).\ \mathit{False}\ :] = \mathit{Magic}$

lemma *demonic-magic*[*simp*]: $[:r:]\ o\ \mathit{Magic} = \mathit{Magic}$

lemma *magic-comp*[*simp*]: $\mathit{Magic}\ o\ S = \mathit{Magic}$

lemma *hvoc-magic*[*simp*]: $\mathit{Havoc} \circ \mathit{Magic} = \mathit{Magic}$

lemma $\mathit{Havoc}\ \top = \top$

lemma *Skip-id*[*simp*]: $\mathit{Skip}\ p = p$

lemma *demonic-pair-skip*: $[:\ x,\ y \leadsto u,\ v.\ x = u \wedge y = v\ :] = \mathit{Skip}$

lemma *comp-demonic-demonic*: $S\ o\ [:r:]\ o\ [:r':] = S\ o\ [:r\ OO\ r':]$

lemma *comp-demonic-assert*: $S\ o\ [:r:]\ o\ \{.p.\} = S\ o\ \{.\ x.\ \forall y\ .\ r\ x\ y \longrightarrow p\ y\ .\}\ o\ [:r:]$

lemma *assert-demonic-eq-demonic*: $(\{.p.\}\ o\ [:r::'a \Rightarrow 'b \Rightarrow \mathit{bool}:] = [:r:]) = (\forall\ x\ .\ p\ x)$

lemma *trs-inpt-top*: $\mathit{inpt}\ r = \top \Longrightarrow \mathit{trs}\ r = [:r:]$

1.3 Product and Fusion of predicate transformers

In this section we define the fusion and product operators from [12]. The fusion of two programs S and T is intuitively equivalent with the parallel execution of the two programs. If S and T assign nondeterministically some value to some program variable x, then the fusion of S and T will assign a value to x which can be assigned by both S and T.

definition *fusion* $:: (('a \Rightarrow \mathit{bool}) \Rightarrow ('b \Rightarrow \mathit{bool})) \Rightarrow (('a \Rightarrow \mathit{bool}) \Rightarrow ('b \Rightarrow \mathit{bool})) \Rightarrow (('a \Rightarrow \mathit{bool}) \Rightarrow ('b \Rightarrow \mathit{bool}))$ (**infixl** $\parallel$ *70*) **where**
$(S \parallel S')\ q\ x = (\exists\ (p::'a \Rightarrow \mathit{bool})\ p'\ .\ p \sqcap p' \le q \wedge S\ p\ x \wedge S'\ p'\ x)$

lemma *fusion-demonic*: $[:r:] \parallel [:r':] = [:r \sqcap r':]$

lemma *fusion-spec*: $(\{.p.\} \circ [:r:]) \parallel (\{.p'.\} \circ [:r':]) = (\{.p \sqcap p'.\} \circ [:r \sqcap r':])$

lemma *fusion-assoc*: $S \parallel (T \parallel U) = (S \parallel T) \parallel U$

lemma *fusion-refinement*: $S \le T \Longrightarrow S' \le T' \Longrightarrow S \parallel S' \le T \parallel T'$

lemma $\mathit{conjunctive}\ S \Longrightarrow S \parallel \top = \top$

lemma *fusion-spec-local*: $a \in \mathit{init} \Longrightarrow ([:\ x \leadsto u,\ y\ .\ u \in \mathit{init} \wedge x = y\ :] \circ \{.p.\} \circ [:r:]) \parallel (\{.p'.\} \circ [:r':])$

$= [:\ x \leadsto u,\ y\ .\ u \in \mathit{init} \wedge x = y\ :] \circ \{.u,x\ .\ p\ (u,\ x) \wedge p'\ x.\} \circ [:u,\ x \leadsto y\ .\ r\ (u,\ x)\ y \wedge r'\ x\ y:]$
(**is** $?p \Longrightarrow ?S = ?T$)

lemma *fusion-demonic-idemp* [*simp*]: $[:r:] \parallel [:r:] = [:r:]$

lemma *fusion-spec-local-a*: $a \in init \Longrightarrow ([:x \leadsto u,\ y\ .\ u \in init \wedge x = y:] \circ \{.p.\} \circ [:r:]) \parallel [:r':]$
$= ([:x \leadsto u,\ y\ .\ u \in init \wedge x = y:] \circ \{.p.\} \circ [:u,\ x \leadsto y\ .\ r\ (u,\ x)\ y \wedge r'\ x\ y:])$

lemma *fusion-local-refinement*:
$a \in init \Longrightarrow (\bigwedge x\ u\ y\ .\ u \in init \Longrightarrow p'\ x \Longrightarrow r\ (u,\ x)\ y \Longrightarrow r'\ x\ y) \Longrightarrow$
$\{.p'.\}\ o\ (([:x \leadsto u,\ y\ .\ u \in init \wedge x = y:] \circ \{.p.\} \circ [:r:]) \parallel [:r':]) \leq [:x \leadsto u,\ y\ .\ u \in init \wedge x = y:]$
$\circ \{.p.\} \circ [:r:]$

lemma *fusion-spec-demonic*: $(\{.p.\}\ o\ [:r:]) \parallel [:r':] = \{.p.\}\ o\ [:r \sqcap r':]$

definition *Fusion* :: $('c \Rightarrow (('a \Rightarrow bool) \Rightarrow ('b \Rightarrow bool))) \Rightarrow (('a \Rightarrow bool) \Rightarrow ('b \Rightarrow bool))$ **where**
$Fusion\ S\ q\ x = (\exists\ (p::'c \Rightarrow 'a \Rightarrow bool)\ .\ (INF\ c\ .\ p\ c) \leq q \wedge (\forall\ c\ .\ (S\ c)\ (p\ c)\ x))$

lemma *Fusion-spec*: $Fusion\ (\lambda\ n\ .\ \{.p\ n.\} \circ [:r\ n:]) = (\{.INFIMUM\ UNIV\ p.\} \circ [:INFIMUM\ UNIV$
$r:])$

lemma *Fusion-demonic*: $Fusion\ (\lambda\ n\ .\ [:r\ n:]) = [:INF\ n\ .\ r\ n:]$

lemma *Fusion-refinement*: $(\bigwedge\ i\ .\ S\ i \leq T\ i) \Longrightarrow Fusion\ S \leq Fusion\ T$

lemma *mono-fusion*[*simp*]: $mono\ (S \parallel T)$

lemma *mono-Fusion*: $mono\ (Fusion\ S)$

definition *prod-pred* $A\ B = (\lambda(a,\ b).\ A\ a \wedge B\ b)$
definition *Prod* :: $(('a \Rightarrow bool) \Rightarrow ('b \Rightarrow bool)) \Rightarrow (('c \Rightarrow bool) \Rightarrow ('d \Rightarrow bool)) \Rightarrow (('a \times 'c \Rightarrow bool)$
$\Rightarrow ('b \times 'd \Rightarrow bool))$
(**infixr** $**$ *70*)
where
$(S\ **\ T)\ q = (\lambda\ (x,\ y)\ .\ \exists\ p\ p'\ .\ prod\text{-}pred\ p\ p' \leq q \wedge S\ p\ x \wedge T\ p'\ y)$

lemma *mono-prod*[*simp*]: $mono\ (S\ **\ T)$

lemma *Prod-spec*: $(\{.p.\}\ o\ [:r:])\ **\ (\{.p'.\}\ o\ [:r':]) = \{.x,y\ .\ p\ x \wedge p'\ y.\}\ o\ [:x,\ y \leadsto u,\ v\ .\ r\ x\ u \wedge r'$
$y\ v:]$

lemma *Prod-demonic*: $[:r:]\ **\ [:r':] = [:x,\ y \leadsto u,\ v\ .\ r\ x\ u \wedge r'\ y\ v:]$

lemma *Prod-spec-Skip*: $(\{.p.\}\ o\ [:r:])\ **\ Skip = \{.x,y\ .\ p\ x.\}\ o\ [:x,\ y \leadsto u,\ v\ .\ r\ x\ u \wedge v = y:]$

lemma *Prod-Skip-spec*: $Skip\ **\ (\{.p.\}\ o\ [:r:]) = \{.x,y\ .\ p\ y.\}\ o\ [:x,\ y \leadsto u,\ v\ .\ x = u \wedge r\ y\ v:]$

lemma *Prod-skip-demonic*: $Skip\ **\ [:r:] = [:x,\ y \leadsto u,\ v\ .\ x = u \wedge r\ y\ v:]$

lemma *Prod-demonic-skip*: $[:r:]\ **\ Skip = [:x,\ y \leadsto u,\ v\ .\ r\ x\ u \wedge\ y = v:]$

lemma *Prod-spec-demonic*: $(\{.p.\}\ o\ [:r:])\ **\ [:r':] = \{.x,\ y\ .\ p\ x.\}\ o\ [:x,\ y \leadsto u,\ v\ .\ r\ x\ u \wedge r'\ y\ v:]$

lemma *Prod-demonic-spec*: $[:r:]\ **\ (\{.p.\}\ o\ [:r':]) = \{.x,\ y\ .\ p\ y.\}\ o\ [:x,\ y \leadsto u,\ v\ .\ r\ x\ u \wedge r'\ y\ v:]$

lemma *pair-eq-demonic-skip*: $[:\ \lambda(x,\ y)\ (u,\ v).\ x = u \wedge v = y\ :] = Skip$

lemma *Prod-assert-skip*: $\{.p.\}\ **\ Skip = \{.x,y\ .\ p\ x.\}$

lemma *Prod-skip-assert*: $Skip ** \{.p.\} = \{.x,y\ .\ p\ y.\}$

lemma *fusion-comute*: $S \parallel T = T \parallel S$

lemma *fusion-mono1*: $S \leq S' \Longrightarrow S \parallel T \leq S' \parallel T$

lemma *prod-mono1*: $S \leq S' \Longrightarrow S ** T \leq S' ** T$

lemma *prod-mono2*: $S \leq S' \Longrightarrow T ** S \leq T ** S'$

lemma *Prod-fusion*: $S ** T = ([:x,y \leadsto x'\ .\ x = x':]\ o\ S\ o\ [:x \leadsto x',\ y\ .\ x = x':]) \parallel ([:x,\ y \leadsto y'\ .\ y = y':]\ o\ T\ o\ [:y \leadsto x,\ y'\ .\ y = y':])$

lemma *refin-comp-right*: $(S::'a \Rightarrow 'b::order) \leq T \Longrightarrow S\ o\ X \leq T\ o\ X$

lemma *refin-comp-left*: $mono\ X \Longrightarrow (S::'a \Rightarrow 'b::order) \leq T \Longrightarrow X\ o\ S \leq X\ o\ T$

lemma *mono-angelic*[*simp*]: $mono\ \{:r:\}$

lemma [*simp*]: $Skip ** Magic = Magic$

lemma [*simp*]: $S ** Fail = Fail$

lemma [*simp*]: $Fail ** S = Fail$

lemma *demonic-conj*: $[:(r::'a \Rightarrow 'b \Rightarrow bool):]\ o\ (S \sqcap S') = ([:r:]\ o\ S) \sqcap ([:r:]\ o\ S')$

lemma *demonic-assume*: $[:r:]\ o\ [.p.] = [:x \leadsto y\ .\ r\ x\ y \wedge p\ y:]$

lemma *assume-demonic*: $[.p.]\ o\ [:r:] = [:x \leadsto y\ .\ p\ x \wedge r\ x\ y:]$

lemma [*simp*]: $(Fail::'a::boolean\text{-}algebra) \leq S$

lemma *prod-skip-skip*[*simp*]: $Skip ** Skip = Skip$

lemma *fusion-prod*: $S \parallel T = [:x \leadsto y,\ z\ .\ x = y \wedge x = z:]\ o\ Prod\ S\ T\ o\ [:y\ ,\ z \leadsto x\ .\ y = x \wedge z = x:]$

lemma [*simp*]: $prec\ S = \top \Longrightarrow prec\ T = \top \Longrightarrow prec\ (S ** T) = \top$

lemma *prec-skip*[*simp*]: $prec\ Skip = (\top::'a \Rightarrow bool)$

lemma [*simp*]: $prec\ S = \top \Longrightarrow prec\ T = \top \Longrightarrow prec\ (S \parallel T) = \top$

1.4 Functional Update

definition *update* $:: ('a \Rightarrow 'b) \Rightarrow ('b \Rightarrow bool) \Rightarrow 'a \Rightarrow bool$ $([-\text{-}-])$ **where**
$[-f-] = [:x \leadsto y\ .\ y = f\ x:]$
syntax
-update $:: patterns \Rightarrow tuple\text{-}args \Rightarrow logic$ $((1[-\ \text{-} \leadsto \text{-}\ -]))$
translations
-update x (*-tuple-args f F*) $==$ *CONST update* ((*-abs* x (*-tuple f F*)))
-update x (*-tuple-arg F*) $==$ *CONST update* (*-abs* x F)

lemma *update-o-def*: $[-f\ o\ g-] = [-x \leadsto f\ (g\ x)-]$

lemma *update-simp*: $[-f-]\ q = (\lambda\ x\ .\ q\ (f\ x))$

lemma *update-assert-comp*: $[-f-]\ o\ \{.p.\} = \{.p\ o\ f.\}\ o\ [-f-]$

lemma *update-comp*: $[-f-]\ o\ [-g-] = [-g\ o\ f-]$

lemma *update-demonic-comp*: $[-f-]\ o\ [:r:] = [:x \rightsquigarrow y\ .\ r\ (f\ x)\ y:]$

lemma *demonic-update-comp*: $[:r:]\ o\ [-f-] = [:x \rightsquigarrow y\ .\ \exists\ z\ .\ r\ x\ z \wedge y = f\ z:]$

lemma *comp-update-demonic*: $S\ o\ [-f-]\ o\ [:r:] = S\ o\ [:x \rightsquigarrow y\ .\ r\ (f\ x)\ y:]$

lemma *comp-demonic-update*: $S\ o\ [:r:]\ o\ [-f-] = S\ o\ [:x \rightsquigarrow y\ .\ \exists\ z\ .\ r\ x\ z \wedge y = f\ z:]$

lemma *convert*: $(\lambda\ x\ y\ .\ (S::('a \Rightarrow bool) \Rightarrow ('b \Rightarrow bool))\ x\ (f\ y)) = [-f-]\ o\ S$

lemma *prod-update*: $[-f-] ** [-g-] = [-x,\ y \rightsquigarrow f\ x,\ g\ y\ -]$

lemma *prod-update-skip*: $[-f-] ** Skip = [-\ x,\ y \rightsquigarrow f\ x,\ y-]$

lemma *prod-skip-update*: $Skip ** [-f-] = [-\ x,\ y \rightsquigarrow x,\ f\ y-]$

lemma *prod-assert-update-skip*: $(\{.p.\}\ o\ [-f-]) ** Skip = \{.x,y\ .\ p\ x.\}\ o\ [-\ x,\ y \rightsquigarrow f\ x,\ y-]$

lemma *prod-skip-assert-update*: $Skip ** (\{.p.\}\ o\ [-f-]) = \{.x,y\ .\ p\ y.\}\ o\ [-\lambda\ (x,\ y)\ .\ (x,\ f\ y)-]$

lemma *prod-assert-update*: $(\{.p.\}\ o\ [-f-]) ** (\{.p'.\}\ o\ [-f'-]) = \{.x,y\ .\ p\ x \wedge p'\ y.\}\ o\ [-\lambda\ (x,\ y)\ .\ (f\ x,\ f'\ y)-]$

lemma *update-id-Skip*: $[-id-] = Skip$

lemma *prod-assert-assert-update*: $\{.p.\} ** (\{.p'.\}\ o\ [-f-]) = \{.x,y\ .\ p\ x \wedge p'\ y.\}\ o\ [-\ x,\ y \rightsquigarrow x,\ f\ y-]$

lemma *prod-assert-update-assert*: $(\{.p.\}\ o\ [-f-])** \{.p'.\} = \{.x,y\ .\ p\ x \wedge p'\ y.\}\ o\ [-\ x,\ y \rightsquigarrow f\ x,\ y-]$

lemma *prod-update-assert-update*: $[-f-] ** (\{.p.\}\ o\ [-f'-]) = \{.x,y\ .\ p\ y.\}\ o\ [-x,\ y \rightsquigarrow f\ x,\ f'\ y-]$

lemma *prod-assert-update-update*: $(\{.p.\}\ o\ [-f-])** [-f'-] = \{.x,y\ .\ p\ x\ .\}\ o\ [-\ x,\ y \rightsquigarrow f\ x,\ f'\ y-]$

lemma *Fail-assert-update*: $Fail = \{.\bot.\}\ o\ [-\ (Eps\ \top)\ -]$

lemma *fail-assert-update*: $\bot = \{.\bot.\}\ o\ [-\ (Eps\ \top)\ -]$

lemma *update-fail*: $[-f-]\ o\ \bot = \bot$

lemma *fail-assert-demonic*: $\bot = \{.\bot.\}\ o\ [:\bot:]$

lemma *false-update-fail*: $\{.\lambda x.\ False.\}\ o\ [-f-] = \bot$

lemma *comp-update-update*: $S \circ [-f-] \circ [-f'-] = S \circ [-\ f'\ o\ f\ -]$

lemma *comp-update-assert*: $S \circ [-f-] \circ \{.p.\} = S \circ \{.p\ o\ f.\}\ o\ [-f-]$

lemma *prod-fail*: $\bot ** S = \bot$

lemma *fail-prod*: $S ** \bot = \bot$

lemma *assert-fail*: $\{.p::'a::boolean\text{-}algebra.\}\ o\ \bot = \bot$

lemma *angelic-assert*: $\{:r:\}\ o\ \{.p.\} = \{:x \rightsquigarrow y\ .\ r\ x\ y \wedge p\ y:\}$

lemma *Prod-Skip-angelic-demonic*: $Skip ** (\{:r:\}\ o\ [:r':]) = \{:s,x \rightsquigarrow s',y\ .\ r\ x\ y \wedge s' = s:\}\ o\ [:s,x \rightsquigarrow s',y\ .\ r'\ x\ y \wedge s' = s:]$

lemma *Prod-angelic-demonic-Skip*: $(\{:r:\}\ o\ [:r':]) ** Skip = \{:x,\ u \rightsquigarrow y,\ u'\ .\ r\ x\ y \wedge u = u':\}\ o\ [:x,\ u \rightsquigarrow y,\ u'\ .\ r'\ x\ y \wedge u = u':]$

lemma *prec-rel-eq*: $p = p' \Longrightarrow r = r' \Longrightarrow \{.p.\}\ o\ [:r:] = \{.p'.\}\ o\ [:r':]$

lemma *prec-rel-le*: $p \le p' \Longrightarrow (\bigwedge x\ .\ p\ x \Longrightarrow r'\ x \le r\ x) \Longrightarrow \{.p.\}\ o\ [:r:] \le \{.p'.\}\ o\ [:r':]$

lemma *assert-update-eq*: $(\{.p.\}\ o\ [-f-] = \{.p'.\}\ o\ [-f'-]) = (p = p' \wedge (\forall\ x.\ p\ x \longrightarrow f\ x = f'\ x))$

lemma *update-eq*: $([-f-] = [-f'-]) = (f = f')$

lemma *spec-eq-iff*:
  shows *spec-eq-iff-1*: $p = p' \Longrightarrow f = f' \Longrightarrow \{.p.\}\ o\ [-f-] = \{.p'.\}\ o\ [-f'-]$
  and *spec-eq-iff-2*: $f = f' \Longrightarrow [-f-] = [-f'-]$
  and *spec-eq-iff-3*: $p = (\lambda\ x\ .\ True) \Longrightarrow f = f' \Longrightarrow \{.p.\}\ o\ [-f-] = [-f'-]$
  and *spec-eq-iff-4*: $p = (\lambda\ x\ .\ True) \Longrightarrow f = f' \Longrightarrow [-f-] = \{.p.\}\ o\ [-f'-]$

lemma *spec-eq-iff-a*:
  shows$(\bigwedge x\ .\ p\ x = p'\ x) \Longrightarrow (\bigwedge x\ .\ f\ x = f'\ x) \Longrightarrow \{.p.\}\ o\ [-f-] = \{.p'.\}\ o\ [-f'-]$
  and $(\bigwedge x\ .\ f\ x = f'\ x) \Longrightarrow [-f-] = [-f'-]$
  and $(\bigwedge x\ .\ p\ x) \Longrightarrow (\bigwedge x\ .\ f\ x = f'\ x) \Longrightarrow \{.p.\}\ o\ [-f-] = [-f'-]$
  and $(\bigwedge x\ .\ p\ x) \Longrightarrow (\bigwedge x\ .\ f\ x = f'\ x) \Longrightarrow [-f-] = \{.p.\}\ o\ [-f'-]$

lemma *spec-eq-iff-prec*: $p = p' \Longrightarrow (\bigwedge x\ .\ p\ x \Longrightarrow f\ x = f'\ x) \Longrightarrow \{.p.\}\ o\ [-f-] = \{.p'.\}\ o\ [-f'-]$

lemma *trs-prod*: $trs\ r ** trs\ r' = trs\ (\lambda\ (x,x')\ (y,y')\ .\ r\ x\ y \wedge r'\ x'\ y')$

lemma *sconjunctiveE*: $sconjunctive\ S \Longrightarrow (\exists\ p\ r\ .\ S = \{.\ p\ .\}\ o\ [:\ r ::'a \Rightarrow 'b \Rightarrow bool:])$

lemma *sconjunctive-prod* [*simp*]: $sconjunctive\ S \Longrightarrow sconjunctive\ S' \Longrightarrow sconjunctive\ (S ** S')$

lemma *nonmagic-prod* [*simp*]: $non\text{-}magic\ S \Longrightarrow non\text{-}magic\ S' \Longrightarrow non\text{-}magic\ (S ** S')$

lemma *non-magic-comp* [*simp*]: $non\text{-}magic\ S \Longrightarrow non\text{-}magic\ S' \Longrightarrow non\text{-}magic\ (S\ o\ S')$

lemma *implementable-pred* [*simp*]: $implementable\ S \Longrightarrow implementable\ S' \Longrightarrow implementable\ (S ** S')$

lemma *implementable-comp*[*simp*]: $implementable\ S \Longrightarrow implementable\ S' \Longrightarrow implementable\ (S\ o\ S')$

lemma *nonmagic-assert*: $non\text{-}magic\ \{.p::'a::boolean\text{-}algebra.\}$

1.5 Control Statements

definition $\mathit{if\text{-}stm}\ p\ S\ T = ([.p.]\ o\ S) \sqcap ([.-p.]\ o\ T)$

definition $\mathit{while\text{-}stm}\ p\ S = \mathit{lfp}\ (\lambda\ X\ .\ \mathit{if\text{-}stm}\ p\ (S\ o\ X)\ \mathit{Skip})$

definition $\mathit{Sup\text{-}less}\ x\ (w::'b::\mathit{wellorder}) = \mathit{Sup}\ \{(x\ v)::'a::\mathit{complete\text{-}lattice} \mid v\ .\ v < w\}$

lemma $\mathit{Sup\text{-}less\text{-}upper}$: $v < w \Longrightarrow P\ v \leq \mathit{Sup\text{-}less}\ P\ w$

lemma $\mathit{Sup\text{-}less\text{-}least}$: $(\bigwedge\ v\ .\ v < w \Longrightarrow P\ v \leq Q) \Longrightarrow \mathit{Sup\text{-}less}\ P\ w \leq Q$

theorem $\mathit{fp\text{-}wf\text{-}induction}$:
$f\ x\ = x \Longrightarrow \mathit{mono}\ f \Longrightarrow (\forall\ w\ .\ (y\ w) \leq f\ (\mathit{Sup\text{-}less}\ y\ w)) \Longrightarrow \mathit{Sup}\ (\mathit{range}\ y) \leq x$

theorem $\mathit{lfp\text{-}wf\text{-}induction}$: $\mathit{mono}\ f \Longrightarrow (\forall\ w\ .\ (p\ w) \leq f\ (\mathit{Sup\text{-}less}\ p\ w)) \Longrightarrow \mathit{Sup}\ (\mathit{range}\ p) \leq \mathit{lfp}\ f$

theorem $\mathit{lfp\text{-}wf\text{-}induction\text{-}a}$: $\mathit{mono}\ f \Longrightarrow (\forall\ w\ .\ (p\ w) \leq f\ (\mathit{Sup\text{-}less}\ p\ w)) \Longrightarrow (\mathit{SUP}\ a.\ p\ a) \leq \mathit{lfp}\ f$

theorem $\mathit{lfp\text{-}wf\text{-}induction\text{-}b}$: $\mathit{mono}\ f \Longrightarrow (\forall\ w\ .\ (p\ w) \leq f\ (\mathit{Sup\text{-}less}\ p\ w)) \Longrightarrow S \leq (\mathit{SUP}\ a.\ p\ a) \Longrightarrow S \leq \mathit{lfp}\ f$

lemma [simp]: $\mathit{mono}\ S \Longrightarrow \mathit{mono}\ (\lambda X.\ \mathit{if\text{-}stm}\ b\ (S \circ X)\ T)$

definition $\mathit{mono\text{-}mono}\ F = (\mathit{mono}\ F \wedge (\forall\ f\ .\ \mathit{mono}\ f \longrightarrow \mathit{mono}\ (F\ f)))$

theorem $\mathit{lfp\text{-}mono}$ [simp]:
$\mathit{mono\text{-}mono}\ F \Longrightarrow \mathit{mono}\ (\mathit{lfp}\ F)$

lemma $\mathit{if\text{-}mono}$[simp]: $\mathit{mono}\ S \Longrightarrow \mathit{mono}\ T \Longrightarrow \mathit{mono}\ (\mathit{if\text{-}stm}\ b\ S\ T)$

1.6 Hoare Total Correctness Rules

definition $\mathit{Hoare}\ p\ S\ q = (p \leq S\ q)$

definition $\mathit{post\text{-}fun}\ (p::'a::\mathit{order})\ q = (\mathit{if}\ p \leq q\ \mathit{then}\ \top\ \mathit{else}\ \bot)$

lemma $\mathit{post\text{-}mono}$ [simp]: $\mathit{mono}\ (\mathit{post\text{-}fun}\ p :: (\text{-}::\{\mathit{order\text{-}bot},\mathit{order\text{-}top}\}))$

lemma $\mathit{post\text{-}refin}$ [simp]: $\mathit{mono}\ S \Longrightarrow ((S\ p)::'a::\mathit{bounded\text{-}lattice}) \sqcap (\mathit{post\text{-}fun}\ p)\ x \leq S\ x$

lemma $\mathit{post\text{-}top}$ [simp]: $\mathit{post\text{-}fun}\ p\ p = \top$

theorem $\mathit{hoare\text{-}refinement\text{-}post}$:
$\mathit{mono}\ f \Longrightarrow\ (\mathit{Hoare}\ x\ \ f\ y) = (\{.x::'a::\mathit{boolean\text{-}algebra}.\}\ o\ (\mathit{post\text{-}fun}\ y) \leq f)$

lemma $\mathit{assert\text{-}Sup\text{-}range}$: $\{.\mathit{Sup}\ (\mathit{range}\ (p::'W \Rightarrow 'a::\mathit{complete\text{-}distrib\text{-}lattice})).\} = \mathit{Sup}(\mathit{range}\ (\mathit{assert}\ o\ p))$

lemma $\mathit{Sup\text{-}range\text{-}comp}$: $(\mathit{Sup}\ (\mathit{range}\ p))\ o\ S = \mathit{Sup}\ (\mathit{range}\ (\lambda\ w\ .\ ((p\ w)\ o\ S)))$

lemma $\mathit{Sup\text{-}less\text{-}comp}$: $(\mathit{Sup\text{-}less}\ P)\ w\ o\ S = \mathit{Sup\text{-}less}\ (\lambda\ w\ .\ ((P\ w)\ o\ S))\ w$

lemma *assert-Sup*: $\{.Sup\ (X{::}'a{::}complete\text{-}distrib\text{-}lattice\ set).\} = Sup\ (assert\ `\ X)$

lemma *Sup-less-assert*: $Sup\text{-}less\ (\lambda w.\ \{.\ (p\ w){::}'a{::}complete\text{-}distrib\text{-}lattice\ .\})\ w = \{.Sup\text{-}less\ p\ w.\}$

lemma [*simp*]: $Sup\text{-}less\ (\lambda n\ x.\ t\ x = n)\ n = (\lambda\ x\ .\ (t\ x < n))$

lemma [*simp*]: $Sup\text{-}less\ (\lambda n.\ \{.x.\ t\ x = n.\} \circ S)\ n = \{.x.\ t\ x < n.\} \circ S$

lemma [*simp*]: $(SUP\ a.\ \{.x\ .t\ x = a.\} \circ S) = S$

theorem *hoare-fixpoint*:
$mono\text{-}mono\ F \Longrightarrow$
$(\forall\ f\ w\ .\ mono\ f \longrightarrow (Hoare\ (Sup\text{-}less\ p\ w)\ f\ y \longrightarrow Hoare\ ((p\ w){::}'a \Rightarrow bool)\ (F\ f)\ y)) \Longrightarrow Hoare(Sup\ (range\ p))\ (lfp\ F)\ y$

theorem *hoare-sequential*:
$mono\ S \Longrightarrow (Hoare\ p\ (S\ o\ T)\ r) = (\ (\exists\ \ q.\ Hoare\ p\ S\ q \wedge Hoare\ q\ T\ r))$

theorem *hoare-choice*:
$Hoare\ \ p\ (S \sqcap T)\ q = (Hoare\ p\ S\ q \wedge Hoare\ p\ T\ q)$

theorem *hoare-assume*:
$(Hoare\ P\ [.R.]\ Q) = (P \sqcap R \le Q)$

lemma *hoare-if*: $mono\ S \Longrightarrow mono\ T \Longrightarrow Hoare\ (p \sqcap b)\ S\ q \Longrightarrow Hoare\ (p \sqcap -b)\ T\ q \Longrightarrow Hoare\ p\ (if\text{-}stm\ b\ S\ T)\ q$

lemma [*simp*]: $mono\ x \Longrightarrow mono\text{-}mono\ (\lambda X\ .\ if\text{-}stm\ b\ (x \circ X)\ Skip)$

lemma *hoare-while*:
$mono\ x \Longrightarrow (\forall\ \ w\ .\ Hoare\ ((p\ w) \sqcap b)\ x\ (Sup\text{-}less\ p\ w)) \Longrightarrow\ \ Hoare\ \ (Sup\ (range\ p))\ (while\text{-}stm\ b\ x)\ ((Sup\ (range\ p)) \sqcap -b)$

lemma *hoare-prec-post*: $mono\ S \Longrightarrow p \le p' \Longrightarrow q' \le q \Longrightarrow Hoare\ p'\ S\ q' \Longrightarrow Hoare\ p\ S\ q$

lemma [*simp*]: $mono\ x \Longrightarrow\ \ mono\ (while\text{-}stm\ b\ x)$

lemma *hoare-while-a*:
$mono\ x \Longrightarrow (\forall\ \ w\ .\ Hoare\ ((p\ w) \sqcap b)\ x\ (Sup\text{-}less\ p\ w)) \Longrightarrow p' \le\ \ (Sup\ (range\ p)) \Longrightarrow ((Sup\ (range\ p)) \sqcap -b) \le q$
$\Longrightarrow\ \ Hoare\ p'\ (while\text{-}stm\ b\ x)\ q$

lemma *hoare-update*: $p \le q\ o\ f \Longrightarrow Hoare\ p\ [-f-]\ q$

lemma *hoare-demonic*: $(\bigwedge\ x\ y\ .\ p\ x \Longrightarrow r\ x\ y \Longrightarrow q\ y) \Longrightarrow Hoare\ p\ [:r:]\ q$

lemma *refinement-hoare*: $S \le T \Longrightarrow Hoare\ (p{::}'a{::}order)\ S\ (q) \Longrightarrow Hoare\ p\ T\ q$

lemma *refinement-hoare-iff*: $(S \le T) = (\forall\ \ p\ q\ .\ Hoare\ (p{::}'a{::}order)\ S\ (q) \longrightarrow Hoare\ p\ T\ q)$

1.7 Data Refinement

lemma *data-refinement*: $mono\ S' \Longrightarrow (\forall\ x\ a\ .\ \exists\ u\ .\ R\ x\ a\ u) \Longrightarrow$
$\{:x,\ a \leadsto x',\ u\ .\ x = x' \wedge R\ x\ a\ u:\}\ o\ S \leq S'\ o\ \{:y,\ b \leadsto y',\ v\ .\ y = y' \wedge R'\ y\ b\ v:\} \Longrightarrow$
$[:x \leadsto x',\ u\ .\ x = x':]\ o\ S\ o\ [:y,\ v \leadsto y'\ .\ y = y'\ :]$
$\leq [:x \leadsto x',\ a\ .\ x = x':]\ o\ S'\ o\ [:y,\ b \leadsto y'\ .\ y = y'\ :]$

lemma *mono-update*[*simp*]: $mono\ [-\ f\ -]$

end

1.8 Feedback Operator on Predicate Transformers

theory *TransitionFeedback*
imports *../RefinementReactive/Refinement Complex*

begin

definition *grd-update* :: $('a \Rightarrow bool) \Rightarrow ('a \Rightarrow 'b) \Rightarrow ('b \Rightarrow bool) \Rightarrow 'a \Rightarrow bool$ $([-(\text{-}){\to}(\text{-})-])$ **where**
$[-p{\to}f-] = [:x \leadsto y\ .\ p\ x \wedge y = f\ x:]$

lemma $[-p{\to}f-] = [.p.]\ o\ [-f-]$

lemma *assert-grd-update*: $(\bigwedge\ x\ .\ p\ x \Longrightarrow p'\ x) \Longrightarrow \{.p.\}\ o\ [-p'{\to}f-] = \{.p.\}\ o\ [-f-]$

lemma *grd-update-comp*: $[-p{\to}f-]\ o\ [-q{\to}g-] = [-p \sqcap (q\ o\ f) \to g\ o\ f-]$

lemma *grd-update-assert-comp*: $[-p{\to}f-]\ o\ \{.q.\} = \{.\ x\ .\ p\ x \longrightarrow q\ (f\ x).\}\ o\ [-p \to f-]$

lemma *grd-update-update-comp*: $[-p{\to}f-]\ o\ [-g-] = [-p \to g\ o\ f-]$

lemma *update-grd-update-comp*: $[-g-]\ o\ [-p{\to}f-] = [-p\ o\ g \to f\ o\ g-]$

lemma *grd-update-update* [*simp*]: $[-\top{\to}f-] = [-f-]$

lemma [*simp*]: $(\exists\, y.\ (a,\ y) = f\ (u,\ x)) = (a = fst\ (f\ (u,\ x)))$

lemma *pair-eq*: $((a,\ b) = x) = (a = fst\ x \wedge b = snd\ x)$

lemma *comp-exists*: $(r\ OO\ r')\ x\ y = (\exists\ z\ .\ r\ x\ z \wedge r'\ z\ y)$

lemma *comp-existsa*: $(r\ OO\ r') = (\lambda\ x\ y\ .\ \exists\ z\ .\ r\ x\ z \wedge r'\ z\ y)$

lemma *drop-assumption*: $p \Longrightarrow True$

lemma *fun-comp-simp*: $((\lambda(x,\ y).\ (f\ x,\ y)) \circ (\lambda(a,\ b).\ (c\ b,\ d\ (a,\ b)))) = (\lambda\ (a,\ b)\ .\ (((f\ o\ c)\ b),\ d\ (a,\ b)))$

lemma *fun-comp-simp-b*: $((\lambda(a::'c,\ b::'d).\ (c\ b,\ d\ (a,\ b))) \circ (\lambda(x::'a,\ y::'d).\ (f\ x,\ y))) = (\lambda\ (x,\ y)\ .\ (c\ y,\ d\ (f\ x,\ y)))$

lemma *fun-comp-simp-c*: $((\lambda((c,\ d),\ a).\ (a,\ c,\ d)) \circ (\lambda(x,\ y).\ (case\ x\ of\ (a,\ b) \Rightarrow (c\ b,\ d\ (a,\ b)),\ f\ y)) \circ (\lambda(a,\ c,\ b).\ ((a,\ b),\ c))) = (\lambda\ (u,v,w)\ .\ (f\ v,\ c\ w,\ d\ (u,\ w)))$

lemma *fun-comp-simp-d*: $(\lambda x.\ case\ case\ x\ of\ (c,\ b) \Rightarrow ((case\ x\ of\ (v,\ w) \Rightarrow f\ v,\ b),\ c)\ of\ (x,\ y) \Rightarrow p\ x \wedge p'\ y) = (\lambda\ (u,v)\ .\ p\ (f\ u,\ v) \wedge p'\ u)$

lemma *fun-comp-simp-e*: $(\lambda x.\ case\ x\ of\ (v,\ w) \Rightarrow (c\ w,\ d\ (case\ x\ of\ (v,\ w) \Rightarrow f\ v,\ w))) = (\lambda\ (u,\ v)\ .\ (c\ v,\ d\ (f\ u,\ v)))$

definition *select* $S = \{.\ x\ .\ (\exists\ u\ .\ prec\ S\ (u,\ x)).\}\ o\ [:x \rightsquigarrow u,\ x'\ .\ x' = x \wedge prec\ S\ (u,\ x)\ :]\ o\ S\ o\ [:v,\ y \rightsquigarrow v'\ .\ v' = v:]$

lemma *selectc-spec*: $select\ (\{.\ p\ .\}\ o\ [:r:]) = \{.\ x\ .\ (\exists\ u\ .\ p\ (u,\ x)).\}\ o\ [:x \rightsquigarrow v\ .\ \exists\ u\ y\ .\ p\ (u,\ x) \wedge r\ (u,x)\ (v,y)\ :]$

lemma *select-sconjunctive*[*simp*]: $sconjunctive\ S \Longrightarrow sconjunctive\ (select\ S)$

lemma *sconjunctive-fusion*[*simp*]: $sconjunctive\ S \Longrightarrow sconjunctive\ S' \Longrightarrow sconjunctive\ (S \parallel S')$

lemma *sconjunctive-Skip*[*simp*]: *sconjunctive Skip*

lemma [*simp*]: $prec\ S = \top \Longrightarrow prec\ (select\ S) = \top$

definition *selectA* $S = \{.\ x\ .\ (\exists\ u\ .\ prec\ S\ (u,\ x)).\}\ o\ [:x \rightsquigarrow u,\ x'\ .\ x' = x \wedge prec\ S\ (u,\ x)\ :]\ o\ (S \parallel [:u,\ x \rightsquigarrow v,\ y\ .\ u = v:])\ o\ [:v,\ y \rightsquigarrow v'\ .\ v' = v:]$

definition *selectB* $S = \{:x \rightsquigarrow u,\ x'\ .\ x = x':\}\ o\ S\ o\ [:v,\ y \rightsquigarrow v'\ .\ v' = v:]$

definition *selectC* $S = \{:x \rightsquigarrow u,\ x'\ .\ x = x':\}\ o\ (S \parallel [:u,\ x \rightsquigarrow v,\ y\ .\ u = v:])\ o\ [:v,\ y \rightsquigarrow v'\ .\ v' = v:]$

definition *feedback* $S = [:x \rightsquigarrow x',\ x''\ .\ x' = x \wedge x'' = x:]\ o\ ((select\ S) ** Skip)\ o\ (S \parallel [:u,\ x \rightsquigarrow v,\ y\ .\ u = v:])\ o\ [:u,y \rightsquigarrow y'\ .\ y' = y:]$

definition *feedbackA* $S = [:x \rightsquigarrow x',\ x''\ .\ x' = x \wedge x'' = x:]\ o\ ((selectA\ S) ** Skip)\ o\ (S \parallel [:u,\ x \rightsquigarrow v,\ y\ .\ u = v:])\ o\ [:u,y \rightsquigarrow y'\ .\ y' = y:]$

definition *feedbackB* $S = [:x \rightsquigarrow x',\ x''\ .\ x' = x \wedge x'' = x:]\ o\ ((selectB\ S) ** Skip)\ o\ (S \parallel [:u,\ x \rightsquigarrow v,\ y\ .\ u = v:])\ o\ [:u,y \rightsquigarrow y'\ .\ y' = y:]$

definition *feedbackC* $S = [:x \rightsquigarrow x',\ x''\ .\ x' = x \wedge x'' = x:]\ o\ ((selectC\ S) ** Skip)\ o\ (S \parallel [:u,\ x \rightsquigarrow v,\ y\ .\ u = v:])\ o\ [:u,y \rightsquigarrow y'\ .\ y' = y:]$

lemma *selectA-spec*: $selectA\ (\{.\ p\ .\}\ o\ [:r:]) = \{.\ x\ .\ (\exists\ u\ .\ p\ (u,\ x)).\}\ o\ [:x \rightsquigarrow u\ .\ \exists\ \ y\ .\ p\ (u,\ x) \wedge r\ (u,x)\ (u,y)\ :]$

thm *Prod-angelic-demonic-Skip*

lemma *feedbackB-spec*: $feedbackB\ (\{.p.\}\ o\ [:r:]) = \{:x \rightsquigarrow u,\ x'\ .\ p\ (u,x) \wedge (\forall\ v\ y\ .\ r\ (u,x)\ (v,\ y) \longrightarrow p\ (v,x)) \wedge x = x':\}\ o\ [:u,x \rightsquigarrow y\ .\ \exists\ v\ y'\ .\ r\ (u,x)\ (v,\ y') \wedge r\ (v,\ x)\ (v,\ y):]$

lemma *feedbackC-spec*: $feedbackC\ (\{.p.\}\ o\ [:r:]) = \{:x \rightsquigarrow u,\ x'\ .\ p\ (u,x) \wedge (\forall\ y\ .\ r\ (u,x)\ (u,\ y) \longrightarrow p\ (u,x)) \wedge x = x':\}\ o\ [:u,x \rightsquigarrow y\ .\ r\ (u,\ x)\ (u,\ y):]$

lemma *feedbackB-decomp*: $p \le inpt\ r \Longrightarrow p' \le inpt\ r' \Longrightarrow$
$feedbackB\ (\ \{.\ u,\ x\ .\ p\ (u,\ x) \wedge p'\ x.\}\ o\ [:u,\ x \rightsquigarrow v,\ y\ .\ r\ (u,\ x)\ y \wedge r'\ x\ v:])$
$= \{.\ x\ .\ p'\ x \wedge (\forall b.\ r'\ x\ b \longrightarrow p\ (b,x)).\}\ o\ [:x \rightsquigarrow y\ .\ \exists\ v\ .\ r'\ x\ v \wedge r\ (v,\ x)\ y:]$

lemma [*simp*]: $prec\ S = \top \Longrightarrow prec\ (feedback\ S) = \top$

lemma *feedback-simp-a*: $feedback\ (\{.p.\}\ o\ [:r:]) =$
$\{.\ \lambda x.\ (\exists u.\ p\ (u,\ x)) \wedge (\forall a.\ (\exists u.\ p\ (u,\ x) \wedge (\exists y.\ r\ (u,\ x)\ (a,\ y))) \longrightarrow p\ (a,\ x))\ .\} \circ$
$[:x \rightsquigarrow y\ .\ (\exists\ v\ .(\exists u.\ p\ (u,\ x) \wedge (\exists y.\ r\ (u,\ x)\ (v,\ y))) \wedge\ r\ (v,\ x)\ (v,\ y)):]$

lemma *feedbackA-simp-a*: $feedbackA\ (\{.p.\}\ o\ [:r:]) =$
$\{.\ x.\ \exists u.\ p\ (u,\ x)\ .\} \circ [:x \rightsquigarrow z.\ \exists a.\ p\ (a,\ x) \wedge r\ (a,\ x)\ (a,\ z):]$

lemma *feedback-simp-b*: $feedback\ (\{.p.\}\ o\ [-q{\rightarrow}f-]) =$
$\{.\ \lambda x.\ (\exists u.\ p\ (u,\ x)) \wedge (\forall u.\ p\ (u,\ x) \wedge q\ (u,\ x) \longrightarrow p\ (fst\ (f\ (u,\ x)),\ x))\ .\} \circ$
$[:x \rightsquigarrow y\ .\ (\exists\ u\ .\ p\ (u,\ x) \wedge q\ (u,\ x) \wedge q\ (fst\ (f\ (u,\ x)),\ x) \wedge fst\ (f\ (u,\ x)) = fst\ (f\ (fst\ (f\ (u,\ x)),\ x)) \wedge y = snd\ (f\ (fst\ (f\ (u,\ x)),\ x))):]$

lemma *feedback-simp-c*: $feedback\ (\{.p.\}\ o\ [-f-]) =$
$\{.\ x.\ (\exists u.\ p\ (u,\ x)) \wedge (\forall u.\ p\ (u,\ x) \longrightarrow p\ (fst\ (f\ (u,\ x)),\ x))\ .\} \circ$
$[:x \rightsquigarrow y\ .\ (\exists\ u\ .\ p\ (u,\ x) \wedge fst\ (f\ (u,\ x)) = fst\ (f\ (fst\ (f\ (u,\ x)),\ x)) \wedge y = snd\ (f\ (fst\ (f\ (u,\ x)),\ x))):]$

lemma *feedback-simp-cc*: $feedback\ ([-f-]) =$
$[:x \rightsquigarrow y\ .\ (\exists\ u\ .\ fst\ (f\ (u,\ x)) = fst\ (f\ (fst\ (f\ (u,\ x)),\ x)) \wedge y = snd\ (f\ (fst\ (f\ (u,\ x)),\ x))):]$

lemma *feedback-test*: $feedback\ ([-(\lambda\ (u{,}x)\ .\ (u\ ,\ u))-]) = [:\top:]$

lemma *feedback-simp-d*: $feedback\ [:r:] = [:\ x \rightsquigarrow y\ .\ \exists\ v\ .\ r\ (v,\ x)\ (v,\ y):]$

lemma *feedback-update-simp*: $feedback\ (\ \{.p.\}\ o\ [-\ \lambda\ (u,\ x)\ .\ (f\,x,\ g\ (u,\ x))-])$
$= \{.\ x\ .\ p\ (f\,x,\ x).\}\ o\ [-\lambda\ x\ .\ g\ (f\,x,\ x)-]$

lemma *feedback-update-simp-x*: $feedback\ (\ \{.\ p.\}\ o\ [-\ \lambda\ ux\ .\ (f\ (snd\ ux),\ g\ ux)-])$
$= \{.\ x\ .\ p\ (f\,x,\ x).\}\ o\ [-\lambda\ x\ .\ g\ (f\,x,\ x)-]$

lemma *feedback-update-simp-a*: $feedback\ (\ \{.p.\}\ o\ [-\ \lambda\ (u,\ s,\ x)\ .\ (f\ (s,\ x),\ g\ (u,\ s,\ x),\ h\ (u,\ s,\ x))\ -])$
$= \{.\ s,\ x\ .\ p\ ((f\ (s,\ x)),\ s,\ x).\}\ o\ [-\lambda\ (s,\ x)\ .\ (g\ ((f\ (s,\ x)),\ s,\ x),\ h\ ((f\ (s,\ x)),\ s,\ x))-]$

lemma *feedback-update-simp-b*: $feedback\ (\ \{.p.\}\ o\ [-\ \lambda\ (u,\ s,\ x)\ .\ (f\ (s,\ x),\ g\ (u,\ s,\ x),\ h\ (u,\ s,\ x))\ -])$
$= \{.\ s,\ x\ .\ p\ ((f\ (s,\ x)),\ s,\ x).\}\ o\ [-\lambda\ (s,\ x)\ .\ (g\ ((f\ (s,\ x)),\ s,\ x),\ h\ ((f\ (s,\ x)),\ s,\ x))-]$

lemma *feedback-update-simp-c*: $feedback\ (\ \{.\ (u,\ s,\ x)\ .\ p\ u\ s\ x\ .\}\ o\ [-\ \lambda\ (u,\ s,\ x)\ .\ (f\,s\,x,\ g\,u\,s\,x,\ h\ u\ s\ x)\ -])$
$= \{.\ s,\ x\ .\ p\ (f\,s\,x)\ s\,x.\}\ o\ [-\lambda\ (s,\ x)\ .\ (g\ (f\,s\,x)\ s\,x,\ h\ (f\,s\,x)\ s\,x)-]$

lemma *feedback-simp-bot*: $feedback\ (\bot{::}(('a \times 'b) \Rightarrow bool) \Rightarrow ('a \times 'c) \Rightarrow bool) = \bot$

lemma $A = \{.p.\}\ o\ [-\lambda\ (a,\ b)\ .\ (c\ b,\ d\ (a,\ b))-] \Longrightarrow B = \{.p'.\}\ o\ [-f-] \Longrightarrow feedback\ (A\ o\ (B\ {**}\ Skip))$
$=\ \{.\ x\ .\ p\ (f\ (c\ x),\ x) \wedge p'\ (c\ x)\ .\} \circ [-\lambda x\ .\ d\ (f\ (c\ x),\ x)-]$

lemma *AAA*: $p = p' \Longrightarrow (\bigwedge\ x\ .\ p\ x \Longrightarrow r\ x = r'\ x) \Longrightarrow \{.p.\}\ o\ [:r:] = \{.p'.\}\ o\ [:r':]$

thm *feedback-simp-a*

lemma $A = \{.p.\}\ o\ [-\lambda\ (a,\ b)\ .\ (c\ b,\ d\ (a,\ b))-] \Longrightarrow B = \{.p'.\}\ o\ [-f-] \Longrightarrow$ *feedback* $((B\ **\ \mathit{Skip})$ $o\ A)$
$\quad = \{.\ x\ .\ p\ (f\ (c\ x),\ x) \wedge p'\ (c\ x)\ .\} \circ [-\lambda x\ .\ d\ (f\ (c\ x),\ x)-]$

lemma $A = \{.p.\}\ o\ [-\lambda\ (a,\ b)\ .\ (c\ b,\ d\ (a,\ b))-] \Longrightarrow B = \{.p'.\}\ o\ [-f-] \Longrightarrow$
feedback (*feedback* $([-\lambda\ (a,c,b)\ .\ ((a,b),\ c)-]\ o\ (A\ **\ B)\ o\ [-\lambda\ ((c,\ d),\ a)\ .\ (a,c,d)-]\ )) = \{.\ x$ $.\ p\ (f\ (c\ x),\ x) \wedge p'\ (c\ x)\ .\} \circ [-\lambda x\ .\ d\ (f\ (c\ x),\ x)-]$
lemma *feedback-simp-aa*: *feedback* $(\{.\mathit{inpt}\ r.\}\ o\ [:r:]) =$
$\{.\ \lambda x.\ (\exists u.\ \mathit{inpt}\ r\ (u,\ x)) \wedge (\forall a.\ (\exists u.\ \mathit{inpt}\ r\ (u,\ x) \wedge (\exists y.\ r\ (u,\ x)\ (a,\ y))) \longrightarrow \mathit{inpt}\ r\ (a,\ x)).\} \circ$
$[:x \rightsquigarrow y\ .\ (\exists\ v\ .(\exists u.\ (\exists y.\ r\ (u,\ x)\ (v,\ y))) \wedge\ r\ (v,\ x)\ (v,\ y)):]$

lemma *feedback-in-simp-aux*: $((\exists u.\ \mathit{inpt}\ r\ (u,\ x)) \wedge (\forall a.\ (\exists u.\ \mathit{inpt}\ r\ (u,\ x) \wedge (\exists y.\ r\ (u,\ x)\ (a,\ y)))$ $\longrightarrow \mathit{inpt}\ r\ (a,\ x)))$
$\quad = ((\exists u.\ \mathit{inpt}\ r\ (u,\ x)) \wedge (\forall a.\ (\exists u\ y.\ r\ (u,\ x)\ (a,\ y)) \longrightarrow \mathit{inpt}\ r\ (a,\ x)))$

lemma *feedback-simp-aaa*: *feedback* $(\{.\mathit{inpt}\ r.\}\ o\ [:r:]) =$
$\{.\ \lambda x.\ (\exists u.\ \mathit{inpt}\ r\ (u,\ x)) \wedge (\forall a.\ (\exists u.\ \mathit{inpt}\ r\ (u,\ x) \wedge (\exists y.\ r\ (u,\ x)\ (a,\ y))) \longrightarrow \mathit{inpt}\ r\ (a,\ x)).\} \circ$
$[:x \rightsquigarrow y\ .\ (\exists\ v\ .\ \ r\ (v,\ x)\ (v,\ y)):]$

lemma *feedbackB-simp-aaaa*: *feedbackB* $(\{.\mathit{inpt}\ r.\}\ o\ [:r:]) =$
$\{:x \rightsquigarrow (u,\ x').\mathit{inpt}\ r\ (u,\ x) \wedge (\forall v.\ (\exists y.\ r\ (u,\ x)\ (v,\ y)) \longrightarrow \mathit{inpt}\ r\ (v,\ x)) \wedge x = x':\} \circ [:(u,\ x) \rightsquigarrow y.\exists v.$ $(\exists y'.\ r\ (u,\ x)\ (v,\ y')) \wedge r\ (v,\ x)\ (v,\ y):]$

lemma *feedbackB-simp-aaaaa*: $p \le \mathit{inpt}\ r \Longrightarrow$ *feedbackB* $(\{.p.\}\ o\ [:r:]) =$
$\{:x \rightsquigarrow (u,\ x').\ p\ (u,\ x) \wedge (\forall v.\ (\exists y.\ r\ (u,\ x)\ (v,\ y)) \longrightarrow p\ (v,\ x)) \wedge x = x':\} \circ [:(u,\ x) \rightsquigarrow y.\exists v.\ (\exists y'.$ $r\ (u,\ x)\ (v,\ y')) \wedge r\ (v,\ x)\ (v,\ y):]$

lemma *feedback-simp-aaaa*: *feedback* $(\{.\mathit{inpt}\ r.\}\ o\ [:r:]) =$
$\{.\ \lambda x.((\exists u.\ \mathit{inpt}\ r\ (u,\ x)) \wedge (\forall a.\ (\exists u\ y.\ r\ (u,\ x)\ (a,\ y)) \longrightarrow \mathit{inpt}\ r\ (a,\ x))).\} \circ$
$[:x \rightsquigarrow y\ .\ (\exists\ v\ .\ \ r\ (v,\ x)\ (v,\ y)):]$

lemma *feedback-simp-aaaaa*: $p \le \mathit{inpt}\ r \Longrightarrow$ *feedback* $(\{.p.\}\ o\ [:r:]) =$
$\{.\ \lambda x.((\exists u.\ p\ (u,\ x)) \wedge (\forall a.\ (\exists u\ y.\ p\ (u,\ x) \wedge r\ (u,\ x)\ (a,\ y)) \longrightarrow p\ (a,\ x))).\} \circ$
$[:x \rightsquigarrow y\ .\ (\exists\ v\ .\ \ p\ (v,\ x) \wedge r\ (v,\ x)\ (v,\ y)):]$

lemma $p \le \mathit{inpt}\ r \Longrightarrow p' \le \mathit{inpt}\ r' \Longrightarrow$ *feedback* $([-\ \lambda\ (x,\ y,\ z)\ .\ ((x,\ y),\ z)\ -]\ o\ ((\{.p.\}\ o\ [:r:])\ **$ $(\{.p'.\}\ o\ [:r':]))\ o\ [-\ \lambda\ ((x,\ y),\ z)\ .\ (x,\ y,\ z)\ -]) =$
(*feedback* $(\{.p.\}\ o\ [:r:]))\ **\ (\{.p'.\}\ o\ [:r':])$

lemma *feedback-in-simp-a*: $p \le \mathit{inpt}\ r \Longrightarrow p' \le \mathit{inpt}\ r' \Longrightarrow$
feedback $(\ \{.\ u,\ x\ .\ p\ (u,\ x) \wedge p'\ x.\}\ o\ [:u,\ x \rightsquigarrow v,\ y\ .\ r\ (u,\ x)\ y \wedge r'\ x\ v:])$
$= \{.\ x\ .\ p'\ x \wedge (\forall b.\ r'\ x\ b \longrightarrow p\ (b,x)).\}\ o\ [:x \rightsquigarrow y\ .\ \exists\ v\ .\ r'\ x\ v \wedge r\ (v,\ x)\ y:]$

lemma *feedback-in-simp-b*: $p \le \mathit{inpt}\ r \Longrightarrow p' \le \mathit{inpt}\ r' \Longrightarrow$
feedback $(\ \{.\ u,\ x\ .\ p\ (u,\ x) \wedge p'\ x.\}\ o\ [:u,\ x \rightsquigarrow v,\ y\ .\ r\ (u,\ x)\ y \wedge r'\ x\ v:])$
$= \{.\ x\ .\ p'\ x \wedge (\forall b.\ r'\ x\ b \longrightarrow p\ (b,x)).\}\ o\ [:x \rightsquigarrow y\ .\ \exists\ v\ .\ r'\ x\ v \wedge r\ (v,\ x)\ y:]$
lemma $p \le \mathit{inpt}\ r \Longrightarrow p'' \le \mathit{inpt}\ r'' \Longrightarrow$ *feedback* $(\ (\mathit{Skip}\ **\ (\{.p.\}\ o\ [:r:]))\ o\ ([-\lambda(x,y)\ .\ (y,x)-])\ o$ $(\mathit{Skip}\ **\ (\{.p''.\}\ o\ [:r'':]))\ )$

$= (\{.p.\}\ o\ [:r:])\ o\ (\{.p''.\}\ o\ [:r'':])$

lemma *feedback-update-simp-aaa*: $(\bigwedge\ u\ x.\ fst(f(u,x)) = fst(f(undefined,x))) \Longrightarrow$
$feedback(\{.p.\}\ o\ [-f-]) = \{.x.\ p(fst(f(undefined,\ x)),\ x).\} \circ [-\ \lambda x.\ snd(f(fst(f(undefined,x)),x))-]$

lemma *feedback-update-simp-bbb*: $(\bigwedge\ u\ x.\ fst(f(u,x)) = fst(f(undefined,x))) \Longrightarrow$
$feedback([-f-]) = [-\ \lambda x.\ snd(f(fst(f(undefined,x)),x))-]$

thm *feedback-def*

thm *feedback-in-simp-a*

definition $feedbackless\ S = (SOME\ T\ .\ \exists\ p\ f\ .\ S = \{.p.\}\ o\ [-f-] \wedge T = \{.x.\ p(fst(f(Eps\ (\lambda\ u\ .\ p\ (u,\ x)),\ x)),\ x).\} \circ [-\ \lambda x.\ snd(f(fst(f(Eps\ (\lambda\ u\ .\ p\ (u,\ x)),x)),x))-])$

definition $fstsome\ p\ x = Eps\ (\lambda\ u\ .\ p\ (u,\ x))$

definition $fbv\ p\ f\ x = fst(f(fstsome\ p\ x,\ x))$

definition $fb\text{-}prec\ p\ f\ x = p(fbv\ p\ f\ x,\ x)$
definition $fb\text{-}func\ p\ f\ x = snd(f(fbv\ p\ f\ x,\ x))$

lemma *fb-prec-simp*: $fb\text{-}prec\ p\ f = (\lambda\ x\ .\ p(fbv\ p\ f\ x,\ x))$

lemma *fb-func-simp*: $fb\text{-}func\ p\ f = (\lambda\ x\ .\ snd(f(fbv\ p\ f\ x,\ x)))$

lemma *feedbackless-update-simp-aaa*: $feedbackless(\{.p.\}\ o\ [-f-]) = \{.fb\text{-}prec\ p\ f.\} \circ [-\ fb\text{-}func\ p\ f\ -]$

lemma $(\bigwedge\ u\ x.\ fst(f(u,x)) = fst(f(undefined,x))) \Longrightarrow feedback(\{.p.\}\ o\ [-f-]) = feedbackless(\{.p.\}\ o\ [-f-])$

lemma *feedbackless-update-simp-bbb*: $feedbackless([-f-]) = [-\ fb\text{-}func\ \top\ f\ -]$

lemma *feedback-update-simp-ccc*: $feedback(\ \{.\bot.\}\ o\ [-f-]) = \bot$

1.8.1 Different Feedback Attempts

definition $select''\ S = [:x \rightsquigarrow u,\ x'\ .\ x' = x \wedge prec\ S\ (u,\ x)\ :]\ o\ S\ o\ [:v,\ y \rightsquigarrow v'\ .\ v' = v:]$

definition $selectb\ S = \{:\ x \rightsquigarrow u,\ x'.\ x = x' \wedge prec\ S\ (u,\ x):\}\ o\ S\ o\ [:v,\ y \rightsquigarrow v'\ .\ v' = v:]$

definition $selectd\ S = [:x \rightsquigarrow u,\ x'\ .\ x' = x \wedge prec\ S\ (u,\ x)\ :]\ o\ S\ o\ [:v,\ y \rightsquigarrow v'\ .\ v' = v:]$

definition $selecte\ S = [:x \rightsquigarrow u,\ x'\ .\ x' = x \wedge grd\ S\ (u,\ x)\ :]\ o\ S\ o\ [:v,\ y \rightsquigarrow v'\ .\ v' = v:]$

definition $feedbackf\ S = \{.\ x\ .\ (\exists\ u\ .\ prec\ S\ (u,\ x)).\}\ o\ [:x \rightsquigarrow (u,\ x'),\ u'\ .\ x' = x \wedge u' = u \wedge prec\ S\ (u,\ x)\ :]$
$o\ (S\ **\ Skip)\ o\ [:(v,\ y),\ u \rightsquigarrow (v',\ y')\ .\ v = u \wedge v' = v \wedge y' = y:]$

definition $feedbackg\ S = [:x \rightsquigarrow (u,\ x'),\ u'\ .\ x' = x \wedge u' = u \wedge grd\ S\ (u,\ x)\ :]\ o\ (S\ **\ Skip)\ o\ [:(v,\ y),\ u \rightsquigarrow v',\ y'\ .\ v = u \wedge y' = y \wedge v' = v:]$

lemma *selectc''-spec*: $select''$ ({. p .} o [:r:]) = [:$x \rightsquigarrow v$. $\exists$ u y . p (u, x) $\wedge$ r (u,x) (v,y) :]

lemma *selectcb-spec*: *selectb* ({. p .} o [:r:]) = {: $x \rightsquigarrow u$,x'. $x = x'$ $\wedge$ p (u, x):} o [:u, $x \rightsquigarrow v$. $\exists$ y . p (u, x) $\wedge$ r (u,x) (v,y) :]

lemma *feedbackf-spec*: *feedbackf* ({. p .} o [:r:]) = {. x . ($\exists$ u . p (u, x)).} o [:$x \rightsquigarrow u$, y . p (u, x) $\wedge$ r (u,x) (u,y) :]

lemma *feedbackg-spec*: *feedbackg* ({. p .} o [:r:]) = {. x . ($\forall$ u . p (u, x)).} o [:$x \rightsquigarrow u$, y .r (u,x) (u,y) :]

lemma *selectd-spec*: *selectd* ({. p .} o [:r:]) = [:$x \rightsquigarrow u$, x' . $x' = x$ $\wedge$ p (u, x) :] o [:r:] o [:v, $y \rightsquigarrow v'$. $v' = v$:]

lemma *selecte-spec*: *selecte* ({. p .} o [:r:]) = {.x . $\forall$ u . p (u, x).} o [:$x \rightsquigarrow v$. $\exists$ u y . r (u, x) (v, y):]

definition $feedback'$ S = [:$x \rightsquigarrow x'$, x'' . $x' = x$ $\wedge$ $x'' = x$:] o ((*select* S) ** *Skip*) o S o [:u,$y \rightsquigarrow y'$. $y' = y$:]
definition $feedback''$ S = [:$x \rightsquigarrow x'$, x'' . $x' = x$ $\wedge$ $x'' = x$:] o (($select''$ S) ** *Skip*) o S o [:u,$y \rightsquigarrow y'$. $y' = y$:]

definition *feedbacka* S = [:$x \rightsquigarrow x'$, x'' . $x' = x$ $\wedge$ $x'' = x$:] o ((*select* S) ** *Skip*) o (S $\|$ [:u, $x \rightsquigarrow v$, y . $u = v$:])
definition *feedbackb* S = [:$x \rightsquigarrow x'$, x'' . $x' = x$ $\wedge$ $x'' = x$:] o ((*selectb* S) ** *Skip*) o (S $\|$ [:u, $x \rightsquigarrow v$, y . $u = v$:]) o [:u,$y \rightsquigarrow y'$. $y' = y$:]

lemma *feedback-simp-a-a*: $feedback'$ ({.p.} o [:r:]) =
{. x. ($\exists u$. p (u, x)) $\wedge$ ($\forall a$. ($\exists u$. p (u, x) $\wedge$ ($\exists y$. r (u, x) (a, y))) $\longrightarrow$ p (a, x)) .} $\circ$
[: λx y. $\exists a$ aa. ($\exists u$. p (u, x) $\wedge$ ($\exists y$. r (u, x) (aa, y))) $\wedge$ r (aa, x) (a, y) :]

lemma *feedback-simp-a-b*: $feedback''$ ({.p.} o [:r:]) =
{. λx. $\forall a$. ($\exists u$. p (u, x) $\wedge$ ($\exists y$. r (u, x) (a, y))) $\longrightarrow$ p (a, x) .} $\circ$ [: λx y. $\exists a$ aa. ($\exists u$. p (u, x) $\wedge$ ($\exists y$. r (u, x) (aa, y))) $\wedge$ r (aa, x) (a, y) :]

lemma *feedbackb-simp-a*: *feedbackb* ({.p.} o [:r:]) =
{:$x \rightsquigarrow u$, x' . $x = x'$ $\wedge$ p (u, x) $\wedge$ ($\forall a$. (($\exists y$. r (u, x) (a, y))) $\longrightarrow$ p (a, x)) :} $\circ$
[:u, $x \rightsquigarrow y$. ($\exists$ v .(($\exists y$. r (u, x) (v, y))) $\wedge$ r (v, x) (v, y)):]

lemma *feedbackb-simp-aa*: *feedbackb* ({.*inpt* r.} o [:r:]) =
{:$x \rightsquigarrow u$, x' . $x = x'$ $\wedge$ *inpt* r (u, x) $\wedge$ ($\forall a$. (($\exists y$. r (u, x) (a, y))) $\longrightarrow$ *inpt* r (a, x)) :} $\circ$
[:u, $x \rightsquigarrow y$. ($\exists$ v .(($\exists y$. r (u, x) (v, y))) $\wedge$ r (v, x) (v, y)):]

lemma *feedbacka-simp-a*: *feedbacka* ({.p.} o [:r:]) =
{. λx. ($\exists u$. p (u, x)) $\wedge$ ($\forall a$. ($\exists u$. p (u, x) $\wedge$ ($\exists y$. r (u, x) (a, y))) $\longrightarrow$ p (a, x)) .} $\circ$
[: λx (v, y) . ($\exists u$. p (u, x) $\wedge$ ($\exists y$. r (u, x) (v, y))) $\wedge$ r (v, x) (v, y):]

lemma *feedback-in-simp-a-a*: $p \leq$ *inpt* $r \Longrightarrow p' \leq$ *inpt* $r' \Longrightarrow$
$feedback'$ ({. u, x . p (u, x) $\wedge$ p' x.} o [:u, $x \rightsquigarrow v$, y . r (u, x) y $\wedge$ r' x v:])
= {. x . p' x $\wedge$ ($\forall b$. r' x b $\longrightarrow$ p (b,x)).} o [:$x \rightsquigarrow y$. $\exists$ v . r' x v $\wedge$ r (v, x) y:]

lemma *feedbacka-in-simp-a*: $p \leq$ *inpt* $r \Longrightarrow p' \leq$ *inpt* $r' \Longrightarrow$
feedbacka ({. u, x . p (u, x) $\wedge$ p' x.} o [:u, $x \rightsquigarrow v$, y . r (u, x) y $\wedge$ r' x v:])

$= \{. \ x \ . \ p' \ x \wedge (\forall b. \ r' \ x \ b \longrightarrow p \ (b,x)).\} \ o \ [:x \rightsquigarrow v, \ y \ . \ r' \ x \ v \wedge r \ (v, \ x) \ y:]$

lemma *feedbacka-simp-b*: $feedbacka \ [:r:] = [: \ x \rightsquigarrow v, \ y \ . \ r \ (v, \ x) \ (v, \ y):]$

1.8.2 Feedback of Decomposable Components

definition *decomposable* $r \ r' \ r'' = (\forall \ u \ x \ v \ y \ . \ r \ (u, \ x) \ (v, \ y) = ((r' \ x \ v) \wedge r'' \ (u, \ x) \ y))$

lemma *decomposabel-iff*: $(\exists \ r' \ r'' \ . \ decomposable \ r \ r' \ r'') = ((\forall \ u \ x \ v \ y \ . \ r \ (u, \ x) \ (v, \ y) = ((\exists \ u \ y \ . \ r \ (u, \ x) \ (v, \ y)) \wedge (\exists \ v \ . \ r \ (u, \ x) \ (v, \ y))) \ ))$

lemma *decomposable-calc*: $(\exists \ r' \ r'' \ . \ decomposable \ r \ r' \ r'') \Longrightarrow decomposable \ r \ (\lambda \ x \ v \ . \ (\exists \ y \ u' \ . \ r \ (u', \ x) \ (v, \ y))) \ (\lambda \ (u,x) \ y \ . \ (\exists \ v \ . \ r \ (u,x) \ (v, \ y)))$

lemma *decomposable-inpt*: $decomposable \ r \ r' \ r'' \Longrightarrow inpt \ r \ (u, \ x) = (inpt \ r' \ x \wedge inpt \ r'' \ (u, \ x))$

lemma *decomposable-feedback-trs*: $decomposable \ r \ r' \ r'' \Longrightarrow feedback \ (trs \ r)$
$= \{. \ x \ . \ inpt \ r' \ x \wedge (\forall b. \ r' \ x \ b \longrightarrow inpt \ r'' \ (b, \ x)).\} \circ [:x \rightsquigarrow y.\exists v. \ r' \ x \ v \wedge r'' \ (v, \ x) \ y:]$

lemma *spec-eq*: $(\bigwedge \ x \ . \ p \ x = p' \ x) \Longrightarrow (\bigwedge \ x \ y \ . \ p \ x \Longrightarrow r \ x \ y = r' \ x \ y) \Longrightarrow \{.p.\} \ o \ [:r:] = \{.p'.\} \ o \ [:r':]$

theorem $decomposable \ r \ r' \ r'' \Longrightarrow \ feedback \ (trs \ r)$
$= trs \ (\lambda \ x \ y \ . \ (\forall v. \ r' \ x \ v \longrightarrow inpt \ r'' \ (v, \ x)) \wedge (\exists v. \ r' \ x \ v \wedge r'' \ (v, \ x) \ y))$

lemma [*simp*]: $((\exists u. \ p \ u \ x) \wedge (\exists v. \ Ex \ (r \ v)) \wedge (\forall a. \ (\exists u. \ p \ u \ x) \wedge (\exists v. \ Ex \ (r \ v)) \wedge Ex \ (r \ a) \longrightarrow p \ a \ x))$
$= (((\exists v. \ Ex \ (r \ v)) \wedge (\forall \ a \ . \ Ex \ (r \ a) \longrightarrow p \ a \ x)))$

definition *Decomposable* $r = (\exists \ r' \ r'' \ . \ decomposable \ r \ r' \ r'')$

definition *fst-dec* $r = (\lambda \ x \ v \ . \ \exists \ u \ y \ . \ r \ (u, \ x) \ (v, \ y))$
definition *snd-dec* $r = (\lambda \ (u, \ x) \ y \ . \ \exists \ v \ . \ r \ (u, \ x) \ (v, \ y))$

lemma *decomosable-fst-snd*: $Decomposable \ r = (decomposable \ r \ (fst\text{-}dec \ r) \ (snd\text{-}dec \ r))$

definition *state-determ* $r = (\forall \ x \ y \ y' \ s \ s' \ s'' \ . \ r \ (s, \ x) \ (s', \ y) \wedge r \ (s, \ x) \ (s'', \ y') \longrightarrow s' = s'')$

lemma *decomposable-and*: $decomposable \ r \ r' \ r'' \Longrightarrow decomposable \ (\lambda \ (u, \ x) \ (v, \ y) \ . \ p(u, \ x) \wedge r \ (u,x) \ (v, \ y)) \ r' \ (\lambda \ (u,x) \ y \ . \ p \ (u, \ x) \wedge r'' \ (u, \ x) \ y)$

end

2 Complete Distributive Lattice

theory *Distributive* **imports** *Main*
begin

notation
bot (⊥) **and**

top ($\top$) **and**
inf (**infixl** $\sqcap$ *70*)
and *sup* (**infixl** $\sqcup$ *65*)

context *complete-lattice*
begin
lemma *Sup-Inf-le*: $Sup\ (Inf\ `\ \{f\ `\ A \mid f\ .\ (\forall\ \ Y \in A\ .\ f\ Y \in Y)\}) \leq Inf\ (Sup\ `\ A)$
end

class *complete-distributive-lattice* = *complete-lattice* +
assumes *Inf-Sup-le*: $Inf\ (Sup\ `\ A) \leq Sup\ (Inf\ `\ \{f\ `\ A \mid f\ .\ (\forall\ \ Y \in A\ .\ f\ Y \in Y)\})$
begin

lemma *Inf-Sup*: $Inf\ (Sup\ `\ A) = Sup\ (Inf\ `\ \{f\ `\ A \mid f\ .\ (\forall\ \ Y \in A\ .\ f\ Y \in Y)\})$

lemma *Sup-Inf*: $Sup\ (Inf\ `\ A) = Inf\ (Sup\ `\ \{f\ `\ A \mid f\ .\ (\forall\ \ Y \in A\ .\ f\ Y \in Y)\})$

lemma *dual-complete-distributive-lattice*:
class.complete-distributive-lattice Sup Inf sup ($op \geq$) ($op >$) *inf* $\top$ $\bot$

lemma *sup-Inf*: $a \sqcup Inf\ B = (INF\ b{:}B.\ a \sqcup b)$

lemma *inf-Sup*: $a \sqcap Sup\ B = (SUP\ b{:}B.\ a \sqcap b)$

subclass *complete-distrib-lattice*

end

instantiation *bool* :: *complete-distributive-lattice*
begin
instance
end

instantiation *set* :: (*type*) *complete-distributive-lattice*
begin
instance
end

context *complete-distributive-lattice*
begin

lemma *INF-SUP*: $(INF\ y.\ SUP\ x.\ ((P\ x\ y){::}'a)) = (SUP\ x.\ INF\ y.\ P\ (x\ y)\ y)$

end

instantiation *fun* :: (*type*, *complete-distributive-lattice*) *complete-distributive-lattice*
begin

instance

end

context *complete-linorder*

begin

subclass *complete-distributive-lattice*

end

end

3 Linear Temporal Logic

theory *Temporal* **imports** *Distributive*
begin

In this section we introduce an algebraic axiomatization of Linear Temporal Logic (LTL). We model LTL formulas semantically as predicates on traces. For example the LTL formula $\alpha = \Box \Diamond (x = 1)$ is modeled as a predicate $\alpha : (nat \Rightarrow nat) \Rightarrow bool$, where $\alpha\ x = True$ if $x\ i = 1$ for infinitely many $i : nat$. In this formula $\Box$ and $\Diamond$ denote the always and eventually operators, respectively. Formulas with multiple variables are modeled similarly. For example a formula α in two variables is modeled as $\alpha : (nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'b) \Rightarrow bool$, and for example $(\Box\ \alpha)\ x\ y$ is defined as $(\forall i.\alpha\ x[i..]\ y[i..])$, where $x[i..]\ j = x\ (i + j)$. We would like to construct an algebraic structure (Isabelle class) which has the temporal operators as operations, and which has instatiations to $(nat \Rightarrow 'a) \Rightarrow bool$, $(nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'b) \Rightarrow bool$, and so on. Ideally our structure should be such that if we have this structure on a type $'a :: temporal$, then we could extend it to $(nat \Rightarrow 'b) \Rightarrow 'a$ in a way similar to the way Boolean algebras are extended from a type $'a :: boolean\_algebra$ to $'b \Rightarrow 'a$. Unfortunately, if we use for example $\Box$ as primitive operation on our temporal structure, then we cannot extend $\Box$ from $'a :: temporal$ to $(nat \Rightarrow 'b) \Rightarrow 'a$. A possible extension of $\Box$ could be

$$(\Box\ \alpha)\ x = \bigwedge_{i:nat} \Box(\alpha\ x[i..]) \text{ and } \Box\ b = b$$

where $\alpha : (nat \Rightarrow 'b) \Rightarrow 'a$ and $b : bool$. However, if we apply this definition to $\alpha : (nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'b) \Rightarrow bool$, then we get

$$(\Box\ \alpha)\ x\ y = (\forall i\ j.\alpha\ x[i..]\ y[j..])$$

which is not correct.

To overcome this problem we introduce as a primitive operation $!! : 'a \Rightarrow nat \Rightarrow 'a$, where $'a$ is the type of temporal formulas, and $\alpha!!i$ is the formula α at time point i. If α is a formula in two variables as before, then

$$(\alpha!!i)\ x\ y = \alpha\ x[i..]\ y[i..].$$

and we define for example the the operator always by

$$\Box\alpha = \bigwedge_{i:nat} \alpha!!i$$

class *temporal* = *complete-boolean-algebra* + *complete-distributive-lattice* +
 fixes *at* :: *'a* ⇒ *nat* ⇒ *'a* (**infixl** !! *150*)
 assumes [*simp*]: *a* !! *i* !! *j* = *a* !! (*i* + *j*)
 assumes [*simp*]: *a* !! *0* = *a*

assumes [*simp*]: $-(a\ !!\ i) = (-a)\ !!\ i$
assumes *Inf-at*[*simp*]: $(Inf\ X)\ !!\ i = (INFIMUM\ X\ (\lambda\ x\ .\ at\ x\ i))$
begin
lemma [*simp*]: $\top\ !!\ i = \top$

lemma *Sup-at*: $(Sup\ X)\ !!\ i = (SUPREMUM\ X\ (\lambda\ x\ .\ x\ !!\ i))$

lemma [*simp*]: $(a \sqcap b)\ !!\ i = (a\ !!\ i) \sqcap (b\ !!\ i)$

lemma [*simp*]: $(INF\ x{:}X.\ f\ x)\ !!\ i = (INF\ x{:}X.\ f\ x\ !!\ i)$

definition *always* :: $'a \Rightarrow 'a$ ($\Box$ (-) [900] 900) **where**
$\Box\ p = (INF\ i\ .\ p\ !!\ i)$

definition *eventually-bounded* :: *nat set* $\Rightarrow 'a \Rightarrow 'a$ ($\Diamond b$ (-) (-) [900,900] 900) **where**
$\Diamond b\ b\ p = (SUP\ i{:}\ b\ .\ p\ !!\ i)$

definition *always-bounded* :: *nat set* $\Rightarrow 'a \Rightarrow 'a$ ($\Box b$ (-) (-) [900,900] 900) **where**
$\Box b\ b\ p = (INF\ i{:}\ b\ .\ p\ !!\ i)$

lemma $(\Box b\ b\ p) \sqcap (\Box b\ b'\ p) = (\Box b\ (b \cup b')\ p)$

definition *eventually* :: $'a \Rightarrow 'a$ ($\Diamond$ (-) [900] 900) **where**
$\Diamond\ p = (SUP\ i\ .\ p\ !!\ i)$

definition *next* :: $'a \Rightarrow 'a$ ($\odot$ (-) [900] 900) **where**
$\odot\ p = p\ !!\ (Suc\ 0)$

definition *until* :: $'a \Rightarrow 'a \Rightarrow 'a$ (**infix** *until* 65) **where**
$(p\ until\ q) = (SUP\ n\ .\ (INFIMUM\ \{i\ .\ i < n\}\ (at\ p)) \sqcap (q\ !!\ n))$

definition *leads* :: $'a \Rightarrow 'a \Rightarrow 'a$ (**infix** *leads* 65) **where**
$(p\ leads\ q) = -(p\ until\ -q)$

lemma *iterate-next*: $(next\ \hat{}\hat{}\ n)\ p = p\ !!\ n$

lemma *always-next*: $\Box\ p = p \sqcap (\Box\ (\odot\ p))$
end

Next lemma, in the context of complete boolean algebras, will be used to prove $-(p\ until\ -p) = \Box\ p$.

context *complete-boolean-algebra*
begin
lemma *until-always*: $(INF\ n.\ (SUP\ i : \{i.\ i < n\}\ .\ -\ p\ i) \sqcup ((p :: nat \Rightarrow 'a)\ n)) \le p\ n$

end

We prove now a number of results of the temporal class.

context *temporal*
begin
lemma [*simp*]: $(a \sqcup b)\ !!\ i = (a\ !!\ i) \sqcup (b\ !!\ i)$

lemma *always-less* [*simp*]: $\Box\ p \le p$

lemma *always-always*: $\Box\ \Box\ x = \Box\ x$

lemma *always-and*: $\Box\ (p \sqcap q) = (\Box\ p) \sqcap (\Box\ q)$

lemma *eventually-or*: $\Diamond\ (p \sqcup q) = (\Diamond\ p) \sqcup (\Diamond\ q)$

lemma *neg-until-always*: $-(p\ \mathit{until}\ -p) = \Box\ p$

lemma *leads-always*: $p\ \mathit{leads}\ p = \Box\ p$

lemma *neg-always-eventually*: $\Box\ p = -\ \Diamond\ (-\ p)$

lemma *neg-true-until-always*: $-(\top\ \mathit{until}\ -p) = \Box\ p$

lemma *top-leads-always*: $\top\ \mathit{leads}\ p = \Box\ p$

lemma *neg-until-true*: $-(p\ \mathit{until}\ -\top) = \top$

lemma *leads-top*: $p\ \mathit{leads}\ \top = \top$

lemma *neg-until-false*: $-(p\ \mathit{until}\ -\bot) = \bot$

lemma *leads-bot*: $p\ \mathit{leads}\ \bot = \bot$

lemma *true-until-eventually*: $(\top\ \mathit{until}\ p) = \Diamond\ p$

end

Boolean algebras with $b!!i = b$ form a temporal class.

instantiation *bool* :: *temporal*
begin
definition *at-bool-def* [*simp*]: $(p::\mathit{bool})\ !!\ i = p$
instance
end

type-synonym $'a\ \mathit{trace} = \mathit{nat} \Rightarrow 'a$

Asumming that $'a :: \mathit{temporal}$ is a type of class *temporal*, and $'b$ is an arbitrary type, we would like to create the instantiation of $'b\ \mathit{trace} \Rightarrow 'a$ as a temporal class. However Isabelle allows only instatiations of functions from a class to another class. To solve this problem we introduce a new class called trace with an operation $\mathit{suffix} :: 'a \Rightarrow \mathit{nat} \Rightarrow 'a$ where $\mathit{suffix}\ a\ i\ j = (a[i..])\ j = a\ (i + j)$ when a is a trace with elements of some type $'b$ ($'a = \mathit{nat} \Rightarrow 'b$).

class *trace* =
fixes $\mathit{suffix} :: 'a \Rightarrow \mathit{nat} \Rightarrow 'a$ (-[- ..] [*80*, *15*] *80*)
fixes $\mathit{eqtop} :: \mathit{nat} \Rightarrow 'a \Rightarrow 'a \Rightarrow \mathit{bool}$
fixes $\mathit{cat} :: \mathit{nat} \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a$
fixes $\mathit{Cat} :: (\mathit{nat} \Rightarrow 'a) \Rightarrow 'a$
assumes *suffix-suffix*[*simp*]: $a[i..][j..] = a[i + j..]$
assumes [*simp*]: $a[0..] = a$
assumes [*simp*]: $\mathit{eqtop}\ 0\ a\ b = \mathit{True}$
assumes [*simp*]: $\mathit{eqtop}\ n\ a\ a = \mathit{True}$
assumes *all-eqtop*[*simp*]: $\forall\ n\ .\ \mathit{eqtop}\ n\ a\ b \Longrightarrow a = b$
assumes *eqtop-sym*: $\mathit{eqtop}\ n\ a\ b = \mathit{eqtop}\ n\ b\ a$
assumes *eqtop-tran*: $\mathit{eqtop}\ n\ a\ b \Longrightarrow \mathit{eqtop}\ n\ b\ c \Longrightarrow \mathit{eqtop}\ n\ a\ c$
assumes [*simp*]: $\mathit{eqtop}\ n\ (\mathit{cat}\ n\ x\ y)\ z = \mathit{eqtop}\ n\ x\ z$
assumes *cat-at-eq*[*simp*]: $(\mathit{cat}\ n\ x\ y)[n..] = y$

assumes *eqtop-Suc*: $eqtop\ (Suc\ n)\ x\ y = (eqtop\ n\ x\ y \wedge eqtop\ (Suc\ 0)\ (x[n..])\ (y[n..]))$
assumes *Cat-Suc*: $Cat\ u = cat\ (Suc\ 0)\ (u\ 0)\ (Cat\ (\lambda\ i\ .\ u\ (Suc\ i)))$
assumes *cat-Suc*: $cat\ (Suc\ n)\ x\ y = cat\ (Suc\ 0)\ x\ (cat\ n\ (x[Suc\ 0..])\ y)$
assumes *cat-Zero*[*simp*]: $cat\ 0\ x\ y = y$

begin
definition *next-trace* :: $'a \Rightarrow 'a$ $(\odot\ (\text{-})\ [900]\ 900)$ **where**
$\odot\ p = p[Suc\ 0..]$

lemma *eq-le*[*simp*]: $\bigwedge\ a\ b\ .\ n \le m \Longrightarrow eqtop\ m\ a\ b \Longrightarrow eqtop\ n\ a\ b$

lemma *eqtop-Suc-Cat*: $\bigwedge\ u\ .\ eqtop\ (Suc\ 0)\ ((Cat\ u)[n..])\ (u\ n)$

lemma *eqtop-tail-eqtop*: $eqtop\ n\ x\ y \Longrightarrow x[n\ ..] = y[n\ ..] \Longrightarrow eqtop\ na\ x\ y$

lemma [*simp*]: $eqtop\ n\ z\ (cat\ n\ x\ y) = eqtop\ n\ z\ x$

lemma *eqtop-tail*: $eqtop\ n\ x\ y \Longrightarrow x[n..] = y[n..] \Longrightarrow x = y$

definition $cons\ x = cat\ (Suc\ 0)\ x\ x$

lemma [*simp*]: $(cons\ a)[Suc\ 0..] = a$

lemma [*simp*]: $eqtop\ 0 = \top$

lemma [*simp*]: $eqtop\ n\ x\ (cat\ n\ x\ y)$

lemma [*simp*]: $\exists\, y.\ x = y[Suc\ 0\ ..]$

lemma *eqtop-plus*: $\bigwedge\ x\ y\ .\ (eqtop\ n\ x\ y \wedge (eqtop\ m\ (x[n..])\ (y[n..]))) = eqtop\ (n + m)\ x\ y$

lemma [*simp*]: $cat\ n\ (cat\ n\ x\ y)\ z = cat\ n\ x\ z$

lemma [*simp*]: $cat\ n\ x\ (x[n..]) = x$

lemma *eqtop-Suc-a*: $eqtop\ (Suc\ n)\ x\ y = (eqtop\ (Suc\ 0)\ x\ y \wedge eqtop\ n\ (x[Suc\ 0\ ..])\ (y[Suc\ 0\ ..]))$

lemma *cat-Suc-b*: $\bigwedge\ x\ y\ .\ cat\ (Suc\ n)\ x\ y = cat\ n\ x\ (cat\ (Suc\ 0)\ (x[n..])\ y)$

lemma *cat-at*: $\bigwedge\ i\ x\ y\ .\ i \le n \Longrightarrow (cat\ n\ x\ y[i..]) = cat\ (n - i)\ (x[i..])\ y$

lemma *eqtop-cat-le*: $\bigwedge\ m\ x\ y\ z\ .\ m \le n \Longrightarrow eqtop\ m\ (cat\ n\ x\ y)\ z = eqtop\ m\ x\ z$

lemma *eqtop-cat-aux*: $i < n \Longrightarrow eqtop\ (Suc\ 0)\ (cat\ n\ x\ y[i..])\ (x[i..])$

end

instantiation *prod* :: $(trace,\ trace)\ trace$
begin

definition *at-prod-def*: $x[i..] \equiv ((fst\ x)[i..], (snd\ x)[i..])$
definition *eqtop-prod-def*: $eqtop\ n\ x\ y \equiv eqtop\ n\ (fst\ x)\ (fst\ y) \wedge eqtop\ n\ (snd\ x)\ (snd\ y)$
definition *cat-prod-def*: $cat\ n\ x\ y \equiv (cat\ n\ (fst\ x)\ (fst\ y),\ cat\ n\ (snd\ x)\ (snd\ y))$
definition *Cat-prod-def*: $Cat\ u \equiv (Cat\ (fst\ o\ u),\ Cat\ (snd\ o\ u))$

instance

end

instantiation *fun* :: (*trace*, *temporal*) *temporal*
begin
definition *at-fun-def*: $(P{::}\ 'a \Rightarrow 'b)\ !!\ i = (\lambda\ x\ .\ (P\ (x[i..]))\ !!\ i)$
instance
end

lemma *SUP-Suc*: $(SUP\ x{:}\{i.\ i < Suc\ n\}.\ p\ x) = (SUP\ x{:}\{i.\ i < n\}.\ p\ x) \sqcup ((p\ n){::}'a{::}complete\text{-}lattice)$

definition $top\text{-}dep\ p = (\forall\ x\ x'\ .\ eqtop\ (Suc\ 0)\ x\ x' \longrightarrow p\ x = p\ x')$

lemma *INF-distrib*: $(INF\ x\ y.\ p\ x \sqcup ((q\ y){::}'a{::}complete\text{-}distrib\text{-}lattice)) = (INF\ x\ .\ p\ x) \sqcup (INF\ y\ .\ q\ y)$

lemma *top-dep-INF-SUP*: $top\text{-}dep\ p \Longrightarrow\ (INF\ x.\ (SUP\ xa{:}\{i.\ i < n\}.\ (-\ p\ (x[xa\ ..]))\ !!\ xa) \sqcup (-\ p\ (x[n\ ..]))\ !!\ n) =$
$(INF\ x\ y.\ (SUP\ xa{:}\{i.\ i < n\}.\ (-\ p\ (x[xa\ ..]))\ !!\ xa) \sqcup (-\ p\ y)\ !!\ n)$

lemma *top-dep-all-leadsto-aux*: $top\text{-}dep\ p \Longrightarrow (INF\ b.\ SUP\ x{:}\{i.\ i < n\}.\ (-\ p\ (b[x\ ..]))\ !!\ x) \le (SUP\ x{:}\{i.\ i < n\}.\ INF\ xa.\ (-\ p\ xa)\ !!\ x)$

theorem *top-dep-all-leadsto*: $top\text{-}dep\ p \Longrightarrow INFIMUM\ UNIV\ (p\ leads\ (\lambda\ y\ .\ q)) = ((SUPREMUM\ UNIV\ p)\ leads\ q)$

theorem *SUP-Always*: $top\text{-}dep\ p \Longrightarrow SUPREMUM\ UNIV\ (\Box\ p) = \Box\ (SUPREMUM\ UNIV\ (p{::}('b{::}trace) \Rightarrow 'a{::}temporal))$

In the last part of our formalization, we need to instantiate the functions from *nat* to some arbitrary type $'a$ as a trace class. However, this again is not possible using the instatiation mechanism of Isabelle. We solve this problem by creating another class called *nat*, and then we instatiate the functions from $'a :: nat$ to $'b$ as traces. The class *nat* is defined such that if we have a type $'a :: nat$, then $'a$ is isomorphic to the type *nat*.

class $nat = zero + plus + minus + one +$
fixes $RepNat :: 'a \Rightarrow nat$
fixes $AbsNat :: nat \Rightarrow 'a$
assumes *RepAbsNat*[*simp*]: $RepNat\ (AbsNat\ n) = n$
and *AbsRepNat*[*simp*]: $AbsNat\ (RepNat\ x) = x$
and *zero-Nat-def*: $0 = AbsNat\ 0$

and *one-Nat-def*: $1 = AbsNat\ 1$
and *plus-Nat-def*: $a + b = AbsNat\ (RepNat\ a + RepNat\ b)$
and *minus-Nat-def*: $a - b = AbsNat\ (RepNat\ a - RepNat\ b)$
begin
lemma *AbsNat-plus*: $AbsNat\ (i + j) = AbsNat\ i + AbsNat\ j$
lemma *AbsNat-minus*: $AbsNat\ (i - j) = AbsNat\ i - AbsNat\ j$
lemma *AbsNat-zero* [*simp*]: $AbsNat\ 0 + i = i$
lemma [*simp*]: $(AbsNat\ (Suc\ 0) + x = 0) = False$

subclass *comm-monoid-diff*
end

The type natural numbers is an instantiation of the class *nat*.

instantiation *nat* :: *nat*
begin
definition *RepNat-nat-def* [*simp*]: $(RepNat{::}\ nat \Rightarrow nat) = id$
definition *AbsNat-nat-def* [*simp*]: $(AbsNat{::}\ nat \Rightarrow nat) = id$
instance
end

Finally, functions from $'a :: nat$ to some arbitrary type $'b$ are instatiated as a trace class.

instantiation *fun* :: (*nat*, *type*) *trace*
begin
definition *at-trace-def* [*simp*]: $((t :: 'a \Rightarrow 'b)[i..])\ j = (t\ \ (AbsNat\ i + j))$
definition *eqtop-trace-def* [*simp*]: $eqtop\ n\ a\ b = (\forall\ \ i < n\ .\ a\ (AbsNat\ i) = b\ (AbsNat\ i))$
definition *cat-trace-def* [*simp*]: $cat\ n\ a\ b\ i = (if\ RepNat\ i < n\ then\ a\ i\ else\ b\ (i - AbsNat\ n))$
definition *Cat-trace-def* [*simp*]: $Cat\ y\ i = (y\ (RepNat\ i)\ \ 0)$
lemma *eqtop-trace-eq*: $\forall\, n\ i.\ i < n \longrightarrow (a{::}'a{\Rightarrow}'b)\ (AbsNat\ i) = b\ (AbsNat\ i) \Longrightarrow a = b$

lemma [*simp*]: $(RepNat\ (AbsNat\ n + xa) < n) = False$

lemma [*simp*]: $AbsNat\ n + AbsNat\ 0 = AbsNat\ n$

lemma *trace-eqtop-tail*: $\forall\, i{<}n.\ x\ (AbsNat\ i) = y\ (AbsNat\ i) \Longrightarrow \forall\, xa.\ x\ (AbsNat\ n + xa) = y\ (AbsNat\ n + xa) \Longrightarrow x\ xa = y\ xa$

lemma *trace-eqtop-Suc*: $\forall\, i{<}n.\ x\ (AbsNat\ i) = y\ (AbsNat\ i) \Longrightarrow x\ (AbsNat\ n) = y\ (AbsNat\ n) \Longrightarrow i < Suc\ n \Longrightarrow x\ (AbsNat\ i) = y\ (AbsNat\ i)$

lemma *RepNat-is-zero*: $RepNat\ x = 0 \Longrightarrow x = 0$

lemma *RepNat-zero*: $RepNat\ x = 0 \Longrightarrow u\ 0\ x = u\ 0\ 0$

lemma [*simp*]: $0 < RepNat\ x \Longrightarrow (Suc\ (RepNat\ (x - AbsNat\ (Suc\ 0)))) = RepNat\ x$

instance
end

By putting together all class definitions and instatiations introduced so far, we obtain the temporal class structure for predicates on traces with arbitrary number of parameters.

For example in the next lemma r and r' are predicate relations, and the operator always is available for them as a consequence of the above construction.

lemma $(\Box\ r)\ OO\ (\Box\ r') \leq (\Box\ (r\ OO\ r'))$

lemma [*simp*]: $(next \ \hat{}\hat{} \ n) \top = \top$

lemma $r\ (u[1..]) = (\exists\ y\ .\ (\bigodot\ (\lambda\ v\ .\ v = y \wedge r\ y))\ u)$

lemma $r\ (u[1..]) = (\ (\bigodot\ (\lambda\ v\ .\ \exists\ y\ .\ v = y \wedge r\ y))\ u)$

lemma $(r\ (u[1..])::bool) = (\ (\bigodot\ r)\ u)$

lemma $((\Box\ r)\ u\ (u[1..])\ x\ y\ ::bool) = (\ (\bigodot\ (\lambda\ u'\ .\ (\Box\ r)\ u\ u'\ x\ y))\ u)$

lemma $r\ (u[1..]) = (\exists\ y\ .\ (\bigodot\ (\lambda\ v\ y\ .\ v = y \wedge r\ \ y))\ u\ y)$

3.1 Propositional Temporal Logic

definition $prop\ P\ \sigma = (P \in \sigma\ (0::nat))$

definition $Exists\ P\ f\ \sigma = (\exists\ \sigma'\ .\ (\forall\ \ i\ .\ \sigma\ i - \{P\} = \sigma'\ i - \{P\}) \wedge f\ \sigma')$
definition $Forall\ P\ f\ \sigma = (\forall\ \sigma'\ .\ (\forall\ \ i\ .\ \sigma\ i - \{P\} = \sigma'\ i - \{P\}) \longrightarrow f\ \sigma')$
definition $impl::\ 'a \Rightarrow 'a \Rightarrow ('a::boolean\text{-}algebra)$ (**infixl** $\rightarrow$ *60*)
  where $x \rightarrow y = ((-x) \sqcup y)$

lemma $x \neq y \Longrightarrow (Exists\ y\ ((\Box\ (prop\ x \rightarrow (\Diamond\ prop\ y))) \sqcap \Box\ \Diamond\ prop\ y)) = \top$

lemma $x \neq y \Longrightarrow (Forall\ y\ ((\Box\ (prop\ x \rightarrow (\Diamond\ prop\ y))) \rightarrow \Box\ \Diamond\ prop\ y)) = (\Box\ \Diamond\ (prop\ x))$

end

4 Monotonic Property Transformers

theory *RefinementReactive*
  imports *Temporal Refinement*
begin

In this section we introduce reactive systems which are modeled as monotonic property transformers where properties are predicates on traces. We start with introducing some examples that uses LTL to specify global behaviour on traces, and later we introduce property transformers based on symbolic transition systems.

definition $HAVOC = [:x \rightsquigarrow y\ .\ True:]$
definition $ASSERT\text{-}LIVE = \{.\ \Box\ \Diamond\ (\lambda\ x\ .\ x\ 0).\}$
definition $GUARANTY\text{-}LIVE = [:x \rightsquigarrow y\ .\ \Box\ \Diamond\ (\lambda\ y\ .\ y\ 0):]$
definition $AE = ASSERT\text{-}LIVE\ o\ HAVOC$
definition $SKIP = [:x \rightsquigarrow y\ .\ x = y:]$

lemma [*simp*]: $SKIP = id$

definition $REQ\text{-}RESP = [:\ \Box(\lambda\ xs\ ys\ .\ xs\ (0::nat) \longrightarrow (\Diamond\ (\lambda\ ys\ .\ ys\ (0::nat)))\ ys)\ :]$

definition $FAIL = \bot$

lemma $HAVOC\ o\ ASSERT\text{-}LIVE = FAIL$

lemma $HAVOC\ o\ AE = FAIL$

lemma $HAVOC\ o\ ASSERT\text{-}LIVE = FAIL$

lemma $SKIP\ o\ AE = AE$

lemma $(REQ\text{-}RESP\ o\ AE) = AE$

4.1 Symbolic transition systems

In this section we introduce property transformers basend on symbolic transition systems. These are systems with local state. The execution starts in some initial state, and with some input value the system computes a new state and an output value. Then using the current state, and a new input value the system computes a new state, and a new output, and so on. The system may fail if at some point the input and the current state do not statisfy a required predicate.

In the folowing definitions the variables u, x, y stand for the state of the system, the input, and the output respectively. The *init* is the property that the initial state should satisfy. The predicate p is the precondition of the input and the current state, and the relation r gives the next state and the output based on the input and the current state.

definition $illegal\text{-}sts\ init\ p\ r\ x = (\exists\ n\ u\ y\ .\ init\ (u\ 0) \land (\forall\ i < n\ .\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i)) \land (\neg\ p\ (u\ n,\ x\ n)))$
definition $run\text{-}sts\ r\ u\ x\ y = (\forall\ i\ .\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i))$

definition $LocalSystem\ init\ p\ r\ q\ x = (\neg\ illegal\text{-}sts\ init\ p\ r\ x \land (\forall\ u\ y\ .\ (init\ (u\ 0) \land run\text{-}sts\ r\ u\ x\ y) \longrightarrow q\ y))$

lemma $LocalSystem\text{-}not\text{-}fail\text{-}run$: $LocalSystem\ init\ p\ r = \{.-\ illegal\text{-}sts\ init\ p\ r.\}\ o\ [:x \leadsto y\ .\ \exists\ u\ .\ init\ (u\ 0) \land run\text{-}sts\ r\ u\ x\ y:]$

definition $fail\text{-}sys\text{-}delete\ init\ p\ r\ x = (\exists\ n\ u\ y\ .\ u \in init \land (\forall\ i < n\ .\ r\ (u\ i)\ (u\ (Suc\ i))\ (x\ i)\ (y\ i)) \land (\neg\ p\ (u\ n)\ (u\ (Suc\ n))\ (x\ n)))$
definition $run\text{-}delete\ r\ u\ x\ y = (\forall\ i\ .\ r\ (u\ i)\ (u\ (Suc\ i))\ (x\ i)\ (y\ i))$

definition $LocalSystem\text{-}delete\ init\ p\ r\ q\ x = (\neg\ fail\text{-}sys\text{-}delete\ init\ p\ r\ x \land (\forall\ u\ y\ .\ (u \in init \land run\text{-}delete\ r\ u\ x\ y) \longrightarrow q\ y))$

lemma $fail\ (LocalSystem\ init\ p\ r) = illegal\text{-}sts\ init\ p\ r$

definition $lift\text{-}pre\ p = (\lambda\ (u,\ x)\ (u',\ y)\ .\ p\ (u\ (0::nat),\ x\ (0::nat)))$
definition $lift\text{-}rel\ r = (\lambda\ (u,\ x)\ (u',\ y)\ .\ r\ (u\ (0::nat),\ x\ (0::nat))\ (u'\ 0,\ y\ (0::nat)))$

definition $prec\text{-}pre\text{-}sts\ init\ p\ r\ x = (\forall\ u\ y\ .\ init\ (u\ 0) \longrightarrow (lift\text{-}rel\ r\ leads\ lift\text{-}pre\ p)\ (u,\ x)\ (u[1..],\ y))$
definition $rel\text{-}pre\text{-}sts\ init\ r\ x\ y = (\exists\ u\ .\ init\ (u\ 0) \land (\Box\ lift\text{-}rel\ r)\ (u,\ x)\ (u[1..],\ y))$

lemma $prec\text{-}pre\text{-}sts\text{-}simp$: $prec\text{-}pre\text{-}sts\ init\ p\ r\ x = (\forall\ u\ y\ .\ init\ (u\ 0) \longrightarrow (\forall n\ .\ (\forall\ i < n\ .\ r\ (u\ i,\ x$

$i)$ $(u$ $(Suc$ $i),$ y $i))$ $\longrightarrow$ p $(u$ $n,$ x $n)))$

lemma *prec-stateless-sts-simp*: *prec-pre-sts* $\top$ $(\lambda$ $(s{::}unit,$ $x)$. *inpt* r $x)$ $(\lambda$ $(s{::}unit,$ $x)$ $(s'{::}unit,$ $y)$. r x y :: *bool*)
$= (\Box\ (\lambda\ x\ .\ inpt\ r\ (x\ 0)))$

lemma *prec-pre-sts-top*[*simp*]: *prec-pre-sts init* $\top$ $r = \top$

lemma *prec-pre-sts-bot*[*simp*]: *init a* $\Longrightarrow$ *prec-pre-sts init* $\bot$ $r = \bot$

lemma *rel-pre-sts-simp*: *rel-pre-sts init r x y* $= (\exists\ u\ .\ init\ (u\ 0) \wedge (\forall\ i\ .\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i)))$

lemma *LocalSystem-simp*: *LocalSystem init p r* $=$ $\{.$*prec-pre-sts init p r*$.\}$ *o* [:*rel-pre-sts init r*:]

definition *local-init init S* $=$ *INFIMUM init S*

definition *zip-set A B* $= \{u\ .\ ((fst\ o\ u) \in A) \wedge ((snd\ o\ u) \in B)\}$

definition *nzip*:: $('x \Rightarrow 'a) \Rightarrow ('x \Rightarrow 'b) \Rightarrow 'x \Rightarrow ('a\times'b)$ (**infixl** || *65*) **where** $(xs\ ||\ ys)\ i = (xs\ i,\ ys\ i)$

lemma *nzip-def-abs*: $(a\ ||\ b) = (\lambda i.\ (a\ i,\ b\ i))$

lemma *nzip-split*: $(fst\ o\ u)\ ||\ (snd\ o\ u) = u$

lemma [*simp*]: $fst \circ x\ ||\ y = x$

lemma [*simp*]: $snd \circ x\ ||\ y = y$

lemma [*simp*]: $x \in A \Longrightarrow y \in B \Longrightarrow (x\ ||\ y) \in$ *zip-set A B*

lemma *local-demonic-init*: *local-init init* $(\lambda\ u\ .\ \{.\ x\ .\ p\ u\ x.\}\ o\ [:x \rightsquigarrow y\ .\ r\ u\ x\ y\ :]) =$
$[:z \rightsquigarrow u,\ x\ .\ u \in init \wedge z = x:]\ o\ \{.u,\ x\ .\ p\ u\ x.\}\ o\ [:u,\ x \rightsquigarrow y\ .\ r\ u\ x\ y\ :]$

lemma *local-init-comp*: $u' \in init' \Longrightarrow (\forall\ u.\ sconjunctive\ (S\ u)) \Longrightarrow$ (*local-init init S*) *o* (*local-init init' S'*)
$=$ *local-init* (*zip-set init init'*) $(\lambda\ u\ .\ (S\ (fst\ o\ u))\ o\ (S'\ (snd\ o\ u)))$

definition *rel-comp-sts r r'* $= (\lambda\ ((u,v),x)\ ((u',v'),\ z)\ .\ (\exists\ y\ .\ r\ (u,x)\ (u',y) \wedge r'\ (v,y)\ (v',z)))$
definition *prec-comp-sts p r p'* $= (\lambda\ ((u,v),x)\ .\ p\ (u,x) \wedge (\forall\ y\ u'\ .\ r\ (u,\ x)\ (u',y) \longrightarrow p'\ (v,y)))$

definition *sts-comp S S'* $= [-(u,v),x \rightsquigarrow (u,x),v\ -]$ *o* $(S$ ** *Skip*) *o* $[-(u,y),v \rightsquigarrow (v,y),u-]$ *o* $(S'$ ** *Skip*) *o* $[-(v,z),u \rightsquigarrow (u,v),z-]$

lemma *sts-comp-prec-rel*: *sts-comp* $(\{.p.\}$ *o* $[:r:])$ $(\{.p'.\}$ *o* $[:r':]) = \{.$*prec-comp-sts p r p'*$.\}$ *o* [:*rel-comp-sts r r'*:]

We show next that the composition of two SymSystem S and S' is not equal to the SymSystem of the compostion of local transitions of S and S'

definition $initS\ u = True$
definition $precS = (\lambda\ (u,\ x)\ .\ True)$
definition $relS = (\lambda\ (u{::}nat,\ x{::}nat)\ (u'{::}nat,\ y{::}nat)\ .\ u = 0 \wedge u' = 1)$

definition $initS'\ v = True$
definition $precS' = (\lambda\ (u,\ x)\ .\ False)$
definition $relS' = (\lambda\ (v{::}nat,\ x)\ (v'{::}nat,\ y{::}nat)\ .\ True)$

definition $symbS = LocalSystem\ initS\ precS\ relS$
definition $symbS' = LocalSystem\ initS'\ precS'\ relS'$
definition $symbS'' = LocalSystem\ (prod\text{-}pred\ initS\ initS')\ (prec\text{-}comp\text{-}sts\ precS\ relS\ precS')\ (rel\text{-}comp\text{-}sts\ relS\ relS')$

lemma [*simp*]: $symbS = Magic$

lemma [*simp*]: $symbS'' = Fail$

theorem $symbS\ o\ symbS' \neq symbS''$

lemma *rel-pre-sts-comp*: $rel\text{-}pre\text{-}sts\ init\ r\ OO\ rel\text{-}pre\text{-}sts\ init'\ r' = rel\text{-}pre\text{-}sts\ (prod\text{-}pred\ init\ init')\ (rel\text{-}comp\text{-}sts\ r\ r')$

theorem *LocalSystem-comp*: $init'\ a \Longrightarrow LocalSystem\ init\ p\ r\ o\ LocalSystem\ init'\ p'\ r' =$
$\{.x.(\forall u.\ init\ (u\ 0) \longrightarrow (\forall y\ n.\ (\forall i<n.\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i)) \longrightarrow p\ (u\ n,\ x\ n))) \wedge$
$(\forall y.\ (\exists u.\ init\ (u\ 0) \wedge (\forall i.\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i))) \longrightarrow (\forall u.\ init'\ (u\ 0) \longrightarrow (\forall ya\ n.\ (\forall i<n.\ r'\ (u\ i,\ y\ i)\ (u\ (Suc\ i),\ ya\ i)) \longrightarrow p'\ (u\ n,\ y\ n))))).\} \circ$
$[:\ rel\text{-}pre\text{-}sts\ init\ r\ OO\ rel\text{-}pre\text{-}sts\ init'\ r'\ :]$

lemma *sts-comp-prec-aux-a*: $p' \leq inpt\ r' \Longrightarrow$
$(\bigwedge\ v\ y\ n\ .v\ 0 = b \Longrightarrow (\forall i<n.\ rel\text{-}comp\text{-}sts\ r\ r'\ ((u\ i,\ v\ i),\ x\ i)\ ((u\ (Suc\ i),\ v\ (Suc\ i)),\ y\ i)) \Longrightarrow prec\text{-}comp\text{-}sts\ p\ r\ p'\ ((u\ n,\ v\ n),\ x\ n)) \Longrightarrow$
$\forall i < n.\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i) \Longrightarrow p\ (u\ n,\ x\ n) \wedge (\exists\ z\ v\ .\ v\ 0 = b \wedge (\forall\ i < n\ .\ r'\ (v\ i,\ y\ i)\ (v\ (Suc\ i),\ z\ i) \wedge p'\ (v\ i,\ y\ i)))$

lemma *sts-comp-prec-b*: $p' \leq inpt\ r' \Longrightarrow init'\ b \Longrightarrow prec\text{-}pre\text{-}sts\ (prod\text{-}pred\ init\ init')\ (prec\text{-}comp\text{-}sts\ p\ r\ p')\ (rel\text{-}comp\text{-}sts\ r\ r')\ x \Longrightarrow$
$(prec\text{-}pre\text{-}sts\ init\ p\ r\ x \wedge (\forall y.\ rel\text{-}pre\text{-}sts\ init\ r\ x\ y \longrightarrow prec\text{-}pre\text{-}sts\ init'\ p'\ r'\ y))$

primrec $u\text{-}y :: ('a \times 'b \Rightarrow 'a \times 'c \Rightarrow bool) \Rightarrow 'a \Rightarrow (nat \Rightarrow 'b) \Rightarrow nat \Rightarrow 'a \times 'c$ **where**
$u\text{-}y\ r\ a\ x\ 0 = (SOME\ (u,y)\ .\ r\ (a,\ x\ 0)\ (u,\ y))\ |$
$u\text{-}y\ r\ a\ x\ (Suc\ n) = (SOME\ (u,\ y)\ .\ r\ (fst\ (u\text{-}y\ r\ a\ x\ n),\ x\ (Suc\ n))\ (u,\ y))$

definition $uu\ r\ a\ x\ i = (case\ i\ of\ 0 \Rightarrow a \mid Suc\ n \Rightarrow fst\ (u\text{-}y\ r\ a\ x\ n))$
definition $yy\ r\ a\ x = snd\ o\ (u\text{-}y\ r\ a\ x)$

lemma *sts-exists-aux*: $p \leq inpt\ r \Longrightarrow\ prec\text{-}pre\text{-}sts\ init\ p\ r\ x \Longrightarrow$
$init\ a \Longrightarrow (\forall\ i \leq n\ .\ r\ (uu\ r\ a\ x\ i,\ x\ i)\ (uu\ r\ a\ x\ (Suc\ i),\ yy\ r\ a\ x\ i))$

lemma *sts-exists*: $p \leq inpt\ r \Longrightarrow\ prec\text{-}pre\text{-}sts\ init\ p\ r\ x \Longrightarrow\ init\ a \Longrightarrow\ r\ (uu\ r\ a\ x\ n,\ x\ n)\ (uu\ r\ a\ x\ (Suc\ n),\ yy\ r\ a\ x\ n)$

lemma *sts-prec*: $p \le inpt\ r \Longrightarrow\ prec\text{-}pre\text{-}sts\ init\ p\ r\ x \Longrightarrow\ init\ a \Longrightarrow\ p\ (uu\ r\ a\ x\ n,\ x\ n)$

lemma *sts-exists-prec*: $p \le inpt\ r \Longrightarrow\ prec\text{-}pre\text{-}sts\ init\ p\ r\ x \Longrightarrow\ init\ a \Longrightarrow\ p\ (uu\ r\ a\ x\ n,\ x\ n) \land r\ (uu\ r\ a\ x\ n,\ x\ n)\ (uu\ r\ a\ x\ (Suc\ n),\ yy\ r\ a\ x\ n)$

lemma *sts-comp-prec-a*: $p \le inpt\ r \Longrightarrow prec\text{-}pre\text{-}sts\ init\ p\ r\ x \Longrightarrow (\bigwedge\ y.\ rel\text{-}pre\text{-}sts\ init\ r\ x\ y \Longrightarrow prec\text{-}pre\text{-}sts\ init'\ p'\ r'\ y)$
$\Longrightarrow prec\text{-}pre\text{-}sts\ (prod\text{-}pred\ init\ init')\ (prec\text{-}comp\text{-}sts\ p\ r\ p')\ (rel\text{-}comp\text{-}sts\ r\ r')\ x$

lemma *prec-pre-sts-comp*: $p \le inpt\ r \Longrightarrow p' \le inpt\ r' \Longrightarrow init'\ b \Longrightarrow$
$(prec\text{-}pre\text{-}sts\ init\ p\ r\ x \land (\forall y.\ rel\text{-}pre\text{-}sts\ init\ r\ x\ y \longrightarrow prec\text{-}pre\text{-}sts\ init'\ p'\ r'\ y))$
$= prec\text{-}pre\text{-}sts\ (prod\text{-}pred\ init\ init')\ (prec\text{-}comp\text{-}sts\ p\ r\ p')\ (rel\text{-}comp\text{-}sts\ r\ r')\ x$

lemma *sts-comp*: $p \le inpt\ r \Longrightarrow p' \le inpt\ r' \Longrightarrow init'\ b \Longrightarrow$
$LocalSystem\ init\ p\ r\ o\ LocalSystem\ init'\ p'\ r' = LocalSystem\ (prod\text{-}pred\ init\ init')\ (prec\text{-}comp\text{-}sts\ p\ r\ p')\ (rel\text{-}comp\text{-}sts\ r\ r')$

4.2 Parallel Composition of STSs

definition $rel\text{-}prod\text{-}sts\ r\ r' = (\lambda\ ((u,v),\ (x,\ y))\ ((u',\ v'),\ (x',\ y'))\ .\ r\ (u,x)\ (u',x') \land r'\ (v,\ y)\ (v',\ y'))$
definition $prec\text{-}prod\text{-}sts\ p\ p' = (\lambda\ ((u,v),\ (x,\ y))\ .\ p\ (u,x) \land p'\ (v,y))$

lemma $(prec\text{-}prod\text{-}sts\ (inpt\ r)\ \ (inpt\ r')) \le inpt\ (rel\text{-}prod\text{-}sts\ r\ r')$

lemma $(prec\text{-}prod\text{-}sts\ (inpt\ r)\ \ (inpt\ r')) = inpt\ (rel\text{-}prod\text{-}sts\ r\ r')$

definition $distrib\text{-}state = [:(u,v),\ (x,\ y) \leadsto (u',\ x'),\ (v',\ y').\ u'=u \land v'=v \land x'=x \land y'=y:]$
definition $merge\text{-}state = [:(u,\ x),\ (v,\ y) \leadsto (u',\ v'),\ (x',\ y').\ u'=u \land v'=v \land x'=x \land y'=y:]$

lemma $distrib\text{-}state\ o\ merge\text{-}state = Skip$

lemma $merge\text{-}state\ o\ distrib\text{-}state = Skip$

definition $prod\text{-}sts\ S\ S' = (distrib\text{-}state\ o\ (S\ {*}{*}\ S')\ o\ merge\text{-}state)$

lemma *prod-sts*: $prod\text{-}sts\ (\{.p.\}\ o\ [:r:])\ (\{.p'.\} o[:r':]) = \{.prec\text{-}prod\text{-}sts\ p\ p'.\}\ o\ [:rel\text{-}prod\text{-}sts\ r\ r':]$

lemma *update-demonic-update*: $[-f-]\ o\ [:r:]\ o\ [-g-] = [:x \leadsto y\ .\ \exists\ z\ .\ r\ (f\ x)\ z \land y = g\ z:]$

lemma *sts-prod-prec*: $p \le inpt\ r \Longrightarrow p' \le inpt\ r' \Longrightarrow init\ a \Longrightarrow init'\ b \Longrightarrow$
$prec\text{-}pre\text{-}sts\ (prod\text{-}pred\ init\ init')\ (prec\text{-}prod\text{-}sts\ p\ p')\ (rel\text{-}prod\text{-}sts\ r\ r')\ (x\ ||\ y)$
$= (prec\text{-}pre\text{-}sts\ init\ p\ r\ x \land prec\text{-}pre\text{-}sts\ init'\ p'\ r'\ y)$

lemma *sts-prod-rel*: $(\lambda\ x\ y\ .\ \exists z.\ rel\text{-}pre\text{-}sts\ (prod\text{-}pred\ init\ init')\ (rel\text{-}prod\text{-}sts\ r\ r')\ (case\ x\ of\ (x,\ xa) \Rightarrow x\ ||\ xa)\ z \land y = (fst \circ z,\ snd \circ z))$
$= (\lambda\ (x,\ y)\ (u,\ v)\ .\ rel\text{-}pre\text{-}sts\ init\ r\ x\ u \land rel\text{-}pre\text{-}sts\ init'\ r'\ y\ v)$

theorem *sts-prod*: $p \le inpt\ r \Longrightarrow p' \le inpt\ r' \Longrightarrow init\ a \Longrightarrow init'\ b \Longrightarrow$
$LocalSystem\ init\ p\ r\ {*}{*}\ LocalSystem\ init'\ p'\ r' =$
$[-x,\ x' \leadsto x\ ||\ x'-]\ o\ LocalSystem\ (prod\text{-}pred\ init\ init')\ (prec\text{-}prod\text{-}sts\ p\ p')\ (rel\text{-}prod\text{-}sts\ r\ r')\ o\ [-y \leadsto fst\ o\ y,\ snd\ o\ y-]$

4.3 Example: COUNTER

In this section we introduce an example counter that counts how many times the input variable x is true. The input is a sequence of boolen values and the output is a sequence of natural numbers. The output at some moment in time is the number of true values seen so far in the input.

We defined the system counter in two different ways and we show that the two definitions are equivalent. The first definition takes the entire input sequence and it computes the corresponding output sequence. We introduce the second version of the counter as a reactive system based on a symbolic transition system. We use a local variable to record the number of true values seen so far, and initially the local variable is zero. At every step we increase the local variable if the input is true. The output of the system at every step is equal to the local variable.

primrec $count :: bool\ trace \Rightarrow nat\ trace$ **where**
$count\ x\ 0 = (if\ x\ 0\ then\ 1\ else\ 0) \mid$
$count\ x\ (Suc\ n) = (if\ x\ (Suc\ n)\ then\ count\ x\ n + 1\ else\ count\ x\ n)$

definition $Counter\text{-}global\ n = \{.x\ .\ (\forall\ k\ .\ count\ x\ k \leq n).\}\ o\ [:x \rightsquigarrow y\ .\ y = count\ x:]$

definition $prec\text{-}count\ M = (\lambda\ (u,\ x)\ .\ u \leq M)$
definition $rel\text{-}count = (\lambda\ (u,x)\ (u',\ y)\ .\ (x \longrightarrow u' = Suc\ u) \wedge (\neg\ x \longrightarrow u' = u) \wedge y = u')$

lemma $counter\text{-}a\text{-}aux$: $u\ 0 = 0 \Longrightarrow \forall\, i < n.\ (x\ i \longrightarrow u\ (Suc\ i) = Suc\ (u\ i)) \wedge (\neg\ x\ i \longrightarrow u\ (Suc\ i) = u\ i) \Longrightarrow (\forall\ i < n\ .\ count\ x\ i = u\ (Suc\ i))$

lemma $counter\text{-}b\text{-}aux$: $u\ 0 = 0 \Longrightarrow \forall\, n.\ (xa\ n \longrightarrow u\ (Suc\ n) = Suc\ (u\ n)) \wedge (\neg\ xa\ n \longrightarrow u\ (Suc\ n) = u\ n) \wedge xb\ n = u\ (Suc\ n)$
$\Longrightarrow count\ xa\ n = u\ (Suc\ n)$

definition $COUNTER\ M = LocalSystem\ (\lambda\ a\ .\ a = 0)\ (prec\text{-}count\ M)\ rel\text{-}count$

lemma $COUNTER = Counter\text{-}global$

4.4 Example: LIVE

The last example of this formalization introduces a system which does some local computation, and ensures some global liveness property. We show that this example is the fusion of a symbolic transition system and a demonic choice which ensures the liveness property of the output sequence. We also show that asumming some liveness property for the input, we can refine the example into an executable system that does not ensure the liveness property of the output on its own, but relies on the liveness of the input.

definition $rel\text{-}ex = (\lambda\ (u,\ x)\ (u',\ y)\ .\ ((x \wedge u' = u + (1::int)) \vee (\neg\ x \wedge u' = u - 1) \vee u' = 0) \wedge (y = (u' = 0)))$
definition $prec\text{-}ex = (\lambda\ (u,\ x)\ .\ -1 \leq u \wedge u \leq 3)$

definition $LIVE = \{.\ prec\text{-}pre\text{-}sts\ (\lambda\ a\ .\ a = 0)\ prec\text{-}ex\ rel\text{-}ex.\}$
$o\ [:x \rightsquigarrow y\ .\ \exists\ u\ .\ u\ (0::nat) = 0 \wedge (\Box(\lambda\ u\ x\ y\ .\ rel\text{-}ex\ (u\ (0::nat),\ x\ (0::nat))\ (u\ 1,\ y\ (0::nat))))\ u\ x\ y\ \wedge (\Box\ (\Diamond\ (\lambda\ y\ .\ y\ 0)))\ y\ :]$

thm *fusion-spec-local-a*

lemma *LIVE-fusion*: $LIVE = (LocalSystem\ (\lambda\ a\ .\ a = 0)\ prec\text{-}ex\ rel\text{-}ex) \parallel [:x \rightsquigarrow y\ .\ (\Box\ (\Diamond\ (\lambda\ y\ .\ y\ 0)))\ y:]$

definition $preca\text{-}ex\ x = (x\ 1 = (\neg x\ (0{::}nat)))$

lemma *monotonic-SymSystem*[*simp*]: $mono\ (LocalSystem\ init\ p\ r)$

lemma *event-ex-aux-a*: $a\ 0 = (0{::}int) \Longrightarrow \forall n.\ xa\ (Suc\ n) = (\neg\ xa\ n) \Longrightarrow$
$\forall n.\ (xa\ n \wedge a\ (Suc\ n) = a\ n + 1 \vee \neg\ xa\ n \wedge a\ (Suc\ n) = a\ n - 1 \vee a\ (Suc\ n) = 0) \Longrightarrow$
$(a\ n = -1 \longrightarrow xa\ n) \wedge (a\ n = 1 \longrightarrow \neg\ xa\ n) \wedge -1 \leq a\ n \wedge a\ n \leq 1$

lemma *event-ex-aux*: $a\ 0 = (0{::}int) \Longrightarrow \forall n.\ xa\ (Suc\ n) = (\neg\ xa\ n) \Longrightarrow$
$\forall n.\ (xa\ n \wedge a\ (Suc\ n) = a\ n + 1 \vee \neg\ xa\ n \wedge a\ (Suc\ n) = a\ n - 1 \vee a\ (Suc\ n) = 0) \Longrightarrow$
$(\forall\ n\ .\ (a\ n = -1 \longrightarrow xa\ n) \wedge (a\ n = 1 \longrightarrow \neg\ xa\ n) \wedge -1 \leq a\ n \wedge a\ n \leq 1)$

thm *fusion-local-refinement*

lemma $\{.\Box\ preca\text{-}ex.\}\ o\ LIVE \leq LocalSystem\ (\lambda\ a\ .\ a = (0{::}int))\ prec\text{-}ex\ rel\text{-}ex$
end

4.5 Iterate Operators

theory *IterateOperators* **imports** *../RefinementReactive/RefinementReactive*
begin

definition $append\text{-}inf :: 'a\ list \Rightarrow (nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'a)$ (**infixr** .. *65*) **where**
$(xs..s)\ i = (if\ i < length\ xs\ then\ xs\ !\ i\ else\ s\ (i - (length\ xs)))$

lemma [*simp*]: $[x\ 0]\ ..\ x[Suc\ 0..] = x$

lemma [*simp*]: $([a]\ ..\ x)[Suc\ 0\ ..] = x$

lemma [*simp*]: $([a]\ ..\ x)\ 0 = a$

definition $SkipNext\ S = [:\ x \rightsquigarrow a,\ b\ .\ a = x \wedge b = x[Suc\ 0..]\ :]\ o\ (Prod\ Skip\ S)\ o\ [:\ a,\ b \rightsquigarrow x\ .\ \ x = cat\ (Suc\ 0)\ a\ b\ :]$

definition $Next\ S = [:x \rightsquigarrow y\ .\ y = x[Suc\ 0..]:]\ o\ S\ o\ [:y \rightsquigarrow x\ .\ y = x[Suc\ 0..]:]$

definition $NextAngelic\ S = \{:\ x \rightsquigarrow y\ .\ y = x[Suc\ 0..]:\}\ o\ S\ o\ \{:y \rightsquigarrow x\ .\ y = x[Suc\ 0..]\ :\}$

definition $SkipTop\ n = [:eqtop\ n:]$

lemma *SkipNext-Next*: $SkipNext\ S = Next\ S \parallel SkipTop\ (Suc\ 0)$

lemma [*simp*]: $SkipTop\ 0 = Havoc$

lemma *proj-skip* [*simp*]: $[:\ y \rightsquigarrow x.\ y = x[Suc\ 0\ ..]\ :] \circ [:\ x \rightsquigarrow y.\ y = x[Suc\ 0\ ..]\ :] = Skip$

lemma *Next-comp*: $Next\ (S\ o\ T) = Next\ S\ o\ Next\ T$

lemma *transp-ref-comp*: $transp\ r \Longrightarrow [:r:] \leq [:r:]\ o\ [:r:]$

lemma *fusion-comp-demonic*: $transp\ r \Longrightarrow (S\ o\ T) \parallel [:r:] \leq (S \parallel [:r:])\ o\ (T \parallel [:r:])$

lemma *fusion-comp-eqtop*: $(S\ o\ T) \parallel [:eqtop\ n:] \leq (S \parallel [:eqtop\ n:])\ o\ (T \parallel [:\ eqtop\ n:])$

lemma *SkipNext-comp-a*[*simp*]: $SkipNext\ (S\ o\ T) \leq (SkipNext\ S)\ o\ (SkipNext\ T)$

definition $auxfun\ p'\ T\ x\ xa = (SUPREMUM\ \{b.\ p'\ b\}\ (\lambda\ b\ .\ (Sup\ \{p'\ .\ (\exists\ p\ .\ (\forall\ a\ b.\ p\ a \wedge p'\ b \longrightarrow x\ (cat\ (Suc\ 0)\ a\ b)) \wedge p\ xa \wedge\ T\ p'\ b)\})))$

lemma *SkipNext-comp-b*[*simp*]: $mono\ S \Longrightarrow mono\ T \Longrightarrow SkipNext\ (S\ o\ T) \geq (SkipNext\ S)\ o\ (SkipNext\ T)$

lemma *SkipNext-comp*: $mono\ S \Longrightarrow mono\ T \Longrightarrow SkipNext\ (S\ o\ T) = (SkipNext\ S)\ o\ (SkipNext\ T)$

lemma *Next-fusion*: $Next\ (S \parallel T) = (Next\ S) \parallel (Next\ T)$

lemma *fusion-SkipTop-idemp* [*simp*]: $SkipTop\ n \parallel SkipTop\ n = SkipTop\ n$

lemma *SkipNext-fusion*: $SkipNext\ (S \parallel T) = (SkipNext\ S) \parallel (SkipNext\ T)$

lemma *SkipNext-SkipTop*: $SkipNext\ (SkipTop\ n) = SkipTop\ (Suc\ n)$

lemma *SkipTop-SkipNext*: $SkipTop\ n = (SkipNext\ \hat{}\hat{}\ n)\ Havoc$

lemma *SkipNext-power*: $(SkipNext\ \hat{}\hat{}\ (Suc\ n))\ S = (Next\ \hat{}\hat{}\ (Suc\ n))\ S \parallel SkipTop\ (Suc\ n)$

lemma *Next-demonic*: $Next\ [:r:] = [:\bigodot\ r:]$

lemma *SkipNext-demonic*: $SkipNext\ \{.p.\} = \{.\bigodot\ p.\}$

lemma *NextAngelic-angelic*: $NextAngelic\ (\{:r::(nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'a) \Rightarrow bool:\}) = \{:\bigodot\ r:\}$

lemma *Next-assert-demonic*: $Next\ (\{.p.\}\ o\ [:r:]) = \{.\bigodot\ p.\}\ o\ [:\bigodot\ r:]$

lemma *Next-angelic-demonic*: $Next\ (\{:r:\}\ o\ [:r':]) = \{:\bigodot\ r:\}\ o\ [:\bigodot\ r':]$

lemma *eqtop-Suc-zero*: $eqtop\ (Suc\ 0) = (\lambda\ x\ y\ .\ x\ 0 = y\ 0)$

definition $idnext\ r = \bigodot\ r \sqcap eqtop\ (Suc\ 0)$

lemma *SkipNext-assert-demonic*: $SkipNext\ (\{.p.\}\ o\ [:r:]) = \{.\ \bigodot\ p\ .\} \circ [:\ idnext\ r\ :]$

lemma *Next-assert-demonic2*: $Next\ (\lambda\ q\ .\ \{.p.\}\ ([:r:]\ q)) = \{.\bigodot\ p.\}\ o\ [:\bigodot\ r:]$

lemma *Iterate-Next-assert-demonic*: $(Next\hat{}\hat{}n)\ (\{.p.\}\ o\ [:r:]) = \{.(next\hat{}\hat{}n)p.\}\ o\ [:(next\hat{}\hat{}n)\ r:]$

lemma *power-SkipNext-assert-demonic*: $(SkipNext\hat{}\hat{}n)\ (\{.p.\}\ o\ [:r:]) = \{.(next\hat{}\hat{}n)p.\}\ o\ [:(idnext\hat{}\hat{}n)\ r:]$

lemma *Iterate-Next-demonic*: $(Next\ \hat{}\hat{}\ n)\ [:r:] = [:(next\ \hat{}\hat{}\ n)\ r:]$

definition $Always\ S = Fusion\ (\lambda\ n\ .\ (Next\ \hat{}\hat{}\ n)\ S)$

lemma *Always-demonic*: $Always\ [:r:] = [:\square\ r:]$

lemma *Always-assert-demonic*: $Always\ (\{.p.\}\ o\ [:r:]) = \{.\square\ p.\}\ o\ [:\square\ r:]$

lemma *SkipNext-simp*: *SkipNext S Q x* =
$(\exists\, p\ p'.\ (\forall\, a\ b.\ p\ a \wedge p'\ b \longrightarrow Q\ (cat\ (Suc\ 0)\ a\ b)) \wedge p\ x \wedge S\ p'\ (x[Suc\ 0..]))$

type-synonym $('a, 'b)$ *trans* = $('b \Rightarrow bool) \Rightarrow ('a \Rightarrow bool)$

primrec *Iterate* :: $(('a, 'a)\ trans \Rightarrow ('a, 'a)\ trans) \Rightarrow ('a, 'a)\ trans \Rightarrow nat \Rightarrow ('a, 'a)\ trans$ **where**
Iterate F S 0 = *Skip* |
Iterate F S (*Suc n*) = (*Iterate F S n*) *o* ((*F* ^^ *n*) *S*)

definition *Mask n S* = *S o* (*SkipTop n*)

definition *IterateNextMask S n* = *Mask n* (*Iterate Next S n*)

lemma *IterateNextMask-simp*: *IterateNextMask S* = (λ *n* . *Mask n* (*Iterate Next S n*))

definition *IterateSkipNextMask S n* = *Mask n* (*Iterate SkipNext S n*)

lemma *IterateSkipNextMask-simp*: *IterateSkipNextMask S* = (λ *n* . *Mask n* (*Iterate SkipNext S n*))

definition *IterateOmegaNextMask S* = *Fusion* (*IterateNextMask S*)

definition *IterateOmegaSkipNextMask S* = *Fusion* (*IterateSkipNextMask S*)

definition *AddUnitDelay S* = $([:u,\ x,\ y \leadsto a,\ b\ .\ a = u\ (0::nat) \wedge b = x\ (0::nat):]\ o\ S\ o\ [:c,\ d \leadsto u',\ x',\ y'\ .\ u'\ (Suc\ 0) = c \wedge y'\ (0::nat) = d:])$
$\parallel [:u,\ x,\ (y::nat \Rightarrow 'a) \leadsto u',\ x',\ (y'::nat \Rightarrow 'a)\ .\ u'\ (0::nat) = u\ (0::nat) \wedge x' = x:]$

lemma *AddUnitDelay-spec*: $AddUnitDelay\ (\{.u,\ x\ .\ p\ u\ x.\}\ o\ [:u,\ x \leadsto u',\ y\ .\ r\ u\ u'\ x\ y:]) =$
$\{.u,\ x,\ y\ .\ p\ (u\ 0)\ (x\ 0).\}\ o\ [:u,\ x,\ y \leadsto u',\ x',\ y'\ .\ r\ (u\ 0)\ (u'\ (Suc\ 0))\ (x\ 0)\ (y'\ 0) \wedge x = x' \wedge u\ 0 = u'\ 0:]$
(**is** *?L* = *?R*)

definition *DelayFeedback init S* = $[:x \leadsto u,\ x',y\ .\ init\ (u\ (0::nat)) \wedge x = x':]$
$o\ IterateOmegaSkipNextMask\ (AddUnitDelay\ S)\ o\ [:u,\ x,\ y \leadsto y'\ .\ y = y':]$

lemma *SkipNext-refinement*: $S \le T \Longrightarrow SkipNext\ S \le SkipNext\ T$

lemma *SkipNext-pow-refinement*: $S \le T \Longrightarrow (SkipNext\ \hat{}\hat{}\ n)\ S \le (SkipNext\ \hat{}\hat{}\ n)\ T$

lemma *Mask-refinement*: $S \le T \Longrightarrow Mask\ i\ S \le Mask\ i\ T$

lemma *mono-SkipNext*[*simp*]: *mono* (*SkipNext S*)

lemma *mono-SkipNext-pow* [*simp*]: $mono\ S \Longrightarrow mono\ ((SkipNext\ \hat{}\hat{}\ n)\ S)$

lemma *mono-Iterate-SkipNext*[*simp*]: $mono\ S \Longrightarrow mono\ (Iterate\ SkipNext\ S\ n)$

lemma *Iterate-SkipNext-refinement*: $\bigwedge\ S\ T\ .\ mono\ S \Longrightarrow S \le T \Longrightarrow Iterate\ SkipNext\ S\ n \le Iterate\ SkipNext\ T\ n$

lemma *IterateSkipNextMask-refinemnt*: $mono\ S \Longrightarrow S \le T \Longrightarrow IterateSkipNextMask\ S\ i \le IterateSkipNextMask\ T\ i$

lemma *IterateOmegaSkipNextMask-refinement*: $mono\ S \Longrightarrow S \leq T \Longrightarrow IterateOmegaSkipNextMask\ S \leq IterateOmegaSkipNextMask\ T$

lemma *AddUnitDelay-refinement*: $S \leq T \Longrightarrow AddUnitDelay\ S \leq AddUnitDelay\ T$

lemma *mono-IterateOmegaSkipNextMask*: $mono\ (IterateOmegaSkipNextMask\ S)$

lemma *mono-AddUnitDelay*: $mono\ (AddUnitDelay\ S)$

theorem *DelayFeedback-refinement*: $init' \leq init \Longrightarrow S \leq T \Longrightarrow DelayFeedback\ init\ S \leq DelayFeedback\ init'\ T$

lemma [*simp*]: $mono\ (SkipTop\ n)$

lemma [*simp*]: $SkipNext\ Skip = Skip$

lemma *Iterate-SkipNextA*: $mono\ S \Longrightarrow S \circ (SkipNext\ (Iterate\ SkipNext\ S\ n)) = Iterate\ SkipNext\ S\ (Suc\ n)$

lemma *skiptop-simp*: $SkipTop\ n\ p = (\lambda\ x\ .\ \forall\ \ y\ .\ eqtop\ n\ x\ y \longrightarrow p\ y)$

definition $HavocTop\ n = [:x \rightsquigarrow y\ .\ x[n..] = y[n..]:]$

lemma *HavocTop-Next*: $HavocTop\ (Suc\ n) = Next\ (HavocTop\ n)$

lemma [*simp*]: $HavocTop\ 0 = Skip$

lemma $HavocTop\ n = (Next\ \hat{}\hat{}\ n)\ Skip$

lemma *Next-NextSkip-aux*: $[:\ \lambda y\ x.\ \forall xa.\ y\ xa = x\ (Suc\ xa)\ :]\ (\lambda a.\ \forall b.\ a[Suc\ 0\ ..] = b[Suc\ 0\ ..] \longrightarrow x\ b) = [:\ \lambda y\ x.\ \forall xa.\ y\ xa = x\ (Suc\ xa)\ :]\ x$

lemma *demonic-apply-pred*: $[:\ \lambda x\ y.\ r\ x\ y\ :]\ p\ = (\lambda x.\ \forall\ \ y\ .\ r\ x\ y \longrightarrow p\ y)$

lemma *Next-SkipNext-HavocTop*: $mono\ S \Longrightarrow Next\ S = SkipNext\ S\ o\ HavocTop\ (Suc\ 0)$

lemma *HavocTop-Next-power*: $HavocTop\ n \circ Next\ ((Next\ \hat{}\hat{}\ n)\ S) =\ Next\ ((Next\ \hat{}\hat{}\ n)\ S)$

lemma *Next-SkipNext*: $mono\ S \Longrightarrow (Next\ \hat{}\hat{}\ n)\ S = (SkipNext\ \hat{}\hat{}\ n)\ S \circ HavocTop\ n$ (**is** $?Q \Longrightarrow\ ?A\ n =\ ?B\ n$)

lemma *Iterate-Next-SkipNext-aux*: $mono\ S \Longrightarrow HavocTop\ n \circ (Next\ \hat{}\hat{}\ (Suc\ n))\ S = (SkipNext\ \hat{}\hat{}\ (Suc\ n))\ S \circ HavocTop\ (Suc\ n)$ (**is** $?P \Longrightarrow\ ?A =\ ?B$)

lemma *Iterate-Next-SkipNext-Suc*: $mono\ S \Longrightarrow Iterate\ Next\ S\ (Suc\ n) = (Iterate\ SkipNext\ S\ (Suc\ n))\ o\ (HavocTop\ n)$ (**is** $?P \Longrightarrow\ ?A\ n =\ ?B\ n$)

lemma *Iterate-Next-SkipNext*: $mono\ S \Longrightarrow Iterate\ Next\ S\ n = (Iterate\ SkipNext\ S\ n)\ o\ (HavocTop\ (n - 1))$

lemma $HavocTop\ n \leq Skip$

lemma $\mathit{mono\text{-}Iterate\text{-}NextSkip}$: $\mathit{mono}\ S \Longrightarrow \mathit{mono}\ (\mathit{Iterate}\ \mathit{SkipNext}\ S\ n)$

lemma $(\mathit{Havoc}\ (X{::}'a{::}\mathit{complete\text{-}lattice}) \neq \bot) = (X = \top)$

type-synonym $('a, 'b)\ \mathit{rel} = ('a \Rightarrow 'b \Rightarrow \mathit{bool})$

primrec $\mathit{IterateRel} :: (('a, 'a)\ \mathit{rel} \Rightarrow ('a, 'a)\ \mathit{rel}) \Rightarrow ('a, 'a)\ \mathit{rel} \Rightarrow \mathit{nat} \Rightarrow ('a, 'a)\ \mathit{rel}$ **where**
$\mathit{IterateRel}\ F\ r\ 0 = (\lambda\ a\ b\ .\ a = b)$ |
$\mathit{IterateRel}\ F\ r\ (\mathit{Suc}\ n) = \mathit{IterateRel}\ F\ r\ n\ \mathit{OO}\ ((F\ \hat{}\hat{}\ n)\ r)$

lemma $\mathit{IterateRel\text{-}init}$: $(\forall\ r\ r'\ .\ F\ (r\ \mathit{OO}\ r') = F\ r\ \mathit{OO}\ F\ r') \Longrightarrow F\ (\mathit{op}\ =) = (\mathit{op}\ =) \Longrightarrow \mathit{IterateRel}\ F\ r\ (\mathit{Suc}\ n) = r\ \mathit{OO}\ F\ (\mathit{IterateRel}\ F\ r\ n)$ (**is** $?P \Longrightarrow ?Q \Longrightarrow ?R\ n$)

lemma $[\mathit{simp}]$: $\mathit{idnext}\ (\mathit{op}\ =) = (\mathit{op}\ =)$

lemma $[\mathit{simp}]$: $\mathit{idnext}\ (r\ \mathit{OO}\ r') = (\mathit{idnext}\ r)\ \mathit{OO}\ \mathit{idnext}\ r'$

lemma $\mathit{IterateRel\text{-}idnext\text{-}init}$: $\mathit{IterateRel}\ \mathit{idnext}\ r\ (\mathit{Suc}\ n) = r\ \mathit{OO}\ \mathit{idnext}\ (\mathit{IterateRel}\ \mathit{idnext}\ r\ n)$

lemma $[\mathit{simp}]$: $(\bigwedge\ (p{::}'a{\Rightarrow}\mathit{bool})\ (r{::}'a{\Rightarrow}'b{\Rightarrow}\mathit{bool})\ .\ F\ (\{.p.\}\ o\ [:r:]) = \{.A\ p.\}\ o\ [:(B{::}('a{\Rightarrow}'b{\Rightarrow}\mathit{bool}) \Rightarrow ('a{\Rightarrow}'b{\Rightarrow}\mathit{bool}))\ r:])$
$\Longrightarrow ((F\ \hat{}\hat{}\ n)\ (\{.p.\}\ o\ [:r:])) = \{.(A\hat{}\hat{}n)\ p.\}\ o\ [:(B\hat{}\hat{}n)\ r:]$

lemma $\mathit{Iterate\text{-}id}$: $\mathit{Iterate}\ \mathit{id}\ S\ n = S\ \hat{}\hat{}\ n$

lemma $\mathit{IterateRel\text{-}id}$: $\mathit{IterateRel}\ \mathit{id}\ r\ n = (r\ \hat{}\hat{}\ n)$

lemma $\mathit{Iterate\text{-}IterateRel}$: $(\bigwedge\ p\ r\ .\ F\ (\{.p.\}\ o\ [:r:]) = \{.A\ p.\}\ o\ [:B\ r:]) \Longrightarrow \mathit{Iterate}\ F\ (\{.p.\}\ o\ [:r:])\ n$
$= \{.x\ .\ (\forall\ i < n\ .(\forall\ y\ .\ \mathit{IterateRel}\ B\ r\ i\ x\ y \longrightarrow (A\hat{}\hat{}i)\ p\ y)).\}\ o\ [:\mathit{IterateRel}\ B\ r\ n:]$

lemma $\mathit{IterateRel\text{-}app}$: $\bigwedge\ y\ .\ \mathit{IterateRel}\ \mathit{next}\ r\ n\ x\ y = (\exists\ a\ .\ a\ 0 = x \wedge a\ n = y \wedge (\forall\ i < n.\ r\ ((a\ i)[i..])\ ((a\ (\mathit{Suc}\ i))[i..])))$

lemma $\mathit{Iterate\text{-}Next\text{-}IterateRel}$: $\mathit{Iterate}\ \mathit{Next}\ (\{.p.\}\ o\ [:r:])\ n$
$= \{.\ x\ .\ (\forall\ k < n\ .\ (\forall\ y\ .\ \mathit{IterateRel}\ \mathit{next}\ r\ k\ x\ y \longrightarrow (\mathit{next}\ \hat{}\hat{}\ k)\ p\ y)\ ).\}\ o\ [:\mathit{IterateRel}\ \mathit{next}\ r\ n:]$

lemma $\mathit{IterateOmegaNextMask\text{-}spec\text{-}aux}$: $\mathit{IterateOmegaNextMask}\ (\{.p.\}\ o\ [:r:])$
$= \{.\ \mathit{INF}\ x.\ (\lambda xa.\ \forall k{<}x.\ \forall y.\ \mathit{IterateRel}\ \mathit{next}\ r\ k\ xa\ y \longrightarrow (\mathit{next}\ \hat{}\hat{}\ k)\ p\ y)\ .\} \circ [:\ \mathit{INF}\ n.\ \mathit{IterateRel}\ \mathit{next}\ r\ n\ \mathit{OO}\ \mathit{eqtop}\ n\ :]$

lemma $\mathit{IterateOmegaNextMask\text{-}spec}$: $\mathit{IterateOmegaNextMask}\ (\{.p.\}\ o\ [:r:])$
$= \{.\ \mathit{INF}\ k\ .\ (\lambda xa.\ \forall y.\ \mathit{IterateRel}\ \mathit{next}\ r\ k\ xa\ y \longrightarrow (\mathit{next}\ \hat{}\hat{}\ k)\ p\ y)\ .\} \circ [:\ \mathit{INF}\ n.\ \mathit{IterateRel}\ \mathit{next}\ r\ n\ \mathit{OO}\ \mathit{eqtop}\ n\ :]$

lemma $\mathit{power\text{-}spec}$: $(\{.p.\}\ o\ [:r:])\ \hat{}\hat{}\ n$
$= \{.x\ .\ (\forall\ i < n\ .(\forall\ y\ .\ (r\ \hat{}\hat{}\ i)\ x\ y \longrightarrow p\ y)).\}\ o\ [:r\ \hat{}\hat{}\ n:]$

lemma $\mathit{Iterate\text{-}SkipNext\text{-}IterateSkipRel}$: $\mathit{Iterate}\ \mathit{SkipNext}\ (\{.p.\}\ o\ [:r:])\ n$
$= \{.\ x\ .\ (\forall\ k < n\ .\ (\forall\ y\ .\ \mathit{IterateRel}\ \mathit{idnext}\ r\ k\ x\ y \longrightarrow (\mathit{next}\ \hat{}\hat{}\ k)\ p\ y)\ ).\}\ o\ [:\mathit{IterateRel}\ \mathit{idnext}\ r\ n:]$

lemma $\mathit{IterateOmegaSkipNextMask\text{-}spec}$: $\mathit{IterateOmegaSkipNextMask}\ (\{.p.\}\ o\ [:r:])$
$= \{.\ (\lambda x\ .\ \forall\ n\ .\ \forall y.\ \mathit{IterateRel}\ \mathit{idnext}\ r\ n\ x\ y \longrightarrow (\mathit{next}\ \hat{}\hat{}\ n)\ p\ y)\ .\}$
$\circ [:\ \mathit{INF}\ n.\ \mathit{IterateRel}\ \mathit{idnext}\ r\ n\ \mathit{OO}\ \mathit{eqtop}\ n\ :]$

lemma *IterateOmegaSkipNextMask-demonic*: *IterateOmegaSkipNextMask* [:*r*:] = [: *INF n. IterateRel idnext r n OO eqtop n* :]

lemma [*simp*]: $(next\ \hat{}\hat{}\ n)\ \top\ x$

lemma *power-idnext*: $(idnext\ \hat{}\hat{}\ n)\ r = ((next\ \hat{}\hat{}\ n)\ r \sqcap eqtop\ n)$

lemma *example-feedback-delay-a*: $\forall xb.\ \exists z.\ IterateRel\ idnext\ (\lambda x\ y.\ \forall xa.\ y\ xa = ([0]\ ..\ x)\ xa)\ xb\ x\ z \wedge (\forall i{<}xb.\ z\ i = xa\ i) \Longrightarrow xa\ n = 0$

lemma *example-feedback-delay-b*: $\forall x.\ xa\ x = 0 \Longrightarrow \exists z.\ IterateRel\ idnext\ (\lambda x\ y.\ \forall xa.\ y\ xa = ([0]\ ..\ x)\ xa)\ n\ x\ z \wedge (\forall i < n.\ z\ i = xa\ i)$

lemma *example-feedback-delay*: *IterateOmegaSkipNextMask* $[:x \leadsto y\ .\ y = [0::nat]\ ..\ x:] = [:x \leadsto y\ .\ y = (\lambda\ i\ .\ 0):]$

lemma *next-simp*: $next\ (r::(nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'b) \Rightarrow bool)\ x\ y = r\ (x[Suc\ 0..])\ (y[Suc\ 0..])$

lemma *idnext-simp*: $idnext\ (r::(nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'a) \Rightarrow bool)\ x\ y = (r\ (x[Suc\ 0..])\ (y[Suc\ 0..]) \wedge x\ 0 = y\ 0)$

lemma *idnext-next-eqtop*: $\bigwedge\ (x::nat \Rightarrow 'a)\ y\ .\ (idnext\ \hat{}\hat{}\ n)\ r\ x\ y = ((next\ \hat{}\hat{}\ n)\ r\ x\ y \wedge eqtop\ n\ x\ y)$

lemma *IrerateRel-IterateSkipRel-aux*: $\forall\ x\ y\ .\ IterateRel\ next\ (r::(nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'a) \Rightarrow bool)\ n\ x\ y \longrightarrow (\exists\ z\ .\ y[(n::nat)..] = z[n..] \wedge IterateRel\ idnext\ r\ n\ x\ z)$

lemma *IrerateRel-IterateSkipRel*: $IterateRel\ next\ (r::(nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'a) \Rightarrow bool)\ n\ x\ y \Longrightarrow (\exists\ z\ .\ y[(n::nat)..] = z[n..] \wedge IterateRel\ idnext\ r\ n\ x\ z)$

lemma *next-eq*: $\forall i{<}k.\ (\forall x.\ fst\ (snd\ (ab\ i))\ (i + x) = fst\ (snd\ (ab\ (Suc\ i)))\ (i + x)) \Longrightarrow$
$i \le k \Longrightarrow (\forall\ j\ .\ fst\ (snd\ (ab\ i))\ (i + j) = fst\ (snd\ (ab\ 0))\ (i + j))$

lemma *IterateSkipRel-SymRel-zero*: $\bigwedge\ u'\ x'\ y'\ .\ (IterateRel\ idnext\ (\lambda(u, x, y)\ (u', x', y').\ r\ (u\ 0)\ (u'\ (Suc\ 0))\ (x\ 0)\ (y'\ 0) \wedge (x = x') \wedge (u\ 0 = u'\ 0))\ 0)\ (u, x, y)\ (u', x', y')$
$= (u = u' \wedge x = x' \wedge y = y')$

lemma *IterateSkipRel-SymRel-Suc*: $\bigwedge\ u'\ x'\ y'\ .\ (IterateRel\ idnext\ (\lambda(u, x, y)\ (u', x', y').\ r\ (u\ 0)\ (u'\ (Suc\ 0))\ (x\ 0)\ (y'\ 0) \wedge (x = x') \wedge (u\ 0 = u'\ 0))\ (Suc\ n))\ (u, x, y)\ (u', x', y')$
$= ((u'\ 0 = u\ 0) \wedge (\forall\ i < (Suc\ n)\ .\ r\ (u'\ i)\ (u'\ (Suc\ i))\ (x\ i)\ (y'\ i)) \wedge x = x')$

lemma *IterateSkipRel-SymRel*: $\bigwedge\ u'\ x'\ y'\ .\ (IterateRel\ idnext\ (\lambda(u, x, y)\ (u', x', y').\ r\ (u\ 0)\ (u'\ (Suc\ 0))\ (x\ 0)\ (y'\ 0) \wedge (x = x') \wedge (u\ 0 = u'\ 0))\ n)\ (u, x, y)\ (u', x', y')$
$= ((u'\ 0 = u\ 0) \wedge (\forall\ i <\ n\ .\ r\ (u'\ i)\ (u'\ (Suc\ i))\ (x\ i)\ (y'\ i)) \wedge x = x' \wedge (n = 0 \longrightarrow (u = u' \wedge y = y')))$

lemma *IterateSkipRel-SymRel-eqtop*: $(IterateRel\ idnext\ (\lambda(u, x, y)\ (u', x', y').\ r\ (u\ (0::nat))\ (u'\ (Suc\ 0))\ (x\ (0::nat))\ (y'\ (0::nat)) \wedge (x = x') \wedge (u\ 0 = u'\ 0))\ n\ OO\ (eqtop\ n))\ (u, x, y)\ (u', x', y')$
$= (\exists\ v\ .\ (v\ 0 = u\ 0\ ) \wedge (\forall\ i < n\ .\ r\ (v\ i)\ (v\ (Suc\ i))\ (x\ i)\ (y'\ i) \wedge v\ i = u'\ i \wedge (x\ i = x'\ i)))$

lemma *INF-IterateSkipRel-SymRel-eqtop*: $(INF\ n.\ IterateRel\ idnext\ (\lambda(u,\ x,\ y)\ (u',\ x',\ y').\ r\ (u\ (0::nat))\ (u'\ (Suc\ 0))\ (x\ (0::nat))\ (y'\ (0::nat)) \wedge x = x' \wedge u\ 0 = u'\ 0)\ n\ OO\ eqtop\ n)\ (u,\ x,\ y)\ (u',\ x',\ y')$
$= (u'\ 0 = u\ 0 \wedge x = x' \wedge (\Box\ (\lambda\ (u,\ x,\ y)\ .\ r\ (u\ 0)\ (u\ (Suc\ 0))\ (x\ 0)\ (y\ 0)))\ (u',\ x,\ y'))$

lemma *INF-IterateSkipRel-SymRel-eqtop-abs*: $(INF\ n.\ IterateRel\ idnext\ (\lambda(u,\ x,\ y)\ (u',\ x',\ y').\ r\ (u\ (0::nat))\ (u'\ (Suc\ 0))\ (x\ (0::nat))\ (y'\ (0::nat)) \wedge x = x' \wedge u\ 0 = u'\ 0)\ n\ OO\ eqtop\ n)$
$= (\lambda\ (u,\ x,\ y)\ (u',\ x',\ y')\ .\ (u'\ 0 = u\ 0 \wedge x = x' \wedge (\Box\ (\lambda\ (u,\ x,\ y)\ .\ r\ (u\ 0)\ (u\ (Suc\ 0))\ (x\ 0)\ (y\ 0)))\ (u',\ x,\ y')))$

lemma *move-down*: $p \Longrightarrow p$

lemma *IterateSkipRel-prec-loc-st*: $(\lambda x.\ \forall a.\ init\ (a\ 0) \longrightarrow$
$(\forall b\ n\ aa\ aaa\ ba.$
$IterateRel\ idnext\ (\lambda(u,\ x,\ y)\ (u',\ x',\ y').\ r\ (u\ (0::nat))\ (u'\ (Suc\ 0))\ (x\ (0::nat))\ (y'\ (0::nat)) \wedge x = x' \wedge u\ 0 = u'\ 0)\ n\ (a,\ x,\ b)\ (aa,\ aaa,\ ba) \longrightarrow$
$(next\ \hat{}\hat{}\ n)\ (\lambda(u,\ x,\ y).\ p\ (u\ 0)\ (x\ 0))\ (aa,\ aaa,\ ba)))$
$= prec\text{-}pre\text{-}sts\ init\ (\lambda\ (u,\ x)\ .\ p\ u\ x)\ (\lambda\ (u,x)\ (u',\ y)\ .\ r\ u\ u'\ x\ y)$

theorem *DelayFeedback-SymbolicSystem-aux*: $DelayFeedback\ init\ (\{.(x,\ y).p\ x\ y.\} \circ [:(u,\ x) \rightsquigarrow (u',\ y).r\ u\ u'\ x\ y:])$
$= LocalSystem\ init\ (\lambda\ (u,\ x)\ .\ p\ u\ x)\ (\lambda\ (u,x)\ (u',\ y)\ .\ r\ u\ u'\ x\ y)$

theorem *DelayFeedback-LocalSystem*: $DelayFeedback\ init\ (\{.p.\} \circ [:r:])$
$= LocalSystem\ init\ p\ r$

lemma *DelayFeedback-simp*: $DelayFeedback\ init\ (\{.p.\}\ o\ [:r:]) = \{.prec\text{-}pre\text{-}sts\ init\ p\ r.\}\ o\ [:rel\text{-}pre\text{-}sts\ init\ r:]$

lemma *prec-pre-sts-prec-rel*: $(\bigwedge s\ s'\ x\ y\ .\ p\ (s,\ x) \Longrightarrow r\ (s,\ x)\ (s',\ y) = r'\ (s,\ x)\ (s',\ y)) \Longrightarrow prec\text{-}pre\text{-}sts\ init\ p\ r = prec\text{-}pre\text{-}sts\ init\ p\ r'$

theorem *DelayFeedback-a-simp*: $DelayFeedback\ init\ (\{.p.\}\ o\ [:r:]) =$
$\{.x\ .(\forall\ u\ y\ .\ init\ (u\ 0) \longrightarrow (\forall n\ .\ (\forall\ i < n\ .\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i)) \longrightarrow p\ (u\ n,\ x\ n))).\}$
$o\ [:x \rightsquigarrow y\ .\ (\exists\ u\ .\ init\ (u\ 0) \wedge (\forall\ i\ .\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i))):]$

theorem *DelayFeedback-b-simp*: $DelayFeedback\ init\ ([:r:])$
$= [:rel\text{-}pre\text{-}sts\ init\ r:]$

lemma *DelayFeedback-comp*: $p \leq inpt\ r \Longrightarrow p' \leq inpt\ r' \Longrightarrow init'\ b \Longrightarrow$
$DelayFeedback\ init\ (\{.p.\}\ o\ [:r:])\ o\ DelayFeedback\ init'\ (\{.p'.\}\ o\ [:r':]) =$
$DelayFeedback\ (prod\text{-}pred\ init\ init')\ (\{.prec\text{-}comp\text{-}sts\ p\ r\ p'.\}\ o\ [:rel\text{-}comp\text{-}sts\ r\ r':])$

lemma *DelayFeedback-empty-init*[*simp*]: $DelayFeedback\ \bot\ S' = \top$

lemma *assert-bot*: $\{.\bot::'a::boolean\text{-}algebra.\} = Fail$

lemma *Fail-comp*: $\mathit{Fail}\ o\ S = \mathit{Fail}$

lemma *DelayFeedback-Fail*[*simp*]: $\mathit{init}\ a \Longrightarrow \mathit{DelayFeedback}\ \mathit{init}\ (\mathit{Fail} :: ('a \times 'b \Rightarrow \mathit{bool}) \Rightarrow ('a \times 'c \Rightarrow \mathit{bool})) = \mathit{Fail}$

lemma *prod-empty* [*simp*]: $\mathit{prod\text{-}pred}\ X\ \bot = \bot$

lemma *sts-serial-comp-empty-init*: $\mathit{DelayFeedback}\ (\mathit{prod\text{-}pred}\ \top\ \bot)\ (\mathit{sts\text{-}comp}\ \mathit{Fail}\ S') \neq \mathit{DelayFeedback}\ \top\ \mathit{Fail}\ o\ \mathit{DelayFeedback}\ \bot\ S'$

thm *DelayFeedback-LocalSystem*

theorem *sts-serial-comp*: $\mathit{implementable}\ S \Longrightarrow \mathit{implementable}\ S' \Longrightarrow \mathit{init}'\ b \Longrightarrow$
$\mathit{DelayFeedback}\ (\mathit{prod\text{-}pred}\ \mathit{init}\ \mathit{init}')\ (\mathit{sts\text{-}comp}\ S\ S') = \mathit{DelayFeedback}\ \mathit{init}\ S\ o\ \mathit{DelayFeedback}\ \mathit{init}'\ S'$

theorem *implementableI*: $p \le \mathit{inpt}\ r \Longrightarrow \mathit{implementable}\ (\{.p.\}\ o\ [:r:])$

lemma *implementable-inpt*[*simp*]: $\mathit{implementable}\ (\{.\mathit{inpt}\ r.\}\ o\ [:r:])$

theorem *implementable-DelayFeedback*: $\mathit{implementable}\ S \Longrightarrow \mathit{init}\ a \Longrightarrow \mathit{implementable}\ (\mathit{DelayFeedback}\ \mathit{init}\ S)$

theorem *LocalSystem-impt-implementable*: $\mathit{init}\ a \Longrightarrow \mathit{implementable}\ (\mathit{LocalSystem}\ \mathit{init}\ (\mathit{inpt}\ r)\ r)$

lemma *prec-pre-sts-inpt*: $\mathit{init}\ a \Longrightarrow \mathit{prec\text{-}pre\text{-}sts}\ \mathit{init}\ (\mathit{inpt}\ r)\ r \le \mathit{inpt}\ (\mathit{rel\text{-}pre\text{-}sts}\ \mathit{init}\ r)$

lemma *comp-middle*: $A\ o\ B\ o\ C\ o\ D = A\ o\ (B\ o\ C)\ o\ D$

lemma *fun-eq*: $(\forall x.\ f\ x = g\ x) = (f = g)$

lemma [*simp*]: $\mathit{SkipNext}\ \bot = \bot$

lemma $\mathit{SkipNext}\ \bot = \bot$

lemma $\mathit{SkipNext}\ \top\ \bot = \top$

lemma $\mathit{SkipNext}\ \top = \top$

4.6 Examples

definition $\mathit{PREC\text{-}ID} = \top$
definition $\mathit{REL\text{-}ID} = (\lambda\ (u,x)\ (u',\ y)\ .(u = u') \land (u = y))$
definition $\mathit{INIT\text{-}ID}\ u = (u = 0)$

lemma *all-eq*: $\forall x.\ u\ x = u\ (\mathit{Suc}\ x) \Longrightarrow u\ x = u\ 0$

lemma $\mathit{LocalSystem}\ \mathit{INIT\text{-}ID}\ \mathit{PREC\text{-}ID}\ \mathit{REL\text{-}ID} = [:x \leadsto y\ .\ \forall\ i\ .\ y\ i = 0:]$

definition $\mathit{PREC\text{-}COUNTER} = \top$
definition $\mathit{REL\text{-}COUNTER} = (\lambda\ (u,\ x)\ (u',\ y)\ .\ (u' = u + 1) \land (u = y))$
definition $\mathit{INIT\text{-}COUNTER}\ u = (u = 0)$

lemma *add-suc*: $\forall x.\ u\ (\mathit{Suc}\ x) = \mathit{Suc}\ (u\ x) \Longrightarrow u\ x = x + u\ 0$

lemma *LocalSystem INIT-COUNTER PREC-COUNTER REL-COUNTER* = $[:x \rightsquigarrow y \,.\, \forall\ i \,.\, y\ i = i:]$

definition *PREC-SUM* = $\top$
definition *REL-SUM* = $(\lambda\ (u,\ x)\ (u',\ y) \,.\, (u' = u + x) \wedge (u = y))$
definition *INIT-SUM* $u = (u = 0)$

primrec *Summm* :: $(nat \Rightarrow nat) \Rightarrow nat \Rightarrow nat$ **where**
Summm $x\ 0 = 0$ |
Summm $x\ (Suc\ n) = Summm\ x\ n + x\ n$

lemma *sum-suc*: $\forall n.\ u\ (Suc\ n) = u\ n + x\ n \Longrightarrow u\ n = Summm\ x\ n + u\ 0$

lemma *LocalSystem INIT-SUM PREC-SUM REL-SUM* = $[:x \rightsquigarrow y \,.\, y = Summm\ x:]$

definition *PREC-A* = $\top$
definition *REL-A* = $(\lambda\ (u,\ x)\ (u',\ y) \,.\, (u' = x) \wedge (u = y))$
definition *INIT-A* $u = (u = 0)$

lemma *LocalSystem INIT-A PREC-A REL-A* = $[:x \rightsquigarrow y \,.\, y = [0]\ ..\ x:]$

definition *PREC-SUM-A* = $(\lambda\ (u,\ x) \,.\, u \leq 100)$
definition *REL-SUM-A* = $(\lambda\ (u,\ x)\ (u',\ y) \,.\, (u' = u + x) \wedge (u = y))$
definition *INIT-SUM-A* $u = (u = 0)$

lemma *sum-suc-le*: $\forall n < k \,.\, u\ (Suc\ n) = u\ n + x\ n \Longrightarrow u\ k = Summm\ x\ k + u\ 0$

lemma *LocalSystem INIT-SUM-A PREC-SUM-A REL-SUM-A* = $\{.x \,.\, \forall\ i \,.\, Summm\ x\ i \leq 100.\}\ o\ [:x \rightsquigarrow y \,.\, y = Summm\ x:]$

definition *PREC-SUM-B* = $(\lambda\ (u,\ x) \,.\, u \leq 100)$
definition *REL-SUM-B* = $(\lambda\ (u,\ x)\ (u',\ y) \,.\, (u' = u + x \vee u' = x) \wedge (u = y))$
definition *INIT-SUM-B* $u = (u = 0)$

lemma *le-sum-suc*: $\forall n < k \,.\, u\ (Suc\ n) = u\ n + x\ n \vee u\ (Suc\ n) = x\ n \Longrightarrow u\ k \leq Summm\ x\ k + u\ 0$

lemma *LocalSystem INIT-SUM-B PREC-SUM-B REL-SUM-B*
$= \{.x \,.\, \forall\ i \,.\, Summm\ x\ i \leq 100.\}\ o\ [:x \rightsquigarrow y \,.\, y\ 0 = 0 \wedge (\forall\ i \,.\, y\ (Suc\ i) = y\ i + x\ i \vee y\ (Suc\ i) = x\ i):]$

lemma *prod-comp-spec*[*simp*]: $pa \leq inpt\ ra \Longrightarrow pb \leq inpt\ rb \Longrightarrow ((\{.pa.\} \circ [:ra:]) ** (\{.pb.\} \circ [:rb:])) \circ ((\{.pc.\} \circ [:rc:]) ** (\{.pd.\} \circ [:rd:]))$
$= (\{.pa.\}\ o\ [:ra:]\ o\ \{.pc.\}\ o\ [:rc:]) ** (\{.pb.\}\ o\ [:rb:]\ o\ \{.pd.\}\ o\ [:rd:])$

lemma *prod-comp-implem*: *implementable* $S \Longrightarrow$ *implementable* $S' \Longrightarrow$ *sconjunctive* $T \Longrightarrow$ *sconjunctive* $T' \Longrightarrow (S ** S')\ o\ (T ** T') = (S\ o\ T) ** (S'\ o\ T')$

definition *ang-rel* $S\ s\ q = S\ q\ s$
definition *dem-rel* $S\ q\ s' = q\ s'$

lemma *mono-rep*: *mono* $S \Longrightarrow S = \{:ang\text{-}rel\ S:\}\ o\ [:dem\text{-}rel\ S:]$

lemma *mono-repE*: *mono* $(S::('a \Rightarrow bool) \Rightarrow ('b \Rightarrow bool)) \Longrightarrow \exists\ (r::'b \Rightarrow ('a \Rightarrow bool) \Rightarrow bool)\ (r') \,.$

$S = \{:r:\}\ o\ [:r':]$

lemma *prod-comp-a*: $(S\ o\ T) ** (S'\ o\ T') \leq (S ** S')\ o\ (T ** T')$

lemma *prod-comp-angelic-demonic*: $(\{:r::'a \Rightarrow 'b \Rightarrow bool:\} ** \{:r'::'c \Rightarrow 'd \Rightarrow bool:\})\ o\ ([:t:] ** [:t':]) = (\{:r:\}\ o\ [:t:]) ** (\{:r':\}\ o\ [:t':])$

definition *prod-rel* $r\ r' = (\lambda\ (x,\ y)\ (u,\ v)\ .\ r\ x\ u \wedge r'\ y\ v)$

lemma *Prod-angelic*: $\{:r:\} ** \{:r':\} = \{:\ prod\text{-}rel\ r\ r'\ :\}$

lemma *Prod-demonic-rel*: $[:r:] ** [:r':] = [:\ prod\text{-}rel\ r\ r'\ :]$

lemma *prod-rel-comp*: $prod\text{-}rel\ r\ r'\ OO\ prod\text{-}rel\ t\ t' = prod\text{-}rel\ (r\ OO\ t)\ (r'\ OO\ t')$

lemma *prod-comp-angelic-demonic-demonic*: $((\{:ra:\}\ o\ [:rd:]) ** (\{:ra':\}\ o\ [:rd':]))\ o\ ([:r:] ** [:r':]) = (\{:ra:\}\ o\ [:rd:]\ o\ [:r:]) ** ((\{:ra':\}\ o\ [:rd':])\ o\ [:r':])$

lemma *prod-comp-demonic*: $mono\ (S::('a \Rightarrow bool) \Rightarrow ('b \Rightarrow bool)) \Longrightarrow mono\ (S'::\ ('c \Rightarrow bool) \Rightarrow ('d \Rightarrow bool)) \Longrightarrow$
$(S ** S')\ o\ ([:r:] ** [:r':]) = (S\ o\ [:r:]) ** (S'\ o\ [:r':])$

theorem *DelayFeedback-prod*: $init\ a \Longrightarrow init'\ a' \Longrightarrow implementable\ S \Longrightarrow implementable\ S' \Longrightarrow DelayFeedback\ init\ S ** DelayFeedback\ init'\ S' =$
$[-\ (x,\ y) \rightsquigarrow x\ ||\ y\ -]\ o\ DelayFeedback\ (prod\text{-}pred\ init\ init')\ (prod\text{-}sts\ S\ S')\ o\ [-\lambda\ x\ .\ (fst\ o\ x,\ snd\ o\ x)\ -]$

lemma *rel-fun-power*: $((\lambda x\ y.\ y = (f::'a \Rightarrow 'a)\ x)\ \hat{}\hat{}\ n) = (\lambda\ x\ y\ .\ (y = (f\ \hat{}\hat{}\ n)\ x))$

lemma [*simp*]: $[:\bot:] = Magic$

definition *IterateMask* $S\ n = Mask\ n\ ((S::('a::trace \Rightarrow bool) \Rightarrow ('a \Rightarrow bool))\ \hat{}\hat{}\ n)$

lemma *IterateMask-simp*: $IterateMask\ S = (\lambda\ n.\ Mask\ n\ (S\ \hat{}\hat{}\ n))$

definition *IterateOmega* $S = Fusion\ (IterateMask\ S)$

definition *IterateMaskA* $S\ n = Mask\ (n - 1)\ ((S::('a::trace \Rightarrow bool) \Rightarrow ('a \Rightarrow bool))\ \hat{}\hat{}\ n)$

lemma *IterateMaskA-simp*: $IterateMaskA\ S = (\lambda\ n.\ Mask\ (n-1)\ (S\ \hat{}\hat{}\ n))$

definition *IterateOmegaA* $S = Fusion\ (IterateMaskA\ S)$

lemma *IterateMaskA* $S\ n = (S\ \hat{}\hat{}\ n) o\ [:x \rightsquigarrow y\ .\ \forall\ (i::nat) < n - 1\ .\ ((y\ i)::'a) = x\ i:]$

lemma *power-refin*: $mono\ S \Longrightarrow (S::'a::order \Rightarrow 'a) \leq T \Longrightarrow S\ \hat{}\hat{}\ n \leq T\ \hat{}\hat{}\ n$

lemma *IterateMaskA-refin*: $mono\ S \Longrightarrow S \leq T \Longrightarrow IterateMaskA\ S\ n \leq IterateMaskA\ T\ n$

lemma *IterateOmegaA-refin*: $mono\ S \Longrightarrow S \le T \Longrightarrow IterateOmegaA\ S \le IterateOmegaA\ T$

lemma *IterateOmega-spec*: $IterateOmega\ (\{.p.\}\ o\ [:r:])$
$= \{.\ (\lambda x\ .\ \forall\ n\ .\ \forall y.\ (r\ \hat{}\hat{}\ n)\ x\ y \longrightarrow p\ y)\ .\}$
$\circ\ [:\ INF\ n.\ (r\ \hat{}\hat{}\ n)\ OO\ eqtop\ n\ :]$

lemma *IterateOmegaA-spec*: $IterateOmegaA\ (\{.p.\}\ o\ [:r:])$
$= \{.\ (\lambda x\ .\ \forall\ n\ y.\ (r\ \hat{}\hat{}\ n)\ x\ y \longrightarrow p\ y)\ .\}$
$\circ\ [:\ INF\ n.\ (r\ \hat{}\hat{}\ n)\ OO\ eqtop\ (n-1)\ :]$

lemma *IterateOmegaA-demonic*: $IterateOmegaA\ ([:r:])$
$= [:\ INF\ n.\ (r\ \hat{}\hat{}\ n)\ OO\ eqtop\ (n-1)\ :]$

lemma *rel-power-a*: $\bigwedge\ y\ .\ ((r :: 'a \Rightarrow 'a \Rightarrow bool)\ \hat{}\hat{}\ n)\ x\ y \Longrightarrow \exists\ a\ .\ x = a\ 0 \wedge y = a\ n \wedge (\forall\ i < n\ .\ r\ (a\ i)\ (a\ (Suc\ i)))$

lemma *rel-power-b*: $\bigwedge\ y\ .\ \exists\ a\ .\ x = a\ 0 \wedge y = a\ n \wedge (\forall\ i < n\ .\ r\ (a\ i)\ (a\ (Suc\ i))) \Longrightarrow ((r :: 'a \Rightarrow 'a \Rightarrow bool)\ \hat{}\hat{}\ n)\ x\ y$

lemma *rel-power*: $((r :: 'a \Rightarrow 'a \Rightarrow bool)\ \hat{}\hat{}\ n)\ x\ y = (\exists\ a\ .\ x = a\ 0 \wedge y = a\ n \wedge (\forall\ i < n\ .\ r\ (a\ i)\ (a\ (Suc\ i))))$

lemma *IterateOmega-demonic-spec*: $IterateOmega\ [:r:] = [:\ INF\ n.\ r\ \hat{}\hat{}\ n\ OO\ eqtop\ n\ :]$

lemma *IterateOmega-func*: $IterateOmega\ [-\ f\ -] = [:\ x \rightsquigarrow y\ .\ \forall\ n.\ eqtop\ n\ ((f\ \hat{}\hat{}\ n)\ x)\ y\ :]$

lemma *IterateOmega-func-aux-a*: $(\forall\ n.\ eqtop\ n\ ((f\ \hat{}\hat{}\ n)\ x)\ y) = (\forall\ n\ .\ \forall\ i < n\ .\ (f\ \hat{}\hat{}\ n)\ x\ i = y\ i)$

lemma *IterateOmega-func-a*: $IterateOmega\ [-\ f\ -] = [:\ x \rightsquigarrow y\ .\ (\forall\ n\ .\ \forall\ i < n\ .\ (f\ \hat{}\hat{}\ n)\ x\ i = y\ i):]$

definition $apply\ x\ i = ((fst\ (fst\ x)\ i,\ snd\ (fst\ x)\ i),\ snd\ x\ i)$

lemma *IterateOmega-func-aux-b*: $(\forall\ n.\ eqtop\ n\ ((f\hat{}\hat{}n)\ x)\ y) = (\forall\ n::nat\ .\ \forall\ i::nat < n\ .\ apply\ ((f\ \hat{}\hat{}\ n)\ x)\ i = apply\ y\ i)$

lemma *IterateOmega-func-aa*: $IterateOmega\ [-\ f\ -] = [:\ x \rightsquigarrow y\ .\ (\forall\ n\ .\ \forall\ i::nat < n\ .\ apply\ ((f\ \hat{}\hat{}\ n)\ x)\ i = apply\ y\ i):]$

lemma *IterateOmega-func-b*: $(\forall\ x\ n\ .\ \forall\ i < n\ .\ (f\ \hat{}\hat{}\ n)\ x\ i = (f\ \hat{}\hat{}\ (Suc\ i))\ x\ i) \Longrightarrow IterateOmega\ [-\ f\ -] = [-\lambda\ x\ .\ (\lambda\ i\ .\ (f\ \hat{}\hat{}\ (Suc\ i))\ x\ i)-]$

lemma *IterateOmega-func-bb*: $(\forall\ x\ n\ .\ \forall\ i::nat < n\ .\ apply\ (((f::(\ ((nat \Rightarrow 'a) \times (nat \Rightarrow 'b)) \times (nat \Rightarrow 'c) \Rightarrow\ ((nat \Rightarrow 'a) \times (nat \Rightarrow 'b)) \times (nat \Rightarrow 'c))\ )\hat{}\hat{}\ n)\ x)\ i = apply\ ((f\ \hat{}\hat{}\ (Suc\ i))\ x)\ i)$
$\Longrightarrow$
$IterateOmega\ [-\ f\ -] =[-\ (\lambda\ x\ .\ (let\ z = (\lambda\ i\ .\ apply\ ((f\ \hat{}\hat{}\ (Suc\ i))\ x)\ i)\ in\ ((fst\ o\ fst\ o\ z,\ snd\ o\ fst\ o\ z),\ snd\ o\ z)))\ -]$

lemma *IterateOmega-func-c*: $\forall\ x\ .\ \neg\ (\forall\ n\ .\ \forall\ i < n\ .\ (f\ \hat{}\hat{}\ n)\ x\ i = (f\ \hat{}\hat{}\ (Suc\ i))\ x\ i) \Longrightarrow IterateOmega\ [-\ f\ -] = Magic$

lemma *IterateOmega-assert-update*: $IterateOmega\ (\{.p.\}\ o\ [-f-])$
$= \{.\ (\lambda x\ .\ \forall\ n\ .\ p\ ((f\ \hat{}\hat{}\ n)\ x))\ .\}$
$\circ\ [:\ x \leadsto y\ .\ \forall\ n.\ eqtop\ n\ ((f\ \hat{}\hat{}\ n)\ x)\ y\ :]$

lemma *IterateOmega-assert-update-a*: $IterateOmega\ (\{.p.\}\ o[-\ f\ -]) = \{.\ (\lambda x\ .\ \forall\ n\ .\ p\ ((f\ \hat{}\hat{}\ n)\ x))\ .\}\ o\ [:\ x \leadsto y\ .\ (\forall\ n\ .\ \forall\ i < n\ .\ (f\ \hat{}\hat{}\ n)\ x\ i = y\ i):]$

lemma *IterateOmega-assert-update-b*: $(\forall\ x\ n\ .\ \forall\ i < n\ .\ (f\ \hat{}\hat{}\ n)\ x\ i = (f\ \hat{}\hat{}\ (Suc\ i))\ x\ i) \Longrightarrow IterateOmega\ (\{.p.\}\ o[-\ f\ -]) = \{.(\lambda x\ .\ \forall\ n\ .\ p\ ((f\ \hat{}\hat{}\ n)\ x)).\}\ o\ [-\lambda\ x\ .\ (\lambda\ i\ .\ (f\ \hat{}\hat{}\ (Suc\ i))\ x\ i)-]$

lemma *IterateOmega-assert-update-c*: $IterateOmega\ (\{.p.\}\ o\ [-\ f\ -]) = \{.(\lambda x\ .\ \forall\ n\ .\ p\ ((f\ \hat{}\hat{}\ n)\ x)).\}\ o\ [:\ x \leadsto y\ .\ (\forall\ n\ .\ \forall\ i{::}nat < n\ .\ apply\ ((f\ \hat{}\hat{}\ n)\ x)\ i = apply\ y\ i):]$

thm *IterateOmega-spec*

lemma *IterateOmega-assert-update-d*: $(\forall\ x\ n\ .\ \forall\ i{::}nat < n\ .\ apply\ (((f{::}(\ ((nat \Rightarrow 'a) \times (nat \Rightarrow 'b)) \times (nat \Rightarrow 'c) \Rightarrow\ ((nat \Rightarrow 'a) \times (nat \Rightarrow 'b)) \times (nat \Rightarrow 'c))\ )\hat{}\hat{}\ n)\ x)\ i = apply\ ((f\ \hat{}\hat{}\ (Suc\ i))\ x)\ i) \Longrightarrow$
$IterateOmega\ (\{.p.\}\ o\ [-\ f\ -]) = \{.(\lambda x\ .\ \forall\ n\ .\ p\ ((f\ \hat{}\hat{}\ n)\ x)).\}\ o\ [-\ (\lambda\ x\ .\ (let\ z = (\lambda\ i\ .\ apply\ ((f\ \hat{}\hat{}\ (Suc\ i))\ x)\ i)\ in\ ((fst\ o\ fst\ o\ z,\ snd\ o\ fst\ o\ z),\ snd\ o\ z)))\ -]$

lemma *IterateOmega-assert-update-e*: $\forall\ x\ .\ \neg\ (\forall\ n\ .\ \forall\ i < n\ .\ (f\ \hat{}\hat{}\ n)\ x\ i = (f\ \hat{}\hat{}\ (Suc\ i))\ x\ i) \wedge (\forall n.\ p\ ((f\ \hat{}\hat{}n)\ x)) \Longrightarrow IterateOmega\ (\{.p.\}\ o\ [-\ f\ -]) = Magic$

definition $defined\ r = (\forall\ x\ .\ \exists\ y\ .\ r\ x\ y)$

fun $calcu :: (nat \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'b) \Rightarrow ('a \times 'b \Rightarrow 'a \times 'c \Rightarrow bool) \Rightarrow nat \Rightarrow nat \Rightarrow 'a$ **where**
$calcu\ u\ x\ r\ n\ i = (if\ i \le n\ then\ u\ i\ else\ SOME\ u'\ .\ (\exists y.\ r\ (calcu\ u\ x\ r\ n\ (i-1),\ x\ (i-1))\ (u',\ y)))$

thm *choice-iff'*

lemma *prec-loc-st-defined-simp*: $defined\ r \Longrightarrow prec\text{-}pre\text{-}sts\ init\ p\ r$
$= (\lambda\ x\ .\ \forall\ u\ .\ init\ (u\ 0) \longrightarrow (\forall n\ .\ \exists\ y.\ r\ (u\ n,\ x\ n)\ (u\ (Suc\ n),\ y)) \longrightarrow (\forall\ n\ .\ p\ (u\ n,\ x\ n)))$

lemma *DelayFeedback-defined-simp*: $defined\ r \Longrightarrow DelayFeedback\ init\ (\{.p.\}\ o\ [:r:])$
$= \{.x\ .\ \forall\ (u{::}nat \Rightarrow 'a)\ .\ init\ (u\ 0) \wedge ((\forall n\ .\ \exists\ y.\ r\ (u\ n,\ x\ n)\ (u\ (Suc\ n),\ y))) \longrightarrow (\forall\ n\ .\ p\ (u\ n,\ x\ n)).\}$
$o\ [:rel\text{-}pre\text{-}sts\ init\ r\ :]$

lemma *defined-fun*[*simp*]: $defined\ (\lambda\ x\ y\ .\ y = f\ x)$

definition $map\text{-}f\ f\ x\ n = f\ (fst\ x\ n,\ snd\ x\ n)$

lemma *DelayFeedback-update-simp-aux-b*: $(\forall n.\ \exists y.\ (u\ (Suc\ n),\ y) = f\ (u\ n,\ x\ n)) = ((\odot\ u) = map\text{-}f\ (fst\ o\ f)\ (u,\ x))$

lemma *DelayFeedback-update-simp-aux-a*: $rel\text{-}pre\text{-}sts\ init\ (\lambda x\ y.\ y = f\ x) = (\lambda\ x\ y\ .\ \exists u.\ init\ (u\ 0) \wedge \odot\ u = map\text{-}f\ (fst \circ f)\ (u,\ x) \wedge y = map\text{-}f\ (snd \circ f)\ (u,\ x))$

lemma *DelayFeedback-update-simp*: $DelayFeedback\ init\ (\{.p.\}\ o\ [-f-])$
$= \{.\ \lambda x.\ \forall\ (u{::}nat \Rightarrow 'a).\ init\ (u\ 0) \wedge (\odot\ u) = map\text{-}f\ (fst\ o\ f)\ (u,\ x) \longrightarrow (\forall\ n\ .\ p\ (u\ n,\ x\ n))\ .\}$
$\circ$ $[:\ \lambda x\ y.\ \exists\ (u{::}\ nat \Rightarrow 'a).\ init\ (u\ 0) \wedge (\odot\ u) = map\text{-}f\ (fst\ o\ f)\ (u,\ x) \wedge y = map\text{-}f\ (snd\ o\ f)\ (u,\ x)\ :]$

primrec *itr* :: $('a \times 'b \Rightarrow 'a) \Rightarrow 'a \Rightarrow (nat \Rightarrow 'b) \Rightarrow nat \Rightarrow 'a$ **where**
$itr\ f\ u0\ x\ 0 = u0\ |$
$itr\ f\ u0\ x\ (Suc\ n) = f\ (itr\ f\ u0\ x\ n,\ x\ n)$

lemma *map-itr-aux*: $((\odot\ u) = map\text{-}f\ f\ (u,\ x)) \Longrightarrow (u\ n = itr\ f\ (u\ 0)\ x\ n)$

lemma *map-itr-simp*: $((\odot\ u) = map\text{-}f\ f\ (u,\ x)) = (u = itr\ f\ (u\ 0)\ x)$

lemma *DelayFeedback-update-itr-simp*: $DelayFeedback\ init\ (\{.p.\}\ o\ [-f-])$
$= \{.\ x.\ \forall\ a\ .\ init\ a \longrightarrow (\forall\ i\ .\ p\ (itr\ (fst\ o\ f)\ a\ x\ i,\ x\ i))\ .\}$
$\circ$ $[:\ \lambda x\ y.\ \exists\ a.\ init\ a \wedge y = map\text{-}f\ (snd\ o\ f)\ (itr\ (fst\ o\ f)\ a\ x,\ x)\ :]$

definition $DelayFeedbackInit\ a\ S = DelayFeedback\ (\lambda\ u\ .\ u = a)\ S$

definition $lft\text{-}1\text{-}2\ p = (\lambda\ (x,\ y)\ .\ p\ (x\ (0{::}nat),\ y\ (0{::}nat)))$
definition $lft\text{-}2\text{-}2\ r = (\lambda\ (x,\ y)\ (z,\ t).\ r\ (x\ (0{::}nat),\ y\ (0{::}nat))\ (z\ (0{::}nat),\ t\ (0{::}nat)))$

theorem *DelayFeedbackInit-update-simp-a*: $DelayFeedbackInit\ u\ (\{.p.\}\ o\ [-f-])$
$= \{.\ x.\ (\forall\ n\ .\ p\ (itr\ (fst\ o\ f)\ u\ x\ n,\ x\ n))\ .\} \circ [-\lambda x\ .\ map\text{-}f\ (snd\ o\ f)\ (itr\ (fst\ o\ f)\ u\ x,\ x)-]$

lemma [*simp*]: $(\Box\ lft\text{-}1\text{-}2\ \top) = \top$

theorem *DelayFeedbackInit-update-simp-b*: $DelayFeedbackInit\ u\ [-f-] = [-\lambda x\ .\ map\text{-}f\ (snd\ o\ f)\ (itr\ (fst\ o\ f)\ u\ x,\ x)-]$

lemma *prec-itr-simp*: $((\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ f\ u\ x,\ x)) = (\forall\ n.\ p\ (itr\ f\ u\ x\ n,\ x\ n))$

lemma *prec-itr-induction-aux*: $p\ (u,\ x\ 0) \Longrightarrow (\bigwedge\ n\ a\ .\ p\ (a,\ x\ n) \Longrightarrow p\ (f\ (a\ ,x\ n),\ x\ (Suc\ n))) \Longrightarrow p\ (itr\ f\ u\ x\ n,\ x\ n)$

lemma *prec-itr-induction*: $p\ (u,\ x\ 0) \Longrightarrow (\bigwedge\ n\ a\ .\ p\ (a,\ x\ n) \Longrightarrow p\ (f\ (a\ ,x\ n),\ x\ (Suc\ n))) \Longrightarrow ((\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ f\ u\ x,\ x))$

definition $lft\text{-}r\ r\ x\ y = r\ (fst\ x\ 0,\ snd\ x\ 0)\ (fst\ y\ 0,\ snd\ y\ 0)$
definition $lft\text{-}r\text{-}b\ r\ x\ y = r\ (x\ 0)\ (y\ 0)$

lemma *rel-itr-simp*: $(\Box\ (lft\text{-}r\text{-}b\ r))\ x\ (map\text{-}f\ g\ (itr\ f\ u\ x,\ x)) = (\forall\ n\ .\ r\ (x\ n)\ (g\ (itr\ f\ u\ x\ n,\ x\ n)))$

lemma *rel-itr-induction-aux*: $r\ (x\ 0)\ (g\ (u,\ x\ 0)) \Longrightarrow (\bigwedge\ n\ a\ .\ r\ (x\ n)\ (g\ (a,\ x\ n)) \Longrightarrow r\ (x\ (Suc\ n))$

$(g\ (f\ (a\ ,x\ n),\ x\ (Suc\ n)))) \Longrightarrow r\ (x\ n)\ (g\ (itr\ f\ u\ x\ n,\ x\ n))$

lemma *rel-itr-induction*: $r\ (x\ 0)\ (g\ (u,\ x\ 0)) \Longrightarrow (\bigwedge n\ a\ .\ r\ (x\ n)\ (g\ (a,\ x\ n)) \Longrightarrow r\ (x\ (Suc\ n))\ (g\ (f\ (a\ ,x\ n),\ x\ (Suc\ n)))) \Longrightarrow (\Box\ (lft\text{-}r\text{-}b\ r))\ x\ (map\text{-}f\ g\ (itr\ f\ u\ x,\ x))$

lemma *rel-bounded-itr-induction-aux*: $(0 \in b \Longrightarrow r\ (x\ 0)\ (g\ (u,\ x\ 0))) \Longrightarrow$
$(\bigwedge n\ a\ .\ (n \in b \Longrightarrow r\ (x\ n)\ (g\ (a,\ x\ n))) \Longrightarrow Suc\ n \in b \Longrightarrow r\ (x\ (Suc\ n))\ (g\ (f\ (a\ ,x\ n),\ x\ (Suc\ n)))) \Longrightarrow n \in b \Longrightarrow r\ (x\ n)\ (g\ (itr\ f\ u\ x\ n,\ x\ n))$

lemma *rel-bounded-itr-induction*: $(0 \in b \Longrightarrow r\ (x\ 0)\ (g\ (u,\ x\ 0))) \Longrightarrow (\bigwedge n\ a\ .\ (n \in b \Longrightarrow r\ (x\ n)\ (g\ (a,\ x\ n))) \Longrightarrow Suc\ n \in b \Longrightarrow r\ (x\ (Suc\ n))\ (g\ (f\ (a\ ,x\ n),\ x\ (Suc\ n))))$
$\Longrightarrow (\Box b\ b\ (lft\text{-}r\text{-}b\ r))\ x\ (map\text{-}f\ g\ (itr\ f\ u\ x,\ x))$

lemma *refin-demonic-spec*: $([:r:] \le \{.p.\}\ o\ [:r':]) = (p = \top \wedge r' \le r)$

lemma *spec-delay-feedback-fun-refine*: $(\{.p'.\}\ o\ [:\ r\ :] \le DelayFeedbackInit\ u\ (\{.p.\}\ o\ [-f-])) = ((p' \le (\lambda x.\ (\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ (fst\ o\ f)\ u\ x,\ x)))$
$\wedge\ (\forall\ x\ .\ p'\ x \longrightarrow\ r\ x\ (\ map\text{-}f\ (snd\ o\ f)\ (itr\ (fst\ o\ f)\ u\ x,\ x))\ ))$

lemma *prec-itr-inductionA*: $(p'\ x \Longrightarrow p\ (u,\ x\ 0)) \Longrightarrow (\bigwedge n\ a\ .\ p'\ x \Longrightarrow p\ (a,\ x\ n) \Longrightarrow p\ (f\ (a\ ,x\ n),\ x\ (Suc\ n))) \Longrightarrow p'\ x \Longrightarrow ((\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ f\ u\ x,\ x))$

lemma *prec-itr-inductionB*: $(\bigwedge x\ .\ p'\ x \Longrightarrow p\ (u,\ x\ 0)) \Longrightarrow (\bigwedge x\ n\ a\ .\ p'\ x \Longrightarrow p\ (a,\ x\ n) \Longrightarrow p\ (f\ (a\ ,x\ n),\ x\ (Suc\ n))) \Longrightarrow p' \le (\lambda\ x\ .\ (\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ f\ u\ x,\ x))$

lemma *rel-itr-inductionA*: $(\bigwedge x\ .\ p'\ x \Longrightarrow r\ (x\ 0)\ (g\ (u,\ x\ 0))) \Longrightarrow (\bigwedge x\ n\ a\ .\ p'\ x \Longrightarrow r\ (x\ n)\ (g\ (a,\ x\ n)) \Longrightarrow r\ (x\ (Suc\ n))\ (g\ (f\ (a\ ,x\ n),\ x\ (Suc\ n))))$
$\Longrightarrow p'\ x \Longrightarrow (\Box\ (lft\text{-}r\text{-}b\ r))\ x\ (map\text{-}f\ g\ (itr\ f\ u\ x,\ x))$

lemma $\{:z \rightsquigarrow x\ .\ x \neq (0::nat):\}\ o\ [:x \rightsquigarrow y\ .\ x = 0 \wedge y = (0::nat):] = \top$

lemma $\{:z \rightsquigarrow x\ .\ x \neq (Suc\ n):\}\ o\ [:x \rightsquigarrow y\ .\ x = 0 \wedge y = (0::nat):] = \top$

lemma $(\{.p'.\}\ o\ [:\ \Box\ (lft\text{-}r\text{-}b\ r)\ :] \le DelayFeedbackInit\ u\ (\{.p.\}\ o\ [-f-])) = ((p' \le (\lambda x.\ (\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ (fst\ o\ f)\ u\ x,\ x)))$
$\wedge\ (\forall\ x\ .\ p'\ x \longrightarrow\ (\Box\ (lft\text{-}r\text{-}b\ r))\ x\ (\ map\text{-}f\ (snd\ o\ f)\ (itr\ (fst\ o\ f)\ u\ x,\ x))\ ))$

lemma *demonic-delay-feedback-fun-refine*: $([:r\ :] \le DelayFeedbackInit\ u\ (\{.p.\}\ o\ [-f-])) = (((\lambda x.\ (\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ (fst\ o\ f)\ u\ x,\ x)) = \top)$
$\wedge\ (\forall\ x\ .\ r\ x\ (map\text{-}f\ (snd\ o\ f)\ (itr\ (fst\ o\ f)\ u\ x,\ x))\ ))$

lemma $([:\ \Box\ (lft\text{-}r\text{-}b\ r)\ :] \le DelayFeedbackInit\ u\ (\{.p.\}\ o\ [-f-])) = (((\lambda x.\ (\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ (fst\ o\ f)\ u\ x,\ x)) = \top)$
$\wedge\ (\forall\ x\ .\ (\Box\ (lft\text{-}r\text{-}b\ r))\ x\ (map\text{-}f\ (snd\ o\ f)\ (itr\ (fst\ o\ f)\ u\ x,\ x))\ ))$

lemma *refin-update-spec*: $([:\ \Box b\ b\ (lft\text{-}r\text{-}b\ r)\ :] \le DelayFeedbackInit\ u\ (\{.p.\}\ o\ [-f-])) = (((\lambda x.\ (\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ (fst\ o\ f)\ u\ x,\ x)) = \top)$
$\wedge\ (\forall\ x\ y\ .\ y = map\text{-}f\ (snd\ o\ f)\ (itr\ (fst\ o\ f)\ u\ x,\ x) \longrightarrow\ (\Box b\ b\ (lft\text{-}r\text{-}b\ r))\ x\ y\ ))$

definition *prec-delay* p *f-state* $u = (\lambda x.\ (\Box\ lft\text{-}1\text{-}2\ p)\ (itr\ (f\text{-}state)\ u\ x,\ x))$
definition *func-delay f-state f-out* $u = (\lambda x\ .\ map\text{-}f\ f\text{-}out\ (itr\ f\text{-}state\ u\ x,\ x))$

theorem *DelayFeedbackInit-update-simp-c*: $DelayFeedbackInit\ u\ (\{.p.\}\ o\ [-f-])$

$= \{.prec\text{-}delay\ p\ (fst\ o\ f)\ u.\} \circ [-func\text{-}delay\ (fst\ o\ f)\ (snd\ o\ f)\ u-]$

theorem *DelayFeedbackInit-update-simp-d*: $DelayFeedbackInit\ u\ [-f-] = [-func\text{-}delay\ (fst\ o\ f)\ (snd\ o\ f)\ u-]$

lemma *always-lft-bot*: $(\Box\ lft\text{-}1\text{-}2\ (\bot::('a \times 'b \Rightarrow bool)\ )) = \bot$

lemma *DelayFeedbackInit-bot*: $DelayFeedbackInit\ u\ ((\bot::(('a \times 'b) \Rightarrow bool) \Rightarrow ('a \times 'c) \Rightarrow bool)) = \bot$

lemma *simp-prec*: $\{.\ p\ .\} \circ [:\ \lambda x\ y.\ \neg\ p\ x \vee r\ x\ y\ :] = \{.p.\}\ o\ [:r:]$

lemma *inpt-and-rel*: $(inpt\ r\ x \wedge r\ x\ y) = r\ x\ y$

lemma [*simp*]: $inpt\ (\lambda x\ y.\ inpt\ r\ x \wedge r\ x\ y) = inpt\ r$

thm *DelayFeedback-defined-simp*
lemma *DelayFeedback-inpt*: $DelayFeedback\ init\ (\{.inpt\ r.\}\ o\ [:r:])$
$= \{.x.\ \forall (u::nat \Rightarrow 'a).\ init\ (u\ 0) \wedge ((\forall n.\ \exists y.\ \neg\ inpt\ r\ (u\ n,\ x\ n) \vee r\ (u\ n,\ x\ n)\ (u\ (Suc\ n),\ y))) \longrightarrow (\forall n.\ inpt\ r\ (u\ n,\ x\ n)).\} \circ$
$[:\ rel\text{-}pre\text{-}sts\ init\ (\lambda x\ y.\ \neg\ inpt\ r\ x \vee r\ x\ y)\ :]$

declare *comp-skip*[*simp del*]
declare *skip-comp*[*simp del*]
declare *prod-skip-skip*[*simp del*]
declare *fail-comp*[*simp del*]

4.7 Data Refinement

definition *data-refin-sts* $d\ S\ S' = (\{:t,\ x \rightsquigarrow s,\ x'\ .\ x = x' \wedge d\ t\ s:\}\ o\ S \leq S'\ o\ \{:t',\ y \rightsquigarrow s',\ y'\ .\ y = y' \wedge d\ t'\ s':\})$

lemma *data-refin-sts-simp*: $data\text{-}refin\text{-}sts\ d\ (\{.\ p\ .\} \circ [:\ r\ :])\ (\{.\ p'\ .\} \circ [:\ r'\ :]) =$
$((\forall t\ x\ s.\ d\ t\ s \wedge p\ (s,\ x) \longrightarrow p'\ (t,\ x)) \wedge$
$(\forall t\ x\ s\ t'\ y.\ d\ t\ s \wedge p\ (s,\ x) \wedge r'\ (t,\ x)\ (t',\ y) \longrightarrow (\exists s'.\ d\ t'\ s' \wedge r\ (s,\ x)\ (s',\ y))))$

primrec $s\text{-}r :: ('a \Rightarrow 'b \Rightarrow bool) \Rightarrow ('b \Rightarrow bool) \Rightarrow ('b \times 'c \Rightarrow 'b \times 'd \Rightarrow bool) \Rightarrow (nat \Rightarrow 'c) \Rightarrow (nat \Rightarrow 'd) \Rightarrow (nat \Rightarrow 'a) \Rightarrow nat \Rightarrow 'b$ **where**
$s\text{-}r\ d\ init\ r\ x\ y\ t\ 0 = (SOME\ s\ .\ d\ (t\ 0)\ s \wedge init\ s)\ |$
$s\text{-}r\ d\ init\ r\ x\ y\ t\ (Suc\ n) = (SOME\ s\ .\ d\ (t\ (Suc\ n))\ s \wedge r\ (s\text{-}r\ d\ init\ r\ x\ y\ t\ n,\ x\ n)\ (s,\ y\ n))$

theorem *data-refinement-sts*: $(\bigwedge\ t\ .\ init'\ t \Longrightarrow \exists\ s\ .\ d\ t\ s \wedge init\ s) \Longrightarrow$
$data\text{-}refin\text{-}sts\ d\ (\{.p.\}\ o\ [:r:])\ (\{.p'.\}\ o\ [:r':]) \Longrightarrow LocalSystem\ init\ p\ r \leq LocalSystem\ init'\ p'\ r'$

4.8 Reachability and Refinement

definition *reach* $init\ r\ n\ x\ y\ s = (init\ (s\ 0) \wedge (\forall\ i < n\ .\ r\ (s\ i,\ x\ i)\ (s\ (Suc\ i),\ y\ i)))$

lemma *reach-prec-always*: $reach\ init\ r\ n\ x\ y\ s \Longrightarrow p \leq inpt\ r \Longrightarrow prec\text{-}pre\text{-}sts\ init\ p\ r\ x$
$\Longrightarrow \exists\ s'\ y'\ .\ init\ (s'\ 0) \wedge (\forall\ i < n\ .\ y'\ i = y\ i) \wedge (\forall\ i \leq n\ .\ s'\ i = s\ i) \wedge (\Box\ lift\text{-}rel\ r)\ (s',\ x)\ (s'[1..],\ y')$

lemma *refinemen-reachable-B*:
  assumes R: *LocalSystem init p r* $\leq$ *LocalSystem init′ p′ r′*
    and [*simp*]: $p' \leq$ *inpt r′*
  shows *prec-pre-sts init p r x* $\Longrightarrow$ *reach init′ r′ n x y t* $\Longrightarrow \exists$ *s . reach init r n x y s*
    and *prec-pre-sts init p r x* $\Longrightarrow$ *reach init′ r′ n x y t* $\Longrightarrow p'$ (*t n*, *x n*)

lemma *sel-inf-a*: *finite X* $\Longrightarrow$ ($\bigwedge$ *i* :: *nat* . *f i* $\in$ *X*) $\Longrightarrow$ ($\exists$ *x* $\in$ *X* . *infinite* {*i* . *f i* = *x*})

lemma $X \neq \{\} \Longrightarrow \exists$ (*x*::′*a*::*wellorder*) $\in X$. $\forall$ $y \in X$. $x \leq y$

primrec *min-rest* :: *nat set* $\Rightarrow$ *nat* $\Rightarrow$ *nat* **where**
  min-rest X 0 = (*LEAST x* . $x \in X$) |
  min-rest X (*Suc n*) = *min-rest* (*X* − {*LEAST x* . $x \in X$}) *n*

lemma *sel-inf-fun*: $\bigwedge$ *X* . *infinite X* $\Longrightarrow$ *min-rest X n* $\in$ *X* $\wedge$ *min-rest X n* < *min-rest X* (*Suc n*)

lemma *sel-inf*: *finite X* $\Longrightarrow$ ($\bigwedge$ *i* :: *nat* . *f i* $\in$ *X*) $\Longrightarrow$ ($\exists$ *g x* . $x \in X$ $\wedge$ ($\forall$ *i* . *f* (*g i*) = *x*) $\wedge$ ($\forall$ *i* . *g i* < *g* (*Suc i*)))

definition *sel-inf f X* = (*SOME g* . $\exists$ *x* . $x \in X$ $\wedge$ ($\forall$ *i* . *f* (*g i*) = *x*) $\wedge$ ($\forall$ *i* . *g i* < *g* (*Suc i*)))

lemma *sel-inf-prop-aux*: *finite X* $\Longrightarrow$ ($\bigwedge$ *i* :: *nat* . *f i* $\in$ *X*) $\Longrightarrow$ ($\exists$ *x* . $x \in X$ $\wedge$ ($\forall$ *i* . *f* (*sel-inf f X i*) = *x*) $\wedge$ ($\forall$ *i* . *sel-inf f X i* < *sel-inf f X* (*Suc i*)))

lemma *sel-inf-prop*:
  assumes *A*: *finite X* **and** *B*: ($\bigwedge$ *i* :: *nat* . *f i* $\in$ *X*)
  shows *f* (*sel-inf f X i*) = *f* (*sel-inf f X 0*) **and** $\bigwedge$ *i* . *sel-inf f X i* < *sel-inf f X* (*Suc i*)
    and *i* $\leq$ *sel-inf f X i*

fun *SSa* :: (′*a* $\Rightarrow$ *bool*) $\Rightarrow$ (′*a* $\times$ ′*b* $\Rightarrow$ ′*a* $\times$ ′*c* $\Rightarrow$ *bool*) $\Rightarrow$ (*nat* $\Rightarrow$ ′*b*) $\Rightarrow$ (*nat* $\Rightarrow$ *nat* $\Rightarrow$ ′*a*) $\Rightarrow$ *nat* $\Rightarrow$ *nat* $\Rightarrow$ *nat* $\Rightarrow$ ′*a* **where**
  SSa init r x s 0 = (*s*[*Suc 0*..] *o sel-inf* (λ *i* . *s* (*Suc i*) *0*) {*s* . *init s*}) |
  SSa init r x s (*Suc n*) = ((*SSa init r x s n*[*Suc 0*..]) *o*
    sel-inf (λ *i* . *SSa init r x s n* (*Suc i*) (*Suc n*)) {*s′* . $\exists$ *y* . *r* ((*SSa init r x s n*[*Suc 0*..]) *0 n*, *x n*) (*s′*, *y*) })

lemma *refinemen-reachable-aux*:
  assumes *finite-next*: $\bigwedge$ *s x* . *finite* {*s′* . $\exists$ *y* . *r* (*s*, *x*) (*s′*, *y*)}
    and *finite-init*[*simp*]: *finite* {*s* . *init s*}
  assumes *A*: ($\bigwedge$ *n* . *reach init r* (*Suc n*) *x y* (*s n*))
  shows ($\forall$ *j* . $\forall$ *k* $\leq$ *n* . *SSa init r x s n j k* = *SSa init r x s n 0 k*) $\wedge$ *reach init r n x y* (*SSa init r x s n n*)
    $\wedge$ ($\exists$ *k* . $\forall$ *i* . *k i* $\geq$ *n* $\wedge$ *SSa init r x s n i* = *s* (*k i*) $\wedge$ *k i* < *k* (*Suc i*))
    $\wedge$ ($\forall$ *j* . $\forall$ *k* $\leq$ *n* . *SSa init r x s* (*Suc n*) *j k* = *SSa init r x s n 0 k*)

lemma *refinemen-reachable-A*:
  assumes *finite-next*: $\bigwedge$ *s x* . *finite* {*s′* . $\exists$ *y* . *r* (*s*, *x*) (*s′*, *y*)}
    and *finite-init*: *finite* {*s* . *init s*}

assumes A: $\bigwedge$ $n\ x\ y\ t$. $prec\text{-}pre\text{-}sts\ init\ p\ r\ x \Longrightarrow reach\ init'\ r'\ n\ x\ y\ t \Longrightarrow p'\ (t\ n,\ x\ n)$
and B: $\bigwedge$ $n\ x\ y\ t$. $prec\text{-}pre\text{-}sts\ init\ p\ r\ x \Longrightarrow reach\ init'\ r'\ n\ x\ y\ t \Longrightarrow \exists\ s\ .\ reach\ init\ r\ n\ x\ y\ s$
shows $LocalSystem\ init\ p\ r \leq LocalSystem\ init'\ p'\ r'$

definition $symb\text{-}sts\text{-}refin\ init\ p\ r\ init'\ p'\ r'$
$=$
$((\forall\ \ n\ x\ y\ t\ .\ prec\text{-}pre\text{-}sts\ init\ p\ r\ x \longrightarrow reach\ init'\ r'\ n\ x\ y\ t \longrightarrow p'\ (t\ n,\ x\ n))$
$\wedge\ (\forall\ \ n\ x\ y\ t\ .\ prec\text{-}pre\text{-}sts\ init\ p\ r\ x \longrightarrow reach\ init'\ r'\ n\ x\ y\ t \longrightarrow (\exists\ \ s\ .\ reach\ init\ r\ n\ x\ y\ s)))$

lemma $refinemen\text{-}reachable\text{-}iff$:
assumes $finite\text{-}next[simp]$: $\bigwedge$ $s\ x$. $finite\ \{s'\ .\ \exists\ \ y\ .\ r\ (s,\ x)\ (s',\ y)\}$
and $finite\text{-}init[simp]$: $finite\ \{s\ .\ init\ s\}$
and $[simp]$: $p' \leq inpt\ r'$
shows $LocalSystem\ init\ p\ r \leq LocalSystem\ init'\ p'\ r' = symb\text{-}sts\text{-}refin\ init\ p\ r\ init'\ p'\ r'$

definition $inv\text{-}top\ n\ P = (\forall\ \ u\ v\ .\ eqtop\ n\ u\ v \longrightarrow (P\ u = P\ v))$
definition $prec\text{-}pre\text{-}sts\text{-}bound\ init\ p\ r\ N\ x = ((\forall u.\ init\ (u\ 0) \longrightarrow (\forall y\ .\ \forall\ \ n < N.\ (\forall i{<}n.\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i)) \longrightarrow p\ (u\ n,\ x\ n))))$

lemma $replace\text{-}variables$: $(inv\text{-}top\ (Suc\ N)\ (P\ N)) \Longrightarrow (inv\text{-}top\ N\ (R\ N)) \Longrightarrow (inv\text{-}top\ N\ (Q'\ N)) \Longrightarrow (\forall\ \ (x{::}nat{\Rightarrow}'z)\ .\ P\ N\ x \wedge (ZZ\ (Q'\ N\ x)\ (Q\ N\ (x[N..]))) \wedge R\ N\ x \longrightarrow S\ N\ (x\ N))$
$=\ \ (\forall\ \ x\ xN\ y\ .\ P\ N\ (x(N := xN)) \wedge y\ 0 = xN \wedge (ZZ\ (Q'\ N\ x)\ (\ Q\ N\ (y))) \wedge R\ N\ x \longrightarrow S\ N\ (xN))$

lemma $prec\text{-}pre\text{-}sts\text{-}reach$: $\bigwedge$ x . $prec\text{-}pre\text{-}sts\ init\ p\ r\ x = (\forall\ \ s\ n.\ (\exists\ \ y\ .\ reach\ init\ r\ n\ x\ y\ s) \longrightarrow p\ (s\ n,\ x\ n))$

lemma $prec\text{-}pre\text{-}sts\text{-}bound\text{-}simp$: $\bigwedge$ $N\ x$. $prec\text{-}pre\text{-}sts\text{-}bound\ init\ p\ r\ N\ x =$
$(\forall u\ n.\ (n < N \wedge init\ (u\ 0) \wedge ((\exists\ \ y\ .\ \forall i{<}n\ .\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i)))) \longrightarrow (\forall\ \ k \leq n\ .\ p\ (u\ k,\ x\ k)))$

lemma $prec\text{-}pre\text{-}sts\text{-}bound$: $\bigwedge$ $x\ N$. $prec\text{-}pre\text{-}sts\ init\ p\ r\ x = (prec\text{-}pre\text{-}sts\text{-}bound\ init\ p\ r\ N\ x$
$\wedge\ (\forall\ \ s\ y\ .\ reach\ init\ r\ N\ x\ y\ s \longrightarrow\ \ prec\text{-}pre\text{-}sts\ (\lambda\ u\ .\ u = s\ N)\ p\ r\ (x[N..])))$

lemma AA: $\bigwedge$ $t\ x\ N\ y$. $((prec\text{-}pre\text{-}sts\ init\ p\ r\ x \wedge reach\ init'\ r'\ N\ x\ y\ t) \longrightarrow p'\ (t\ N,\ x\ N))$
$= ((prec\text{-}pre\text{-}sts\text{-}bound\ init\ p\ r\ N\ x \wedge (\forall\ \ s\ y\ .\ reach\ init\ r\ N\ x\ y\ s \longrightarrow\ \ prec\text{-}pre\text{-}sts\ (\lambda\ u\ .\ u = s\ N)\ p\ r\ (x[N..])) \wedge reach\ init'\ r'\ N\ x\ y\ t) \longrightarrow p'\ (t\ N,\ x\ N))$

lemma $[simp]$: $inv\text{-}top\ (Suc\ N)\ (prec\text{-}pre\text{-}sts\text{-}bound\ init\ p\ r\ N)$

lemma $[simp]$: $inv\text{-}top\ N\ (\lambda x.\ \exists y.\ reach\ init'\ r'\ N\ x\ y\ t)$

lemma $[simp]$: $inv\text{-}top\ N\ (\lambda x\ s.\ \exists y.\ reach\ init\ r\ N\ x\ y\ s)$

lemma $sts\text{-}refinement\text{-}A\text{-}bounded$: $(\forall\ \ x\ y\ .\ (prec\text{-}pre\text{-}sts\ init\ p\ r\ x \wedge reach\ init'\ r'\ N\ x\ y\ t) \longrightarrow p'\ (t\ N,\ x\ N))$
$= (\forall\ \ xN\ .\ (\exists\ \ x\ .\ prec\text{-}pre\text{-}sts\text{-}bound\ init\ p\ r\ N\ (x(N := xN))$
$\wedge\ (\exists\ \ xz\ .\ xz\ 0 = xN \wedge (\forall\ \ s\ y\ .\ reach\ init\ r\ N\ x\ y\ s \longrightarrow\ \ prec\text{-}pre\text{-}sts\ (\lambda\ u\ .\ u = s\ N)\ p\ r\ xz))$
$\wedge\ (\exists\ \ y\ .\ reach\ init'\ r'\ N\ x\ y\ t))$
$\longrightarrow p'\ (t\ N,\ xN))$

lemma $reach\text{-}until$: $(\exists\ \ x\ s\ y\ n.\ reach\ init\ r\ n\ x\ y\ s \wedge s\ n = t)$
$= (\exists\ \ sa\ .\ init\ (sa\ 0) \wedge ((\lambda\ sa\ .\ (\exists\ \ x\ y\ .\ r\ (sa\ 0,\ x)\ (sa\ (Suc\ 0),\ y)))\ until\ (\lambda\ sa\ .\ sa\ 0 = t))\ sa)$

lemma *LocalSystem-prec-top*: *LocalSystem init* $\top$ *r* = [: *rel-pre-sts init r*:]

lemma *LocalSystem-input-complete*: (*LocalSystem init p r* = [:*rel-pre-sts init r*:])
= ((∀ *x s* . *init s* ⟶ *p* (*s*,*x*)) ∧
(∀ *s s' x x' y n* .
(∃ *x y* . *reach init r n x y s*) ∧ *p* (*s n*, *x*) ∧ *r* (*s n*,*x*) (*s'*, *y*) ⟶ *p* (*s'*, *x'*)))

end

4.9 Reactive Feedback

theory *ReactiveFeedback*
imports *TransitionFeedback IterateOperators*

begin

definition *Feedback S* = {:*x* ⇝ (*u*, *y*), *x'* . (*x* = *x'*):} *o* *IterateOmegaA* ([−λ ((*u*, *y*), *x*) . ((*u*, *x*), *x*)−] *o* (*S* ∗∗ *Skip*)) *o* [−λ ((*u*,*y*), *x*) . *y* −]

lemma *Feedback-refin*: *S* ≤ *T* ⟹ *Feedback S* ≤ *Feedback T*

definition *FeedbackX Init S* = [:*x* ⇝ (*u*, *y*), *x'* . (*u* = ()) ∧ (*x* = *x'*):] *o* ((*Init* ∗∗ *Skip*) ∗∗ *Skip*) *o* *IterateOmega* ([−λ ((*u*, *y*), *x*) . ((*u*, *x*), *x*)−] *o* (*S* ∗∗ *Skip*)) *o* [−λ ((*u*,*y*), *x*) . *y* −]

definition *FeedbackA Init S* = [:*x* ⇝ (*x''*, *y*), *x'* . (*x''* = *x*) ∧ (*x* = *x'*):] *o* ((*Init* ∗∗ *Skip*) ∗∗ *Skip*) *o* *IterateOmegaA* ([−λ ((*u*, *y*), *x*) . ((*u*, *x*), *x*)−] *o* (*S* ∗∗ *Skip*)) *o* [−λ ((*u*,*y*), *x*) . *y* −]

lemma *feedback-update-simp-e*: *feedback* ([− λ (*u*, *s*, *x*) . (*f s x*, *g u s x*, *h u s x*) −])
= [−λ (*s*, *x*) . (*g* (*f s x*) *s x*, *h* (*f s x*) *s x*)−]

definition *InitDF init* = [: *s* ⇝ *s'*. (□(λ*s*. *init* (*s* (*0*::*nat*)))) *s'* :]

definition *Add* = [− λ(*x*,*y*). *x*+*y*−]
definition *UD* = [−λ(*x*,*s*). (*s*,*x*) −]
definition *Split* = [−λ*x*. (*x*,*x*)−]

definition *RT1* = [− λ(*u*, (*s*,*x*)). ((*u*,*x*),*s*)−]
definition *RT2* = [− λ((*v*,*y*),*s*). (*v*, (*s*,*y*)) −]
definition *RT3* = [− λ(*x*,*s*). (*s*,*x*)−]

definition *Res* = [−λ*x*. *Summ x*−]

definition *init-ExFb* = (λ *u* . *u* = (*0*::*nat*))
definition *ExFb* = *RT1 o* (*Add* ∗∗ *Skip*) *o UD o* (*Split* ∗∗ *Skip*) *o RT2*

lemma *ExFb-simp* : *ExFb* = [− λ(*u*, (*s*,*x*)). (*s*, (*u*+*x*,*s*))−]

definition *ExFb-transfb* = *feedback ExFb*

lemma *ExFb-transfb-simp*: *ExFb-transfb* = [− λ(*s*,*x*). (*s*+*x*,*s*)−]

definition *ExFb-genfb* = *DelayFeedback init-ExFb ExFb-transfb*

lemma *DelayFeedback-example*: *ExFb-genfb* = *Res*

definition *RT4* = $[-\ \lambda(s,\ (u,\ x)).\ (u,\ (s,\ x))\ -]$
definition *RT5* = $[-\ \lambda(v,\ (s,\ y)).\ (s,\ (v,\ y))\ -]$

definition *Res-aux* = $[-\lambda(u,\ x).\ ((\lambda i.\ \mathit{if}\ i = 0\ \mathit{then}\ 0\ \mathit{else}\ u\ (i-1) + x\ (i-1)),(\lambda i.\ \mathit{if}\ i = 0\ \mathit{then}\ 0\ \mathit{else}\ u\ (i-1) + x\ (i-1)))-]$

definition *ExFb-delayfb-aux* = *RT4 o ExFb o RT5*

lemma *ExFb-delayfb-aux-simp*: *ExFb-delayfb-aux* = $[-\lambda(s,\ (u,\ x)).\ (u+x,\ (s,\ s))-]$

definition *ExFb-delayfb* = $[-\lambda(u,x).\ \mathit{nzip}\ u\ x-]$ *o* (*DelayFeedback* ($\lambda\ u\ .\ u = (0{::}nat)$) *ExFb-delayfb-aux*) *o* $[-\lambda x.\ (\mathit{fst}\ o\ x,\ \mathit{snd}\ o\ x)-]$

lemma *aaa-ind*: $\forall x.\ (x = 0 \longrightarrow aa\ 0 = 0) \wedge (0 < x \longrightarrow aa\ x = a\ (x - Suc\ 0) + b\ (x - Suc\ 0)) \Longrightarrow$
$\forall x.\ (x = 0 \longrightarrow ba\ 0 = 0) \wedge (0 < x \longrightarrow ba\ x = a\ (x - Suc\ 0) + b\ (x - Suc\ 0)) \Longrightarrow (aa\ x = ba\ x)$

lemma *ExFb-delayfb-simp*: *ExFb-delayfb* = *Res-aux*

definition *Init-ExFb* = *InitDF init-ExFb*

lemma *Res-aux-simp*: $[-\lambda((u,\ y),\ x).\ ((u,\ x),\ x)-] \circ$ *Res-aux* $**$ *Skip* = $[-\ \lambda((u,\ y),\ x).\ (((\lambda i.\ \mathit{if}\ i = 0\ \mathit{then}\ 0\ \mathit{else}\ u\ (i-1) + x\ (i-1)),(\lambda i.\ \mathit{if}\ i = 0\ \mathit{then}\ 0\ \mathit{else}\ u\ (i-1) + x\ (i-1))),\ x)\ -]$

definition *Res-aux-fun* = $(\lambda((u{::}nat\Rightarrow nat,\ y{::}nat\Rightarrow nat),\ x{::}nat\Rightarrow nat).\ (((\lambda(i{::}nat).\ \mathit{if}\ i = (0{::}nat)\ \mathit{then}\ (0{::}nat)\ \mathit{else}\ u\ (i-(1{::}nat)) + x\ (i-(1{::}nat))),\ (\lambda(i{::}nat).\ \mathit{if}\ i = (0{::}nat)\ \mathit{then}\ (0{::}nat)\ \mathit{else}\ u\ (i-(1{::}nat)) + x\ (i-(1{::}nat)))),\ x))$

lemma *Res-aux-fun-aux-a*: $\bigwedge\ a\ b\ c\ .\ (\mathit{Res\text{-}aux\text{-}fun}\ \hat{}\hat{}\ (n{::}nat))\ z = ((a,b),\ c)$
$\Longrightarrow (\forall\ i < n\ .\ a\ i = (\ \mathit{Summ}\ c\ (i{::}nat))\ \wedge\ b\ i = (\ \mathit{Summ}\ c\ (i{::}nat))) \wedge c = (\mathit{snd}\ z)$

lemma *Res-aux-fun-aux-b*: $(i < n \Longrightarrow\ \mathit{apply}\ (((\mathit{Res\text{-}aux\text{-}fun}\ )\hat{}\hat{}\ n)\ z)\ i = \mathit{apply}\ ((\mathit{Res\text{-}aux\text{-}fun}\ \hat{}\hat{}\ (\mathit{Suc}\ i))\ z)\ i)$

lemma *Res-aux-fun-aux-c*: $(\lambda x.\ \mathit{let}\ z = \lambda i.\ \mathit{apply}\ (\mathit{Res\text{-}aux\text{-}fun}\ ((\mathit{Res\text{-}aux\text{-}fun}\ \hat{}\hat{}\ i)\ x))\ i\ \mathit{in}\ ((\mathit{fst} \circ \mathit{fst} \circ z,\ \mathit{snd} \circ \mathit{fst} \circ z),\ \mathit{snd} \circ z))$
$= (\lambda\ x\ .\ ((\mathit{Summ}\ (\mathit{snd}\ x),\ \mathit{Summ}\ (\mathit{snd}\ x)),\ \mathit{snd}\ x)\ )$

definition *Init-adder3* $= [- \lambda x.\ (\lambda\ (i::nat).\ (2::nat))-]$
definition *S-adder3* $= [- \lambda\ (x,\ (x'::nat \Rightarrow unit))\ .\ x-]\ o\ [- \lambda x\ .\ (\lambda\ (i::nat).\ (x\ i) + 1)-]\ o\ [- \lambda x\ .\ (\lambda\ (i::nat).\ if\ i = 0\ then\ (0::nat)\ else\ x\ (i-1))\ -]\ o$
$[- \lambda x.\ (\lambda\ (i::nat)\ .\ x\ i + 2)\ -]\ o\ [- \lambda x.\ (x,\ x)\ -]$
definition *Res-adder3* $= [- \lambda x\ .\ (\lambda\ (i::nat)\ .\ 3 * i + 2)\ -]$

definition *S-simp-adder3* $= [- \lambda\ (x,\ (x'::nat \Rightarrow unit)).\ ((\lambda i.\ if\ i = 0\ then\ 2\ else\ x(i-1) + 3),\ (\lambda i.\ if\ i = 0\ then\ 2\ else\ x(i-1) + 3))-]$

lemma *S-adder3-simp*: *S-adder3* = *S-simp-adder3*

lemma *Adder3-inner-simp*: $[-\lambda((u,\ y),\ x).\ ((u,\ x),\ x)-] \circ$ *S-simp-adder3* $**$ *Skip* $=\ [- \lambda((u,\ y),\ x).\ (((\lambda i.\ if\ i = 0\ then\ 2\ else\ u(i-1) + 3),\ (\lambda i.\ if\ i = 0\ then\ 2\ else\ u(i-1) + 3)),\ x)\ -]$

definition *Adder3-iter-fun* $=\ (\lambda((u::nat \Rightarrow nat,\ y::nat \Rightarrow nat),\ x::nat \Rightarrow unit).\ ((\lambda i::nat.\ if\ i = (0::nat)\ then\ 2::nat\ else\ u\ (i - (1::nat)) + (3::nat),\ \lambda i::nat.\ if\ i = (0::nat)\ then\ 2::nat\ else\ u\ (i - (1::nat)) + (3::nat)),\ x))$

lemma *Adder3-iter-aux-a*: $\bigwedge\ a\ b\ c\ .\ (Adder3\text{-}iter\text{-}fun\ \hat{}\hat{}\ (n::nat))\ z = ((a,b),\ c) \Longrightarrow (\forall\ \ i < n\ .\ a\ i = 3 * i + 2 \wedge b\ i = 3 * i + 2) \wedge c = (snd\ z)$

lemma *Adder3-iter-aux-b*[*simp*]: $i < n \Longrightarrow apply\ ((Adder3\text{-}iter\text{-}fun\ \hat{}\hat{}\ n)\ z)\ i = apply\ ((Adder3\text{-}iter\text{-}fun\ \hat{}\hat{}\ Suc\ i)\ z)\ i$

lemma *Adder3-iter-aux-c*: $(\lambda x.\ let\ z = \lambda i.\ apply\ (Adder3\text{-}iter\text{-}fun\ ((Adder3\text{-}iter\text{-}fun\ \hat{}\hat{}\ i)\ x))\ i\ in\ ((fst \circ fst \circ z,\ snd \circ fst \circ z),\ snd \circ z)) = (\lambda\ x\ .\ (((\lambda\ i\ .\ 3 * i + 2),\ (\lambda\ i\ .\ 3 * i + 2)),\ snd\ x)\ )$

lemma *FeedbackX Init-adder3 S-adder3* = *Res-adder3*

definition *Init-sum* $= [-\lambda x.\ (\lambda\ (i::nat).\ (0::nat))-]$
definition *S-sum* $= [-\lambda(x,\ x').\ (\lambda i.\ x\ i + x'\ i)\ -]\ o\ [- \lambda x\ .\ (\lambda\ (i::nat).\ if\ i = 0\ then\ (0::nat)\ else\ x\ (i-1))\ -]\ o\ [- \lambda x.\ (x,\ x)\ -]$
definition *Res-sum* $= [-\lambda x.\ Summ\ x-]$

definition *S-simp-sum* $= [-\lambda(x,\ x').\ ((\lambda i.\ if\ i = 0\ then\ 0\ else\ x\ (i-1) + x'\ (i-1)),(\lambda i.\ if\ i = 0\ then\ 0\ else\ x\ (i-1) + x'\ (i-1)))\ -]$

lemma *S-sum-simp*: *S-sum* = *S-simp-sum*

lemma *Sum-inner-simp*: $[-\lambda((u,\ y),\ x).\ ((u,\ x),\ x)-] \circ$ *S-simp-sum* $**$ *Skip* $=\ [- \lambda((u,\ y),\ x).\ (((\lambda i.\ if\ i = 0\ then\ 0\ else\ u\ (i-1) + x\ (i-1)),(\lambda i.\ if\ i = 0\ then\ 0\ else\ u\ (i-1) + x\ (i-1))),\ x)\ -]$

definition *Sum-iter-fun* $=\ (\lambda((u::nat\Rightarrow nat,\ y::nat\Rightarrow nat),\ x::nat\Rightarrow nat).\ (((\lambda(i::nat).\ if\ i = (0::nat)\ then\ (0::nat)\ else\ u\ (i-(1::nat)) + x\ (i-(1::nat))),\ (\lambda(i::nat).\ if\ i = (0::nat)\ then\ (0::nat)\ else\ u\ (i-(1::nat)) + x\ (i-(1::nat)))),\ x))$

lemma *Sum-iter-aux-a*: $\bigwedge$ *a b c* . (*Sum-iter-fun* ^^ (*n::nat*)) *z* = ((*a*,*b*), *c*) $\Longrightarrow$ ($\forall$ *i* < *n* . *a i* = (*Summ c* (*i::nat*)) $\wedge$ *b i* = (*Summ c* (*i::nat*))) $\wedge$ *c* = (*snd z*)

lemma *Sum-iter-aux-b*: (*i* < *n* $\Longrightarrow$ *apply* (((*Sum-iter-fun*) ^^ *n*) *z*) *i* = *apply* ((*Sum-iter-fun* ^^ (*Suc i*)) *z*) *i*)

lemma *Sum-iter-aux-c*: (λ*x*. *let z* = λ*i*. *apply* (*Sum-iter-fun* ((*Sum-iter-fun* ^^ *i*) *x*)) *i in* ((*fst* $\circ$ *fst* $\circ$ *z*, *snd* $\circ$ *fst* $\circ$ *z*), *snd* $\circ$ *z*))
= (λ *x* . ((*Summ* (*snd x*), *Summ* (*snd x*)), *snd x*))

lemma *FeedbackX Init-sum S-sum* = *Res-sum*

definition *Init-adder3-wp* = [− λ*x*. (λ (*i::nat*). (*2::nat*))−]
definition *S-adder3-wp* = [− λ (*x*, (*x′::nat* $\Rightarrow$ *unit*)) . *x*−] *o* {.$\Box$ (λ*x*. *x 0* $\neq$ *0*).} *o* [− λ*x* . (λ (*i::nat*). (*x i*) + *1*)−] *o* [− λ*x* . (λ (*i::nat*). *if i* = *0 then* (*0::nat*) *else x* (*i*−*1*)) −] *o*
[− λ*x*. (λ (*i::nat*) . *x i* + *2*) −] *o* [− λ*x*. (*x*, *x*) −]
definition *Res-adder3-wp* = {. *x*. *True*.} *o* [− λ*x* . (λ (*i::nat*) . *3* $*$ *i* + *2*) −]

definition *S-simp-adder3-wp* = {. $\Box$ (λ (*x*, (*x′::nat* $\Rightarrow$ *unit*)). *x 0* $\neq$ *0*) .} *o*[− λ (*x*, (*x′::nat* $\Rightarrow$ *unit*)). ((λ*i*. *if i* = *0 then 2 else x*(*i*−*1*) + *3*), (λ*i*. *if i* = *0 then 2 else x*(*i*−*1*) + *3*))−]

lemma *S-adder3-wp-simp*: *S-adder3-wp* = *S-simp-adder3-wp*

lemma *Adder3-wp-inner-simp*: [−λ((*u*, *y*), *x*). ((*u*, *x*), *x*)−] $\circ$ *S-simp-adder3-wp* $**$ *Skip* = {. $\Box$ (λ ((*u*, *y*), *x*). *u 0* $\neq$ *0*).} *o* [−λ((*u*, *y*), *x*). (((λ*i*. *if i* = *0 then 2 else u*(*i*−*1*) + *3*), (λ*i*. *if i* = *0 then 2 else u*(*i*−*1*) + *3*)), *x*)−]

definition *Adder3-iter-wp-fun* = (λ((*u::nat* $\Rightarrow$ *nat*, *y::nat* $\Rightarrow$ *nat*), *x::nat* $\Rightarrow$ *unit*). ((λ*i::nat*. *if i* = (*0::nat*) *then 2::nat else u* (*i* − (*1::nat*)) + (*3::nat*), λ*i::nat*. *if i* = (*0::nat*) *then 2::nat else u* (*i* − (*1::nat*)) + (*3::nat*)), *x*))
definition *Adder3-iter-wp-prec* = ($\Box$ (λ ((*u*, *y*), *x*). *u 0* $\neq$ *0*))

lemma *Adder3-iter-wp-aux-a*: $\bigwedge$ *a b c* . (*Adder3-iter-wp-fun* ^^ (*n::nat*)) *z* = ((*a*,*b*), *c*) $\Longrightarrow$ ($\forall$ *i* < *n* . *a i* = *3* $*$ *i* + *2* $\wedge$ *b i* = *3* $*$ *i* + *2*) $\wedge$ *c* = (*snd z*)

lemma *Adder3-iter-wp-aux-b*: *i* < *n* $\Longrightarrow$ *apply* ((*Adder3-iter-wp-fun* ^^ *n*) *z*) *i* = *apply* ((*Adder3-iter-wp-fun* ^^ *Suc i*) *z*) *i*

lemma *Adder3-iter-wp-aux-c*: (λ*x*. *let z* = λ*i*. *apply* (*Adder3-iter-wp-fun* ((*Adder3-iter-wp-fun* ^^ *i*) *x*)) *i in* ((*fst* $\circ$ *fst* $\circ$ *z*, *snd* $\circ$ *fst* $\circ$ *z*), *snd* $\circ$ *z*)) = (λ *x* . (((λ *i* . *3* $*$ *i* + *2*), (λ *i* . *3* $*$ *i* + *2*)), *snd x*))

lemma *Adder3-iter-wp-aux-d*: $\bigwedge$ *i* . *i* $\geq$ *n* $\Longrightarrow$ *fst* (*fst* ((*Adder3-iter-wp-fun* ^^ *n*) ((λ*i*. *2*, *b*), *ba*))) *i* = *3* $*$ *n* + *2*

lemma *Adder3-iter-wp-aux-e*: $\bigwedge$ *i*. *i* < *n* $\Longrightarrow$ *fst* (*fst* ((*Adder3-iter-wp-fun* ^^ *n*) ((λ*i*. *2*, *b*), *ba*))) *i*

$= \ 3 * i + 2$

lemma *Adder3-iter-wp-prec-aux*: $0 < fst\ (fst\ ((Adder3\text{-}iter\text{-}wp\text{-}fun\ \hat{}\hat{}\ n)\ ((\lambda i.\ 2,\ b),\ ba)))\ i$

lemma *Adder3-iter-wp-prec*: $(\Box\ (\lambda((u,\ y),\ x).\ 0 < u\ 0))\ ((Adder3\text{-}iter\text{-}wp\text{-}fun\ \hat{}\hat{}\ n)\ ((\lambda i.\ 2,\ b),\ ba))$

lemma *FeedbackX Init-adder3-wp S-adder3-wp* = *Res-adder3-wp*

definition *Init-adder3-havoc* = $[-\lambda x.\ (\lambda i.\ 0)-]$
definition *Res-adder3-havoc* = $\bot$

lemma [*simp*]: $(\lambda x.\ \forall\, b\ ba\ n.\ (\Box\ (\lambda((u,\ y),\ x).\ 0 < u\ 0))\ ((Adder3\text{-}iter\text{-}wp\text{-}fun\ \hat{}\hat{}\ n)\ ((\lambda i.\ 0,\ b),\ ba)))$
$= \bot$

lemma [*simp*]: $\{.\lambda x.\ False.\}\ o\ [:r:] = \bot$

lemma *FeedbackX Init-adder3-havoc S-adder3-wp* = *Res-adder3-havoc*

lemma *Feedback-ExFb*: *FeedbackX Init-ExFb ExFb-delayfb* = *Res*

lemma *feedback-in-simp-aaa*: $p \le inpt\ r \Longrightarrow p' \le inpt\ r' \Longrightarrow$
$feedback\ (\ \{.\ u,\ (s,x)\ .\ \ p'\ (s,x) \wedge p\ (u,\ (s,x)).\}\ o\ [:u,\ (s,x) \leadsto v,\ (s',y)\ .\ \ r'\ (s,x)\ v \wedge r\ (u,\ (s,x))\ (s',y):])$
$= \{.\ (s,x)\ .\ p'\ (s,x) \wedge (\forall\, b.\ r'\ (s,x)\ b \longrightarrow p\ (b,(s,x))).\}\ o\ [:(s,x) \leadsto (s',y)\ .\ \exists\ v\ .\ r'\ (s,x)\ v \wedge r\ (v,\ (s,x))\ (s',y):]$

lemma *IterateOmega-spec-a*: $IterateOmega\ (\{.\ p\ .\} \circ [:\ r\ :]) = \{.((u,y),x)\ .\forall\, n\ v\ y'\ z.\ (r\ \hat{}\hat{}\ n)\ ((u,y),\ x)\ ((v,\ y'),\ z) \longrightarrow p\ ((v,y'),z).\} \circ [:\ INF\ n.\ r\ \hat{}\hat{}\ n\ OO\ eqtop\ n\ :]$

lemma *AAA*: $\bigwedge u'\ y'\ .\ (((\lambda((u::'a,\ y::'b),\ x)\ ((u'::'a,\ y'::'b),\ x').\ r\ (u,\ x)\ (u',\ y') \wedge x = x')\ \hat{}\hat{}\ n)\ ((u,y::'b),\ x)\ ((u',\ y'::'b),\ x')) \Longrightarrow x = x'$

lemma *BBB*: $\bigwedge u'\ y'\ .\ (((\lambda((u::'a,\ y::'b),\ x)\ ((u'::'a,\ y'::'b),\ x').\ r\ (u,\ x)\ (u',\ y') \wedge x = x')\ \hat{}\hat{}\ n)\ ((u,y::'b),\ x)\ ((u',\ y'::'b),\ x')) =$
$(x = x' \wedge (((\lambda\ (u::'a,\ y::'b)\ (u'::'a,\ y'::'b)\ .\ r\ (u,\ x)\ (u',\ y'))\ \hat{}\hat{}\ n)\ (u,y::'b)\ (u',\ y'::'b)))$

lemma *CCC*: $(((\lambda((u::'a,\ y),\ x)\ ((u'::'a,\ y'),\ x').\ r\ (u,\ x)\ (u',\ y') \wedge x = x')\ \hat{}\hat{}\ n)\ ((u,y::'b),\ x)\ ((u',\ y'::'b),\ x')) =$
$(x = x' \wedge (\exists\ U\ Y\ .\ U\ 0 = u \wedge U\ n = u' \wedge Y\ 0 = y \wedge Y\ n = y' \wedge (\forall\ i < n\ .\ r\ (U\ i,\ x)\ (U\ (Suc\ i),\ Y\ (Suc\ i)))))$

lemma *IterateOmegaA-simp-a*: $IterateOmegaA\ ([-\lambda\ ((u,\ y::nat \Rightarrow 'a),\ x)\ .\ ((u,\ x),\ x)-]\ o\ ((\{.p.\}\ o\ [:r:])\ **\ Skip)) =$
$\{.((ua,\ ya),\ xa).\forall\, n\ a.\ (\exists\, b\ U.\ U\ 0 = ua \wedge U\ n = a \wedge (\exists\, Y.\ Y\ 0 = ya \wedge Y\ n = b \wedge (\forall\, i{<}n.\ r\ (U\ i,\ xa)\ (U\ (Suc\ i),\ Y\ (Suc\ i)))))) \longrightarrow p\ (a,\ xa).\} \circ$
$[:\ INF\ n.\ (\lambda((u,\ y),\ x)\ ((u',\ y'),\ x').\ r\ (u,\ x)\ (u',\ y') \wedge x = x')\ \hat{}\hat{}\ n\ OO\ eqtop\ (n-1)\ :]$

lemma *IterateOmegaA-simp-b*: *IterateOmegaA* $([-\lambda\ ((u,\ y::nat \Rightarrow 'a),\ x)\ .\ ((u,\ x),\ x)-]\ o\ ((\{.p.\}\ o\ [:r:])\ **\ Skip)) =$
$\{.((ua,\ ya),\ xa).\forall n\ U\ Y\ .\ (U\ 0 = ua \wedge Y\ 0 = ya \wedge (\forall i<n.\ r\ (U\ i,\ xa)\ (U\ (Suc\ i),\ Y\ (Suc\ i)))) \longrightarrow p\ (U\ n,\ xa).\} \circ$
$[:\ INF\ n.\ (\lambda((u,\ y),\ x)\ ((u',\ y'),\ x').\ r\ (u,\ x)\ (u',\ y') \wedge x = x')\ \hat{}\hat{}\ n\ OO\ eqtop\ (n-1)\ :]$

lemma *IterateOmegaA-simp-aux*: $(INF\ n.\ (\lambda((u,\ y),\ x)\ ((u',\ y'),\ x').\ r\ (u,\ x)\ (u',\ y') \wedge x = x')\ \hat{}\hat{}\ n\ OO\ eqtop\ (n-1))\ ((u::nat\Rightarrow 'a,y::nat\Rightarrow 'b),\ x::nat\Rightarrow 'c)\ \ ((u'::nat\Rightarrow 'a,y'::nat\Rightarrow 'b),\ x'::nat\Rightarrow 'c) =$
$(x = x' \wedge (\forall xa.\ \exists a\ b.\ (\exists U.\ U\ 0 = u \wedge U\ xa = a \wedge (\exists Y.\ Y\ 0 = y \wedge Y\ xa = b \wedge (\forall i<xa.\ r\ (U\ i,\ x)\ (U\ (Suc\ i),\ Y\ (Suc\ i)))))) \wedge (\forall i<xa-1.\ a\ i = u'\ i) \wedge (\forall i<xa-1.\ b\ i = y'\ i)))$

lemma *IterateOmegaA-simp-c*: *IterateOmegaA* $([-\lambda\ ((u::nat \Rightarrow 'a,\ y::nat \Rightarrow 'b),\ x::nat\Rightarrow 'c)\ .\ ((u,\ x),\ x)-]\ o\ ((\{.p.\}\ o\ [:r:])\ **\ Skip)) =$
$\{.((ua,\ ya),\ xa).\forall n\ U\ Y\ .\ (U\ 0 = ua \wedge Y\ 0 = ya \wedge (\forall i<n.\ r\ (U\ i,\ xa)\ (U\ (Suc\ i),\ Y\ (Suc\ i)))) \longrightarrow p\ (U\ n,\ xa).\} \circ$
$[:\ (u,\ y),\ x \rightsquigarrow (u'::nat\Rightarrow 'a,\ y'::nat\Rightarrow 'b),\ x'::nat\Rightarrow 'c\ .\ x = x'$
$\wedge (\forall xa.\ \exists a\ b.\ (\exists U.\ U\ 0 = u \wedge U\ xa = a \wedge (\exists Y.\ Y\ 0 = y \wedge Y\ xa = b \wedge (\forall i<xa.\ r\ (U\ i,\ x)\ (U\ (Suc\ i),\ Y\ (Suc\ i)))))) \wedge (\forall i<xa-1.\ a\ i = u'\ i) \wedge (\forall i<xa-1.\ b\ i = y'\ i))\ :]$

lemma *IterateOmegaA-simp-d*: *IterateOmegaA* $([-\lambda\ ((u::nat \Rightarrow 'a,\ y::nat \Rightarrow 'b),\ x::nat\Rightarrow 'c)\ .\ ((u,\ x),\ x)-]\ o\ ((\{.p.\}\ o\ [:r:])\ **\ Skip)) =$
$\{.((ua,\ ya),\ xa).\forall n\ U\ Y\ .\ (U\ 0 = ua \wedge Y\ 0 = ya \wedge (\forall i<n.\ r\ (U\ i,\ xa)\ (U\ (Suc\ i),\ Y\ (Suc\ i)))) \longrightarrow p\ (U\ n,\ xa).\} \circ$
$[:\ (u,\ y),\ x \rightsquigarrow (u'::nat\Rightarrow 'a,\ y'::nat\Rightarrow 'b),\ x'::nat\Rightarrow 'c\ .\ x = x'$
$\wedge (\forall xa.\ (\exists U.\ U\ 0 = u \wedge (\exists Y.\ Y\ 0 = y \wedge (\forall i<xa.\ r\ (U\ i,\ x)\ (U\ (Suc\ i),\ Y\ (Suc\ i))) \wedge (\forall i<xa-1.\ U\ xa\ i = u'\ i) \wedge (\forall i<xa-1.\ Y\ xa\ i = y'\ i))))\ :]$

lemma *DelayFeedback-feedback-simp*: *DelayFeedback init* $(feedback\ (\{.(u,\ s,\ x).\ \ p\ u\ s\ x.\} \circ [-\lambda(u,\ s,\ x).\ (f\ s\ x,\ g\ u\ s\ x,\ h\ u\ s\ x)-])) =$
$\{.prec\text{-}pre\text{-}sts\ init\ (\lambda(s,\ x)\ .\ p\ (f\ s\ x)\ s\ x)\ (\lambda(s,\ x)\ y\ .\ y = (g\ (f\ s\ x)\ s\ x,\ h\ (f\ s\ x)\ s\ x)).\} \circ$
$[:rel\text{-}pre\text{-}sts\ init\ (\lambda(s,\ x)\ y.\ y = (g\ (f\ s\ x)\ s\ x,\ h\ (f\ s\ x)\ s\ x)):]$

lemma *input-output-switch*: $([-\lambda(s,\ u,\ x).\ (u,\ s,\ x)-] \circ (\{.\ p\ .\} \circ [-\lambda(u,\ s,\ x).\ (f\ s\ x,\ g\ u\ s\ x,\ h\ u\ s\ x)-]) \circ [-\lambda(v,\ s,\ y).\ (s,\ v,\ y)-]) =$
$\{.\ (s,u,x).\ p\ (u,\ s,\ x)\ .\}\ o\ [-\ \lambda(s,\ u,\ x).(g\ u\ s\ x,\ f\ s\ x,\ h\ u\ s\ x)\ -]$

primrec *ss* :: $'a \Rightarrow ('b \Rightarrow 'a \Rightarrow 'c \Rightarrow 'a) \Rightarrow ('a \Rightarrow 'c \Rightarrow 'b) \Rightarrow (nat \Rightarrow 'c) \Rightarrow nat \Rightarrow 'a$ **where**
$ss\ a\ g\ f\ xa\ 0 = a\ |$
$ss\ a\ g\ f\ xa\ (Suc\ i) = g\ (f\ \ (ss\ a\ g\ f\ xa\ i)\ (xa\ i))\ (ss\ a\ g\ f\ xa\ i)\ (xa\ i)$

primrec *ssu* :: $'a \Rightarrow ('b \Rightarrow 'a \Rightarrow 'c \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'b) \Rightarrow (nat \Rightarrow 'c) \Rightarrow nat \Rightarrow 'a$ **where**
$ssu\ a\ g\ u\ x\ 0 = a\ |$
$ssu\ a\ g\ u\ x\ (Suc\ i) = g\ (u\ i)\ (ssu\ a\ g\ u\ x\ i)\ (x\ i)$

lemma *BBBd*: $a = sa\ 0 \Longrightarrow \forall fb<fa.\ sa\ (Suc\ fb) = g\ (u\ fb)\ (sa\ fb)\ (x\ fb)\ \Longrightarrow i \le fa \Longrightarrow ssu\ a\ g\ u\ x\ i = sa\ i$

definition *prec-pre-sts-st init p r u x* $= (\forall\ \ y\ .\ init\ (u\ 0) \longrightarrow (lift\text{-}rel\ r\ leads\ lift\text{-}pre\ p)\ (u,\ x)\ (u[1..],\ y))$

lemma *prec-pre-sts-st-simp*: *prec-pre-sts-st init p r u x* $=$
$(\forall\ y\ .\ init\ (u\ 0) \longrightarrow (\forall n\ .\ (\forall\ i < n\ .\ r\ (u\ i,\ x\ i)\ (u\ (Suc\ i),\ y\ i)) \longrightarrow p\ (u\ n,\ x\ n)))$

lemma *BBBc*: $s = ssu\ a\ g\ u\ x \Longrightarrow prec\text{-}pre\text{-}sts\ (\lambda\ s\ .\ s = a)\ (\lambda(s,\ u,\ x).\ p\ (u,\ s,\ x))\ (\lambda(s,\ u,\ x)\ y.\ y = (g\ u\ s\ x,\ f\ s\ x,\ h\ u\ s\ x))\ (\lambda i.\ (u\ i,\ x\ i)) =$
$((\forall\ fa.\ (\forall\ fb{<}fa.\ s\ (Suc\ fb) = g\ (u\ fb)\ (s\ fb)\ (x\ fb)) \longrightarrow p\ (u\ fa,\ s\ fa,\ x\ fa)))$

lemma *BBBx*: $s = ssu\ a\ g\ u\ x \Longrightarrow prec\text{-}pre\text{-}sts\ (\lambda\ s\ .\ s = a)\ (\lambda(s,\ u,\ x).\ p\ (u,\ s,\ x))\ (\lambda(s,\ u,\ x)\ y.\ y = (g\ u\ s\ x,\ f\ s\ x,\ h\ u\ s\ x))\ (\lambda i.\ (u\ i,\ x\ i)) =$
$((\forall\ fa.\ p\ (u\ fa,\ s\ fa,\ x\ fa)))$

lemma *BBBy*: $(prec\text{-}pre\text{-}sts\ (\lambda\ s\ .\ s = a)\ (\lambda(s,\ u,\ x).\ p\ (u,\ s,\ x))\ (\lambda(s,\ u,\ x)\ y.\ y = (g\ u\ s\ x,\ f\ s\ x,\ h\ u\ s\ x))\ (\lambda i.\ (u\ i,\ x\ i))) =$
$((\forall\ fa.\ p\ (u\ fa,\ \ ssu\ a\ g\ u\ x\ fa,\ x\ fa)))$

lemmas *BBBu* $=$ *BBBd* $[of\ \text{-}\ \text{-}\ \text{-}\ \text{-}\ (\lambda\ i\ .\ f\ (s\ i)\ (x\ i))\ ]$

lemma *BBBe*: $a = sa\ 0 \Longrightarrow \forall fb{<}fa.\ sa\ (Suc\ fb) = g\ (f\ (sa\ fb)\ (x\ fb))\ (sa\ fb)\ (x\ fb) \Longrightarrow i \le fa \Longrightarrow ss\ a\ g\ f\ x\ i = sa\ i$

lemma *BBBz*: $(prec\text{-}pre\text{-}sts\ (\lambda\ s\ .\ s = a)\ (\lambda(s,\ x).\ p\ (f\ s\ x,\ s,\ x))\ (\lambda(s,\ x)\ y.\ y = (g\ (f\ s\ x)\ s\ x,\ h\ (f\ s\ x)\ s\ x))\ x)$
$= ((\forall\ fa.\ p\ (f\ (\ ss\ a\ g\ f\ x\ fa)\ (x\ fa),\ \ ss\ a\ g\ f\ x\ fa,\ x\ fa)))$

primrec *ssc* :: $'c \Rightarrow (nat \Rightarrow 'a) \Rightarrow ('a \Rightarrow 'c \Rightarrow 'de \Rightarrow 'c)\ \Rightarrow (nat \Rightarrow 'de) \Rightarrow nat \Rightarrow nat \Rightarrow 'c$ **where**
$ssc\ a\ U\ g\ xa\ i\ 0 = a\ |$
$ssc\ a\ U\ g\ xa\ i\ (Suc\ fa) =\ \ g\ (U\ fa)\ (ssc\ a\ U\ g\ xa\ i\ fa)\ (xa\ fa)$

primrec *UUc* :: $(nat \Rightarrow 'a) \Rightarrow 'b \Rightarrow ('b \Rightarrow 'c \Rightarrow 'a) \Rightarrow ('a \Rightarrow 'b \Rightarrow 'c \Rightarrow 'b) \Rightarrow (nat \Rightarrow 'c) \Rightarrow nat \Rightarrow nat \Rightarrow 'a$ **where**
$UUc\ u\ a\ f\ g\ x\ 0 = u\ |$
$UUc\ u\ a\ f\ g\ x\ (Suc\ i) = (\lambda\ xa\ .\ f\ (ssc\ a\ (UUc\ u\ a\ f\ g\ x\ i)\ g\ x\ i\ xa)\ (x\ xa))$

lemma *DDDa*: $\forall fa.\ sa\ (Suc\ fa) = g\ (U\ i\ fa)\ (sa\ fa)\ (xa\ fa) \wedge U\ (Suc\ i)\ fa = f\ (sa\ fa)\ (xa\ fa) \wedge Y\ (Suc\ i)\ fa = h\ (U\ i\ fa)\ (sa\ fa)\ (xa\ fa) \Longrightarrow$
$a = sa\ 0 \Longrightarrow sa\ k = ssc\ a\ (U\ i)\ g\ xa\ i\ k$

lemma *AAAAU*: $U\ 0 = ua \Longrightarrow aa = U\ n \Longrightarrow \forall i{<}n.\ \forall fa.\ U\ (Suc\ i)\ fa = f\ (ssc\ a\ (U\ i)\ g\ xa\ i\ fa)\ (xa\ fa) \Longrightarrow k \le n \Longrightarrow UUc\ (U\ 0)\ a\ f\ g\ xa\ k = U\ k$

lemma *AAAAAka*: $0 < n \Longrightarrow\ \ (\exists b\ U.\ (n = 0 \longrightarrow U\ 0 = ua \wedge U\ 0 = aa \wedge ya = b) \wedge$
$(0 < n \longrightarrow U\ 0 = ua \wedge U\ n = aa \wedge (\forall i{<}n.\ \forall fa.\ U\ (Suc\ i)\ fa = f\ (ssc\ a\ (U\ i)\ g\ xa\ i\ fa)\ (xa\ fa)) \wedge$
$(\forall fa.\ h\ (U\ (n - Suc\ 0)\ fa)\ (ssc\ a\ (U\ (n - Suc\ 0))\ g\ xa\ (n - Suc\ 0)\ fa)\ (xa\ fa) = b\ fa)))$
$=\ \ (UUc\ ua\ a\ f\ g\ xa\ n = aa)$

lemma *AAAAAk*: $(\exists b\ U.\ (n = 0 \longrightarrow U\ 0 = ua \wedge U\ 0 = aa \wedge ya = b) \wedge$
$(0 < n \longrightarrow U\ 0 = ua \wedge U\ n = aa \wedge (\forall i{<}n.\ \forall fa.\ U\ (Suc\ i)\ fa = f\ (ssc\ a\ (U\ i)\ g\ xa\ i\ fa)\ (xa\ fa))$
$\wedge\ (\forall fa.\ h\ (U\ (n - Suc\ 0)\ fa)\ (ssc\ a\ (U\ (n - Suc\ 0))\ g\ xa\ (n - Suc\ 0)\ fa)\ (xa\ fa) = b\ fa)))$

$= \ (UUc\ ua\ a\ f\ g\ xa\ n = aa)$

lemma *ZZZp*: $\forall xa{::}nat.\ sa\ (Suc\ xa) = g\ (U\ i\ xa)\ (sa\ xa)\ (x\ xa) \wedge U\ (Suc\ i)\ xa = f\ (sa\ xa)\ (x\ xa) \wedge Y\ (Suc\ i)\ xa = h\ (U\ i\ xa)\ (sa\ xa)\ (x\ xa) \Longrightarrow a = sa\ (0{::}nat) \Longrightarrow sa\ k = ssc\ a\ (U\ i)\ g\ x\ i\ k$

lemma *ZZZq*: $s = ssc\ a\ (U\ i)\ g\ x\ i \Longrightarrow\ (\exists s.\ s\ 0 = a \wedge (\forall xa.\ s\ (Suc\ xa) = g\ (U\ i\ xa)\ (s\ xa)\ (x\ xa) \wedge U\ (Suc\ i)\ xa = f\ (s\ xa)\ (x\ xa) \wedge Y\ (Suc\ i)\ xa = h\ (U\ i\ xa)\ (s\ xa)\ (x\ xa))) =$
$(\forall\ xa\ .\ U\ (Suc\ i)\ xa = f\ (s\ xa)\ (x\ xa) \wedge Y\ (Suc\ i)\ xa = h\ (U\ i\ xa)\ (s\ xa)\ (x\ xa))$

lemma *ZZZr*: $0 < xa \Longrightarrow (\exists Y\ .\ Y\ 0 = y \wedge Y\ xa = b \wedge (\forall i{<}xa.\ \forall xa{::}nat.\ U\ (Suc\ i)\ xa = f\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa) \wedge Y\ (Suc\ i)\ xa = h\ (U\ i\ xa)\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa)))$
$= ((\forall i{<}xa.\ \forall xa{::}nat.\ U\ (Suc\ i)\ xa = f\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa)) \wedge (\forall\ k\ .\ h\ (U\ (xa - 1)\ k)\ (ssc\ a\ (U\ (xa - 1))\ g\ x\ (xa - 1)\ k)\ (x\ k) = b\ k))$

lemma *ZZZc*: $(\exists Y\ .\ Y\ 0 = y \wedge Y\ xa = b \wedge (\forall i{<}xa.\ \forall xa{::}nat.\ U\ (Suc\ i)\ xa = f\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa) \wedge Y\ (Suc\ i)\ xa = h\ (U\ i\ xa)\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa))) =$
$(if\ xa = 0\ then\ y = b\ else\ ((\forall i{<}xa.\ \forall xa{::}nat.\ U\ (Suc\ i)\ xa = f\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa)) \wedge (\forall\ k\ .\ h\ (U\ (xa - 1)\ k)\ (ssc\ a\ (U\ (xa - 1))\ g\ x\ (xa - 1)\ k)\ (x\ k) = b\ k)))$

lemma [*simp*]: $\forall i{<}xa.\ \forall xa{::}nat.\ Ua\ (Suc\ i)\ xa = f\ (ssc\ a\ (Ua\ i)\ g\ x\ i\ xa)\ (x\ xa) \Longrightarrow UUc\ (Ua\ (0{::}nat))\ a\ f\ g\ x\ xa = Ua\ xa$

lemma *TTTb*: $U = UUc\ u\ a\ f\ g\ x \Longrightarrow (0 < xa \longrightarrow (\exists\ U\ .\ U\ 0 = u \wedge U\ xa = aa \wedge (\forall i{<}xa.\ \forall xa.\ U\ (Suc\ i)\ xa = f\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa)) \wedge$
$(\forall k.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k)))$
$= (0 < xa \longrightarrow (U\ xa = aa \wedge (\forall k.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k)))$

lemma *TTTa*: $(\exists U.\ (xa = 0 \longrightarrow U\ 0 = u \wedge U\ 0 = aa \wedge y = b) \wedge$
$(0 < xa \longrightarrow U\ 0 = u \wedge U\ xa = aa \wedge (\forall i{<}xa.\ \forall xa.\ U\ (Suc\ i)\ xa = f\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa)) \wedge (\forall k.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k)))$
$=((xa = 0 \longrightarrow u = aa \wedge y = b) \wedge$
$(0 < xa \longrightarrow (\exists\ U\ .\ U\ 0 = u \wedge U\ xa = aa \wedge (\forall i{<}xa.\ \forall xa.\ U\ (Suc\ i)\ xa = f\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa)) \wedge$
$(\forall k.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k))))$

lemma *TTTc*: $U = UUc\ u\ a\ f\ g\ x \Longrightarrow (\exists U.\ (xa = 0 \longrightarrow U\ 0 = u \wedge U\ 0 = aa \wedge y = b) \wedge$
$(0 < xa \longrightarrow U\ 0 = u \wedge U\ xa = aa \wedge (\forall i{<}xa.\ \forall xa.\ U\ (Suc\ i)\ xa = f\ (ssc\ a\ (U\ i)\ g\ x\ i\ xa)\ (x\ xa)) \wedge (\forall k.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k)))$

$=((xa = 0 \longrightarrow u = aa \wedge y = b) \wedge (0 < xa \longrightarrow\ (U\ xa = aa \wedge (\forall k.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k))))$

lemma *TTTe*: $(\exists\ b.\ ((xa = 0 \longrightarrow u = aa \wedge y = b) \wedge (0 < xa \longrightarrow\ (U\ xa = aa \wedge (\forall k.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k)))) \wedge$

$(\forall i<xa - Suc\ 0.\ aa\ i = u'\ i) \wedge (\forall i<xa - Suc\ 0.\ b\ i = y'\ i))$
$= (((xa = 0 \longrightarrow u = aa) \wedge (0 < xa \longrightarrow ((U\ xa = aa \wedge (\exists\ b\ .\ (\forall k.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k) \wedge$
$(\forall i<xa - Suc\ 0.\ aa\ i = u'\ i) \wedge (\forall i<xa - Suc\ 0.\ b\ i = y'\ i)))))))$

lemma *TTTf*: $(\exists\ b.\ ((xa = 0 \longrightarrow u = aa \wedge y = b) \wedge (0 < xa \longrightarrow (U\ xa = aa \wedge (\forall k.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k)))) \wedge$
$(\forall i<xa - Suc\ 0.\ aa\ i = u'\ i) \wedge (\forall i<xa - Suc\ 0.\ b\ i = y'\ i))$
$= (((xa = 0 \longrightarrow u = aa) \wedge (0 < xa \longrightarrow ((U\ xa = aa \wedge$
$(\forall i<xa - Suc\ 0.\ aa\ i = u'\ i) \wedge (\forall k<xa - Suc\ 0.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = y'\ k))))))$

thm *UUc.simps*

thm *ssc.simps*

primrec $SS{::}'b \Rightarrow ('a \Rightarrow 'b \Rightarrow 'c \Rightarrow 'b) \Rightarrow ('b \Rightarrow 'c \Rightarrow 'a) \Rightarrow (nat \Rightarrow 'c) \Rightarrow nat \Rightarrow 'b$ **where**
$SS\ a\ g\ f\ x\ 0 = a\ |$
$SS\ a\ g\ f\ x\ (Suc\ i) = g\ (f\ (SS\ a\ g\ f\ x\ i)\ (x\ i))\ (SS\ a\ g\ f\ x\ i)\ (x\ i)$

lemma *UU-SS*: $\bigwedge xa\ .\ i < xa \Longrightarrow UUc\ u\ a\ f\ g\ x\ xa\ i = f\ (SS\ a\ g\ f\ x\ i)\ (x\ i) \wedge ssc\ a\ (UUc\ u\ a\ f\ g\ x\ xa)\ g\ x\ xa\ i = SS\ a\ g\ f\ x\ i$

lemma *TTTza*: $(x = x' \wedge (\forall xa>0{::}nat.\ (\forall i<xa - Suc\ (0{::}nat).\ f\ (SS\ a\ g\ f\ x\ i)\ (x\ i) = u'\ i) \wedge (\forall k<xa - Suc\ (0{::}nat).\ h\ (f\ (SS\ a\ g\ f\ x\ k)\ (x\ k))\ (SS\ a\ g\ f\ x\ k)\ (x\ k) = y'\ k))) =$
$(x = x' \wedge (\forall\ k\ .\ f\ (SS\ a\ g\ f\ x\ k)\ (x\ k) = u'\ k) \wedge (\forall k\ .\ h\ (f\ (SS\ a\ g\ f\ x\ k)\ (x\ k))\ (SS\ a\ g\ f\ x\ k)\ (x\ k) = y'\ k))$

lemma *AAAAta*: $0 < n \Longrightarrow s = (\lambda\ i\ .\ ssc\ a\ (U\ i)\ g\ xa\ i) \Longrightarrow$
$(\exists\ Y.\ Y\ 0 = ya \wedge Y\ n = b \wedge (\forall i<n.\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)\ (\lambda(s,\ u,\ x)\ y.\ y = (g\ u\ s\ x,\ f\ s\ x,\ h\ u\ s\ x))\ (U\ i\ ||\ xa)\ (U\ (Suc\ i)\ ||\ Y\ (Suc\ i)))) =$
$((\forall i<n.\ \forall\ fa\ .\ U\ (Suc\ i)\ fa = f\ (s\ i\ fa)\ (xa\ fa)) \wedge ((\forall\ fa\ .\ h\ (U\ (n - 1)\ fa)\ (s\ (n - 1)\ fa)\ (xa\ fa) = b\ fa)))$

lemma *AAAAt*: $s = (\lambda\ i\ .\ ssc\ a\ (U\ i)\ g\ xa\ i) \Longrightarrow (\exists\ Y.\ Y\ 0 = ya \wedge Y\ n = b \wedge (\forall i<n.\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)\ (\lambda(s,\ u,\ x)\ y.\ y = (g\ u\ s\ x,\ f\ s\ x,\ h\ u\ s\ x))\ (U\ i\ ||\ xa)\ (U\ (Suc\ i)\ ||\ Y\ (Suc\ i))))$
$= (if\ n = 0\ then\ ya = b\ else\ ((\forall i<n.\ \forall\ fa\ .\ U\ (Suc\ i)\ fa = f\ (s\ i\ fa)\ (xa\ fa)) \wedge ((\forall\ fa\ .\ h\ (U\ (n - 1)\ fa)\ (s\ (n - 1)\ fa)\ (xa\ fa) = b\ fa))))$

lemma *BBBq*: $s = ssc\ a\ (UUc\ ua\ a\ f\ g\ xa\ n)\ g\ xa\ \ n \Longrightarrow (\forall\ s.\ s\ 0 = a \longrightarrow (\forall xb.\ (\forall fa<xb.\ s\ (Suc\ fa) = g\ (UUc\ ua\ a\ f\ g\ xa\ n\ fa)\ (s\ fa)\ (xa\ fa)) \longrightarrow p\ (UUc\ ua\ a\ f\ g\ xa\ n\ xb,\ s\ xb,\ xa\ xb))) =$
$(\ (\forall xb.\ p\ (UUc\ ua\ a\ f\ g\ xa\ n\ xb,\ s\ xb,\ xa\ xb)))$

lemma *BBBk*: $prec\text{-}pre\text{-}sts\ (\lambda b.\ b = a)\ (\lambda(s,\ u,\ x).\ p\ (u,\ s,\ x))\ (\lambda(s,\ u,\ x)\ y.\ y = (g\ u\ s\ x,\ f\ s\ x,\ h\ u\ s\ x))\ (UU\ ua\ a\ f\ g\ xa\ n\ ||\ xa) =$
$(\forall\ s\ .\ s\ 0 = a \longrightarrow (\forall xb.\ (\forall\ fa < xb.\ s\ (Suc\ fa) = g\ (UU\ ua\ a\ f\ g\ xa\ n\ fa)\ (s\ fa)\ (xa\ fa)) \longrightarrow p\ (UU\ ua\ a\ f\ g\ xa\ n\ xb,\ s\ xb,\ xa\ xb)))$

lemma *ZZZaa*: $(INF\ x.\ (\lambda((u,\ y),\ x)\ ((u',\ y'),\ x').\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)\ (\lambda(s,\ u,\ x)\ y.\ y = (g\ u\ s\ x,\ f\ s\ x,\ h\ u\ s\ x))\ (u\ ||\ x)\ (u'\ ||\ y') \wedge x = x')\ \hat{}\hat{}\ x\ OO\ eqtop\ (x - Suc\ 0))$
$((u,\ (y{::}nat \Rightarrow 'c)),\ x)\ ((u',\ y'{::}nat \Rightarrow 'c),\ x') =$

$(x = x' \wedge (\forall xa.\ \exists aa\ b.\ (\exists U.\ U\ 0 = u \wedge U\ xa = aa \wedge (\exists Y.\ Y\ 0 = y \wedge Y\ xa = b \wedge (\forall i<xa.$ $rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)\ (\lambda(s, u, x)\ y.\ y = (g\ u\ s\ x, f\ s\ x, h\ u\ s\ x))\ (U\ i \parallel x)\ (U\ (Suc\ i) \parallel Y\ (Suc\ i))))))$ $\wedge$

$(\forall i<xa - Suc\ 0.\ aa\ i = u'\ i) \wedge (\forall i<xa - Suc\ 0.\ b\ i = y'\ i)))$

lemma *TTTd*: $U = UUc\ u\ a\ f\ g\ x \Longrightarrow (INF\ x.\ (\lambda((u, y), x)\ ((u', y'), x').\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)$ $(\lambda(s, u, x)\ y.\ y = (g\ u\ s\ x, f\ s\ x, h\ u\ s\ x))\ (u \parallel x)\ (u' \parallel y') \wedge x = x')\ \hat{}\hat{}\ x\ OO\ eqtop\ (x - Suc\ 0))$
$((u, (y::nat \Rightarrow 'c)), x)\ ((u', y'::nat \Rightarrow 'c), x') =$
$(x = x' \wedge (\forall xa.\ \exists aa\ b.\ ((xa = 0 \longrightarrow u = aa \wedge y = b) \wedge (0 < xa \longrightarrow (U\ xa = aa \wedge (\forall k.\ h$ $(U\ (xa - Suc\ 0)\ k)\ (ssc\ a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = b\ k)))) \wedge$
$(\forall i<xa - Suc\ 0.\ aa\ i = u'\ i) \wedge (\forall i<xa - Suc\ 0.\ b\ i = y'\ i)))$

lemma *TTTr*: $U = UUc\ u\ a\ f\ g\ x \Longrightarrow (INF\ x.\ (\lambda((u, y), x)\ ((u', y'), x').\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)$ $(\lambda(s, u, x)\ y.\ y = (g\ u\ s\ x, f\ s\ x, h\ u\ s\ x))\ (u \parallel x)\ (u' \parallel y') \wedge x = x')\ \hat{}\hat{}\ x\ OO\ eqtop\ (x - Suc\ 0))$
$((u, (y::nat \Rightarrow 'c)), x)\ ((u', y'::nat \Rightarrow 'c), x') =$
$(x = x' \wedge (\forall xa.\ \exists aa\ .\ (((xa = 0 \longrightarrow u = aa) \wedge (0 < xa \longrightarrow ((U\ xa = aa \wedge$
$(\forall i<xa - Suc\ 0.\ aa\ i = u'\ i) \wedge (\forall k<xa - Suc\ 0.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc\ a$ $(U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = y'\ k))))))))$

lemma *TTTt*: $U = UUc\ u\ a\ f\ g\ x \Longrightarrow (INF\ x.\ (\lambda((u, y), x)\ ((u', y'), x').\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)$ $(\lambda(s, u, x)\ y.\ y = (g\ u\ s\ x, f\ s\ x, h\ u\ s\ x))\ (u \parallel x)\ (u' \parallel y') \wedge x = x')\ \hat{}\hat{}\ x\ OO\ eqtop\ (x - Suc\ 0))$
$((u, (y::nat \Rightarrow 'c)), x)\ ((u', y'::nat \Rightarrow 'c), x') =$
$(x = x' \wedge (\forall xa.\ (((xa = 0 \longrightarrow True) \wedge (0 < xa \longrightarrow (($
$(\forall i<xa - Suc\ 0.\ U\ xa\ i = u'\ i) \wedge (\forall k<xa - Suc\ 0.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc$ $a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = y'\ k))))))))$

lemma *TTTy*: $U = UUc\ u\ a\ f\ g\ x \Longrightarrow (INF\ x.\ (\lambda((u, y), x)\ ((u', y'), x').\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)$ $(\lambda(s, u, x)\ y.\ y = (g\ u\ s\ x, f\ s\ x, h\ u\ s\ x))\ (u \parallel x)\ (u' \parallel y') \wedge x = x')\ \hat{}\hat{}\ x\ OO\ eqtop\ (x - Suc\ 0))$
$((u, (y::nat \Rightarrow 'c)), x)\ ((u', y'::nat \Rightarrow 'c), x') =$
$(x = x' \wedge (\forall xa.\ (((0 < xa \longrightarrow (($
$(\forall i<xa - Suc\ 0.\ U\ xa\ i = u'\ i) \wedge (\forall k<xa - Suc\ 0.\ h\ (U\ (xa - Suc\ 0)\ k)\ (ssc$ $a\ (U\ (xa - Suc\ 0))\ g\ x\ (xa - Suc\ 0)\ k)\ (x\ k) = y'\ k))))))))$

lemma *TTTz*: $(INF\ x.\ (\lambda((u, y), x)\ ((u', y'), x').\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)\ (\lambda(s, u, x)\ y.\ y = (g\ u\ s$ $x, f\ s\ x, h\ u\ s\ x))\ (u \parallel x)\ (u' \parallel y') \wedge x = x')\ \hat{}\hat{}\ x\ OO\ eqtop\ (x - Suc\ 0))$
$((u, (y::nat \Rightarrow 'c)), x)\ ((u', y'::nat \Rightarrow 'c), x') =$
$(x = x' \wedge (\forall xa>0::nat.\ (\forall i<xa - Suc\ (0::nat).\ f\ (SS\ a\ g\ f\ x\ i)\ (x\ i) = u'\ i) \wedge (\forall k<xa - Suc$ $(0::nat).\ h\ (f\ (SS\ a\ g\ f\ x\ k)\ (x\ k))\ (SS\ a\ g\ f\ x\ k)\ (x\ k) = y'\ k)))$

lemma *TTTyt*: $(INF\ x.\ (\lambda((u, y), x)\ ((u', y'), x').\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)\ (\lambda(s, u, x)\ y.\ y = (g\ u\ s\ x,$ $f\ s\ x, h\ u\ s\ x))\ (u \parallel x)\ (u' \parallel y') \wedge x = x')\ \hat{}\hat{}\ x\ OO\ eqtop\ (x - Suc\ 0))$
$((u, (y::nat \Rightarrow 'c)), x)\ ((u', y'::nat \Rightarrow 'c), x') = (x = x' \wedge (\forall\ k\ .\ f\ (SS\ a\ g\ f\ x\ k)\ (x\ k) = u'\ k)$ $\wedge (\forall k\ .\ h\ (f\ (SS\ a\ g\ f\ x\ k)\ (x\ k))\ (SS\ a\ g\ f\ x\ k)\ (x\ k) = y'\ k))$

lemma *TTT*: $(INF\ x.\ (\lambda((u, y), x)\ ((u', y'), x').\ rel\text{-}pre\text{-}sts\ (\lambda b.\ b = a)\ (\lambda(s, u, x)\ y.\ y = (g\ u\ s\ x, f$ $s\ x, h\ u\ s\ x))\ (u \parallel x)\ (u' \parallel y') \wedge x = x')\ \hat{}\hat{}\ x\ OO\ eqtop\ (x - Suc\ 0))$
$= (\lambda\ ((u, (y::nat \Rightarrow 'c)), x)\ ((u', y'::nat \Rightarrow 'c), x')\ .\ (x = x' \wedge (\lambda\ k\ .\ f\ (SS\ a\ g\ f\ x\ k)\ (x\ k)) = u' \wedge$

$(\lambda\ k\ .\ h\ (f\ (SS\ a\ g\ f\ x\ k)\ (x\ k))\ (SS\ a\ g\ f\ x\ k)\ (x\ k)) = y'))$

lemma *IterateOmegaA-DelayFeedback*: $IterateOmegaA\ ([-\lambda((u, y), x).\ ((u, x), x)-] \circ ([-\lambda(x, y).\ x \parallel y-]$
$\circ\ DelayFeedback\ (\lambda x.\ x = a)\ (\{.(s, u, x).p\ (u, s, x).\} \circ [-\lambda(s, u, x).\ (g\ u\ s\ x, f\ s\ x, h\ u\ s\ x)-])$
$\circ\ [-z \rightsquigarrow fst \circ z, snd \circ z-])\ **\ Skip) =$
$\{.((ua, ya), xa).\forall\, n\ xb.\ p\ (UUc\ ua\ a\ f\ g\ xa\ n\ xb, ssc\ a\ (UUc\ ua\ a\ f\ g\ xa\ n)\ g\ xa\ n\ xb, xa\ xb).\} \circ$
$[:((u, y), x)\rightsquigarrow((u', y'), x').x = x' \wedge (\lambda\ k\ .\ f\ (SS\ a\ g\ f\ x\ k)\ (x\ k)) = u' \wedge (\lambda\ k.\ h\ (f\ (SS\ a\ g\ f\ x\ k)\ (x\ k))\ (SS\ a\ g\ f\ x\ k)\ (x\ k)) = y':]$

lemma *angelic-not-demonic*: $p = (r \sqcap (\lambda\ x\ uy\ .\ x = snd\ uy)) \Longrightarrow \{:x\rightsquigarrow uy\ .\ p\ x\ uy:\}\ o\ [:uy \rightsquigarrow z\ .\ q\ (snd\ uy)\ z:] = \{.x\ .\ (\exists\ u\ .\ p\ x\ (u, x)).\}\ o\ [:y \rightsquigarrow z\ .\ q\ y\ z:]$

lemma *SS-simp*: $\bigwedge\ xa\ .\ i < xa \Longrightarrow ssc\ a\ (\lambda i.\ f\ (SS\ a\ g\ f\ x\ i)\ (x\ i))\ g\ x\ xa\ i = SS\ a\ g\ f\ x\ i$

lemma *SS-simp-a*: $\bigwedge\ xa\ .\ xa \leq i \Longrightarrow\ u = (\lambda\ i\ .\ f\ (SS\ a\ g\ f\ x\ i)\ (x\ i)) \Longrightarrow ssc\ a\ u\ g\ x\ xa\ i = SS\ a\ g\ f\ x\ i$

lemma *SS-simp-b*: $u = (\lambda\ i\ .\ f\ (SS\ a\ g\ f\ x\ i)\ (x\ i)) \Longrightarrow ssc\ a\ u\ g\ x\ xa\ i = SS\ a\ g\ f\ x\ i$

lemma *UU-SS-simp*: $\bigwedge\ i\ .\ u = (\lambda\ i\ .\ f\ (SS\ a\ g\ f\ x\ i)\ (x\ i)) \Longrightarrow UUc\ u\ a\ f\ g\ x\ xa\ i =\ f\ (SS\ a\ g\ f\ x\ i)\ (x\ i) \wedge ssc\ a\ (UUc\ u\ a\ f\ g\ x\ xa)\ g\ x\ xa\ i = SS\ a\ g\ f\ x\ i$

declare *ssc.simps* [*simp del*]
declare *SS.simps* [*simp del*]
declare *UUc.simps* [*simp del*]

lemma *SSS*: $(\exists\, aa.\ \forall\, n\ xb.\ p\ (UUc\ aa\ a\ f\ g\ x\ n\ xb, ssc\ a\ (UUc\ aa\ a\ f\ g\ x\ n)\ g\ x\ n\ xb, x\ xb))$
$= (\forall\ n.\ p\ (f\ (SS\ a\ g\ f\ x\ n)\ (x\ n)\ , SS\ a\ g\ f\ x\ n, x\ n))$

lemma *SSSa*: $\forall fa{<}xaa.\ s\ (Suc\ fa) = g\ (f\ (s\ fa)\ (x\ fa))\ (s\ fa)\ (x\ fa) \Longrightarrow i \leq xaa \Longrightarrow\ s\ i = SS\ (s\ 0)\ g\ f\ x\ i$

lemma *SSSb*: $prec\text{-}pre\text{-}sts\ (\lambda\ s\ .\ s = a)\ (\lambda pa.\ p\ (f\ (fst\ pa)\ (snd\ pa), pa))\ (\lambda p\ y.\ y = (g\ (f\ (fst\ p)\ (snd\ p))\ (fst\ p)\ (snd\ p), h\ (f\ (fst\ p)\ (snd\ p))\ (fst\ p)\ (snd\ p)))$
$= (\lambda\ x\ .\ \forall\ n.\ p\ (f\ (SS\ a\ g\ f\ x\ n)\ (x\ n)\ , SS\ a\ g\ f\ x\ n, x\ n))$

lemma *SSSc*: $\forall fa.\ s\ (Suc\ fa) = g\ (f\ (s\ fa)\ (x\ fa))\ (s\ fa)\ (x\ fa) \Longrightarrow SS\ (s\ 0)\ g\ f\ x\ i = s\ i$

lemma *SSSd*: $(rel\text{-}pre\text{-}sts\ (\lambda\ s.\ s = a)\ (\lambda p\ y.\ y = (g\ (f\ (fst\ p)\ (snd\ p))\ (fst\ p)\ (snd\ p), h\ (f\ (fst\ p)\ (snd\ p))\ (fst\ p)\ (snd\ p))))$
$= (\lambda\ x\ y\ .\ y = (\lambda k.\ h\ (f\ (SS\ a\ g\ f\ x\ k)\ (x\ k))\ (SS\ a\ g\ f\ x\ k)\ (x\ k)))$

thm *IterateOmegaA-spec*

lemma *IterateOmegaA-update*: $IterateOmegaA\ [-f-] = [:\ INF\ n.\ (\lambda\ x\ y\ .\ f\ x = y)\ \hat{}\hat{}\ n\ OO\ eqtop\ (n - 1)\ :]$

lemma *power-example*: $(n{::}nat) > 0 \Longrightarrow$
$((\lambda((u{::}nat \Rightarrow 'a, y{::}nat \Rightarrow 'a), x{::}nat \Rightarrow 'b)\ ((u', y'), x').\ u = u' \wedge u = y' \wedge x = x')\ \hat{}\hat{}\ n)$

$= (\lambda((u, y), x)\ ((u', y'), x').\ u = u' \wedge u = y' \wedge x = x')$

lemma *power-example-a*: $(n{::}nat) > 0 \Longrightarrow$
$((\lambda((u{::}nat \Rightarrow 'a,\ y{::}nat \Rightarrow 'a),\ x{::}nat \Rightarrow 'b)\ ((u', y'), x').\ u = u' \wedge u = y' \wedge x = x')\ \hat{}\hat{}\ n)\ ((a,b), c)\ ((a', b'), c')$
$= (a = a' \wedge a = b' \wedge c = c')$

lemma *example-simp*: $\{:x \rightsquigarrow ((u, y), x').x = x':\} \circ [:((u, y), x) \rightsquigarrow ((u', y'), x').u = u' \wedge u = y' \wedge x = x':] \circ [-\lambda((u, y), x).\ y-] = \{:\ \top\ :\}$

lemma *Feedback-example*: $Feedback([-u{::}nat \Rightarrow 'a,\ x{::}nat \Rightarrow 'b \rightsquigarrow u,\ u-]) = \{:\top:\}$

lemma *Feedback-deterministic*: $init = (\lambda\ x\ .\ x = a) \Longrightarrow$
$DelayFeedback\ init\ (feedback(\{.(u, s, x).\ \ p\ (u, s, x).\} \circ [-\lambda(u, s, x).\ (f\ s\ x,\ g\ u\ s\ x,\ h\ u\ s\ x)-])) =$
$Feedback\ ([-\ u,x \rightsquigarrow\ \ u\ ||\ x\ -]\ o\ (DelayFeedback\ init\ ([-\ \lambda\ (s,(u,x))\ .\ (u,\ s,\ x)\ -]$
$o\ (\{.\ p\ .\} \circ [-\ u,\ s,\ x \rightsquigarrow f\ s\ x,\ g\ u\ s\ x,\ h\ u\ s\ x\ -])$
$o\ [-\ v,\ s,\ y \rightsquigarrow s,\ v,\ y\ -]))\ o\ [-\ z \rightsquigarrow fst\ o\ z,\ snd\ o\ z\ -])$

lemma *DF-fb-simp*: $init = (\lambda\ x\ .\ x = a) \Longrightarrow$
$DelayFeedback\ init\ (feedback(\{.(u, s, x).\ \ p\ (u,s, x).\} \circ [-\ u,\ s,\ x \rightsquigarrow f\ s\ x,\ g\ u\ s\ x,\ h\ u\ s\ x-])) =$
$\{.x.\forall n.\ p\ (f\ (SS\ a\ g\ f\ x\ n)\ (x\ n),\ SS\ a\ g\ f\ x\ n,\ x\ n).\} \circ [:y \rightsquigarrow z.\ z = (\lambda k.\ h\ (f\ (SS\ a\ g\ f\ y\ k)\ (y\ k))\ (SS\ a\ g\ f\ y\ k)\ (y\ k)):]$

lemma *DF-fb-simp-a*: $init = (\lambda\ x\ .\ x = a) \Longrightarrow$
$DelayFeedback\ init\ (feedback(\{.\ p\ .\} \circ [-\lambda(u, s, x).\ (f\ s\ x,\ g\ u\ s\ x,\ h\ u\ s\ x)-])) =$
$\{.x.\forall n.\ p\ (f\ (SS\ a\ g\ f\ x\ n)\ (x\ n),\ SS\ a\ g\ f\ x\ n,\ x\ n).\} \circ [:y \rightsquigarrow z.\ z = (\lambda k.\ h\ (f\ (SS\ a\ g\ f\ y\ k)\ (y\ k))\ (SS\ a\ g\ f\ y\ k)\ (y\ k)):]$

lemma *FB-DF-simp*: $init = (\lambda\ x\ .\ x = a) \Longrightarrow$
$Feedback\ ([-\ u,x \rightsquigarrow\ \ nzip\ u\ x\ -]\ o\ (DelayFeedback\ init\ ([-\ \lambda\ (s,(u,x))\ .\ (u,\ s,\ x)\ -]$
$o\ (\{.(u, s, x).\ \ p\ (u, s, x).\} \circ [-\ u,\ s,\ x \rightsquigarrow f\ s\ x,\ g\ u\ s\ x,\ h\ u\ s\ x-])$
$o\ [-\ v,\ s,\ y \rightsquigarrow s,\ v,y\ -]))\ o\ [-\ z \rightsquigarrow fst\ o\ z,\ snd\ o\ z\ -])$
$=\ \{.x.\forall n.\ p\ (f\ (SS\ a\ g\ f\ x\ n)\ (x\ n),\ SS\ a\ g\ f\ x\ n,\ x\ n).\} \circ [:y \rightsquigarrow z.\ z = (\lambda k.\ h\ (f\ (SS\ a\ g\ f\ y\ k)\ (y\ k))\ (SS\ a\ g\ f\ y\ k)\ (y\ k)):]$

definition $init\text{-}ex = (\lambda\ s\ .\ s = (0{::}nat))$
definition $p1 = (\lambda(u,s,x).\ u = s + 1)$
definition $f1 = (\lambda\ s\ x.\ s + 1)$
definition $g1 = (\lambda\ u\ s\ x.\ s + 1)$
definition $h1 = (\lambda\ u\ s\ x.\ x)$
definition $spec\text{-}ex = \{.(u, s, x).\ p1\ (u, s, x).\}\ o\ [-\lambda\ (u, s, x).\ (f1\ s\ x,\ g1\ u\ s\ x,\ h1\ u\ s\ x)-]$

lemma *DelayFeedback-feedback-ex*: $DelayFeedback\ init\text{-}ex\ (feedback\ (\ spec\text{-}ex\ )) = [:y \rightsquigarrow z.\ z = y:]$

lemma *jjj*: $[:x \rightsquigarrow ((x'', y), x').x'' = x \wedge x = x':] \circ ([:\ \lambda s.\ \Box\ (\lambda s.\ s\ 0 = b)\ :] ** Skip) ** Skip = [:x \rightsquigarrow ((x'', y), x').(\Box\ (\lambda s.\ s\ 0 = b))\ x'' \wedge x' = x:]$

lemma [*simp*]: $(\forall a. (\square (\lambda s.\ s\ 0 = b))\ a \longrightarrow (\forall n\ xb.\ UUc\ a\ 0\ (\lambda s\ x.\ Suc\ s)\ (\lambda u\ s\ x.\ Suc\ s)\ x\ n\ xb = Suc\ (ssc\ 0\ (UUc\ a\ 0\ (\lambda s\ x.\ Suc\ s)\ (\lambda u\ s\ x.\ Suc\ s)\ x\ n)\ (\lambda u\ s\ x.\ Suc\ s)\ x\ n\ xb)))$
$= ((\forall n\ xb.\ UUc\ (\lambda\ i\ .\ b)\ 0\ (\lambda s\ x.\ Suc\ s)\ (\lambda u\ s\ x.\ Suc\ s)\ x\ n\ xb = Suc\ (ssc\ 0\ (UUc\ (\lambda\ i\ .\ b)\ 0\ (\lambda s\ x.\ Suc\ s)\ (\lambda u\ s\ x.\ Suc\ s)\ x\ n)\ (\lambda u\ s\ x.\ Suc\ s)\ x\ n\ xb)))$

lemma [*simp*]: $((\forall n\ xb.\ UUc\ (\lambda\ i\ .\ b)\ 0\ (\lambda s\ x.\ Suc\ s)\ (\lambda u\ s\ x.\ Suc\ s)\ x\ n\ xb = Suc\ (ssc\ 0\ (UUc\ (\lambda\ i\ .\ b)\ 0\ (\lambda s\ x.\ Suc\ s)\ (\lambda u\ s\ x.\ Suc\ s)\ x\ n)\ (\lambda u\ s\ x.\ Suc\ s)\ x\ n\ xb))) = False$

lemma *FeedbackA-example*: $init = (\lambda\ s\ .\ s = b) \Longrightarrow$
$FeedbackA\ (InitDF\ init)\ ([-\ u,x \rightsquigarrow nzip\ u\ x\ -]\ o\ (DelayFeedback\ init\text{-}ex\ ([-\ \lambda\ (s,(u,x))\ .\ (u,\ s,\ x)\ -]$
$o\ spec\text{-}ex$
$o\ [-\ v,\ s,\ y \rightsquigarrow s,\ v,\ y\ -]))\ o\ [-\ z \rightsquigarrow fst\ o\ z,\ snd\ o\ z\ -]) =$
$\bot$

definition $init\text{-}ex\text{-}a = (\lambda\ s\ .\ s = (0{::}nat))$
definition $p1\text{-}a = (\lambda\ (u,\ s,\ x)\ .\ u = s + 1)$
definition $f1\text{-}a = (\lambda\ s\ x.\ s + 1)$
definition $g1\text{-}a = (\lambda\ u\ s\ x.\ s + 1)$
definition $h1\text{-}a = (\lambda\ u\ s\ x.\ x + s)$
definition $spec\text{-}ex\text{-}a = \{.p1\text{-}a.\}\ o\ [-\lambda\ (u,\ s,\ x).\ (f1\text{-}a\ s\ x,\ g1\text{-}a\ u\ s\ x,\ h1\text{-}a\ u\ s\ x)-]$

lemma [*simp*]: $SS\ 0\ (\lambda u\ s\ x.\ Suc\ s)\ (\lambda s\ x.\ Suc\ s)\ y\ k = k$

lemma *DelayFeedback-feedback-ex-a*: $DelayFeedback\ init\text{-}ex\text{-}a\ (feedback\ (\ spec\text{-}ex\text{-}a\ )) = [:y \rightsquigarrow z.\ z = (\lambda k.\ y\ k + k):]$
end

5 Overview of the Refinement Calculus of Reactive Systems (RCRS)

theory *RCRS-Overview* **imports** *Feedback/ReactiveFeedback*
begin

This theory file refers to the results presented in the paper "The Refinement Calculus of Reactive Systems", by Preoteasa, Dragomir, and Tripakis, on arxiv.org, 2017, and under submission to a journal.

The section, subsection, etc., numbers and titles below refer to those in the aforementioned paper.

5.1 Section 3: Language

5.1.1 Section 3.1: An Algebra of Components

The grammar of components defined in Section 3.1 is not explicitly formalized in this theory. However, GEN_STS, STATELESS_STS, DET_STS, DET_STATELESS_STS, and QLTL components can be defined as semantic objects as they are given in Section 4.3

5.1.2 Section 3.2: Symbolic Transition System Components

5.1.3 Section 3.2.1: General STS Components

The semantics version of an STS component is given by the next definition which matches equation (6) from the paper. Another difference between the semantic sts defined here and the syntactic version from the paper is that init and r are functions in the semantic version.

definition $\mathit{sts}\ \mathit{init}\ r = \{.\ -\mathit{illegal\text{-}sts}\ \mathit{init}\ (\mathit{inpt}\ r)\ r\ .\}\ o\ [:\ x \rightsquigarrow y\ .\ \exists\ s\ .\ (\mathit{init}\ (s\ 0) \wedge \mathit{run\text{-}sts}\ r\ s\ x\ y)\ :]$

definition $\mathit{C1\text{-}sts} = \mathit{sts}\ \ (\lambda\ s\ .\ s > 0)\ (\lambda\ (s,(n,x))\ (s',\ y)\ .\ s' > s \wedge y + s = x\ \hat{}\ n)$
definition $\mathit{C2\text{-}sts} = \mathit{sts}\ \ (\lambda\ s\ .\ s > 0)\ (\lambda\ (s,z)\ (s',\ y)\ .\ s' > s \wedge y + s = (\mathit{snd}\ z)\ \ \hat{}\ (\mathit{fst}\ z))$

lemma $\mathit{C1\text{-}sts} = \mathit{C2\text{-}sts}$

definition $\mathit{UnitDelay} = \mathit{sts}\ (\lambda\ s\ .\ s = 0)\ (\lambda\ (s,x)\ (s',y)\ .\ y = s \wedge s' = x)$

definition $\mathit{Sum\text{-}sts} = \mathit{sts}\ (\lambda\ s\ .\ s = (0::\mathit{nat}))\ (\lambda\ (s,x)\ (s',y)\ .\ y = s \wedge s' = s + x)$

definition $\mathit{C\text{-}sts} = \mathit{sts}\ (\lambda\ s\ .\ s = 0)\ (\lambda\ (s,\ x)\ (s',\ y)\ .\ \ x + s \leq y\ )$

definition $\mathit{Div\text{-}sts} = \mathit{sts}\ \top\ (\lambda\ (s::\mathit{unit},(x,y))\ (s'::\mathit{unit},\ z)\ .\ y \neq 0 \wedge z = x\ /\ y)$

definition $\mathit{Integrator}\ \mathit{dt} = \mathit{sts}\ (\lambda\ s\ .\ s = 0)\ (\lambda\ (s,x)\ (s',y)\ .\ y = s \wedge s' = s + x * \mathit{dt})$

definition $\mathit{TransferFcn}\ \mathit{dt} = \ \mathit{sts}\ (\lambda\ (s,t)\ .\ s = 0 \wedge t = 0)\ (\lambda\ ((s,t),x)\ ((s',t'),\ y)\ .$
$y = -8 * s + 2 * x \wedge s' = s + (-4 * s - 2 * t + x) * \mathit{dt} \wedge t' = t + s * \mathit{dt})$

5.1.4 Section 3.2.2: Variable Name Scope

definition $\mathit{A\text{-}sts} = \mathit{sts}\ (\lambda\ s.\ s > 0)\ (\lambda\ (s,\ (x,y))\ (s',\ z).\ z > s + x + y)$
definition $\mathit{B\text{-}sts} = \mathit{sts}\ (\lambda\ t.\ t > 0)\ (\lambda\ (t,\ (u,\ v))\ (t',\ w).\ w > t + u + v)$

lemma $\mathit{A\text{-}sts} = \mathit{B\text{-}sts}$

5.1.5 Section 3.2.3: Stateless STS Components

The semantic version of the stateless STS component is defined using the mapping stateless2sts from the paper.

definition $\mathit{stateless\text{-}sts}\ r = \mathit{sts}\ \top\ (\lambda\ (u::\mathit{unit},x)\ (v::\mathit{unit},\ y)\ .\ r\ x\ y)$

definition $\mathit{Id\text{-}sts} = \mathit{stateless\text{-}sts}\ (\lambda\ x\ y\ .\ y = x)$

definition $\mathit{Add\text{-}sts} = \mathit{stateless\text{-}sts}\ (\lambda\ (x,y)\ z\ .\ z = x + y)$

definition $\mathit{Split\text{-}sts} = \mathit{stateless\text{-}sts}\ (\lambda\ x\ (y,z)\ .\ y = x \wedge z = x)$

Div components can also be defined as sts component

lemma $\mathit{Div\text{-}stateless}$: $\mathit{Div\text{-}sts} = \mathit{stateless\text{-}sts}\ (\lambda\ (x,y)\ z\ .\ y \neq 0 \wedge z = x\ /\ y)$

5.1.6 Section 3.2.3: Deterministic STS Components

The semantic version of the deterministic STS component is defined using the mapping det2sts from the paper.

definition *det-sts s0 p state out* = *sts* (λ *s* . *s* = *s0*) (λ (*s*,*x*) (*s*′,*y*) . *p* (*s*, *x*) ∧ *s*′ = *state* (*s*,*x*) ∧ *y* = *out* (*s*, *x*))

lemma *UnitDelay-det*: *UnitDelay* = *det-sts 0* ⊤ (λ (*s*::′*a*::*zero*, *x*) . *x*) (λ (*s*, *x*) . *s*)

lemma *Id-sts-det*: *Id-sts* = *det-sts* () ⊤ (λ (*s*::*unit*, *x*) . ()) (λ (*s*::*unit*, *x*) . *x*)

lemma *Add-sts-det*: *Add-sts* = *det-sts* () ⊤ (λ (*s*::*unit*, (*x*,*y*)) . ()) (λ (*s*::*unit*, (*x*,*y*)) . *x* + *y*)

lemma *Div-sts-det*: *Div-sts* = *det-sts* () (λ (*s*::*unit*, (*x*,*y*)) . *y* ≠ *0*) (λ (*s*::*unit*, (*x*,*y*)) . ()) (λ (*s*::*unit*, (*x*,*y*)) . *x* / *y*)

lemma *Split-sts-det*: *Split-sts* = *det-sts* () ⊤ (λ (*s*::*unit*, *x*) . ()) (λ (*s*::*unit*, *x*) . (*x*, *x*))

lemma *Sum-sts-det*: *Sum-sts* = *det-sts 0* ⊤ (λ (*s*, *x*) . *s* + *x*) (λ (*s*, *x*) . *s*)

5.1.7 Section 3.2.3: Stateless Deterministic STS Components

The semantic version of the stateless deterministic STS component is defined using the mapping stateless_det2det from the paper.

definition *stateless-det-sts p out* = *det-sts* () (λ (*s*::*unit*, *x*) . *p x*) (λ (*s*::*unit*, *x*) . ()) (λ (*s*::*unit*, *x*) . *out x*)

Many of the examples introduced above are both deterministic and stateless

lemma *Id-sts-stateless-det*: *Id-sts* = *stateless-det-sts* ⊤ (λ *x* . *x*)

lemma *Add-sts-stateless-det*: *Add-sts* = *stateless-det-sts* ⊤ (λ (*x*, *y*) . *x* + *y*)

lemma *Split-sts-stateless-det*: *Split-sts* = *stateless-det-sts* ⊤ (λ *x* . (*x*, *x*))

lemma *Div-sts-stateless-det*: *Div-sts* = *stateless-det-sts* (λ (*x*, *y*) . *y* ≠ *0*) (λ (*x*, *y*) . *x* / *y*)

fdbk is similar to Feedback but it requires the argument to have as input and output traces of pairs, while Feedback has as input and output pairs of traces.

definition *fdbk S* = *Feedback* ([− *u*, *x* ⇝ *u* || *x* −] *o S o* [− *uy* ⇝ *fst o uy*, *snd o uy* −])

Here is how the "Sum" composite component is defined (Simulink diagram in Fig.2).

definition *Sum-comp* = *fdbk* (*Add-sts o UnitDelay o Split-sts*)

We can prove later that Sum_sts = Sum_comp

thm *Sum-sts-def*
thm *sts-def*

5.1.8 Section 3.3: Quantified Linear Temporal Logic Components

5.1.9 Section 3.3.1: QLTL

For details on how QLTL is formalized in RCRS/Isabelle, see Temporal.thy

Lemma 1.

1. *top_dep p* is the semantic equivalent of *p* does not contain temporal operators.

definition *EXISTS* = *SUPREMUM UNIV*

definition *FORALL* = *INFIMUM UNIV*

The functions EXISTS and FORALL model the existential and universal quantifiers for QLTL formulas. If $p : A \to B \to \mathit{bool}$ is a predicate with two parameters, then $EXISTSp : B \to \mathit{bool}$ is a predicate with one parameter and $EXISTSpb = (\exists a.p\ a\ b)$.

lemma *lemma-1-1*: $\mathit{top\text{-}dep}\ p \Longrightarrow \mathit{EXISTS}\ (\Box\ p) = \Box\ (\mathit{EXISTS}\ \ p)$

2.

lemma *lemma-1-2*: $p\ \mathit{leads}\ p = \Box\ p$

3.

lemma *lemma-1-3*: $\top\ \mathit{leads}\ p = \Box\ p$

4.

lemma *lemma-1-4*: $p\ \mathit{leads}\ \top = \top$

5.

lemma *lemma-1-5*: $p\ \mathit{leads}\ \bot = \bot$

6.

lemma *lemma-1-6*: $\mathit{top\text{-}dep}\ p \Longrightarrow \mathit{FORALL}\ (p\ \mathit{leads}\ (\lambda\ y\ .\ q)) = ((\mathit{EXISTS}\ p)\ \mathit{leads}\ q)$

5.1.10 Section 3.3.2: QLTL Components

Semantically a QLTL component is a guarded property transformer on input output traces defined by a QLTL property. If $\alpha\ x\ y$ is a QLTL property then the QLTL component of α is:

definition $\mathit{qltl}\ \alpha = \{:\ \alpha\ :]$

However, for QLTL components, we use the syntax $\{:\ \alpha\ :]$ and its variant $\{:\ x \leadsto y.\mathit{expr}\ :]$, where *expr* is a QLTL expression on x and y

For example the oven QLTL component is defined by

definition $\mathit{thermostat} = \Box\ (\lambda\ t\ .\ 180 \le t\ (0{::}\mathit{nat}) \wedge t\ 0 \le 220)$
definition $\mathit{oven} = \ (\lambda\ t\ .\ t\ 0 = (20{::}\mathit{nat})) \sqcap ((\lambda\ t\ .\ t\ 0 < t\ 1 \wedge t\ 0 < 180)\ \mathit{until}\ \mathit{thermostat})$
definition $\mathit{theromstat\text{-}liveness} = \Diamond\ (\lambda\ t.\ t\ (0{::}\mathit{nat}) > 200)$

definition $\mathit{Oven\text{-}qltl} = \{:x{::}(\mathit{nat} \Rightarrow \mathit{unit}) \leadsto t\ .\ \mathit{oven}\ t{:}]$

5.1.11 Section 3.4: Well Formed Components

Since in Isabelle the components are semantic objects, they are well formed if they type check in Isabelle

Next definition introduced a variant of the parallel composition closer to the parallel composition from the paper. In the paper we assume that traces of pairs are equivalent to pair of traces $(x, y) = (\lambda i.(x\ i, y\ i))$. The input of the new parallel composition variant is a trace of pairs, and the output is also a trace of pairs.

definition *parallel-component* :: $(((nat \Rightarrow 'a) \Rightarrow bool) \Rightarrow ((nat \Rightarrow 'b) \Rightarrow bool)) \Rightarrow (((nat \Rightarrow 'c) \Rightarrow bool)$ $\Rightarrow ((nat \Rightarrow 'd) \Rightarrow bool))$
$\Rightarrow (((nat \Rightarrow 'a \times 'c) \Rightarrow bool) \Rightarrow ((nat \Rightarrow 'b \times 'd) \Rightarrow bool))$
(**infixr** $***$ *70*)
where
$(S *** T) = [-uv \rightsquigarrow fst\ o\ uv,\ snd\ o\ uv\ -]\ o\ (S ** T)\ o\ [-x,y \rightsquigarrow x \mid\mid y\ -]$

definition $Switch1 = stateless\text{-}det\text{-}sts\ \top\ (\lambda\ (x,y).\ ((x,y),x))$
definition $Switch2 = stateless\text{-}det\text{-}sts\ \top\ (\lambda\ ((u,v),x).\ ((u,x),v))$

definition $Fig3\ A\ B\ C = A\ o\ Switch1\ o\ (B *** Id\text{-}sts)\ o\ Switch2\ o\ (C *** Id\text{-}sts)$

5.2 Section 4: Semantics

5.2.1 Section 4.1: Monotonic Property Transformers

Definition 8 (Skip) can be found in Refinement.thy. You can see the definition by placing your cursor on the line "thm Skip_def". You can also control-click on "Skip_def" to be taken automatically to the definition.

thm *Skip-def*

Definition 9 (Fail) can be found in Refinement.thy.

thm *Fail-def*

Definition 10 (Assert) can be found in Refinement.thy.

thm *assert-def*

Definition 11 (Demonic update) can be found in Refinement.thy.

thm *demonic-def*

definition $DemonicEx1 = [:x,\ y \rightsquigarrow z.\ (\forall\ i.\ z\ i = x\ i + y\ i)\ :]$
definition $DemonicEx3 = [:\ x \rightsquigarrow y.\ \ y = (\lambda\ i.\ x\ i + 1)\ :]$

Lemma 2. The first equality is proved below; the second and third are proved in Refinement.thy by lemmas assert_true_skip and assert_rel_skip, whose definitions are repeated below.

lemma *skip-demonic-rel*: $Skip = [:\ x \rightsquigarrow x'.\ x'=x\ :]$
thm *assert-true-skip*
thm *assert-rel-skip*

Definition 12 (Angelic update) can be found in Refinement.thy.

thm *angelic-def*

Lemma 3.

lemma *assert-angelic-upd*: $\{.p.\} = \{:\ x \rightsquigarrow x'.\ p\ x \land x' = x:\}$

Results for serial composition. These results are proved in Refinement.thy by mono_comp_a, comp_skip and skip_comp.

thm *mono-comp-a*
thm *comp-skip*
thm *skip-comp*

Definition 13 (Product) can be found in Refinement.thy. Instead of the product notation $\otimes$ used in the paper, the notation ** is used in RCRS/Isabelle. That is, product corresponds to parallel composition.

thm *Prod-def*

Lemma 4 is proved in Refinement.thy by lemma mono_prod.

thm *mono-prod*

Skip with Unit as input and output type is the neutral element for product.

lemma $[:x \leadsto y.\ r\ x\ y:]\ {**}\ (\mathit{Skip}{::}(\mathit{unit} \Rightarrow \mathit{bool}) \Rightarrow (\mathit{unit} \Rightarrow \mathit{bool})) = [:\ (x,\ u{::}\mathit{unit}) \leadsto (y,\ v{::}\mathit{unit}).\ r\ x\ y\ :]$

lemma $(\mathit{Skip}{::}(\mathit{unit} \Rightarrow \mathit{bool}) \Rightarrow (\mathit{unit} \Rightarrow \mathit{bool}))\ {**}\ [:r:] = [:\ (u{::}\mathit{unit},\ x) \leadsto (v{::}\mathit{unit},\ y).\ r\ x\ y\ :]$

Definition 14 (Fusion) can be found in Refinement.thy.

thm *Fusion-def*

Lemma 5 is proved in Refinement.thy by lemma Fusion_spec.

thm *Fusion-spec*

Definition 15 (IterateOmega) can be found in DelayFeedback.thy.

thm *IterateOmegaA-def*

Definition 16 (Feedback) can be found in DelayFeedback.thy.

thm *Feedback-def*
thm *IterateOmegaA-def*
thm *IterateMaskA-def*
thm *Mask-def*

Computing feedback of delayed sum.

definition $\mathit{S\text{-}comp} = [-\ \lambda\ (u,\ x).\ ((\lambda i.\ \mathit{if}\ i = 0\ \mathit{then}\ 0\ \mathit{else}\ x(i - 1) + u(i - 1)),\ (\lambda i.\ \mathit{if}\ i = 0\ \mathit{then}\ 0\ \mathit{else}\ x(i - 1) + u(i - 1)))-]$

definition $\mathit{T\text{-}comp} = [-(u,\ (y{::}\mathit{nat} \Rightarrow \mathit{nat})),\ x \leadsto ((u{::}\mathit{nat} \Rightarrow \mathit{nat}),\ x),\ x-] \circ \mathit{S\text{-}comp}\ {**}\ \mathit{Skip}$

lemma $\mathit{T\text{-}comp\text{-}simp}$: $\mathit{T\text{-}comp}$
$= [-(u,y),\ x \leadsto ((\lambda i.\ \mathit{if}\ i = 0\ \mathit{then}\ 0\ \mathit{else}\ x(i - 1) + u(i - 1)),(\lambda i.\ \mathit{if}\ i = 0\ \mathit{then}\ 0\ \mathit{else}\ x(i - 1) + u(i - 1))),\ x\ -]$

thm *Summ.simps*

lemma $\mathit{Summ\text{-}Suc}$: $\mathit{Summ}\ (\lambda a.\ b\ (\mathit{Suc}\ a))\ n + b\ 0 = \mathit{Summ}\ b\ n + b\ n$

lemma $\mathit{Summ\text{-}at\text{-}Suc}$: $\bigwedge\ b\ .\ \mathit{Summ}\ (b[\mathit{Suc}\ k\ ..])\ n + b\ k = \mathit{Summ}\ (b[k..])\ n + b\ (n + k)$

lemma $\mathit{T\text{-}comp\text{-}power}$: $\mathit{T\text{-}comp}\ \hat{}\hat{}\ (\mathit{Suc}\ n) =$
$[-(u,y),\ x \leadsto ((\lambda i.\ \mathit{if}\ i \le n\ \mathit{then}\ \mathit{Summ}\ x\ i\ \mathit{else}\ \mathit{Summ}\ (x[i - \mathit{Suc}\ n..])\ (\mathit{Suc}\ n)\ + u\ (i - \mathit{Suc}\ n)),$
$(\lambda i.\ \mathit{if}\ i \le n\ \mathit{then}\ \mathit{Summ}\ x\ i\ \mathit{else}\ \mathit{Summ}\ (x[i - \mathit{Suc}\ n..])\ (\mathit{Suc}\ n)\ + u\ (i - \mathit{Suc}\ n))),\ x\ -]$

lemma $\mathit{T\text{-}comp\text{-}IterateMaskA}$: $\mathit{IterateMaskA}\ \mathit{T\text{-}comp}\ n = [:(u,\ y),\ x \leadsto (u',\ y'),\ x'\ .$
$(\forall\ i < n - 1\ .\ x'\ i = x\ i \wedge y'\ i = \mathit{Summ}\ x\ i \wedge u'\ i = y'\ i):]$

Next lemma proves relation (1) from the paper.

lemma $\mathit{Feedback\text{-}S\text{-}comp}$: $\mathit{Feedback}\ \mathit{S\text{-}comp} = [-\mathit{Summ}-]$

Definition 17 (Refinement) is part of the Isabelle libraries (Orderings.thy). Since MPTs are functions, refinement is simply an ordering on functions:

thm *le-fun-def*

Theorem 1

Theorem 1.1. These results are proved in Refinement.thy by lemmas mono_comp, prod_mono1, prod_mono2, and fusion_mono1.

thm *mono-comp*
thm *prod-mono1*
thm *prod-mono2*
thm *Fusion-refinement*
thm *fusion-mono1*

Theorem 1.2.

lemma *theorem-1-2*: $mono\ S \Longrightarrow S \le T \Longrightarrow IterateOmegaA\ S \le IterateOmegaA\ T$

Theorem 1.3.

lemma *theorem-1-3*: $S \le T \Longrightarrow Feedback\ S \le Feedback\ T$

5.2.2 Section 4.2: Subclasses of MPTs

Def.18 simply defines the terminology RPT. Note that Property Transformers are instances of Predicate Transformers (and predicate transformers are themselves instances of functions). A predicate transformer is a function of type ('a → bool) → ('b → bool) where types 'a and 'b are arbitrary. When these types are types of infinite sequences, we get a property transformer, which is a function of type: ((nat → 'a) → bool) → ((nat → 'b) → bool).

Much of the RCRS formalization in Isabelle is done in terms of predicate transformers, in order to establish more general results. Results that hold for (general) predicate transformers automatically hold also for (the more specific) property transformers.

We sometimes wish to work with property transformers directly. Below, we define the construct "sts init r", which produces a property transformer of type ((nat → 'a) → bool) → ((nat → 'b) → bool) where init is of type ('c → bool) and r of type ('c × 'b → 'c × 'a → bool).

A series of small RPT examples after Def.18, stated as lemmas:

lemma *Fail-is-a-RPT*: $Fail = \{.\ x\ .\ False\ .\}\ o\ [:\ x \leadsto y\ .\ True\ :]$

lemma *Skip-is-a-RPT*: $Skip = \{.\ x.\ True.\}\ o\ [:\ x \leadsto y.\ y = x\ :]$

lemma *Assert-is-a-RPT*: $\{.p.\} = \{.p.\}\ o\ [:\ x \leadsto y.\ y{=}x{:}]$

lemma *Demonic-is-a-RPT*: $[:r:] = \{.\top.\}\ o\ [:r:]$

definition $RPT\text{-}S1 = \{.\ \top\ .\}\ o\ [:\ (x,\ y) \leadsto z\ .\ y \ne 0 \wedge z = x\ /\ y\ :]$
definition $RPT\text{-}S2 = \{.\ (x,\ y)\ .\ y \ne 0\ .\}\ o\ [:\ (x,\ y) \leadsto z\ .\ z = x\ /\ y\ :]$

Theorem 2 is proved in Refinement.thy by lemmas assert_demonic_comp, Prod_spec, fusion_spec

thm *assert-demonic-comp*
thm *Prod-spec*
thm *Fusion-spec*

The theorem 2 in the paper uses Fusion applied to two RPTs, but Fusion_spec is proved for an arbitrary number of RPTs.

RPTs are not closed under Feedback operation.

lemma $\mathit{Feedback}\ [-u{::}nat \Rightarrow {}'a,\ x{::}nat \Rightarrow{}'b \rightsquigarrow u,\ u-] = \{:\top:\}$

Theorem 3 is proved in Refinement.thy by lemma assert_demonic_refinement

thm *assert-demonic-refinement*

5.2.3 Section 4.2.2: Guarded MPTs

Definition 19 is given in Refinement.thy by the definition of trs

thm *trs-def*

thm *Magic-def*
lemma *MagicAlternativeDef*: $\mathit{Magic} = [:\ x \rightsquigarrow y\ .\ \mathit{False}\ :]$

lemma *Fail-is-a-GPT*: $\mathit{Fail} = \{:\ \bot\ :]$

lemma *Skip-is-s-GPT*: $\mathit{Skip} = \{:\ x \rightsquigarrow y.\ y = x\ :]$

lemma *Assert-is-a-GPT*: $\{.p.\} = \{:\ x \rightsquigarrow y.\ p\ x \wedge y = x\ :]$

lemma $\mathit{inpt}\ r = \top \Longrightarrow [:r:] = \{:r:]$

lemma $[:r:] = \{:\ r:] \Longrightarrow \mathit{inpt}\ r = \top$

Theorem 4 is proved in Refinement.thy by lemmas trs_trs and trs_prod.

thm *trs-trs*
thm *trs-prod*

Corollary 1 is proved in Refinement.thy by lemmas trs_refinement.

thm *trs-refinement*

5.2.4 Section 4.3: Semantics of Components as MPTs

As mentioned already, the components are semantic objects. The semantics of qltl component, relation (2), is the definition qltl_def. The semantics of the serial composition, relation (3), is the function composition of property transformers. The semantics of the parallel composition, relation (4), is the definition parallel_component_def. The semantics of the feedback composition, relation (5), is the definition fdbk_def

thm *qltl-def*
thm *parallel-component-def*
thm *fdbk-def*

Lemma 6.

lemma *lemma-6*: $\{:\ x \rightsquigarrow y.\ \mathit{inpt}\ r\ x \wedge r\ x\ y\ :] = \{:\ x \rightsquigarrow y.\ r\ x\ y:]$

The semantics of the sts components, relation (6), is given by sts_def

thm *sts-def*

The semantics of the other components are given by their definitions:

thm *stateless-sts-def*
thm *det-sts-def*
thm *stateless-det-sts-def*

Next lemma is an auxiliary results that links the definition oo sts to LocalSystem defined in RefinementReactive.thy.

lemma *sts-LocalSystem*: $sts\ init\ r = LocalSystem\ init\ (inpt\ r)\ r$

lemma *sts-inpt-top*: $inpt\ r = \top \Longrightarrow sts\ init\ r = [:rel\text{-}pre\text{-}sts\ init\ r:]$

lemma *stateless2LocalSystem*: $stateless\text{-}sts\ r = LocalSystem\ (\top::unit \Rightarrow bool)\ (\lambda\ (s::unit,\ x)\ .\ inpt\ r\ x)\ (\lambda\ (s::unit,\ x)\ (s'::unit,\ y)\ .\ r\ x\ y)$

lemma *det2LocalSystem*: $det\text{-}sts\ s0\ p\ state\ out = LocalSystem\ (\lambda\ s\ .\ s = s0)\ p\ (\lambda\ (s,x)\ (s',y)\ .\ s' = state\ (s,x) \wedge y = out\ (s,\ x)\ )$

lemma *stateless-det2LocalSystem*: $stateless\text{-}det\text{-}sts\ p\ out = LocalSystem\ (\top::unit \Rightarrow bool)\ (\lambda\ (s::unit,\ x)\ .\ p\ x)\ (\lambda\ (s::unit,\ x)\ (s'::unit,\ y)\ .\ y = out\ x)$

Lemma 7.

theorem *stateless-det2stateless*: $stateless\text{-}det\text{-}sts\ p\ out = stateless\text{-}sts\ (\lambda\ x\ y\ .\ p\ x \wedge y = out\ x)$

thm *Sum-comp-def*

5.2.5 Section 4.3.1: Example: Two Alternative Derivations of the Semantics of Diagram Sum

lemma *Add-sts-simp*: $Add\text{-}sts = [-ux \rightsquigarrow (\lambda\ i\ .\ fst\ (ux\ i) + snd\ (ux\ i))-]$

lemma *UnitDelay-simp*: $UnitDelay = [-x \rightsquigarrow (\lambda\ i\ .\ if\ i = 0\ then\ 0\ else\ x\ (i - 1))-]$

lemma *Split-sts-simp*: $Split\text{-}sts = [-x \rightsquigarrow (\lambda\ i\ .\ (x\ i,\ x\ i))-]$

lemma *Sum-comp-simp*: $Sum\text{-}comp = [-Summ-]$

The SumAtomic sts is the same as Sum_sts defined above

thm *Sum-sts-def*

lemma *Sum-sts-simp*: $Sum\text{-}sts = [:\ x \rightsquigarrow y\ .\ \exists\ s\ .\ s\ 0 = 0 \wedge (\forall\ i\ .\ y\ i = s\ i \wedge s\ (Suc\ i) = s\ i + x\ i)\ :]$

lemma *Sum-comp-Sum-sts*: $Sum\text{-}comp = Sum\text{-}sts$

lemmas $ex1 = Sum\text{-}comp\text{-}Sum\text{-}sts$

5.2.6 Section 4.3.2: Characterization of Legal Input Traces

The function legal from the paper is implemented by the function prec in the Isabelle theories

definition $legal\ S = S\ \top$
lemma *legal-prec*: $legal\ S = ((prec\ S)::'a::boolean\text{-}algebra)$

Lemma 8 is proved below.

lemma *legal-RPT*: $legal\ (\{.p.\}\ o\ [:r::'a \Rightarrow 'b \Rightarrow bool:]) = p$

lemma *legal-GPT*: $legal\ (\{:r:]) = (inpt\ r)$

lemma *legal-sts-1*: $legal\ (sts\ init\ r) = (-illegal\text{-}sts\ init\ (inpt\ r)\ r)$

lemma *legal-sts-2*: $legal\ (sts\ init\ r) = (prec\text{-}pre\text{-}sts\ init\ (inpt\ r)\ r)$

lemma *legal-qltl*: $legal\ (qltl\ r) = (inpt\ r)$

lemmas *lemma-8 = legal-RPT legal-GPT legal-sts-1 legal-sts-2 legal-qltl*

Theorem 5. The first result is the associativity of function composition. The second item cannot be expressed as clean as in the paper. In the paper we assume concatenation of tuples that cannot be defined in Isabelle

thm *comp-assoc*

theorem *theorem-5-2*: $S ** (S' ** S'') = [-x,y,z \rightsquigarrow (x,y),\ z-]\ o\ ((S ** S') ** S'')\ o\ [-(x,y),z \rightsquigarrow x,y,z-]$

Theorem 5. The third item is proved next

lemma $(Skip ** Magic)\ o\ (Fail ** Fail) \neq (Skip\ o\ Fail) ** (Magic\ o\ Fail)$

theorem *theorem-5-3-aux*: $p \le inpt\ r \Longrightarrow p' \le inpt\ r' \Longrightarrow ((\{.p.\}\ o\ [:r:]) ** (\{.p'.\}\ o\ [:r':]))\ o\ ((\{.q.\}\ o\ [:s:]) ** (\{.q'.\}\ o\ [:s':]))$
$= ((\{.p.\}\ o\ [:r:])\ o\ (\{.q.\}\ o\ [:s:])) ** ((\{.p'.\}\ o\ [:r':])\ o\ (\{.q'.\}\ o\ [:s':]))$

theorem *theorem-5-3*: $(\{:r:] ** \{:r':])\ o\ ((\{.q.\}\ o\ [:s:]) ** (\{.q'.\}\ o\ [:s':]))$
$= ((\{:r:])\ o\ (\{.q.\}\ o\ [:s:])) ** ((\{:r':])\ o\ (\{.q'.\}\ o\ [:s':]))$

Theorem 5. The fourth result is proved by in Refinement.thy by lemma mono_comp, by lemma prod_ref below and in ReactiveRefinement.thy by lemma Feedback_refin, respectively.

thm *mono-comp*

lemma *prod-ref*: $S \le S' \Longrightarrow T \le T' \Longrightarrow S ** T \le S' ** T'$

lemma *theorem-5-4-c*: $mono\ S \Longrightarrow S \le T \Longrightarrow fdbk\ S \le fdbk\ T$

lemmas *theorem-5 = comp-assoc theorem-5-2 theorem-5-3*
mono-comp prod-ref theorem-5-4-c

lemma *theorem-6*: $(S \le T) = (\forall\ p\ q\ .\ Hoare\ (p::'a::order)\ S\ q \longrightarrow Hoare\ p\ T\ q)$

5.3 Section 5: Symbolic Reasoning

Theorem 7.

definition $sts2qltl\ init\ r = (\lambda\ x\ y\ .\ prec\text{-}pre\text{-}sts\ init\ (inpt\ r)\ r\ x \wedge rel\text{-}pre\text{-}sts\ init\ r\ x\ y)$

thm *prec-pre-sts-def*
thm *rel-pre-sts-def*

theorem *theorem-7-sts-a*: $init\ a \Longrightarrow sts\ init\ r = \{:sts2qltl\ init\ r:]$

theorem *theorem-7-sts*: $init\ a \Longrightarrow sts\ init\ r = qltl\ (sts2qltl\ init\ r)$

lemma *stateless-sts-simp*: $stateless\text{-}sts\ r = \{.(\Box\ (\lambda\ x\ .\ inpt\ r\ (x\ 0))).\}\ o\ [:\ (\Box\ (\lambda\ x\ y.\ r\ (x\ 0)\ (y\ 0))):]$

theorem *theorem-7-stateless-sts-a*: $stateless\text{-}sts\ r = \{:\ (\Box\ (\lambda\ x\ y.\ r\ (x\ (0::nat))\ (y\ (0::nat)))):]$

theorem *theorem-7-stateless-sts*: $stateless\text{-}sts\ r = qltl\ (\Box\ (\lambda\ x\ y.\ r\ (\ x\ (0::nat))\ (y\ (0::nat))))$

lemmas *theorem-7* = *theorem-7-sts theorem-7-stateless-sts*

lemma $stateless\text{-}sts\ (\lambda\ x\ y\ .\ y > x) = qltl\ (\Box\ (\lambda\ x\ y\ .\ y\ (0::nat) > x\ (0::nat)))$

lemma $stateless\text{-}sts\ (\lambda\ x\ (y::unit)\ .\ x > 0) = qltl\ (\Box\ (\lambda\ x\ y\ .\ x\ (0::nat) > 0))$

lemma $UnitDelay = qltl\ (\lambda\ x\ y\ .\ y\ 0 = 0 \wedge (\Box\ (\lambda\ x\ y\ .\ y\ (1::nat) = x\ (0::nat)))\ x\ y)$

5.3.1 Section 5.3: Symbolic Computation of Serial Composition.

Theorem 8 for Equation 13.

theorem *qltl-serial-a*: $r'' = (\lambda\ x\ z\ .\ (\forall\ y\ .\ r\ x\ y \longrightarrow inpt\ r'\ y) \wedge (\exists\ y\ .\ r\ x\ y \wedge r'\ y\ z))$
$\Longrightarrow \{:r:]\ o\ \{:r':] = \{:r'':]$

theorem *qltl-serial*: $r'' = (\lambda\ x\ z\ .\ (\forall\ y\ .\ r\ x\ y \longrightarrow inpt\ r'\ y) \wedge (\exists\ y\ .\ r\ x\ y \wedge r'\ y\ z))$
$\Longrightarrow qltl\ r\ o\ qltl\ r' = qltl\ r''$

Theorem 8 for Equation 14.

definition $sts\text{-}comp\text{-}rel\ r\ r' = (\lambda\ ((u,v),\ x)\ ((u',v'),\ z)\ .\ inpt\ r\ (u,x) \wedge (\forall\ y\ u'\ .\ r\ (u,\ x)\ (u',y)$
$\longrightarrow inpt\ r'\ (v,y)) \wedge (\exists\ y\ .\ r\ (u,x)\ (u',y) \wedge r'\ (v,y)\ (v',z))\ )$

theorem *sts-serial*: $init'\ a \Longrightarrow sts\ init\ r\ o\ sts\ init'\ r' = sts\ (prod\text{-}pred\ init\ init')\ (sts\text{-}comp\text{-}rel\ r\ r')$

Theorem 8 for Equation 15.

theorem *stateless-serial*: $stateless\text{-}sts\ r\ o\ stateless\text{-}sts\ r'$
$= stateless\text{-}sts\ (\lambda\ x\ z\ .\ (\forall\ y\ .\ r\ x\ y \longrightarrow inpt\ r'\ y) \wedge (\exists\ y\ .\ r\ x\ y \wedge r'\ y\ z))$

Theorem 8 for Equation 16.

theorem *det-serial*: $det\text{-}sts\ s0\ p\ state\ out\ o\ det\text{-}sts\ s0'\ p'\ state'\ out'$
$= det\text{-}sts\ (s0,\ s0')\ \ (\lambda\ ((s,s'),x)\ .\ p\ (s,\ x) \wedge p'\ (s',\ out\ (s,\ x)))\ (\lambda\ ((s,s'),x)\ .\ (state\ (s,x),\ state'\ (s',$
$out(s,x))))$
$(\lambda\ ((s,s'),x)\ .\ (out'\ (s',\ out(s,x))))$

Theorem 8 for Equation 17.

theorem *stateless-det-serial*: $stateless\text{-}det\text{-}sts\ p\ out\ o\ stateless\text{-}det\text{-}sts\ p'\ out' =$
$stateless\text{-}det\text{-}sts\ (p \sqcap\ (p'\ o\ out))\ (out'\ o\ out)$

lemmas *theorem-8* = *qltl-serial sts-serial stateless-serial det-serial stateless-det-serial*

definition $C1\text{-}comp = stateless\text{-}sts\ \top$
definition $C2\text{-}comp = stateless\text{-}det\text{-}sts\ (\lambda\ (x,\ y)\ .\ y \neq (0::real))\ \ (\lambda\ (x,\ y)\ .\ x\ /\ y)$

lemma $C1\text{-}comp\ o\ C2\text{-}comp = stateless\text{-}sts\ \bot$

lemma assumes x: $x = (\lambda\ x\ y\ .\ x\ (0::nat))$ **and** y: $y = (\lambda\ x\ y\ .\ y\ (0::nat))$
shows $qltl\ (\Box\ (x \to \Diamond\ y))\ o\ qltl\ (\Box\ \Diamond\ x) = qltl\ (\Box\ \Diamond\ x)$

5.3.2 Section 5.4: Symbolic Computation of Parallel composition

Theorem 9 for Equation 18.

theorem *qltl-parallel-a*: $\{:r:\} ** \{:r':\} = \{:\ (x,x') \rightsquigarrow (y,y')\ .\ r\ x\ y \wedge r'\ x'\ y':\}$

theorem *qltl-parallel-b*: $\{:r:\} *** \{:r':\} = \{:\ x \rightsquigarrow y\ .\ r\ (fst\ o\ x)\ (fst\ o\ y) \wedge r'\ (snd\ o\ x)\ (snd\ o\ y):\}$

theorem *qltl-parallel*: $qltl\ r ** qltl\ r' = qltl\ (\lambda\ (x,\ x')\ (y,\ y').\ r\ x\ y \wedge\ r'\ x'\ y')$

Theorem 9 for Equation 19.

theorem *sts-parallel-a*: $init\ a \Longrightarrow init'\ b \Longrightarrow sts\ init\ r ** sts\ init'\ r' =$
$[-\ (x,\ x') \rightsquigarrow x \mid\mid x'\ -] \circ sts\ (prod\text{-}pred\ init\ init')\ (rel\text{-}prod\text{-}sts\ r\ r')\ o\ [-\ y \rightsquigarrow (fst \circ y,\ snd \circ y)\ -]$

lemma *split-nzip*: $[-\ uv \rightsquigarrow (fst \circ uv,\ snd \circ uv)\ -] \circ [-\ (x,\ x') \rightsquigarrow x \mid\mid x'\ -] = [-id-]$

theorem *sts-parallel*: $init\ a \Longrightarrow init'\ b \Longrightarrow sts\ init\ r *** sts\ init'\ r' = sts\ (prod\text{-}pred\ init\ init')\ (rel\text{-}prod\text{-}sts\ r\ r')$

Theorem 9 for Equation 20.

theorem *stateless-parallel-a*: $stateless\text{-}sts\ r ** stateless\text{-}sts\ r' =$
$[-\ (x,\ x') \rightsquigarrow x \mid\mid x'\ -] \circ stateless\text{-}sts\ (\lambda\ (x,x')\ (y,y')\ .\ r\ x\ y \wedge r'\ x'\ y')\ o\ [-\ y \rightsquigarrow (fst \circ y,\ snd \circ y)\ -]$

theorem *stateless-parallel*: $stateless\text{-}sts\ r *** stateless\text{-}sts\ r' = stateless\text{-}sts\ (\lambda\ (x,x')\ (y,y')\ .\ r\ x\ y \wedge r'\ x'\ y')$

Theorem 9 for Equation 21.

theorem *det-parallel-a*: $(det\text{-}sts\ s0\ p\ state\ out) ** (det\text{-}sts\ s0'\ p'\ state'\ out')$
$= [-\ (x,\ x') \rightsquigarrow x \mid\mid x'\ -] \circ det\text{-}sts\ (s0,\ s0')\ (prec\text{-}prod\text{-}sts\ p\ p')\ (\lambda\ ((s,s'),\ (x,x'))\ .\ (state\ (s,x),\ state'\ (s',x')))$
$(\lambda\ ((s,s'),\ (x,x'))\ .\ (out\ (s,x),\ out'\ (s',x')))\ o\ [-\ y \rightsquigarrow (fst \circ y,\ snd \circ y)\ -]$

theorem *det-parallel*: $(det\text{-}sts\ s0\ p\ state\ out) *** (det\text{-}sts\ s0'\ p'\ state'\ out')$
$= det\text{-}sts\ (s0,\ s0')\ (prec\text{-}prod\text{-}sts\ p\ p')\ (\lambda\ ((s,s'),\ (x,x'))\ .\ (state\ (s,x),\ state'\ (s',x')))$
$(\lambda\ ((s,s'),\ (x,x'))\ .\ (out\ (s,x),\ out'\ (s',x')))$

Theorem 9 for Equation 22.

theorem *stateless-det-parallel-a*: $stateless\text{-}det\text{-}sts\ p\ out ** stateless\text{-}det\text{-}sts\ p'\ out' =$
$[-\ (x,\ x') \rightsquigarrow x \mid\mid x'\ -] \circ stateless\text{-}det\text{-}sts\ (prod\text{-}pred\ p\ p')\ (\lambda\ (x,x')\ .\ (out\ x,\ out'\ x'))\ o\ [-\ y \rightsquigarrow (fst \circ y,\ snd \circ y)\ -]$

theorem *stateless-det-parallel*: $stateless\text{-}det\text{-}sts\ p\ out *** stateless\text{-}det\text{-}sts\ p'\ out' =$
$stateless\text{-}det\text{-}sts\ (prod\text{-}pred\ p\ p')\ (\lambda\ (x,x')\ .\ (out\ x,\ out'\ x'))$

lemmas *theorem-9* = *qltl-parallel sts-parallel stateless-parallel det-parallel stateless-det-parallel*

5.5 Symbolic Computation of Feedback Composition

Theorem 10 for Equation 23.

theorem *det-decomposable-feedback*: $Feedback\ ([-\ u,\ x \rightsquigarrow u \mid\mid x\ -]\ o\ det\text{-}sts\ s0\ p\ state\ (\lambda\ (s,\ (u,x))\ .\ (f\ s\ x,\ g\ u\ s\ x)\ )\ o\ [-\ uy \rightsquigarrow fst\ o\ uy,\ snd\ o\ uy\ -])$
$= det\text{-}sts\ s0\ (\lambda\ (s,x)\ .\ p\ (s,\ (f\ s\ x,\ x)))\ (\lambda\ (s,x)\ .\ state\ (s,\ (f\ s\ x,\ x)))\ (\lambda\ (s,x)\ .\ g\ (f\ s\ x)\ s\ x)$

theorem *det-decomposable-feedback-a*: $fdbk\ (det\text{-}sts\ s0\ p\ state\ (\lambda\ (s,\ (u,x))\ .\ (f\ s\ x,\ g\ u\ s\ x)\ ))$
$= det\text{-}sts\ s0\ (\lambda\ (s,x)\ .\ p\ (s,\ (f\ s\ x,\ x)))\ (\lambda\ (s,x)\ .\ state\ (s,\ (f\ s\ x,\ x)))\ (\lambda\ (s,x)\ .\ g\ (f\ s\ x)\ s\ x)$

Theorem 10 for Equation 24.

theorem *stateless-det-decomposable-feedback*: $Feedback\ ([-\ u,\ x \rightsquigarrow u \mid\mid x\ -]\ o\ stateless\text{-}det\text{-}sts\ p\ (\lambda\ (u,x)\ .\ (f\ x,\ g\ u\ x)\ )\ o\ [-\ uy \rightsquigarrow fst\ o\ uy,\ snd\ o\ uy\ -])$
$= stateless\text{-}det\text{-}sts\ (\lambda\ x\ .\ p\ (f\ x,\ x))\ (\lambda\ x\ .\ g\ (f\ x)\ x)$

theorem *stateless-det-decomposable-feedback-a*: $fdbk\ (stateless\text{-}det\text{-}sts\ p\ (\lambda\ (u,x)\ .\ (f\ x,\ g\ u\ x)\ ))$
$= stateless\text{-}det\text{-}sts\ (\lambda\ x\ .\ p\ (f\ x,\ x))\ (\lambda\ x\ .\ g\ (f\ x)\ x)$

lemmas *theorem-10* = *det-decomposable-feedback-a stateless-det-decomposable-feedback-a*

lemma *Sum-comp* $= det\text{-}sts\ (0{::}nat)\ \top\ (\lambda\ (s,\ y)\ .\ s\ +\ y)\ (\lambda\ (s,\ x)\ .\ s)$

lemma *illegal-sts-top*: $illegal\text{-}sts\ init\ \top = \bot$

lemma *illegal-sts-top-a*: $illegal\text{-}sts\ init\ (\lambda\ x\ .\ True) = \bot$

definition *Nondet-sts* $= sts\ (\lambda\ s\ .\ s = (0{::}nat))\ (\lambda\ (s,\ (x,a{::}unit))\ (s',\ (y,z))\ .\ z = x \wedge y = s \wedge (s' = s \vee s' = s\ +\ 1))$
lemma *Nondet-sts-simp*: $Nondet\text{-}sts = [{:}xa \rightsquigarrow yz\ .\ snd\ o\ yz = fst\ o\ xa \wedge (fst\ o\ yz)\ 0 = 0 \wedge (\forall\ i\ .\ fst\ (yz\ (Suc\ i)) = fst\ (yz\ i) \vee fst\ (yz\ (Suc\ i)) = fst\ (yz\ i)\ +\ 1){:}]$

lemma $fdbk\ Nondet\text{-}sts =\ \{{:}x \rightsquigarrow ((u,\ y),\ x').\, True{:}\} \circ$
$[{:}\ INF\ x.\ (\lambda((u{::}nat \Rightarrow nat,\ y{::}nat{\Rightarrow}nat),\ x{::}nat \Rightarrow unit)\ ((y',\ z),\ x'{::}nat \Rightarrow unit).\ z = u \wedge y'\ 0 = 0 \wedge (\forall i.\ y'\ (Suc\ i) = y'\ i \vee y'\ (Suc\ i) = Suc\ (y'\ i)))\ \hat{}\hat{}\ x\ OO\ eqtop\ (x\ -\ Suc\ 0)\ {:}] \circ$
$[-\ ((u,\ y),\ x) \rightsquigarrow y\ -]$

definition *AND-sts* $= stateless\text{-}det\text{-}sts\ \top\ (\lambda\ (x,y)\ .\ (x \wedge y,\ x \wedge y))$
lemma *AND-sts-simp*: $AND\text{-}sts = [{:}ux \rightsquigarrow vy\ .\ (\forall\ i\ .\ fst\ (vy\ i) = (fst\ (ux\ i) \wedge snd\ (ux\ i)) \wedge snd\ (vy\ i) = (fst\ (ux\ i) \wedge snd\ (ux\ i)))\ {:}]$

lemma *AND-power-simp*: $n > 0 \Longrightarrow (\lambda((u{::}nat \Rightarrow bool,\ y{::}nat \Rightarrow bool),\ x{::}nat \Rightarrow bool)\ ((v,\ z),\ x').\ (\forall i.\ v\ i = (u\ i \wedge x\ i) \wedge z\ i = (u\ i \wedge x\ i)) \wedge x' = x)\ \hat{}\hat{}\ n$
$= (\lambda((u,\ y{::}nat \Rightarrow bool),\ x)\ ((v,\ z),\ x').\ (\forall i.\ v\ i = (u\ i \wedge x\ i) \wedge z\ i = (u\ i \wedge x\ i)) \wedge x' = x)$

lemma *fdbk-AND-sts*: $fdbk\ AND\text{-}sts = \{{:}x \rightsquigarrow\ u,\ x'\ .\ x = x'{:}\} \circ [{:}\ u,\ x \rightsquigarrow z.\ (\forall i.\ z\ i = (u\ i \wedge x\ i))\ {:}]$

lemma *False-fdbk-AND-sts*: $[-x \rightsquigarrow \bot-]\ o\ fdbk\ AND\text{-}sts = [-x \rightsquigarrow \bot-]$

5.3.3 Section 5.8: Checking Validity

Theorem 12 for QLTL components.

theorem *theorem-12-qltl-a*: $(\{:r:] = \mathit{Fail}) = (r = \bot)$

theorem *theorem-12-qltl*: $(\mathit{qltl}\ r = \mathit{Fail}) = (r = \bot)$

Theorem 12 for stateless STS components.

theorem *theorem-12-stateless-sts*: $(\mathit{stateless\text{-}sts}\ r = \mathit{Fail}) = (r = \bot)$

lemmas *theorem-12 = theorem-12-qltl theorem-12-stateless-sts*

Legal inputs

Theorem 13 for Equation 25.

thm *legal-qltl*

Theorem 13 for Equation 26.

lemma *legal-sts*: $\mathit{init}\ a \Longrightarrow \mathit{legal}\ (\mathit{sts}\ \mathit{init}\ r) = \mathit{prec\text{-}pre\text{-}sts}\ \mathit{init}\ (\mathit{inpt}\ r)\ r$

Theorem 13 for Equation 27.

lemma *legal-stateless*: $\mathit{legal}\ (\mathit{stateless\text{-}sts}\ r) = (\Box\ (\lambda x\ .\ \mathit{inpt}\ r\ (x\ (0::\mathit{nat}))))$

Theorem 13 for Equation 28.

lemma *legal-det*: $\mathit{legal}\ (\mathit{det\text{-}sts}\ s0\ p\ \mathit{state}\ \mathit{out}) =$
$\mathit{prec\text{-}pre\text{-}sts}\ (\lambda s.\ s = s0)\ p\ (\lambda(s, x)\ (s', y).\ (s' = \mathit{state}\ (s, x) \wedge y = \mathit{out}\ (s, x)))$

Theorem 13 for Equation 29.

lemma *legal-stateless-det*: $\mathit{legal}\ (\mathit{stateless\text{-}det\text{-}sts}\ p\ \mathit{out}) = \Box\ (\lambda\ x\ .\ p\ (x\ 0))$

lemmas *theorem-13 = legal-qltl legal-sts legal-det legal-stateless legal-stateless-det*

5.3.4 Section 5.10: Checking Refinement Symbolically

lemma *refinement-LocalSystem*: $\mathit{init}' \le \mathit{init} \Longrightarrow p \le p' \Longrightarrow (\bigwedge\ x\ .\ p\ x \Longrightarrow r'\ x \le r\ x) \Longrightarrow \mathit{LocalSystem}\ \mathit{init}\ p\ r \le \mathit{LocalSystem}\ \mathit{init}'\ p'\ r'$

Theorem 14 for STS components.

theorem *refinement-sts*: $\mathit{init}' \le \mathit{init} \Longrightarrow \mathit{inpt}\ r \le \mathit{inpt}\ r' \Longrightarrow (\bigwedge\ x\ .\ \mathit{inpt}\ r\ x \Longrightarrow r'\ x \le r\ x) \Longrightarrow \mathit{sts}\ \mathit{init}\ r \le \mathit{sts}\ \mathit{init}'\ r'$

Theorem 14 for stateless STS components.

theorem *refinement-stateless*: $(\mathit{stateless\text{-}sts}\ r \le \mathit{stateless\text{-}sts}\ r') = ((\mathit{inpt}\ r \le \mathit{inpt}\ r') \wedge ((\forall\ x\ .\ \mathit{inpt}\ r\ x \longrightarrow r'\ x \le r\ x)))$

Theorem 14 for QLTL components.

theorem *refinement-qltl-a*: $(\{:r:] \leq \{:r':]) = ((\forall\ x\ .\ inpt\ r\ x \longrightarrow inpt\ r'\ x) \wedge (\forall\ x\ y\ .\ inpt\ r\ x \wedge r'\ x\ y \longrightarrow r\ x\ y))$

theorem *refinement-qltl*: $(qltl\ r \leq qltl\ r') = ((\forall\ x\ .\ inpt\ r\ x \longrightarrow inpt\ r'\ x) \wedge (\forall\ x\ y\ .\ inpt\ r\ x \wedge r'\ x\ y \longrightarrow r\ x\ y))$

lemmas *theorem-14* = *refinement-sts refinement-stateless refinement-qltl*

Data refinement

Theorem 15.

theorem *theorem-15*:
assumes A: $(\bigwedge\ t\ .\ init'\ t \Longrightarrow \exists\ s\ .\ d\ t\ s \wedge init\ s)$
and B: $\bigwedge\ t\ x\ s.\ d\ t\ s \Longrightarrow inpt\ r\ (s,\ x) \Longrightarrow inpt\ r'\ (t,\ x)$
and C: $\bigwedge\ t\ x\ s\ t'\ y.\ d\ t\ s \Longrightarrow inpt\ r\ (s,\ x) \Longrightarrow r'\ (t,\ x)\ (t',\ y) \Longrightarrow (\exists\, s'.\ d\ t'\ s' \wedge r\ (s,\ x)\ (s',\ y))$
shows $sts\ init\ r \leq sts\ init'\ r'$

Example of stateless sts refinement

lemma $stateless\text{-}sts\ (\lambda\ x\ y\ .\ x \geq 0 \wedge y \geq (x{::}nat)) \leq stateless\text{-}sts\ (\lambda\ x\ y\ .\ x \leq y \wedge y \leq x + 10)$

5.3.5 Proof of refinement for the Oven example

datatype *oven-state* = *on* | *off*

definition $oven\text{-}trs = (\lambda\ ((s{::}nat,sw),\ x{::}unit)\ ((s',sw'),t)\ .\ (t = s) \wedge$
$(if\ sw = on\ then\ s < s' \wedge s' < s + 5\ else\ (if\ s > 10\ then\ s - 5 < s' \wedge s' < s\ else\ s' = s)) \wedge$
$(if\ sw = on \wedge s > 210\ then\ sw' = off\ else$
$(if\ sw = off \wedge s < 190\ then\ sw' = on\ else\ sw' = sw)))$

definition $oven\text{-}init = (\lambda\ (s,\ sw)\ .\ s = (20{::}nat) \wedge sw = on)$

lemma *oven-refinement*: $Oven\text{-}qltl \leq sts\ oven\text{-}init\ oven\text{-}trs$

end

6 Instantaneous Feedback

theory *InstantaneousFeedback* **imports** *../RefinementReactive/Refinement*
begin

datatype *'a fail-option* = *Fail* $(\bullet)$ | *OK* $(elem\ :'a)$

class *order-bot-max* = *order-bot* +
fixes *maximal* :: $'a \Rightarrow bool$
assumes *maximal-def*: $maximal\ x = (\forall\ y\ .\ \neg\ x < y)$
assumes [*simp*]: $\neg\ maximal\ \bot$
begin
lemma *ex-not-le-bot*[*simp*]: $\exists\ a.\ \neg\ a \leq \bot$
end

instantiation *option* :: (*type*) *order-bot-max*
begin
definition *bot-option-def*: $(\bot{::}'a\ option) = None$

definition *le-option-def*: $((x::'a\ option) \leq y) = (x = None \vee x = y)$
definition *less-option-def*: $((x::'a\ option) < y) = (x \leq y \wedge \neg (y \leq x))$
definition *maximal-option-def*: $maximal\ (x::'a\ option) = (\forall\ y .\ \neg\ x < y)$

instance

lemma [*simp*]: $None \leq x$
end

context *order-bot*
begin
definition $is\text{-}lfp\ f\ x = ((f\ x = x) \wedge (\forall\ y .\ f\ y = y \longrightarrow x \leq y))$
definition $emono\ f = (\forall\ x\ y.\ x \leq y \longrightarrow f\ x \leq f\ y)$

definition $Lfp\ f = Eps\ (is\text{-}lfp\ f)$

lemma *lfp-unique*: $is\text{-}lfp\ f\ x \Longrightarrow is\text{-}lfp\ f\ y \Longrightarrow x = y$

lemma *lfp-exists*: $is\text{-}lfp\ f\ x \Longrightarrow Lfp\ f = x$

lemma *emono-a*: $emono\ f \Longrightarrow x \leq y \Longrightarrow f\ x \leq f\ y$

lemma *emono-fix*: $emono\ f \Longrightarrow f\ y = y \Longrightarrow (f\ \hat{}\hat{}\ n)\ \bot \leq y$

lemma *emono-is-lfp*: $emono\ (f::'a \Rightarrow 'a) \Longrightarrow (f\ \hat{}\hat{}\ (n + 1))\ \bot = (f\ \hat{}\hat{}\ n)\ \bot \Longrightarrow is\text{-}lfp\ f\ ((f\ \hat{}\hat{}\ n)\ \bot)$

lemma *emono-lfp-bot*: $emono\ (f::'a \Rightarrow 'a) \Longrightarrow (f\ \hat{}\hat{}\ (n + 1))\ \bot = (f\ \hat{}\hat{}\ n)\ \bot \Longrightarrow Lfp\ f = ((f\ \hat{}\hat{}\ n)\ \bot)$

lemma *emono-up*: $emono\ f \Longrightarrow (f\ \hat{}\hat{}\ n)\ \bot \leq (f\ \hat{}\hat{}\ (Suc\ n))\ \bot$
end

context *order*
begin
definition $min\text{-}set\ A = (SOME\ n .\ n \in A \wedge (\forall\ x \in A .\ n \leq x))$
end

lemma *min-nonempty-nat-set-aux*: $\forall\ A .\ (n::nat) \in A \longrightarrow (\exists\ k \in A .\ (\forall\ x \in A .\ k \leq x))$

lemma *min-nonempty-nat-set*: $(n::nat) \in A \Longrightarrow (\exists\ k .\ k \in A \wedge (\forall\ x \in A .\ k \leq x))$

thm *someI-ex*

lemma *min-set-nat-aux*: $(n::nat) \in A \Longrightarrow min\text{-}set\ A \in A \wedge (\forall\ x \in A .\ min\text{-}set\ A \leq x)$

lemma $(n::nat) \in A \Longrightarrow min\text{-}set\ A \in A \wedge min\text{-}set\ A \leq n$

lemma *min-set-in*: $(n::nat) \in A \Longrightarrow min\text{-}set\ A \in A$

lemma *min-set-less*: $(n::nat) \in A \Longrightarrow min\text{-}set\ A \leq n$

class *fin-cpo* = *order-bot-max* +

assumes *fin-up-chain*: $(\forall\ i{::}\ nat\ .\ a\ i \leq a\ (Suc\ i)) \Longrightarrow \exists\ n\ .\ \forall\ i \geq n\ .\ a\ i = a\ n$
begin
lemma *emono-ex-lfp*: $emono\ f \Longrightarrow \exists\ n\ .\ is\text{-}lfp\ f\ ((f\ \hat{}\hat{}\ n)\ \bot)$

lemma *emono-lfp*: $emono\ f \Longrightarrow \exists\ n\ .\ Lfp\ f = (f\ \hat{}\hat{}\ n)\ \bot$

lemma *emono-is-lfp*: $emono\ f \Longrightarrow is\text{-}lfp\ f\ (Lfp\ f)$

definition $lfp\text{-}index\ (f{::}'a \Rightarrow 'a) = min\text{-}set\ \{n\ .\ (f\ \hat{}\hat{}\ n)\ \bot = (f\ \hat{}\hat{}\ (n + 1))\ \bot\}$

lemma *lfp-index-aux*: $emono\ f \Longrightarrow (\forall\ i < (lfp\text{-}index\ f)\ .\ (f\ \hat{}\hat{}\ i)\ \bot < (f\ \hat{}\hat{}\ (i + 1))\ \bot) \wedge (f\ \hat{}\hat{}\ (lfp\text{-}index\ f))\ \bot = (f\ \hat{}\hat{}\ ((lfp\text{-}index\ f) + 1))\ \bot$

lemma [*simp*]: $emono\ f \Longrightarrow i < lfp\text{-}index\ f \Longrightarrow (f\ \hat{}\hat{}\ i)\ \bot < f\ ((f\ \hat{}\hat{}\ i)\ \bot)$

lemma [*simp*]: $emono\ f \Longrightarrow f\ ((f\ \hat{}\hat{}\ (lfp\text{-}index\ f))\ \bot) = (f\ \hat{}\hat{}\ (lfp\text{-}index\ f))\ \bot$

lemma [*simp*]: $emono\ f \Longrightarrow Lfp\ f = (f\ \hat{}\hat{}\ lfp\text{-}index\ f)\ \bot$

end

declare [[*show-types*]]
instantiation *option* :: (*type*) *fin-cpo*
begin
lemma *fin-up-non-bot*: $(\forall\ i\ .\ (a{::}nat \Rightarrow 'a\ option)\ i \leq a\ (Suc\ i)) \Longrightarrow a\ n \neq \bot \Longrightarrow n \leq i \Longrightarrow a\ i = a\ n$

lemma *fin-up-chain-option*: $(\forall\ i{::}\ nat\ .\ (a{::}nat \Rightarrow 'a\ option)\ i \leq a\ (Suc\ i)) \Longrightarrow \exists\ n\ .\ \forall\ i \geq n\ .\ a\ i = a\ n$

instance
end

instantiation *prod* :: (*order-bot-max*, *order-bot-max*) *order-bot-max*
begin
definition *bot-prod-def*: $(\bot :: 'a \times 'b) = (\bot, \bot)$
definition *le-prod-def*: $(x \leq y) = (fst\ x \leq fst\ y \wedge snd\ x \leq snd\ y)$
definition *less-prod-def*: $((x{::}'a\times'b) < y) = (x \leq y \wedge \neg\ (y \leq x))$
definition *maximal-prod-def*: $maximal\ (x{::}'a \times 'b) = (\forall\ y\ .\ \neg\ x < y)$

instance
end

instantiation *prod* :: (*fin-cpo*, *fin-cpo*) *fin-cpo*
begin

lemma *fin-up-chain-prod*: $(\forall\ i{::}\ nat\ .\ (a{::}nat \Rightarrow 'a \times 'b)\ i \leq a\ (Suc\ i)) \Longrightarrow \exists\ n\ .\ \forall\ i \geq n\ .\ a\ i = a\ n$
instance
end

instantiation *fail-option* :: (*order-bot*) {*order-bot*, *order-top*}

begin
definition *bot-fail-option-def*: $(\bot::'a\ \mathit{fail\text{-}option}) = OK\ \bot$
definition *top-fail-option-def*: $(\top::'a\ \mathit{fail\text{-}option}) = \bullet$
definition *le-fail-option-def*: $((x::'a\ \mathit{fail\text{-}option}) \le y) = ((\mathit{case}\ x\ \mathit{of}\ OK\ a \Rightarrow (\mathit{case}\ y\ \mathit{of}\ OK\ b \Rightarrow a \le b \mid \bullet \Rightarrow \mathit{True}) \mid \bullet \Rightarrow y = \bullet))$
definition *less-fail-option-def*: $((x::'a\ \mathit{fail\text{-}option}) < y) = (x \le y \wedge \neg\ (y \le x))$
instance
end

lemma *maximal-prod-1*: $\mathit{maximal}\ (a,\ b) \Longrightarrow \mathit{maximal}\ a$

lemma *maximal-prod-2*: $\mathit{maximal}\ (a,\ b) \Longrightarrow \mathit{maximal}\ b$

lemma *maximal-prod*: $\mathit{maximal}\ (a,\ b) = (\mathit{maximal}\ a \wedge \mathit{maximal}\ b)$

lemma *drop-assumption*: $p \Longrightarrow \mathit{True}$

lemma *Sup-OO*: $(\mathit{Sup}\ A)\ OO\ r = \mathit{Sup}\ \{x\ .\ \exists\ y{\in}A\ .\ x = y\ OO\ r\}$

lemma *OO-Sup*: $r\ OO\ (\mathit{Sup}\ A) = \mathit{Sup}\ \{x\ .\ \exists\ y{\in}A\ .\ x = r\ OO\ y\}$

lemma *OO-SUP*: $r\ OO\ (\mathit{SUP}\ n\ .\ A\ n) = (\mathit{SUP}\ n\ .\ r\ OO\ (A\ n))$

lemma *SUP-OO*: $(\mathit{SUP}\ n\ .\ A\ n)\ OO\ r = (\mathit{SUP}\ n\ .\ (A\ n)\ OO\ r)$

definition *InstFeedback* $r = (\lambda\ x\ uy\ .\ \mathit{case}\ x\ \mathit{of}\ \bullet \Rightarrow uy = \bullet \mid OK\ z \Rightarrow$
$(\exists\ n\ a\ .\ \ (a\ 0 = \bot) \wedge (\forall\ \ i < n\ .\ a\ i < a\ (\mathit{Suc}\ i)) \wedge (\forall\ \ i < n\ .\ \exists\ y\ .\ r\ (OK\ (a\ i,\ z))\ (OK\ (a\ (\mathit{Suc}\ i),\ y))) \wedge$
$((\exists\ y\ .\ r\ (OK\ (a\ n,\ z))\ (OK\ (a\ (\mathit{Suc}\ n),\ y)) \wedge a\ n = a\ (\mathit{Suc}\ n) \wedge uy = OK\ (a\ (\mathit{Suc}\ n),\ y)) \vee$
$(r\ (OK\ (a\ n,\ z))\ \bullet \wedge uy = \bullet))\ ))$

lemma *InstFeedback-alt*: $\mathit{InstFeedback}\ r = \ (\lambda\ x\ uy\ .\ \mathit{case}\ x\ \mathit{of}\ \bullet \Rightarrow uy = \bullet \mid OK\ z \Rightarrow$
$(\exists\ n\ a\ .\ \ (a\ 0 = \bot) \wedge (\forall\ \ i < n\ .\ a\ i < a\ (\mathit{Suc}\ i) \wedge (\exists\ y\ .\ r\ (OK\ (a\ i,\ z))\ (OK\ (a\ (\mathit{Suc}\ i),\ y)))) \wedge$
$r\ (OK\ (a\ n,\ z))\ uy \wedge (\exists\ y\ .\ uy = OK\ (a\ n,\ y) \vee uy = \bullet)\ ))$

definition *functional* $r\ f\ g = (\forall\ \ u\ x\ z\ .\ r\ (OK\ (u,\ x))\ z = (z = OK(f\ x\ u,\ g\ x\ u)))$

lemma *chain-power*: $a\ 0 = b \Longrightarrow \forall\, i{\le}n.\ a\ (\mathit{Suc}\ i) = f\ (a\ i) \Longrightarrow i \le \mathit{Suc}\ n \Longrightarrow a\ i = (f\ \hat{}\hat{}\ i)\ b$

theorem *InstFeedback-constructive*: $\mathit{emono}\ ((f\ x)::'a::\mathit{fin\text{-}cpo} \Rightarrow 'a) \Longrightarrow \mathit{functional}\ r\ f\ g \Longrightarrow$
$(\mathit{InstFeedback}\ r\ (OK\ x)\ uy) = (uy = \ OK\ (\mathit{Lfp}\ (f\ x),\ g\ x\ (\mathit{Lfp}\ (f\ x))))$

definition *InstFeedback-1* $r = (\lambda\ x\ uy\ .\ \mathit{case}\ x\ \mathit{of}\ \bullet \Rightarrow uy = \bullet \mid OK\ z \Rightarrow$
$(\exists\ a\ .\ \bot < a \wedge (\exists\ y\ .\ r\ (OK\ (\bot,\ z))\ (OK\ (a,\ y))) \wedge r\ (OK\ (a,\ z))\ uy \wedge (\exists\ y\ .\ uy = OK\ (a,\ y) \vee uy = \bullet)\ )$
$\vee\ (r\ (OK\ (\bot,\ z))\ uy \wedge (\exists\ y\ .\ uy = OK\ (\bot,\ y) \vee uy = \bullet)))$

lemma [*simp*]: $(\bot < (a::'a::\mathit{order\text{-}bot})) = (\bot \ne a)$

definition *unkn-mono* $r = (\forall\ \ a\ b\ x\ .\ (a::'a::\mathit{order\text{-}bot}) \le b \longrightarrow (\forall\ \ z\ .\ r\ (OK\ (b,\ x))\ (OK\ z) \longrightarrow r\ (OK\ (a,\ x))\ (OK\ z)))$

lemma *unkn-mono-fb-fun*: $\mathit{unkn\text{-}mono}\ r \Longrightarrow \mathit{InstFeedback\text{-}1}\ r = \mathit{InstFeedback}\ r$

definition *fb-begin* = $(\lambda\ x\ ux\ .\ ux = (case\ x\ of\ \cdot \Rightarrow \cdot \mid OK\ x \Rightarrow OK\ (\bot, x)))$

definition *fb-a* $r = (\lambda\ ux\ ux'\ .\ (case\ ux\ of\ \cdot \Rightarrow ux' = \cdot \mid OK\ (u, x) \Rightarrow$
$(r\ (OK\ (u, x))\ \cdot \wedge ux' = \cdot) \vee (\exists\ u'\ y'\ .\ r\ (OK\ (u, x))\ (OK\ (u', y')) \wedge u < u' \wedge ux' = OK\ (u', x))))$

definition *fb-b* $r = (\lambda\ ux\ uy'\ .\ (case\ ux\ of\ \cdot \Rightarrow uy' = \cdot \mid OK\ (u, x) \Rightarrow$
$(r\ (OK\ (u, x))\ \cdot \wedge uy' = \cdot) \vee (\exists\ y'\ .\ r\ (OK\ (u, x))\ (OK\ (u, y')) \wedge uy' = OK\ (u, y'))))$

definition *fb-end* $= (\lambda\ uy\ y'\ .\ case\ uy\ of\ \cdot \Rightarrow y' = \cdot \mid OK\ (u, y) \Rightarrow (if\ maximal\ u\ then\ y' = OK\ y\ else\ y' = \cdot))$

definition *fb-hide* $r = (InstFeedback\ r)\ OO\ fb\text{-}end$

definition *ff* $r = r\ \cdot\ \cdot$
definition *f-f* $r = (\forall\ x\ .\ r\ \cdot\ x \longrightarrow x = \cdot)$

lemma [*simp*]:$(case\ y\ of\ \cdot \Rightarrow \cdot = \cdot \mid OK\ (u, ya) \Rightarrow (maximal\ u \longrightarrow \cdot = OK\ ya) \wedge (\neg\ maximal\ u \longrightarrow \cdot = \cdot)) = (\forall\ u\ x\ .\ y = OK\ (u, x) \longrightarrow \neg\ maximal\ u)$

lemma [*simp*]: *InstFeedback-1* $r\ \cdot\ \cdot$

lemma [*simp*]: $(case\ y\ of\ \cdot \Rightarrow \cdot = \cdot \mid OK\ (u, v, x) \Rightarrow \cdot = OK\ (v, u, x)) = (y = \cdot)$

lemma *case-b-simp*: $(case\ b\ of\ \cdot \Rightarrow OK\ y = \cdot \mid OK\ (w, u, a) \Rightarrow OK\ y = OK\ ((u, w), a)) = (b \neq \cdot \wedge (case\ b\ of\ OK\ (w, u, a) \Rightarrow y = ((u, w), a)))$

lemma [*simp*]: $(x::'a::order\text{-}bot) \leq \bot \Longrightarrow x = \bot$

definition *mono-fail* $r = (\forall\ a\ b\ x.\ a \leq b \longrightarrow r\ (OK\ (a, x))\ \cdot \longrightarrow r\ (OK\ (b, x))\ \cdot)$

lemma *sconjunctive-comp-simp*: $sconjunctive\ S \Longrightarrow S \circ (INF\ n::nat.\ T\ n) = (INF\ n\ .\ S\ o\ (T\ n))$

lemma *sconj-star-a*: $sconjunctive\ S \Longrightarrow (INF\ n::nat.\ S\ \hat{}\hat{}\ n) \leq gfp\ (\lambda X.\ Skip \sqcap (S \circ X))$

lemma *mono-comp-simp*: $mono\ S \Longrightarrow T \leq T' \Longrightarrow S\ o\ T \leq S\ o\ T'$

lemma *sconj-star-b-aux*: $mono\ S \Longrightarrow u \leq Skip \Longrightarrow u \leq S \circ u \Longrightarrow u \leq S\ \hat{}\hat{}\ n$

lemma *sconj-star-b*: $mono\ S \Longrightarrow gfp\ (\lambda X.\ Skip \sqcap (S \circ X)) \leq (INF\ n::nat.\ S\ \hat{}\hat{}\ n)$

lemma *sconj-star*: $sconjunctive\ S \Longrightarrow gfp\ (\lambda X.\ Skip \sqcap (S \circ X)) = (INF\ n::nat.\ S\ \hat{}\hat{}\ n)$

lemma [*simp*]: $(case\ ya\ of\ \cdot \Rightarrow OK\ y = \cdot \mid OK\ z \Rightarrow p\ z) = (\exists\ z\ .\ ya = OK\ z \wedge p\ z)$

lemma [*simp*]: $((p \longrightarrow q) \wedge p) = (p \wedge q)$

lemma *relpowp-chain*: $\bigwedge\ x\ y\ .\ (R\ \hat{}\hat{}\ n)\ x\ y = (\exists\ a\ .\ (\forall\ i < n\ .\ R\ (a\ i)\ (a\ (Suc\ i))) \wedge x = a\ 0 \wedge y = a\ n)$

lemma [*simp*]: $fb\text{-}a\ r\ \cdot\ x = (x = \cdot)$

lemma [*simp*]: $fb\text{-}a\ r\ (OK\ (u, x))\ (OK\ (u', x')) = ((\exists\ y\ .\ r\ (OK\ (u, x))\ (OK\ (u', y))) \wedge u < u' \wedge x = x')$

lemma [*simp*]: $\mathit{fb\text{-}a}\ r\ (\mathit{OK}\ \mathit{ux})\ \bullet = r\ (\mathit{OK}\ \mathit{ux})\ \bullet$

lemma *fb-a-id*: $\bigwedge\ u\ x\ u'\ x'\ .\ (\mathit{fb\text{-}a}\ r\ \hat{}\hat{}\ n)\ (\mathit{OK}\ (u,\ x))\ (\mathit{OK}\ (u',\ x')) \Longrightarrow x = x'$

lemma *fb-a-id-a*: $(\forall\, i < n.\ \mathit{fb\text{-}a}\ r\ (a\ i)\ (a\ (\mathit{Suc}\ i))) \longrightarrow (\forall\ \ i \le n\ .\ a\ i \ne \bullet \longrightarrow (\mathit{snd}\ (\mathit{elem}\ (a\ i))) = (\mathit{snd}\ (\mathit{elem}\ (a\ 0))))$

lemma *fb-a-id-b*: $(\forall\, i < n.\ \mathit{fb\text{-}a}\ r\ (a\ i)\ (a\ (\mathit{Suc}\ i))) \Longrightarrow (\forall\ \ i \le n\ .\ a\ i \ne \bullet \longrightarrow \mathit{snd}\ (\mathit{elem}\ (a\ i)) = \mathit{snd}\ (\mathit{elem}\ (a\ 0)))$

lemma [*simp*]: $x < y \Longrightarrow x \ne \bullet$

lemma [*simp*]: $\bigwedge\ x\ .\ ((\mathit{fb\text{-}a}\ r)\ \ \hat{}\hat{}\ n)\ \bullet\ x = (x = \bullet)$

lemma *chain-fail*: $\bigwedge\ k\ .\ \forall\, i < n.\ \mathit{fb\text{-}a}\ r\ (a\ i)\ (a\ (\mathit{Suc}\ i)) \Longrightarrow k < n \Longrightarrow a\ (\mathit{Suc}\ k) = \bullet \Longrightarrow a\ n = \bullet$

lemma [*simp*]: $\mathit{OK}\ x < \bullet$

lemma *chain-not-fail*: $a\ 0 \ne \bullet \Longrightarrow \forall\, k.\ a\ (\mathit{Suc}\ k) = \bullet \longrightarrow k < n \longrightarrow (\exists\, j \le k.\ a\ j = \bullet) \Longrightarrow (\forall\ \ i \le n\ .\ a\ i \ne \bullet)$

lemma [*simp*]: $\mathit{fb\text{-}b}\ r\ (\mathit{OK}\ (u,\ x))\ (\mathit{OK}\ (u',\ y)) = (r\ (\mathit{OK}\ (u,\ x))\ (\mathit{OK}\ \ (u',\ y)) \wedge u = u')$

lemma [*simp*]: $\mathit{fb\text{-}b}\ r\ (\mathit{OK}\ (u,\ x))\ \bullet = r\ (\mathit{OK}\ (u,\ x))\ \bullet$

lemma [*simp*]: $\mathit{fb\text{-}b}\ r\ \bullet\ x = (x = \bullet)$

lemma *chain-all-fail*: $\bigwedge\ i\ .\ a\ (0{::}\mathit{nat}) = \bullet \Longrightarrow \forall\, i < n.\ \mathit{fb\text{-}a}\ r\ (a\ i)\ (a\ (\mathit{Suc}\ i)) \Longrightarrow i \le n \Longrightarrow a\ i = \bullet$

theorem *InstFeedback-simp*: $\mathit{InstFeedback}\ r = \mathit{fb\text{-}begin}\ \mathit{OO}\ ((\mathit{fb\text{-}a}\ r)\hat{}{**})\ \mathit{OO}\ (\mathit{fb\text{-}b}\ r)$

lemma *SUP-pointwise*: $(\forall\ \ n\ .\ (S{::}'a \Rightarrow 'b{::}\mathit{complete\text{-}lattice})\ n \le S'\ n) \Longrightarrow (\mathit{SUP}\ n\ .\ S\ n) \le (\mathit{SUP}\ n\ .\ S'\ n)$

lemma *INF-pointwise*: $(\forall\ \ n\ .\ (S{::}'a \Rightarrow 'b{::}\mathit{complete\text{-}lattice})\ n \le S'\ n) \Longrightarrow (\mathit{INF}\ n\ .\ S\ n) \le (\mathit{INF}\ n\ .\ S'\ n)$

definition $\mathit{faila}\ r\ x = ((r\ (\mathit{OK}\ x)\ \bullet){::}\mathit{bool})$
definition $\mathit{rela}\ r\ x\ y = (r\ (\mathit{OK}\ x)\ (\mathit{OK}\ y))$
definition $\mathit{preca}\ r = -\mathit{faila}\ r$

definition $\mathit{wp}\ r = \{.\mathit{preca}\ r.\}\ o\ [:\mathit{rela}\ r:]$

lemma $(\mathit{wp}\ r \le \mathit{wp}\ r') = ((\forall\, x\ .\ r'\ (\mathit{OK}\ x)\ \bullet \longrightarrow r\ (\mathit{OK}\ x)\ \bullet) \wedge (\forall\, x.\ \neg\ r\ (\mathit{OK}\ x)\ \bullet \longrightarrow (\forall\, y.\ r'\ (\mathit{OK}\ x)\ (\mathit{OK}\ y) \longrightarrow r\ (\mathit{OK}\ x)\ (\mathit{OK}\ y))))$

definition $\mathit{Fb\text{-}a}\ S = [:u,x \rightsquigarrow (u',x'),\ x''\ .\ u' = u \wedge x' = x \wedge x'' = x:]\ o\ ((S\ \|\ [:u,x \rightsquigarrow v,y\ .\ u < v:])\ {**}\ \mathit{Skip})\ o\ [:(v,y),\ x \rightsquigarrow v',x'\ .\ v' = v \wedge x' = x:]$

thm *fusion-spec*

thm *Prod-spec-Skip*

lemma $wp\ (fb\text{-}a\ r) = Fb\text{-}a\ (wp\ r)$

lemma $ff\ r \Longrightarrow (wp\ r \le wp\ r') = (\forall\ \ x\ .\ r\ x \bullet \vee r'\ x \le r\ x)$

lemma $[simp]$: $preca\ (op\ =) = \top$

lemma $[simp]$: $(rela\ (op\ =)) = (op\ =)$

lemma $[simp]$: $wp\ (op\ =) = Skip$

lemma $mono\ (wp\ r)$

definition $serial\ r\ r' = (r\ OO\ r')$

lemma $pred\text{-}bot\text{-}comp$: $ff\ r \Longrightarrow ff\ r' \Longrightarrow\ preca\ (r\ OO\ r') = (\lambda x.\ preca\ r\ x \wedge (\forall\, y.\ rela\ r\ x\ y \longrightarrow preca\ r'\ y))$

lemma $fb\text{-}a\text{-}not\text{-}fail\text{-}fail\text{-}simp$: $fb\text{-}a\ r\ (OK\ (u,\ x)) \bullet = (r\ (OK\ (u,\ x)) \bullet)$

lemma $fb\text{-}b\text{-}not\text{-}fail\text{-}simp$: $fb\text{-}b\ r\ (OK\ (u,\ x))\ (OK\ (u',\ y')) = (u = u' \wedge r\ (OK\ (u,\ x))\ (OK\ (u',\ y')))$

lemma $fb\text{-}b\text{-}fail\text{-}simp$: $fb\text{-}b\ r\ (OK\ (u,\ x)) \bullet = r\ (OK\ (u,\ x)) \bullet$

lemma $refine\text{-}fba\text{-}a$: $wp\ r \le wp\ r' \Longrightarrow wp\ (fb\text{-}a\ r) \le wp\ (fb\text{-}a\ r')$

lemma $refine\text{-}fba\text{-}b'$: $wp\ r \le wp\ r' \Longrightarrow wp\ (fb\text{-}b\ r) \le wp\ (fb\text{-}b\ r')$

lemma $rel\text{-}bot\text{-}comp$: $(preca\ r\ x \wedge rela\ (r\ OO\ r')\ x\ y) = (preca\ r\ x \wedge (rela\ r\ OO\ rela\ r')\ x\ y)$

lemma $prec\text{-}demonic$: $\{.p \sqcap q.\}\ o\ [:r:] = \{.p \sqcap q.\}\ o\ [:x \leadsto y\ .\ p\ x \wedge r\ x\ y:]$

lemma $wp\text{-}refine$: $(wp\ r \le wp\ r') = (preca\ r \le preca\ r' \wedge (\forall\ \ x\ .\ preca\ r\ x \longrightarrow rela\ r'\ x \le rela\ r\ x))$

lemma $wp\text{-}comp$: $ff\ r \Longrightarrow ff\ r' \Longrightarrow wp\ (r\ OO\ r') = ((wp\ r)\ o\ (wp\ r'))$

lemma $not\text{-}maximal\text{-}prod$: $(\neg\ maximal\ (a,\ b)) = (\neg\ maximal\ a \vee \neg\ maximal\ b)$

lemma $[simp]$: $ff\ fb\text{-}end$

lemma $refine\text{-}left$: $S \le S' \Longrightarrow S\ o\ T \le S'\ o\ T$

lemma $prec\text{-}SUP$: $preca\ (SUP\ n\ .\ r\ n) = (INF\ n\ .\ preca\ (r\ n))$

lemma $rel\text{-}SUP$: $rela\ (SUP\ n\ .\ r\ n) = (SUP\ n\ .\ rela\ (r\ n))$

lemma $INF\text{-}spec$: $(INF\ n\ .\ \{.p\ n.\}\ o\ [:(r\ n)::('a \Rightarrow 'b \Rightarrow bool):]) = \{.INF\ n\ .\ p\ n.\}\ o\ [:SUP\ n\ .\ r\ n:]$

lemma $wp\text{-}SUP$: $wp\ (SUP\ n\ .\ r\ n) = (INF\ n\ .\ wp\ (r\ n))$

thm $wp\text{-}def$

lemma $demonic\text{-}choice$: $[:r:] \sqcap [:r':] = [:r \sqcup r':]$

term $(f::'a \Rightarrow 'b)\ \hat{}\hat{}\ n$

thm *funpow-times-power*

lemma *le-power*: $mono\ g \Longrightarrow (f{::}'a{::}order \Rightarrow 'a{::}order) \le g \Longrightarrow f\ \hat{}\hat{}\ n \le g\ \hat{}\hat{}\ n$

lemma [*simp*]: $mono\ (wp\ r)$

lemma [*simp*]: $ff\ r \Longrightarrow ff\ ((r{::}'a\ fail\text{-}option \Rightarrow 'a\ fail\text{-}option \Rightarrow bool)\ \hat{}\hat{}\ n)$

lemma *wp-power*: $ff\ r \Longrightarrow wp\ ((r{::}\ 'a\ fail\text{-}option \Rightarrow 'a\ fail\text{-}option \Rightarrow bool)\ \hat{}\hat{}\ n) = (wp\ r)\ \hat{}\hat{}\ n$

lemma *wp-power-refin*: $ff\ r \Longrightarrow ff\ r' \Longrightarrow wp\ (r{::}'a\ fail\text{-}option \Rightarrow 'a\ fail\text{-}option \Rightarrow bool) \le wp\ r' \Longrightarrow wp\ (r\hat{}\hat{}n) \le wp\ (r'\hat{}\hat{}n)$

thm *INF-lower*

lemma *wp-rt-refine*: $ff\ r \Longrightarrow ff\ r' \Longrightarrow wp\ r \le wp\ r' \Longrightarrow wp\ (r\hat{}{**}) \le wp\ (r'\hat{}{**})$

lemma [*simp*]: $ff\ fb\text{-}begin$

lemma [*simp*]: $ff\ (fb\text{-}a\ r)$

lemma [*simp*]: $ff\ (fb\text{-}b\ r)$

lemma [*simp*]: $ff\ ((fb\text{-}a\ r)^{**})$

lemma [*simp*]: $ff\ r \Longrightarrow ff\ r' \Longrightarrow ff\ (r\ OO\ r')$

theorem *InstFeedback-refine*: $ff\ r \Longrightarrow ff\ r' \Longrightarrow wp\ r \le wp\ r' \Longrightarrow wp\ (InstFeedback\ r) \le wp\ (InstFeedback\ r')$

lemma [*simp*]: $ff\ r \Longrightarrow ff\ (InstFeedback\ r)$

theorem *fb-hide-refine*: $ff\ r \Longrightarrow ff\ r' \Longrightarrow wp\ r \le wp\ r' \Longrightarrow wp\ (fb\text{-}hide\ r) \le wp\ (fb\text{-}hide\ r')$

definition $cross\text{-}prod\ r\ r' = \ (\lambda\ ux\ vy\ .\ (case\ ux\ of\ \bullet \Rightarrow vy = \bullet \mid OK\ (u{::}'a{::}order\text{-}bot,\ x) \Rightarrow$
$(\exists\ v\ y\ .\ vy = OK\ (v,\ y) \wedge r\ (OK\ x)\ (OK\ v) \wedge r'\ (OK\ u)\ (OK\ y))$
$\vee (vy = \bullet \wedge r\ (OK\ x)\ \bullet) \vee\ (vy = \bullet \wedge r'\ (OK\ u)\ \bullet)\ \ ))$

definition $InstFeedback\text{-}cross\text{-}prod\ r\ r' = (\lambda\ x\ vy.\ (case\ x\ of\ \bullet \Rightarrow vy = \bullet \mid OK\ x \Rightarrow$
$(\exists\ v\ y\ .\ vy = OK\ (v,\ y) \wedge r\ (OK\ x)\ (OK\ v) \wedge r'\ (OK\ v)\ (OK\ y)) \vee$
$(vy = \bullet \wedge r\ (OK\ x)\ \bullet) \vee (\exists\ v\ .\ vy = \bullet \wedge r\ (OK\ x)\ (OK\ v) \wedge r'\ (OK\ v)\ \bullet\ )\ \ \ ))$

lemma [*simp*]: $(\bullet < x) = False$

type-synonym $('a,\ 'b)\ fail\text{-}pair = (('a\ option) \times ('b))\ fail\text{-}option$
type-synonym $('a,\ 'b,\ 'c)\ fail\text{-}pair\text{-}rel = ('a,'c)\ fail\text{-}pair \Rightarrow ('a,'b)\ fail\text{-}pair \Rightarrow bool$

lemma [*simp*]: $op = \sqcup fba\text{-}a\ r \sqcup (op = OO\ fba\text{-}a\ r)\ OO\ fba\text{-}a\ r \sqcup ((op = OO\ fba\text{-}a\ r)\ OO\ fba\text{-}a\ r)\ OO\ fba\text{-}a\ r \le (SUP\ n.\ fba\text{-}a\ r\ \hat{}\hat{}\ n)$

lemma *all-fail*: $\forall\, i{<}xb.\ fb\text{-}a\ r\ (a\ i)\ (a\ (Suc\ i)) \Longrightarrow a\ 0 = \bullet \Longrightarrow \forall\ i \le xb\ .\ a\ i = \bullet$

lemma *fba-a-pair*: $(fb\text{-}a\ (r :: ('a,'b,'c)\ fail\text{-}pair\text{-}rel))\hat{}{**} = ((op{=}) \sqcup fb\text{-}a\ r \sqcup (fb\text{-}a\ r)\ \hat{}\hat{}\ (Suc\ (Suc$

0)))

lemma [*simp*]: *ff* (*cross-prod* r r')

lemma [*simp*]: *fb-begin* $\cdot$ x = (x = $\cdot$)

lemma [*simp*]: *InstFeedback-cross-prod* r r' $\cdot$ x = (x = $\cdot$)

definition *complete* $r = (\forall\ x\ .\ \exists\ y\ .\ r\ x\ y)$
definition *fail-mono* $r = (\forall\ x\ y\ .\ x \leq y \wedge r\ x\ \cdot \longrightarrow r\ y\ \cdot)$

definition *unkn-not-fail* $r = (\neg\ r\ (OK\ \bot)\ \cdot)$

lemma [*simp*]: *unkn-not-fail* $r' \Longrightarrow$ *cross-prod* $r\ r'\ (OK\ (\bot,\ x2))\ \cdot \Longrightarrow$ *InstFeedback-cross-prod* $r\ r'\ (OK\ x2)\ \cdot$

lemma [*simp*]: *cross-prod* $r\ r'\ (OK\ (ab,\ bb))\ (OK\ (ab,\ c)) \Longrightarrow$ *InstFeedback-cross-prod* $r\ r'\ (OK\ bb)\ (OK\ (ab,\ c))$

lemma [*simp*]: $OK\ (\bot,\ \bot) < OK\ (\bot,\ Some\ a)$

lemma [*simp*]: $OK\ (\bot,\ \bot) < OK\ (Some\ a,\ \bot)$

lemma [*simp*]: $OK\ (\bot,\ \bot) < OK\ (Some\ a,\ Some\ b)$

lemma [*simp*]: $OK\ (None,\ None) < OK\ (Some\ a,\ y)$

lemma *move-down*: $p \Longrightarrow p$

lemma [*simp*]: $None < Some\ a$

lemma [*simp*]: $\bot < Some\ a$

thm *InstFeedback-cross-prod-def*

thm *unkn-not-fail-def*
thm *complete-def*

lemma *f-f-fb-begin*: *f-f fb-begin*

lemma *f-f-fb-a*: *f-f* (*fb-a* r)

lemma *f-f-fb-b*: *f-f* (*fb-b* r)

lemma *f-f-comp*: *f-f* $r \Longrightarrow$ *f-f* $r' \Longrightarrow$ *f-f* (r *OO* r')

lemma [*simp*]: $(fb\text{-}a\ r)^{**}\ \cdot\ x = (x = \cdot)$

lemma *f-f-InstFeedback*: *f-f* (*InstFeedback* r)

lemma *InstFeedback-cross-prod-aux*: *complete* $r' \Longrightarrow$ *unkn-not-fail* $r' \Longrightarrow$ *InstFeedback-cross-prod* $r\ r'\ x\ xa \Longrightarrow$ *InstFeedback* (*cross-prod* $r\ r'$) $x\ xa$

theorem *InstFeedback-cross-prod*: $complete\ r' \Longrightarrow unkn\text{-}not\text{-}fail\ r' \Longrightarrow InstFeedback\ (cross\text{-}prod\ r\ r') = InstFeedback\text{-}cross\text{-}prod\ r\ r'$

lemma [*simp*]: $OK\ (Some\ a,\ None) < OK\ (Some\ a,\ Some\ aa)$

thm *fb-hide-def*
thm *fb-end-def*

definition $fb\text{-}end\text{-}ukn = (\lambda uy\ y'.\ case\ uy\ of\ \bullet \Rightarrow y' = \bullet \mid OK\ (u,\ y) \Rightarrow y' = OK\ y)$

definition $fb\text{-}hide\text{-}cross\text{-}prod\ r\ r' = (\lambda\ x\ y.\ (case\ x\ of\ \bullet \Rightarrow y = \bullet \mid OK\ x \Rightarrow (\exists\ v\ .\ r\ (OK\ x)\ (OK\ (Some\ v)) \wedge r'\ (OK\ (Some\ v))\ y) \vee (y = \bullet \wedge (r\ (OK\ x)\ \bullet \vee r\ (OK\ x)\ (OK\ \bot)))))$

lemma [*simp*]: $InstFeedback\text{-}cross\text{-}prod\ r\ r'\ \bullet\ y = (y = \bullet)$

lemma [*simp*]: $ff\ r \Longrightarrow f\text{-}f\ r \Longrightarrow (r\ \bullet\ x) = (x = \bullet)$

lemma *rel-union*: $rela\ (r \sqcup r') = rela\ r \sqcup rela\ r'$

lemma *prec-union*: $preca\ (r \sqcup r') = preca\ r \sqcap preca\ r'$

lemma $wp\ (r \sqcup r') = wp\ r \sqcap wp\ r'$

lemma *chain-OK*: $\bigwedge\ a'\ b'\ .\ \forall i{<}n.\ aa\ i < aa\ (Suc\ i) \Longrightarrow aa\ 0 = OK\ (a,\ b) \Longrightarrow aa\ n = OK\ (a',\ b') \Longrightarrow (\exists\ u\ y\ .\ \forall\ i \le n\ .\ aa\ i = OK\ (u\ i,\ y\ i))$

lemma [*simp*]: $maximal\ (None) = False$

lemma [*simp*]: $maximal\ u = (u \neq None)$

lemma [*simp*]: $OK\ (\bot,\ \bot) \le OK\ (a,\ b)$

thm *InstFeedback-cross-prod-def*

lemma *fb-hide-cross-proda*: $complete\ r' \Longrightarrow unkn\text{-}not\text{-}fail\ r' \Longrightarrow fb\text{-}hide\ (cross\text{-}prod\ r\ r')\ x\ y = fb\text{-}hide\text{-}cross\text{-}prod\ r\ r'\ x\ y$

6.1 Examples

definition $havoc\ x\ y = (maximal\ x \longrightarrow maximal\ y)$

definition $EQ = (\lambda\ ux\ vy\ .\ vy = (case\ ux\ of\ \bullet \Rightarrow \bullet \mid OK\ ((u{::}'a\ option),\ x) \Rightarrow OK\ (u,\ u)\ ))$

lemma [*simp*]: $(a{::}'a{::}order) < a = False$

lemma *fb-hide-fun-EQ*: $InstFeedback\ EQ\ x\ uy = (uy = (case\ x\ of\ \bullet \Rightarrow \bullet \mid \text{-} \Rightarrow OK\ (\bot,\bot)))$

lemma $fb\text{-}hide\ EQ\ x\ y = (y = \bullet)$

definition $TRUEa = (\lambda\ ux\ vy\ .\ (case\ ux\ of\ \bullet \Rightarrow vy = \bullet \mid OK\ ((u{::}'a\ option),\ x) \Rightarrow (\exists\ v\ .\ vy = OK\ (v,\ v) \wedge (u \neq None \longrightarrow v \neq None))\ ))$

lemma *move-assumption*: $p \Longrightarrow p$

lemma *fb-hide-fun-TRUEa*: $InstFeedback\ TRUEa\ x\ uy = \ (case\ x\ of\ \bullet \Rightarrow uy = \bullet \mid \text{-} \Rightarrow (\exists\ u\ .\ uy = OK\ (u,\ u)))$

lemma $fb\text{-}hide\ TRUEa\ x\ y = (case\ x\ of\ \bullet \Rightarrow y = \bullet \mid \text{-} \Rightarrow (y = \bullet \vee (\exists\ u\ .\ maximal\ u \wedge y = OK\ u)))$

definition $TRUE = (\lambda\ ux\ vy\ .\ (case\ ux\ of\ \bullet \Rightarrow vy = \bullet \mid OK\ ((u{::}'a\ option),\ x) \Rightarrow (\exists\ u\ .\ vy = OK\ (u,\ u))\ ))$

lemma *fb-hide-fun-TRUE*: $InstFeedback\ TRUE\ x\ uy = \ (case\ x\ of\ \bullet \Rightarrow uy = \bullet \mid \text{-} \Rightarrow (\exists\ u\ .\ uy = OK\ (u,\ u)))$

lemma $fb\text{-}hide\ TRUE\ x\ y = (case\ x\ of\ \bullet \Rightarrow y = \bullet \mid \text{-} \Rightarrow (y = \bullet \vee (\exists\ u\ .\ maximal\ u \wedge y = OK\ u)))$

definition $NEQ = (\lambda\ ux\ vy\ .\ (case\ ux\ of\ \bullet \Rightarrow vy = \bullet \mid OK\ (u,\ x) \Rightarrow$
$(\exists\ v\ .\ vy = OK\ (v,\ v) \wedge ((u = None \longrightarrow v = None) \wedge (u \neq None \longrightarrow u \neq v)))))$

definition $NEQ2 = (\lambda\ ux\ vy\ .\ (case\ ux\ of\ \bullet \Rightarrow vy = \bullet \mid OK\ (u,\ x) \Rightarrow$
$(\exists\ v\ .\ vy = OK\ (v,\ v) \wedge ((u = None \longrightarrow v = None) \wedge (u \neq None \longrightarrow u \neq v \wedge v \neq None)))))$

lemma *fb-hide-fun-NEQ2*: $InstFeedback\ NEQ2\ x\ uy = (case\ x\ of\ \bullet \Rightarrow uy = \bullet \mid \text{-} \Rightarrow uy = OK\ (None,\ None))$

lemma *fb-hide-fun-NEQ*: $InstFeedback\ NEQ\ x\ uy = (case\ x\ of\ \bullet \Rightarrow uy = \bullet \mid \text{-} \Rightarrow uy = OK\ (None,\ None))$

lemma $fb\text{-}hide\ NEQ\ x\ y = (y = \bullet)$

lemma $fb\text{-}hide\ NEQ2\ x\ y = (y = \bullet)$

definition $rel\text{-}bot\text{-}true\ r = (\forall\ x\ y\ .\ \neg\ maximal\ x \longrightarrow r\ x\ y)$
definition $rel\text{-}maximal\ r = (\forall\ x\ y\ .\ r\ x\ y \wedge maximal\ x \longrightarrow maximal\ y)$

definition $assert\text{-}rel\ p\ x\ y = (if\ p\ x\ then\ y = x\ else\ y = \bot)$

definition $comp\text{-}rel\ r\ r'\ x\ y = (if\ r\ x\ \bot\ then\ y = \bot\ else\ (\exists\ z\ .\ r\ x\ z \wedge r'\ z\ y))$

definition $AND\ x\ y = (case\ (x,y)\ of\ (Some\ a,\ Some\ b) \Rightarrow Some\ (a \wedge b)$
$\mid (None,\ Some\ False) \Rightarrow Some\ False \mid (Some\ False,\ None) \Rightarrow Some\ False \mid \text{-} \Rightarrow None)$

definition $AND\text{-}rel\ ux\ vy = (case\ ux\ of\ \bullet \Rightarrow vy = \bullet \mid OK\ (u,\ x) \Rightarrow vy = OK\ (AND\ u\ x,\ AND\ u\ x))$

lemma [*simp*]: *ff AND-rel*

lemma [*simp*]: $((None,\ Some\ a) \leq (None,\ None)) = False$

lemma [*simp*]: *AND-rel* (*OK* (*u*, *Some False*)) (*OK* (*v*, *y*)) = ((*v* = *Some False*) $\wedge$ (*y* = *Some False*))

lemma [*simp*]: *AND-rel* (*OK* (*Some False*, *u*)) (*OK* (*v*, *y*)) = ((*v* = *Some False*) $\wedge$ (*y* = *Some False*))

lemma *AND-comute*: *AND x y* = *AND y x*

lemma *AND-rel-comute*: *AND-rel* (*OK* (*x*, *y*)) = *AND-rel* (*OK* (*y*, *x*))

lemma [*simp*]: *AND-rel* (*OK x*) $\bullet$ = *False*

lemma *fb-hide-fun-AND*: *InstFeedback AND-rel x uy* = (*case x of* $\bullet \Rightarrow$ *uy* = $\bullet$ | *OK* (*Some False*) $\Rightarrow$ *uy* = *OK* (*Some False*, *Some False*) | - $\Rightarrow$ (*uy* = *OK* ($\perp$, $\perp$)))

lemma *fb-hide AND-rel x y* = (*case x of* $\bullet \Rightarrow$ *y* = $\bullet$ | *OK* (*Some False*) $\Rightarrow$ *y* = *OK* (*Some False*) | - $\Rightarrow$ *y* = $\bullet$)

definition *AND-rel2a* = (λ ((*w*, *u*),*x*) ((*v*, *w'*), *y*) . (*v* = *AND u x*) $\wedge$ (*w* = *w'*) $\wedge$ (*v* = *y*))

definition *AND-rel2 wux vwy* = (*case wux of* $\bullet \Rightarrow$ *vwy* = $\bullet$ | *OK* ((*w*, *u*), *x*) $\Rightarrow$ *vwy* = *OK* ((*AND u x*, *w*), *AND u x*))

lemma [*simp*]: *ff AND-rel2*

lemma [*simp*]: *AND-rel2* (*OK* ((*w*, *u*), *Some False*)) (*OK* ((*v*, *w'*), *c*)) = (*v* = *Some False* $\wedge$ *w* = *w'* $\wedge$ *Some False* = *c*)

lemma [*simp*]: *AND-rel2* (*OK* (*a*, *Some False*)) (*OK* (*b*, *c*)) = (*fst b* = *Some False* $\wedge$ *fst a* = *snd b* $\wedge$ *Some False* = *c*)

thm *f-f-def*

lemma [*simp*]: $\bigwedge$*u x* . ($\bigwedge$ *u* . *preca r* (*u*, *x*)) $\Longrightarrow$ (*fb-a r* ^^ *n*) (*OK* (*u*, *x*)) $\bullet$ = *False*

lemma [*simp*]: *preca AND-rel2 x*

lemma [*simp*]:*AND-rel2* (*OK x*) $\bullet$ = *False*

lemma [*simp*]: *AND None None* = *None*

lemma [*simp*]: *AND* (*Some True*) (*Some True*) = (*Some True*)

lemma [*simp*]: *AND* (*Some False*) *x* = (*Some False*)

lemma [*simp*]: *AND x* (*Some False*) = (*Some False*)

lemma [*simp*]: *AND-rel2* (*OK* ((*None*, *None*), *None*)) (*OK* ((*v*, *w*), *y*)) = (*v* = *None* $\wedge$ *v* = *y* $\wedge$ *v* = *w*)

lemma [*simp*]: $AND\text{-}rel2\ (OK\ ((None,\ Some\ a),\ None))\ (OK\ ((u,\ w),\ y)) = \ (u = AND\ (Some\ a)\ None \wedge y = AND\ (Some\ a)\ None \wedge w = None)$

lemma [*simp*]: $AND\text{-}rel2\ (OK\ ((None,\ None),\ Some\ True))\ (OK\ ((v,\ w),\ y)) = (v = AND\ None\ (Some\ True) \wedge y = AND\ None\ (Some\ True) \wedge w = None)$

lemma [*simp*]: $AND\text{-}rel2\ (OK\ ((None,\ None),\ Some\ False))\ (OK\ ((v,\ w),\ y)) = (v = Some\ False \wedge y = Some\ False \wedge w = None)$

lemma [*simp*]: $AND\text{-}rel2\ (OK\ ((Some\ False,\ w),\ Some\ False))\ (OK\ ((v,\ w'),\ y)) = (v = Some\ False \wedge w' = Some\ False \wedge y = Some\ False)$

lemma *AND2-simp*: $AND\text{-}rel2\ (OK\ (((u{::}'a\ option),\ w),\ x))\ (OK\ ((v,\ w'),\ y)) = (v = AND\ w\ x \wedge w' = u \wedge y = AND\ w\ x)$

lemma [*simp*]: $AND\text{-}rel2\ (OK\ ((None,\ None),\ x))\ (OK\ ((v,\ w),\ y)) = (v = AND\ None\ x \wedge w = None \wedge y = AND\ None\ x)$

lemma *chain-triple*: $x < y \Longrightarrow y < z \Longrightarrow z < w \Longrightarrow w < OK\ ((a{::}'a\ option\ ,\ b{::}'b\ option),\ c{::}'c\ option) \Longrightarrow False$

lemma [*simp*]: $AND\text{-}rel2\ (OK\ ((None,\ None),\ None))\ (OK\ ((v,\ w),\ y)) = \ (v = None \wedge w = None \wedge y = None)$

definition *rel-and* $a\ b = \ (if\ a = None\ then\ b = None \vee b = Some\ True\ else\ a = b)$

lemma [*simp*]: $\exists\, b\ ba.\ None = AND\ b\ ba$

lemma [*simp*]:$(\exists\, b.\ None = AND\ (Some\ True)\ b)$

lemma [*simp*]: $OK\ (\bot,\ \bot) < OK\ ((Some\ False,\ Some\ False),\ Some\ False)$

lemma [*simp*]: $OK\ (\bot,\ \bot) < OK\ ((Some\ True,\ Some\ True),\ Some\ True)$

lemma [*simp*]: $\exists\, b\ ba.\ Some\ False = AND\ b\ ba$

lemma [*simp*]: $\exists\, b\ ba.\ Some\ x = AND\ b\ ba$

lemma [*simp*]: $\exists\, ba.\ Some\ True = AND\ (Some\ True)\ ba$

lemma [*simp*]: $(((\bot),\ \bot) < (\bot,\ None)) = False$
lemma [*simp*]: $\exists\, b.\ Some\ False = AND\ b\ (Some\ True)$

lemma [*simp*]: $\exists\, b.\ Some\ True = AND\ b\ (Some\ True)$

lemma *OK-less-less*: $(OK\ x < OK\ y) = (x < y)$

lemma *fba-a-chain*: $\bigwedge u'\ .\ n > 0 \Longrightarrow (fb\text{-}a\ r\ \hat{}\hat{}\ n)\ (OK\ (u,\ x))\ (OK\ (u',\ x')) \Longrightarrow u < (u'{::}'a{::}order)$

lemma *fb-hide-and-eq*: $InstFeedback\ (AND\text{-}rel2)\ (OK\ x)\ (OK\ ((v,\ w),\ y)) \Longrightarrow v = y$

lemma [*simp*]: $InstFeedback\ (AND\text{-}rel2)\ (OK\ None)\ (OK\ ((None,\ Some\ False),\ None)) = False$

lemma [*simp*]: *InstFeedback AND-rel2* (*OK None*) (*OK* ((*None*, *None*), *None*))

lemma [*simp*]: *InstFeedback AND-rel2* (*OK None*) (*OK* ((*None*, *Some True*), *None*)) = *False*

lemma [*simp*]: *InstFeedback AND-rel2* (*OK None*) (*OK* ((*Some False*, *None*), *Some False*)) = *False*

lemma [*simp*]: *InstFeedback AND-rel2* (*OK None*) (*OK* ((*Some False*, *Some True*), *Some False*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK None*) (*OK* ((*Some False*, *Some False*), *Some False*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK None*) (*OK* ((*Some True*, *Some True*), *Some True*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK None*) (*OK* ((*Some True*, *None*), *Some True*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK None*) (*OK* ((*Some True*, *Some False*), *Some True*)) = *False*

lemma *fb-and-wire-bot*: *InstFeedback* (*AND-rel2*) (*OK None*) (*OK* ((*v*, *w*), *y*)) = (v = y ∧ v = w ∧ v = *None*)

lemma *fb-and-wire-false*: *InstFeedback* (*AND-rel2*) (*OK* (*Some False*)) (*OK* ((*v*, *w*), *y*)) = (v = *Some False* ∧ w = v ∧ y = v)

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*None*, *Some False*), *None*)) = *False*

lemma [*simp*]: (∃ *b*. *None* = *AND b* (*Some True*))

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*None*, *None*), *None*))

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*None*, *Some True*), *None*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*Some False*, *None*), *Some False*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*Some False*, *Some True*), *Some False*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*Some False*, *Some False*), *Some False*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*Some True*, *Some True*), *Some True*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*Some True*, *None*), *Some True*)) = *False*

lemma [*simp*]: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*Some True*, *Some False*), *Some True*)) = *False*

lemma *fb-and-wire-true*: *InstFeedback* (*AND-rel2*) (*OK* (*Some True*)) (*OK* ((*v*, *w*), *y*)) = ($v = y \wedge v = w \wedge v = None$)

thm *fb-and-wire-true*
thm *fb-and-wire-false*
thm *fb-and-wire-bot*

lemma *InstFeedback* (*AND-rel2*) *x y* = (*case x of* $\bullet \Rightarrow y = \bullet$ | *OK* (*Some False*) $\Rightarrow$ *y* = *OK* ((*Some False*, *Some False*), *Some False*) | - $\Rightarrow$ *y* = *OK* ((*None*, *None*), *None*))

definition *NonDet ux vy* = (*case ux of* $\bullet \Rightarrow vy = \bullet$ | *OK* (*Some u*, *x*) $\Rightarrow$
(*if* $u = 2$ *then* $vy = \bullet$ *else*
$vy = OK(Some\ (x + 1), x + 1) \vee vy = OK(Some\ (x + 1), x + 2) \vee$
$vy = OK(Some\ (x + 2), x + 2) \vee vy = OK(Some\ (x + 2), x + 3) \vee$
$vy = OK(Some\ 6, 6) \vee vy = OK(Some\ 6, 7))$
| $OK(None, x) \Rightarrow$
$vy = OK(Some\ (x + 1), x + 1) \vee vy = OK(Some\ (x + 1), x + 2) \vee$
$vy = OK(Some\ (x + 2), x + 2) \vee vy = OK(Some\ (x + 2), x + 3) \vee$
$vy = OK(Some\ 7, 7) \vee vy = OK(Some\ 7, 8)$)

definition *InstFeedbackNonDet x vy* = (*case x of* $\bullet \Rightarrow vy = \bullet$ |
OK a $\Rightarrow (a = Suc\ 0 \wedge vy = \bullet) \vee (a = 0 \wedge vy = \bullet) \vee$
$(a \neq 1 \wedge (vy = OK(Some\ (a + 1), a + 1) \vee vy = OK(Some\ (a + 1), a + 2))) \vee$
$(a \neq 0 \wedge (vy = OK(Some\ (a + 2), a + 2) \vee vy = OK(Some\ (a + 2), a + 3))))$

lemma *InstFeedbackNonDet-a*: *InstFeedback NonDet x vy* $\Longrightarrow$ *InstFeedbackNonDet x vy*

lemma *InstFeedbackNonDet-b*: *InstFeedbackNonDet x vy* $\Longrightarrow$ *InstFeedback NonDet x vy*

lemma *InstFeedbackNonDet*: *InstFeedback NonDet* = *InstFeedbackNonDet*

6.2 Associativity of Instantaneous Feedback

definition *adapt r a b* = (*case a of* $\bullet \Rightarrow b = \bullet$ | *OK* (*u*, (*v*, *x*)) $\Rightarrow$
($\exists\ u'\ v'\ y$. *r* (*OK* ((*u*,*v*), *x*)) (*OK* (((*u'*,*v'*),*y*))) $\wedge$ *b* = *OK* (*u'*, (*v'*, *y*))) $\vee$ (*r* (*OK* ((*u*,*v*), *x*)) $\bullet \wedge b = \bullet$))

definition *adapt-b a b* = (*case a of* $\bullet \Rightarrow b = \bullet$ | *OK* (*u*, (*v*, *x*)) $\Rightarrow$ *b* = *OK* (*v*, (*u*, *x*)))

definition *adapt-c x y* = (*case x of* $\bullet \Rightarrow y = \bullet$ |
OK (*w*, (*u*, *a*)) $\Rightarrow$ *y* = *OK* ((*u*, *w*), *a*))

definition *adapt-a x y* = (*case x of* $\bullet \Rightarrow y = \bullet$ | *OK* (*u*, (*v*, *x*)) $\Rightarrow$ *y* = *OK* ((*u*, *v*), *x*))

lemma *ff r* $\Longrightarrow$ *f-f r* $\Longrightarrow$ *adapt r* = *adapt-a OO r OO adapt-a*$^{-1-1}$

lemma [*simp*]: *unkn-mono r* $\Longrightarrow$ *unkn-mono* (*adapt r*)

lemma [*simp*]: $(case\ y\ of\ \cdot \Rightarrow OK\ (b,\ a,\ yaa) = \cdot \mid OK\ (u,\ v,\ x) \Rightarrow OK\ (b,\ a,\ yaa) = OK\ (v,\ u,\ x))$
$= (y = OK\ (a,\ b,\ yaa))$

lemma [*simp*]: $(case\ y\ of\ \cdot \Rightarrow OK\ ((a,\ b),\ yaa) = \cdot \mid OK\ (w,\ u,\ aa) \Rightarrow OK\ ((a,\ b),\ yaa) = OK\ ((u,\ w),\ aa))$
$= (y = OK\ (b,\ a,\ yaa))$

lemma [*simp*]: $(case\ y\ of\ \cdot \Rightarrow \cdot = \cdot \mid OK\ (w,\ u,\ a) \Rightarrow \cdot = OK\ ((u,\ w),\ a)) = (y = \cdot)$

lemma [*simp*]: $unkn\text{-}mono\ r \Longrightarrow r\ (OK\ ((a,\ b),\ x2))\ (OK\ ((u,\ v),\ z)) \Longrightarrow r\ (OK\ ((\bot,\ \bot),\ x2))\ (OK\ ((u,\ v),\ z))$

lemma [*simp*]: $unkn\text{-}mono\ r \Longrightarrow r\ (OK\ ((a,\ b),\ x2))\ (OK\ ((u,\ v),\ z)) \Longrightarrow r\ (OK\ ((\bot,\ b),\ x2))\ (OK\ ((u,\ v),\ z))$

lemma [*simp*]: $unkn\text{-}mono\ r \Longrightarrow r\ (OK\ ((a,\ b),\ x2))\ (OK\ ((u,\ v),\ z)) \Longrightarrow r\ (OK\ ((a,\ \bot),\ x2))\ (OK\ ((u,\ v),\ z))$

lemma [*simp*]: $unkn\text{-}mono\ r \Longrightarrow unkn\text{-}mono\ (InstFeedback\ (adapt\ r)\ OO\ adapt\text{-}b)$

term $InstFeedback\ (fb\text{-}fun\ (adapt\ r)\ OO\ adapt\text{-}b)\ OO\ adapt\text{-}c$

lemma *fb-hide-comp-aux*: $unkn\text{-}mono\ (InstFeedback\ (adapt\ r)\ OO\ adapt\text{-}b) \Longrightarrow InstFeedback\ (InstFeedback\ (adapt\ r)\ OO\ adapt\text{-}b) = InstFeedback\text{-}1\ (InstFeedback\ (adapt\ r)\ OO\ adapt\text{-}b)$

lemma [*simp*]: $adapt\ r\ \cdot\ \cdot$

lemma [*simp*]: $adapt\text{-}b\ \cdot\ \cdot$

lemma [*simp*]: $adapt\text{-}c\ \cdot\ \cdot$

lemma [*simp*]: $unkn\text{-}mono\ r \Longrightarrow$
$r\ (OK\ ((\bot,\ \bot),\ x2))\ (OK\ ((a,\ b),\ ya)) \Longrightarrow$
$r\ (OK\ ((a,\ b),\ x2))\ (OK\ ((a,\ b),\ yaa)) \Longrightarrow$
$InstFeedback\text{-}1\ (adapt\ r)\ (OK\ (\bot,\ x2))\ (OK\ (a,\ b,\ yaa))$

lemma [*simp*]: $unkn\text{-}mono\ r \Longrightarrow$
$r\ (OK\ ((\bot,\ \bot),\ x2))\ (OK\ ((a,\ b),\ ya)) \Longrightarrow$
$r\ (OK\ ((a,\ b),\ x2))\ (OK\ ((a,\ b),\ yaa)) \Longrightarrow$
$\exists\, a\ ba.\ InstFeedback\text{-}1\ (adapt\ r)\ (OK\ (\bot,\ x2))\ (OK\ (a,\ b,\ ba))$

lemma [*simp*]: $unkn\text{-}mono\ r \Longrightarrow$
$r\ (OK\ ((\bot,\ \bot),\ x2))\ (OK\ ((a,\ b),\ ya)) \Longrightarrow$
$r\ (OK\ ((a,\ b),\ x2))\ (OK\ ((a,\ b),\ yaa)) \Longrightarrow$
$InstFeedback\text{-}1\ (adapt\ r)\ (OK\ (b,\ x2))\ (OK\ (a,\ b,\ yaa))$

definition $indep\ r = (\forall\ x\ y\ z\ z'\ .\ r\ (OK\ ((\bot,\bot),\ z))\ (OK\ ((x,\ y),\ z')) \longrightarrow$
$((\exists\ a\ .\ r\ (OK\ ((x,\ \bot),\ z))\ (OK\ ((x,\ y),\ a))) \wedge ((\exists\ a\ .\ r\ (OK\ ((\bot,\ y),\ z))\ (OK\ ((x,\ y),\ a))))))$

lemma *InstFeedback-assoc-fail-a*: *indep r* $\Longrightarrow$ *unkn-mono r* $\Longrightarrow$ *InstFeedback r x* $\bullet$ $\Longrightarrow$ ((*InstFeedback* (*InstFeedback* (*adapt r*) *OO adapt-b*)) *OO adapt-c*) *x* $\bullet$

definition *indep-a r* = ($\forall$ *x y y' a b a' b'* . *r* (*OK* (($\bot$, $\bot$), *x*)) (*OK* ((*a*, *b*), *y*)) $\wedge$ *r* (*OK* (($\bot$, $\bot$), *x*)) (*OK* ((*a'*, *b'*), *y'*))
$\longrightarrow$ ($\exists$ *z* . *r* (*OK* (($\bot$, $\bot$),*x*)) (*OK* ((*a*, *b'*), *z*))))

lemma *InstFeedback-assoc-fail-b*: *indep-a r* $\Longrightarrow$ *mono-fail r* $\Longrightarrow$ *unkn-mono r* $\Longrightarrow$ ((*InstFeedback* (*InstFeedback* (*adapt r*) *OO adapt-b*)) *OO adapt-c*) *x* $\bullet$ $\Longrightarrow$ *InstFeedback r x* $\bullet$

lemma *InstFeedback-assoc-OK*: *unkn-mono r* $\Longrightarrow$ *InstFeedback r x* (*OK y*) = ((*InstFeedback* (*InstFeedback* (*adapt r*) *OO adapt-b*)) *OO adapt-c*) *x* (*OK y*)

theorem *InstFeedback-assoc*: *indep r* $\Longrightarrow$ *indep-a r* $\Longrightarrow$ *mono-fail r* $\Longrightarrow$ *unkn-mono r* $\Longrightarrow$
(*InstFeedback* (*InstFeedback* (*adapt r*) *OO adapt-b*)) *OO adapt-c* = *InstFeedback r*

definition *unkn-mono-up r* = ($\forall$ *a b x u y*. *a* $\le$ *b* $\wedge$ *r* (*OK* (*a*, *x*)) (*OK* (*u*, *y*)) $\longrightarrow$ (($\exists$ *v* . *u* $\le$ *v* $\wedge$ *r* (*OK* (*b*, *x*)) (*OK* (*v*, *y*))) $\vee$ *r* (*OK* (*b*, *x*)) $\bullet$))
lemma *unkn-mono-up-A*: *unkn-mono-up r* $\Longrightarrow$ *a* $\le$ *b* $\Longrightarrow$ *r* (*OK* (*a*, *x*)) (*OK* (*u*, *y*)) $\Longrightarrow$ (($\exists$ *v* . *u* $\le$ *v* $\wedge$ *r* (*OK* (*b*, *x*)) (*OK* (*v*, *y*))) $\vee$ *r* (*OK* (*b*, *x*)) $\bullet$)
lemma *unkn-mono-a-A*: *unkn-mono r* $\Longrightarrow$ *a* $\le$ *b* $\Longrightarrow$ *r* (*OK* (*b*, *x*)) (*OK z*) $\Longrightarrow$ *r* (*OK* (*a*, *x*)) (*OK z*)

lemma *feedback-comp-fail-Z*: *mono-fail* (*r*::(('*a option* $\times$ '*b option*) $\times$ '*c*) *fail-option* $\Rightarrow$ ((('*a option* $\times$ '*b option*) $\times$ '*d*) *fail-option*) $\Rightarrow$ *bool*)
$\Longrightarrow$ *unkn-mono r* $\Longrightarrow$ *unkn-mono-up r* $\Longrightarrow$ *InstFeedback r x* $\bullet$ $\Longrightarrow$ ((*InstFeedback* (*InstFeedback* (*adapt r*) *OO adapt-b*)) *OO adapt-c*) *x* $\bullet$

end

7 Formalizing Simulink in RCRS

7.1 Types for Simulink Modeling Elements

theory *SimulinkTypes* **imports** *Real Transcendental*
begin

instantiation *bool*::*zero*
begin
definition *zero-bool-def*[*simp*]: *0* = *False*
instance
end

instantiation *bool*::*one*
begin
definition *one-bool-def*[*simp*]: *1* = *True*
instance
end

instantiation *bool*::*plus*
begin
definition *plus-bool-def*[*simp*]: (*a*::*bool*) + *b* = (*a* $\vee$ *b*)
instance
end

instance *bool*::*semigroup-add*

instantiation *bool*::*numeral*
begin
  instance
  lemma [*simp*]: *numeral a* = *True*
end

instantiation *bool*::*divide*
begin
  definition *divide-bool-def* [*simp*]: (*a*::*bool*) *div b* = (*a* ∧ *b*)
  instance
end

instantiation *bool*::*inverse*
begin
  definition *inverse-bool-def* [*simp*]: *inverse* (*a*::*bool*) = *a*
  instance
end

class *s-pi* =
  fixes *s-pi*::'*a*

instantiation *real*::*s-pi*
begin
  definition *s-pi-real-def* [*simp*]: *s-pi* = *pi*
  instance
end

class *s-sqrt* =
  fixes *s-sqrt*:: '*a* ⇒ '*a*

instantiation *real*::*s-sqrt*
begin
  definition *s-sqrt-real-def* [*simp*]: *s-sqrt* = *sqrt*
  instance
end

class *s-abs* =
  fixes *s-abs*:: '*a* ⇒ '*a*

instantiation *real*::*s-abs*
begin
  definition *s-abs-real-def* [*simp*]: *s-abs* = (*abs*::*real* ⇒ *real*)
  instance
end

class *s-exp* =
  fixes *s-exp*:: '*a* ⇒ '*a*

instantiation *real*::*s-exp*
begin
  definition *s-exp-real-def* [*simp*]: *s-exp* = (*exp* :: *real* ⇒ *real*)
  instance

end

class *s-ln* =
  fixes *s-ln*:: *'a* ⇒ *'a*

instantiation *real*::*s-ln*
begin
  definition *s-ln-real-def* [*simp*]: *s-ln* = (*ln*::*real* ⇒ *real*)
  instance
end

class *s-sin* =
  fixes *s-sin*:: *'a* ⇒ *'a*

class *s-cos* =
  fixes *s-cos*:: *'a* ⇒ *'a*

instantiation *real*::*s-sin*
begin

  definition *s-sin-real-def* [*simp*]: *s-sin* = (*sin* :: *real* ⇒ *real*)
  instance
end

instantiation *real*::*s-cos*
begin

  definition *s-cos-real-def* [*simp*]: *s-cos* = (*cos* :: *real* ⇒ *real*)
  instance
end

definition *MyIf*:: *bool* ⇒ *'a* ⇒ *'a* ⇒ *'a* ((*If* (-)/ *Then* (-)/ *Else* (-)) [*0*, *0*, *10*] *10*) **where**
  (*If b Then x Else y*) = (*if b then x else y*)

lemma *If-prod*: (*If b Then* (*x*, *y*) *Else* (*u*, *v*)) = ((*If b Then x Else u*), (*If b Then y Else v*))

lemma *If-eq*: (*If b Then x Else x*) = *x*

class *simulink* = *minus* + *uminus* + *numeral* + *power* + *zero* + *ord* + *s-sqrt* + *s-abs* + *s-exp* + *s-ln* + *s-sin* + *s-cos* + *s-pi* + *inverse* +
  assumes *numeral-nzero*[*simp*]: *numeral n* ≠ *0*
begin
  lemma [*simp*]: (*1* = *0*) = *False*
  lemma [*simp*]: (*0* = *1*) = *False*

  lemma [*simp*]: ((*if b then* (*1*::*'a*) *else 0*) = *0*) = (¬ *b*)

  lemma [*simp*]: ((*if b then* (*1*::*'a*) *else 0*) = *1*) = *b*

end

lemma [*simp*]: (*if b then True else False*) = *b*

instantiation *real*::*simulink*
begin
instance
end

instantiation *nat*::*simulink*
begin
instance
end

instantiation *bool*::*simulink*
begin
instance
end

definition *is-eq-num x y* = (*if x* = *y then 1 else 0*)
lemma *is-eq-num-a*: ((*is-eq-num x y*)::*bool*) = (*x* = *y*)
lemmas *is-eq-num-simp* [*simp*] = *is-eq-num-a is-eq-num-def*

definition *is-neq-num x y* = (*if x* ≠ *y then 1 else 0*)
lemma *is-neq-num-a*: ((*is-neq-num x y*)::*bool*) = (*x* ≠ *y*)
lemmas *is-neq-num-simp* [*simp*] = *is-neq-num-a is-neq-num-def*

definition *is-less-num x y* = (*if x* < *y then 1 else 0*)
lemma *is-less-num-a*: ((*is-less-num x y*)::*bool*) = (*x* < *y*)
lemmas *is-less-num-simp* [*simp*] = *is-less-num-a is-less-num-def*

definition *is-less-eq-num x y* = (*if x* ≤ *y then 1 else 0*)
lemma *is-less-eq-num-a*: ((*is-less-eq-num x y*)::*bool*) = (*x* ≤ *y*)
lemmas *is-less-eq-num-simp* [*simp*] = *is-less-eq-num-a is-less-eq-num-def*

definition *is-gt-num x y* = (*if x* > *y then 1 else 0*)
lemma *is-gt-num-a*: ((*is-gt-num x y*)::*bool*) = (*x* > *y*)
lemmas *is-gt-num-simp* [*simp*] = *is-gt-num-a is-gt-num-def*

definition *is-ge-num x y* = (*if x* ≥ *y then 1 else 0*)
lemma *is-ge-num-a*: ((*is-ge-num x y*)::*bool*) = (*x* ≥ *y*)

lemmas *is-ge-num-simp* [*simp*] = *is-ge-num-a is-ge-num-def*

consts *conversion* :: *'a* ⇒ *'b*

overloading
conversion-id ≡ *conversion*:: *'a* ⇒ *'a* (**unchecked**)
conversion-bool-real ≡ *conversion*:: *bool* ⇒ *real* (**unchecked**)
conversion-bool-nat ≡ *conversion*:: *bool* ⇒ *nat* (**unchecked**)
conversion-real-bool ≡ *conversion*:: *real* ⇒ *bool* (**unchecked**)
begin
definition [*simp*]: *conversion-id a* = *a*
definition [*simp*]: *conversion-bool-real* (*b*::*bool*) = (*if b then* (*1*::*real*) *else 0*)

definition [*simp*]: *conversion-bool-nat* (*b*::*bool*) = (*if b then* (*1*::*nat*) *else 0*)
definition [*simp*]: *conversion-real-bool* (*x*::*real*) = ($x \neq 0$)
end

end

7.2 Formalization of Simulink Blocks as Predicate Transformers

theory *Simulink*
imports *Complex-Main ../Feedback/TransitionFeedback SimulinkTypes*
begin

declare *comp-skip* [*simp del*]
declare *skip-comp* [*simp del*]
declare *prod-skip-skip* [*simp del*]
declare *fail-comp* [*simp del*]

declare [[*show-sorts=false*]]

definition *UnitVal* = ()

definition *Constant c* = [: *x*::*unit* ⇝ *y*. *y* = *c*:]

lemma *Constant-func*: *Constant c* = [− *x* ⇝ *c*−]

definition *Inport* = *Skip*

definition *Gain k* = [:*x* ⇝ *y*. *y* = *x* ∗ *k*:]

lemma *Gain-func*: *Gain k* = [− *x* ⇝ *x* ∗ *k*−]

definition *Square* = [:*x* ⇝ *y*. *y* = *x* ∗ *x*:]

lemma *Square-func*: *Square* = [− *x* ⇝ *x* ∗ *x*−]

definition *Power* = [: (*x*, *y*) ⇝ *z*. *z* = *x* ˆ *y*:]

lemma *Power-func*: $Power = [-\ x,\ y \leadsto x\ \hat{}\ y-]$

definition $Power10 = [:\ x \leadsto y.\ y = 10\ \hat{}\ x:]$

lemma *Power10-func*: $Power10 = [-\ x \leadsto 10\ \hat{}\ x-]$

definition $Exp = [:\ x \leadsto y.\ y = s\text{-}exp\ x\ :]$

lemma *Exp-func*: $Exp = [-\ x \leadsto s\text{-}exp\ x-]$

definition $Ln = [:\ x \leadsto y.\ y = s\text{-}ln\ x:]$

lemma *Ln-func*: $Ln = [-\ x \leadsto\ s\text{-}ln\ x-]$

definition $Sqrt = \{.\ x.\ x \geq 0\ .\} \circ [:x \leadsto y.\ y = s\text{-}sqrt\ x:]$

lemma *Sqrt-func*: $Sqrt = \{.\ x.\ x \geq 0\ .\} \circ [-\ x \leadsto s\text{-}sqrt\ x-]$

definition $Outport = Skip$

definition $Scope = Skip$

definition $Terminator = [:\ x \leadsto (u::unit).\ True:]$

lemma *Terminator-func*: $Terminator = [-\ \ x \leadsto ()-]$

definition $Integrator\ dt = [:(x,s) \leadsto (y,\ s').\ y = s \wedge s' = s + x * dt:]$

lemma *Integrator-func*: $Integrator\ dt = [-x,\ s \leadsto s,\ s + x * dt-]$

definition *IntegratorA* = [:$s \leadsto y$. $y = s$:]

lemma *IntegratorA-func*: *IntegratorA* = [$-id-$]

definition *IntegratorB dt* = [:$(x,s) \leadsto s'$. $s' = s + x * dt$:]

lemma *IntegratorB-func*: *IntegratorB dt* = [$-$ x, $s \leadsto s + x * dt-$]

definition *IntegratorLimit high low dt* = [: $(x, s) \leadsto (y, s')$. $y = s \wedge s' =$ (*If* $s + x * dt >$ *high Then high Else If* $s + x * dt <$ *low Then low Else* $s + x * dt$):]

lemma *IntegratorLimit-func* : *IntegratorLimit high low dt* = [$-$ x, $s \leadsto s$, *If* $s + x * dt >$ *high Then high Else If* $s + x * dt <$ *low Then low Else* $s + x * dt$ $-$]

definition *IntegratorLimitA* = [:$s \leadsto y$. $y = s$:]

lemma *IntegratorLimitA-func*: *IntegratorLimitA* = [$-$ *id* $-$]

definition *IntegratorLimitB high low dt* = [: $(x, s) \leadsto y$. $y =$ (*If* $s + x * dt >$ *high Then high Else If* $s + x * dt <$ *low Then low Else* $s + x * dt$) :]

lemma *IntegratorLimitB-func*: *IntegratorLimitB high low dt* = [$-$ x, $s \leadsto$ *If* $s + x * dt >$ *high Then high Else If* $s + x * dt <$ *low Then low Else* $s + x * dt$ $-$]

definition *Saturation low-limit high-limit* = [: $x \leadsto y$.
$y =$ (*If* $x <$ *low-limit Then low-limit*
Else If $x >$ *high-limit Then high-limit*
Else x):]

lemma *Saturation-func*: *Saturation low-limit high-limit* =
[$-$ $x \leadsto$ *If* $x <$ *low-limit Then low-limit*
Else If $x >$ *high-limit Then high-limit*
Else $x-$]

definition *Relay low-limit high-limit value-low value-high* = [: x, $s \leadsto y$, s' .
$y =$ (*If high-limit* $\leq x$ *Then value-high*
Else (*If* $x \leq$ *low-limit Then value-low Else* s))
$\wedge\ s' = y$:]

lemma *Relay-func*: *Relay low-limit high-limit value-low value-high* =
[$-$ x, $s \leadsto$ *If high-limit* $\leq x$ *Then value-high Else If* $x \leq$ *low-limit Then value-low Else* s,
If high-limit $\leq x$ *Then value-high Else If* $x \leq$ *low-limit Then value-low Else* $s-$]

definition *RelayA low-limit high-limit value-low value-high* = [: x, $s \rightsquigarrow y$.
y = (*If high-limit* $\leq x$ *Then value-high*
Else (*If* $x \leq$ *low-limit Then value-low Else* s)) :]

lemma *RelayA-func*: *RelayA low-limit high-limit value-low value-high* =
[− x, $s \rightsquigarrow$ *If high-limit* $\leq x$ *Then value-high Else If* $x \leq$ *low-limit Then value-low Else* s−]

definition *RelayB low-limit high-limit value-low value-high* = [: x, $s \rightsquigarrow s'$.
s' = (*If high-limit* $\leq x$ *Then value-high*
Else (*If* $x \leq$ *low-limit Then value-low Else* s)) :]

lemma *RelayB-func*: *RelayB low-limit high-limit value-low value-high* =
[− x, $s \rightsquigarrow$ *If high-limit* $\leq x$ *Then value-high Else If* $x \leq$ *low-limit Then value-low Else* s−]

definition *PulseGenerator period phase-delay pulse-width amplitude dt* = [: $(i,c) \rightsquigarrow y$, i',c'. i'=i+1 $\wedge$
(*If* ($i * dt$ < *phase-delay*) *Then* (y = 0 $\wedge$ c' = 0) *Else*
If ($i * dt \geq$ *phase-delay* $\wedge$ ($c * dt$) < (*pulse-width* $*$ *period*) $\wedge$ (*pulse-width* $*$ *period*) < *period*) *Then* (y=*amplitude* $\wedge$ (c' = c + 1)) *Else*
If ($i * dt \geq$ *phase-delay* $\wedge$ ($c * dt$) $\geq$ (*pulse-width* $*$ *period*) $\wedge$ ($c * dt$) < (*period* − *dt*) $\wedge$ (*pulse-width* $*$ *period*) < *period*) *Then* (y=0 $\wedge$ (c' = c + 1))
Else (c' = 0 $\wedge$ y = 0)):]

lemma *PulseGenerator-func*: *PulseGenerator period phase-delay pulse-width amplitude dt* =
[− i, $c \rightsquigarrow$
If ($i * dt$ < *phase-delay*) *Then* (0, i + 1, 0) *Else*
If ($i * dt \geq$ *phase-delay* $\wedge$ ($c * dt$) < (*pulse-width* $*$ *period*) $\wedge$ (*pulse-width* $*$ *period*) < *period*) *Then* (*amplitude*, i+1, c + 1) *Else*
If ($i * dt \geq$ *phase-delay* $\wedge$ ($c * dt$) $\geq$ (*pulse-width* $*$ *period*) $\wedge$ ($c * dt$) < (*period* − *dt*) $\wedge$ (*pulse-width* $*$ *period*) < *period*) *Then* (0, i+1, c + 1)
Else (0, i+1, 0)−]

definition *PulseGeneratorA period phase-delay pulse-width amplitude dt* = [: $(i,c) \rightsquigarrow y$.
(*If* ($i * dt$ < *phase-delay*) *Then* y = 0 *Else*
If ($i * dt \geq$ *phase-delay* $\wedge$ ($c * dt$) < (*pulse-width* $*$ *period*) $\wedge$ (*pulse-width* $*$ *period*) < *period*) *Then* y = *amplitude*
Else y = 0):]

lemma *PulseGeneratorA-func* : *PulseGeneratorA period phase-delay pulse-width amplitude dt* =
[− i, $c \rightsquigarrow$
If ($i * dt$ < *phase-delay*) *Then* 0 *Else*
If ($i * dt \geq$ *phase-delay* $\wedge$ ($c * dt$) < (*pulse-width* $*$ *period*) $\wedge$ (*pulse-width* $*$ *period*) < *period*) *Then amplitude Else* 0 −]

definition *PulseGeneratorB* = [: $i \rightsquigarrow i'$. i' = i + 1 :]

lemma *PulseGeneratorB-func*: *PulseGeneratorB* = [− *i* ⇝ *i* + *1* −]

definition *PulseGeneratorC period phase-delay pulse-width dt* = [: (*i*,*c*) ⇝ *c*′.
(*If* (*i* ∗ *dt* < *phase-delay*) *Then c*′ = *0 Else*
If (*i* ∗ *dt* ≥ *phase-delay* ∧ (*c* ∗ *dt*) < (*pulse-width* ∗ *period*) ∧ (*pulse-width* ∗ *period*) < *period*) *Then c*′ = *c* + *1 Else*
If (*i* ∗ *dt* ≥ *phase-delay* ∧ (*c* ∗ *dt*) ≥ (*pulse-width* ∗ *period*) ∧ (*c* ∗ *dt*) < (*period* − *dt*) ∧ (*pulse-width* ∗ *period*) < *period*) *Then c*′ = *c* + *1*
Else c′ = *0*) :]

lemma *PulseGeneratorC-func*: *PulseGeneratorC period phase-delay pulse-width dt* =
[− *i*, *c* ⇝
If (*i* ∗ *dt* < *phase-delay*) *Then 0 Else*
If (*i* ∗ *dt* ≥ *phase-delay* ∧ (*c* ∗ *dt*) < (*pulse-width* ∗ *period*) ∧ (*pulse-width* ∗ *period*) < *period*) *Then c* + *1 Else*
If (*i* ∗ *dt* ≥ *phase-delay* ∧ (*c* ∗ *dt*) ≥ (*pulse-width* ∗ *period*) ∧ (*c* ∗ *dt*) < (*period* − *dt*) ∧ (*pulse-width* ∗ *period*) < *period*) *Then c* + *1*
Else 0−]

definition *PulseGeneratorS period phase-delay pulse-width amplitude dt* = [: *t* ⇝ *y*, *t*′.
(*If* (*t* < *phase-delay*) *Then* (*y* = *0* ∧ *t*′= *t* + *dt*) *Else*
If t − *phase-delay* < *period* ∗ *pulse-width* / *100 Then* (*y* = *amplitude* ∧ *t*′ = *t* + *dt*) *Else*
If t − *phase-delay* < *period Then* (*y* = *0* ∧ *t*′= *t* + *dt*)
Else (*y* = *amplitude* ∧ *t*′ = *t* + *dt* − *period*)):]

lemma *PulseGeneratorS-func*: *PulseGeneratorS period phase-delay pulse-width amplitude dt* = [− *t* ⇝
If (*t* < *phase-delay*) *Then* (*0*, *t* + *dt*) *Else*
If t − *phase-delay* < *period* ∗ *pulse-width* / *100 Then* (*amplitude*, *t* + *dt*) *Else*
If t − *phase-delay* < *period Then* (*0*, *t* + *dt*)
Else (*amplitude*, *t* + *dt* − *period*) −]

definition *PulseGeneratorSA period phase-delay pulse-width amplitude dt* = *PulseGeneratorS period phase-delay pulse-width amplitude dt o* [:*y*, *t* ⇝ *y*′ . *y* = *y*′:]

lemma *PulseGeneratorSA-func*: *PulseGeneratorSA period phase-delay pulse-width amplitude dt* = [− *t* ⇝
If (*t* < *phase-delay*) *Then 0 Else*
If t − *phase-delay* < *period* ∗ *pulse-width* / *100 Then amplitude Else*
If t − *phase-delay* < *period Then 0*
Else amplitude −]

thm *PulseGeneratorS-def*

definition *PulseGeneratorSB period phase-delay pulse-width dt* = [: *t* ⇝ *t*′.
(*If* (*t* < *phase-delay*) *Then t*′ = *t* + *dt Else*

If $t - phase\text{-}delay < period * pulse\text{-}width / 100$ *Then* $t' = t + dt$ *Else*
If $t - phase\text{-}delay < period$ *Then* $t' = t + dt$
Else $t' = t + dt - period$) :]

lemma *PulseGeneratorSB-func*: *PulseGeneratorSB period phase-delay pulse-width dt* = [− λ *t* .
(*If* ($t < phase\text{-}delay$) *Then* $t + dt$ *Else*
If $t - phase\text{-}delay < period * pulse\text{-}width / 100$ *Then* $t + dt$ *Else*
If $t - phase\text{-}delay < period$ *Then* $t + dt$
Else $t + dt - period$) −]

lemma *PulseGeneratorSB-func-real*[*simp*]: $0 \le phase\text{-}delay \Longrightarrow 0 < period \Longrightarrow 0 < pulse\text{-}width \Longrightarrow pulse\text{-}width < 100 \Longrightarrow$
(λ (*t*::*real*) .
(*If* ($t < phase\text{-}delay$) *Then* $t + dt$ *Else*
If $t - phase\text{-}delay < period * pulse\text{-}width / 100$ *Then* $t + dt$ *Else*
If $t - phase\text{-}delay < period$ *Then* $t + dt$
Else $t + dt - period$))
= (λ (*t*::*real*) . (*If* $t - phase\text{-}delay < period$ *Then* $t + dt$ *Else* $t + dt - period$))

definition *Step step-time initial-value final-value dt* = [:$i \leadsto y$, i'. $i' = i + 1 \wedge$
y = (*If* ($i * dt$) < *step-time* *Then* *initial-value* *Else* *final-value*):]

lemma *Step-func*: *Step step-time initial-value final-value dt* = [− $i \leadsto$ *If* ($i * dt$) < *step-time* *Then* *initial-value* *Else* *final-value*, $i{+}1$−]

definition *StepA step-time initial-value final-value dt* = [:$i \leadsto y$.
y = (*If* ($i * dt$) < *step-time* *Then* *initial-value* *Else* *final-value*):]

lemma *StepA-func*: *StepA step-time initial-value final-value dt* = [− $i \leadsto$ *If* ($i * dt$) < *step-time* *Then* *initial-value* *Else* *final-value*−]

definition *StepB* = [:$i \leadsto i'$. $i' = i + 1$:]

lemma *StepB-func*: *StepB* = [− $i \leadsto i{+}1$−]

definition *StepT step-time initial-value final-value dt* = [:$t \leadsto y$, t'. $t' = t + dt \wedge$
y = (*If* t < *step-time* *Then* *initial-value* *Else* *final-value*):]

lemma *StepT-func*: *StepT step-time initial-value final-value dt* = [− $t \leadsto$ *If* t < *step-time* *Then* *initial-value* *Else* *final-value*, $t + dt$−]

definition *StepTA step-time initial-value final-value dt* = [:$t \leadsto y$.
y = (*If* t < *step-time* *Then* *initial-value* *Else* *final-value*):]

lemma *StepTA-func*: *StepTA step-time initial-value final-value dt* = $[-\ t \rightsquigarrow$ *If* $t <$ *step-time Then initial-value Else final-value* $-]$

definition *StepTB dt* = $[:t \rightsquigarrow t'.\ t' = t + dt:]$

lemma *StepTB-func*: *StepTB dt* = $[-\ t \rightsquigarrow t + dt-]$

definition *TransferFcn k a dt* = $[:(x, i, s) \rightsquigarrow (y, i', s').\ y = (s * s\text{-}exp(a * i * dt) + k * x * s\text{-}exp(a * (i + 1) * dt) * dt) \ /\ s\text{-}exp(a * (i + 1) * dt) \wedge$
$i' = i + 1 \wedge s' = y:]$

lemma *TransferFcn-func*: *TransferFcn k a dt* = $[-\ x, i, s \rightsquigarrow (s * s\text{-}exp(a * i * dt) + k * x * s\text{-}exp(a * (i + 1) * dt) * dt) \ /\ s\text{-}exp(a * (i + 1) * dt),$
$i{+}1, (s * s\text{-}exp(a * i * dt) + k * x * s\text{-}exp(a * (i + 1) * dt) * dt) \ /\ s\text{-}exp(a * (i + 1) * dt)-]$

definition *TransferFcnA k a dt* = $[:\ (x, i, s) \rightsquigarrow y.\ y = (s * s\text{-}exp(a * i * dt) + k * x * s\text{-}exp(a * (i + 1) * dt) * dt) \ /\ s\text{-}exp(a * (i + 1) * dt)\ :]$

lemma *TransferFcnA-func*: *TransferFcnA k a dt* = $[-\ x, i, s \rightsquigarrow (s * s\text{-}exp(a * i * dt) + k * x * s\text{-}exp(a * (i + 1) * dt) * dt) \ /\ s\text{-}exp(a * (i + 1) * dt)-]$

definition *TransferFcnB* = $[:\ i \rightsquigarrow i'.\ i' = i + 1:]$

lemma *TransferFcnB-func*: *TransferFcnB* = $[-\ i \rightsquigarrow i{+}\ 1-]$

definition *TransferTFcn k a dt* = $[:(x, t, s) \rightsquigarrow (y, t', s').\ y = (s * s\text{-}exp(a * t) + k * x * s\text{-}exp(a * (t + dt)) * dt) \ /\ s\text{-}exp(a * (t + dt)) \wedge$
$t' = t + dt \wedge s' = y:]$

lemma *TransferTFcn-func*: *TransferTFcn k a dt* = $[-\ x, t, s \rightsquigarrow (s * s\text{-}exp(a * t) + k * x * s\text{-}exp(a * (t + dt)) * dt) \ /\ s\text{-}exp(a * (t + dt)),$
$t + dt, (s * s\text{-}exp(a * t) + k * x * s\text{-}exp(a * (t + dt)) * dt) \ /\ s\text{-}exp(a * (t + dt))-]$

definition *TransferTFcnA k a dt* = $[:\ (x, t, s) \rightsquigarrow y.\ y = (s * s\text{-}exp(a * t) + k * x * s\text{-}exp(a * (t + dt)) * dt) \ /\ s\text{-}exp(a * (t + dt))\ :]$

lemma *TransferTFcnA-func*: *TransferTFcnA k a dt* = $[-\ x, t, s \rightsquigarrow (s * s\text{-}exp(a * t) + k * x * s\text{-}exp(a * (t + dt)) * dt) \ /\ s\text{-}exp(a * (t + dt))-]$

definition $\mathit{TransferTFcnB}\ dt = [: t \leadsto t'.\ t' = t + dt:]$

lemma $\mathit{TransferTFcnB\text{-}func}$: $\mathit{TransferTFcnB}\ dt = [- t \leadsto t + dt-]$

definition $\mathit{SinWave}\ \mathit{amplitude}\ \mathit{frequency}\ \mathit{phase}\ \mathit{bias}\ dt = [: i \leadsto (y, i').\ y = \mathit{amplitude} * \mathit{s\text{-}sin}(\mathit{frequency} * i * dt + \mathit{phase}) + \mathit{bias} \wedge i' = i + \mathit{1}\ :]$

lemma $\mathit{SinWave\text{-}func}$: $\mathit{SinWave}\ \mathit{amplitude}\ \mathit{frequency}\ \mathit{phase}\ \mathit{bias}\ dt = [- i \leadsto \mathit{amplitude} * \mathit{s\text{-}sin}(\mathit{frequency} * i * dt + \mathit{phase}) + \mathit{bias},\ i+\mathit{1}-]$

definition $\mathit{SinWaveA}\ \mathit{amplitude}\ \mathit{frequency}\ \mathit{phase}\ \mathit{bias}\ dt = [: i \leadsto y.\ y = \mathit{amplitude} * \mathit{s\text{-}sin}(\mathit{frequency} * i * dt + \mathit{phase}) + \mathit{bias}\ :]$

lemma $\mathit{SinWaveA\text{-}func}$: $\mathit{SinWaveA}\ \mathit{amplitude}\ \mathit{frequency}\ \mathit{phase}\ \mathit{bias}\ dt = [- i \leadsto \mathit{amplitude} * \mathit{s\text{-}sin}(\mathit{frequency} * i * dt + \mathit{phase}) + \mathit{bias}\ -]$

definition $\mathit{SinWaveB} = [: i \leadsto i'.\ i' = i + \mathit{1}\ :]$

lemma $\mathit{SinWaveB\text{-}func}$: $\mathit{SinWaveB} = [- i \leadsto i + \mathit{1}\ -]$

definition $\mathit{SinWaveT}\ \mathit{amplitude}\ \mathit{frequency}\ \mathit{phase}\ \mathit{bias}\ dt = [: t \leadsto (y, t').\ y = \mathit{amplitude} * \mathit{s\text{-}sin}(\mathit{frequency} * t + \mathit{phase}) + \mathit{bias} \wedge t' = t + dt\ :]$

lemma $\mathit{SinWaveT\text{-}func}$: $\mathit{SinWaveT}\ \mathit{amplitude}\ \mathit{frequency}\ \mathit{phase}\ \mathit{bias}\ dt = [- t \leadsto \mathit{amplitude} * \mathit{s\text{-}sin}(\mathit{frequency} * t + \mathit{phase}) + \mathit{bias},\ t + dt-]$

definition $\mathit{SinWaveTA}\ \mathit{amplitude}\ \mathit{frequency}\ \mathit{phase}\ \mathit{bias}\ dt = [: t \leadsto y.\ y = \mathit{amplitude} * \mathit{s\text{-}sin}(\mathit{frequency} * t + \mathit{phase}) + \mathit{bias}\ :]$

lemma $\mathit{SinWaveTA\text{-}func}$: $\mathit{SinWaveTA}\ \mathit{amplitude}\ \mathit{frequency}\ \mathit{phase}\ \mathit{bias}\ dt = [- t \leadsto \mathit{amplitude} * \mathit{s\text{-}sin}(\mathit{frequency} * t + \mathit{phase}) + \mathit{bias}\ -]$

definition $\mathit{SinWaveTB}\ dt = [: t \leadsto t'.\ t' = t + dt\ :]$

lemma $\mathit{SinWaveTB\text{-}func}$: $\mathit{SinWaveTB}\ dt = [- t \leadsto t + dt\ -]$

fun MIN:: $'a$::$\mathit{ord}\ \mathit{list} \Rightarrow {'a}$ **where**
$\mathit{MIN}\ [] = \mathit{Eps}\ \top$ |
$\mathit{MIN}\ [x] = x$ |
$\mathit{MIN}\ (x \# \mathit{xs}) = \mathit{min}\ x\ (\mathit{MIN}\ \mathit{xs})$

fun *MAX*:: *'a::ord list* ⇒ *'a* **where**
MAX [] = *Eps* ⊤ |
MAX [*x*] = *x* |
MAX (*x* # *xs*) = *max x* (*MAX xs*)

definition *slope-val x xi xj yi yj* = (*yj* − *yi*) ∗ (*x* − *xi*) / (*xj* − *xi*) + *yi*

definition *siggen-square x* = (*If s-sin x* < *0 Then* (−*1*::*'a*::*simulink*) *Else* (*1*::*'a*::*simulink*))

lemmas *additional-simps* =

slope-val-def siggen-square-def MIN.simps MAX.simps

lemmas *basic-block-rel-simps* =
Gain-def Square-def Power-def Power10-def Exp-def Ln-def Sqrt-def Constant-def Saturation-def Relay-def Integrator-def
PulseGenerator-def Step-def TransferFcn-def
Scope-def Outport-def Inport-def
IntegratorA-def IntegratorB-def Terminator-def SinWave-def SinWaveA-def SinWaveB-def IntegratorLimit-def IntegratorLimitA-def IntegratorLimitB-def

lemmas *basic-block-func-simps* =
Gain-func Square-func Power-func Power10-func Exp-func Ln-func Sqrt-func Constant-func Saturation-func

Relay-func RelayA-func RelayB-func
Integrator-func IntegratorA-func IntegratorB-func
PulseGenerator-func PulseGeneratorA-func PulseGeneratorB-func PulseGeneratorC-func

PulseGeneratorS-func PulseGeneratorSA-func PulseGeneratorSB-func
TransferFcn-func TransferFcnA-func TransferFcnB-func
TransferTFcn-func TransferTFcnA-func TransferTFcnB-func

Scope-def Outport-def Inport-def
Step-func StepA-func StepB-func
StepT-func StepTA-func StepTB-func
Terminator-func
SinWave-func SinWaveA-func SinWaveB-func
SinWaveT-func SinWaveTA-func SinWaveTB-func
IntegratorLimit-func IntegratorLimitA-func IntegratorLimitB-func

lemmas *comp-rel-simps* = *Prod-spec-Skip Prod-Skip-spec Prod-demonic-skip Prod-skip-demonic Prod-demonic Prod-spec-demonic Prod-demonic-spec*
comp-assoc [*THEN sym*] *demonic-demonic comp-demonic-demonic assert-assert-comp comp-demonic-assert demonic-assert-comp*
OO-def Prod-spec Fail-assert fail-assert-demonic fail-comp
prod-skip-skip skip-comp comp-skip prod-fail fail-prod
update-demonic-comp demonic-update-comp comp-update-demonic comp-demonic-update

lemmas *comp-func-simps* =

prod-update prod-update-skip prod-skip-update
prod-assert-update-skip prod-skip-assert-update
Prod-assert-skip Prod-skip-assert prod-assert-update
prod-assert-assert-update prod-assert-update-assert
prod-update-assert-update prod-assert-update-update
comp-update-update comp-update-assert update-assert-comp
assert-assert-comp-pred
update-comp comp-assoc [*THEN sym*]
Fail-def fail-comp update-fail assert-fail prod-fail fail-prod
prod-skip-skip skip-comp comp-skip

lemmas *refinement-simps* = *assert-demonic-refinement spec-demonic-refinement*

lemmas *simulink-simps* = *basic-block-func-simps comp-func-simps*

lemmas *comp-var-simps* = *demonic-def assert-def le-fun-def Prod-spec-Skip Prod-Skip-spec Prod-demonic-skip Prod-skip-demonic Prod-demonic Prod-spec-demonic Prod-demonic-spec*
comp-assoc [*THEN sym*] *demonic-demonic comp-demonic-demonic assert-assert-comp comp-demonic-assert demonic-assert-comp OO-def Prod-spec Fail-assert*

lemmas *fail-simps* = *fail-def demonic-def Prod-spec-Skip Prod-Skip-spec Prod-demonic-skip Prod-skip-demonic assert-def le-fun-def Prod-demonic Prod-spec-demonic Prod-demonic-spec*
comp-assoc [*THEN sym*] *demonic-demonic comp-demonic-demonic assert-assert-comp comp-demonic-assert demonic-assert-comp OO-def Prod-spec Fail-assert*

lemmas *prec-simps* = *prec-def fail-def demonic-def Prod-spec-Skip Prod-Skip-spec Prod-demonic-skip Prod-skip-demonic assert-def le-fun-def Prod-spec-demonic Prod-demonic-spec*
comp-assoc [*THEN sym*] *demonic-demonic comp-demonic-demonic assert-assert-comp comp-demonic-assert demonic-assert-comp OO-def Prod-demonic Prod-spec Fail-assert*

lemmas *rel-simps* = *rel-def demonic-def Prod-spec-Skip Prod-Skip-spec Prod-demonic-skip Prod-skip-demonic assert-def le-fun-def Prod-demonic Prod-spec-demonic Prod-demonic-spec*
comp-assoc [*THEN sym*] *demonic-demonic comp-demonic-demonic assert-assert-comp comp-demonic-assert demonic-assert-comp OO-def Prod-spec Fail-assert*

lemmas *sconjunctive-simps* = *sconjunctive-simp-a sconjunctive-simp-b sconjunctive-simp-c*

lemmas *feedback-rel-simps* = *feedback-simp-a feedback-simp-b feedback-simp-bot*

lemmas *feedback-func-simps* = *feedback-update-simp-aaa feedback-update-simp-bbb feedback-simp-bot*

lemmas *feedbackless-func-simps* = *feedbackless-update-simp-aaa feedbackless-update-simp-bbb feedback-simp-bot*

lemma [*simp*]: $(\exists\ x\ y\ z\ .\ x = f\ y\ z)$

lemma [*simp*]: $(\exists\ x\ y\ z\ .\ f\ y\ z = x)$

lemma [*simp*]: $(\exists\ x\ y\ \ .\ x = f\ y\ )$

lemma [*simp*]: $(\exists\ x\ y\ \ .\ f\ y = x)$

lemma [*simp*]: $(\forall\, x::real.\ \neg\ 0 \leq x) = False$

lemma [*simp*]: $Ex\ (op \leq (0::real)) = True$

lemma [*simp*]: $(\exists\ a\ b\ .\ a + b = (x::'a::group\text{-}add)) = True$

lemma *common-imp-right-a*[*simp*]: $((p \longrightarrow (a \wedge b)) \wedge (\neg\ p \longrightarrow (c \wedge b))) = (((p \longrightarrow a) \wedge (\neg\ p \longrightarrow c)) \wedge b)$

lemma *common-imp-right-b*[*simp*]: $((\neg\ p \longrightarrow (a \wedge b)) \wedge (p \longrightarrow (c \wedge b))) = (((\neg\ p \longrightarrow a) \wedge (p \longrightarrow c)) \wedge b)$

lemma *common-imp-left-a* [*simp*]: $((p \longrightarrow b \wedge a) \wedge (\neg\ p \longrightarrow b \wedge c)) = (b \wedge (p \longrightarrow a) \wedge (\neg\ p \longrightarrow c))$

lemma *common-imp-left-b* [*simp*]: $((\neg\ p \longrightarrow b \wedge a) \wedge (p \longrightarrow b \wedge c)) = (b \wedge (\neg\ p \longrightarrow a) \wedge (p \longrightarrow c))$

lemma *common-dimp*: $((p \longrightarrow (q \longrightarrow a)) \wedge (r \longrightarrow (q \longrightarrow b))) = (q \longrightarrow ((p \longrightarrow a) \wedge (r \longrightarrow b)))$

lemma *fst-case-prod-eqa*: $(\bigwedge\ x\ y\ .\ fst\ (f1\ x\ y) = fst\ (f2\ x\ y)) \Longrightarrow fst\ (case\text{-}prod\ f1\ p) =\ fst\ (case\text{-}prod\ f2\ p)$

lemma *fst-case-prod-eqa-x*: $(\bigwedge\ x\ y\ .\ f\ (f1\ x\ y) = f\ (f2\ x\ y)) \Longrightarrow f\ (case\text{-}prod\ f1\ p) =\ f\ (case\text{-}prod\ f2\ p)$

lemma *fst-case-prod-eq*: $fst\ (f1\ (fst\ p1)\ (snd\ p1)) = fst\ (f2\ (fst\ p2)\ (snd\ p2)) \Longrightarrow fst\ (case\text{-}prod\ f1\ p1) =\ fst\ (case\text{-}prod\ f2\ p2)$

lemma *fst-case-prod-eqc*: $(\bigwedge\ z\ .\ fst\ (f1\ u\ z) = fst\ (f2\ u'\ z)) \Longrightarrow fst\ (case\text{-}prod\ f1\ (u,\ x)) =\ fst\ (case\text{-}prod\ f2\ (u',\ x))$

lemma *fst-case-prod-eqd*: $(\bigwedge\ y\ z\ .\ fst\ (f1\ y\ z) = fst\ (f2\ y\ z)) \Longrightarrow fst\ (case\text{-}prod\ f1\ x) =\ fst\ (case\text{-}prod\ f2\ x)$

definition $Snd = snd$

lemma *fst-case-prod-eqb*: $(fst\ (case\text{-}prod\ f1\ p1) = \ fst\ (case\text{-}prod\ f2\ p2)) = (fst\ (f1\ (fst\ p1)\ (Snd\ p1)) = fst\ (f2\ (fst\ p2)\ (Snd\ p2)))$

lemma *fst-case-prod-eqb-a*: $(fst\ (case\text{-}prod\ f1\ (u,\ x)) = \ fst\ (case\text{-}prod\ f2\ (v,\ x))) = (fst\ (f1\ u\ x) = fst\ (f2\ v\ x))$

lemma *fst-case-prod-eqb-b*: $(fst\ (case\text{-}prod\ f1\ p) = \ fst\ (case\text{-}prod\ f2\ p)) = (fst\ (f1\ (fst\ p)\ (Snd\ p)) = fst\ (f2\ (fst\ p)\ (Snd\ p)))$

definition $FstA = fst$

lemma *Fst-simp*: $FstA\ (x,y) = x$

lemma *fst-case-prod-eqc-a*: $(fst\ (case\text{-}prod\ f1\ (u,\ x)) = \ fst\ (case\text{-}prod\ f2\ (v,\ x))) = (FstA\ (f1\ u\ x) = FstA\ (f2\ v\ x))$

lemma *fst-case-prod-eqc-b*: $(FstA\ (case\text{-}prod\ f1\ p) = \ FstA\ (case\text{-}prod\ f2\ q)) = (FstA\ (f1\ (fst\ p)\ (Snd\ p)) = FstA\ (f2\ (fst\ q)\ (Snd\ q)))$

lemma *Snd-simp*: $Snd\ (x,\ y) = y$

lemma *fst-case-prod-eqb-x*: $(f\ (case\text{-}prod\ f1\ p1) = \ f\ (case\text{-}prod\ f2\ p2)) = (f\ (f1\ (fst\ p1)\ (Snd\ p1)) = f\ (f2\ (fst\ p2)\ (Snd\ p2)))$

lemma *fst-case-prod-eqba*: $(\forall\ x\ .\ fst\ (case\text{-}prod\ f1\ x) = \ fst\ (case\text{-}prod\ f2\ x)) = (\forall\ x\ y\ .\ fst\ (f1\ x\ y) = fst\ (f2\ x\ y))$

lemma [*simp*]: $(p \wedge (p \longrightarrow q)) = (p \wedge q)$

lemma [*simp*]: $(\forall\ x.\ x \neq y) = False$

lemma [*simp*]: $(\forall\ x.\ y \neq x) = False$

lemma [*simp*]: $(\exists\ x{::}real.\ y \neq x) = \ True$

lemma [*simp*]: $(\exists\ x{::}real.\ x \neq y) = \ True$

lemma *rel-if-expr-1*: $p\ x\ z \Longrightarrow p\ (if\ b\ then\ x\ else\ y)\ z = (b \vee\ \ p\ y\ z)$

lemma *rel-if-expr-2*: $p\ y\ z \Longrightarrow p\ (if\ b\ then\ x\ else\ y)\ z = (\neg\ b \vee p\ x\ z)$

lemma *rel-if-not-expr-1*: $\neg\ p\ x\ z \Longrightarrow p\ (if\ b\ then\ x\ else\ y)\ z = (\neg\ b \wedge p\ y\ z)$

lemma *rel-if-not-expr-2*: $\neg\ p\ y\ z \Longrightarrow p\ (if\ b\ then\ x\ else\ y)\ z = (b \wedge p\ x\ z)$

lemma *rel-expr-if-1*: $p\ z\ x \Longrightarrow p\ z\ (if\ b\ then\ x\ else\ y) = (b \vee\ \ p\ z\ y)$

lemma *rel-expr-if-2*: $p\ z\ y \Longrightarrow p\ z\ (if\ b\ then\ x\ else\ y) = (\neg\ b \vee p\ z\ x)$

lemma *rel-expr-if-not-1*: $\neg\ p\ z\ x \Longrightarrow p\ z\ (if\ b\ then\ x\ else\ y) = (\neg\ b \wedge p\ z\ y)$

lemma *rel-expr-if-not-2*: $\neg\ p\ z\ y \Longrightarrow p\ z\ (if\ b\ then\ x\ else\ y) = (b \wedge p\ z\ x)$

lemma *if-not*: $(if\ \neg\ b\ then\ x\ else\ y) = (if\ b\ then\ y\ else\ x)$

lemma *rel-not-if-expr-1*: $p\ y\ z \Longrightarrow p\ (if\ \neg\ b\ then\ x\ else\ y)\ z = (b \lor p\ x\ z)$

lemma *rel-not-if-expr-2*: $p\ x\ z \Longrightarrow p\ (if\ \neg\ b\ then\ x\ else\ y)\ z = (\neg b \lor\ \ p\ y\ z)$

lemma *rel-not-if-not-expr-1*: $\neg\ p\ y\ z \Longrightarrow p\ (if\ \neg\ b\ then\ x\ else\ y)\ z = (\neg\ b \land p\ x\ z)$

lemma *rel-not-if-not-expr-2*: $\neg\ p\ x\ z \Longrightarrow p\ (if\ \neg\ b\ then\ x\ else\ y)\ z = (b \land p\ y\ z)$

lemma *rel-expr-not-if-1*: $p\ z\ y \Longrightarrow p\ z\ (if\ \neg\ b\ then\ x\ else\ y) = (b \lor p\ z\ x)$

lemma *rel-expr-not-if-2*: $p\ z\ x \Longrightarrow p\ z\ (if\ \neg\ b\ then\ x\ else\ y) = (\neg\ b \lor p\ z\ y)$

lemma *rel-expr-not-if-not-1*: $\neg\ p\ z\ y \Longrightarrow p\ z\ (if\ \neg\ b\ then\ x\ else\ y) = (\neg\ b \land p\ z\ x)$

lemma *rel-expr-not-if-not-2*: $\neg\ p\ z\ x \Longrightarrow p\ z\ (if\ \neg\ b\ then\ x\ else\ y) = (b \land p\ z\ y)$

lemma *not-inf*: $(\neg\ (x{::}real) < y) = (y \leq x)$

lemmas *if-simps = rel-if-expr-1 rel-if-expr-2 rel-if-not-expr-1 rel-if-not-expr-2 rel-expr-if-1 rel-expr-if-2 rel-expr-if-not-1 rel-expr-if-not-2*
rel-not-if-expr-1 rel-not-if-expr-2 rel-not-if-not-expr-1 rel-not-if-not-expr-2 rel-expr-not-if-1 rel-expr-not-if-2 rel-expr-not-if-not-1 rel-expr-not-if-not-2
if-not not-inf MyIf-def

end

7.3 Automated Simplification

theory *SimplifyRCRS* **imports** *Simulink*
keywords *simplify-RCRS simplify-RCRS-f* :: *thy-decl*
begin

thm *update-assert-comp*

definition *prod-fun f g* $= (\lambda\ (x,\ y)\ .\ (f\ x,\ g\ y))$
definition *prod-prec p q* $= (\lambda\ (x,\ y)\ .\ p\ x \land q\ y)$

lemma *asseert-update-comp*: $(\bigwedge x\ .\ let\ y = f\ x\ in\ p''\ x = (p\ x \land p'\ y) \land f''\ x = f'\ y) \Longrightarrow (\{.p.\}\ o\ [-f-])\ o\ (\{.p'.\}\ o\ [-f'-]) = \{.p''.\}\ o\ [-f''-]$

lemma *asseert-update-comp-abs-aux*: $p'' = p \sqcap (p'\ o\ f) \Longrightarrow\ f'' = f'\ o\ f \Longrightarrow (\{.p.\}\ o\ [-f-])\ o\ (\{.p'.\}\ o\ [-f'-]) = \{.p''.\}\ o\ [-f''-]$

lemma *asseert-update-comp-abs*: $p \sqcap (p'\ o\ f) \equiv p'' \Longrightarrow\ f'\ o\ f \equiv f'' \Longrightarrow (\{.p.\}\ o\ [-f-])\ o\ (\{.p'.\}\ o\ [-f'-]) = \{.p''.\}\ o\ [-f''-]$

lemma *asseert-update-prod-abs*: $prod\text{-}prec\ p\ p' \equiv p'' \Longrightarrow\ prod\text{-}fun\ f\ f' \equiv f'' \Longrightarrow (\{.p.\}\ o\ [-f-]) ** (\{.p'.\}\ o\ [-f'-]) = \{.p''.\}\ o\ [-f''-]$

thm *If-prod*

term *Product-Type.prod.case-prod*

lemma *case-prod* $f\ (a,\ b) = f\ a\ b$

thm *Product-Type.case-prod-conv*

declare [[*show-sorts*]]

lemma *case-prod-eta-eq-sym*: $f \equiv (\lambda\ (x,\ y)\ .\ f\ (x,\ y))$

thm *Product-Type.case-prod-eta*

term $T\ ((x,y)\ ,z) = (x+y,x+z)$

definition *TtestTerm* $x \equiv x\ +\ 3$

definition *TTtestTerm* $\equiv (\lambda\ (x,\ (u,v),\ y)\ .\ (x,\ x+y,\ u+v))$

lemma *TT-simp*: *TTtestTerm* $(x,\ (u,v),\ y) \equiv (x,\ x\ +\ y,\ u+v)$

lemma *TTa-simp*: $(G \equiv$ *TTtestTerm*$) \Longrightarrow (G\ (x,\ (u,v),\ y) \equiv (x,\ x\ +\ y,\ u+v))$

thm *TtestTerm-def* [*of x*]

lemmas *T-inst* = *TtestTerm-def* [*of x*]

declare [[*show-sorts* = *false*]]

thm *cond-case-prod-eta*

thm *case-prod-eta*

thm *eta-contract-eq*

lemma *remove-aux-var*: $(\bigwedge X\ .\ X \equiv A \Longrightarrow X \equiv B) \Longrightarrow (A \equiv B)$

thm *Product-Type.case-prod-eta*

thm *cond-case-prod-eta*

declare [[*eta-contract*=*false*]]

lemma $(\{.(x,y).\ y{\neq}0.\}\ o\ [-\lambda(x,y).\ x/y-])\ o\ (\{.z.\ z{\geq}0.\}\ o\ [-\lambda z.\ sqrt\ z-]) = \{.\ (\lambda(x,\ y).\ y \neq 0) \sqcap ((\lambda z.\ z{\geq}0) \circ (\lambda(x,\ y).\ x\ /\ y))\ .\} \circ [-(\lambda z.\ sqrt\ z)\ o\ (\lambda(x,\ y).\ x\ /\ y)-]$

definition *dup* $y = (y,y)$

lemma $(snd\ o\ f\ o\ Pair\ (g\ x\ y))\ y = (snd\ o\ f\ o\ (prod\text{-}fun\ (g\ x)\ id)\ o\ dup)\ y$

lemma *feedback-asseert-update-abs-aux*: $g = (\lambda\ x\ .\ fst\ o\ f\ o\ Pair\ x) \Longrightarrow (\bigwedge\ x\ x'\ .\ g\ x = g\ x') \Longrightarrow\ snd\ o\ (f\ o\ (prod\text{-}fun\ (g\ x)\ id\ o\ dup)) = f' \Longrightarrow$
$p\ o\ (prod\text{-}fun\ (g\ x)\ id\ o\ dup) = p' \Longrightarrow feedback\ (\{.p.\}\ o\ [-f-]) = \{.p'.\}\ o\ [-f'-]$

lemma *feedback-asseert-update-abs*: $(\lambda\ x\ .\ fst\ o\ f\ o\ Pair\ x) \equiv g \Longrightarrow (\bigwedge\ x\ x'\ .\ g\ x \equiv g\ x') \Longrightarrow\ snd\ o\ (f\ o\ (prod\text{-}fun\ (g\ x)\ id\ o\ dup)) \equiv f' \Longrightarrow$
$p\ o\ (prod\text{-}fun\ (g\ x)\ id\ o\ dup) \equiv p' \Longrightarrow feedback\ (\{.p.\}\ o\ [-f-]) = \{.p'.\}\ o\ [-f'-]$

declare [[*eta-contract* = *false*]]

thm *eta-contract-eq*

thm *transitive*

lemma *Skip-th*: $\top \equiv p \Longrightarrow id \equiv f \Longrightarrow Skip = \{.p.\}\ o\ [-f-]$

lemma *Fail-th*: $\bot \equiv p \Longrightarrow f \equiv f \Longrightarrow \bot = \{.p.\}\ o\ [-f-]$

lemma *assert-th*: $p \equiv p' \Longrightarrow id \equiv f \Longrightarrow \{.p.\} = \{.p'.\}\ o\ [-f-]$

lemma *update-eq*: $\top \equiv p \Longrightarrow f \equiv g \Longrightarrow [-f-] = \{.p.\}\ o\ [-g-]$

lemma *demonic-eq*: $\top \equiv p \Longrightarrow r \equiv r' \Longrightarrow [:r:] = \{.p.\}\ o\ [:r':]$

lemma *assert-update-eq*: $p \equiv q \Longrightarrow f \equiv g \Longrightarrow \{.p.\}\ o\ [-f-] = \{.q.\}\ o\ [-g-]$

lemma *assert-demonic-eq*: $p \equiv q \Longrightarrow r \equiv r' \Longrightarrow \{.p.\}\ o\ [:r:] = \{.q.\}\ o\ [:r':]$

lemma *prec-simp-rel*: $((p \Longrightarrow r) \equiv (p \Longrightarrow r')) \Longrightarrow p \wedge r \equiv p \wedge r'$

lemma $((p \Longrightarrow r) \equiv Trueprop\ True) \Longrightarrow p \wedge r \equiv p$

definition *inter-pre-rel* $p\ r\ x\ y = (p\ x \wedge r\ x\ y)$

lemma *prop-eq-true*: $X \equiv True \Longrightarrow X$

lemma *inter-pre-rel-sym*: $(p\ x \wedge r\ x\ y) = inter\text{-}pre\text{-}rel\ p\ r\ x\ y$

theorem *assert-simp-demonic-eq*: $p \equiv p' \Longrightarrow inter\text{-}pre\text{-}rel\ p'\ r \equiv inter\text{-}pre\text{-}rel\ p'\ r' \Longrightarrow \{.p.\}\ o\ [:r:] = \{.p'.\}\ o\ [:r':]$

lemma *feedback-cong*: $B = A \Longrightarrow feedback\ A = F \Longrightarrow feedback\ B = F$

lemma *comp-cong*: $S = A \Longrightarrow T = B \Longrightarrow A\ o\ B = F \Longrightarrow S\ o\ T = F$

lemma *prod-cong*: $S = A \Longrightarrow T = B \Longrightarrow A ** B = F \Longrightarrow S ** T = F$

lemma *eq-eq-tran*: $a = b \Longrightarrow b \equiv c \Longrightarrow c = d \Longrightarrow a = d$

lemma *rename-vars*: $Skip = A \Longrightarrow A\ o\ B = C \Longrightarrow M = B \Longrightarrow M = C$

lemma *simp-to-fail*: $A = \{.p.\}\ o\ T \Longrightarrow (\bigwedge x\ .\ p\ x = False) \Longrightarrow A = \bot$

lemma *assert-true-comp*: $A = \{.p.\}\ o\ T \Longrightarrow (\bigwedge x\ .\ p\ x = True) \Longrightarrow A = T$

lemma *test-types*: $(a::real) = a \wedge b + 0 = b + 0 \wedge (c :: 'a \Rightarrow 'b) = c$

declare [[*show-types*]]

declare [[*show-types=false*]]

end

7.4 Python Simulation Code Generation

theory *PythonSimulation* **imports** *Real Transcendental SimulinkTypes*
begin

definition *PI-PY* $= (\lambda x::nat.\ s\text{-}pi)$

lemma *PI-PY-gen-simp*: $s\text{-}pi = PI\text{-}PY(0)$

lemma *PI-PY-simp*: $pi = PI\text{-}PY(0)$

definition *NOT-PY* $= Not$

lemma *NOT-PY-simp*: $Not\ x = NOT\text{-}PY(x)$

definition *AND-PY* $= (\lambda\ (x,\ y).\ x \wedge y)$

lemma *AND-PY-simp*: $(x \wedge y) = AND\text{-}PY(x,y)$

definition $OR\text{-}PY = (\lambda\ (x,y).\ x \vee y)$

lemma $OR\text{-}PY\text{-}simp$: $(x \vee y) = OR\text{-}PY(x,y)$

definition $LESS\text{-}PY = (\lambda\ (x,\ y)\ .\ x < y)$

lemma $LESS\text{-}PY\text{-}simp$: $(x < y) = LESS\text{-}PY\ (x,\ y)$

definition $LE\text{-}PY = (\lambda\ (x,\ y)\ .\ x \leq y)$

lemma $LE\text{-}PY\text{-}simp$: $(x \leq y) = LE\text{-}PY\ (x,\ y)$

definition $EQ\text{-}PY = (\lambda\ (x,\ y)\ .\ x = y)$

lemma $EQ\text{-}PY\text{-}simp$: $(x = y) = EQ\text{-}PY\ (x,\ y)$

definition $ADD\text{-}PY = (\lambda\ (x,\ y).\ x + y)$

lemma $ADD\text{-}PY\text{-}simp$: $(x + y) = ADD\text{-}PY\ (x,\ y)$

definition $SUBS\text{-}PY = (\lambda\ (x,\ y).\ x - y)$

lemma $SUBS\text{-}PY\text{-}simp$: $(x - y) = SUBS\text{-}PY\ (x,\ y)$

definition $MULT\text{-}PY = (\lambda\ (x,\ y).\ x * y)$

lemma $MULT\text{-}PY\text{-}simp$: $(x * y) = MULT\text{-}PY\ (x,\ y)$

definition $DIV\text{-}PY = (\lambda\ (x,y)\ .\ x\ /\ y)$

lemma $DIV\text{-}PY\text{-}simp$: $x\ /\ y = DIV\text{-}PY\ (x,\ y)$

definition $ABS\text{-}PY = (\lambda\ x.\ s\text{-}abs\ x)$

lemma *ABS-PY-gen-simp*: $s\text{-}abs\ x = ABS\text{-}PY\ x$

lemma *ABS-PY-simp*: $abs\ (x{::}real) = ABS\text{-}PY\ x$

definition $POW\text{-}PY = (\lambda(x,y).\ power\ x\ y)$

lemma *POW-PY-simp*: $(x \,\hat{}\, y) = POW\text{-}PY\ (x,\ y)$

definition $SQRT\text{-}PY = s\text{-}sqrt$

lemma *SQRT-PY-gen-simp*: $s\text{-}sqrt\ x = SQRT\text{-}PY(x)$

lemma *SQRT-PY-simp*: $sqrt\ x = SQRT\text{-}PY(x)$

definition $EXP\text{-}PY = s\text{-}exp$

lemma *EXP-PY-gen-simp*: $s\text{-}exp\ x = EXP\text{-}PY(x)$

lemma *EXP-PY-simp*: $exp\ (x{::}real) = EXP\text{-}PY(x)$

definition $SIN\text{-}PY = s\text{-}sin$

lemma *SIN-PY-gen-simp*: $s\text{-}sin\ x = SIN\text{-}PY(x)$

lemma *SIN-PY-simp*: $sin\ (x{::}real) = SIN\text{-}PY(x)$

definition $FST\text{-}PY = fst$

lemma *FST-PY-simp*: $fst\ x = FST\text{-}PY\ (x)$

definition $SND\text{-}PY = snd$

lemma *SND-PY-simp*: *snd x* = *SND-PY* (*x*)

definition *IF-PY* = (λ (*b*, *x*, *y*) . *If b Then x Else y*)

lemma *IF-PY-gen-simp*: (*If b Then x Else y*) = *IF-PY* (*b*, *x*, *y*)

lemma *IF-PY-simp*: (*if b then x else y*) = *IF-PY* (*b*, *x*, *y*)

definition *IMP-PY* = (λ (*x*, *y*) . *x* ⟶ *y*)

lemma *IMP-PY-simp*: (*x* ⟶ *y*) = *IMP-PY* (*x*, *y*)

definition *CONVERSION-PY* = (λ (*x*, *y*::*nat*) . *conversion x*)

lemma *CONVERSION-PY-simp*: *conversion x* = *CONVERSION-PY* (*x*,*0*)

lemmas *python-simps* = *PI-PY-simp PI-PY-gen-simp NOT-PY-simp AND-PY-simp OR-PY-simp LESS-PY-simp LE-PY-simp EQ-PY-simp*
ADD-PY-simp SUBS-PY-simp MULT-PY-simp DIV-PY-simp ABS-PY-gen-simp ABS-PY-simp
POW-PY-simp SQRT-PY-gen-simp SQRT-PY-simp
EXP-PY-gen-simp EXP-PY-simp SIN-PY-gen-simp SIN-PY-simp
FST-PY-simp SND-PY-simp
IF-PY-simp IF-PY-gen-simp IMP-PY-simp
CONVERSION-PY-simp

end

8 List Operations. Permutations and Substitutions

theory *ListProp* **imports** *Main* ~~/*src*/*HOL*/*Library*/*Permutation*
begin

lemma *perm-mset*: *perm x y* = (*mset x* = *mset y*)

lemma *perm-tp*: *perm* (*x*@*y*) (*y*@*x*)

lemma *perm-union-left*: *perm x z* ⟹ *perm* (*x* @ *y*) (*z* @ *y*)

lemma *perm-union-right*: *perm x z* ⟹ *perm* (*y* @ *x*) (*y* @ *z*)

lemma *perm-trans*: *perm x y* ⟹ *perm y z* ⟹ *perm x z*

lemma *perm-sym*: *perm x y* ⟹ *perm y x*

lemma *perm-length*: *perm u v* ⟹ *length u* = *length v*

lemma *perm-set-eq*: $perm\ x\ y \Longrightarrow set\ x = set\ y$

lemma *perm-empty*[*simp*]: $(perm\ []\ v) = (v = [])$ **and** $(perm\ v\ []) = (v = [])$

lemma *perm-refl*[*simp*]: $perm\ x\ x$

lemma *dist-perm*: $\bigwedge\ y\ .\ distinct\ x \Longrightarrow perm\ x\ y \Longrightarrow distinct\ y$

lemma *split-perm*: $perm\ (a\ \#\ x)\ x' = (\exists\ y\ y'\ .\ x' = y\ @\ a\ \#\ y' \wedge perm\ x\ (y\ @\ y'))$

fun *subst*:: $'a\ list \Rightarrow\ 'a\ list \Rightarrow\ 'a \Rightarrow\ 'a$ **where**
$subst\ []\ []\ c = c$ |
$subst\ (a\#x)\ (b\#y)\ c = (if\ a = c\ then\ b\ else\ subst\ x\ y\ c)$ |
$subst\ x\ y\ c = undefined$

lemma *subst-notin* [*simp*]: $\bigwedge\ y\ .\ length\ x = length\ y \Longrightarrow a \notin set\ x \Longrightarrow subst\ x\ y\ a = a$

lemma *subst-cons-a*:$\bigwedge\ y\ .\ distinct\ x \Longrightarrow a \notin set\ x \Longrightarrow b \notin set\ x \Longrightarrow length\ x = length\ y \Longrightarrow\ subst\ (a\ \#\ x)\ (b\ \#\ y)\ c =\ (subst\ x\ y\ (subst\ [a]\ [b]\ c))$

lemma *subst-eq*: $subst\ x\ x\ y = y$

fun *Subst* :: $'a\ list \Rightarrow\ 'a\ list \Rightarrow\ 'a\ list \Rightarrow\ 'a\ list$ **where**
$Subst\ x\ y\ [] = []$ |
$Subst\ x\ y\ (a\ \#\ z) = subst\ x\ y\ a\ \#\ (Subst\ x\ y\ z)$

lemma *Subst-empty*[*simp*]: $Subst\ []\ []\ y = y$

lemma *Subst-eq*: $Subst\ x\ x\ y = y$

lemma *Subst-append*: $Subst\ a\ b\ (x@y) = Subst\ a\ b\ x\ @\ Subst\ a\ b\ y$

lemma *Subst-notin*[*simp*]: $a \notin set\ z \Longrightarrow Subst\ (a\ \#\ x)\ (b\ \#\ y)\ z = Subst\ x\ y\ z$

lemma *Subst-all*[*simp*]: $\bigwedge\ v\ .\ distinct\ u \Longrightarrow length\ u = length\ v \Longrightarrow Subst\ u\ v\ u = v$

lemma *Subst-inex*[*simp*]: $\bigwedge\ b.\ set\ a \cap set\ x = \{\} \Longrightarrow length\ a = length\ b \Longrightarrow Subst\ a\ b\ x = x$

lemma *set-Subst*: $set\ (Subst\ [a]\ [b]\ x) = (if\ a \in set\ x\ then\ (set\ x - \{a\}) \cup \{b\}\ else\ set\ x)$

lemma *distinct-Subst*: $distinct\ (b\#x) \Longrightarrow distinct\ (Subst\ [a]\ [b]\ x)$

lemma *inter-Subst*: $distinct(b\#y) \Longrightarrow set\ x \cap set\ y = \{\} \Longrightarrow b \notin set\ x \Longrightarrow set\ x \cap set\ (Subst\ [a]\ [b]\ y) = \{\}$

lemma *incl-Subst*: $distinct(b\#x) \Longrightarrow set\ y \subseteq set\ x \Longrightarrow set\ (Subst\ [a]\ [b]\ y) \subseteq set\ (Subst\ [a]\ [b]\ x)$

lemma *subst-in-set*: $\bigwedge y.\ length\ x = length\ y \Longrightarrow a \in set\ x \Longrightarrow subst\ x\ y\ a \in set\ y$

lemma *Subst-set-incl*: $length\ x = length\ y \Longrightarrow set\ z \subseteq set\ x \Longrightarrow set\ (Subst\ x\ y\ z) \subseteq set\ y$

lemma *subst-not-in*: $\bigwedge y . a \notin set\ x' \Longrightarrow length\ x = length\ y \Longrightarrow length\ x' = length\ y' \Longrightarrow subst\ (x @ x')\ (y @ y')\ a = subst\ x\ y\ a$

lemma *subst-not-in-b*: $\bigwedge y . a \notin set\ x \Longrightarrow length\ x = length\ y \Longrightarrow length\ x' = length\ y' \Longrightarrow subst\ (x @ x')\ (y @ y')\ a = subst\ x'\ y'\ a$

lemma *Subst-not-in*: $set\ x' \cap set\ z = \{\} \Longrightarrow length\ x = length\ y \Longrightarrow length\ x' = length\ y' \Longrightarrow Subst\ (x @ x')\ (y @ y')\ z = Subst\ x\ y\ z$

lemma *Subst-not-in-a*: $set\ x \cap set\ z = \{\} \Longrightarrow length\ x = length\ y \Longrightarrow length\ x' = length\ y' \Longrightarrow Subst\ (x @ x')\ (y @ y')\ z = Subst\ x'\ y'\ z$

lemma *subst-cancel-right* [*simp*]: $\bigwedge y\ z . set\ x \cap set\ y = \{\} \Longrightarrow length\ y = length\ z \Longrightarrow subst\ (x @ y)\ (x @ z)\ a = subst\ y\ z\ a$

lemma *Subst-cancel-right*: $set\ x \cap set\ y = \{\} \Longrightarrow length\ y = length\ z \Longrightarrow Subst\ (x @ y)\ (x @ z)\ w = Subst\ y\ z\ w$

lemma *subst-cancel-left* [*simp*]: $\bigwedge y\ z . set\ x \cap set\ z = \{\} \Longrightarrow length\ x = length\ y \Longrightarrow subst\ (x @ z)\ (y @ z)\ a = subst\ x\ y\ a$

lemma *Subst-cancel-left*: $set\ x \cap set\ z = \{\} \Longrightarrow length\ x = length\ y \Longrightarrow Subst\ (x @ z)\ (y @ z)\ w = Subst\ x\ y\ w$

lemma *Subst-cancel-right-a*: $a \notin set\ y \Longrightarrow length\ y = length\ z \Longrightarrow Subst\ (a \# y)\ (a \# z)\ w = Subst\ y\ z\ w$

lemma *subst-subst-id* [*simp*]: $\bigwedge y . a \in set\ y \Longrightarrow distinct\ x \Longrightarrow length\ x = length\ y \Longrightarrow subst\ x\ y\ (subst\ y\ x\ a) = a$

lemma *Subst-Subst-id*[*simp*]: $set\ z \subseteq set\ y \Longrightarrow distinct\ x \Longrightarrow length\ x = length\ y \Longrightarrow Subst\ x\ y\ (Subst\ y\ x\ z) = z$

lemma *Subst-cons-aux-a*: $set\ x \cap set\ y = \{\} \Longrightarrow distinct\ y \Longrightarrow length\ y = length\ z \Longrightarrow Subst\ (x @ y)\ (x @ z)\ y = z$

lemma *Subst-set-empty* [*simp*]: $set\ z \cap set\ x = \{\} \Longrightarrow length\ x = length\ y \Longrightarrow Subst\ x\ y\ z = z$

lemma *length-Subst*[*simp*]: $length\ (Subst\ x\ y\ z) = length\ z$

lemma *subst-Subst*: $\bigwedge y\ y' . length\ y = length\ y' \Longrightarrow a \in set\ w \Longrightarrow subst\ w\ (Subst\ y\ y'\ w)\ a = subst\ y\ y'\ a$

lemma *Subst-Subst*: $length\ y = length\ y' \Longrightarrow set\ z \subseteq set\ w \Longrightarrow Subst\ w\ (Subst\ y\ y'\ w)\ z = Subst\ y\ y'\ z$

primrec *listinter* :: *'a list* ⇒ *'a list* ⇒ *'a list* (**infixl** ⊗ *60*) **where**
$[] \otimes y = []$ |
$(a \# x) \otimes y = (if\ a \in set\ y\ then\ a \# (x \otimes y)\ else\ x \otimes y)$

lemma *inter-filter*: $x \otimes y = \mathit{filter}\ (\lambda\ a\ .\ a \in \mathit{set}\ y)\ x$

lemma *inter-append*: $\mathit{set}\ y \cap \mathit{set}\ z = \{\} \Longrightarrow \mathit{perm}\ (x \otimes (y\ @\ z))\ ((x \otimes y)\ @\ (x \otimes z))$

lemma *append-inter*: $(x\ @\ y) \otimes z = (x \otimes z)\ @\ (y \otimes z)$

lemma *notin-inter* [*simp*]: $a \notin \mathit{set}\ x \Longrightarrow a \notin \mathit{set}\ (x \otimes y)$

lemma *distinct-inter*: $\mathit{distinct}\ x \Longrightarrow \mathit{distinct}\ (x \otimes y)$

lemma *set-inter*: $\mathit{set}\ (x \otimes y) = \mathit{set}\ x \cap \mathit{set}\ y$

primrec *diff* $::\ 'a\ \mathit{list} \Rightarrow\ 'a\ \mathit{list} \Rightarrow\ 'a\ \mathit{list}$ (**infixl** $\ominus$ *52*) **where**
$[] \ominus y = []\ |$
$(a\ \#\ x) \ominus y = (\mathit{if}\ a \in \mathit{set}\ y\ \mathit{then}\ x \ominus y\ \mathit{else}\ a\ \#\ (x \ominus y))$

lemma *diff-filter*: $x \ominus y = \mathit{filter}\ (\lambda\ a\ .\ a \notin \mathit{set}\ y)\ x$

lemma *diff-distinct*: $\mathit{set}\ x \cap \mathit{set}\ y = \{\} \Longrightarrow (y \ominus x) = y$

lemma *set-diff*: $\mathit{set}\ (x \ominus y) = \mathit{set}\ x - \mathit{set}\ y$

lemma *distinct-diff*: $\mathit{distinct}\ x \Longrightarrow \mathit{distinct}\ (x \ominus y)$

definition *addvars* $::\ 'a\ \mathit{list} \Rightarrow\ 'a\ \mathit{list} \Rightarrow\ 'a\ \mathit{list}$ (**infixl** $\oplus$ *55*) **where**
$\mathit{addvars}\ x\ y = x\ @\ (y \ominus x)$

lemma *addvars-distinct*: $\mathit{set}\ x \cap \mathit{set}\ y = \{\} \Longrightarrow x \oplus y = x\ @\ y$

lemma *set-addvars*: $\mathit{set}\ (x \oplus y) = \mathit{set}\ x \cup \mathit{set}\ y$

lemma *distinct-addvars*: $\mathit{distinct}\ x \Longrightarrow \mathit{distinct}\ y \Longrightarrow \mathit{distinct}\ (x \oplus y)$

lemma *mset-inter-diff*: $\mathit{mset}\ \mathit{oa} = \mathit{mset}\ (\mathit{oa} \otimes \mathit{ia}) + \mathit{mset}\ (\mathit{oa} \ominus (\mathit{oa} \otimes \mathit{ia}))$

lemma *diff-inter-left*: $(x \ominus (x \otimes y)) = (x \ominus y)$

lemma *diff-inter-right*: $(x \ominus (y \otimes x)) = (x \ominus y)$

lemma *addvars-minus*: $(x \oplus y) \ominus z = (x \ominus z) \oplus (y \ominus z)$

lemma *addvars-assoc*: $x \oplus y \oplus z = x \oplus (y \oplus z)$

lemma *diff-sym*: $(x \ominus y \ominus z) = (x \ominus z \ominus y)$

lemma *diff-union*: $(x \ominus y\ @\ z) = (x \ominus y \ominus z)$

lemma *diff-notin*: $\mathit{set}\ x \cap \mathit{set}\ z = \{\} \Longrightarrow (x \ominus (y \ominus z)) = (x \ominus y)$

lemma *union-diff*: $x\ @\ y \ominus z = ((x \ominus z)\ @\ (y \ominus z))$

lemma *diff-inter-empty*: $\mathit{set}\ x \cap \mathit{set}\ y = \{\} \Longrightarrow x \ominus y \otimes z = x$

lemma *inter-diff-empty*: $set\ x \cap set\ z = \{\} \Longrightarrow x \otimes (y \ominus z) = (x \otimes y)$

lemma *inter-diff-distrib*: $(x \ominus y) \otimes z = ((x \otimes z) \ominus (y \otimes z))$

lemma *diff-emptyset*: $x \ominus [] = x$

lemma *diff-eq*: $x \ominus x = []$

lemma *diff-subset*: $set\ x \subseteq set\ y \Longrightarrow x \ominus y = []$

lemma *empty-inter*: $set\ x \cap set\ y = \{\} \Longrightarrow x \otimes y = []$

lemma *empty-inter-diff*: $set\ x \cap set\ y = \{\} \Longrightarrow x \otimes (y \ominus z) = []$

lemma *inter-addvars-empty*: $set\ x \cap set\ z = \{\} \Longrightarrow x \otimes y\ @\ z = x \otimes y$

lemma *diff-disjoint*: $set\ x \cap set\ y = \{\} \Longrightarrow x \ominus y = x$

lemma *addvars-empty*[*simp*]: $x \oplus [] = x$

lemma *empty-addvars*[*simp*]: $[] \oplus x = x$

lemma *distrib-diff-addvars*: $x \ominus (y\ @\ z) = ((x \ominus y) \otimes (x \ominus z))$

lemma *inter-subset*: $x \otimes (x \ominus y) = (x \ominus y)$

lemma *diff-cancel*: $x \ominus y \ominus (z \ominus y) = (x \ominus y \ominus z)$

lemma *diff-cancel-set*: $set\ x \cap set\ u = \{\} \Longrightarrow x \ominus y \ominus (z \ominus u) = (x \ominus y \ominus z)$

lemma *inter-subset-l1*: $\bigwedge y.\ distinct\ x \Longrightarrow length\ y = 1 \Longrightarrow set\ y \subseteq set\ x \Longrightarrow x \otimes y = y$

lemma *perm-diff-left-inter*: $perm\ (x \ominus y)\ (((x \ominus y) \otimes z)\ @\ ((x \ominus y) \ominus z))$

lemma *perm-diff-right-inter*: $perm\ (x \ominus y)\ (((x \ominus y) \ominus z)\ @\ ((x \ominus y) \otimes z))$

lemma *perm-switch-aux-a*: $perm\ x\ ((x \ominus y)\ @\ (x \otimes y))$

lemma *perm-switch-aux-b*: $perm\ (x\ @\ (y \ominus x))\ ((x \ominus y)\ @\ (x \otimes y)\ @\ (y \ominus x))$

lemma *perm-switch-aux-c*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow perm\ ((y \otimes x)\ @\ (y \ominus x))\ y$

lemma *perm-switch-aux-d*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow perm\ (x \otimes y)\ (y \otimes x)$

lemma *perm-switch-aux-e*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow perm\ ((x \otimes y)\ @\ (y \ominus x))\ ((y \otimes x)\ @\ (y \ominus x))$

lemma *perm-switch-aux-f*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow perm\ ((x \otimes y)\ @\ (y \ominus x))\ y$

lemma *perm-switch-aux-h*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow perm\ ((x \ominus y)\ @\ (x \otimes y)\ @\ (y \ominus x))\ ((x \ominus y)\ @\ y)$

lemma *perm-switch*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow perm\ (x\ @\ (y \ominus x))\ ((x \ominus y)\ @\ y)$

lemma *perm-aux-a*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow x \otimes y = x \Longrightarrow perm\ (x\ @\ (y \ominus x))\ y$

lemma *ZZZ-a*: $x \oplus (y \ominus x) = (x \oplus y)$

lemma *ZZZ-b*: $set\ (y \otimes z) \cap set\ x = \{\} \Longrightarrow (x \ominus (y \ominus z) \ominus (z \ominus y)) = (x \ominus y \ominus z)$

lemma *subst-subst*: $\bigwedge\ y\ z\ .\ a \in set\ z \Longrightarrow distinct\ x \Longrightarrow length\ x = length\ y \Longrightarrow length\ z = length\ x$
$\Longrightarrow subst\ x\ y\ (subst\ z\ x\ a) = subst\ z\ y\ a$

lemma *Subst-Subst-a*: $set\ u \subseteq set\ z \Longrightarrow distinct\ x \Longrightarrow length\ x = length\ y \Longrightarrow length\ z = length\ x$
$\Longrightarrow Subst\ x\ y\ (Subst\ z\ x\ u) = (Subst\ z\ y\ u)$

lemma *subst-in*: $\bigwedge\ x'\ .\ length\ x = length\ x' \Longrightarrow a \in set\ x \Longrightarrow subst\ (x\ @\ y)\ (x'\ @\ y')\ a = subst\ x\ x'\ a$

lemma *subst-switch*: $\bigwedge\ x'\ .\ set\ x \cap set\ y = \{\} \Longrightarrow length\ x = length\ x' \Longrightarrow length\ y = length\ y'$
$\Longrightarrow subst\ (x\ @\ y)\ (x'\ @\ y')\ a = subst\ (y\ @\ x)\ (y'\ @\ x')\ a$

lemma *Subst-switch*: $set\ x \cap set\ y = \{\} \Longrightarrow length\ x = length\ x' \Longrightarrow length\ y = length\ y'$
$\Longrightarrow Subst\ (x\ @\ y)\ (x' @\ y')\ z = Subst\ (y\ @\ x)\ (y' @\ x')\ z$

lemma *subst-comp*: $\bigwedge\ x'\ .\ set\ x \cap set\ y = \{\} \Longrightarrow set\ x' \cap set\ y = \{\} \Longrightarrow length\ x = length\ x'$
$\Longrightarrow length\ y = length\ y' \Longrightarrow subst\ (x\ @\ y)\ (x'\ @\ y')\ a = subst\ y\ y'\ (subst\ x\ x'\ a)$

lemma *Subst-comp*: $set\ x \cap set\ y = \{\} \Longrightarrow set\ x' \cap set\ y = \{\} \Longrightarrow length\ x = length\ x'$
$\Longrightarrow length\ y = length\ y' \Longrightarrow Subst\ (x\ @\ y)\ (x'\ @\ y')\ z = Subst\ y\ y'\ (Subst\ x\ x'\ z)$

lemma *set-subst*: $\bigwedge\ u'\ .\ length\ u = length\ u' \Longrightarrow subst\ u\ u'\ a \in set\ u' \cup (\{a\} - set\ u)$

lemma *set-Subst-a*: $length\ u = length\ u' \Longrightarrow set\ (Subst\ u\ u'\ z) \subseteq set\ u' \cup (set\ z - set\ u)$

lemma *set-SubstI*: $length\ u = length\ u' \Longrightarrow set\ u' \cup (set\ z - set\ u) \subseteq X \Longrightarrow set\ (Subst\ u\ u'\ z) \subseteq X$

lemma *not-in-set-diff*: $a \notin set\ x \Longrightarrow x \ominus ys\ @\ a\ \#\ zs = x \ominus ys\ @\ zs$

lemma [*simp*]: $(X \cap (Y \cup Z) = \{\}) = (X \cap Y = \{\} \wedge X \cap Z = \{\})$

lemma *Comp-assoc-new-subst-aux*: $set\ u \cap set\ y \cap set\ z = \{\} \Longrightarrow distinct\ z \Longrightarrow length\ u = length\ u'$
$\Longrightarrow Subst\ (z \ominus v)\ (Subst\ u\ u'\ (z \ominus v))\ z = Subst\ (u \ominus y \ominus v)\ (Subst\ u\ u'\ (u \ominus y \ominus v))\ z$

lemma [*simp*]: $(x \ominus y \ominus (y \ominus z)) = (x \ominus y)$

lemma [*simp*]: $(x \ominus y \ominus (y \ominus z \ominus z')) = (x \ominus y)$

lemma *diff-addvars*: $x \ominus (y \oplus z) = (x \ominus y \ominus z)$

lemma *diff-redundant-a*: $x \ominus y \ominus z \ominus (y \ominus u) = (x \ominus y \ominus z)$

lemma *diff-redundant-b*: $x \ominus y \ominus z \ominus (z \ominus u) = (x \ominus y \ominus z)$

lemma *diff-redundant-c*: $x \ominus y \ominus z \ominus (y \ominus u \ominus v) = (x \ominus y \ominus z)$

lemma *diff-redundant-d*: $x \ominus y \ominus z \ominus (z \ominus u \ominus v) = (x \ominus y \ominus z)$

lemma *set-list-empty*: $set\ x = \{\} \Longrightarrow x = []$

lemma [*simp*]: $(x \ominus x \otimes y) \otimes (y \ominus x \otimes y) = []$

lemma [*simp*]: $set\ x \cap set\ (y \ominus x) = \{\}$

lemma [*simp*]: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow set\ x \subseteq set\ y \Longrightarrow perm\ (x\ @\ (y \ominus x))\ y$

lemma [*simp*]: $perm\ x\ y \Longrightarrow set\ x \subseteq set\ y$
lemma [*simp*]: $perm\ x\ y \Longrightarrow set\ y \subseteq set\ x$

lemma [*simp*]: $set\ (x \ominus y) \subseteq set\ x$

lemma *perm-diff*[*simp*]: $\bigwedge x'\ .\ perm\ x\ x' \Longrightarrow perm\ y\ y' \Longrightarrow perm\ (x \ominus y)\ (x' \ominus y')$

lemma [*simp*]: $perm\ x\ x' \Longrightarrow perm\ y\ y' \Longrightarrow perm\ (x\ @\ y)\ (x'\ @\ y')$

lemma [*simp*]: $perm\ x\ x' \Longrightarrow perm\ y\ y' \Longrightarrow perm\ (x \oplus y)\ (x' \oplus y')$

thm *distinct-diff*

declare *distinct-diff* [*simp*]

lemma [*simp*]: $\bigwedge x'\ .\ perm\ x\ x' \Longrightarrow perm\ y\ y' \Longrightarrow perm\ (x \otimes y)\ (x' \otimes y')$

declare *distinct-inter* [*simp*]

lemma *perm-ops*: $perm\ x\ x' \Longrightarrow perm\ y\ y' \Longrightarrow f = op\ \otimes \vee f = op\ \ominus \vee f = op\ \oplus \Longrightarrow perm\ (f\ x\ y)\ (f\ x'\ y')$

lemma [*simp*]: $perm\ x'\ x \Longrightarrow perm\ y'\ y \Longrightarrow f = op\ \otimes \vee f = op\ \ominus \vee f = op\ \oplus \Longrightarrow perm\ (f\ x\ y)\ (f\ x'\ y')$

lemma [*simp*]: $perm\ x\ x' \Longrightarrow perm\ y'\ y \Longrightarrow f = op\ \otimes \vee f = op\ \ominus \vee f = op\ \oplus \Longrightarrow perm\ (f\ x\ y)\ (f\ x'\ y')$

lemma [*simp*]: $perm\ x'\ x \Longrightarrow perm\ y\ y' \Longrightarrow f = op\ \otimes \vee f = op\ \ominus \vee f = op\ \oplus \Longrightarrow perm\ (f\ x\ y)\ (f\ x'\ y')$

lemma *diff-cons*: $(x \ominus (a\ \#\ y)) = (x \ominus [a] \ominus y)$

lemma [*simp*]: $x \oplus y \oplus x = x \oplus y$

lemma *subst-subst-inv*: $\bigwedge y\ .\ distinct\ y \Longrightarrow length\ x = length\ y \Longrightarrow a \in set\ x \Longrightarrow subst\ y\ x\ (subst\ x\ y\ a) = a$

lemma *Subst-Subst-inv*: $distinct\ y \Longrightarrow length\ x = length\ y \Longrightarrow set\ z \subseteq set\ x \Longrightarrow Subst\ y\ x\ (Subst$

$x\ y\ z) = z$

lemma *perm-append*: $perm\ x\ x' \Longrightarrow perm\ y\ y' \Longrightarrow perm\ (x\ @\ y)\ (x'\ @\ y')$

lemma $x' = y\ @\ a\ \#\ y' \Longrightarrow perm\ x\ (y\ @\ y') \Longrightarrow perm\ (a\ \#\ x)\ x'$

lemma *perm-diff-eq*: $perm\ y\ y' \Longrightarrow (x \ominus y) = (x \ominus y')$

lemma [*simp*]: $A \cap B = \{\} \Longrightarrow x \in A \Longrightarrow x \in B \Longrightarrow False$
lemma [*simp*]: $A \cap B = \{\} \Longrightarrow x \in A \Longrightarrow x \notin B$

lemma [*simp*]: $B \cap A = \{\} \Longrightarrow x \in A \Longrightarrow x \notin B$
lemma [*simp*]: $B \cap A = \{\} \Longrightarrow x \in A \Longrightarrow x \in B \Longrightarrow False$

lemma *distinct-perm-set-eq*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow perm\ x\ y = (set\ x = set\ y)$

lemma *set-perm*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow set\ x = set\ y \Longrightarrow perm\ x\ y$

lemma *distinct-perm-switch*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow perm\ (x \oplus y)\ (y \oplus x)$
lemma *listinter-diff*: $(x \otimes y) \ominus z = (x \ominus z) \otimes (y \ominus z)$

lemma *set-listinter*: $set\ y = set\ z \Longrightarrow x \otimes y = x \otimes z$

lemma *AAA-c*: $a \notin set\ x \Longrightarrow x \ominus [a] = x$

lemma *distinct-perm-cons*: $distinct\ x \Longrightarrow perm\ (a\ \#\ y)\ x \Longrightarrow perm\ y\ (x \ominus [a])$

lemma *listinter-empty*[*simp*]: $y \otimes [] = []$

lemma *subsetset-inter*: $set\ x \subseteq set\ y \Longrightarrow (x \otimes y) = x$

lemma *addvars-addsame*: $x \oplus y \oplus (x \ominus z) = x \oplus y$

lemma *ZZZ*: $x \ominus x \oplus y = []$

lemma *perm-dist-mem*: $distinct\ x \Longrightarrow a \in set\ x \Longrightarrow perm\ (a\ \#\ (x \ominus [a]))\ x$

lemma *addvars-diff*: $b\ \#\ (x \oplus (z \ominus [b])) = (b\ \#\ x) \oplus z$

lemma *perm-cons*: $a \in set\ y \Longrightarrow distinct\ y \Longrightarrow perm\ x\ (y \ominus [a]) \Longrightarrow perm\ (a\ \#\ x)\ y$

end

9 Translation of Hierarchical Block Diagrams

9.1 Abstract Algebra of Hierarchical Block Diagrams (except one axiom for feedback)

theory *HBDAlgebra* **imports** *ListProp*
begin

locale *BaseOperationFeedbackless* =

fixes *TI TO* :: $'a \Rightarrow 'tp\ list$

fixes *ID* :: $'tp\ list \Rightarrow 'a$
assumes [*simp*]: $TI(ID\ ts) = ts$
assumes [*simp*]: $TO(ID\ ts) = ts$

fixes *comp* :: $'a \Rightarrow 'a \Rightarrow 'a$ (**infixl** *oo 70*)
assumes *TI-comp*[*simp*]: $TI\ S' = TO\ S \Longrightarrow TI\ (S\ oo\ S') = TI\ S$
assumes *TO-comp*[*simp*]: $TI\ S' = TO\ S \Longrightarrow TO\ (S\ oo\ S') = TO\ S'$
assumes *comp-id-left* [*simp*]: $ID\ (TI\ S)\ oo\ S\ = S$
assumes *comp-id-right* [*simp*]: $S\ oo\ ID\ (TO\ S) = S$
assumes *comp-assoc*: $TI\ T = TO\ S \Longrightarrow TI\ R = TO\ T \Longrightarrow S\ oo\ T\ oo\ R = S\ oo\ (T\ oo\ R)$

fixes *parallel* :: $'a \Rightarrow 'a \Rightarrow 'a$ (**infixl** $\parallel$ *80*)
assumes *TI-par* [*simp*]: $TI\ (S \parallel T) = TI\ S\ @\ TI\ T$
assumes *TO-par* [*simp*]: $TO\ (S \parallel T) = TO\ S\ @\ TO\ T$
assumes *par-assoc*: $A \parallel B \parallel C = A \parallel (B \parallel C)$
assumes *empty-par*[*simp*]: $ID\ [] \parallel S = S$
assumes *par-empty*[*simp*]: $S \parallel ID\ [] = S$
assumes *parallel-ID* [*simp*]: $ID\ ts \parallel ID\ ts' = ID\ (ts\ @\ ts')$

assumes *comp-parallel-distrib*: $TO\ S = TI\ S' \Longrightarrow TO\ T = TI\ T' \Longrightarrow (S \parallel T)\ oo\ (S' \parallel T') = (S\ oo\ S') \parallel (T\ oo\ T')$

fixes *Split* :: $'tp\ list \Rightarrow 'a$
fixes *Sink* :: $'tp\ list \Rightarrow 'a$
fixes *Switch* :: $'tp\ list \Rightarrow 'tp\ list \Rightarrow 'a$

assumes *TI-Split*[*simp*]: $TI\ (Split\ ts) = ts$
assumes *TO-Split*[*simp*]: $TO\ (Split\ ts) = ts\ @\ ts$

assumes *TI-Sink*[*simp*]: $TI\ (Sink\ ts) = ts$
assumes *TO-Sink*[*simp*]: $TO\ (Sink\ ts) = []$

assumes *TI-Switch*[*simp*]: $TI\ (Switch\ ts\ ts') = ts\ @\ ts'$
assumes *TO-Switch*[*simp*]: $TO\ (Switch\ ts\ ts') = ts'\ @\ ts$

assumes *Split-Sink-id*[*simp*]: $Split\ ts\ oo\ Sink\ ts \parallel ID\ ts = ID\ ts$

assumes *Split-Switch*[*simp*]: $Split\ ts\ oo\ Switch\ ts\ ts = Split\ ts$
assumes *Split-assoc*: $Split\ ts\ oo\ ID\ ts \parallel Split\ ts = Split\ ts\ oo\ Split\ ts \parallel ID\ ts$

assumes *Switch-append*: $Switch\ ts\ (ts' @ ts'') = Switch\ ts\ ts' \parallel ID\ ts''\ oo\ ID\ ts' \parallel Switch\ ts\ ts''$
assumes *Sink-append*: $Sink\ ts \parallel Sink\ ts' = Sink\ (ts @ ts')$
assumes *Split-append*: $Split\ (ts @ ts') = Split\ ts \parallel Split\ ts'\ oo\ ID\ ts \parallel Switch\ ts\ ts' \parallel ID\ ts'$

assumes *switch-par-no-vars*: $TI\ A = ti \Longrightarrow TO\ A = to \Longrightarrow TI\ B = ti' \Longrightarrow TO\ B = to' \Longrightarrow Switch\ ti\ ti'\ oo\ B \parallel A\ oo\ Switch\ to'\ to = A \parallel B$

fixes $fb :: 'a \Rightarrow 'a$
assumes *TI-fb*: $TI\ S = t \# ts \Longrightarrow TO\ S = t \# ts' \Longrightarrow TI\ (fb\ S) = ts$
assumes *TO-fb*: $TI\ S = t \# ts \Longrightarrow TO\ S = t \# ts' \Longrightarrow TO\ (fb\ S) = ts'$
assumes *fb-comp*: $TI\ S = t \# TO\ A \Longrightarrow TO\ S = t \# TI\ B \Longrightarrow fb\ (ID\ [t] \parallel A\ oo\ S\ oo\ ID\ [t] \parallel B) = A\ oo\ fb\ S\ oo\ B$
assumes *fb-par-indep*: $TI\ S = t \# ts \Longrightarrow TO\ S = t \# ts' \Longrightarrow fb\ (S \parallel T) = fb\ S \parallel T$

assumes *fb-switch*: $fb\ (Switch\ [t]\ [t]) = ID\ [t]$

begin
definition $fbtype\ S\ tsa\ ts\ ts' = (TI\ S = tsa @ ts \wedge TO\ S = tsa @ ts')$

lemma *fb-comp-fbtype*: $fbtype\ S\ [t]\ (TO\ A)\ (TI\ B)$
$\Longrightarrow fb\ ((ID\ [t] \parallel A)\ oo\ S\ oo\ (ID\ [t] \parallel B)) = A\ oo\ fb\ S\ oo\ B$

lemma *fb-serial-no-vars*: $TO\ A = t \# ts \Longrightarrow TI\ B = t \# ts$
$\Longrightarrow fb\ (\ ID\ [t] \parallel A\ oo\ Switch\ [t]\ [t] \parallel ID\ ts\ oo\ ID\ [t] \parallel B) = A\ oo\ B$

lemma *TI-fb-fbtype*: $fbtype\ S\ [t]\ ts\ ts' \Longrightarrow TI\ (fb\ S) = ts$

lemma *TO-fb-fbtype*: $fbtype\ S\ [t]\ ts\ ts' \Longrightarrow TO\ (fb\ S) = ts'$

lemma *fb-par-indep-fbtype*: $fbtype\ S\ [t]\ ts\ ts' \Longrightarrow fb\ (S \parallel T) = fb\ S \parallel T$

lemma *comp-id-left-simp* [*simp*]: $TI\ S = ts \Longrightarrow ID\ ts\ oo\ S\ = S$

lemma *comp-id-right-simp* [*simp*]: $TO\ S = ts \Longrightarrow S\ oo\ ID\ ts = S$

lemma *par-Sink-comp*: $TI\ A = TO\ B \Longrightarrow B \parallel Sink\ t\ oo\ A = (B\ oo\ A) \parallel Sink\ t$

lemma *Sink-par-comp*: $TI\ A = TO\ B \Longrightarrow Sink\ t \parallel B\ oo\ A = Sink\ t \parallel (B\ oo\ A)$

lemma *Split-Sink-par*[*simp*]: $TI\ A = ts \Longrightarrow Split\ ts\ oo\ Sink\ ts \parallel A = A$

lemma *Switch-Switch-ID*[*simp*]: $Switch\ ts\ ts'\ oo\ Switch\ ts'\ ts = ID\ (ts @ ts')$

lemma *Switch-parallel*: $TI\ A = ts' \Longrightarrow TI\ B = ts \Longrightarrow Switch\ ts\ ts'\ oo\ A \parallel B = B \parallel A\ oo\ Switch\ (TO\ B)\ (TO\ A)$

lemma *Switch-type-empty*[*simp*]: $Switch\ ts\ [] = ID\ ts$

lemma *Switch-empty-type*[*simp*]: $Switch\ []\ ts = ID\ ts$

lemma *Split-id-Sink*[*simp*]: $Split\ ts\ oo\ ID\ ts \parallel Sink\ ts = ID\ ts$

lemma *Split-par-Sink*[*simp*]: $TI\ A = ts \Longrightarrow Split\ ts\ oo\ A \parallel Sink\ ts = A$

lemma *Split-empty* [*simp*]: $Split\ [] = ID\ []$

lemma *Sink-empty*[*simp*]: $Sink\ [] = ID\ []$

lemma *Switch-Split*: $Switch\ ts\ ts' = Split\ (ts\ @\ ts')\ oo\ Sink\ ts \parallel ID\ ts' \parallel ID\ ts \parallel Sink\ ts'$

lemma *Sink-cons*: $Sink\ (t\ \#\ ts) = Sink\ [t] \parallel Sink\ ts$

lemma *Split-cons*: $Split\ (t\ \#\ ts) = Split\ [t] \parallel Split\ ts\ oo\ ID\ [t] \parallel Switch\ [t]\ ts \parallel ID\ ts$

lemma *Split-assoc-comp*: $TI\ A = ts \Longrightarrow TI\ B = ts \Longrightarrow TI\ C = ts \Longrightarrow Split\ ts\ oo\ A \parallel (Split\ ts\ oo\ B \parallel C) = Split\ ts\ oo\ (Split\ ts\ oo\ A \parallel B) \parallel C$

lemma *Split-Split-Switch*: $Split\ ts\ oo\ Split\ ts \parallel Split\ ts\ oo\ ID\ ts \parallel Switch\ ts\ ts \parallel ID\ ts = Split\ ts\ oo\ Split\ ts \parallel Split\ ts$

lemma *parallel-empty-commute*: $TI\ A = [] \Longrightarrow TO\ B = [] \Longrightarrow A \parallel B = B \parallel A$

lemma *comp-assoc-middle-ext*: $TI\ S2 = TO\ S1 \Longrightarrow TI\ S3 = TO\ S2 \Longrightarrow TI\ S4 = TO\ S3 \Longrightarrow TI\ S5 = TO\ S4 \Longrightarrow$
$S1\ oo\ (S2\ oo\ S3\ oo\ S4)\ oo\ S5 = (S1\ oo\ S2)\ oo\ S3\ oo\ (S4\ oo\ S5)$

lemma *fb-gen-parallel*: $\bigwedge\ S\ .\ fbtype\ S\ tsa\ ts\ ts' \Longrightarrow (fb\hat{}\hat{}(length\ tsa))\ (S \parallel T) = ((fb\hat{}\hat{}(length\ tsa))\ (S)) \parallel T$

lemmas *parallel-ID-sym* = *parallel-ID* [*THEN sym*]
declare *parallel-ID* [*simp del*]

lemma *fb-indep*: $\bigwedge S.\ fbtype\ S\ tsa\ (TO\ A)\ (TI\ B) \Longrightarrow (fb\hat{}\hat{}(length\ tsa))\ ((ID\ tsa \parallel A)\ oo\ S\ oo\ (ID\ tsa \parallel B)) = A\ oo\ (fb\hat{}\hat{}(length\ tsa))\ S\ oo\ B$

lemma *fb-indep-a*: $\bigwedge S.\ fbtype\ S\ tsa\ (TO\ A)\ (TI\ B) \Longrightarrow length\ tsa = n \Longrightarrow (fb\ \hat{}\hat{}\ n)\ ((ID\ tsa \parallel A)\ oo\ S\ oo\ (ID\ tsa \parallel B)) = A\ oo\ (fb\ \hat{}\hat{}\ n)\ S\ oo\ B$

lemma *fb-comp-right*: $fbtype\ S\ [t]\ ts\ (TI\ B) \Longrightarrow fb\ (S\ oo\ (ID\ [t] \parallel B)) = fb\ S\ oo\ B$

lemma *fb-comp-left*: $fbtype\ S\ [t]\ (TO\ A)\ ts \Longrightarrow fb\ ((ID\ [t] \parallel A)\ oo\ S) = A\ oo\ fb\ S$

lemma *fb-indep-right*: $\bigwedge S.\ fbtype\ S\ tsa\ ts\ (TI\ B) \Longrightarrow (fb\hat{}\hat{}(length\ tsa))\ (S\ oo\ (ID\ tsa \parallel B)) = (fb\hat{}\hat{}(length\ tsa))\ S\ oo\ B$

lemma *fb-indep-left*: $\bigwedge S.\ fbtype\ S\ tsa\ (TO\ A)\ ts \Longrightarrow (fb\hat{}\hat{}(length\ tsa))\ ((ID\ tsa \parallel A)\ oo\ S) = A\ oo\ (fb\hat{}\hat{}(length\ tsa))\ S$

lemma *TI-fb-fbtype-n*: $\bigwedge S.\ fbtype\ S\ t\ ts\ ts' \Longrightarrow TI\ ((fb\hat{}\hat{}(length\ t))\ S) = ts$

and *TO-fb-fbtype-n*: $\bigwedge S.\ fbtype\ S\ t\ ts\ ts' \Longrightarrow TO\ ((fb\ \hat{}\ \hat{}\ (length\ t))\ S) = ts'$

declare *parallel-ID* [*simp*]
end

locale *BaseOperationFeedbacklessVars* = *BaseOperationFeedbackless* +
fixes $TV :: 'var \Rightarrow 'b$
fixes $newvar :: 'var\ list \Rightarrow 'b \Rightarrow 'var$
assumes *newvar-type*[*simp*]: $TV(newvar\ x\ t) = t$
assumes *newvar-distinct* [*simp*]: $newvar\ x\ t \notin set\ x$
assumes $ID\ [TV\ a] = ID\ [TV\ a]$
begin
primrec $TVs{::}'var\ list \Rightarrow 'b\ list$ **where**
$TVs\ [] = []\ |$
$TVs\ (a\ \#\ x) = TV\ a\ \#\ TVs\ x$

lemma *TVs-append*: $TVs\ (x\ @\ y) = TVs\ x\ @\ TVs\ y$

definition $Arb\ t = fb\ (Split\ [t])$

lemma *TI-Arb*[*simp*]: $TI\ (Arb\ t) = []$

lemma *TO-Arb*[*simp*]: $TO\ (Arb\ t) = [t]$

fun $set\text{-}var{::}\ 'var\ list \Rightarrow 'var \Rightarrow 'a$ **where**
$set\text{-}var\ []\ b = Arb\ (TV\ b)\ |$
$set\text{-}var\ (a\ \#\ x)\ b = (if\ a = b\ then\ ID\ [TV\ a] \parallel Sink\ (TVs\ x)\ else\ Sink\ [TV\ a] \parallel set\text{-}var\ x\ b)$

lemma *TO-set-var*[*simp*]: $TO\ (set\text{-}var\ x\ a) = [TV\ a]$

lemma *TI-set-var*[*simp*]: $TI\ (set\text{-}var\ x\ a) = TVs\ x$

primrec $switch :: 'var\ list \Rightarrow 'var\ list \Rightarrow 'a\ ([\text{-} \leadsto \text{-}])$ **where**
$[x \leadsto []] = Sink\ (TVs\ x)\ |$
$[x \leadsto a\ \#\ y] = Split\ (TVs\ x)\ oo\ set\text{-}var\ x\ a \parallel [x \leadsto y]$

lemma *TI-switch*[*simp*]: $TI\ [x \leadsto y] = TVs\ x$

lemma *TO-switch*[*simp*]: $TO\ [x \leadsto y] = TVs\ y$

lemma *switch-not-in-Sink*: $a \notin set\ y \Longrightarrow [a\ \#\ x \leadsto y] = Sink\ [TV\ a] \parallel [x \leadsto y]$

lemma *distinct-id*: $distinct\ x \Longrightarrow [x \leadsto x] = ID\ (TVs\ x)$

lemma *set-var-nin*: $a \notin set\ x \Longrightarrow set\text{-}var\ (x\ @\ y)\ a = Sink\ (TVs\ x) \parallel set\text{-}var\ y\ a$

lemma *set-var-in*: $a \in set\ x \Longrightarrow set\text{-}var\ (x\ @\ y)\ a = set\text{-}var\ x\ a \parallel Sink\ (TVs\ y)$

lemma *set-var-not-in*: $a \notin set\ y \Longrightarrow set\text{-}var\ y\ a = Arb\ (TV\ a) \parallel Sink\ (TVs\ y)$

lemma *set-var-in-a*: $a \notin set\ y \Longrightarrow set\text{-}var\ (x\ @\ y)\ a = set\text{-}var\ x\ a \parallel Sink\ (TVs\ y)$

lemma *switch-append*: $[x \leadsto y\ @\ z] = \mathit{Split}\ (\mathit{TVs}\ x)\ oo\ [x \leadsto y] \parallel [x \leadsto z]$

lemma *switch-nin-a-new*: $\mathit{set}\ x \cap \mathit{set}\ y' = \{\} \Longrightarrow [x\ @\ y \leadsto y'] = \mathit{Sink}\ (\mathit{TVs}\ x) \parallel [y \leadsto y']$

lemma *switch-nin-b-new*: $\mathit{set}\ y \cap \mathit{set}\ z = \{\} \Longrightarrow [x\ @\ y \leadsto z] = [x \leadsto z] \parallel \mathit{Sink}\ (\mathit{TVs}\ y)$

lemma *var-switch*: $\mathit{distinct}\ (x\ @\ y) \Longrightarrow [x\ @\ y \leadsto y\ @\ x] = \mathit{Switch}\ (\mathit{TVs}\ x)\ (\mathit{TVs}\ y)$

lemma *switch-par*: $\mathit{distinct}\ (x\ @\ y) \Longrightarrow \mathit{distinct}\ (u\ @\ v) \Longrightarrow \mathit{TI}\ S = \mathit{TVs}\ x \Longrightarrow \mathit{TI}\ T = \mathit{TVs}\ y \Longrightarrow \mathit{TO}\ S = \mathit{TVs}\ v \Longrightarrow \mathit{TO}\ T = \mathit{TVs}\ u \Longrightarrow$
$S \parallel T = [x\ @\ y \leadsto y\ @\ x]\ oo\ T \parallel S\ oo\ [u\ @\ v \leadsto v\ @\ u]$

lemma *par-switch*: $\mathit{distinct}\ (x\ @\ y) \Longrightarrow \mathit{set}\ x' \subseteq \mathit{set}\ x \Longrightarrow \mathit{set}\ y' \subseteq \mathit{set}\ y \Longrightarrow [x \leadsto x'] \parallel [y \leadsto y'] = [x\ @\ y \leadsto x'\ @\ y']$

lemma *set-var-sink*[*simp*]: $a \in \mathit{set}\ x \Longrightarrow (\mathit{TV}\ a) = t \Longrightarrow \mathit{set\text{-}var}\ x\ a\ oo\ \mathit{Sink}\ [t] = \mathit{Sink}\ (\mathit{TVs}\ x)$

lemma *switch-Sink*[*simp*]: $\bigwedge ts\ .\ \mathit{set}\ u \subseteq \mathit{set}\ x \Longrightarrow \mathit{TVs}\ u = ts \Longrightarrow [x \leadsto u]\ oo\ \mathit{Sink}\ ts = \mathit{Sink}\ (\mathit{TVs}\ x)$

lemma *set-var-dup*: $a \in \mathit{set}\ x \Longrightarrow \mathit{TV}\ a = t \Longrightarrow \mathit{set\text{-}var}\ x\ a\ oo\ \mathit{Split}\ [t] = \mathit{Split}\ (\mathit{TVs}\ x)\ oo\ \mathit{set\text{-}var}\ x\ a \parallel \mathit{set\text{-}var}\ x\ a$

lemma *switch-dup*: $\bigwedge ts\ .\ \mathit{set}\ y \subseteq \mathit{set}\ x \Longrightarrow \mathit{TVs}\ y = ts \Longrightarrow [x \leadsto y]\ oo\ \mathit{Split}\ ts = \mathit{Split}\ (\mathit{TVs}\ x)\ oo\ [x \leadsto y] \parallel [x \leadsto y]$

lemma *TVs-length-eq*: $\bigwedge y\ .\ \mathit{TVs}\ x = \mathit{TVs}\ y \Longrightarrow \mathit{length}\ x = \mathit{length}\ y$

lemma *set-var-comp-subst*: $\bigwedge y\ .\ \mathit{set}\ u \subseteq \mathit{set}\ x \Longrightarrow \mathit{TVs}\ u = \mathit{TVs}\ y \Longrightarrow a \in \mathit{set}\ y \Longrightarrow [x \leadsto u]\ oo\ \mathit{set\text{-}var}\ y\ a = \mathit{set\text{-}var}\ x\ (\mathit{subst}\ y\ u\ a)$

lemma *switch-comp-subst*: $\mathit{set}\ u \subseteq \mathit{set}\ x \Longrightarrow \mathit{set}\ v \subseteq \mathit{set}\ y \Longrightarrow \mathit{TVs}\ u = \mathit{TVs}\ y \Longrightarrow [x \leadsto u]\ oo\ [y \leadsto v] = [x \leadsto \mathit{Subst}\ y\ u\ v]$

declare *switch.simps* [*simp del*]

lemma *sw-hd-var*: $\mathit{distinct}\ (a \# b \# x) \Longrightarrow [a \# b \# x \leadsto b \# a \# x] = \mathit{Switch}\ [\mathit{TV}\ a]\ [\mathit{TV}\ b] \parallel \mathit{ID}\ (\mathit{TVs}\ x)$

lemma *fb-serial*: $\mathit{distinct}\ (a \# b \# x) \Longrightarrow \mathit{TV}\ a = \mathit{TV}\ b \Longrightarrow \mathit{TO}\ A = \mathit{TVs}\ (b \# x) \Longrightarrow \mathit{TI}\ B = \mathit{TVs}\ (a \# x) \Longrightarrow \mathit{fb}\ ((([a] \leadsto [a]] \parallel A)\ oo\ [a \# b \# x \leadsto b \# a \# x]\ oo\ ([[b] \leadsto [b]] \parallel B)) = A\ oo\ B$

lemma *Switch-Split*: $\mathit{distinct}\ x \Longrightarrow [x \leadsto x\ @\ x] = \mathit{Split}\ (\mathit{TVs}\ x)$

lemma *switch-comp*: $\mathit{distinct}\ x \Longrightarrow \mathit{perm}\ x\ y \Longrightarrow \mathit{set}\ z \subseteq \mathit{set}\ y \Longrightarrow [x \leadsto y]\ oo\ [y \leadsto z] = [x \leadsto z]$

lemma *switch-comp-a*: $\mathit{distinct}\ x \Longrightarrow \mathit{distinct}\ y \Longrightarrow \mathit{set}\ y \subseteq \mathit{set}\ x \Longrightarrow \mathit{set}\ z \subseteq \mathit{set}\ y \Longrightarrow [x \leadsto y]\ oo\ [y \leadsto z] = [x \leadsto z]$

primrec *newvars*::$'var\ list \Rightarrow 'b\ list \Rightarrow 'var\ list$ **where**
newvars $x\ [] = []\ |$

$newvars\ x\ (t\ \#\ ts) = (let\ y = newvars\ x\ ts\ in\ newvar\ (y@x)\ t\ \#\ y)$

lemma *newvars-type*[*simp*]: $TVs(newvars\ x\ ts) = ts$

lemma *newvars-distinct*[*simp*]: $distinct\ (newvars\ x\ ts)$

lemma *newvars-old-distinct*[*simp*]: $set\ (newvars\ x\ ts) \cap set\ x = \{\}$

lemma *newvars-old-distinct-a*[*simp*]: $set\ x \cap set\ (newvars\ x\ ts) = \{\}$

lemma *newvars-length*: $length(newvars\ x\ ts) = length\ ts$

lemma *TV-subst*[*simp*]: $\bigwedge\ y\ .\ TVs\ x = TVs\ y \Longrightarrow TV\ (subst\ x\ y\ a) = TV\ a$

lemma *TV-Subst*[*simp*]: $TVs\ x = TVs\ y \Longrightarrow TVs\ (Subst\ x\ y\ z) = TVs\ z$

lemma *Subst-cons*: $distinct\ x \Longrightarrow a \notin set\ x \Longrightarrow b \notin set\ x \Longrightarrow length\ x = length\ y$
$\Longrightarrow\ Subst\ (a\ \#\ x)\ (b\ \#\ y)\ z = Subst\ x\ y\ (Subst\ [a]\ [b]\ z)$

declare *TVs-append* [*simp*]
declare *distinct-id* [*simp*]

lemma *par-empty-right*: $A \parallel [[] \rightsquigarrow []] = A$

lemma *par-empty-left*: $[[] \rightsquigarrow []] \parallel A = A$
lemma *distinct-vars-comp*: $distinct\ x \Longrightarrow perm\ x\ y \Longrightarrow [x \rightsquigarrow y]\ oo\ [y \rightsquigarrow x] = ID\ (TVs\ x)$

lemma *comp-switch-id*[*simp*]: $distinct\ x \Longrightarrow TO\ S = TVs\ x \Longrightarrow S\ oo\ [x \rightsquigarrow x] = S$

lemma *comp-id-switch*[*simp*]: $distinct\ x \Longrightarrow TI\ S = TVs\ x \Longrightarrow [x \rightsquigarrow x]\ oo\ S = S$

lemma *distinct-Subst-a*: $\bigwedge\ v\ .\ a \neq aa \Longrightarrow a \notin set\ v \Longrightarrow aa \notin set\ v \Longrightarrow\ distinct\ v \Longrightarrow length\ u = length\ v \Longrightarrow subst\ u\ v\ a \neq subst\ u\ v\ aa$

lemma *distinct-Subst-b*: $\bigwedge\ v\ .\ a \notin set\ x \Longrightarrow distinct\ x \Longrightarrow a \notin set\ v \Longrightarrow distinct\ v \Longrightarrow set\ v \cap set\ x = \{\} \Longrightarrow length\ u = length\ v \Longrightarrow subst\ u\ v\ a \notin set\ (Subst\ u\ v\ x)$

lemma *distinct-Subst*: $distinct\ u \Longrightarrow distinct\ (v\ @\ x) \Longrightarrow length\ u = length\ v \Longrightarrow distinct\ (Subst\ u\ v\ x)$

lemma *Subst-switch-more-general*: $distinct\ u \Longrightarrow distinct\ (v\ @\ x) \Longrightarrow set\ y \subseteq set\ x$
$\Longrightarrow TVs\ u = TVs\ v \Longrightarrow [x \rightsquigarrow y] = [Subst\ u\ v\ x \rightsquigarrow Subst\ u\ v\ y]$

lemma *id-par-comp*: $distinct\ x \Longrightarrow TO\ A = TI\ B \Longrightarrow [x \rightsquigarrow x] \parallel (A\ oo\ B) = ([x \rightsquigarrow x] \parallel A\ )\ oo\ ([x \rightsquigarrow x] \parallel B)$

lemma *par-id-comp*: $distinct\ x \Longrightarrow TO\ A = TI\ B \Longrightarrow (A\ oo\ B) \parallel [x \rightsquigarrow x] = (A \parallel [x \rightsquigarrow x])\ oo\ (B\ \parallel [x \rightsquigarrow x])$

lemma *switch-parallel-a*: $distinct\ (x\ @\ y) \Longrightarrow distinct\ (u\ @\ v) \Longrightarrow TI\ S = TVs\ x \Longrightarrow TI\ T = TVs\ y \Longrightarrow TO\ S = TVs\ u \Longrightarrow TO\ T = TVs\ v \Longrightarrow$
$S \parallel T\ oo\ [u@v \rightsquigarrow v@u] = [x@y \rightsquigarrow y@x]\ oo\ T \parallel S$

declare *distinct-id* [*simp del*]

lemma *fb-gen-serial*: $\bigwedge A\ B\ v\ x\ .\ distinct\ (u\ @\ v\ @\ x) \Longrightarrow TO\ A = TVs\ (v@x) \Longrightarrow TI\ B = TVs\ (u\ @\ x) \Longrightarrow\ \ TVs\ u = TVs\ v$
$\Longrightarrow (fb\ \hat{}\hat{}\ length\ u)\ (([u \rightsquigarrow u] \parallel A)\ oo\ [u\ @\ v\ @\ x \rightsquigarrow v\ @\ u\ @\ x]\ oo\ ([v \rightsquigarrow v] \parallel B)) = A\ oo\ B$

lemma *fb-par-serial*: $distinct(u\ @\ x\ @\ x') \Longrightarrow distinct\ (u\ @\ y\ @\ x') \Longrightarrow TI\ A = TVs\ x \Longrightarrow TO\ A = TVs\ (u@y) \Longrightarrow TI\ B = TVs\ (u@x') \Longrightarrow TO\ B = TVs\ y' \Longrightarrow$
$(fb\ \hat{}\hat{}(length\ u))\ ([u\ @\ x\ @\ x' \rightsquigarrow x\ @\ u\ @\ x']\ oo\ (A \parallel B)) = (A \parallel ID\ (TVs\ x')\ oo\ [u\ @\ y\ @\ x' \rightsquigarrow y\ @\ u\ @\ x']\ oo\ ID\ (TVs\ y) \parallel B)$

lemma *switch-newvars*: $distinct\ x \Longrightarrow [newvars\ w\ (TVs\ x) \rightsquigarrow newvars\ w\ (TVs\ x)] = [x \rightsquigarrow x]$

lemma *switch-par-comp-Subst*: $distinct\ x \Longrightarrow distinct\ y' \Longrightarrow distinct\ z' \Longrightarrow set\ y \subseteq set\ x$
$\Longrightarrow set\ z \subseteq set\ x$
$\Longrightarrow set\ u \subseteq set\ y' \Longrightarrow set\ v \subseteq set\ z' \Longrightarrow TVs\ y = TVs\ y' \Longrightarrow TVs\ z = TVs\ z' \Longrightarrow$
$[x \rightsquigarrow y\ @\ z]\ oo\ [y' \rightsquigarrow u] \parallel [z' \rightsquigarrow v] = [x \rightsquigarrow Subst\ y'\ y\ u\ @\ Subst\ z'\ z\ v]$

lemma *switch-par-comp*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow distinct\ z \Longrightarrow set\ y \subseteq set\ x \Longrightarrow set\ z \subseteq set\ x$
$\Longrightarrow set\ y' \subseteq set\ y \Longrightarrow set\ z' \subseteq set\ z \Longrightarrow [x \rightsquigarrow y\ @\ z]\ oo\ [y \rightsquigarrow y'] \parallel [z \rightsquigarrow z'] = [x \rightsquigarrow y'\ @\ z']$

lemma *par-switch-eq*: $distinct\ u \Longrightarrow distinct\ v \Longrightarrow distinct\ y' \Longrightarrow distinct\ z'$
$\Longrightarrow TI\ A = TVs\ x \Longrightarrow TO\ A = TVs\ v \Longrightarrow TI\ C = TVs\ v\ @\ TVs\ y \Longrightarrow TVs\ y = TVs\ y' \Longrightarrow$
$TI\ C' = TVs\ v\ @\ TVs\ z \Longrightarrow TVs\ z = TVs\ z' \Longrightarrow$
$set\ x \subseteq set\ u \Longrightarrow set\ y \subseteq set\ u \Longrightarrow set\ z \subseteq set\ u \Longrightarrow$
$[v \rightsquigarrow v] \parallel [u \rightsquigarrow y]\ oo\ C = [v \rightsquigarrow v] \parallel [u \rightsquigarrow z]\ oo\ C'$
$\Longrightarrow [u \rightsquigarrow x\ @\ y]\ oo\ (\ A \parallel [y' \rightsquigarrow y])\ oo\ C = [u \rightsquigarrow x\ @\ z]\ oo\ (\ A \parallel [z' \rightsquigarrow z])\ oo\ C'$

lemma *paralle-switch*: $\exists\ x\ y\ u\ v.\ distinct\ (x\ @\ y) \wedge distinct\ (u\ @\ v) \wedge TVs\ x = TI\ A$
$\wedge\ TVs\ u = TO\ A \wedge TVs\ y = TI\ B \wedge$
$TVs\ v = TO\ B \wedge A \parallel B = [x\ @\ y \rightsquigarrow y\ @\ x]\ oo\ (B \parallel A)\ oo\ [v\ @\ u \rightsquigarrow u\ @\ v]$

lemma *par-switch-eq-dist*: $distinct\ (u\ @\ v) \Longrightarrow distinct\ y' \Longrightarrow distinct\ z' \Longrightarrow TI\ A = TVs\ x \Longrightarrow TO\ A = TVs\ v \Longrightarrow TI\ C = TVs\ v\ @\ TVs\ y \Longrightarrow TVs\ y = TVs\ y' \Longrightarrow$
$TI\ C' = TVs\ v\ @\ TVs\ z \Longrightarrow TVs\ z = TVs\ z' \Longrightarrow$
$set\ x \subseteq set\ u \Longrightarrow set\ y \subseteq set\ u \Longrightarrow set\ z \subseteq set\ u \Longrightarrow$
$[v\ @\ u \rightsquigarrow v\ @\ y]\ oo\ C = [v\ @\ u \rightsquigarrow v\ @\ z]\ oo\ C' \Longrightarrow [u \rightsquigarrow x\ @\ y]\ oo\ (\ A \parallel [y' \rightsquigarrow y])\ oo\ C = [u \rightsquigarrow x\ @\ z]\ oo\ (\ A \parallel [z' \rightsquigarrow z])\ oo\ C'$

lemma *par-switch-eq-dist-a*: $distinct\ (u\ @\ v) \Longrightarrow TI\ A = TVs\ x \Longrightarrow TO\ A = TVs\ v \Longrightarrow TI\ C = TVs\ v\ @\ TVs\ y \Longrightarrow TVs\ y = ty \Longrightarrow TVs\ z = tz \Longrightarrow$
$TI\ C' = TVs\ v\ @\ TVs\ z \Longrightarrow set\ x \subseteq set\ u \Longrightarrow set\ y \subseteq set\ u \Longrightarrow set\ z \subseteq set\ u \Longrightarrow$
$[v\ @\ u \rightsquigarrow v\ @\ y]\ oo\ C = [v\ @\ u \rightsquigarrow v\ @\ z]\ oo\ C' \Longrightarrow [u \rightsquigarrow x\ @\ y]\ oo\ A \parallel ID\ ty\ oo\ C = [u \rightsquigarrow x\ @\ z]\ oo\ A \parallel ID\ tz\ oo\ C'$

lemma *par-switch-eq-a*: $distinct\ (u\ @\ v) \Longrightarrow distinct\ y' \Longrightarrow distinct\ z' \Longrightarrow distinct\ t' \Longrightarrow distinct$

s'
$\Longrightarrow$ *TI A* = *TVs x* $\Longrightarrow$ *TO A* = *TVs v* $\Longrightarrow$ *TI C* = *TVs t* @ *TVs v* @ *TVs y* $\Longrightarrow$ *TVs y* = *TVs y'* $\Longrightarrow$
TI C' = *TVs s* @ *TVs v* @ *TVs z* $\Longrightarrow$ *TVs z* = *TVs z'* $\Longrightarrow$ *TVs t* = *TVs t'* $\Longrightarrow$ *TVs s* = *TVs s'* $\Longrightarrow$
set t $\subseteq$ *set u* $\Longrightarrow$ *set x* $\subseteq$ *set u* $\Longrightarrow$ *set y* $\subseteq$ *set u* $\Longrightarrow$ *set s* $\subseteq$ *set u* $\Longrightarrow$ *set z* $\subseteq$ *set u* $\Longrightarrow$
$[u$ @ $v \rightsquigarrow t$ @ v @ $y]$ *oo C* = $[u$ @ $v \rightsquigarrow s$ @ v @ $z]$ *oo C'* $\Longrightarrow$
$[u \rightsquigarrow t$ @ x @ $y]$ *oo* $([t' \rightsquigarrow t'] \parallel A \parallel [y' \rightsquigarrow y'])$ *oo C* = $[u \rightsquigarrow s$ @ x @ $z]$ *oo* $([s' \rightsquigarrow s'] \parallel A \parallel [z' \rightsquigarrow z'])$ *oo C'*

lemma *length-TVs*: *length* (*TVs x*) = *length x*

lemma *comp-par*: *distinct x* $\Longrightarrow$ *set y* $\subseteq$ *set x* $\Longrightarrow$ $[x \rightsquigarrow x$ @ $x]$ *oo* $[x \rightsquigarrow y] \parallel [x \rightsquigarrow y] = [x \rightsquigarrow y$ @ $y]$

lemma *Subst-switch-a*: *distinct x* $\Longrightarrow$ *distinct y* $\Longrightarrow$ *set z* $\subseteq$ *set x* $\Longrightarrow$ *TVs x* = *TVs y* $\Longrightarrow$ $[x \rightsquigarrow z] = [y \rightsquigarrow$ *Subst x y z*$]$

lemma *change-var-names*: *distinct a* $\Longrightarrow$ *distinct b* $\Longrightarrow$ *TVs a* = *TVs b* $\Longrightarrow$ $[a \rightsquigarrow a$ @ $a] = [b \rightsquigarrow b$ @ $b]$

9.1.1 Deterministic diagrams

definition *deterministic S* = (*Split* (*TI S*) *oo S* $\parallel$ *S* = *S oo Split* (*TO S*))

lemma *deterministic-split*:
assumes *deterministic S*
and *distinct* ($a\#x$)
and *TO S* = *TVs* (a # x)
shows *S* = *Split* (*TI S*) *oo* (*S oo* [a # $x \rightsquigarrow [a]$]) $\parallel$ (*S oo* [a # $x \rightsquigarrow x$])

lemma *deterministicE*: *deterministic A* $\Longrightarrow$ *distinct x* $\Longrightarrow$ *distinct y* $\Longrightarrow$ *TI A* = *TVs x* $\Longrightarrow$ *TO A* = *TVs y*
$\Longrightarrow$ $[x \rightsquigarrow x$ @ $x]$ *oo* $(A \parallel A) = A$ *oo* $[y \rightsquigarrow y$ @ $y]$

lemma *deterministicI*: *distinct x* $\Longrightarrow$ *distinct y* $\Longrightarrow$ *TI A* = *TVs x* $\Longrightarrow$ *TO A* = *TVs y* $\Longrightarrow$
$[x \rightsquigarrow x$ @ $x]$ *oo* $A \parallel A = A$ *oo* $[y \rightsquigarrow y$ @ $y]$ $\Longrightarrow$ *deterministic A*

lemma *deterministic-switch*: *distinct x* $\Longrightarrow$ *set y* $\subseteq$ *set x* $\Longrightarrow$ *deterministic* $[x \rightsquigarrow y]$

lemma *deterministic-comp*: *deterministic A* $\Longrightarrow$ *deterministic B* $\Longrightarrow$ *TO A* = *TI B* $\Longrightarrow$ *deterministic* (*A oo B*)

lemma *deterministic-par*: *deterministic A* $\Longrightarrow$ *deterministic B* $\Longrightarrow$ *deterministic* $(A \parallel B)$

end

end

9.2 Abstract Algebra of Hierarchical Block Diagrams with All Axioms

theory *ExtendedHBDAlgebra* **imports** *HBDAlgebra*
begin

locale *BaseOperation* = *BaseOperationFeedbackless* +
assumes *fb-twice-switch-no-vars*: $TI\ S = t' \# t \# ts \Longrightarrow TO\ S = t' \# t \# ts'$
$\Longrightarrow (fb\ \hat{}\hat{}\ (2{::}nat))\ (Switch\ [t]\ [t'] \parallel ID\ ts\ oo\ S\ oo\ Switch\ [t']\ [t] \parallel ID\ ts') = (fb\ \hat{}\hat{}\ (2{::}\ nat))\ S$

locale *BaseOperationVars* = *BaseOperation* + *BaseOperationFeedbacklessVars*
begin
lemma *fb-twice-switch*: $distinct\ (a \# b \# x) \Longrightarrow distinct\ (a \# b \# y) \Longrightarrow TI\ S = TVs\ (b \# a \# x) \Longrightarrow TO\ S = TVs\ (b \# a \# y)$
$\Longrightarrow (fb\ \hat{}\hat{}\ (2{::}nat))\ ([a \# b \# x \leadsto b \# a \# x]\ oo\ S\ oo\ [b \# a \# y \leadsto a \# b \# y]) = (fb\ \hat{}\hat{}\ (2{::}nat))\ S$

lemma *fb-switch-a*: $\bigwedge\ S\ .\ distinct\ (a \# z\ @\ x) \Longrightarrow distinct\ (a \# z\ @\ y) \Longrightarrow TI\ S = TVs\ (z\ @\ a \# x) \Longrightarrow TO\ S = TVs\ (z\ @\ a \# y)$
$\Longrightarrow (fb\ \hat{}\hat{}\ (Suc\ (length\ z)))\ ([a \# z\ @\ x \leadsto z\ @\ a \# x]\ oo\ S\ oo\ [z\ @\ a \# y \leadsto a \# z\ @\ y]) = (fb\ \hat{}\hat{}\ (Suc\ (length\ z)))\ S$

lemma *swap-power*: $(f\ \hat{}\hat{}\ n)\ ((f\ \hat{}\hat{}\ m)\ S) = (f\ \hat{}\hat{}\ m)\ ((f\ \hat{}\hat{}\ n)\ S)$

lemma *fb-switch-b*: $\bigwedge\ v\ x\ y\ S\ .\ distinct\ (u\ @\ v\ @\ x) \Longrightarrow distinct\ (u\ @\ v\ @\ y) \Longrightarrow TI\ S = TVs\ (v\ @\ u\ @\ x) \Longrightarrow TO\ S = TVs\ (v\ @\ u\ @\ y)$
$\Longrightarrow (fb\ \hat{}\hat{}\ (length\ (u\ @\ v)))\ ([u\ @\ v\ @\ x \leadsto v\ @\ u\ @\ x]\ oo\ S\ oo\ [v\ @\ u\ @\ y \leadsto u\ @\ v\ @\ y]) = (fb\ \hat{}\hat{}\ (length\ (u\ @\ v)))\ S$

theorem *fb-perm*: $\bigwedge\ v\ S\ .\ perm\ u\ v \Longrightarrow distinct\ (u\ @\ x) \Longrightarrow distinct\ (u\ @\ y) \Longrightarrow fbtype\ S\ (TVs\ u)\ (TVs\ x)\ (TVs\ y)$
$\Longrightarrow (fb\ \hat{}\hat{}\ (length\ u))\ ([v\ @\ x \leadsto u\ @\ x]\ oo\ S\ oo\ [u\ @\ y \leadsto v\ @\ y]) = (fb\ \hat{}\hat{}\ (length\ u))\ S$

end

end

9.3 Diagrams with Named Inputs and Outputs

theory *Diagrams* **imports** *HBDAlgebra*
begin

This file contains the definition and properties for the named input output diagrams

record ('*var*, '*a*) *Dgr* =
In:: '*var list*
Out:: '*var list*
Trs:: '*a*

context *BaseOperationFeedbacklessVars*
begin
definition $Var\ A\ B = (Out\ A) \otimes (In\ B)$

definition $io\text{-}diagram\ A = (TVs\ (In\ A) = TI\ (Trs\ A) \wedge TVs\ (Out\ A) = TO\ (Trs\ A) \wedge distinct\ (In\ A) \wedge distinct\ (Out\ A))$

definition $Comp :: ('var, 'a)\ Dgr \Rightarrow ('var, 'a)\ Dgr \Rightarrow ('var, 'a)\ Dgr$ (**infixl** ;; *70*) **where**
$A\ ;;\ B = (let\ I = In\ B \ominus Var\ A\ B\ in\ let\ O' = Out\ A \ominus Var\ A\ B\ in$
$(\!|In = (In\ A) \oplus I,\ Out = O'\ @\ Out\ B,$

$Trs = [(In\ A) \oplus I \rightsquigarrow In\ A\ @\ I\ ]\ oo\ Trs\ A \parallel [I \rightsquigarrow I]\ oo\ [Out\ A\ @\ I \rightsquigarrow O'\ @\ In\ B]\ \ oo\ ([O' \rightsquigarrow O'] \parallel Trs\ B)\ \|)$)

lemma *io-diagram-Comp*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B$
$\Longrightarrow set\ (Out\ A \ominus In\ B) \cap set\ (Out\ B) = \{\} \Longrightarrow io\text{-}diagram\ (A\ ;;\ B)$

lemma *Comp-in-disjoint*:
assumes $io\text{-}diagram\ A$
and $io\text{-}diagram\ B$
and $set\ (In\ A) \cap set\ (In\ B) = \{\}$
shows $A\ ;;\ B = (let\ I = In\ B \ominus Var\ A\ B\ in\ let\ O' = Out\ A \ominus Var\ A\ B\ in$
$(\!|In = (In\ A)\ @\ I,\ Out = O'\ @\ Out\ B,\ Trs = Trs\ A \parallel [I \rightsquigarrow I]\ oo\ [Out\ A\ @\ I \rightsquigarrow O'\ @\ In\ B]\ \ oo\ ([O' \rightsquigarrow O'] \parallel Trs\ B)\ |\!))$

lemma *Comp-full*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow Out\ A = In\ B \Longrightarrow$
$A\ ;;\ B = (\!|In = In\ A,\ Out = Out\ B,\ Trs = Trs\ A\ oo\ Trs\ B\ |\!)$

lemma *Comp-in-out*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow set\ (Out\ A) \subseteq set\ (In\ B) \Longrightarrow$
$A\ ;;\ B = (let\ I = diff\ (In\ B)\ (Var\ A\ B)\ in\ let\ O' = diff\ (Out\ A)\ (Var\ A\ B)\ in$
$(\!|In = In\ A \oplus I,\ Out = Out\ B,\ Trs = [In\ A \oplus I \rightsquigarrow In\ A\ @\ I\ ]\ oo\ Trs\ A \parallel [I \rightsquigarrow I]\ oo\ [Out\ A\ @\ I \rightsquigarrow In\ B]\ oo\ Trs\ B\ |\!))$

lemma *Comp-assoc-new*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C \Longrightarrow$
$set\ (Out\ A \ominus In\ B) \cap set\ (Out\ B) = \{\} \Longrightarrow\ set\ (Out\ A \otimes In\ B) \cap set\ (In\ C) = \{\}$
$\Longrightarrow A\ ;;\ B\ ;;\ C = A\ ;;\ (B\ ;;\ C)$

lemma *Comp-assoc-a*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C \Longrightarrow$
$set\ (In\ B) \cap set\ (In\ C) = \{\} \Longrightarrow$
$set\ (Out\ A) \cap set\ (Out\ B) = \{\} \Longrightarrow$
$A\ ;;\ B\ ;;\ C = A\ ;;\ (B\ ;;\ C)$

definition *Parallel* :: $('var,\ 'a)\ Dgr \Rightarrow ('var,\ 'a)\ Dgr \Rightarrow ('var,\ 'a)\ Dgr$ (**infixl** $|||$ *80*) **where**
$A\ |||\ B = (\!|In = In\ A \oplus In\ B,\ Out = Out\ A\ @\ Out\ B,\ Trs = [In\ A \oplus In\ B \rightsquigarrow In\ A\ @\ In\ B]\ oo\ (Trs\ A \parallel Trs\ B)\ |\!)$

lemma *io-diagram-Parallel*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B\ \Longrightarrow set\ (Out\ A) \cap set\ (Out\ B) = \{\} \Longrightarrow io\text{-}diagram\ (A\ |||\ B)$

lemma *Parallel-indep*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B\ \Longrightarrow set\ (In\ A) \cap set\ (In\ B) = \{\} \Longrightarrow$
$A\ |||\ B = (\!|In = In\ A\ @\ In\ B,\ Out = Out\ A\ @\ Out\ B,\ Trs = (Trs\ A \parallel Trs\ B)\ |\!)$

lemma *Parallel-assoc-gen*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C \Longrightarrow$
$A\ |||\ B\ |||\ C = A\ |||\ (B\ |||\ C)$

definition $VarFB\ A = Var\ A\ A$
definition $InFB\ A{=}\ In\ A \ominus VarFB\ A$
definition $OutFB\ A = Out\ A \ominus VarFB\ A$

definition $FB :: ('var,\ 'a)\ Dgr \Rightarrow ('var,\ 'a)\ Dgr$ **where**
$FB\ A = (let\ I = In\ A \ominus Var\ A\ A\ in\ let\ O' = Out\ A \ominus Var\ A\ A\ in$
$(\!|In = I,\ Out = O',\ Trs = (fb\ \hat{}\hat{}\ (length\ (Var\ A\ A)))\ ([Var\ A\ A\ @\ I \leadsto In\ A]\ oo\ Trs\ A\ oo\ [Out\ A \leadsto Var\ A\ A\ @\ O'])\ |\!))$

lemma *Type-ok-FB*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ (FB\ A)$

lemma *perm-var-Par*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow set\ (In\ A) \cap set\ (In\ B) = \{\}$
$\Longrightarrow perm\ (Var\ (A\ |||\ B)\ (A\ |||\ B))\ (Var\ A\ A\ @\ Var\ B\ B\ @\ Var\ A\ B\ @\ Var\ B\ A)$

lemma *distinct-Parallel-Var*[*simp*]: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B$
$\Longrightarrow set\ (Out\ A) \cap set\ (Out\ B) = \{\} \Longrightarrow distinct\ (Var\ (A\ |||\ B)\ (A\ |||\ B))$

lemma *distinct-Parallel-In*[*simp*]: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow distinct\ (In\ (A\ |||\ B))$

lemma *drop-assumption*: $p \Longrightarrow True$

lemma *Dgr-eq*: $In\ A = x \Longrightarrow Out\ A = y \Longrightarrow Trs\ A = S \Longrightarrow (\!|In = x,\ Out = y,\ Trs = S|\!) = A$

lemma *Var-FB*[*simp*]: $Var\ (FB\ A)\ (FB\ A) = []$

theorem *FB-idemp*: $io\text{-}diagram\ A \Longrightarrow FB\ (FB\ A) = FB\ A$

definition $VarSwitch :: 'var\ list \Rightarrow 'var\ list \Rightarrow ('var,\ 'a)\ Dgr\ ([[- \leadsto -]])$ **where**
$VarSwitch\ x\ y = (\!|In = x,\ Out = y,\ Trs = [x \leadsto y]|\!)$

definition $in\text{-}equiv\ A\ B = (perm\ (In\ A)\ (In\ B) \wedge Trs\ A = [In\ A \leadsto In\ B]\ oo\ Trs\ B \wedge Out\ A = Out\ B)$
definition $out\text{-}equiv\ A\ B = (perm\ (Out\ A)\ (Out\ B) \wedge Trs\ A = Trs\ B\ oo\ [Out\ B \leadsto Out\ A] \wedge In\ A = In\ B)$

definition $in\text{-}out\text{-}equiv\ A\ B = (perm\ (In\ A)\ (In\ B) \wedge perm\ (Out\ A)\ (Out\ B) \wedge Trs\ A = [In\ A \leadsto In\ B]\ oo\ Trs\ B\ oo\ [Out\ B \leadsto Out\ A])$

lemma *in-equiv-io-diagram*: $in\text{-}equiv\ A\ B \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ A$

lemma *in-out-equiv-io-diagram*: $in\text{-}out\text{-}equiv\ A\ B \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ A$

lemma *in-equiv-sym*: $io\text{-}diagram\ B \Longrightarrow in\text{-}equiv\ A\ B \Longrightarrow in\text{-}equiv\ B\ A$

lemma *in-equiv-eq*: $io\text{-}diagram\ A \Longrightarrow A = B \Longrightarrow in\text{-}equiv\ A\ B$

lemma [*simp*]: $io\text{-}diagram\ A \Longrightarrow [In\ A \leadsto In\ A]\ oo\ Trs\ A\ oo\ [Out\ A \leadsto Out\ A] = Trs\ A$

lemma *in-equiv-tran*: $io\text{-}diagram\ C \Longrightarrow in\text{-}equiv\ A\ B \Longrightarrow in\text{-}equiv\ B\ C \Longrightarrow in\text{-}equiv\ A\ C$

lemma *in-out-equiv-refl*: $io\text{-}diagram\ A \Longrightarrow in\text{-}out\text{-}equiv\ A\ A$

lemma *in-out-equiv-sym*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow in\text{-}out\text{-}equiv\ A\ B \Longrightarrow in\text{-}out\text{-}equiv\ B$

A

lemma *in-out-equiv-tran*: *io-diagram* $A \Longrightarrow$ *io-diagram* $B \Longrightarrow$ *io-diagram* $C \Longrightarrow$ *in-out-equiv* A B $\Longrightarrow$ *in-out-equiv* B $C \Longrightarrow$ *in-out-equiv* A C

lemma [*simp*]: *distinct* (*Out* A) $\Longrightarrow$ *distinct* (*Var* A B)

lemma [*simp*]: *set* (*Var* A B) $\subseteq$ *set* (*Out* A)
lemma [*simp*]: *set* (*Var* A B) $\subseteq$ *set* (*In* B)

lemmas *fb-indep-sym* = *fb-indep* [*THEN sym*]

declare *length-TVs* [*simp*]

end

primrec *op-list* :: $'a \Rightarrow ('a \Rightarrow 'a \Rightarrow 'a) \Rightarrow 'a$ *list* $\Rightarrow 'a$ **where**
op-list e opr [] = *e* |
op-list e opr (*a* # *x*) = *opr a* (*op-list e opr x*)

primrec *inter-set* :: $'a$ *list* $\Rightarrow 'a$ *set* $\Rightarrow 'a$ *list* **where**
inter-set [] *X* = [] |
inter-set (*x* # *xs*) *X* = (*if* $x \in X$ *then x* # *inter-set xs X else inter-set xs X*)

lemma *list-inter-set*: $x \otimes y$ = *inter-set x* (*set y*)

fun *map2* :: $('a \Rightarrow 'b \Rightarrow bool) \Rightarrow 'a$ *list* $\Rightarrow 'b$ *list* $\Rightarrow$ *bool* **where**
map2 f [] [] = *True* |
map2 f (*a* # *x*) (*b* # *y*) = (*f a b* $\wedge$ *map2 f x y*) |
map2 - - - = *False*

thm *map-def*

context *BaseOperationFeedbacklessVars*
begin
definition *ParallelId* :: (*'var*, *'a*) *Dgr* (□)
where □ = (|*In* = [], *Out* = [], *Trs* = *ID* []|)

lemma [*simp*]: *Out* □ = []

lemma [*simp*]: *In* □ = []

lemma [*simp*]: *Trs* □ = *ID* []

lemma *ParallelId-right*[*simp*]: *io-diagram* $A \Longrightarrow A$ ||| □ = A

lemma *ParallelId-left*: *io-diagram* $A \Longrightarrow$ □ ||| $A = A$

definition *parallel-list* = *op-list* (*ID* []) (*op* ‖)

definition *Parallel-list* = *op-list* □ (*op* |||)

lemma [*simp*]: *Parallel-list* [] = $\square$

definition *io-distinct As* = (*distinct* (*concat* (*map In As*)) $\wedge$ *distinct* (*concat* (*map Out As*)) $\wedge$ ($\forall$ *A* $\in$ *set As* . *io-diagram A*))

definition *io-rel A* = *set* (*Out A*) $\times$ *set* (*In A*)

definition *IO-Rel As* = $\bigcup$ (*set* (*map io-rel As*))

definition *out A* = *hd* (*Out A*)

definition *Type-OK As* = (($\forall$ *B* $\in$ *set As* . *io-diagram B* $\wedge$ *length* (*Out B*) = *1*)
$\wedge$ *distinct* (*concat* (*map Out As*)))

lemma *concat-map-out*: ($\forall$ *A* $\in$ *set As* . *length* (*Out A*) = *1*) $\Longrightarrow$ *concat* (*map Out As*) = *map out As*

lemma *Type-OK-simp*: *Type-OK As* = (($\forall$ *B* $\in$ *set As* . *io-diagram B* $\wedge$ *length* (*Out B*) = *1*) $\wedge$ *distinct* (*map out As*))

definition *single-out A* = (*io-diagram A* $\wedge$ *length* (*Out A*) = *1*)

definition *CompA* :: ('*var*, '*a*) *Dgr* $\Rightarrow$ ('*var*, '*a*) *Dgr* $\Rightarrow$ ('*var*, '*a*) *Dgr* (**infixl** $\rhd$ *75*) **where**

A $\rhd$ *B* = (*if out A* $\in$ *set* (*In B*) *then A* ;; *B else B*)

definition *internal As* = {*x* . ($\exists$ *A* $\in$ *set As* . $\exists$ *B* $\in$ *set As* . *x* $\in$ *set* (*Out A*) $\wedge$ *x* $\in$ *set* (*In B*))}

primrec *get-comp-out* :: '*var* $\Rightarrow$ ('*var*, '*a*) *Dgr list* $\Rightarrow$ ('*var*, '*a*) *Dgr* **where**
get-comp-out x [] = (|*In* = [*x*], *Out* = [*x*], *Trs* = [[*x*] $\leadsto$ [*x*]]|) |
get-comp-out x (*A* # *As*) = (*if x* $\in$ *set* (*Out A*) *then A else get-comp-out x As*)

primrec *get-other-out* :: '*c* $\Rightarrow$ ('*c*, '*d*) *Dgr list* $\Rightarrow$ ('*c*, '*d*) *Dgr list* **where**
get-other-out x [] = [] |
get-other-out x (*A* # *As*) = (*if x* $\in$ *set* (*Out A*) *then get-other-out x As else A* # *get-other-out x As*)

definition *fb-less-step A As* = *map* (*CompA A*) *As*

definition *fb-out-less-step x As* = *fb-less-step* (*get-comp-out x As*) (*get-other-out x As*)

primrec *fb-less* :: '*var list* $\Rightarrow$ ('*var*, '*a*) *Dgr list* $\Rightarrow$ ('*var*, '*a*) *Dgr list* **where**
fb-less [] *As* = *As* |
fb-less (*x* # *xs*) *As* = *fb-less xs* (*fb-out-less-step x As*)

lemma [*simp*]: *VarFB* $\square$ = []
lemma [*simp*]: *InFB* $\square$ = []
lemma [*simp*]: *OutFB* $\square$ = []

definition *loop-free As* $= (\forall\ x\ .\ (x,x) \notin (IO\text{-}Rel\ As)^{+})$

lemma [*simp*]: $Parallel\text{-}list\ (A\ \#\ As) = (A\ |||\ Parallel\text{-}list\ As)$

lemma [*simp*]: $Out\ (A\ |||\ B) = Out\ A\ @\ Out\ B$

lemma [*simp*]: $In\ (A\ |||\ B) = In\ A \oplus In\ B$

lemma *Type-OK-cons*: $Type\text{-}OK\ (A\ \#\ As) = (io\text{-}diagram\ A \wedge length\ (Out\ A) = 1 \wedge set\ (Out\ A) \cap (\bigcup a{\in}set\ As.\ set\ (Out\ a)) = \{\} \wedge Type\text{-}OK\ As)$

lemma *Out-Parallel*: $Out\ (Parallel\text{-}list\ As) = concat\ (map\ Out\ As)$

lemma *internal-cons*: $internal\ (A\ \#\ As) = \{x.\ x \in set\ (Out\ A) \wedge (x \in set\ (In\ A) \vee (\exists B{\in}set\ As.\ x \in set\ (In\ B)))\} \cup \{x\ .\ (\exists Aa{\in}set\ As.\ x \in set\ (Out\ Aa) \wedge (x \in set\ (In\ A)))\}$
$\cup\ internal\ As$

lemma *Out-out*: $length\ (Out\ A) = Suc\ 0 \Longrightarrow Out\ A = [out\ A]$

lemma *Type-OK-out*: $Type\text{-}OK\ As \Longrightarrow A \in set\ As \Longrightarrow Out\ A = [out\ A]$

lemma *In-Parallel*: $In\ (Parallel\text{-}list\ As) = op\text{-}list\ []\ (op \oplus)\ (map\ In\ As)$

lemma [*simp*]: $set\ (op\text{-}list\ []\ op \oplus xs) = \bigcup\ set\ (map\ set\ xs)$

lemma *internal-VarFB*: $Type\text{-}OK\ As \Longrightarrow internal\ As = set\ (VarFB\ (Parallel\text{-}list\ As))$

lemma *map-Out-fb-less-step*: $length\ (Out\ A) = 1 \Longrightarrow map\ Out\ (fb\text{-}less\text{-}step\ A\ As) = map\ Out\ As$

lemma *mem-get-comp-out*: $Type\text{-}OK\ As \Longrightarrow A \in set\ As \Longrightarrow get\text{-}comp\text{-}out\ (out\ A)\ As = A$

lemma *map-Out-fb-out-less-step*: $A \in set\ As \Longrightarrow Type\text{-}OK\ As \Longrightarrow a = out\ A \Longrightarrow map\ Out\ (fb\text{-}out\text{-}less\text{-}step\ a\ As) = map\ Out\ (get\text{-}other\text{-}out\ a\ As)$

lemma [*simp*]: $Type\text{-}OK\ (A\ \#\ As) \Longrightarrow Type\text{-}OK\ As$

lemma *Type-OK-Out*: $Type\text{-}OK\ (A\ \#\ As) \Longrightarrow Out\ A = [out\ A]$

lemma *concat-map-Out-get-other-out*: $Type\text{-}OK\ As \Longrightarrow concat\ (map\ Out\ (get\text{-}other\text{-}out\ a\ As)) = (concat\ (map\ Out\ As) \ominus [a])$
thm *Out-out*
lemma *VarFB-cons-out*: $Type\text{-}OK\ As \Longrightarrow VarFB\ (Parallel\text{-}list\ As) = a\ \#\ L \Longrightarrow \exists\ A \in set\ As\ .\ out\ A = a$

lemma *VarFB-cons-out-In*: $Type\text{-}OK\ As \Longrightarrow VarFB\ (Parallel\text{-}list\ As) = a\ \#\ L \Longrightarrow \exists\ B \in set\ As\ .\ a \in set\ (In\ B)$

lemma *AAA-a*: $Type\text{-}OK\ (A\ \#\ As) \Longrightarrow A \notin set\ As$

lemma *AAA-b*: $(\forall\ A \in set\ As.\ a \notin set\ (Out\ A)) \Longrightarrow get\text{-}other\text{-}out\ a\ As = As$

lemma *AAA-d*: $Type\text{-}OK\ (A\ \#\ As) \Longrightarrow \forall\, Aa{\in}set\ As.\ out\ A \neq out\ Aa$

lemma *mem-get-other-out*: $Type\text{-}OK\ As \Longrightarrow A \in set\ As \Longrightarrow get\text{-}other\text{-}out\ (out\ A)\ As = (As \ominus [A])$

lemma *In-CompA*: $In\ (A \rhd B) = (if\ out\ A \in set\ (In\ B)\ then\ In\ A \oplus (In\ B \ominus Out\ A)\ else\ In\ B)$

lemma *union-set-In-CompA*: $\bigwedge\ B\ .\ length\ (Out\ A) = 1 \Longrightarrow B \in set\ As \Longrightarrow out\ A \in set\ (In\ B)$
$\Longrightarrow (\bigcup x{\in}set\ As.\ set\ (In\ (CompA\ A\ x))) = set\ (In\ A) \cup ((\bigcup\ B \in set\ As\ .\ set\ (In\ B)) - \{out\ A\})$

lemma *BBBB-e*: $Type\text{-}OK\ As \Longrightarrow VarFB\ (Parallel\text{-}list\ As) = out\ A\ \#\ L \Longrightarrow A \in set\ As \Longrightarrow out\ A \notin set\ L$

lemma *BBBB-f*: $loop\text{-}free\ As \Longrightarrow$
$Type\text{-}OK\ As \Longrightarrow A \in set\ As \Longrightarrow B \in set\ As \Longrightarrow out\ A \in set\ (In\ B) \Longrightarrow B \neq A$

thm *union-set-In-CompA*

lemma [*simp*]: $x \in set\ (Out\ (get\text{-}comp\text{-}out\ x\ As))$

lemma *comp-out-in*: $A \in set\ As \Longrightarrow a \in set\ (Out\ A) \Longrightarrow (get\text{-}comp\text{-}out\ a\ As) \in set\ As$

lemma [*simp*]: $a \in internal\ As \Longrightarrow get\text{-}comp\text{-}out\ a\ As \in set\ As$

lemma *out-CompA*: $length\ (Out\ A) = 1 \Longrightarrow out\ (CompA\ A\ B) = out\ B$

lemma *Type-OK-loop-free-elem*: $Type\text{-}OK\ As \Longrightarrow loop\text{-}free\ As \Longrightarrow A \in set\ As \Longrightarrow out\ A \notin set\ (In\ A)$

lemma *BBB-a*: $length\ (Out\ A) = 1 \Longrightarrow Out\ (CompA\ A\ B) = Out\ B$

lemma *BBB-b*: $length\ (Out\ A) = 1 \Longrightarrow map\ (Out \circ CompA\ A)\ As = map\ Out\ As$

lemma *VarFB-fb-out-less-step-gen*:
assumes *loop-free As*
assumes *Type-OK As*
and *internal-a*: $a \in internal\ As$
shows $VarFB\ (Parallel\text{-}list\ (fb\text{-}out\text{-}less\text{-}step\ a\ As)) = (VarFB\ (Parallel\text{-}list\ As)) \ominus [a]$

thm *internal-VarFB*
thm *VarFB-fb-out-less-step-gen*

lemma *VarFB-fb-out-less-step*: $loop\text{-}free\ As \Longrightarrow Type\text{-}OK\ As \Longrightarrow VarFB\ (Parallel\text{-}list\ As) = a\ \#\ L \Longrightarrow VarFB\ (Parallel\text{-}list\ (fb\text{-}out\text{-}less\text{-}step\ a\ As)) = L$

lemma *Parallel-list-cons*:*Parallel-list* $(a \# As) = a \mathbin{|||}$ *Parallel-list As*

lemma *io-diagram-parallel-list*: *Type-OK As* $\Longrightarrow$ *io-diagram* (*Parallel-list As*)

lemma *BBB-c*: *distinct* (*map f As*) $\Longrightarrow$ *distinct* (*map f* (*As* $\ominus$ *Bs*))

lemma *io-diagram-CompA*: *io-diagram A* $\Longrightarrow$ *length* (*Out A*) = *1* $\Longrightarrow$ *io-diagram B* $\Longrightarrow$ *io-diagram* (*CompA A B*)

lemma *Type-OK-fb-out-less-step-aux*: *Type-OK As* $\Longrightarrow$ *A* $\in$ *set As* $\Longrightarrow$ *Type-OK* (*fb-less-step A* (*As* $\ominus$ [*A*]))

thm *VarFB-cons-out*

theorem *Type-OK-fb-out-less-step-new*: *Type-OK As* $\Longrightarrow$
a $\in$ *internal As* $\Longrightarrow$
Bs = *fb-out-less-step a As* $\Longrightarrow$ *Type-OK Bs*

theorem *Type-OK-fb-out-less-step*: *loop-free As* $\Longrightarrow$ *Type-OK As* $\Longrightarrow$
VarFB (*Parallel-list As*) = *a* # *L* $\Longrightarrow$ *Bs* = *fb-out-less-step a As* $\Longrightarrow$ *Type-OK Bs*

lemma *perm-FB-Parallel*[*simp*]: *loop-free As* $\Longrightarrow$ *Type-OK As*
$\Longrightarrow$ *VarFB* (*Parallel-list As*) = *a* # *L* $\Longrightarrow$ *Bs* = *fb-out-less-step a As*
$\Longrightarrow$ *perm* (*In* (*FB* (*Parallel-list As*))) (*In* (*FB* (*Parallel-list Bs*)))

lemma [*simp*]: *loop-free As* $\Longrightarrow$ *Type-OK As* $\Longrightarrow$
VarFB (*Parallel-list As*) = *a* # *L* $\Longrightarrow$
Out (*FB* (*Parallel-list* (*fb-out-less-step a As*))) = *Out* (*FB* (*Parallel-list As*))

lemma *TI-Parallel-list*: ($\forall$ *A* $\in$ *set As* . *io-diagram A*) $\Longrightarrow$ *TI* (*Trs* (*Parallel-list As*)) = *TVs* (*op-list* [] *op* $\oplus$ (*map In As*))

lemma *TO-Parallel-list*: ($\forall$ *A* $\in$ *set As* . *io-diagram A*) $\Longrightarrow$ *TO* (*Trs* (*Parallel-list As*)) = *TVs* (*concat* (*map Out As*))

lemma *fbtype-aux*: (*Type-OK As*) $\Longrightarrow$ *loop-free As* $\Longrightarrow$ *VarFB* (*Parallel-list As*) = *a* # *L* $\Longrightarrow$
fbtype ([*L* @ (*In* (*Parallel-list* (*fb-out-less-step a As*)) $\ominus$ *L*) $\leadsto$ *In* (*Parallel-list* (*fb-out-less-step a As*))] *oo Trs* (*Parallel-list* (*fb-out-less-step a As*)) *oo*
[*Out* (*Parallel-list* (*fb-out-less-step a As*)) $\leadsto$ *L* @ (*Out* (*Parallel-list* (*fb-out-less-step a As*)) $\ominus$ *L*)])
(*TVs L*) (*TO* [*In* (*Parallel-list As*) $\ominus$ *a* # *L* $\leadsto$ *In* (*Parallel-list* (*fb-out-less-step a As*)) $\ominus$ *L*]) (*TVs* (*Out* (*Parallel-list* (*fb-out-less-step a As*)) $\ominus$ *L*))

lemma *fb-indep-left-a*: *fbtype S tsa* (*TO A*) *ts* $\Longrightarrow$ *A oo* (*fb*ˆˆ(*length tsa*)) *S* = (*fb*ˆˆ(*length tsa*)) ((*ID tsa* $\|$ *A*) *oo S*)

lemma *parallel-list-cons*: $\mathit{parallel\text{-}list}\ (A \# As) = A \parallel \mathit{parallel\text{-}list}\ As$

lemma *TI-parallel-list*: $(\forall\ A \in \mathit{set}\ As\ .\ \mathit{io\text{-}diagram}\ A) \Longrightarrow TI\ (\mathit{parallel\text{-}list}\ (\mathit{map}\ \mathit{Trs}\ As)) = TVs\ (\mathit{concat}\ (\mathit{map}\ \mathit{In}\ As))$

lemma *TO-parallel-list*: $(\forall\ A \in \mathit{set}\ As\ .\ \mathit{io\text{-}diagram}\ A) \Longrightarrow TO\ (\mathit{parallel\text{-}list}\ (\mathit{map}\ \mathit{Trs}\ As)) = TVs\ (\mathit{concat}\ (\mathit{map}\ \mathit{Out}\ As))$

lemma *Trs-Parallel-list-aux-a*: $\mathit{Type\text{-}OK}\ As \Longrightarrow \mathit{io\text{-}diagram}\ a \Longrightarrow$
$[\mathit{In}\ a \oplus \mathit{In}\ (\mathit{Parallel\text{-}list}\ As) \rightsquigarrow \mathit{In}\ a\ @\ \mathit{In}\ (\mathit{Parallel\text{-}list}\ As)]\ oo\ \mathit{Trs}\ a \parallel ([\mathit{In}\ (\mathit{Parallel\text{-}list}\ As) \rightsquigarrow \mathit{concat}\ (\mathit{map}\ \mathit{In}\ As)]\ oo\ \mathit{parallel\text{-}list}\ (\mathit{map}\ \mathit{Trs}\ As)) =$
$[\mathit{In}\ a \oplus \mathit{In}\ (\mathit{Parallel\text{-}list}\ As) \rightsquigarrow \mathit{In}\ a\ @\ \mathit{In}\ (\mathit{Parallel\text{-}list}\ As)]\ oo\ ([\mathit{In}\ a \rightsquigarrow \mathit{In}\ a\ ] \parallel [\mathit{In}\ (\mathit{Parallel\text{-}list}\ As) \rightsquigarrow \mathit{concat}\ (\mathit{map}\ \mathit{In}\ As)]\ oo\ \mathit{Trs}\ a \parallel \mathit{parallel\text{-}list}\ (\mathit{map}\ \mathit{Trs}\ As))$

lemma *Trs-Parallel-list-aux-b* :$\mathit{distinct}\ x \Longrightarrow \mathit{distinct}\ y \Longrightarrow\ \mathit{set}\ z \subseteq \mathit{set}\ y \Longrightarrow [x \oplus y \rightsquigarrow x\ @\ y]\ oo\ [x \rightsquigarrow x] \parallel [y \rightsquigarrow z] = [x \oplus y \rightsquigarrow x\ @\ z]$

lemma *Trs-Parallel-list*: $\mathit{Type\text{-}OK}\ As \Longrightarrow \mathit{Trs}\ (\mathit{Parallel\text{-}list}\ As) = [\mathit{In}\ (\mathit{Parallel\text{-}list}\ As) \rightsquigarrow \mathit{concat}\ (\mathit{map}\ \mathit{In}\ As)]\ oo\ \mathit{parallel\text{-}list}\ (\mathit{map}\ \mathit{Trs}\ As)$

lemma *CompA-Id*[*simp*]: $A \rhd \square = \square$

lemma *io-diagram-ParallelId*[*simp*]: $\mathit{io\text{-}diagram}\ \square$

lemma *in-equiv-aux-a* :$\mathit{distinct}\ x \Longrightarrow \mathit{distinct}\ y \Longrightarrow\ \mathit{set}\ z \subseteq \mathit{set}\ x \Longrightarrow [x \oplus y \rightsquigarrow x\ @\ y]\ oo\ [x \rightsquigarrow z] \parallel [y \rightsquigarrow y] = [x \oplus y \rightsquigarrow z\ @\ y]$

lemma *in-equiv-Parallel-aux-d*: $\mathit{distinct}\ x \Longrightarrow \mathit{distinct}\ y \Longrightarrow \mathit{set}\ u \subseteq \mathit{set}\ x \Longrightarrow \mathit{perm}\ y\ v$
$\Longrightarrow [x \oplus y \rightsquigarrow x\ @\ v]\ oo\ [x \rightsquigarrow u] \parallel [v \rightsquigarrow v] = [x \oplus y \rightsquigarrow u\ @\ v]$

lemma *comp-par-switch-subst*: $\mathit{distinct}\ x \Longrightarrow \mathit{distinct}\ y \Longrightarrow \mathit{set}\ u \subseteq \mathit{set}\ x \Longrightarrow \mathit{set}\ v \subseteq \mathit{set}\ y$
$\Longrightarrow [x \oplus y \rightsquigarrow x\ @\ y]\ oo\ [x \rightsquigarrow u] \parallel [y \rightsquigarrow v] = [x \oplus y \rightsquigarrow u\ @\ v]$

lemma *in-equiv-Parallel-aux-b* :$\mathit{distinct}\ x \Longrightarrow \mathit{distinct}\ y \Longrightarrow \mathit{perm}\ u\ x \Longrightarrow \mathit{perm}\ y\ v \Longrightarrow [x \oplus y \rightsquigarrow x\ @\ y]\ oo\ [x \rightsquigarrow u] \parallel [y \rightsquigarrow v] = [x \oplus y \rightsquigarrow u\ @\ v]$

lemma [*simp*]: $\mathit{set}\ x \subseteq \mathit{set}\ (x \oplus y)$

lemma [*simp*]: $\mathit{set}\ y \subseteq \mathit{set}\ (x \oplus y)$

declare *distinct-addvars* [*simp*]

lemma *in-equiv-Parallel*: $\mathit{io\text{-}diagram}\ B \Longrightarrow \mathit{io\text{-}diagram}\ B' \Longrightarrow \mathit{in\text{-}equiv}\ A\ B \Longrightarrow \mathit{in\text{-}equiv}\ A'\ B' \Longrightarrow \mathit{in\text{-}equiv}\ (A\ |||\ A')\ (B\ |||\ B')$

thm *local.BBB-a*

lemma *map-Out-CompA*: $length\ (Out\ A) = 1 \Longrightarrow map\ (out \circ CompA\ A)\ As = map\ out\ As$

lemma *CompA-in*[*simp*]: $out\ A \in set\ (In\ B) \Longrightarrow A \rhd B = A\ ;;\ B$

lemma *CompA-not-in*[*simp*]: $out\ A \notin set\ (In\ B) \Longrightarrow A \rhd B = B$

lemma *in-equiv-CompA-Parallel-a*: $deterministic\ (Trs\ A) \Longrightarrow length\ (Out\ A) = 1 \Longrightarrow io\text{-}diagram\ A$
$\Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C$
$\Longrightarrow out\ A \in set\ (In\ B) \Longrightarrow out\ A \in set\ (In\ C)$
$\Longrightarrow in\text{-}equiv\ ((A \rhd B)\ |||\ (A \rhd C))\ (A \rhd (B\ |||\ C))$

lemma *in-equiv-CompA-Parallel-c*: $length\ (Out\ A) = 1 \Longrightarrow io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C \Longrightarrow out\ A \notin set\ (In\ B) \Longrightarrow out\ A \in set\ (In\ C) \Longrightarrow$
$in\text{-}equiv\ (CompA\ A\ B\ |||\ CompA\ A\ C)\ (CompA\ A\ (B\ |||\ C))$

lemmas *distinct-addvars distinct-diff*

lemma *io-diagram-distinct*: **assumes** A: *io-diagram A* **shows** [*simp*]: $distinct\ (In\ A)$
and [*simp*]: $distinct\ (Out\ A)$ **and** [*simp*]: $TI\ (Trs\ A) = TVs\ (In\ A)$
and [*simp*]: $TO\ (Trs\ A) = TVs\ (Out\ A)$

declare *Subst-not-in-a* [*simp*]
declare *Subst-not-in* [*simp*]

lemma [*simp*]: $set\ x' \cap set\ z = \{\} \Longrightarrow TVs\ x = TVs\ y \Longrightarrow TVs\ x' = TVs\ y' \Longrightarrow Subst\ (x\ @\ x')\ (y\ @\ y')\ z = Subst\ x\ y\ z$

lemma [*simp*]: $set\ x \cap set\ z = \{\} \Longrightarrow TVs\ x = TVs\ y \Longrightarrow TVs\ x' = TVs\ y' \Longrightarrow Subst\ (x\ @\ x')\ (y\ @\ y')\ z = Subst\ x'\ y'\ z$

lemma [*simp*]: $set\ x \cap set\ z = \{\} \Longrightarrow TVs\ x = TVs\ y \Longrightarrow Subst\ x\ y\ z = z$

lemma [*simp*]: $distinct\ x \Longrightarrow TVs\ x = TVs\ y \Longrightarrow Subst\ x\ y\ x = y$

lemma $TVs\ x = TVs\ y \Longrightarrow length\ x = length\ y$

thm *length-TVs*

lemma *in-equiv-switch-Parallel*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow set\ (Out\ A) \cap set\ (Out\ B) = \{\} \Longrightarrow$
$in\text{-}equiv\ (A\ |||\ B)\ ((B\ |||\ A)\ ;;\ [[\ Out\ B\ @\ Out\ A \leadsto Out\ A\ @\ Out\ B]])$

lemma *in-out-equiv-Parallel*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow set\ (Out\ A) \cap set\ (Out\ B) = \{\} \Longrightarrow in\text{-}out\text{-}equiv\ (A\ |||\ B)\ (B\ |||\ A)$

declare *Subst-eq* [*simp*]

lemma assumes $in\text{-}equiv\ A\ A'$ **shows** [*simp*]: $perm\ (In\ A)\ (In\ A')$

lemma *Subst-cancel-left-type*: $set\ x \cap set\ z = \{\} \Longrightarrow TVs\ x = TVs\ y \Longrightarrow Subst\ (x\ @\ z)\ (y\ @\ z)\ w = Subst\ x\ y\ w$

lemma *diff-eq-set-right*: $set\ y = set\ z \Longrightarrow (x \ominus y) = (x \ominus z)$

lemma [*simp*]: $set\ (y \ominus x) \cap set\ x = \{\}$

lemma *in-equiv-Comp*: $io\text{-}diagram\ A' \Longrightarrow io\text{-}diagram\ B' \Longrightarrow in\text{-}equiv\ A\ A' \Longrightarrow in\text{-}equiv\ B\ B' \Longrightarrow in\text{-}equiv\ (A\ ;;\ B)\ (A'\ ;;\ B')$

lemma $io\text{-}diagram\ A' \Longrightarrow io\text{-}diagram\ B' \Longrightarrow in\text{-}equiv\ A\ A' \Longrightarrow in\text{-}equiv\ B\ B' \Longrightarrow in\text{-}equiv\ (CompA\ A\ B)\ (CompA\ A'\ B')$

thm *in-equiv-tran*

thm *in-equiv-CompA-Parallel-c*

lemma *comp-parallel-distrib-a*: $TO\ A = TI\ B \Longrightarrow (A\ oo\ B) \parallel C = (A \parallel (ID\ (TI\ C)))\ oo\ (B \parallel C)$

lemma *comp-parallel-distrib-b*: $TO\ A = TI\ B \Longrightarrow C \parallel (A\ oo\ B) = ((ID\ (TI\ C)) \parallel A)\ oo\ (C \parallel B)$

thm *switch-comp-subst*

lemma *CCC-d*: $distinct\ x \Longrightarrow distinct\ y' \Longrightarrow set\ y \subseteq set\ x \Longrightarrow set\ z \subseteq set\ x \Longrightarrow set\ u \subseteq set\ y' \Longrightarrow TVs\ y = TVs\ y' \Longrightarrow$
$TVs\ z = ts \Longrightarrow [x \leadsto y\ @\ z]\ oo\ [y' \leadsto u] \parallel (ID\ ts) = [x \leadsto Subst\ y'\ y\ u\ @\ z]$

lemma *CCC-e*: $distinct\ x \Longrightarrow distinct\ y' \Longrightarrow set\ y \subseteq set\ x \Longrightarrow set\ z \subseteq set\ x \Longrightarrow set\ u \subseteq set\ y' \Longrightarrow TVs\ y = TVs\ y' \Longrightarrow$
$TVs\ z = ts \Longrightarrow [x \leadsto z\ @\ y]\ oo\ (ID\ ts) \parallel [y' \leadsto u] = [x \leadsto z\ @\ Subst\ y'\ y\ u]$

lemma *CCC-a*: $distinct\ x \Longrightarrow distinct\ y \Longrightarrow set\ y \subseteq set\ x \Longrightarrow set\ z \subseteq set\ x \Longrightarrow set\ u \subseteq set\ y \Longrightarrow TVs\ z = ts$
$\Longrightarrow [x \leadsto y\ @\ z]\ oo\ [y \leadsto u] \parallel (ID\ ts) = [x \leadsto u\ @\ z]$

lemma *CCC-b*: $distinct\ x \Longrightarrow distinct\ z \Longrightarrow set\ y \subseteq set\ x \Longrightarrow set\ z \subseteq set\ x \Longrightarrow set\ u \subseteq set\ z$
$\Longrightarrow TVs\ y = ts \Longrightarrow [x \leadsto y\ @\ z]\ oo\ (ID\ ts) \parallel [z \leadsto u] = [x \leadsto y\ @\ u]$

thm *par-switch-eq-dist*

lemma *in-equiv-CompA-Parallel-b*: $length\ (Out\ A) = 1 \Longrightarrow io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C \Longrightarrow out\ A \in set\ (In\ B)$
$\Longrightarrow out\ A \notin set\ (In\ C) \Longrightarrow in\text{-}equiv\ (CompA\ A\ B\ |||\ CompA\ A\ C)\ (CompA\ A\ (B\ |||\ C))$

lemma *in-equiv-CompA-Parallel-d*: $length\ (Out\ A) = 1 \Longrightarrow io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C \Longrightarrow out\ A \notin set\ (In\ B) \Longrightarrow out\ A \notin set\ (In\ C) \Longrightarrow$
$in\text{-}equiv\ (CompA\ A\ B\ |||\ CompA\ A\ C)\ (CompA\ A\ (B\ |||\ C))$

lemma *in-equiv-CompA-Parallel*: $deterministic\ (Trs\ A) \Longrightarrow length\ (Out\ A) = 1 \Longrightarrow io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C \Longrightarrow$
$in\text{-}equiv\ ((A \rhd B)\ |||\ (A \rhd C))\ (A \rhd (B\ |||\ C))$

lemma *fb-less-step-compA*: $deterministic\ (Trs\ A) \Longrightarrow length\ (Out\ A) = 1 \Longrightarrow io\text{-}diagram\ A \Longrightarrow Type\text{-}OK\ As$
$\Longrightarrow in\text{-}equiv\ (Parallel\text{-}list\ (fb\text{-}less\text{-}step\ A\ As))\ (CompA\ A\ (Parallel\text{-}list\ As))$

lemma *switch-eq-Subst*: $distinct\ x \Longrightarrow distinct\ u \Longrightarrow set\ y \subseteq set\ x \Longrightarrow set\ v \subseteq set\ u \Longrightarrow TVs\ x = TVs\ u$
$\Longrightarrow Subst\ x\ u\ y = v \Longrightarrow [x \rightsquigarrow y] = [u \rightsquigarrow v]$

lemma [*simp*]: $set\ y \subseteq set\ y1 \Longrightarrow distinct\ x1 \Longrightarrow TVs\ x1 = TVs\ y1 \Longrightarrow Subst\ x1\ y1\ (Subst\ y1\ x1\ y) = y$

lemma [*simp*]: $set\ z \subseteq set\ x \Longrightarrow TVs\ x\ = TVs\ y \Longrightarrow set\ (Subst\ x\ y\ z) \subseteq set\ y$

thm *distinct-Subst*

lemma *distinct-Subst-aa*: $\bigwedge\ y\ .$
$distinct\ y \Longrightarrow length\ x = length\ y \Longrightarrow a \notin set\ y \Longrightarrow set\ z \cap (set\ y - set\ x) = \{\} \Longrightarrow a \neq aa$
$\Longrightarrow a \notin set\ z \Longrightarrow aa \notin set\ z \Longrightarrow distinct\ z \Longrightarrow aa \in set\ x$
$\Longrightarrow subst\ x\ y\ a \neq subst\ x\ y\ aa$

lemma *distinct-Subst-ba*: $distinct\ y \Longrightarrow length\ x = length\ y \Longrightarrow set\ z \cap (set\ y - set\ x) = \{\}$
$\Longrightarrow a \notin set\ z \Longrightarrow distinct\ z \Longrightarrow a \notin set\ y \Longrightarrow subst\ x\ y\ a \notin set\ (Subst\ x\ y\ z)$

lemma *distinct-Subst-ca*: $distinct\ y \Longrightarrow length\ x = length\ y \Longrightarrow set\ z \cap (set\ y - set\ x) = \{\}$
$\Longrightarrow a \notin set\ z \Longrightarrow distinct\ z \Longrightarrow a \in set\ x \Longrightarrow subst\ x\ y\ a \notin set\ (Subst\ x\ y\ z)$

lemma [*simp*]: $set\ z \cap (set\ y - set\ x) = \{\} \Longrightarrow distinct\ y \Longrightarrow distinct\ z \Longrightarrow length\ x = length\ y$
$\Longrightarrow distinct\ (Subst\ x\ y\ z)$

lemma *deterministic-Comp*: *io-diagram* $A \Longrightarrow$ *io-diagram* $B \Longrightarrow$ *deterministic* (*Trs* A) $\Longrightarrow$ *deterministic* (*Trs* B)
$\Longrightarrow$ *deterministic* (*Trs* (A ;; B))

lemma *deterministic-CompA*: *io-diagram* $A \Longrightarrow$ *io-diagram* $B \Longrightarrow$ *deterministic* (*Trs* A) $\Longrightarrow$ *deterministic* (*Trs* B)
$\Longrightarrow$ *deterministic* (*Trs* ($A \rhd B$))

lemma *parallel-list-empty*[*simp*]: *parallel-list* [] = *ID* []

lemma *parallel-list-append*: *parallel-list* (*As* @ *Bs*) = *parallel-list As* $\|$ *parallel-list Bs*

lemma *par-swap-aux*: *distinct* $p \Longrightarrow$ *distinct* (v @ u @ w) $\Longrightarrow$

TI A = *TVs* $x \Longrightarrow$ *TI* B = *TVs* $y \Longrightarrow$ *TI* C = *TVs* $z \Longrightarrow$
TO A = *TVs* $u \Longrightarrow$ *TO* B = *TVs* $v \Longrightarrow$ *TO* C = *TVs* $w \Longrightarrow$
set $x \subseteq$ *set* $p \Longrightarrow$ *set* $y \subseteq$ *set* $p \Longrightarrow$ *set* $z \subseteq$ *set* $p \Longrightarrow$ *set* $q \subseteq$ *set* (u @ v @ w) $\Longrightarrow$
[$p \rightsquigarrow x$ @ y @ z] *oo* ($A \| B \| C$) *oo* [u @ v @ $w \rightsquigarrow q$] = [$p \rightsquigarrow y$ @ x @ z] *oo* ($B \| A \| C$) *oo* [v @ u @ $w \rightsquigarrow q$]

lemma *Type-OK-distinct*: *Type-OK As* $\Longrightarrow$ *distinct As*

lemma *TI-parallel-list-a*: *TI* (*parallel-list As*) = *concat* (*map TI As*)

lemma *fb-CompA-aux*: *Type-OK As* $\Longrightarrow A \in$ *set As* $\Longrightarrow$ *out* $A = a \Longrightarrow a \notin$ *set* (*In* A) $\Longrightarrow$
InAs = *In* (*Parallel-list As*) $\Longrightarrow$ *OutAs* = *Out* (*Parallel-list As*) $\Longrightarrow$ *perm* (a # y) *InAs* $\Longrightarrow$ *perm* (a # z) *OutAs* $\Longrightarrow$
InAs' = *In* (*Parallel-list* (*As* $\ominus$ [A])) $\Longrightarrow$
fb ([a # $y \rightsquigarrow$ *concat* (*map In As*)] *oo parallel-list* (*map Trs As*) *oo* [*OutAs* $\rightsquigarrow a$ # z]) =
[$y \rightsquigarrow$ *In* A @ (*InAs'* $\ominus$ [a])]
oo (*Trs* $A \|$ [(*InAs'* $\ominus$ [a]) $\rightsquigarrow$ (*InAs'* $\ominus$ [a])])
oo [a # (*InAs'* $\ominus$ [a]) $\rightsquigarrow$ *InAs'*] *oo Trs* (*Parallel-list* (*As* $\ominus$ [A]))
oo [*OutAs* $\ominus$ [a] $\rightsquigarrow z$] (**is** -$\Longrightarrow$ - $\Longrightarrow$ - $\Longrightarrow$ - $\Longrightarrow$ - $\Longrightarrow$ - $\Longrightarrow$ - $\Longrightarrow$ - $\Longrightarrow$ - $\Longrightarrow$ *fb* ?*Ta* = ?*Tb*)

lemma [*simp*]: *perm* (a # x) (a # y) = *perm* x y

lemma *fb-CompA*: *Type-OK As* $\Longrightarrow A \in$ *set As* $\Longrightarrow$ *out* $A = a \Longrightarrow a \notin$ *set* (*In* A) $\Longrightarrow C = A \rhd$ (*Parallel-list* (*As* $\ominus$ [A])) $\Longrightarrow$
OutAs = *Out* (*Parallel-list As*) $\Longrightarrow$ *perm* y (*In* C) $\Longrightarrow$ *perm* z (*Out* C) $\Longrightarrow B \in$ *set As* $-$ $\{A\}$ $\Longrightarrow a \in$ *set* (*In* B) $\Longrightarrow$
fb ([a # $y \rightsquigarrow$ *concat* (*map In As*)] *oo parallel-list* (*map Trs As*) *oo* [*OutAs* $\rightsquigarrow a$ # z]) = [$y \rightsquigarrow$ *In* C] *oo Trs* C *oo* [*Out* $C \rightsquigarrow z$]

definition *Deterministic As* = ($\forall$ $A \in$ *set As* . *deterministic* (*Trs* A))

lemma *Deterministic-fb-out-less-step*: *Type-OK As* $\Longrightarrow A \in$ *set As* $\Longrightarrow a$ = *out* $A \Longrightarrow$ *Deterministic*

As $\Longrightarrow$ *Deterministic* (*fb-out-less-step a As*)

lemma *in-equiv-fb-fb-less-step-TO-CHECK*: *loop-free As* $\Longrightarrow$ *Type-OK As* $\Longrightarrow$ *Deterministic As* $\Longrightarrow$
VarFB (*Parallel-list As*) = *a* # *L* $\Longrightarrow$ *Bs* = *fb-out-less-step a As*
$\Longrightarrow$ *in-equiv* (*FB* (*Parallel-list As*)) (*FB* (*Parallel-list Bs*))

lemma *io-diagram-FB-Parallel-list*: *Type-OK As* $\Longrightarrow$ *io-diagram* (*FB* (*Parallel-list As*))

lemma [*simp*]: *io-diagram A* $\Longrightarrow$ (|*In* = *In A*, *Out* = *Out A*, *Trs* = *Trs A*|) = *A*

thm *loop-free-def*

lemma *io-rel-compA*: *length* (*Out A*) = *1* $\Longrightarrow$ *io-rel* (*CompA A B*) $\subseteq$ *io-rel B* $\cup$ (*io-rel B O io-rel A*)

theorem *loop-free-fb-out-less-step*: *loop-free As* $\Longrightarrow$ *Type-OK As* $\Longrightarrow$ *A* $\in$ *set As* $\Longrightarrow$ *out A* = *a* $\Longrightarrow$ *loop-free* (*fb-out-less-step a As*)

theorem *in-equiv-FB-fb-less-delete*: $\bigwedge$ *As* . *Deterministic As* $\Longrightarrow$ *loop-free As* $\Longrightarrow$ *Type-OK As* $\Longrightarrow$ *VarFB* (*Parallel-list As*) = *L* $\Longrightarrow$
in-equiv (*FB* (*Parallel-list As*)) (*Parallel-list* (*fb-less L As*)) $\wedge$ *io-diagram* (*Parallel-list* (*fb-less L As*))

lemmas [*simp*] = *diff-emptyset*

lemma [*simp*]: $\bigwedge$ *x* . *distinct x* $\Longrightarrow$ *distinct y* $\Longrightarrow$ *perm* (((*y* $\otimes$ *x*) @ (*x* $\ominus$ *y* $\otimes$ *x*))) *x*

lemma [*simp*]: *io-diagram X* $\Longrightarrow$ *perm* (*VarFB X* @ (*In X* $\ominus$ *VarFB X*)) (*In X*)

lemma *Type-OK-diff* [*simp*]: *Type-OK As* $\Longrightarrow$ *Type-OK* (*As* $\ominus$ *Bs*)

lemma *internal-fb-out-less-step*:
assumes [*simp*]: *loop-free As*
assumes [*simp*]: *Type-OK As*
and [*simp*]: *a* $\in$ *internal As*
shows *internal* (*fb-out-less-step a As*) = *internal As* − {*a*}

end

context *BaseOperationFeedbacklessVars*
begin

lemma [*simp*]: *Type-OK As* $\Longrightarrow$ *a* $\in$ *internal As* $\Longrightarrow$ *out* (*get-comp-out a As*) = *a*

lemma *internal-Type-OK-simp*: *Type-OK As* $\Longrightarrow$ *internal As* = {*a* . ($\exists$ *A* $\in$ *set As* . *out A* = *a* $\wedge$ ($\exists$ *B* $\in$ *set As*. *a* $\in$ *set* (*In B*)))}

thm *Type-OK-def*

lemma *Type-OK-fb-less*: $\bigwedge$ *As* . *Type-OK As* $\Longrightarrow$ *loop-free As* $\Longrightarrow$ *distinct x* $\Longrightarrow$ *set x* $\subseteq$ *internal As* $\Longrightarrow$ *Type-OK* (*fb-less x As*)

lemma *fb-Parallel-list-fb-out-less-step*:
assumes [*simp*]: *Type-OK As*
and *Deterministic As*
and *loop-free As*
and *internal*: *a* $\in$ *internal As*
and *X*: *X* = *Parallel-list As*
and *Y*: *Y* = (*Parallel-list* (*fb-out-less-step a As*))
and [*simp*]: *perm y* (*In Y*)
and [*simp*]: *perm z* (*Out Y*)
shows *fb* ([*a* # *y* $\rightsquigarrow$ *In X*] *oo Trs X oo* [*Out X* $\rightsquigarrow$ *a* # *z*]) = [*y* $\rightsquigarrow$ *In Y*] *oo Trs Y oo* [*Out Y* $\rightsquigarrow$ *z*] **and** *perm* (*a* # *In Y*) (*In X*)

lemma *internal-In-Parallel-list*: *a* $\in$ *internal As* $\Longrightarrow$ *a* $\in$ *set* (*In* (*Parallel-list As*))

lemma *internal-Out-Parallel-list*: *a* $\in$ *internal As* $\Longrightarrow$ *a* $\in$ *set* (*Out* (*Parallel-list As*))

theorem *fb-power-internal-fb-less*: $\bigwedge$ *As X Y* . *Deterministic As* $\Longrightarrow$ *loop-free As* $\Longrightarrow$ *Type-OK As* $\Longrightarrow$ *set L* $\subseteq$ *internal As*
$\Longrightarrow$ *distinct L* $\Longrightarrow$
X = (*Parallel-list As*) $\Longrightarrow$ *Y* = *Parallel-list* (*fb-less L As*) $\Longrightarrow$
(*fb* ^^ *length* (*L*)) ([*L* @ (*In X* $\ominus$ *L*) $\rightsquigarrow$ *In X*] *oo Trs X oo* [*Out X* $\rightsquigarrow$ *L* @ (*Out X* $\ominus$ *L*)]) = [*In X* $\ominus$ *L* $\rightsquigarrow$ *In Y*] *oo Trs Y*
$\wedge$ *perm* (*In X* $\ominus$ *L*) (*In Y*)

thm *fb-power-internal-fb-less*

theorem *FB-fb-less*:
assumes [*simp*]: *Deterministic As*
and [*simp*]: *loop-free As*
and [*simp*]: *Type-OK As*
and [*simp*]: *perm* (*VarFB X*) *L*
and *X*: *X* = (*Parallel-list As*)
and *Y*: *Y* = *Parallel-list* (*fb-less L As*)
shows (*fb* ^^ *length* (*L*)) ([*L* @ *InFB X* $\rightsquigarrow$ *In X*] *oo Trs X oo* [*Out X* $\rightsquigarrow$ *L* @ *OutFB X*]) = [*InFB X* $\rightsquigarrow$ *In Y*] *oo Trs Y*
and *B*: *perm* (*InFB X*) (*In Y*)

definition *fb-perm-eq A* = ($\forall$ *x*. *perm x* (*VarFB A*) $\longrightarrow$
(*fb* ^^ *length* (*VarFB A*)) ([*VarFB A* @ *InFB A* $\rightsquigarrow$ *In A*] *oo Trs A oo* [*Out A* $\rightsquigarrow$ *VarFB A* @ *OutFB A*]) =
(*fb* ^^ *length* (*VarFB A*)) ([*x* @ *InFB A* $\rightsquigarrow$ *In A*] *oo Trs A oo* [*Out A* $\rightsquigarrow$ *x* @ *OutFB A*]))

lemma *fb-perm-eq-simp*: *fb-perm-eq A* = (∀ *x*. *perm x* (*VarFB A*) ⟶
Trs (*FB A*) = (*fb* ^^ *length* (*VarFB A*)) ([*x* @ *InFB A* ⇝ *In A*] *oo Trs A oo* [*Out A* ⇝ *x* @ *OutFB A*]))

lemma *in-equiv-in-out-equiv*: *io-diagram B* ⟹ *in-equiv A B* ⟹ *in-out-equiv A B*

lemma [*simp*]: *distinct* (*concat* (*map f As*)) ⟹ *distinct* (*concat* (*map f* (*As* ⊖ [*A*])))

lemma *set-op-list-addvars*: *set* (*op-list* [] *op* ⊕ *x*) = (⋃ *a* ∈ *set x* . *set a*)

end

context *BaseOperationFeedbacklessVars*

begin

lemma [*simp*]: *set* (*Out A*) ⊆ *set* (*In B*) ⟹ *Out* ((*A* ;; *B*)) = *Out B*

lemma [*simp*]: *set* (*Out A*) ⊆ *set* (*In B*) ⟹ *out* ((*A* ;; *B*)) = *out B*

lemma *switch-par-comp3*:
assumes [*simp*]: *distinct x* **and**
[*simp*]: *distinct y*
and [*simp*]: *distinct z*
and [*simp*]: *distinct u*
and [*simp*]: *set y* ⊆ *set x*
and [*simp*]: *set z* ⊆ *set x*
and [*simp*]: *set u* ⊆ *set x*
and [*simp*]: *set y'* ⊆ *set y*
and [*simp*]: *set z'* ⊆ *set z*
and [*simp*]: *set u'* ⊆ *set u*
shows [*x* ⇝ *y* @ *z* @ *u*] *oo* [*y* ⇝ *y'*] ∥ [*z* ⇝ *z'*] ∥ [*u* ⇝ *u'*] = [*x* ⇝ *y'* @ *z'* @ *u'*]

lemma *switch-par-comp-Subst3*:
assumes [*simp*]: *distinct x* **and** [*simp*]: *distinct y'* **and** [*simp*]: *distinct z'* **and** [*simp*]: *distinct t'*
and [*simp*]: *set y* ⊆ *set x* **and** [*simp*]: *set z* ⊆ *set x* **and** [*simp*]: *set t* ⊆ *set x*
and [*simp*]: *set u* ⊆ *set y'* **and** [*simp*]: *set v* ⊆ *set z'* **and** [*simp*]: *set w* ⊆ *set t'*
and [*simp*]: *TVs y* = *TVs y'* **and** [*simp*]: *TVs z* = *TVs z'* **and** [*simp*]: *TVs t* = *TVs t'*

shows [*x* ⇝ *y* @ *z* @ *t*] *oo* [*y'* ⇝ *u*] ∥ [*z'* ⇝ *v*] ∥ [*t'* ⇝ *w*] = [*x* ⇝ *Subst y' y u* @ *Subst z' z v* @ *Subst t' t w*]

lemma *Comp-assoc-single*: *length* (*Out A*) = *1* ⟹ *length* (*Out B*) = *1* ⟹ *out A* ≠ *out B* ⟹ *io-diagram A*
⟹ *io-diagram B* ⟹ *io-diagram C* ⟹ *out B* ∉ *set* (*In A*) ⟹
deterministic (*Trs A*) ⟹

$out\ A \in set\ (In\ B) \Longrightarrow out\ A \in set\ (In\ C) \Longrightarrow out\ B \in set\ (In\ C) \Longrightarrow (A\ ;;\ (B\ ;;\ C)) = (A\ ;;\ B\ ;;\ (A\ ;;\ C))$

lemma *Comp-commute-aux*:
assumes [*simp*]: $length\ (Out\ A) = 1$
and [*simp*]: $length\ (Out\ B) = 1$
and [*simp*]: *io-diagram A*
and [*simp*]: *io-diagram B*
and [*simp*]: *io-diagram C*
and [*simp*]: $out\ B \notin set\ (In\ A)$
and [*simp*]: $out\ A \notin set\ (In\ B)$
and [*simp*]: $out\ A \in set\ (In\ C)$
and [*simp*]: $out\ B \in set\ (In\ C)$
and *Diff*: $out\ A \neq out\ B$

shows $Trs\ (A\ ;;\ (B\ ;;\ C)) =$
$[In\ A \oplus In\ B \oplus (In\ C \ominus [out\ A] \ominus [out\ B]) \rightsquigarrow In\ A\ @\ In\ B\ @\ (In\ C \ominus [out\ A] \ominus [out\ B])]$
$oo\ Trs\ A \parallel Trs\ B \parallel [\ In\ C \ominus [out\ A] \ominus [out\ B] \rightsquigarrow In\ C \ominus [out\ A] \ominus [out\ B]\ ]$
$oo\ [out\ A\ \#\ out\ B\ \#\ (In\ C \ominus [out\ A] \ominus [out\ B]) \rightsquigarrow In\ C]$
$oo\ Trs\ C$
and $In\ (A\ ;;\ (B\ ;;\ C)) = In\ A \oplus In\ B \oplus (In\ C \ominus [out\ A] \ominus [out\ B])$
and $Out\ (A\ ;;\ (B\ ;;\ C)) = Out\ C$

lemma *Comp-commute*:
assumes [*simp*]: $length\ (Out\ A) = 1$
and [*simp*]: $length\ (Out\ B) = 1$
and [*simp*]: *io-diagram A*
and [*simp*]: *io-diagram B*
and [*simp*]: *io-diagram C*
and [*simp*]: $out\ B \notin set\ (In\ A)$
and [*simp*]: $out\ A \notin set\ (In\ B)$
and [*simp*]: $out\ A \in set\ (In\ C)$
and [*simp*]: $out\ B \in set\ (In\ C)$
and *Diff*: $out\ A \neq out\ B$
shows $in\text{-}equiv\ (A\ ;;\ (B\ ;;\ C))\ (B\ ;;\ (A\ ;;\ C))$

lemma *CompA-commute-aux-a*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C \Longrightarrow length\ (Out\ A) = 1 \Longrightarrow length\ (Out\ B) = 1$
$\Longrightarrow out\ A \notin set\ (Out\ C) \Longrightarrow out\ B \notin set\ (Out\ C)$
$\Longrightarrow out\ A \neq out\ B \Longrightarrow out\ A \in set\ (In\ B) \Longrightarrow out\ B \notin set\ (In\ A)$
$\Longrightarrow deterministic\ (Trs\ A)$
$\Longrightarrow (CompA\ (CompA\ B\ A)\ (CompA\ B\ C)) = (CompA\ (CompA\ A\ B)\ (CompA\ A\ C))$

lemma *CompA-commute-aux-b*: $io\text{-}diagram\ A \Longrightarrow io\text{-}diagram\ B \Longrightarrow io\text{-}diagram\ C \Longrightarrow length\ (Out\ A) = 1 \Longrightarrow length\ (Out\ B) = 1$
$\Longrightarrow out\ A \notin set\ (Out\ C) \Longrightarrow out\ B \notin set\ (Out\ C)$
$\Longrightarrow out\ A \neq out\ B \Longrightarrow out\ A \notin set\ (In\ B) \Longrightarrow out\ B \notin set\ (In\ A)$
$\Longrightarrow in\text{-}equiv\ (CompA\ (CompA\ B\ A)\ (CompA\ B\ C))\ (CompA\ (CompA\ A\ B)\ (CompA\ A\ C))$

fun *In-Equiv* :: $(('var, 'a)\ Dgr)\ list \Rightarrow (('var, 'a)\ Dgr)\ list \Rightarrow bool$ **where**
$In\text{-}Equiv\ []\ [] = True\ |$
$In\text{-}Equiv\ (A\ \#\ As)\ (B\#\ Bs) = (in\text{-}equiv\ A\ B \wedge In\text{-}Equiv\ As\ Bs)\ |$

In-Equiv - - = False

thm *internal-def*

thm *fb-out-less-step-def*
thm *fb-less-step-def*

thm *CompA-commute-aux-b*
thm *CompA-commute-aux-a*

lemma *CompA-commute*:
assumes [*simp*]: *io-diagram A*
and [*simp*]: *io-diagram B*
and [*simp*]: *io-diagram C*
and [*simp*]: *length* (*Out A*) = *1*
and [*simp*]: *length* (*Out B*) = *1*
and [*simp*]: *out A* $\notin$ *set* (*Out C*)
and [*simp*]: *out B* $\notin$ *set* (*Out C*)
and [*simp*]: *out A* $\neq$ *out B*
and [*simp*]: *deterministic* (*Trs A*)
and [*simp*]: *deterministic* (*Trs B*)
and *A*: (*out A* $\in$ *set* (*In B*) $\Longrightarrow$ *out B* $\notin$ *set* (*In A*))
shows *in-equiv* (*CompA* (*CompA B A*) (*CompA B C*)) (*CompA* (*CompA A B*) (*CompA A C*))

lemma *In-Equiv-CompA-twice*: ($\bigwedge$ *C* . *C* $\in$ *set As* $\Longrightarrow$ *io-diagram C* $\wedge$ *out A* $\notin$ *set* (*Out C*) $\wedge$ *out B* $\notin$ *set* (*Out C*)) $\Longrightarrow$ *io-diagram A* $\Longrightarrow$ *io-diagram B*
$\Longrightarrow$ *length* (*Out A*) = *1* $\Longrightarrow$ *length* (*Out B*) = *1* $\Longrightarrow$ *out A* $\neq$ *out B*
$\Longrightarrow$ *deterministic* (*Trs A*) $\Longrightarrow$ *deterministic* (*Trs B*)
$\Longrightarrow$ (*out A* $\in$ *set* (*In B*) $\Longrightarrow$ *out B* $\notin$ *set* (*In A*))
$\Longrightarrow$ *In-Equiv* (*map* (*CompA* (*CompA B A*)) (*map* (*CompA B*) *As*)) (*map* (*CompA* (*CompA A B*)) (*map* (*CompA A*) *As*))

thm *Type-OK-def*
thm *Deterministic-def*
thm *internal-def*
thm *fb-out-less-step-def*

thm *mem-get-other-out*

thm *mem-get-comp-out*

thm *comp-out-in*

lemma *map-diff*: ($\bigwedge$ *b* . *b* $\in$ *set x* $\Longrightarrow$ *b* $\neq$ *a* $\Longrightarrow$ *f b* $\neq$ *f a*) $\Longrightarrow$ *map f x* $\ominus$ [*f a*] = *map f* (*x* $\ominus$ [*a*])

lemma *In-Equiv-fb-out-less-step-commute*: *Type-OK As* $\Longrightarrow$ *Deterministic As* $\Longrightarrow$ *x* $\in$ *internal As* $\Longrightarrow$ *y* $\in$ *internal As* $\Longrightarrow$ *x* $\neq$ *y* $\Longrightarrow$ *loop-free As*
$\Longrightarrow$ *In-Equiv* (*fb-out-less-step x* (*fb-out-less-step y As*)) (*fb-out-less-step y* (*fb-out-less-step x As*))

lemma [*simp*]: *Type-OK As* $\Longrightarrow$ *In-Equiv As As*

lemma *fb-less-append*: $\bigwedge$ *As* . *fb-less* $(x$ @ $y)$ *As* = *fb-less* y (*fb-less* x *As*)

thm *in-equiv-tran*

lemma *In-Equiv-trans*: $\bigwedge$ *Bs Cs* . *Type-OK Cs* $\Longrightarrow$ *In-Equiv As Bs* $\Longrightarrow$ *In-Equiv Bs Cs* $\Longrightarrow$ *In-Equiv As Cs*

lemma *In-Equiv-exists*: $\bigwedge$ *Bs* . *In-Equiv As Bs* $\Longrightarrow$ $A \in$ *set As* $\Longrightarrow$ $\exists$ $B \in$ *set Bs* . *in-equiv A B*

lemma *In-Equiv-Type-OK*: $\bigwedge$*Bs* . *Type-OK Bs* $\Longrightarrow$ *In-Equiv As Bs* $\Longrightarrow$ *Type-OK As*

lemma *In-Equiv-internal-aux*: *Type-OK Bs* $\Longrightarrow$ *In-Equiv As Bs* $\Longrightarrow$ *internal As* $\subseteq$ *internal Bs*

lemma *In-Equiv-sym*: $\bigwedge$ *Bs* . *Type-OK Bs* $\Longrightarrow$ *In-Equiv As Bs* $\Longrightarrow$ *In-Equiv Bs As*

lemma *In-Equiv-internal*: *Type-OK Bs* $\Longrightarrow$ *In-Equiv As Bs* $\Longrightarrow$ *internal As* = *internal Bs*

lemma *in-equiv-CompA*: *in-equiv* A A' $\Longrightarrow$ *in-equiv* B B' $\Longrightarrow$ *io-diagram* A' $\Longrightarrow$ *io-diagram* B' $\Longrightarrow$ *in-equiv* (*CompA* A B) (*CompA* A' B')

lemma *In-Equiv-fb-less-step-cong*: $\bigwedge$ *Bs* . *Type-OK Bs* $\Longrightarrow$ *in-equiv A B* $\Longrightarrow$ *io-diagram B* $\Longrightarrow$ *In-Equiv As Bs*
$\Longrightarrow$ *In-Equiv* (*fb-less-step A As*) (*fb-less-step B Bs*)

lemma *In-Equiv-append*: $\bigwedge$ *As'* . *In-Equiv As As'* $\Longrightarrow$ *In-Equiv Bs Bs'* $\Longrightarrow$ *In-Equiv* (*As* @ *Bs*) (*As'* @ *Bs'*)

lemma *In-Equiv-split*: $\bigwedge$ *Bs* . *In-Equiv As Bs* $\Longrightarrow$ $A \in$ *set As*
$\Longrightarrow$ $\exists$ *B As' As'' Bs' Bs''* . *As* = *As'* @ *A* # *As''* $\wedge$ *Bs* = *Bs'* @ *B* # *Bs''* $\wedge$ *in-equiv A B* $\wedge$ *In-Equiv As' Bs'* $\wedge$ *In-Equiv As'' Bs''*

lemma *In-Equiv-fb-out-less-step-cong*:
assumes [*simp*]: *Type-OK Bs*
and *In-Equiv As Bs*
and *internal*: $a \in$ *internal As*
shows *In-Equiv* (*fb-out-less-step a As*) (*fb-out-less-step a Bs*)

lemma *In-Equiv-IO-Rel*: $\bigwedge$ *Bs* . *In-Equiv As Bs* $\Longrightarrow$ *IO-Rel Bs* = *IO-Rel As*

lemma *In-Equiv-loop-free*: *In-Equiv As Bs* $\Longrightarrow$ *loop-free Bs* $\Longrightarrow$ *loop-free As*

lemma *loop-free-fb-out-less-step-internal*:
assumes [*simp*]: *loop-free As*
and [*simp*]: *Type-OK As*
and $a \in$ *internal As*
shows *loop-free* (*fb-out-less-step a As*)

lemma *loop-free-fb-less-internal*:

$\bigwedge$ *As* . *loop-free As* $\Longrightarrow$ *Type-OK As* $\Longrightarrow$ *set x* $\subseteq$ *internal As* $\Longrightarrow$ *distinct x* $\Longrightarrow$ *loop-free* (*fb-less x As*)

lemma *In-Equiv-fb-less-cong*: $\bigwedge$ *As Bs* . *Type-OK Bs* $\Longrightarrow$ *In-Equiv As Bs* $\Longrightarrow$ *set x* $\subseteq$ *internal As* $\Longrightarrow$ *distinct x* $\Longrightarrow$ *loop-free Bs* $\Longrightarrow$ *In-Equiv* (*fb-less x As*) (*fb-less x Bs*)

thm *Type-OK-fb-out-less-step-new*

thm *Type-OK-fb-less*

lemma *Type-OK-fb-less-delete*: $\bigwedge$ *As* . *Type-OK As* $\Longrightarrow$ *set x* $\subseteq$ *internal As* $\Longrightarrow$ *distinct x* $\Longrightarrow$ *loop-free As* $\Longrightarrow$ *Type-OK* (*fb-less x As*)

thm *Deterministic-fb-out-less-step*

thm *internal-fb-out-less-step*

lemma *internal-fb-less*:
$\bigwedge$ *As* . *loop-free As* $\Longrightarrow$ *Type-OK As* $\Longrightarrow$ *set x* $\subseteq$ *internal As* $\Longrightarrow$ *distinct x* $\Longrightarrow$ *internal* (*fb-less x As*) = *internal As* − *set x*

thm *Deterministic-fb-out-less-step*

lemma *Deterministic-fb-out-less-step-internal*:
assumes [*simp*]: *Type-OK As*
and *Deterministic As*
and *internal*: *a* $\in$ *internal As*
shows *Deterministic* (*fb-out-less-step a As*)

lemma *Deterministic-fb-less-internal*: $\bigwedge$ *As* . *Type-OK As* $\Longrightarrow$ *Deterministic As* $\Longrightarrow$ *set x* $\subseteq$ *internal As* $\Longrightarrow$ *distinct x*
$\Longrightarrow$ *loop-free As* $\Longrightarrow$ *Deterministic* (*fb-less x As*)

lemma *In-Equiv-fb-less-Cons*: $\bigwedge$ *As* . *Type-OK As* $\Longrightarrow$ *Deterministic As* $\Longrightarrow$ *loop-free As* $\Longrightarrow$ *a* $\in$ *internal As*
$\Longrightarrow$ *set x* $\subseteq$ *internal As* $\Longrightarrow$ *distinct* (*a* # *x*)
$\Longrightarrow$ *In-Equiv* (*fb-less* (*a* # *x*) *As*) (*fb-less* (*x* @ [*a*]) *As*)

theorem *In-Equiv-fb-less*: $\bigwedge$ *y As* . *Type-OK As* $\Longrightarrow$ *Deterministic As* $\Longrightarrow$ *loop-free As* $\Longrightarrow$ *set x* $\subseteq$ *internal As* $\Longrightarrow$ *distinct x* $\Longrightarrow$ *perm x y*
$\Longrightarrow$ *In-Equiv* (*fb-less x As*) (*fb-less y As*)

lemma [*simp*]: *in-equiv* $\square$ $\square$

lemma *in-equiv-Parallel-list*: $\bigwedge$ *Bs* . *Type-OK Bs* $\Longrightarrow$ *In-Equiv As Bs* $\Longrightarrow$ *in-equiv* (*Parallel-list As*) (*Parallel-list Bs*)

thm *FB-fb-less*

lemma [*simp*]: *io-diagram A* $\Longrightarrow$ *distinct* (*VarFB A*)

lemma [*simp*]: *io-diagram A* $\Longrightarrow$ *distinct* (*InFB A*)

theorem *fb-perm-eq-Parallel-list*:
  assumes [*simp*]: *Type-OK As*
    and [*simp*]: *Deterministic As*
    and [*simp*]: *loop-free As*
    shows *fb-perm-eq* (*Parallel-list As*)

theorem *FeedbackSerial-Feedbackless*: *io-diagram A* $\Longrightarrow$ *io-diagram B* $\Longrightarrow$ *set* (*In A*) $\cap$ *set* (*In B*) = {} (**required**)
  $\Longrightarrow$ *set* (*Out A*) $\cap$ *set* (*Out B*) = {} $\Longrightarrow$ *fb-perm-eq* (*A* ||| *B*) $\Longrightarrow$ *FB* (*A* ||| *B*) = *FB* (*FB* (*A*) ;; *FB* (*B*))

declare *io-diagram-distinct* [*simp del*]

lemma *in-out-equiv-FB-less*: *io-diagram B* $\Longrightarrow$ *in-out-equiv A B* $\Longrightarrow$ *fb-perm-eq A* $\Longrightarrow$ *in-out-equiv* (*FB A*) (*FB B*)

lemma [*simp*]: *io-diagram A* $\Longrightarrow$ *distinct* (*OutFB A*)

end

end

9.4 Properties for Proving the Abstract Translation Algorithm

theory *HBDTranslationProperties* **imports** *ExtendedHBDAlgebra Diagrams*
begin
context *BaseOperationVars*
begin

lemma *io-diagram-fb-perm-eq*: *io-diagram A* $\Longrightarrow$ *fb-perm-eq A*

theorem *FeedbackSerial*: *io-diagram A* $\Longrightarrow$ *io-diagram B* $\Longrightarrow$ *set* (*In A*) $\cap$ *set* (*In B*) = {} (**required**)
  $\Longrightarrow$ *set* (*Out A*) $\cap$ *set* (*Out B*) = {} $\Longrightarrow$ *FB* (*A* ||| *B*) = *FB* (*FB* (*A*) ;; *FB* (*B*))

lemmas *fb-perm-sym* = *fb-perm* [*THEN sym*]

declare *length-TVs* [*simp del*]

declare [[*simp-trace-depth-limit=40*]]

lemma *in-out-equiv-FB*: *io-diagram B* $\Longrightarrow$ *in-out-equiv A B* $\Longrightarrow$ *in-out-equiv* (*FB A*) (*FB B*)

end

end

9.5 HBD Translation Algorithms that use Feedback Composition

theory *HBDTranslationsUsingFeedback* **imports** *HBDTranslationProperties ../RefinementReactive/Refinement*
begin

context *BaseOperationVars*
begin

definition *TranslateHBD* =
while-stm (λ *As* . *length As* > *1*)(
[:*As* $\rightsquigarrow$ *As'* . $\exists$ *Bs Cs* . *1* < *length Bs* $\wedge$ *perm As* (*Bs* @ *Cs*) $\wedge$ *As'* = *FB* (*Parallel-list Bs*) # *Cs*:]
$\sqcap$
[:*As* $\rightsquigarrow$ *As'* . $\exists$ *A B Bs* . *perm As* (*A* # *B* # *Bs*) $\wedge$ *As'* = (*FB* (*FB A* ;; *FB B*)) # *Bs*:]
)
o [$-$(λ *As* . *FB*(*As* ! *0*))$-$]

lemma [*simp*]:*Suc 0* $\leq$ *length As-init* $\Longrightarrow$
Hoare (λ*As*. *in-out-equiv* (*FB* (*As* ! *0*)) (*FB* (*Parallel-list As-init*))) [$-\lambda$*As*. *FB* (*As* ! *0*)$-$] (λ*S*. *in-out-equiv S* (*FB* (*Parallel-list As-init*)))

definition *invariant As-init n As* = (*length As* = *n* $\wedge$ *io-distinct As* $\wedge$ *in-out-equiv* (*FB* (*Parallel-list As*)) (*FB* (*Parallel-list As-init*)) $\wedge$ *n* $\geq$ *1*)

lemma *io-diagram-Parallel-list*: $\forall$ *A* $\in$ *set As* . *io-diagram A* $\Longrightarrow$ *distinct* (*concat* (*map Out As*)) $\Longrightarrow$ *io-diagram* (*Parallel-list As*)

lemma *io-diagram-Parallel-list-a*: *io-distinct As* $\Longrightarrow$ *io-diagram* (*Parallel-list As*)

thm *Parallel-list-cons*

thm *Parallel-assoc-gen*

thm *ParallelId-left*
thm *io-diagram-Parallel-list*

lemma *Parallel-list-append*: $\forall$ *A* $\in$ *set As* . *io-diagram A* $\Longrightarrow$ *distinct* (*concat* (*map Out As*)) $\Longrightarrow$ $\forall$ *A* $\in$ *set Bs* . *io-diagram A*
$\Longrightarrow$ *distinct* (*concat* (*map Out Bs*))$\Longrightarrow$
Parallel-list (*As* @ *Bs*) = *Parallel-list As* ||| *Parallel-list Bs*

primrec *sequence* :: *nat* $\Rightarrow$ *nat list* **where**
sequence 0 = [] |
sequence (*Suc n*) = *sequence n* @ [*n*]

lemma *sequence* (*Suc* (*Suc 0*)) = [*0*,*1*]

lemma *in-out-equiv-io-diagram*[*simp*]: *in-out-equiv A B* $\Longrightarrow$ *io-diagram B* $\Longrightarrow$ *io-diagram A*

thm *comp-parallel-distrib*

lemma *in-out-equiv-Parallel-cong-right*: *io-diagram A* $\Longrightarrow$ *io-diagram C* $\Longrightarrow$ *set* (*Out A*) $\cap$ *set* (*Out B*) = {} $\Longrightarrow$ *in-out-equiv B C*
$\Longrightarrow$ *in-out-equiv* (*A* ||| *B*) (*A* ||| *C*)

lemma *perm-map*: *perm x y* $\Longrightarrow$ *perm* (*map f x*) (*map f y*)

lemma *distinct-concat-perm*: $\bigwedge$ *Y* . *distinct* (*concat X*) $\Longrightarrow$ *perm X Y* $\Longrightarrow$ *distinct* (*concat Y*)

lemma *distinct-Par-equiv-a*: $\bigwedge$ *Bs* . $\forall$ *A* $\in$ *set As* . *io-diagram A* $\Longrightarrow$ *distinct* (*concat* (*map Out As*)) $\Longrightarrow$ *perm As Bs* $\Longrightarrow$
in-out-equiv (*Parallel-list As*) (*Parallel-list Bs*)

thm *distinct-concat-perm*
thm *perm-map*

lemma *distinct-FB*: *distinct* (*In A*) $\Longrightarrow$ *distinct* (*In* (*FB A*))

lemma *io-distinct-FB-cat*: *io-distinct* (*A* # *Cs*) $\Longrightarrow$ *io-distinct* (*FB A* # *Cs*)

lemma *io-distinct-perm*: *io-distinct As* $\Longrightarrow$ *perm As Bs* $\Longrightarrow$ *io-distinct Bs*

lemma [*simp*]: *distinct* (*concat X*) $\Longrightarrow$ *op-list* [] *op* $\oplus$ (*X*) = *concat X*

lemma [*simp*]: *io-distinct As* $\Longrightarrow$ *perm As* (*Bs* @ *Cs*) $\Longrightarrow$ *io-distinct* (*FB* (*Parallel-list Bs*) # *Cs*)

lemma *io-distinct-append-a*: *io-distinct As* $\Longrightarrow$ *perm As* (*Bs* @ *Cs*) $\Longrightarrow$ *io-distinct Bs*

lemma *io-distinct-append-b*: *io-distinct As* $\Longrightarrow$ *perm As* (*Bs* @ *Cs*) $\Longrightarrow$ *io-distinct Cs*

lemma [*simp*]: *io-distinct As* $\Longrightarrow$ *perm As* (*Bs* @ *Cs*) $\Longrightarrow$ *io-diagram* (*FB* (*FB* (*Parallel-list Bs*) ||| *Parallel-list Cs*))

lemma [*simp*]: *io-distinct As* $\Longrightarrow$ *io-diagram* (*FB* (*Parallel-list As*))

lemma *io-distinct-set-In*[*simp*]: *io-distinct x* $\Longrightarrow$ *perm x* (*A* # *B* # *Bs*) $\Longrightarrow$ *set* (*In A*) $\cap$ *set* (*In B*) = {}

lemma *io-distinct-set-Out*[*simp*]: *io-distinct x* $\Longrightarrow$ *perm x* (*A* # *B* # *Bs*) $\Longrightarrow$ *set* (*Out A*) $\cap$ *set* (*Out B*) = {}

lemma *distinct-Par-equiv-b*: *io-distinct As* $\Longrightarrow$ *perm As* (*Bs* @ *Cs*) $\Longrightarrow$ *in-out-equiv* (*FB* (*FB* (*Parallel-list Bs*) ||| *Parallel-list Cs*)) (*FB* (*Parallel-list As*))

lemma *distinct-Par-equiv*: *io-distinct As-init* $\Longrightarrow$ *Suc 0* $\leq$ *length As-init* $\Longrightarrow$
length As = *w* $\Longrightarrow$ *io-distinct As* $\Longrightarrow$ *in-out-equiv* (*FB* (*Parallel-list As*)) (*FB* (*Parallel-list As-init*)) $\Longrightarrow$
Suc 0 < *w* $\Longrightarrow$ *Suc 0* < *length Bs* $\Longrightarrow$ *perm As* (*Bs* @ *Cs*) $\Longrightarrow$
io-distinct (*FB* (*Parallel-list Bs*) # *Cs*) $\wedge$ *in-out-equiv* (*FB* (*FB* (*Parallel-list Bs*) ||| *Parallel-list Cs*)) (*FB* (*Parallel-list As-init*))

lemma *AAAA-x*[*simp*]: *io-distinct As-init* $\Longrightarrow$ *Suc 0* $\leq$ *length As-init* $\Longrightarrow$ *invariant As-init w x* $\Longrightarrow$ *Suc 0* $<$ *length x* $\Longrightarrow$ *Suc 0* $<$ *length Bs*
$\Longrightarrow$ *perm x* (*Bs* @ *Cs*)
$\Longrightarrow$ *invariant As-init* (*Suc* (*length Cs*)) (*FB* (*Parallel-list Bs*) # *Cs*)

term {*1*,*2*,*3*} − {*2*,*3*}

thm *ParallelId-right*

lemma [*simp*]: *io-distinct As-init* $\Longrightarrow$
Suc 0 $\leq$ *length As-init* $\Longrightarrow$ *invariant As-init w x* $\Longrightarrow$ *Suc 0* $<$ *length x* $\Longrightarrow$ *perm x* (*A* # *B* # *Bs*)
$\Longrightarrow$ *invariant As-init* (*Suc* (*length Bs*)) (*FB* (*FB A* ;; *FB B*) # *Bs*)

lemma [*simp*]: *io-distinct As-init* $\Longrightarrow$ *Suc 0* $\leq$ *length As-init* $\Longrightarrow$
Hoare (*invariant As-init w* $\sqcap$ (λ*As. Suc 0* $<$ *length As*))
[:*As*$\rightsquigarrow$*As*$'$.$\exists$ *Bs. Suc 0* $<$ *length Bs* $\wedge$ ($\exists$ *Cs. perm As* (*Bs* @ *Cs*) $\wedge$ *As*$'$ = *FB* (*Parallel-list Bs*) # *Cs*):] (*Sup-less* (*invariant As-init*) *w*)

lemma [*simp*]: *io-distinct As-init* $\Longrightarrow$ *Suc 0* $\leq$ *length As-init* $\Longrightarrow$
Hoare (*invariant As-init w* $\sqcap$ (λ*As. Suc 0* $<$ *length As*))
[:*As*$\rightsquigarrow$*As*$'$.$\exists$ *A B Bs. perm As* (*A* # *B* # *Bs*) $\wedge$ *As*$'$ = *FB* (*FB A* ;; *FB B*) # *Bs*:] (*Sup-less* (*invariant As-init*) *w*)

theorem *CorrectnessTranslateHBD*: *io-distinct As-init* $\Longrightarrow$ *length As-init* $\geq$ *1* $\Longrightarrow$
Hoare (*io-distinct* $\sqcap$ (λ *As* . *As* = *As-init*)) *TranslateHBD* (λ *S* . *in-out-equiv S* (*FB* (*Parallel-list As-init*)))
end

end

9.6 Feedbackless HBD Translation

theory *FeedbacklessHBDTranslation* **imports** *Diagrams ../RefinementReactive/Refinement*
begin
context *BaseOperationFeedbacklessVars*
begin
definition *WhileFeedbackless* =
while-stm (λ *As* . *internal As* $\neq$ {})
[:*As* $\rightsquigarrow$ *As*$'$. $\exists$ *A* . *A* $\in$ *set As* $\wedge$ (*out A*) $\in$ *internal As* $\wedge$ *As*$'$= *map* (*CompA A*) (*As* $\ominus$ [*A*]):]

definition *TranslateHBDFeedbackless* = *WhileFeedbackless o* [−(λ *As* . *Parallel-list As*)−]

definition *ok-fbless As* = (*Deterministic As* $\wedge$ *loop-free As* $\wedge$ *Type-OK As*)

definition *TranslateHBDRec* = {. *ok-fbless* .}
o [:*As* $\rightsquigarrow$ *As*$'$. $\exists$ *L* . *perm* (*VarFB* (*Parallel-list As*)) *L* $\wedge$ *As*$'$ = *fb-less L As* :]

lemma [*simp*]:{.*As. length* (*VarFB* (*Parallel-list As*)) = *w*.} (*TranslateHBDRec x*) *y* $\Longrightarrow$ [. − (λ*As. internal As* $\neq$ {}) .] *x y*

lemma *internal-fb-less-step*: *loop-free As* $\Longrightarrow$ *Type-OK As* $\Longrightarrow$ *A* $\in$ *set As* $\Longrightarrow$ *out A* $\in$ *internal As* $\Longrightarrow$ *internal* (*fb-less-step A* (*As* $\ominus$ [*A*])) = *internal As* − {*out A*}

lemma *ok-fbless-fb-less-step*: *ok-fbless As* $\Longrightarrow$ *A* $\in$ *set As* $\Longrightarrow$ *out A* $\in$ *internal As* $\Longrightarrow$ *ok-fbless* (*fb-less-step A* (*As* $\ominus$ [*A*]))

lemma *map-CompA-fb-out-less-step*: *Deterministic As* $\Longrightarrow$
loop-free As $\Longrightarrow$
Type-OK As $\Longrightarrow$ *A* $\in$ *set As* $\Longrightarrow$ *out A* $\in$ *internal As* $\Longrightarrow$ *map* (*CompA A*) (*As* $\ominus$ [*A*]) = *fb-out-less-step* (*out A*) *As*

lemma *length-diff*: *a* $\in$ *set x* $\Longrightarrow$ *length* (*x* $\ominus$ [*a*]) < *length x*

thm *perm-cons*

lemma *perm-cons-a*: $\bigwedge$ *y* . *a* $\in$ *set x* $\Longrightarrow$ *distinct x* $\Longrightarrow$ *perm* (*x* $\ominus$ [*a*]) *y* $\Longrightarrow$ *perm x* (*a* # *y*)

lemma [*simp*]: {.*As*. *length* (*VarFB* (*Parallel-list As*)) = *w*.} (*TranslateHBDRec x*) *y* $\Longrightarrow$
[. λ*As*. *internal As* $\neq$ {} .]
([:*As*$\rightsquigarrow$*As'*.$\exists$ *A*. *A* $\in$ *set As* $\wedge$ *out A* $\in$ *internal As* $\wedge$ *As'* = *map* (*CompA A*) (*As* $\ominus$ [*A*]):]
({.*As*. *length* (*VarFB* (*Parallel-list As*)) < *w*.} (*TranslateHBDRec x*))) *y*

lemma *Feedbackless-Rec-While-refinement*: *TranslateHBDRec* $\leq$ *WhileFeedbackless*

lemma [*simp*]: *TranslateHBDRec o* [−(λ *As* . *Parallel-list As*)−] $\leq$ *TranslateHBDFeedbackless*

thm *FB-fb-less*(*1*)

lemma *Out-Parallel-fb-less*: $\bigwedge$ *As* . *Type-OK As* $\Longrightarrow$ *loop-free As* $\Longrightarrow$ *distinct L* $\Longrightarrow$ *set L* $\subseteq$ *internal As* $\Longrightarrow$
Out (*Parallel-list* (*fb-less L As*)) = *concat* (*map Out As*) $\ominus$ *L*

lemma *io-diagram-distinct-VarFB*: *io-diagram A* $\Longrightarrow$ *distinct* (*VarFB A*)

theorem *fbless-correctness*: *ok-fbless As* $\Longrightarrow$ *perm* (*VarFB* (*Parallel-list As*)) *L* $\Longrightarrow$
in-equiv (*FB* (*Parallel-list As*)) (*Parallel-list* (*fb-less L As*))

lemma *Hoare-TranslateHBDRec*: *Hoare* (λ *As* . *As* = *As-init* $\wedge$ *ok-fbless As*)
(*TranslateHBDRec o* [−(λ *As* . *Parallel-list As*)−])
(λ *A* . *in-equiv* (*FB* (*Parallel-list As-init*)) *A*)

theorem *TranslateHBDFeedbacklessCorrectness*: *Hoare* (λ *As* . *As* = *As-init* $\wedge$ *ok-fbless As*)
TranslateHBDFeedbackless
(λ *A* . *in-equiv* (*FB* (*Parallel-list As-init*)) *A*)

end

end

9.7 Constructive Functions

theory *Constructive* **imports** *Main*
begin

notation

bot (⊥) **and**
top (⊤) **and**
inf (**infixl** ⊓ *70*)
and *sup* (**infixl** ⊔ *65*)

class *order-bot-max* = *order-bot* +
fixes *maximal* :: *'a* ⇒ *bool*
assumes *maximal-def*: *maximal x* = (∀ *y* . ¬ *x* < *y*)
assumes [*simp*]: ¬ *maximal* ⊥
begin
lemma *ex-not-le-bot*[*simp*]: ∃ *a*. ¬ *a* ≤ ⊥
end

instantiation *option* :: (*type*) *order-bot-max*
begin
definition *bot-option-def*: (⊥::*'a option*) = *None*
definition *le-option-def*: ((*x*::*'a option*) ≤ *y*) = (*x* = *None* ∨ *x* = *y*)
definition *less-option-def*: ((*x*::*'a option*) < *y*) = (*x* ≤ *y* ∧ ¬ (*y* ≤ *x*))
definition *maximal-option-def*: *maximal* (*x*::*'a option*) = (∀ *y* . ¬ *x* < *y*)

instance

lemma [*simp*]: *None* ≤ *x*
end

context *order-bot*
begin
definition *is-lfp f x* = ((*f x* = *x*) ∧ (∀ *y* . *f y* = *y* ⟶ *x* ≤ *y*))
definition *emono f* = (∀ *x y*. *x* ≤ *y* ⟶ *f x* ≤ *f y*)

definition *Lfp f* = *Eps* (*is-lfp f*)

lemma *lfp-unique*: *is-lfp f x* ⟹ *is-lfp f y* ⟹ *x* = *y*

lemma *lfp-exists*: *is-lfp f x* ⟹ *Lfp f* = *x*

lemma *emono-a*: *emono f* ⟹ *x* ≤ *y* ⟹ *f x* ≤ *f y*

lemma *emono-fix*: *emono f* ⟹ *f y* = *y* ⟹ (*f* ^^ *n*) ⊥ ≤ *y*

lemma *emono-is-lfp*: *emono* (*f*::*'a* ⇒ *'a*) ⟹ (*f* ^^ (*n* + *1*)) ⊥ = (*f* ^^ *n*) ⊥ ⟹ *is-lfp f* ((*f* ^^ *n*) ⊥)

lemma *emono-lfp-bot*: *emono* (*f*::*'a* ⇒ *'a*) ⟹ (*f* ^^ (*n* + *1*)) ⊥ = (*f* ^^ *n*) ⊥ ⟹ *Lfp f* = ((*f* ^^ *n*) ⊥)

lemma *emono-up*: *emono f* ⟹ (*f* ^^ *n*) ⊥ ≤ (*f* ^^ (*Suc n*)) ⊥
end

context *order*
begin
definition *min-set A* = (*SOME n* . *n* ∈ *A* ∧ (∀ *x* ∈ *A* . *n* ≤ *x*))
end

lemma *min-nonempty-nat-set-aux*: $\forall\ A\ .\ (n{::}nat) \in A \longrightarrow (\exists\ k \in A\ .\ (\forall\ x \in A\ .\ k \leq x))$

lemma *min-nonempty-nat-set*: $(n{::}nat) \in A \Longrightarrow (\exists\ k\ .\ k \in A \wedge (\forall\ x \in A\ .\ k \leq x))$

thm *someI-ex*

lemma *min-set-nat-aux*: $(n{::}nat) \in A \Longrightarrow min\text{-}set\ A \in A \wedge (\forall\ x \in A\ .\ min\text{-}set\ A \leq x)$

lemma $(n{::}nat) \in A \Longrightarrow min\text{-}set\ A \in A \wedge min\text{-}set\ A \leq n$

lemma *min-set-in*: $(n{::}nat) \in A \Longrightarrow min\text{-}set\ A \in A$

lemma *min-set-less*: $(n{::}nat) \in A \Longrightarrow min\text{-}set\ A \leq n$

definition *mono-a* $f = (\forall\ a\ b\ a'\ b'.\ (a{::}'a{::}order) \leq a' \wedge (b{::}'b{::}order) \leq b' \longrightarrow f\ a\ b \leq f\ a'\ b')$

class *fin-cpo* = *order-bot-max* +

assumes *fin-up-chain*: $(\forall\ i{::}\ nat\ .\ a\ i \leq a\ (Suc\ i)) \Longrightarrow \exists\ n\ .\ \forall\ i \geq n\ .\ a\ i = a\ n$
begin
lemma *emono-ex-lfp*: $emono\ f \Longrightarrow \exists\ n\ .\ is\text{-}lfp\ f\ ((f\ \hat{}\hat{}\ n)\ \bot)$

lemma *emono-lfp*: $emono\ f \Longrightarrow \exists\ n\ .\ Lfp\ f = (f\ \hat{}\hat{}\ n)\ \bot$

lemma *emono-is-lfp*: $emono\ f \Longrightarrow is\text{-}lfp\ f\ (Lfp\ f)$

definition *lfp-index* $(f{::}'a \Rightarrow 'a) = min\text{-}set\ \{n\ .\ (f\ \hat{}\hat{}\ n)\ \bot = (f\ \hat{}\hat{}\ (n + 1))\ \bot\}$

lemma *lfp-index-aux*: $emono\ f \Longrightarrow (\forall\ i < (lfp\text{-}index\ f)\ .\ (f\ \hat{}\hat{}\ i)\ \bot < (f\ \hat{}\hat{}\ (i + 1))\ \bot) \wedge (f\ \hat{}\hat{}\ (lfp\text{-}index\ f))\ \bot = (f\ \hat{}\hat{}\ ((lfp\text{-}index\ f) + 1))\ \bot$

lemma [*simp*]: $emono\ f \Longrightarrow i < lfp\text{-}index\ f \Longrightarrow (f\ \hat{}\hat{}\ i)\ \bot < f\ ((f\ \hat{}\hat{}\ i)\ \bot)$

lemma [*simp*]: $emono\ f \Longrightarrow f\ ((f\ \hat{}\hat{}\ (lfp\text{-}index\ f))\ \bot) = (f\ \hat{}\hat{}\ (lfp\text{-}index\ f))\ \bot$

lemma $emono\ f \Longrightarrow Lfp\ f = (f\ \hat{}\hat{}\ lfp\text{-}index\ f)\ \bot$

lemma *AA-aux*: $emono\ f \Longrightarrow (\bigwedge\ b\ .\ b \leq a \Longrightarrow f\ b \leq a) \Longrightarrow (f\ \hat{}\hat{}\ n)\ \bot \leq a$

lemma *AA*: $emono\ f \Longrightarrow (\bigwedge\ b\ .\ b \leq a \Longrightarrow f\ b \leq a) \Longrightarrow Lfp\ f \leq a$

lemma *BB*: $emono\ f \Longrightarrow f\ (Lfp\ f) = Lfp\ f$

lemma *Lfp-mono*: $emono\ f \Longrightarrow emono\ g \Longrightarrow (\bigwedge\ a\ .\ f\ a \leq g\ a) \Longrightarrow Lfp\ f \leq Lfp\ g$

end
declare [[*show-types*]]

lemma [*simp*]: $mono\text{-}a\ f \Longrightarrow emono\ (f\ a)$

lemma [*simp*]: $mono\text{-}a\ f \Longrightarrow emono\ (\lambda\ a\ .\ f\ a\ b)$

lemma *mono-aD*: $mono\text{-}a\ f \Longrightarrow a \leq a' \Longrightarrow b \leq b' \Longrightarrow f\ a\ b \leq f\ a'\ b'$

lemma [*simp*]: $mono\text{-}a\ (f{::}'a{::}fin\text{-}cpo \Rightarrow 'b{::}fin\text{-}cpo \Rightarrow 'b) \Longrightarrow mono\text{-}a\ g \Longrightarrow emono\ (\lambda b.\ f\ (Lfp\ (g\ b))\ b)$

lemma *CCC*: $mono\text{-}a\ \ (f{::}'a{::}fin\text{-}cpo \Rightarrow 'b{::}fin\text{-}cpo \Rightarrow 'b) \Longrightarrow mono\text{-}a\ g \Longrightarrow Lfp\ (\lambda a.\ g\ (Lfp\ (f\ a))\ a) \leq Lfp\ (g\ (Lfp\ (\lambda b.\ f\ (Lfp\ (g\ b))\ b)))$

lemma *Lfp-commute*: $mono\text{-}a\ (f{::}'a{::}fin\text{-}cpo \Rightarrow 'b{::}fin\text{-}cpo \Rightarrow 'b{::}fin\text{-}cpo) \Longrightarrow mono\text{-}a\ g \Longrightarrow Lfp\ (\lambda\ b\ .\ f\ \ (Lfp\ (\lambda\ a\ .\ (g\ (Lfp\ (f\ a)))\ a))\ b) = Lfp\ (\lambda\ b\ .\ f\ \ (Lfp\ (g\ b))\ b)$

instantiation *option* :: (*type*) *fin-cpo*
begin
lemma *fin-up-non-bot*: $(\forall\ \ i\ .\ (a{::}nat \Rightarrow 'a\ option)\ i \leq a\ (Suc\ i)) \Longrightarrow a\ n \neq \bot \Longrightarrow n \leq i \Longrightarrow a\ i = a\ n$

lemma *fin-up-chain-option*: $(\forall\ \ i{::}\ nat\ .\ (a{::}nat \Rightarrow 'a\ option)\ i \leq a\ (Suc\ i)) \Longrightarrow \exists\ \ n\ .\ \forall\ \ i \geq n\ .\ a\ i = a\ n$

instance
end

instantiation *prod* :: (*order-bot-max*, *order-bot-max*) *order-bot-max*
begin
definition *bot-prod-def*: $(\bot\ ::\ 'a \times 'b) = (\bot,\ \bot)$
definition *le-prod-def*: $(x \leq y) = (fst\ x \leq fst\ y \wedge snd\ x \leq snd\ y)$
definition *less-prod-def*: $((x{::}'a{\times}'b) < y) = (x \leq y \wedge \neg\ (y \leq x))$
definition *maximal-prod-def*: $maximal\ (x{::}'a \times 'b) = (\forall\ \ y\ .\ \neg\ x < y)$

instance
end

instantiation *prod* :: (*fin-cpo*, *fin-cpo*) *fin-cpo*
begin

lemma *fin-up-chain-prod*: $(\forall\ \ i{::}\ nat\ .\ (a{::}nat \Rightarrow 'a \times 'b)\ i \leq a\ (Suc\ i)) \Longrightarrow \exists\ \ n\ .\ \forall\ \ i \geq n\ .\ a\ i = a\ n$
instance
end

end

9.8 Constructive Functions are a Model of the HBD Algebra

theory *ConsFuncHBDModel* **imports** *ExtendedHBDAlgebra Constructive*
begin

datatype *Types* = *int* | *bool* | *nat*

datatype *Values* = *Inte* (*integer* : *int option*) | *Bool* (*boolean*: *bool option*) | *Nat* (*natural*: *nat option*)

primrec *tv* :: *Values* ⇒ *Types* **where**
tv (*Inte i*) = *int* |
tv (*Bool b*) = *bool* |

$tv\ (Nat\ n) = nat$

primrec $tp :: Values\ list \Rightarrow Types\ list$ **where**
$tp\ [] = []\ |$
$tp\ (a\ \#\ v) = tv\ a\ \#\ tp\ v$

fun $le\text{-}val :: Values \Rightarrow Values \Rightarrow bool$ **where**
$(le\text{-}val\ (Inte\ v)\ (Inte\ u)) = (v \le u)\ |$
$(le\text{-}val\ (Bool\ v)\ (Bool\ u)) = (v \le u)\ |$
$(le\text{-}val\ (Nat\ v)\ (Nat\ u)) = (v \le u)\ |$
$le\text{-}val\ \text{-}\ \text{-} = False$

instantiation $Values :: order$
begin
definition $le\text{-}Values\text{-}def$: $((v{::}Values) \le u) = le\text{-}val\ v\ u$
definition $less\text{-}Values\text{-}def$: $((v{::}Values) < u) = (v \le u \wedge \neg\ u \le v)$
instance
end

fun $le\text{-}list :: 'a{::}order\ list \Rightarrow 'a{::}order\ list \Rightarrow bool$ **where**
$le\text{-}list\ []\ [] = True\ |$
$le\text{-}list\ (a\ \#\ x)\ (b\ \#\ y) = (a \le b \wedge le\text{-}list\ x\ y)\ |$
$le\text{-}list\ \text{-}\ \text{-} = False$

instantiation $list :: (order)\ order$
begin
definition $le\text{-}list\text{-}def$: $((v{::}'a\ list) \le u) = le\text{-}list\ u\ v$
definition $less\text{-}list\text{-}def$: $((v{::}'a\ list) < u) = (v \le u \wedge \neg\ u \le v)$
instance
end

lemma [$simp$]: $mono\ integer$

lemma [$simp$]: $mono\ boolean$

lemma [$simp$]: $mono\ natural$

definition $has\text{-}in\text{-}type\ x = \{f\ .\ (dom\ f = \{v\ .\ tp\ v = x\})\}$
definition $has\text{-}out\text{-}type\ x = \{f\ .\ (image\ f\ (dom\ f) \subseteq Some\ `\ \{v\ .\ tp\ v = x\})\}$

definition $has\text{-}in\text{-}out\text{-}type\ x\ y = has\text{-}in\text{-}type\ x \cap has\text{-}out\text{-}type\ y$

definition $ID\text{-}f\ x\ v = (if\ tp\ v = x\ then\ Some\ v\ else\ None)$

lemma [$simp$]: $(tp\ x = []) = (x = [])$

lemma $map\text{-}comp\text{-}type$: $f \in has\text{-}in\text{-}out\text{-}type\ x\ y \Longrightarrow g \in has\text{-}in\text{-}out\text{-}type\ y\ z \Longrightarrow g \circ_m f \in has\text{-}in\text{-}out\text{-}type\ x\ z$

definition $TI\text{-}f\ f = (SOME\ x\ .\ (\exists\ y\ .\ f \in has\text{-}in\text{-}out\text{-}type\ x\ y))$

definition $TO\text{-}f\ f = (SOME\ y\ .\ (\exists\ x\ .\ f \in has\text{-}in\text{-}out\text{-}type\ x\ y))$

fun $pref :: Values\ list \Rightarrow Types\ list \Rightarrow Values\ list$ **where**
$pref\ v\ [] = []\ |$

$pref\ (a \ \# \ v)\ (t \ \# \ x) = (if\ tv\ a = t\ then\ a \ \# \ pref\ v\ x\ else\ undefined) \mid$
$pref\ v\ x = undefined$

fun *suff* :: *Values list* ⇒ *Types list* ⇒ *Values list* **where**
$suff\ v\ [] = v \mid$
$suff\ (a \ \# \ v)\ (t \ \# \ x) = (if\ tv\ a = t\ then\ suff\ v\ x\ else\ undefined) \mid$
$suff\ v\ x = undefined$

lemma *tp-pref-suff*: $\bigwedge x\ y\ .\ tp\ v = x\ @\ y \Longrightarrow tp\ (pref\ v\ x) = x \wedge tp\ (suff\ v\ x) = y$

definition $par\text{-}f\ f\ g\ v = (if\ tp\ v = (TI\text{-}f\ f)\ @\ (TI\text{-}f\ g)\ then\ Some\ (the\ (f\ (pref\ v\ (TI\text{-}f\ f)))\ @\ (the\ (g\ (suff\ v\ (TI\text{-}f\ f)))))\ else\ None)$

fun *some-v*:: *Types list* ⇒ *Values list* **where**
$some\text{-}v\ [] = [] \mid$
$some\text{-}v\ (int \ \# \ x) = (Inte\ undefined) \ \# \ some\text{-}v\ x \mid$
$some\text{-}v\ (bool \ \# \ x) = (Bool\ undefined) \ \# \ some\text{-}v\ x \mid$
$some\text{-}v\ (nat \ \# \ x) = (Nat\ undefined) \ \# \ some\text{-}v\ x$

lemma [*simp*]: $tp\ (some\text{-}v\ x) = x$

lemma *same-in-type*: $f \in has\text{-}in\text{-}type\ x \Longrightarrow f \in has\text{-}in\text{-}type\ y \Longrightarrow x = y$

lemma *same-out-type*: $f \in has\text{-}in\text{-}type\ z \Longrightarrow f \in has\text{-}out\text{-}type\ x \Longrightarrow f \in has\text{-}out\text{-}type\ y \Longrightarrow x = y$

lemma *type-has-type*:
assumes *A*: $f \in has\text{-}in\text{-}out\text{-}type\ x\ y$
shows $TI\text{-}f\ f = x$ **and** $TO\text{-}f\ f = y$

lemma *has-type-out-type*: $f \in has\text{-}in\text{-}out\text{-}type\ x\ y \Longrightarrow tp\ v = x \Longrightarrow tp\ (the\ (f\ v)) = y$

lemma *tp-append*: $tp\ (v\ @\ u) = tp\ v\ @\ tp\ u$

lemma *par-f-type*: $f \in has\text{-}in\text{-}out\text{-}type\ x\ y \Longrightarrow g \in has\text{-}in\text{-}out\text{-}type\ x'\ y' \Longrightarrow par\text{-}f\ f\ g \in has\text{-}in\text{-}out\text{-}type\ (x\ @\ x')\ (y\ @\ y')$

definition $Dup\text{-}f\ x\ v = (if\ tp\ v = x\ then\ Some\ (v\ @\ v)\ else\ None)$

lemma *Dup-has-in-out-type*: $Dup\text{-}f\ x \in has\text{-}in\text{-}out\text{-}type\ x\ (x\ @\ x)$

definition $Sink\text{-}f\ x\ v = (if\ tp\ v = x\ then\ Some\ []\ else\ None)$

lemma *Sink-has-in-out-type*: $Sink\text{-}f\ x \in has\text{-}in\text{-}out\text{-}type\ x\ []$

definition $Switch\text{-}f\ x\ y\ v = (if\ tp\ v = x\ @\ y\ then\ Some\ (suff\ v\ x\ @\ pref\ v\ x)\ else\ None)$

lemma *Switch-has-in-out-type*: $Switch\text{-}f\ x\ y \in has\text{-}in\text{-}out\text{-}type\ (x\ @\ y)\ (y\ @\ x)$

primrec *fb-t* :: *Types* ⇒ (*Values* ⇒ *Values*) ⇒ *Values* **where**
$fb\text{-}t\ int\ f = Inte\ (Lfp\ (\lambda\ a\ .\ integer\ (f\ (Inte\ a)))) \mid$
$fb\text{-}t\ bool\ f = Bool\ (Lfp\ (\lambda\ a\ .\ boolean\ (f\ (Bool\ a)))) \mid$
$fb\text{-}t\ nat\ f = Nat\ \ (Lfp\ (\lambda\ a\ .\ natural\ (f\ (Nat\ a))))$

definition *fb-f f v =* $(if\ tp\ v = tl\ (TI\text{-}f\ f)\ then\ Some\ (tl\ (the\ (f\ ((fb\text{-}t\ (hd\ (TI\text{-}f\ f))\ (\lambda\ a\ .\ hd\ (the\ (f\ (a\ \#\ v)))))\ \#\ v))))\ else\ None)$

thm *le-Values-def*
thm *le-val.simps*

lemma [*simp*]: *mono Inte*

lemma [*simp*]: *mono Bool*

lemma [*simp*]: *mono Nat*

thm *monoE*
thm *monoI*
thm *mono-aD*
lemma [*simp*]: $mono\ A \Longrightarrow mono\ B \Longrightarrow mono\ C \Longrightarrow mono\text{-}a\ f \Longrightarrow mono\text{-}a\ (\lambda a\ b.\ C\ (f\ (A\ a)\ (B\ b)))$

lemma *fb-t-commute*: $mono\text{-}a\ f \Longrightarrow mono\text{-}a\ g$
$\Longrightarrow fb\text{-}t\ t\ \ (\lambda\ b\ .\ f\ (fb\text{-}t\ t'\ (\lambda\ a\ .\ (g\ (fb\text{-}t\ t\ (f\ a)))\ a))\ b) = fb\text{-}t\ t\ (\lambda\ b\ .\ f\ (fb\text{-}t\ t'\ (g\ b))\ b)$

lemma *fb-t-eq-type*: $(\bigwedge\ a\ .\ tv\ a = t \Longrightarrow f\ a = g\ a) \Longrightarrow fb\text{-}t\ t\ f = fb\text{-}t\ t\ g$

lemma [*simp*]: $tv\ (fb\text{-}t\ t\ f) = t$

lemma *has-type-type-in*: $f\ v = Some\ u \Longrightarrow f \in has\text{-}in\text{-}out\text{-}type\ x\ y \Longrightarrow tp\ v = x$

lemma *has-type-type-in-a*: $f\ v = None \Longrightarrow f \in has\text{-}in\text{-}out\text{-}type\ x\ y \Longrightarrow tp\ v \neq x$

lemma *has-type-defined*: $f \in has\text{-}in\text{-}out\text{-}type\ x\ y \Longrightarrow tp\ v = x \Longrightarrow \exists\ u\ .\ f\ v = Some\ u$

lemma *tp-tail*: $tp\ (tl\ x) = tl\ (tp\ x)$

lemma *fb-type*: $f \in has\text{-}in\text{-}out\text{-}type\ (t\ \#\ x)\ (t\ \#\ y) \Longrightarrow fb\text{-}f\ f \in has\text{-}in\text{-}out\text{-}type\ x\ y$

lemma [*simp*]: $TI\text{-}f\ \ (Switch\text{-}f\ x\ y) = x\ @\ y$

lemma *ID-f-type*[*simp*]: $ID\text{-}f\ ts \in has\text{-}in\text{-}out\text{-}type\ ts\ ts$

lemma [*simp*]: $TI\text{-}f\ \ (ID\text{-}f\ ts) = ts$

lemma [*simp*]: $tp\ v = ts \Longrightarrow ID\text{-}f\ ts\ v = Some\ v$

lemma *fb-switch-aux*: $f \in\ has\text{-}in\text{-}out\text{-}type\ (t'\ \#\ t\ \#\ ts)\ (\ t'\ \#\ t\ \#\ ts') \Longrightarrow$
$par\text{-}f\ \ (Switch\text{-}f\ [t']\ [t])\ (ID\text{-}f\ ts') \circ_m (f \circ_m par\text{-}f\ \ (Switch\text{-}f\ [t]\ [t'])\ (ID\text{-}f\ ts)) =$
$(\lambda\ v\ .\ (if\ tp\ v = t\ \#\ t'\ \#\ ts\ then\ case\ v\ of\ a\ \#\ b\ \#\ v' \Rightarrow (case\ f\ \ (b\ \#\ a\ \#\ v')\ of\ Some\ (c\ \#\ d\ \#\ u) \Rightarrow Some\ (d\ \#\ c\ \#\ u))\ else\ None))$

lemma *TI-f-fb-f* [*simp*]: $f \in$ *has-in-out-type* $(t \# ts)$ $(t \# ts')$ $\Longrightarrow$ *TI-f* (*fb-f f*) $= ts$

declare [[*show-types=false*]]

lemma *fb-t-type*: *fb-t t* ($\lambda a.$ *if tv a* $= t$ *then f a else g a*) $=$ *fb-t t f*

lemma *le-values-same-type*: $a \le b \Longrightarrow$ *tv a* $=$ *tv b*

thm *has-type-out-type*

definition *mono-f* $= \{f$. ($\forall$ *x y* . *le-list x y* $\longrightarrow$ *le-list* (*the* (*f x*)) (*the* (*f y*)))$\}$

lemma [*simp*]: *le-list v v*

lemma *le-pref*: $\bigwedge$ *v x* . *le-list u v* $\Longrightarrow$ *le-list* (*pref u x*) (*pref v x*)

lemma *le-suff*: $\bigwedge$ *v x* . *le-list u v* $\Longrightarrow$ *le-list* (*suff u x*) (*suff v x*)

lemma *le-list-append*: $\bigwedge$ *y* . *le-list x y* $\Longrightarrow$ *le-list x' y'* $\Longrightarrow$ *le-list* (x @ x') (y @ y')

thm *monoD*

lemma *mono-fD*: $f \in$ *mono-f* $\Longrightarrow$ *le-list x y* $\Longrightarrow$ *le-list* (*the* (*f x*)) (*the* (*f y*))

lemma *le-values-list-same-type*: $\bigwedge$ (*y*::*Values list*) . *le-list x y* $\Longrightarrow$ *tp x* $=$ *tp y*

lemma *map-comp-mono*: $f \in$ *mono-f* $\Longrightarrow g \in$ *mono-f* $\Longrightarrow$ ($\bigwedge$ *x y* . *tp x* $=$ *tp y* $\Longrightarrow$ *f x* $=$ *None* $\Longrightarrow$ *f y* $=$ *None*) $\Longrightarrow$ ($\bigwedge$ *x y* . *tp x* $=$ *tp y* $\Longrightarrow$ *g x* $=$ *None* $\Longrightarrow$ *g y* $=$ *None*) $\Longrightarrow g \circ_m f \in$ *mono-f*

lemma *par-mono*: $f \in$ *mono-f* $\Longrightarrow g \in$ *mono-f* $\Longrightarrow$ ($\bigwedge$ *x y* . *tp x* $=$ *tp y* $\Longrightarrow$ *f x* $=$ *None* $\Longrightarrow$ *f y* $=$ *None*) $\Longrightarrow$ ($\bigwedge$ *x y* . *tp x* $=$ *tp y* $\Longrightarrow$ *g x* $=$ *None* $\Longrightarrow$ *g y* $=$ *None*) $\Longrightarrow$ *par-f f g* $\in$ *mono-f*

lemma *mono-f-emono*: $f \in$ *mono-f* $\Longrightarrow$ ($\bigwedge$ *x y* . *tp x* $=$ *tp y* $\Longrightarrow$ *f x* $=$ *None* $\Longrightarrow$ *f y* $=$ *None*) $\Longrightarrow$ *mono A* $\Longrightarrow$ *mono B* $\Longrightarrow$ *emono* ($\lambda a.$ *A* (*hd* (*the* (*f* (*B a* $\#$ *x*)))))

lemma *mono-fb-t-aux*: $f \in$ *mono-f* $\Longrightarrow$
le-list x y $\Longrightarrow$ ($\bigwedge$*x y*. *tp x* $=$ *tp y* $\Longrightarrow$ *f x* $=$ *None* $\Longrightarrow$ *f y* $=$ *None*) $\Longrightarrow$ *mono* (*A*::*'a*::*order* $\Rightarrow$ *'b*::*fin-cpo*) $\Longrightarrow$ *mono B*
$\Longrightarrow$ *B* (*Lfp* ($\lambda a.$ *A* (*hd* (*the* (*f* (*B a* $\#$ *x*)))))) $\le$ *B* (*Lfp* ($\lambda a.$ *A* (*hd* (*the* (*f* (*B a* $\#$ *y*))))))

thm *mono-fb-t-aux* [*of f x y integer*]

lemma *mono-fb-f*: $f \in$ *mono-f* $\Longrightarrow$ *le-list x y* $\Longrightarrow$ ($\bigwedge$ *x y* . *tp x* $=$ *tp y* $\Longrightarrow$ *f x* $=$ *None* $\Longrightarrow$ *f y* $=$ *None*)
$\Longrightarrow$ *fb-t* (*hd* (*TI-f f*)) ($\lambda a.$ *hd* (*the* (*f* (*a* $\#$ *x*)))) $\le$ *fb-t* (*hd* (*TI-f f*)) ($\lambda a.$ *hd* (*the* (*f* (*a* $\#$ *y*))))

lemma *fb-mono*: $f \in$ *mono-f* $\Longrightarrow$ ($\bigwedge$ *x y* . *tp x* $=$ *tp y* $\Longrightarrow$ *f x* $=$ *None* $\Longrightarrow$ *f y* $=$ *None*) $\Longrightarrow$ *fb-f f* $\in$ *mono-f*

lemma *mono-f-mono-a*[*simp*]: $f \in$ *mono-f* $\Longrightarrow f \in$ *has-in-out-type* $(t \# t' \# ts)$ $ts' \Longrightarrow$ *tp* $v = ts$ $\Longrightarrow$ *mono-a* $(\lambda a\ b.\ hd\ (the\ (f\ (b \# a \# v))))$

lemma *mono-f-mono-a-b*[*simp*]: $f \in$ *mono-f* $\Longrightarrow f \in$ *has-in-out-type* $(t \# t' \# ts)$ $ts' \Longrightarrow$ *tp* $v = ts$ $\Longrightarrow$ *mono-a* $(\lambda a\ b.\ hd\ (tl\ (the\ (f\ (a \# b \# v)))))$

lemma [*simp*]: *Switch-f* x $y \in$ *mono-f*

lemma [*simp*]: *ID-f* $x \in$ *mono-f*

lemma *has-type-None*: $f \in$ *has-in-out-type* x $y \Longrightarrow$ *tp* $u =$ *tp* $v \Longrightarrow f\ u = None \Longrightarrow f\ v = None$

lemma *fb-f-commute*: $f \in$ *mono-f* $\Longrightarrow f \in$ *has-in-out-type* $(t' \# t \# ts)$ $(t' \# t \# ts') \Longrightarrow$
fb-f (*fb-f* (*par-f* (*Switch-f* $[t']$ $[t]$) (*ID-f* ts') $\circ_m$ (f $\circ_m$ *par-f* (*Switch-f* $[t]$ $[t']$) (*ID-f* ts)))) = (*fb-f* (*fb-f* f))

definition *typed-func* = $(\bigcup\ x\ .\ (\bigcup\ y\ .$ *has-in-out-type* $x\ y)) \cap$ *mono-f*

typedef *func* = *typed-func*

definition *fb-func* f = *Abs-func* (*fb-f* (*Rep-func* f))

definition *TI-func* f = (*TI-f* (*Rep-func* f))
definition *TO-func* f = (*TO-f* (*Rep-func* f))
definition *ID-func* t = *Abs-func* (*ID-f* t)

definition *comp-func* f g = *Abs-func* ((*Rep-func* g) $\circ_m$ (*Rep-func* f))

definition *parallel-func* f g = *Abs-func* (*par-f* (*Rep-func* f) (*Rep-func* g))

definition *Dup-func* x = *Abs-func* (*Dup-f* x)

definition *Sink-func* x = *Abs-func* (*Sink-f* x)
definition *Switch-func* x y = *Abs-func* (*Switch-f* x y)

lemma [*simp*]: *ID-f* $t \in$ *typed-func*

lemma *map-comp-typed-func*[*simp*]: $f \in$ *typed-func* $\Longrightarrow g \in$ *typed-func* $\Longrightarrow$ *TI-f* g = *TO-f* $f \Longrightarrow$ (g $\circ_m$ f) $\in$ *typed-func*

lemma *par-typed-func*[*simp*]: $f \in$ *typed-func* $\Longrightarrow g \in$ *typed-func* $\Longrightarrow$ *par-f* f $g \in$ *typed-func*

lemma *fb-typed-func*[*simp*]: $f \in$ *typed-func* $\Longrightarrow$ *TI-f* $f = t \# x \Longrightarrow$ *TO-f* $f = t \# y \Longrightarrow$ *fb-f* $f \in$ *typed-func*

lemma [*simp*]: *Switch-f* x $y \in$ *typed-func*

lemma [*simp*]: *Dup-f* $x \in$ *mono-f*

lemma [*simp*]: *Dup-f* $x \in$ *typed-func*

lemma [*simp*]: *Sink-f* $x \in$ *mono-f*

lemma [*simp*]: *Sink-f* $x \in$ *typed-func*

thm *Rep-func*
thm *Abs-func-inverse*
thm *Rep-func-inverse*

lemma *map-comp-assoc*: $(f \circ_m g) \circ_m h = f \circ_m (g \circ_m h)$

lemma *map-comp-id*: $f \in$ *has-in-out-type* $x\ y \Longrightarrow (f \circ_m$ *ID-f* $x) = f$

lemma *id-map-comp*: $f \in$ *has-in-out-type* $x\ y \Longrightarrow$ (*ID-f* $y \circ_m f) = f$

lemma [*simp*]: $\bigwedge x\ x'$. *tp* $v = x$ @ x' @ $x'' \Longrightarrow$ *pref* (*pref* v (x @ x')) $x =$ *pref* $v\ x$

lemma [*simp*]: $\bigwedge x\ x'$. *tp* $v = x$ @ x' @ $x'' \Longrightarrow$ *suff* (*pref* v (x @ x')) $x =$ *pref* (*suff* $v\ x$) x'

lemma [*simp*]: $\bigwedge x\ x'$. *tp* $v = x$ @ x' @ $x'' \Longrightarrow$*suff* (*suff* $v\ x$) $x' =$ *suff* v (x @ x')

lemma *par-f-assoc*: $f \in$ *has-in-out-type* $x\ y \Longrightarrow g \in$ *has-in-out-type* $x'\ y' \Longrightarrow h \in$ *has-in-out-type* x'' $y'' \Longrightarrow$
par-f (*par-f* $f\ g$) $h =$ *par-f* f (*par-f* $g\ h$)

lemma $f \in$ *has-in-out-type* $x\ y \Longrightarrow$ *par-f* (*ID-f* []) $f = f$

lemma *id-par-f*: $f \in$ *has-in-out-type* $x\ y \Longrightarrow$ *par-f* (*ID-f* []) $f = f$

lemma [*simp*]: $\bigwedge x$. *tp* $v = x \Longrightarrow$ *pref* $v\ x = v$

lemma [*simp*]: $\bigwedge x$. *tp* $v = x \Longrightarrow$ *suff* $v\ x =$ []

lemma *par-f-id*: $f \in$ *has-in-out-type* $x\ y \Longrightarrow$ *par-f* f (*ID-f* []) $= f$
lemma [*simp*]: $\bigwedge x$. *tp* $v = x$ @ $y \Longrightarrow$ *pref* $v\ x$ @ *suff* $v\ x = v$

lemma [*simp*]: $\bigwedge x$. *tp* $v = x$ @ $x' \Longrightarrow$ *tp* (*pref* $v\ x$) $= x$

lemma [*simp*]: $\bigwedge x$. *tp* $v = x$ @ $x' \Longrightarrow$ *tp* (*suff* $v\ x$) $= x'$

lemma [*simp*]: $\bigwedge x$. *tp* $u = x \Longrightarrow$ *pref* (u @ v) $x = u$

lemma [*simp*]: $\bigwedge x$. *tp* $u = x \Longrightarrow$ *suff* (u @ v) $x = v$

lemma *par-comp-distrib*: $f \in$ *has-in-out-type* $x\ y \Longrightarrow g \in$ *has-in-out-type* $y\ z \Longrightarrow$
$f' \in$ *has-in-out-type* $x'\ y' \Longrightarrow g' \in$ *has-in-out-type* $y'\ z' \Longrightarrow$
par-f $g\ g' \circ_m$ *par-f* $f\ f' =$ (*par-f* ($g \circ_m f$) ($g' \circ_m f'$))

lemma *TI-f-par*: $f \in$ *typed-func* $\Longrightarrow g \in$ *typed-func* $\Longrightarrow$ *TI-f* (*par-f* $f\ g$) $=$ *TI-f* f @ *TI-f* g

lemma *TO-f-par*: $f \in$ *typed-func* $\Longrightarrow g \in$ *typed-func* $\Longrightarrow$ *TO-f* (*par-f* $f\ g$) $=$ *TO-f* f @ *TO-f* g

lemma *TI-f-map-comp*[*simp*]: $f \in$ *typed-func* $\Longrightarrow g \in$ *typed-func* $\Longrightarrow$ *TO-f* $g =$ *TI-f* $f \Longrightarrow$ *TI-f* (f $\circ_m g$) $=$ *TI-f* g

lemma *TO-f-map-comp*[*simp*]: $f \in$ *typed-func* $\Longrightarrow g \in$ *typed-func* $\Longrightarrow$ *TO-f* g = *TI-f* f $\Longrightarrow$ *TO-f* ($f \circ_m g$) = *TO-f* f

lemma [*simp*]: *TI-f* (*Sink-f* *ts*) = *ts*

lemma [*simp*]: *TO-f* (*Sink-f* *ts*) = []

lemma *suff-append*: $\bigwedge$ t . *tp* $x = t \Longrightarrow$ *suff* (x @ y) $t = y$

lemma [*simp*]: *TI-f* (*Dup-f* x) = x

lemma [*simp*]: *TO-f* (*Dup-f* x) = (x @ x)

lemma [*simp*]: *pref* (x @ y) (*tp* x) = x

lemma [*simp*]: *TO-f* (*Switch-f* x y) = (y @ x)

lemma [*simp*]: *TO-f* (*ID-f* x) = x

declare *TO-f-par* [*simp*]

declare *TI-f-par* [*simp*]

lemma [*simp*]: $\bigwedge$ *ts* . *tp* x = *ts* @ *ts*$'$ @ *ts*$''$ $\Longrightarrow$ *pref* (*suff* x *ts*) *ts*$'$ @ *suff* x (*ts* @ *ts*$'$) = *suff* x *ts*

lemma [*simp*]: $\bigwedge$*ts* . *tp* x = *ts* $\Longrightarrow$ *suff* (x @ y) (*ts* @ *ts*$'$) = *suff* y *ts*$'$

lemma *AAA*: S $x \neq$ *None* $\Longrightarrow$ *tv* $a = t \Longrightarrow$ *tp* x = *TI-f* $S \Longrightarrow$ *the* ((*par-f* (*ID-f* [t]) S) (a # x)) = a # *the* (S x)

lemma *AAAb*: S $x \neq$ *None* $\Longrightarrow$ *tv* $a = t \Longrightarrow$ *tp* x = *TI-f* $S \Longrightarrow$ ((*par-f* (*ID-f* [t]) S) (a # x)) = *Some* (a # *the* (S x))

lemma *pref-suff-append*: $\bigwedge$ *ts* . *tp* x = *ts* @ *ts*$'$ $\Longrightarrow$ *pref* x *ts* @ *suff* x *ts* = x

lemma [*simp*]: *Lfp* (λ b. a) = a

lemma [*simp*]: *fb-t* (*tv* a) (λ b . a) = a

interpretation *func*: *BaseOperation* *TI-func* *TO-func* *ID-func* *comp-func* *parallel-func* *Dup-func* *Sink-func* *Switch-func* *fb-func*
end

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