Generalised Reactive Processes in Isabelle/UTP

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Abstract

Hoare and He's UTP theory of reactive processes provides a unifying foundation for the semantics of process calculi and reactive programming. A reactive process is a form of UTP relation which can refer to both state variables and also a trace history of events. In their original presentation, a trace was modelled solely by a discrete sequence of events. Here, we generalise the trace model using "trace algebra", which characterises traces abstractly using cancellative monoids, and thus enables application of the theory to a wider family of computational models, including hybrid computation. We recast the reactive healthiness conditions in this setting, and prove all the associated distributivity laws. We tackle parallel composition of reactive processes using the "parallel-by-merge" scheme from UTP. We also identify the associated theory of "reactive relations", and use it to define generic reactive laws, a Hoare logic, and a weakest precondition calculus.

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1 Reactive Processes Core Definitions

theory *utp-rea-core*
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1.1 Alphabet and Signature

The alphabet of reactive processes contains a boolean variable *wait*, which denotes whether a process is exhibiting an intermediate observation. It also has the variable *tr* which denotes the trace history of a process. The type parameter $'t$ represents the trace model being used, which must form a trace algebra [4], and thus provides the theory of "generalised reactive processes" [4]. The reactive process alphabet also extends the design alphabet, and thus includes the *ok* variable. For more information on these, see the UTP book [5], or the associated tutorial [2].

alphabet $'t$::*trace rp-vars* = *des-vars* +
wait :: *bool*
tr :: $'t$

type-synonym $('t, '\alpha)$ *rp* = $('t, '\alpha)$ *rp-vars-scheme des*

type-synonym $('t,'\alpha,'\beta)$ *rel-rp* = $(('t,'\alpha)$ *rp*, $('t,'\beta)$ *rp*$)$ *urel*
type-synonym $('t,'\alpha)$ *hrel-rp* = $('t,'\alpha)$ *rp hrel*

translations
(*type*) $('t,'\alpha)$ *rp* <= (*type*) $('t, '\alpha)$ *rp-vars-scheme des*
(*type*) $('t,'\alpha)$ *rp* <= (*type*) $('t, '\alpha)$ *rp-vars-ext des*

$(type)\ ('t,'\alpha,'\beta)\ rel\text{-}rp <= (type)\ (('t,'\alpha)\ rp,\ ('\gamma,'\beta)\ rp)\ urel$
$(type)\ ('t,\ '\alpha)\ hrel\text{-}rp <= (type)\ ('t,\ '\alpha)\ rp\ hrel$

As for designs, we set up various types to represent reactive processes. The main types to be used are $('t,\ '\alpha,\ '\beta)$ *rel-rp* and $('t,\ '\alpha)$ *hrel-rp*, which correspond to heterogeneous/homogeneous reactive processes whose trace model is $'t$ and alphabet types are $'\alpha$ and $'\beta$. We also set up some useful syntax translations for these.

notation *rp-vars-child-lens*$_a$ (Σ_r)
notation *rp-vars-child-lens* (Σ_R)

syntax
-svid-rea-alpha :: *svid* (Σ_R)

translations
-svid-rea-alpha => *CONST rp-vars-child-lens*

Lens Σ_R exists because reactive alphabets are extensible. Σ_R points to the portion of the alphabet / state space that is neither *ok*, *wait*, or *tr*.

declare *rp-vars.splits* [*alpha-splits*]
declare *rp-vars.defs* [*lens-defs*]
declare *zero-list-def* [*upred-defs*]
declare *plus-list-def* [*upred-defs*]
declare *prefixE* [*elim*]

The two locale interpretations below are a technicality to improve automatic proof support via the predicate and relational tactics. This is to enable the (re-)interpretation of state spaces to remove any occurrences of lens types after the proof tactics *pred-simp* and *rel-simp*, or any of their derivatives have been applied. Eventually, it would be desirable to automate both interpretations as part of a custom outer command for defining alphabets.

interpretation *rp-vars*:
lens-interp $\lambda(ok,\ r).\ (ok,\ wait_v\ r,\ tr_v\ r,\ more\ r)$
apply (*unfold-locales*)
apply (*rule injI*)
apply (*clarsimp*)
done

interpretation *rp-vars-rel*: *lens-interp* $\lambda(ok,\ ok',\ r,\ r').$
$(ok,\ ok',\ wait_v\ r,\ wait_v\ r',\ tr_v\ r,\ tr_v\ r',\ more\ r,\ more\ r')$
apply (*unfold-locales*)
apply (*rule injI*)
apply (*clarsimp*)
done

abbreviation $wait\text{-}f::('t::trace,\ '\alpha,\ '\beta)\ rel\text{-}rp \Rightarrow ('t,\ '\alpha,\ '\beta)\ rel\text{-}rp$
where $wait\text{-}f\ R \equiv R[\![false/\$wait]\!]$

abbreviation $wait\text{-}t::('t::trace,\ '\alpha,\ '\beta)\ rel\text{-}rp \Rightarrow ('t,\ '\alpha,\ '\beta)\ rel\text{-}rp$
where $wait\text{-}t\ R \equiv R[\![true/\$wait]\!]$

syntax
-wait-f :: *logic* $\Rightarrow$ *logic* $(\text{-}_f\ [1000]\ 1000)$
-wait-t :: *logic* $\Rightarrow$ *logic* $(\text{-}_t\ [1000]\ 1000)$

translations

$P\ _f \rightleftharpoons CONST\ usubst\ (CONST\ subst\text{-}upd\ CONST\ id\ (CONST\ ivar\ CONST\ wait)\ false)\ P$
$P\ _t \rightleftharpoons CONST\ usubst\ (CONST\ subst\text{-}upd\ CONST\ id\ (CONST\ ivar\ CONST\ wait)\ true)\ P$

abbreviation *lift-rea* :: - $\Rightarrow$ - ($\lceil\text{-}\rceil_R$) **where**
$\lceil P\rceil_R \equiv P \oplus_p (\Sigma_R \times_L \Sigma_R)$

abbreviation *drop-rea* :: $('t{::}trace, '\alpha, '\beta)\ rel\text{-}rp \Rightarrow ('\alpha, '\beta)\ urel$ ($\lfloor\text{-}\rfloor_R$) **where**
$\lfloor P\rfloor_R \equiv P \restriction_e (\Sigma_R \times_L \Sigma_R)$

abbreviation *rea-pre-lift* :: - $\Rightarrow$ - ($\lceil\text{-}\rceil_{R<}$) **where** $\lceil n\rceil_{R<} \equiv \lceil\lceil n\rceil_<\rceil_R$

1.2 Reactive Lemmas

lemma *unrest-ok-lift-rea* [*unrest*]:
$\$ok \sharp \lceil P\rceil_R\ \$ok' \sharp \lceil P\rceil_R$
by (*pred-auto*)+

lemma *unrest-wait-lift-rea* [*unrest*]:
$\$wait \sharp \lceil P\rceil_R\ \$wait' \sharp \lceil P\rceil_R$
by (*pred-auto*)+

lemma *unrest-tr-lift-rea* [*unrest*]:
$\$tr \sharp \lceil P\rceil_R\ \$tr' \sharp \lceil P\rceil_R$
by (*pred-auto*)+

lemma *wait-tr-bij-lemma*: *bij-lens* $(wait_a +_L tr_a +_L \Sigma_r)$
by (*unfold-locales*, *auto simp add*: *lens-defs*)

lemma *des-lens-equiv-wait-tr-rest*: $\Sigma_D \approx_L wait +_L tr +_L \Sigma_R$
proof −
have $wait +_L tr +_L \Sigma_R = (wait_a +_L tr_a +_L \Sigma_r) ;_L \Sigma_D$
by (*simp add*: *plus-lens-distr wait-def tr-def rp-vars-child-lens-def*)
also have ... $\approx_L 1_L ;_L \Sigma_D$
using *lens-equiv-via-bij wait-tr-bij-lemma* **by** *auto*
also have ... $= \Sigma_D$
by (*simp*)
finally show *?thesis*
using *lens-equiv-sym* **by** *blast*
qed

lemma *rea-lens-bij*: *bij-lens* $(ok +_L wait +_L tr +_L \Sigma_R)$
proof −
have $ok +_L wait +_L tr +_L \Sigma_R \approx_L ok +_L \Sigma_D$
using *des-lens-equiv-wait-tr-rest des-vars-indeps lens-equiv-sym lens-plus-eq-right* **by** *blast*
also have ... $\approx_L 1_L$
using *bij-lens-equiv-id*[*of* $ok +_L \Sigma_D$] **by** (*simp add*: *ok-des-bij-lens*)
finally show *?thesis*
by (*simp add*: *bij-lens-equiv-id*)
qed

lemma *seqr-wait-true* [*usubst*]: $(P ;; Q)\ _t = (P\ _t ;; Q)$
by (*rel-auto*)

lemma *seqr-wait-false* [*usubst*]: $(P ;; Q)\ _f = (P\ _f ;; Q)$
by (*rel-auto*)

1.3 Trace contribution lens

The following lens represents the portion of the state-space that is the difference between tr' and tr, that is the contribution that a process is making to the trace history.

definition *tcontr* :: *'t::trace* $\Longrightarrow$ *('t, 'α) rp* × *('t, 'α) rp* (*tt*) **where**
  [*lens-defs*]:
  tcontr = ⦇ *lens-get* = (λ *s*. $get_{(\$tr')_v}$ *s* − $get_{(\$tr)_v}$ *s*) ,
      lens-put = (λ *s v*. $put_{(\$tr')_v}$ *s* ($get_{(\$tr)_v}$ *s* + *v*)) ⦈

definition *itrace* :: *'t::trace* $\Longrightarrow$ *('t, 'α) rp* × *('t, 'α) rp* (**it**) **where**
  [*lens-defs*]:
  itrace = ⦇ *lens-get* = $get_{(\$tr)_v}$,
      lens-put = (λ *s v*. $put_{(\$tr')_v}$ ($put_{(\$tr)_v}$ *s v*) *v*) ⦈

lemma *tcontr-mwb-lens* [*simp*]: *mwb-lens tt*
  by (*unfold-locales*, *simp-all add*: *lens-defs prod.case-eq-if*)

lemma *itrace-mwb-lens* [*simp*]: *mwb-lens* **it**
  by (*unfold-locales*, *simp-all add*: *lens-defs prod.case-eq-if*)

syntax
  -svid-tcontr :: *svid* (*tt*)
  -svid-itrace :: *svid* (**it**)

translations
  -svid-tcontr == *CONST tcontr*
  -svid-itrace == *CONST itrace*

lemma *tcontr-alt-def*: &*tt* = (\$*tr*´ − \$*tr*)
  by (*rel-auto*)

lemma *tcontr-alt-def'*: *utp-expr.var tt* = (\$*tr*´ − \$*tr*)
  by (*rel-auto*)

lemma *tt-indeps* [*simp*]:
  assumes $x \bowtie (\$tr)_v$ $x \bowtie (\$tr')_v$
  shows $x \bowtie tt$ $tt \bowtie x$
  using *assms*
  by (*unfold lens-indep-def*, *safe*, *simp-all add*: *tcontr-def*, (*metis lens-indep-get var-update-out*)+)

end

2 Reactive Healthiness Conditions

theory *utp-rea-healths*
  imports *utp-rea-core*
begin

2.1 R1: Events cannot be undone

definition *R1* :: (*'t::trace*, *'α*, *'β*) *rel-rp* ⇒ (*'t*, *'α*, *'β*) *rel-rp* **where**
R1-def [*upred-defs*]: *R1* (*P*) = (*P* ∧ (\$*tr* $\le_u$ \$*tr*´))

lemma *R1-idem*: *R1*(*R1*(*P*)) = *R1*(*P*)

by *pred-auto*

lemma *R1-Idempotent* [*closure*]: *Idempotent R1*
by (*simp add*: *Idempotent-def R1-idem*)

lemma *R1-mono*: $P \sqsubseteq Q \Longrightarrow R1(P) \sqsubseteq R1(Q)$
by *pred-auto*

lemma *R1-Monotonic*: *Monotonic R1*
by (*simp add*: *mono-def R1-mono*)

lemma *R1-Continuous*: *Continuous R1*
by (*auto simp add*: *Continuous-def*, *rel-auto*)

lemma *R1-unrest* [*unrest*]: $[\![x \bowtie \textit{in-var tr}; x \bowtie \textit{out-var tr}; x \sharp P]\!] \Longrightarrow x \sharp R1(P)$
by (*simp add*: *R1-def unrest lens-indep-sym*)

lemma *R1-false*: $R1(\textit{false}) = \textit{false}$
by *pred-auto*

lemma *R1-conj*: $R1(P \wedge Q) = (R1(P) \wedge R1(Q))$
by *pred-auto*

lemma *conj-R1-closed-1* [*closure*]: $P \textit{ is } R1 \Longrightarrow (P \wedge Q) \textit{ is } R1$
by (*rel-blast*)

lemma *conj-R1-closed-2* [*closure*]: $Q \textit{ is } R1 \Longrightarrow (P \wedge Q) \textit{ is } R1$
by (*rel-blast*)

lemma *R1-disj*: $R1(P \vee Q) = (R1(P) \vee R1(Q))$
by *pred-auto*

lemma *disj-R1-closed* [*closure*]: $[\![P \textit{ is } R1; Q \textit{ is } R1]\!] \Longrightarrow (P \vee Q) \textit{ is } R1$
by (*simp add*: *Healthy-def R1-def utp-pred-laws.inf-sup-distrib2*)

lemma *R1-impl*: $R1(P \Rightarrow Q) = ((\neg R1(\neg P)) \Rightarrow R1(Q))$
by (*rel-auto*)

lemma *R1-inf*: $R1(P \sqcap Q) = (R1(P) \sqcap R1(Q))$
by *pred-auto*

lemma *R1-USUP*:
$R1(\bigsqcap i \in A \cdot P(i)) = (\bigsqcap i \in A \cdot R1(P(i)))$
by (*rel-auto*)

lemma *R1-Sup* [*closure*]: $[\![\bigwedge P. P \in A \Longrightarrow P \textit{ is } R1; A \neq \{\}]\!] \Longrightarrow \bigsqcap A \textit{ is } R1$
using *R1-Continuous* **by** (*auto simp add*: *Continuous-def Healthy-def*)

lemma *R1-UINF*:
assumes $A \neq \{\}$
shows $R1(\bigsqcup i \in A \cdot P(i)) = (\bigsqcup i \in A \cdot R1(P(i)))$
using *assms* **by** (*rel-auto*)

lemma *R1-UINF-ind*:
$R1(\bigsqcup i \cdot P(i)) = (\bigsqcup i \cdot R1(P(i)))$

by (*rel-auto*)

lemma *UINF-ind-R1-closed* [*closure*]:
$[\![\bigwedge i.\ P(i)\ is\ R1\ ]\!] \Longrightarrow (\prod\ i \cdot P(i))\ is\ R1$
by (*rel-blast*)

lemma *UINF-R1-closed* [*closure*]:
$[\![\bigwedge i.\ P\ i\ is\ R1\ ]\!] \Longrightarrow (\prod\ i \in A \cdot P\ i)\ is\ R1$
by (*rel-blast*)

lemma *tr-ext-conj-R1* [*closure*]:
$\$tr\acute{} =_u \$tr\ \hat{}_u\ e \wedge P\ is\ R1$
by (*rel-auto*, *simp add*: *Prefix-Order.prefixI*)

lemma *tr-id-conj-R1* [*closure*]:
$\$tr\acute{} =_u \$tr \wedge P\ is\ R1$
by (*rel-auto*)

lemma *R1-extend-conj*: $R1(P \wedge Q) = (R1(P) \wedge Q)$
by *pred-auto*

lemma *R1-extend-conj'*: $R1(P \wedge Q) = (P \wedge R1(Q))$
by *pred-auto*

lemma *R1-cond*: $R1(P \triangleleft b \triangleright Q) = (R1(P) \triangleleft b \triangleright R1(Q))$
by (*rel-auto*)

lemma *R1-cond'*: $R1(P \triangleleft b \triangleright Q) = (R1(P) \triangleleft R1(b) \triangleright R1(Q))$
by (*rel-auto*)

lemma *R1-negate-R1*: $R1(\neg R1(P)) = R1(\neg P)$
by *pred-auto*

lemma *R1-wait-true* [*usubst*]: $(R1\ P)_t = R1(P)_t$
by *pred-auto*

lemma *R1-wait-false* [*usubst*]: $(R1\ P)\ _f = R1(P)\ _f$
by *pred-auto*

lemma *R1-wait'-true* [*usubst*]: $(R1\ P)[\![true/\$wait\acute{}]\!] = R1(P[\![true/\$wait\acute{}]\!])$
by (*rel-auto*)

lemma *R1-wait'-false* [*usubst*]: $(R1\ P)[\![false/\$wait\acute{}]\!] = R1(P[\![false/\$wait\acute{}]\!])$
by (*rel-auto*)

lemma *R1-wait-false-closed* [*closure*]: $P\ is\ R1 \Longrightarrow P[\![false/\$wait]\!]\ is\ R1$
by (*rel-auto*)

lemma *R1-wait'-false-closed* [*closure*]: $P\ is\ R1 \Longrightarrow P[\![false/\$wait\acute{}]\!]\ is\ R1$
by (*rel-auto*)

lemma *R1-skip*: $R1(II) = II$
by (*rel-auto*)

lemma *skip-is-R1* [*closure*]: $II\ is\ R1$

by (*rel-auto*)

lemma *subst-R1*: $[\![$ $\$tr \sharp \sigma$; $\$tr' \sharp \sigma$ $]\!] \Longrightarrow \sigma \dagger (R1\ P) = R1(\sigma \dagger P)$
by (*simp add*: *R1-def usubst*)

lemma *subst-R1-closed* [*closure*]: $[\![$ $\$tr \sharp \sigma$; $\$tr' \sharp \sigma$; P *is* $R1$ $]\!] \Longrightarrow \sigma \dagger P$ *is* $R1$
by (*metis Healthy-def subst-R1*)

lemma *R1-by-refinement*:
P *is* $R1 \longleftrightarrow ((\$tr \leq_u \$tr') \sqsubseteq P)$
by (*rel-blast*)

lemma *R1-trace-extension* [*closure*]:
$\$tr' \geq_u \$tr\ \hat{}_u\ e$ *is* $R1$
by (*rel-auto*)

lemma *tr-le-trans*:
$((\$tr \leq_u \$tr')\ ;;\ (\$tr \leq_u \$tr')) = (\$tr \leq_u \$tr')$
by (*rel-auto*)

lemma *R1-seqr*:
$R1(R1(P)\ ;;\ R1(Q)) = (R1(P)\ ;;\ R1(Q))$
by (*rel-auto*)

lemma *R1-seqr-closure* [*closure*]:
assumes P *is* $R1$ Q *is* $R1$
shows $(P\ ;;\ Q)$ *is* $R1$
using *assms* **unfolding** *R1-by-refinement*
by (*metis seqr-mono tr-le-trans*)

lemma *R1-power* [*closure*]: P *is* $R1 \Longrightarrow P\hat{}n$ *is* $R1$
by (*induct n*, *simp-all add*: *upred-semiring.power-Suc closure*)

lemma *R1-true-comp* [*simp*]: $(R1(true)\ ;;\ R1(true)) = R1(true)$
by (*rel-auto*)

lemma *R1-ok'-true*: $(R1(P))^t = R1(P^t)$
by *pred-auto*

lemma *R1-ok'-false*: $(R1(P))^f = R1(P^f)$
by *pred-auto*

lemma *R1-ok-true*: $(R1(P))[\![true/\$ok]\!] = R1(P[\![true/\$ok]\!])$
by *pred-auto*

lemma *R1-ok-false*: $(R1(P))[\![false/\$ok]\!] = R1(P[\![false/\$ok]\!])$
by *pred-auto*

lemma *seqr-R1-true-right*: $((P\ ;;\ R1(true)) \vee P) = (P\ ;;\ (\$tr \leq_u \$tr'))$
by (*rel-auto*)

lemma *conj-R1-true-right*: $(P;;R1(true) \wedge Q;;R1(true))\ ;;\ R1(true) = (P;;R1(true) \wedge Q;;R1(true))$
apply (*rel-auto*) **using** *dual-order.trans* **by** *blast+*

lemma *R1-extend-conj-unrest*: $[\![$ $\$tr \sharp Q$; $\$tr' \sharp Q$ $]\!] \Longrightarrow R1(P \wedge Q) = (R1(P) \wedge Q)$

by *pred-auto*

lemma *R1-extend-conj-unrest'*: ⟦ $\$tr \sharp P$; $\$tr' \sharp P$ ⟧ $\Longrightarrow$ $R1(P \wedge Q) = (P \wedge R1(Q))$
by *pred-auto*

lemma *R1-tr'-eq-tr*: $R1(\$tr' =_u \$tr) = (\$tr' =_u \$tr)$
by (*rel-auto*)

lemma *R1-tr-less-tr'*: $R1(\$tr <_u \$tr') = (\$tr <_u \$tr')$
by (*rel-auto*)

lemma *tr-strict-prefix-R1-closed* [*closure*]: $\$tr <_u \$tr'$ *is R1*
by (*rel-auto*)

lemma *R1-H2-commute*: $R1(H2(P)) = H2(R1(P))$
by (*simp add*: *H2-split R1-def usubst*, *rel-auto*)

2.2 R2: No dependence upon trace history

There are various ways of expressing $R2$, which are enumerated below.

definition *R2a* :: ('t::*trace*, 'α, 'β) *rel-rp* ⇒ ('t,'α,'β) *rel-rp* **where**
[*upred-defs*]: $R2a\ (P) = (\bigsqcap\ s \cdot P⟦«s»,(«s»+(\$tr'-\$tr))/\$tr,\$tr'⟧)$

definition *R2a'* :: ('t::*trace*, 'α, 'β) *rel-rp* ⇒ ('t,'α,'β) *rel-rp* **where**
[*upred-defs*]: $R2a'\ P = (R2a(P) \triangleleft R1(true) \triangleright P)$

definition *R2s* :: ('t::*trace*, 'α, 'β) *rel-rp* ⇒ ('t,'α,'β) *rel-rp* **where**
[*upred-defs*]: $R2s\ (P) = (P⟦0/\$tr⟧⟦(\$tr'-\$tr)/\$tr'⟧)$

definition *R2* :: ('t::*trace*, 'α, 'β) *rel-rp* ⇒ ('t, 'α, 'β) *rel-rp* **where**
[*upred-defs*]: $R2(P) = R1(R2s(P))$

definition *R2c* :: ('t::*trace*, 'α, 'β) *rel-rp* ⇒ ('t, 'α, 'β) *rel-rp* **where**
[*upred-defs*]: $R2c(P) = (R2s(P) \triangleleft R1(true) \triangleright P)$

R2a and *R2s* are the standard definitions from the UTP book [5]. An issue with these forms is that their definition depends upon *R1* also being satisfied [4], since otherwise the trace minus operator is not well defined. We overcome this with our own version, *R2c*, which applies *R2s* if *R1* holds, and otherwise has no effect. This latter healthiness condition can therefore be reasoned about independently of *R1*, which is useful in some circumstances.

lemma *unrest-ok-R2s* [*unrest*]: $\$ok \sharp P \Longrightarrow \$ok \sharp R2s(P)$
by (*simp add*: *R2s-def unrest*)

lemma *unrest-ok'-R2s* [*unrest*]: $\$ok' \sharp P \Longrightarrow \$ok' \sharp R2s(P)$
by (*simp add*: *R2s-def unrest*)

lemma *unrest-ok-R2c* [*unrest*]: $\$ok \sharp P \Longrightarrow \$ok \sharp R2c(P)$
by (*simp add*: *R2c-def unrest*)

lemma *unrest-ok'-R2c* [*unrest*]: $\$ok' \sharp P \Longrightarrow \$ok' \sharp R2c(P)$
by (*simp add*: *R2c-def unrest*)

lemma *R2s-unrest* [*unrest*]: ⟦ *vwb-lens x*; $x \bowtie$ *in-var tr*; $x \bowtie$ *out-var tr*; $x \sharp P$ ⟧ $\Longrightarrow x \sharp R2s(P)$
by (*simp add*: *R2s-def unrest usubst lens-indep-sym*)

lemma *R2s-subst-wait-true* [*usubst*]:
$(R2s(P))[\![true/\$wait]\!] = R2s(P[\![true/\$wait]\!])$
by (*simp add*: *R2s-def usubst unrest*)

lemma *R2s-subst-wait′-true* [*usubst*]:
$(R2s(P))[\![true/\$wait´]\!] = R2s(P[\![true/\$wait´]\!])$
by (*simp add*: *R2s-def usubst unrest*)

lemma *R2-subst-wait-true* [*usubst*]:
$(R2(P))[\![true/\$wait]\!] = R2(P[\![true/\$wait]\!])$
by (*simp add*: *R2-def R1-def R2s-def usubst unrest*)

lemma *R2-subst-wait′-true* [*usubst*]:
$(R2(P))[\![true/\$wait´]\!] = R2(P[\![true/\$wait´]\!])$
by (*simp add*: *R2-def R1-def R2s-def usubst unrest*)

lemma *R2-subst-wait-false* [*usubst*]:
$(R2(P))[\![false/\$wait]\!] = R2(P[\![false/\$wait]\!])$
by (*simp add*: *R2-def R1-def R2s-def usubst unrest*)

lemma *R2-subst-wait′-false* [*usubst*]:
$(R2(P))[\![false/\$wait´]\!] = R2(P[\![false/\$wait´]\!])$
by (*simp add*: *R2-def R1-def R2s-def usubst unrest*)

lemma *R2c-R2s-absorb*: $R2c(R2s(P)) = R2s(P)$
by (*rel-auto*)

lemma *R2a-R2s*: $R2a(R2s(P)) = R2s(P)$
by (*rel-auto*)

lemma *R2s-R2a*: $R2s(R2a(P)) = R2a(P)$
by (*rel-auto*)

lemma *R2a-equiv-R2s*: P *is* $R2a \longleftrightarrow P$ *is* $R2s$
by (*metis Healthy-def′ R2a-R2s R2s-R2a*)

lemma *R2a-idem*: $R2a(R2a(P)) = R2a(P)$
by (*rel-auto*)

lemma *R2a′-idem*: $R2a'(R2a'(P)) = R2a'(P)$
by (*rel-auto*)

lemma *R2a-mono*: $P \sqsubseteq Q \Longrightarrow R2a(P) \sqsubseteq R2a(Q)$
by (*rel-blast*)

lemma *R2a′-mono*: $P \sqsubseteq Q \Longrightarrow R2a'(P) \sqsubseteq R2a'(Q)$
by (*rel-blast*)

lemma *R2a′-weakening*: $R2a'(P) \sqsubseteq P$
apply (*rel-simp*)
apply (*rename-tac ok wait tr more ok′ wait′ tr′ more′*)
apply (*rule-tac x=tr* **in** *exI*)
apply (*simp add*: *diff-add-cancel-left′*)
done

lemma *R2s-idem*: $R2s(R2s(P)) = R2s(P)$
by (*pred-auto*)

lemma *R2-idem*: $R2(R2(P)) = R2(P)$
by (*pred-auto*)

lemma *R2-mono*: $P \sqsubseteq Q \Longrightarrow R2(P) \sqsubseteq R2(Q)$
by (*pred-auto*)

lemma *R2-implies-R1* [*closure*]: P *is* $R2 \Longrightarrow P$ *is* $R1$
by (*rel-blast*)

lemma *R2c-Continuous*: *Continuous R2c*
by (*rel-simp*)

lemma *R2c-lit*: $R2c(\ll x \gg) = \ll x \gg$
by (*rel-auto*)

lemma *tr-strict-prefix-R2c-closed* [*closure*]: $\$tr <_u \$tr'$ *is* $R2c$
by (*rel-auto*)

lemma *R2s-conj*: $R2s(P \wedge Q) = (R2s(P) \wedge R2s(Q))$
by (*pred-auto*)

lemma *R2-conj*: $R2(P \wedge Q) = (R2(P) \wedge R2(Q))$
by (*pred-auto*)

lemma *R2s-disj*: $R2s(P \vee Q) = (R2s(P) \vee R2s(Q))$
by *pred-auto*

lemma *R2s-USUP*:
$R2s(\bigsqcap\ i \in A \cdot P(i)) = (\bigsqcap\ i \in A \cdot R2s(P(i)))$
by (*simp add*: *R2s-def usubst*)

lemma *R2c-USUP*:
$R2c(\bigsqcap\ i \in A \cdot P(i)) = (\bigsqcap\ i \in A \cdot R2c(P(i)))$
by (*rel-auto*)

lemma *R2s-UINF*:
$R2s(\bigsqcup\ i \in A \cdot P(i)) = (\bigsqcup\ i \in A \cdot R2s(P(i)))$
by (*simp add*: *R2s-def usubst*)

lemma *R2c-UINF*:
$R2c(\bigsqcup\ i \in A \cdot P(i)) = (\bigsqcup\ i \in A \cdot R2c(P(i)))$
by (*rel-auto*)

lemma *R2-disj*: $R2(P \vee Q) = (R2(P) \vee R2(Q))$
by (*pred-auto*)

lemma *R2s-not*: $R2s(\neg\ P) = (\neg\ R2s(P))$
by *pred-auto*

lemma *R2s-condr*: $R2s(P \triangleleft b \triangleright Q) = (R2s(P) \triangleleft R2s(b) \triangleright R2s(Q))$
by (*rel-auto*)

lemma *R2-condr*: $R2(P \triangleleft b \triangleright Q) = (R2(P) \triangleleft R2(b) \triangleright R2(Q))$
by (*rel-auto*)

lemma *R2-condr'*: $R2(P \triangleleft b \triangleright Q) = (R2(P) \triangleleft R2s(b) \triangleright R2(Q))$
by (*rel-auto*)

lemma *R2s-ok*: $R2s(\$ok) = \$ok$
by (*rel-auto*)

lemma *R2s-ok'*: $R2s(\$ok\acute{}) = \$ok\acute{}$
by (*rel-auto*)

lemma *R2s-wait*: $R2s(\$wait) = \$wait$
by (*rel-auto*)

lemma *R2s-wait'*: $R2s(\$wait\acute{}) = \$wait\acute{}$
by (*rel-auto*)

lemma *R2s-true*: $R2s(true) = true$
by *pred-auto*

lemma *R2s-false*: $R2s(false) = false$
by *pred-auto*

lemma *true-is-R2s*:
true is R2s
by (*simp add*: *Healthy-def R2s-true*)

lemma *R2s-lift-rea*: $R2s(\lceil P \rceil_R) = \lceil P \rceil_R$
by (*simp add*: *R2s-def usubst unrest*)

lemma *R2c-lift-rea*: $R2c(\lceil P \rceil_R) = \lceil P \rceil_R$
by (*simp add*: *R2c-def R2s-lift-rea cond-idem usubst unrest*)

lemma *R2c-true*: $R2c(true) = true$
by (*rel-auto*)

lemma *R2c-false*: $R2c(false) = false$
by (*rel-auto*)

lemma *R2c-and*: $R2c(P \wedge Q) = (R2c(P) \wedge R2c(Q))$
by (*rel-auto*)

lemma *conj-R2c-closed* [*closure*]: $[\![P \text{ is } R2c; Q \text{ is } R2c]\!] \Longrightarrow (P \wedge Q) \text{ is } R2c$
by (*simp add*: *Healthy-def R2c-and*)

lemma *R2c-disj*: $R2c(P \vee Q) = (R2c(P) \vee R2c(Q))$
by (*rel-auto*)

lemma *R2c-inf*: $R2c(P \sqcap Q) = (R2c(P) \sqcap R2c(Q))$
by (*rel-auto*)

lemma *R2c-not*: $R2c(\neg P) = (\neg R2c(P))$
by (*rel-auto*)

lemma *R2c-ok*: $R2c(\$ok) = (\$ok)$
  by (*rel-auto*)

lemma *R2c-ok′*: $R2c(\$ok') = (\$ok')$
  by (*rel-auto*)

lemma *R2c-wait*: $R2c(\$wait) = \$wait$
  by (*rel-auto*)

lemma *R2c-wait′*: $R2c(\$wait') = \$wait'$
  by (*rel-auto*)

lemma *R2c-wait′-true* [*usubst*]: $(R2c\ P)[\![true/\$wait']\!] = R2c(P[\![true/\$wait']\!])$
  by (*rel-auto*)

lemma *R2c-wait′-false* [*usubst*]: $(R2c\ P)[\![false/\$wait']\!] = R2c(P[\![false/\$wait']\!])$
  by (*rel-auto*)

lemma *R2c-tr′-minus-tr*: $R2c(\$tr' =_u \$tr) = (\$tr' =_u \$tr)$
  apply (*rel-auto*) **using** *minus-zero-eq* **by** *blast*

lemma *R2c-tr′-ge-tr*: $R2c(\$tr' \geq_u \$tr) = (\$tr' \geq_u \$tr)$
  by (*rel-auto*)

lemma *R2c-tr-less-tr′*: $R2c(\$tr <_u \$tr') = (\$tr <_u \$tr')$
  by (*rel-auto*)

lemma *R2c-condr*: $R2c(P \triangleleft b \triangleright Q) = (R2c(P) \triangleleft R2c(b) \triangleright R2c(Q))$
  by (*rel-auto*)

lemma *R2c-shAll*: $R2c\ (\forall\ x \cdot P\ x) = (\forall\ x \cdot R2c(P\ x))$
  by (*rel-auto*)

lemma *R2c-impl*: $R2c(P \Rightarrow Q) = (R2c(P) \Rightarrow R2c(Q))$
  by (*metis* (*no-types*, *lifting*) *R2c-and R2c-not double-negation impl-alt-def not-conj-deMorgans*)

lemma *R2c-skip-r*: $R2c(II) = II$
proof −
  have $R2c(II) = R2c(\$tr' =_u \$tr \wedge II{\restriction_\alpha}tr)$
    by (*subst skip-r-unfold*[*of tr*], *simp-all*)
  also have ... $= (R2c(\$tr' =_u \$tr) \wedge II{\restriction_\alpha}tr)$
    by (*simp add*: *R2c-and*, *simp add*: *R2c-def R2s-def usubst unrest cond-idem*)
  also have ... $= (\$tr' =_u \$tr \wedge II{\restriction_\alpha}tr)$
    by (*simp add*: *R2c-tr′-minus-tr*)
  finally show *?thesis*
    by (*subst skip-r-unfold*[*of tr*], *simp-all*)
qed

lemma *R1-R2c-commute*: $R1(R2c(P)) = R2c(R1(P))$
  by (*rel-auto*)

lemma *R1-R2c-is-R2*: $R1(R2c(P)) = R2(P)$
  by (*rel-auto*)

lemma *R1-R2s-R2c*: $R1(R2s(P)) = R1(R2c(P))$
  by (*rel-auto*)

lemma *R1-R2s-tr-wait*:
  $R1\ (R2s\ (\$tr\acute{} =_u \$tr \wedge \$wait\acute{})) = (\$tr\acute{} =_u \$tr \wedge \$wait\acute{})$
  apply *rel-auto* **using** *minus-zero-eq* **by** *blast*

lemma *R1-R2s-tr′-eq-tr*:
  $R1\ (R2s\ (\$tr\acute{} =_u \$tr)) = (\$tr\acute{} =_u \$tr)$
  apply (*rel-auto*) **using** *minus-zero-eq* **by** *blast*

lemma *R1-R2s-tr′-extend-tr*:
  $[\![\ \$tr \sharp\ v;\ \$tr\acute{} \sharp\ v\ ]\!] \Longrightarrow R1\ (R2s\ (\$tr\acute{} =_u \$tr\ \hat{}_u\ v)) = (\$tr\acute{} =_u \$tr\ \ \hat{}_u\ v)$
  apply (*rel-auto*)
   apply (*metis append-minus*)
  apply (*simp add*: *Prefix-Order.prefixI*)
  done

lemma *R2-tr-prefix*: $R2(\$tr \leq_u \$tr\acute{}) = (\$tr \leq_u \$tr\acute{})$
  by (*pred-auto*)

lemma *R2-form*:
  $R2(P) = (\exists\ tt_0 \cdot P[\![0/\$tr]\!][\![\ll tt_0\gg/\$tr\acute{}]\!] \wedge \$tr\acute{} =_u \$tr + \ll tt_0\gg)$
  by (*rel-auto*, *metis trace-class.add-diff-cancel-left trace-class.le-iff-add*)

lemma *R2-subst-tr*:
  assumes *P is R2*
  shows $[\$tr \mapsto_s tr_0, \$tr\acute{} \mapsto_s tr_0 + t] \dagger P = [\$tr \mapsto_s 0, \$tr\acute{} \mapsto_s t] \dagger P$
proof −
  have $[\$tr \mapsto_s tr_0, \$tr\acute{} \mapsto_s tr_0 + t] \dagger R2\ P = [\$tr \mapsto_s 0, \$tr\acute{} \mapsto_s t] \dagger R2\ P$
    by (*rel-auto*)
  thus *?thesis*
    by (*simp add*: *Healthy-if assms*)
qed

lemma *R2-seqr-form*:
  shows $(R2(P)\ ;;\ R2(Q)) =$
        $(\exists\ tt_1 \cdot \exists\ tt_2 \cdot ((P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr\acute{}]\!])\ ;;\ (Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr\acute{}]\!]))$
                  $\wedge\ (\$tr\acute{} =_u \$tr + \ll tt_1\gg + \ll tt_2\gg))$
proof −
  have $(R2(P)\ ;;\ R2(Q)) = (\exists\ tr_0 \cdot (R2(P))[\![\ll tr_0\gg/\$tr\acute{}]\!]\ ;;\ (R2(Q))[\![\ll tr_0\gg/\$tr]\!])$
    by (*subst seqr-middle*[*of tr*], *simp-all*)
  also have ... =
      $(\exists\ tr_0 \cdot \exists\ tt_1 \cdot \exists\ tt_2 \cdot ((P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr\acute{}]\!] \wedge \ll tr_0\gg =_u \$tr + \ll tt_1\gg)\ ;;$
                     $(Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr\acute{}]\!] \wedge \$tr\acute{} =_u \ll tr_0\gg + \ll tt_2\gg)))$
    by (*simp add*: *R2-form usubst unrest uquant-lift*, *rel-blast*)
  also have ... =
      $(\exists\ tr_0 \cdot \exists\ tt_1 \cdot \exists\ tt_2 \cdot ((\ll tr_0\gg =_u \$tr + \ll tt_1\gg \wedge P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr\acute{}]\!])\ ;;$
                     $(Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr\acute{}]\!] \wedge \$tr\acute{} =_u \ll tr_0\gg + \ll tt_2\gg)))$
    by (*simp add*: *conj-comm*)
  also have ... =
      $(\exists\ tt_1 \cdot \exists\ tt_2 \cdot \exists\ tr_0 \cdot ((P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr\acute{}]\!])\ ;;\ (Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr\acute{}]\!]))$
                     $\wedge \ll tr_0\gg =_u \$tr + \ll tt_1\gg \wedge \$tr\acute{} =_u \ll tr_0\gg + \ll tt_2\gg)$
    by (*rel-blast*)
  also have ... =

$(\exists\ tt_1 \cdot \exists\ tt_2 \cdot ((P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr']\!]) ;; (Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr']\!]))$
$\wedge (\exists\ tr_0 \cdot \ll tr_0\gg =_u \$tr + \ll tt_1\gg \wedge \$tr' =_u \ll tr_0\gg + \ll tt_2\gg))$
by (*rel-auto*)
also have ... =
$(\exists\ tt_1 \cdot \exists\ tt_2 \cdot ((P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr']\!]) ;; (Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr']\!]))$
$\wedge (\$tr' =_u \$tr + \ll tt_1\gg + \ll tt_2\gg))$
by (*rel-auto*)
finally show *?thesis* **.**
qed

lemma *R2-seqr-form′*:
assumes *P is R2 Q is R2*
shows $P ;; Q =$
$(\exists\ tt_1 \cdot \exists\ tt_2 \cdot ((P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr']\!]) ;; (Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr']\!]))$
$\wedge (\$tr' =_u \$tr + \ll tt_1\gg + \ll tt_2\gg))$
using *R2-seqr-form*[*of P Q*] **by** (*simp add*: *Healthy-if assms*)

lemma *R2-seqr-form″*:
assumes *P is R2 Q is R2*
shows $P ;; Q =$
$(\exists\ (tt_1, tt_2) \cdot ((P[\![0,\ll tt_1\gg/\$tr,\$tr']\!]) ;; (Q[\![0,\ll tt_2\gg/\$tr,\$tr']\!]))$
$\wedge (\$tr' =_u \$tr + \ll tt_1\gg + \ll tt_2\gg))$
by (*subst R2-seqr-form′*, *simp-all add*: *assms*, *rel-auto*)

lemma *R2-tr-middle*:
assumes *P is R2 Q is R2*
shows $(\exists\ tr_0 \cdot (P[\![\ll tr_0\gg/\$tr']\!] ;; Q[\![\ll tr_0\gg/\$tr]\!]) \wedge \ll tr_0\gg \leq_u \$tr') = (P ;; Q)$
proof −
have $(P ;; Q) = (\exists\ tr_0 \cdot (P[\![\ll tr_0\gg/\$tr']\!] ;; Q[\![\ll tr_0\gg/\$tr]\!]))$
by (*simp add*: *seqr-middle*)
also have ... $= (\exists\ tr_0 \cdot ((R2\ P)[\![\ll tr_0\gg/\$tr']\!] ;; (R2\ Q)[\![\ll tr_0\gg/\$tr]\!]))$
by (*simp add*: *assms Healthy-if*)
also have ... $= (\exists\ tr_0 \cdot ((R2\ P)[\![\ll tr_0\gg/\$tr']\!] ;; (R2\ Q)[\![\ll tr_0\gg/\$tr]\!]) \wedge \ll tr_0\gg \leq_u \$tr')$
by (*rel-auto*)
also have ... $= (\exists\ tr_0 \cdot (P[\![\ll tr_0\gg/\$tr']\!] ;; Q[\![\ll tr_0\gg/\$tr]\!]) \wedge \ll tr_0\gg \leq_u \$tr')$
by (*simp add*: *assms Healthy-if*)
finally show *?thesis* **..**
qed

lemma *R2-seqr-distribute*:
fixes P :: $('t{::}trace,'\alpha,'\beta)$ *rel-rp* **and** Q :: $('t,'\beta,'\gamma)$ *rel-rp*
shows $R2(R2(P) ;; R2(Q)) = (R2(P) ;; R2(Q))$
proof −
have $R2(R2(P) ;; R2(Q)) =$
$((\exists\ tt_1 \cdot \exists\ tt_2 \cdot (P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr']\!] ;; Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr']\!])[\![(\$tr' - \$tr)/\$tr']\!]$
$\wedge \$tr' - \$tr =_u \ll tt_1\gg + \ll tt_2\gg) \wedge \$tr' \geq_u \$tr)$
by (*simp add*: *R2-seqr-form*, *simp add*: *R2s-def usubst unrest*, *rel-auto*)
also have ... =
$((\exists\ tt_1 \cdot \exists\ tt_2 \cdot (P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr']\!] ;; Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr']\!])[\![(\ll tt_1\gg + \ll tt_2\gg)/\$tr']\!]$
$\wedge \$tr' - \$tr =_u \ll tt_1\gg + \ll tt_2\gg) \wedge \$tr' \geq_u \$tr)$
by (*subst subst-eq-replace*, *simp*)
also have ... =
$((\exists\ tt_1 \cdot \exists\ tt_2 \cdot (P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr']\!] ;; Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr']\!])$
$\wedge \$tr' - \$tr =_u \ll tt_1\gg + \ll tt_2\gg) \wedge \$tr' \geq_u \$tr)$
by (*rel-auto*)

also have ... =
$(\exists\ tt_1 \cdot \exists\ tt_2 \cdot (P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr\acute{}]\!] \ ;;\ Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr\acute{}]\!])$
$\wedge\ (\$tr\acute{} - \$tr =_u \ll tt_1\gg + \ll tt_2\gg \wedge \$tr\acute{} \geq_u \$tr))$
by *pred-auto*
also have ... =
$((\exists\ tt_1 \cdot \exists\ tt_2 \cdot (P[\![0/\$tr]\!][\![\ll tt_1\gg/\$tr\acute{}]\!] \ ;;\ Q[\![0/\$tr]\!][\![\ll tt_2\gg/\$tr\acute{}]\!])$
$\wedge\ \$tr\acute{} =_u \$tr + \ll tt_1\gg + \ll tt_2\gg))$
proof −
have $\bigwedge\ tt_1\ tt_2.\ (((\$tr\acute{} - \$tr =_u \ll tt_1\gg + \ll tt_2\gg) \wedge \$tr\acute{} \geq_u \$tr) :: ('t,'\alpha,'\gamma)\ \textit{rel-rp})$
$= (\$tr\acute{} =_u \$tr + \ll tt_1\gg + \ll tt_2\gg)$
apply (*rel-auto*)
apply (*metis add.assoc diff-add-cancel-left'*)
apply (*simp add*: *add.assoc*)
apply (*meson le-add order-trans*)
done
thus *?thesis* **by** *simp*
qed
also have ... = $(R2(P)\ ;;\ R2(Q))$
by (*simp add*: *R2-seqr-form*)
finally show *?thesis* **.**
qed

lemma *R2-seqr-closure* [*closure*]:
assumes *P is R2 Q is R2*
shows (*P* ;; *Q*) *is R2*
by (*metis Healthy-def' R2-seqr-distribute assms*(*1*) *assms*(*2*))

lemma *false-R2* [*closure*]: *false is R2*
by (*rel-auto*)

lemma *R1-R2-commute*:
$R1(R2(P)) = R2(R1(P))$
by *pred-auto*

lemma *R2-R1-form*: $R2(R1(P)) = R1(R2s(P))$
by (*rel-auto*)

lemma *R2s-H1-commute*:
$R2s(H1(P)) = H1(R2s(P))$
by (*rel-auto*)

lemma *R2s-H2-commute*:
$R2s(H2(P)) = H2(R2s(P))$
by (*simp add*: *H2-split R2s-def usubst*)

lemma *R2-R1-seq-drop-left*:
$R2(R1(P)\ ;;\ R1(Q)) = R2(P\ ;;\ R1(Q))$
by (*rel-auto*)

lemma *R2c-idem*: $R2c(R2c(P)) = R2c(P)$
by (*rel-auto*)

lemma *R2c-Idempotent* [*closure*]: *Idempotent R2c*
by (*simp add*: *Idempotent-def R2c-idem*)

lemma *R2c-Monotonic* [*closure*]: *Monotonic R2c*
by (*rel-auto*)

lemma *R2c-H2-commute*: $R2c(H2(P)) = H2(R2c(P))$
by (*simp add*: *H2-split R2c-disj R2c-def R2s-def usubst*, *rel-auto*)

lemma *R2c-seq*: $R2c(R2(P) \;;; R2(Q)) = (R2(P) \;;; R2(Q))$
by (*metis* (*no-types*, *lifting*) *R1-R2c-commute R1-R2c-is-R2 R2-seqr-distribute R2c-idem*)

lemma *R2-R2c-def*: $R2(P) = R1(R2c(P))$
by (*rel-auto*)

lemma *R2-comp-def*: $R2 = R1 \circ R2c$
by (*auto simp add*: *R2-R2c-def*)

lemma *R2c-R1-seq*: $R2c(R1(R2c(P)) \;;; R1(R2c(Q))) = (R1(R2c(P)) \;;; R1(R2c(Q)))$
using *R2c-seq*[*of P Q*] **by** (*simp add*: *R2-R2c-def*)

lemma *R1-R2c-seqr-distribute*:
fixes P :: $('t{::}trace,'\alpha,'\beta)$ *rel-rp* **and** Q :: $('t,'\beta,'\gamma)$ *rel-rp*
assumes *P is R1 P is R2c Q is R1 Q is R2c*
shows $R1(R2c(P \;;; Q)) = P \;;; Q$
by (*metis Healthy-if R1-seqr R2c-R1-seq assms*)

lemma *R2-R1-true*:
$R2(R1(true)) = R1(true)$
by (*simp add*: *R2-R1-form R2s-true*)

lemma *R1-true-R2* [*closure*]: *R1*(*true*) *is R2*
by (*rel-auto*)

lemma *R1-R2s-R1-true-lemma*:
$R1(R2s(R1\ (\neg\ R2s\ P) \;;; R1\ true)) = R1(R2s((\neg\ P) \;;; R1\ true))$
by (*rel-auto*)

lemma *R2c-healthy-R2s*: *P is R2c* $\Longrightarrow R1(R2s(P)) = R1(P)$
by (*simp add*: *Healthy-def R1-R2s-R2c*)

2.3 R3: No activity while predecessor is waiting

definition *R3* :: $('t{::}trace,\ '\alpha)$ *hrel-rp* $\Rightarrow$ $('t,\ '\alpha)$ *hrel-rp* **where**
[*upred-defs*]: $R3(P) = (II \triangleleft \$wait \triangleright P)$

lemma *R3-idem*: $R3(R3(P)) = R3(P)$
by (*rel-auto*)

lemma *R3-Idempotent* [*closure*]: *Idempotent R3*
by (*simp add*: *Idempotent-def R3-idem*)

lemma *R3-mono*: $P \sqsubseteq Q \Longrightarrow R3(P) \sqsubseteq R3(Q)$
by (*rel-auto*)

lemma *R3-Monotonic*: *Monotonic R3*
by (*simp add*: *mono-def R3-mono*)

lemma *R3-Continuous*: *Continuous R3*

by (*rel-auto*)

lemma *R3-conj*: $R3(P \wedge Q) = (R3(P) \wedge R3(Q))$
by (*rel-auto*)

lemma *R3-disj*: $R3(P \vee Q) = (R3(P) \vee R3(Q))$
by (*rel-auto*)

lemma *R3-USUP*:
assumes $A \neq \{\}$
shows $R3(\bigsqcap\ i \in A \cdot P(i)) = (\bigsqcap\ i \in A \cdot R3(P(i)))$
using *assms* **by** (*rel-auto*)

lemma *R3-UINF*:
assumes $A \neq \{\}$
shows $R3(\bigsqcup\ i \in A \cdot P(i)) = (\bigsqcup\ i \in A \cdot R3(P(i)))$
using *assms* **by** (*rel-auto*)

lemma *R3-condr*: $R3(P \triangleleft b \triangleright Q) = (R3(P) \triangleleft b \triangleright R3(Q))$
by (*rel-auto*)

lemma *R3-skipr*: $R3(II) = II$
by (*rel-auto*)

lemma *R3-form*: $R3(P) = ((\$wait \wedge II) \vee (\neg\ \$wait \wedge P))$
by (*rel-auto*)

lemma *wait-R3*:
$(\$wait \wedge R3(P)) = (II \wedge \$wait')$
by (*rel-auto*)

lemma *nwait-R3*:
$(\neg\$wait \wedge R3(P)) = (\neg\$wait \wedge P)$
by (*rel-auto*)

lemma *R3-semir-form*:
$(R3(P)\ ;;\ R3(Q)) = R3(P\ ;;\ R3(Q))$
by (*rel-auto*)

lemma *R3-semir-closure*:
assumes *P is R3 Q is R3*
shows $(P\ ;;\ Q)$ *is R3*
using *assms*
by (*metis Healthy-def' R3-semir-form*)

lemma *R1-R3-commute*: $R1(R3(P)) = R3(R1(P))$
by (*rel-auto*)

lemma *R2-R3-commute*: $R2(R3(P)) = R3(R2(P))$
apply (*rel-auto*)
using *minus-zero-eq* **apply** *blast+*
done

2.4 R4: The trace strictly increases

definition *R4* :: $('t::trace, '\alpha, '\beta)$ *rel-rp* $\Rightarrow$ $('t, '\alpha, '\beta)$ *rel-rp* **where**

[*upred-defs*]: $R4(P) = (P \wedge \$tr <_u \$tr')$

lemma *R4-implies-R1* [*closure*]: P *is* $R4 \Longrightarrow P$ *is* $R1$
using *less-iff* **by** *rel-blast*

lemma *R4-iff-refine*:
P *is* $R4 \longleftrightarrow (\$tr <_u \$tr') \sqsubseteq P$
by (*rel-blast*)

lemma *R4-idem*: $R4\ (R4\ P) = R4\ P$
by (*rel-auto*)

lemma *R4-false*: $R4(false) = false$
by (*rel-auto*)

lemma *R4-conj*: $R4(P \wedge Q) = (R4(P) \wedge R4(Q))$
by (*rel-auto*)

lemma *R4-disj*: $R4(P \vee Q) = (R4(P) \vee R4(Q))$
by (*rel-auto*)

lemma *R4-is-R4* [*closure*]: $R4(P)$ *is* $R4$
by (*rel-auto*)

lemma *false-R4* [*closure*]: *false is* $R4$
by (*rel-auto*)

lemma *UINF-R4-closed* [*closure*]:
$[\![\bigwedge i.\ P\ i \text{ is } R4]\!] \Longrightarrow (\bigsqcap\ i \cdot P\ i) \text{ is } R4$
by (*rel-blast*)

lemma *conj-R4-closed* [*closure*]:
$[\![P \text{ is } R4;\ Q \text{ is } R4]\!] \Longrightarrow (P \wedge Q) \text{ is } R4$
by (*simp add*: *Healthy-def R4-conj*)

lemma *disj-R4-closed* [*closure*]:
$[\![P \text{ is } R4;\ Q \text{ is } R4]\!] \Longrightarrow (P \vee Q) \text{ is } R4$
by (*simp add*: *Healthy-def R4-disj*)

lemma *seq-R4-closed-1* [*closure*]:
$[\![P \text{ is } R4;\ Q \text{ is } R1]\!] \Longrightarrow (P\ ;;\ Q) \text{ is } R4$
using *less-le-trans* **by** *rel-blast*

lemma *seq-R4-closed-2* [*closure*]:
$[\![P \text{ is } R1;\ Q \text{ is } R4]\!] \Longrightarrow (P\ ;;\ Q) \text{ is } R4$
using *le-less-trans* **by** *rel-blast*

2.5 R5: The trace does not increase

definition $R5$ :: $('t{::}trace,\ '\alpha,\ '\beta)$ *rel-rp* $\Rightarrow$ $('t,\ '\alpha,\ '\beta)$ *rel-rp* **where**
[*upred-defs*]: $R5(P) = (P \wedge \$tr =_u \$tr')$

lemma *R5-implies-R1* [*closure*]: P *is* $R5 \Longrightarrow P$ *is* $R1$
using *eq-iff* **by** *rel-blast*

lemma *R5-iff-refine*:

P *is* $R5 \longleftrightarrow (\$tr =_u \$tr') \sqsubseteq P$
by (*rel-blast*)

lemma *R5-conj*: $R5(P \wedge Q) = (R5(P) \wedge R5(Q))$
by (*rel-auto*)

lemma *R5-disj*: $R5(P \vee Q) = (R5(P) \vee R5(Q))$
by (*rel-auto*)

lemma *R4-R5*: $R4\ (R5\ P) = \mathit{false}$
by (*rel-auto*)

lemma *R5-R4*: $R5\ (R4\ P) = \mathit{false}$
by (*rel-auto*)

lemma *UINF-R5-closed* [*closure*]:
$[\![\bigwedge i.\ P\ i$ *is* $R5\ ]\!] \Longrightarrow (\bigsqcap\ i \cdot P\ i)$ *is* $R5$
by (*rel-blast*)

lemma *conj-R5-closed* [*closure*]:
$[\![P$ *is* $R5;\ Q$ *is* $R5\ ]\!] \Longrightarrow (P \wedge Q)$ *is* $R5$
by (*simp add*: *Healthy-def R5-conj*)

lemma *disj-R5-closed* [*closure*]:
$[\![P$ *is* $R5;\ Q$ *is* $R5\ ]\!] \Longrightarrow (P \vee Q)$ *is* $R5$
by (*simp add*: *Healthy-def R5-disj*)

lemma *seq-R5-closed* [*closure*]:
$[\![P$ *is* $R5;\ Q$ *is* $R5\ ]\!] \Longrightarrow (P\ ;;\ Q)$ *is* $R5$
by (*rel-auto*, *metis*)

2.6 RP laws

definition *RP-def* [*upred-defs*]: $RP(P) = R1(R2c(R3(P)))$

lemma *RP-comp-def*: $RP = R1 \circ R2c \circ R3$
by (*auto simp add*: *RP-def*)

lemma *RP-alt-def*: $RP(P) = R1(R2(R3(P)))$
by (*metis R1-R2c-is-R2 R1-idem RP-def*)

lemma *RP-intro*: $[\![P$ *is* $R1;\ P$ *is* $R2;\ P$ *is* $R3\ ]\!] \Longrightarrow P$ *is* RP
by (*simp add*: *Healthy-def' RP-alt-def*)

lemma *RP-idem*: $RP(RP(P)) = RP(P)$
by (*simp add*: *R1-R2c-is-R2 R2-R3-commute R2-idem R3-idem RP-def*)

lemma *RP-Idempotent* [*closure*]: *Idempotent RP*
by (*simp add*: *Idempotent-def RP-idem*)

lemma *RP-mono*: $P \sqsubseteq Q \Longrightarrow RP(P) \sqsubseteq RP(Q)$
by (*simp add*: *R1-R2c-is-R2 R2-mono R3-mono RP-def*)

lemma *RP-Monotonic*: *Monotonic RP*
by (*simp add*: *mono-def RP-mono*)

lemma *RP-Continuous*: *Continuous RP*
by (*simp add*: *Continuous-comp R1-Continuous R2c-Continuous R3-Continuous RP-comp-def*)

lemma *RP-skip*:
$RP(II) = II$
by (*simp add*: *R1-skip R2c-skip-r R3-skipr RP-def*)

lemma *RP-skip-closure*:
II is RP
by (*simp add*: *Healthy-def' RP-skip*)

lemma *RP-seq-closure*:
assumes *P is RP Q is RP*
shows (*P* ;; *Q*) *is RP*
proof (*rule RP-intro*)
show (*P* ;; *Q*) *is R1*
by (*metis Healthy-def R1-seqr RP-def assms*)
thus (*P* ;; *Q*) *is R2*
by (*metis Healthy-def' R2-R2c-def R2c-R1-seq RP-def assms*)
show (*P* ;; *Q*) *is R3*
by (*metis* (*no-types*, *lifting*) *Healthy-def' R1-R2c-is-R2 R2-R3-commute R3-idem R3-semir-form RP-def assms*)
qed

2.7 UTP theories

typedecl *REA*
abbreviation $REA \equiv UTHY(REA, ('t::trace,'\alpha)\ rp)$

overloading
rea-hcond == *utp-hcond* :: $(REA, ('t::trace,'\alpha)\ rp)\ uthy \Rightarrow (('t,'\alpha)\ rp \times ('t,'\alpha)\ rp)\ health$
rea-unit == *utp-unit* :: $(REA, ('t::trace,'\alpha)\ rp)\ uthy \Rightarrow ('t,'\alpha)\ hrel\text{-}rp$
begin
definition *rea-hcond* :: $(REA, ('t::trace,'\alpha)\ rp)\ uthy \Rightarrow (('t,'\alpha)\ rp \times ('t,'\alpha)\ rp)\ health$
where [*upred-defs*]: *rea-hcond* $T = RP$
definition *rea-unit* :: $(REA, ('t::trace,'\alpha)\ rp)\ uthy \Rightarrow ('t,'\alpha)\ hrel\text{-}rp$
where [*upred-defs*]: *rea-unit* $T = II$
end

interpretation *rea-utp-theory*: *utp-theory* $UTHY(REA, ('t::trace,'\alpha)\ rp)$
rewrites *carrier* (*uthy-order REA*) $= [\![RP]\!]_H$
by (*simp-all add*: *rea-hcond-def utp-theory-def RP-idem*)

interpretation *rea-utp-theory-mono*: *utp-theory-continuous* $UTHY(REA, ('t::trace,'\alpha)\ rp)$
rewrites *carrier* (*uthy-order REA*) $= [\![RP]\!]_H$
by (*unfold-locales*, *simp-all add*: *RP-Continuous rea-hcond-def*)

interpretation *rea-utp-theory-rel*: *utp-theory-unital* $UTHY(REA, ('t::trace,'\alpha)\ rp)$
rewrites *carrier* (*uthy-order REA*) $= [\![RP]\!]_H$
by (*unfold-locales*, *simp-all add*: *rea-hcond-def rea-unit-def RP-seq-closure RP-skip-closure*)

lemma *rea-top*: $\top_{REA} = (\$wait \wedge II)$
proof −
have $\top_{REA} = RP(false)$
by (*simp add*: *rea-utp-theory-mono.healthy-top*, *simp add*: *rea-hcond-def*)
also have ... $= (\$wait \wedge II)$

by (*rel-auto*, *metis minus-zero-eq*)
finally show *?thesis* **.**
qed

lemma *rea-top-left-zero*:
assumes *P is RP*
shows $(\top_{REA} \;;;\; P) = \top_{REA}$
proof −
have $(\top_{REA} \;;;\; P) = ((\$wait \wedge II) \;;;\; R3(P))$
by (*metis* (*no-types*, *lifting*) *Healthy-def R1-R2c-is-R2 R2-R3-commute R3-idem RP-def assms rea-top*)
also have ... $= (\$wait \wedge R3(P))$
by (*rel-auto*)
also have ... $= (\$wait \wedge II)$
by (*metis R3-skipr wait-R3*)
also have ... $= \top_{REA}$
by (*simp add*: *rea-top*)
finally show *?thesis* **.**
qed

lemma *rea-bottom*: $\bot_{REA} = R1(\$wait \Rightarrow II)$
proof −
have $\bot_{REA} = RP(true)$
by (*simp add*: *rea-utp-theory-mono.healthy-bottom*, *simp add*: *rea-hcond-def*)
also have ... $= R1(\$wait \Rightarrow II)$
by (*rel-auto*, *metis minus-zero-eq*)
finally show *?thesis* **.**
qed

end

3 Reactive Parallel-by-Merge

theory *utp-rea-parallel*
imports *utp-rea-healths*
begin

We show closure of parallel by merge under the reactive healthiness conditions by means of suitable restrictions on the merge predicate [4]. We first define healthiness conditions for $R1$ and $R2$ merge predicates.

definition $R1m$ :: $('t :: trace, '\alpha)$ *rp merge* $\Rightarrow$ $('t, '\alpha)$ *rp merge*
where [*upred-defs*]: $R1m(M) = (M \wedge \$tr_< \leq_u \$tr\,')$

definition $R1m'$ :: $('t :: trace, '\alpha)$ *rp merge* $\Rightarrow$ $('t, '\alpha)$ *rp merge*
where [*upred-defs*]: $R1m'(M) = (M \wedge \$tr_< \leq_u \$tr\,' \wedge \$tr_< \leq_u \$0{-}tr \wedge \$tr_< \leq_u \$1{-}tr)$

A merge predicate can access the history through tr, as usual, but also through $0.tr$ and $1.tr$. Thus we have to remove the latter two histories as well to satisfy R2 for the overall construction.

definition $R2m$ :: $('t :: trace, '\alpha)$ *rp merge* $\Rightarrow$ $('t, '\alpha)$ *rp merge*
where [*upred-defs*]: $R2m(M) = R1m(M[\![0,(\$tr\,'-\$tr_<),(\$0{-}tr-\$tr_<),(\$1{-}tr-\$tr_<)/\$tr_<,\$tr\,',\$0{-}tr,\$1{-}tr]\!])$

definition $R2m'$ :: $('t :: trace, '\alpha)$ *rp merge* $\Rightarrow$ $('t, '\alpha)$ *rp merge*
where [*upred-defs*]: $R2m'(M) = R1m'(M[\![0,(\$tr\,'-\$tr_<),(\$0{-}tr-\$tr_<),(\$1{-}tr-\$tr_<)/\$tr_<,\$tr\,',\$0{-}tr,\$1{-}tr]\!])$

definition $R2cm$ :: $('t :: trace, '\alpha)$ rp $merge \Rightarrow ('t, '\alpha)$ rp $merge$
where [*upred-defs*]: $R2cm(M) = M[\![0,(\$tr' - \$tr_<),(\$0{-}tr - \$tr_<),(\$1{-}tr - \$tr_<)/\$tr_<,\$tr',\$0{-}tr,\$1{-}tr]\!]$
$\triangleleft \$tr_< \le_u \$tr' \triangleright M$

lemma *R2m′-form*:
$R2m'(M) =$
$(\exists\ (tt_p,\ tt_0,\ tt_1) \cdot M[\![0,\ll tt_p\gg,\ll tt_0\gg,\ll tt_1\gg/\$tr_<,\$tr',\$0{-}tr,\$1{-}tr]\!]$
$\wedge\ \$tr' =_u \$tr_< + \ll tt_p\gg$
$\wedge\ \$0{-}tr =_u \$tr_< + \ll tt_0\gg$
$\wedge\ \$1{-}tr =_u \$tr_< + \ll tt_1\gg)$
by (*rel-auto*, *metis diff-add-cancel-left′*)

lemma *R1m-idem*: $R1m(R1m(P)) = R1m(P)$
by (*rel-auto*)

lemma *R1m-seq-lemma*: $R1m(R1m(M)\ ;;\ R1(P)) = R1m(M)\ ;;\ R1(P)$
by (*rel-auto*)

lemma *R1m-seq* [*closure*]:
assumes *M is R1m P is R1*
shows *M ;; P is R1m*
proof −
from *assms* **have** $R1m(M\ ;;\ P) = R1m(R1m(M)\ ;;\ R1(P))$
by (*simp add*: *Healthy-if*)
also have ... $= R1m(M)\ ;;\ R1(P)$
by (*simp add*: *R1m-seq-lemma*)
also have ... $= M\ ;;\ P$
by (*simp add*: *Healthy-if assms*)
finally show *?thesis*
by (*simp add*: *Healthy-def*)
qed

lemma *R2m-idem*: $R2m(R2m(P)) = R2m(P)$
by (*rel-auto*)

lemma *R2m-seq-lemma*: $R2m'(R2m'(M)\ ;;\ R2(P)) = R2m'(M)\ ;;\ R2(P)$
apply (*simp add*: *R2m′-form R2-form*)
apply (*rel-auto*)
apply (*metis* (*no-types*, *lifting*) *add.assoc*)+
done

lemma *R2m′-seq* [*closure*]:
assumes *M is R2m′ P is R2*
shows *M ;; P is R2m′*
by (*metis Healthy-def′ R2m-seq-lemma assms*(*1*) *assms*(*2*))

lemma *R1-par-by-merge* [*closure*]:
M *is* $R1m \Longrightarrow (P \parallel_M Q)$ *is* $R1$
by (*rel-blast*)

lemma *R2-R2m′-pbm*: $R2(P \parallel_M Q) = (R2(P) \parallel_{R2m'(M)} R2(Q))$
proof −
have $(R2(P) \parallel_{R2m'(M)} R2(Q)) = ((R2(P) \parallel_s R2(Q))\ ;;$
$(\exists\ (tt_p,\ tt_0,\ tt_1) \cdot M[\![0,\ll tt_p\gg,\ll tt_0\gg,\ll tt_1\gg/\$tr_<,\$tr',\$0{-}tr,\$1{-}tr]\!]$
$\wedge\ \$tr' =_u \$tr_< + \ll tt_p\gg$

$\wedge\ \$0{-}tr =_u \$tr_< + \ll tt_0 \gg$
$\wedge\ \$1{-}tr =_u \$tr_< + \ll tt_1 \gg))$
by (*simp add*: *par-by-merge-def R2m′-form*)
also have ... = $(\exists\ (tt_p, tt_0, tt_1) \cdot ((R2(P) \parallel_s R2(Q)) ;; (M[\![0,\ll tt_p\gg,\ll tt_0\gg,\ll tt_1\gg/\$tr_<,\$tr´,\$0{-}tr,\$1{-}tr]\!]$
$\wedge\ \$tr´ =_u \$tr_< + \ll tt_p\gg$
$\wedge\ \$0{-}tr =_u \$tr_< + \ll tt_0\gg$
$\wedge\ \$1{-}tr =_u \$tr_< + \ll tt_1\gg)))$
by (*rel-blast*)
also have ... = $(\exists\ (tt_p, tt_0, tt_1) \cdot (((R2(P) \parallel_s R2(Q)) \wedge \$0{-}tr´ =_u \$tr_<´ + \ll tt_0\gg \wedge \$1{-}tr´ =_u \$tr_<´ + \ll tt_1\gg) ;;$
$(M[\![0,\ll tt_p\gg,\ll tt_0\gg,\ll tt_1\gg/\$tr_<,\$tr´,\$0{-}tr,\$1{-}tr]\!] \wedge \$tr´ =_u \$tr_< + \ll tt_p\gg)))$
by (*rel-blast*)
also have ... = $(\exists\ (tt_p, tt_0, tt_1) \cdot (((R2(P) \parallel_s R2(Q)) \wedge \$0{-}tr´ =_u \$tr_<´ + \ll tt_0\gg \wedge \$1{-}tr´ =_u \$tr_<´ + \ll tt_1\gg) ;;$
$(M[\![0,\ll tt_p\gg,\ll tt_0\gg,\ll tt_1\gg/\$tr_<,\$tr´,\$0{-}tr,\$1{-}tr]\!])) \wedge \$tr´ =_u \$tr + \ll tt_p\gg)$
by (*rel-blast*)
also have ... = $(\exists\ (tt_p, tt_0, tt_1) \cdot (((R2(P) \wedge \$tr´ =_u \$tr + \ll tt_0\gg) \parallel_s (R2(Q) \wedge \$tr´ =_u \$tr + \ll tt_1\gg)) ;;$
$(M[\![0,\ll tt_p\gg,\ll tt_0\gg,\ll tt_1\gg/\$tr_<,\$tr´,\$0{-}tr,\$1{-}tr]\!])) \wedge \$tr´ =_u \$tr + \ll tt_p\gg)$
by (*rel-auto*, *blast*, *metis le-add trace-class.add-diff-cancel-left*)
also have ... = $(\exists\ (tt_p, tt_0, tt_1) \cdot ((\ \ ((\exists\ tt_0{}' \cdot P[\![0,\ll tt_0{}'\gg/\$tr,\$tr´]\!] \wedge \$tr´ =_u \$tr + \ll tt_0{}'\gg) \wedge \$tr´ =_u \$tr + \ll tt_0\gg)$
$\parallel_s ((\exists\ tt_1{}' \cdot Q[\![0,\ll tt_1{}'\gg/\$tr,\$tr´]\!] \wedge \$tr´ =_u \$tr + \ll tt_1{}'\gg) \wedge \$tr´ =_u \$tr + \ll tt_1\gg)) ;;$
$(M[\![0,\ll tt_p\gg,\ll tt_0\gg,\ll tt_1\gg/\$tr_<,\$tr´,\$0{-}tr,\$1{-}tr]\!])) \wedge \$tr´ =_u \$tr + \ll tt_p\gg)$
by (*simp add*: *R2-form usubst*)
also have ... = $(\exists\ (tt_p, tt_0, tt_1) \cdot ((\ \ (P[\![0,\ll tt_0\gg/\$tr,\$tr´]\!]\ \wedge \$tr´ =_u \$tr + \ll tt_0\gg)$
$\parallel_s (Q[\![0,\ll tt_1\gg/\$tr,\$tr´]\!] \wedge \$tr´ =_u \$tr + \ll tt_1\gg)) ;;$
$(M[\![0,\ll tt_p\gg,\ll tt_0\gg,\ll tt_1\gg/\$tr_<,\$tr´,\$0{-}tr,\$1{-}tr]\!])) \wedge \$tr´ =_u \$tr + \ll tt_p\gg)$
by (*rel-auto*, *metis left-cancel-monoid-class.add-left-imp-eq*, *blast*)
also have ... = $R2(P \parallel_M Q)$
by (*rel-auto*, *blast*, *metis diff-add-cancel-left′*)
finally show *?thesis* **..**
qed

lemma *R2m-R2m′-pbm*: $(R2(P) \parallel_{R2m(M)} R2(Q)) = (R2(P) \parallel_{R2m'(M)} R2(Q))$
by (*rel-blast*)

lemma *R2-par-by-merge* [*closure*]:
assumes *P is R2 Q is R2 M is R2m*
shows $(P \parallel_M Q)$ *is R2*
by (*metis Healthy-def′ R2-R2m′-pbm R2m-R2m′-pbm assms*(*1*) *assms*(*2*) *assms*(*3*))

lemma *R2-par-by-merge′* [*closure*]:
assumes *P is R2 Q is R2 M is R2m′*
shows $(P \parallel_M Q)$ *is R2*
by (*metis Healthy-def′ R2-R2m′-pbm assms*(*1*) *assms*(*2*) *assms*(*3*))

lemma *R1m-skip-merge*: $R1m(skip_m) = skip_m$
by (*rel-auto*)

lemma *R1m-disj*: $R1m(P \vee Q) = (R1m(P) \vee R1m(Q))$
by (*rel-auto*)

lemma *R1m-conj*: $R1m(P \wedge Q) = (R1m(P) \wedge R1m(Q))$
by (*rel-auto*)

lemma *R2m-skip-merge*: $R2m(skip_m) = skip_m$
apply (*rel-auto*) **using** *minus-zero-eq* **by** *blast*

lemma *R2m-disj*: $R2m(P \vee Q) = (R2m(P) \vee R2m(Q))$
by (*rel-auto*)

lemma *R2m-conj*: $R2m(P \wedge Q) = (R2m(P) \wedge R2m(Q))$
by (*rel-auto*)

definition $R3m$ :: $('t :: trace, '\alpha)\ rp\ merge \Rightarrow ('t, '\alpha)\ rp\ merge$ **where**
[*upred-defs*]: $R3m(M) = skip_m \triangleleft \$wait_< \triangleright M$

lemma *R3-par-by-merge*:
assumes
P is R3 Q is R3 M is R3m
shows $(P \parallel_M Q)$ *is R3*
proof −
have $(P \parallel_M Q) = ((P \parallel_M Q)[\![true/\$wait]\!] \triangleleft \$wait \triangleright (P \parallel_M Q))$
by (*metis cond-L6 cond-var-split in-var-uvar wait-vwb-lens*)
also have ... $= (((R3\ P)[\![true/\$wait]\!] \parallel_{(R3m\ M)[\![true/\$wait_<]\!]} (R3\ Q)[\![true/\$wait]\!]) \triangleleft \$wait \triangleright (P \parallel_M Q))$
by (*subst-tac*, *simp add*: *Healthy-if assms*)
also have ... $= ((II[\![true/\$wait]\!] \parallel_{skip_m[\![true/\$wait_<]\!]} II[\![true/\$wait]\!]) \triangleleft \$wait \triangleright (P \parallel_M Q))$
by (*simp add*: *R3-def R3m-def usubst*)
also have ... $= ((II \parallel_{skip_m} II)[\![true/\$wait]\!] \triangleleft \$wait \triangleright (P \parallel_M Q))$
by (*subst-tac*)
also have ... $= (II \triangleleft \$wait \triangleright (P \parallel_M Q))$
by (*simp add*: *cond-var-subst-left par-by-merge-skip*)
also have ... $= R3(P \parallel_M Q)$
by (*simp add*: *R3-def*)
finally show *?thesis*
by (*simp add*: *Healthy-def*)
qed

lemma *SymMerge-R1-true* [*closure*]:
M *is SymMerge* $\Longrightarrow M$;; $R1(true)$ *is SymMerge*
by (*rel-auto*)

end

4 Reactive Relations

theory *utp-rea-rel*
imports
utp-rea-healths
UTP−KAT.utp-kleene
begin

This theory defines a reactive relational calculus for *R1-R2* predicates as an extension of the standard alphabetised predicate calculus. This enables us to formally characterise relational programs that refer to both state variables and a trace history. For more details on reactive relations, please see the associated journal paper [3].

4.1 Healthiness Conditions

definition *RR* :: ('*t*::*trace*, 'α, 'β) *rel-rp* $\Rightarrow$ ('*t*, 'α, 'β) *rel-rp* **where**
[*upred-defs*]: *RR*(*P*) = ($\exists$ {\$*ok*,\$*ok*´,\$*wait*,\$*wait*´} $\cdot$ *R2*(*P*))

lemma *RR-idem*: *RR*(*RR*(*P*)) = *RR*(*P*)
 by (*rel-auto*)

lemma *RR-Idempotent* [*closure*]: *Idempotent RR*
 by (*simp add*: *Idempotent-def RR-idem*)

lemma *RR-Continuous* [*closure*]: *Continuous RR*
 by (*rel-blast*)

lemma *R1-RR*: *R1*(*RR*(*P*)) = *RR*(*P*)
 by (*rel-auto*)

lemma *R2c-RR*: *R2c*(*RR*(*P*)) = *RR*(*P*)
 by (*rel-auto*)

lemma *RR-implies-R1* [*closure*]: *P is RR* $\Longrightarrow$ *P is R1*
 by (*metis Healthy-def R1-RR*)

lemma *RR-implies-R2c*: *P is RR* $\Longrightarrow$ *P is R2c*
 by (*metis Healthy-def R2c-RR*)

lemma *RR-implies-R2* [*closure*]: *P is RR* $\Longrightarrow$ *P is R2*
 by (*metis Healthy-def R1-RR R2-R2c-def R2c-RR*)

lemma *RR-intro*:
 assumes \$*ok* $\sharp$ *P* \$*ok*´ $\sharp$ *P* \$*wait* $\sharp$ *P* \$*wait*´ $\sharp$ *P P is R1 P is R2c*
 shows *P is RR*
 by (*simp add*: *RR-def Healthy-def ex-plus R2-R2c-def*, *simp add*: *Healthy-if assms ex-unrest*)

lemma *RR-R2-intro*:
 assumes \$*ok* $\sharp$ *P* \$*ok*´ $\sharp$ *P* \$*wait* $\sharp$ *P* \$*wait*´ $\sharp$ *P P is R2*
 shows *P is RR*
 by (*simp add*: *RR-def Healthy-def ex-plus*, *simp add*: *Healthy-if assms ex-unrest*)

lemma *RR-unrests* [*unrest*]:
 assumes *P is RR*
 shows \$*ok* $\sharp$ *P* \$*ok*´ $\sharp$ *P* \$*wait* $\sharp$ *P* \$*wait*´ $\sharp$ *P*
proof –
 have \$*ok* $\sharp$ *RR*(*P*) \$*ok*´ $\sharp$ *RR*(*P*) \$*wait* $\sharp$ *RR*(*P*) \$*wait*´ $\sharp$ *RR*(*P*)
  by (*simp-all add*: *RR-def ex-plus unrest*)
 thus \$*ok* $\sharp$ *P* \$*ok*´ $\sharp$ *P* \$*wait* $\sharp$ *P* \$*wait*´ $\sharp$ *P*
  by (*simp-all add*: *assms Healthy-if*)
qed

lemma *RR-refine-intro*:

assumes P *is* RR Q *is* RR $\bigwedge$ t. $P[\![0,\ll t\gg/\$tr,\$tr']\!] \sqsubseteq Q[\![0,\ll t\gg/\$tr,\$tr']\!]$
shows $P \sqsubseteq Q$
proof −
have $\bigwedge$ t. $(RR\ P)[\![0,\ll t\gg/\$tr,\$tr']\!] \sqsubseteq (RR\ Q)[\![0,\ll t\gg/\$tr,\$tr']\!]$
by (*simp add*: *Healthy-if assms*)
hence $RR(P) \sqsubseteq RR(Q)$
by (*rel-auto*)
thus *?thesis*
by (*simp add*: *Healthy-if assms*)
qed

lemma *R4-RR-closed* [*closure*]:
assumes P *is* RR
shows $R4(P)$ *is* RR
proof −
have $R4(RR(P))$ *is* RR
by (*rel-blast*)
thus *?thesis*
by (*simp add*: *Healthy-if assms*)
qed

lemma *R5-RR-closed* [*closure*]:
assumes P *is* RR
shows $R5(P)$ *is* RR
proof −
have $R5(RR(P))$ *is* RR
using *minus-zero-eq* **by** *rel-auto*
thus *?thesis*
by (*simp add*: *Healthy-if assms*)
qed

4.2 Reactive relational operators

named-theorems *rpred*

abbreviation *rea-true* :: $('t::trace,'\alpha,'\beta)$ *rel-rp* $(true_r)$ **where**
$true_r \equiv R1(true)$

definition *rea-not* :: $('t::trace,'\alpha,'\beta)$ *rel-rp* $\Rightarrow$ $('t,'\alpha,'\beta)$ *rel-rp* $(\neg_r$ - $[40]$ $40)$
where [*upred-defs*]: $(\neg_r\ P) = R1(\neg\ P)$

definition *rea-diff* :: $('t::trace,'\alpha,'\beta)$ *rel-rp* $\Rightarrow$ $('t,'\alpha,'\beta)$ *rel-rp* $\Rightarrow$ $('t,'\alpha,'\beta)$ *rel-rp* (**infixl** $-_r$ 65)
where [*upred-defs*]: *rea-diff* $P\ Q = (P \wedge \neg_r\ Q)$

definition *rea-impl* ::
$('t::trace,'\alpha,'\beta)$ *rel-rp* $\Rightarrow$ $('t,'\alpha,'\beta)$ *rel-rp* $\Rightarrow$ $('t,'\alpha,'\beta)$ *rel-rp* (**infixr** $\Rightarrow_r$ 25)
where [*upred-defs*]: $(P \Rightarrow_r Q) = (\neg_r\ P \vee Q)$

definition *rea-lift* :: $('t::trace,'\alpha,'\beta)$ *rel-rp* $\Rightarrow$ $('t,'\alpha,'\beta)$ *rel-rp* $([-]_r)$
where [*upred-defs*]: $[P]_r = R1(P)$

definition *rea-skip* :: $('t::trace,'\alpha)$ *hrel-rp* (II_r)
where [*upred-defs*]: $II_r = (\$tr' =_u \$tr \wedge \$\Sigma_R' =_u \$\Sigma_R)$

definition *rea-assert* :: $('t::trace,'\alpha)$ *hrel-rp* $\Rightarrow$ $('t,'\alpha)$ *hrel-rp* $(\{\text{-}\}_r)$
where [*upred-defs*]: $\{b\}_r = (II_r \vee \neg_r\ b)$

Convert from one trace algebra to another using renamer functions, which are a kind of monoid homomorphism.

locale *renamer* =
  fixes f :: $'a$::*trace* ⇒ $'b$::*trace*
  assumes
    injective: *inj f* **and**
    add: $f\ (x + y) = f\,x + f\,y$
begin
  lemma *zero*: $f\ 0 = 0$
    by (*metis add add.right-neutral add-monoid-diff-cancel-left*)

  lemma *monotonic*: *mono f*
    by (*metis add monoI trace-class.le-iff-add*)

  lemma *minus*: $x \le y \Longrightarrow f\ (y - x) = f(y) - f(x)$
    by (*metis add diff-add-cancel-left′ trace-class.add-diff-cancel-left*)
end

declare *renamer.add* [*simp*]
declare *renamer.zero* [*simp*]
declare *renamer.minus* [*simp*]

lemma *renamer-id*: *renamer id*
  by (*unfold-locales*, *simp-all*)

lemma *renamer-comp*: ⟦ *renamer f*; *renamer g* ⟧ ⟹ *renamer* $(f \circ g)$
  by (*unfold-locales*, *simp-all add*: *inj-comp renamer.injective*)

lemma *renamer-map*: *inj f* ⟹ *renamer* (*map f*)
  by (*unfold-locales*, *simp-all add*: *plus-list-def*)

definition *rea-rename* :: $('t_1$::*trace*,$'\alpha)$ *hrel-rp* ⇒ $('t_1 \Rightarrow 't_2)$ ⇒ $('t_2$::*trace*,$'\alpha)$ *hrel-rp* $((\text{-})(\!|\text{-}|\!)_r\ [999,\ 0]\ 999)$ **where**
[*upred-defs*]: *rea-rename P f* = $R2((\$tr' =_u 0 \wedge \$\Sigma_R' =_u \$\Sigma_R)\ ;;\ P\ ;;\ (\$tr' =_u \mathit{uop}\ f\ \$tr \wedge \$\Sigma_R' =_u \$\Sigma_R))$

Trace contribution substitution: make a substitution for the trace contribution lens *tt*, and apply *R1* to make the resulting predicate healthy again.

definition *rea-subst* :: $('t$::*trace*, $'\alpha)$ *hrel-rp* ⇒ $('t, ('t, '\alpha)\ rp)$ *hexpr* ⇒ $('t, '\alpha)$ *hrel-rp* $(\text{-}[\![\text{-}]\!]_r\ [999,0]\ 999)$
where [*upred-defs*]: $P[\![v]\!]_r = R1(P[\![v/\&tt]\!])$

4.3 Unrestriction and substitution laws

lemma *rea-true-unrest* [*unrest*]:
  $[\![\ x \bowtie (\$tr)_v;\ x \bowtie (\$tr')_v\ ]\!] \Longrightarrow x \sharp\ true_r$
  by (*simp add*: *R1-def unrest lens-indep-sym*)

lemma *rea-not-unrest* [*unrest*]:
  $[\![\ x \bowtie (\$tr)_v;\ x \bowtie (\$tr')_v;\ x \sharp P\ ]\!] \Longrightarrow x \sharp \neg_r P$
  by (*simp add*: *rea-not-def R1-def unrest lens-indep-sym*)

lemma *rea-impl-unrest* [*unrest*]:
  $[\![\ x \bowtie (\$tr)_v;\ x \bowtie (\$tr')_v;\ x \sharp P;\ x \sharp Q\ ]\!] \Longrightarrow x \sharp (P \Rightarrow_r Q)$
  by (*simp add*: *rea-impl-def unrest*)

lemma *rea-true-usubst* [*usubst*]:
$[\![\$tr \sharp \sigma; \$tr' \sharp \sigma]\!] \Longrightarrow \sigma \dagger true_r = true_r$
by (*simp add*: *R1-def usubst*)

lemma *rea-not-usubst* [*usubst*]:
$[\![\$tr \sharp \sigma; \$tr' \sharp \sigma]\!] \Longrightarrow \sigma \dagger (\neg_r P) = (\neg_r \sigma \dagger P)$
by (*simp add*: *rea-not-def R1-def usubst*)

lemma *rea-impl-usubst* [*usubst*]:
$[\![\$tr \sharp \sigma; \$tr' \sharp \sigma]\!] \Longrightarrow \sigma \dagger (P \Rightarrow_r Q) = (\sigma \dagger P \Rightarrow_r \sigma \dagger Q)$
by (*simp add*: *rea-impl-def usubst R1-def*)

lemma *rea-true-usubst-tt* [*usubst*]:
$R1(true)[\![e/\&tt]\!] = true$
by (*rel-simp*)

lemma *unrests-rea-rename* [*unrest*]:
$\$ok \sharp P \Longrightarrow \$ok \sharp P(\!|f|\!)_r$
$\$ok' \sharp P \Longrightarrow \$ok' \sharp P(\!|f|\!)_r$
$\$wait \sharp P \Longrightarrow \$wait \sharp P(\!|f|\!)_r$
$\$wait' \sharp P \Longrightarrow \$wait' \sharp P(\!|f|\!)_r$
by (*simp-all add*: *rea-rename-def R2-def unrest*)

lemma *unrest-rea-subst* [*unrest*]:
$[\![mwb\text{-}lens\ x; x \bowtie (\$tr)_v; x \bowtie (\$tr')_v; x \sharp v; x \sharp P]\!] \Longrightarrow x \sharp P[\![v]\!]_r$
by (*simp add*: *rea-subst-def R1-def unrest lens-indep-sym*)

lemma *rea-substs* [*usubst*]:
$true_r[\![v]\!]_r = true_r$ $true[\![v]\!]_r = true_r$ $false[\![v]\!]_r = false$
$(\neg_r P)[\![v]\!]_r = (\neg_r P[\![v]\!]_r)$ $(P \wedge Q)[\![v]\!]_r = (P[\![v]\!]_r \wedge Q[\![v]\!]_r)$ $(P \vee Q)[\![v]\!]_r = (P[\![v]\!]_r \vee Q[\![v]\!]_r)$
$(P \Rightarrow_r Q)[\![v]\!]_r = (P[\![v]\!]_r \Rightarrow_r Q[\![v]\!]_r)$
by *rel-auto+*

lemma *rea-substs-lattice* [*usubst*]:
$(\bigsqcap i \cdot P(i))[\![v]\!]_r = (\bigsqcap i \cdot (P(i))[\![v]\!]_r)$
$(\bigsqcap i{\in}A \cdot P(i))[\![v]\!]_r = (\bigsqcap i{\in}A \cdot (P(i))[\![v]\!]_r)$
$(\bigsqcup i \cdot P(i))[\![v]\!]_r = (\bigsqcup i \cdot (P(i))[\![v]\!]_r)$
by (*rel-auto*)+

lemma *rea-subst-USUP-set* [*usubst*]:
$A \neq \{\} \Longrightarrow (\bigsqcup i{\in}A \cdot P(i))[\![v]\!]_r = (\bigsqcup i{\in}A \cdot (P(i))[\![v]\!]_r)$
by (*rel-auto*)+

4.4 Closure laws

lemma *rea-lift-R1* [*closure*]: $[P]_r$ *is R1*
by (*rel-simp*)

lemma *R1-rea-not*: $R1(\neg_r P) = (\neg_r P)$
by *rel-auto*

lemma *R1-rea-not'*: $R1(\neg_r P) = (\neg_r R1(P))$
by *rel-auto*

lemma *R2c-rea-not*: $R2c(\neg_r P) = (\neg_r R2c(P))$

by *rel-auto*

lemma *RR-rea-not*: $RR(\neg_r\ RR(P)) = (\neg_r\ RR(P))$
by (*rel-auto*)

lemma *R1-rea-impl*: $R1(P \Rightarrow_r Q) = (P \Rightarrow_r R1(Q))$
by (*rel-auto*)

lemma *R1-rea-impl'*: $R1(P \Rightarrow_r Q) = (R1(P) \Rightarrow_r R1(Q))$
by (*rel-auto*)

lemma *R2c-rea-impl*: $R2c(P \Rightarrow_r Q) = (R2c(P) \Rightarrow_r R2c(Q))$
by (*rel-auto*)

lemma *RR-rea-impl*: $RR(RR(P) \Rightarrow_r RR(Q)) = (RR(P) \Rightarrow_r RR(Q))$
by (*rel-auto*)

lemma *rea-true-R1* [*closure*]: $true_r$ *is R1*
by (*rel-auto*)

lemma *rea-true-R2c* [*closure*]: $true_r$ *is R2c*
by (*rel-auto*)

lemma *rea-true-RR* [*closure*]: $true_r$ *is RR*
by (*rel-auto*)

lemma *rea-not-R1* [*closure*]: $\neg_r$ *P is R1*
by (*rel-auto*)

lemma *rea-not-R2c* [*closure*]: *P is R2c* $\Longrightarrow$ $\neg_r$ *P is R2c*
by (*simp add*: *Healthy-def rea-not-def R1-R2c-commute*[*THEN sym*] *R2c-not*)

lemma *rea-not-R2-closed* [*closure*]:
P is R2 $\Longrightarrow$ ($\neg_r$ *P*) *is R2*
by (*simp add*: *Healthy-def' R1-rea-not' R2-R2c-def R2c-rea-not*)

lemma *rea-no-RR* [*closure*]:
$[\![$ *P is RR* $]\!]$ $\Longrightarrow$ ($\neg_r$ *P*) *is RR*
by (*metis Healthy-def' RR-rea-not*)

lemma *rea-impl-R1* [*closure*]:
Q is R1 $\Longrightarrow$ ($P \Rightarrow_r Q$) *is R1*
by (*rel-blast*)

lemma *rea-impl-R2c* [*closure*]:
$[\![$ *P is R2c*; *Q is R2c* $]\!]$ $\Longrightarrow$ ($P \Rightarrow_r Q$) *is R2c*
by (*simp add*: *rea-impl-def Healthy-def rea-not-def R1-R2c-commute*[*THEN sym*] *R2c-not R2c-disj*)

lemma *rea-impl-R2* [*closure*]:
$[\![$ *P is R2*; *Q is R2* $]\!]$ $\Longrightarrow$ ($P \Rightarrow_r Q$) *is R2*
by (*rel-blast*)

lemma *rea-impl-RR* [*closure*]:
$[\![$ *P is RR*; *Q is RR* $]\!]$ $\Longrightarrow$ ($P \Rightarrow_r Q$) *is RR*
by (*metis Healthy-def' RR-rea-impl*)

lemma *conj-RR* [*closure*]:
  $\llbracket$ *P is RR*; *Q is RR* $\rrbracket \Longrightarrow$ $(P \wedge Q)$ *is RR*
  by (*meson RR-implies-R1 RR-implies-R2c RR-intro RR-unrests*(*1*−*4*) *conj-R1-closed-1 conj-R2c-closed unrest-conj*)

lemma *disj-RR* [*closure*]:
  $\llbracket$ *P is RR*; *Q is RR* $\rrbracket \Longrightarrow$ $(P \vee Q)$ *is RR*
  by (*metis Healthy-def′ R1-RR R1-idem R1-rea-not′ RR-rea-impl RR-rea-not disj-comm double-negation rea-impl-def rea-not-def*)

lemma *USUP-mem-RR-closed* [*closure*]:
  assumes $\bigwedge$ *i*. *i* $\in$ *A* $\Longrightarrow$ *P i is RR* *A* $\neq$ {}
  shows ($\bigsqcup$ *i*$\in$*A* · *P*(*i*)) *is RR*
proof −
  have *1*:($\bigsqcup$ *i*$\in$*A* · *P*(*i*)) *is R1*
    by (*unfold Healthy-def*, *subst R1-UINF*, *simp-all add*: *Healthy-if assms closure cong*: *USUP-cong*)
  have *2*:($\bigsqcup$ *i*$\in$*A* · *P*(*i*)) *is R2c*
    by (*unfold Healthy-def*, *subst R2c-UINF*, *simp-all add*: *Healthy-if assms RR-implies-R2c closure cong*: *USUP-cong*)
  show *?thesis*
    using *1 2* **by** (*rule-tac RR-intro*, *simp-all add*: *unrest assms*)
qed

lemma *USUP-ind-RR-closed* [*closure*]:
  assumes $\bigwedge$ *i*. *P i is RR*
  shows ($\bigsqcup$ *i* · *P*(*i*)) *is RR*
  using *USUP-mem-RR-closed*[*of UNIV P*] **by** (*simp add*: *assms*)

lemma *UINF-mem-RR-closed* [*closure*]:
  assumes $\bigwedge$ *i*. *i* $\in$ *A* $\Longrightarrow$ *P i is RR*
  shows ($\bigsqcap$ *i*$\in$*A* · *P*(*i*)) *is RR*
proof −
  have *1*:($\bigsqcap$ *i*$\in$*A* · *P*(*i*)) *is R1*
    by (*unfold Healthy-def*, *subst R1-USUP*, *simp add*: *Healthy-if RR-implies-R1 assms cong*: *UINF-cong*)
  have *2*:($\bigsqcap$ *i*$\in$*A* · *P*(*i*)) *is R2c*
    by (*unfold Healthy-def*, *subst R2c-USUP*, *simp add*: *Healthy-if RR-implies-R2c assms cong*: *UINF-cong*)
  show *?thesis*
    using *1 2* **by** (*rule-tac RR-intro*, *simp-all add*: *unrest assms*)
qed

lemma *UINF-ind-RR-closed* [*closure*]:
  assumes $\bigwedge$ *i*. *P i is RR*
  shows ($\bigsqcap$ *i* · *P*(*i*)) *is RR*
  by (*simp add*: *assms closure*)

lemma *USUP-elem-RR* [*closure*]:
  assumes $\bigwedge$ *i*. *P i is RR* *A* $\neq$ {}
  shows ($\bigsqcup$ *i* $\in$ *A* · *P i*) *is RR*
proof −
  have *1*:($\bigsqcup$ *i*$\in$*A* · *P*(*i*)) *is R1*
    by (*unfold Healthy-def*, *subst R1-UINF*, *simp-all add*: *Healthy-if assms closure*)
  have *2*:($\bigsqcup$ *i*$\in$*A* · *P*(*i*)) *is R2c*
    by (*unfold Healthy-def*, *subst R2c-UINF*, *simp-all add*: *Healthy-if assms RR-implies-R2c closure*)
  show *?thesis*

using *1 2* **by** (*rule-tac RR-intro*, *simp-all add*: *unrest assms*)
qed

lemma *seq-RR-closed* [*closure*]:
assumes *P is RR Q is RR*
shows *P* ;; *Q is RR*
unfolding *Healthy-def*
by (*simp add*: *RR-def Healthy-if assms closure RR-implies-R2 ex-unrest unrest*)

lemma *power-Suc-RR-closed* [*closure*]:
$P\ is\ RR \Longrightarrow P\ ;;\ P\ \hat{}\ i\ is\ RR$
by (*induct i*, *simp-all add*: *closure upred-semiring.power-Suc*)

lemma *seqr-iter-RR-closed* [*closure*]:
$[\![\ I \neq []; \bigwedge i.\ i \in set(I) \Longrightarrow P(i)\ is\ RR\ ]\!] \Longrightarrow (;;\ i : I \cdot P(i))\ is\ RR$
apply (*induct I*, *simp-all*)
apply (*rename-tac i I*)
apply (*case-tac I*)
apply (*simp-all add*: *seq-RR-closed*)
done

lemma *cond-tt-RR-closed* [*closure*]:
assumes *P is RR Q is RR*
shows $P \triangleleft \$tr' =_u \$tr \triangleright Q\ is\ RR$
apply (*rule RR-intro*)
apply (*simp-all add*: *unrest assms*)
apply (*simp-all add*: *Healthy-def*)
apply (*simp-all add*: *R1-cond R2c-condr Healthy-if assms RR-implies-R2c closure R2c-tr′-minus-tr*)
done

lemma *rea-skip-RR* [*closure*]:
$II_r\ is\ RR$
apply (*rel-auto*) **using** *minus-zero-eq* **by** *blast*

lemma *tr′-eq-tr-RR-closed* [*closure*]: $\$tr' =_u \$tr\ is\ RR$
apply (*rel-auto*) **using** *minus-zero-eq* **by** *auto*

lemma *inf-RR-closed* [*closure*]:
$[\![\ P\ is\ RR;\ Q\ is\ RR\ ]\!] \Longrightarrow P \sqcap Q\ is\ RR$
by (*simp add*: *disj-RR uinf-or*)

lemma *conj-tr-strict-RR-closed* [*closure*]:
assumes *P is RR*
shows $(P \wedge \$tr <_u \$tr')\ is\ RR$
proof −
have $RR(RR(P) \wedge \$tr <_u \$tr') = (RR(P) \wedge \$tr <_u \$tr')$
by (*rel-auto*)
thus *?thesis*
by (*metis Healthy-def assms*)
qed

lemma *rea-assert-RR-closed* [*closure*]:
assumes *b is RR*
shows $\{b\}_r\ is\ RR$
by (*simp add*: *closure assms rea-assert-def*)

lemma *upower-RR-closed* [*closure*]:
  $[\![i > 0; P \text{ is } RR]\!] \Longrightarrow P \hat{} i \text{ is } RR$
  apply (*induct i*, *simp-all*)
  apply (*rename-tac i*)
  apply (*case-tac i = 0*)
   apply (*simp-all add*: *closure upred-semiring.power-Suc*)
  done

lemma *seq-power-RR-closed* [*closure*]:
  assumes *P is RR Q is RR*
  shows $(P \hat{} i)$;; *Q is RR*
  by (*metis assms neq0-conv seq-RR-closed seqr-left-unit upower-RR-closed upred-semiring.power-0*)

lemma *ustar-right-RR-closed* [*closure*]:
  assumes *P is RR Q is RR*
  shows P ;; $Q^\star$ *is RR*
proof –
  have $P ;; Q^\star = P ;; (\bigsqcap\ i \in \{0..\} \cdot Q \hat{} i)$
    by (*simp add*: *ustar-def*)
  also have ... $= P ;; (II \sqcap (\bigsqcap\ i \in \{1..\} \cdot Q \hat{} i))$
    by (*metis One-nat-def UINF-atLeast-first upred-semiring.power-0*)
  also have ... $= (P \vee P ;; (\bigsqcap\ i \in \{1..\} \cdot Q \hat{} i))$
    by (*simp add*: *disj-upred-def*[*THEN sym*] *seqr-or-distr*)
  also have ... *is RR*
  proof –
    have $(\bigsqcap\ i \in \{1..\} \cdot Q \hat{} i)$ *is RR*
      by (*rule UINF-mem-Continuous-closed*, *simp-all add*: *assms closure*)
    thus *?thesis*
      by (*simp add*: *assms closure*)
  qed
  finally show *?thesis* **.**
qed

lemma *ustar-left-RR-closed* [*closure*]:
  assumes *P is RR Q is RR*
  shows $P^\star$;; *Q is RR*
proof –
  have $P^\star ;; Q = (\bigsqcap\ i \in \{0..\} \cdot P \hat{} i) ;; Q$
    by (*simp add*: *ustar-def*)
  also have ... $= (II \sqcap (\bigsqcap\ i \in \{1..\} \cdot P \hat{} i)) ;; Q$
    by (*metis One-nat-def UINF-atLeast-first upred-semiring.power-0*)
  also have ... $= (Q \vee (\bigsqcap\ i \in \{1..\} \cdot P \hat{} i) ;; Q)$
    by (*simp add*: *disj-upred-def*[*THEN sym*] *seqr-or-distl*)
  also have ... *is RR*
  proof –
    have $(\bigsqcap\ i \in \{1..\} \cdot P \hat{} i)$ *is RR*
      by (*rule UINF-mem-Continuous-closed*, *simp-all add*: *assms closure*)
    thus *?thesis*
      by (*simp add*: *assms closure*)
  qed
  finally show *?thesis* **.**
qed

lemma *uplus-RR-closed* [*closure*]: *P is RR* $\Longrightarrow P^+$ *is RR*

by (*simp add*: *uplus-def ustar-right-RR-closed*)

lemma *trace-ext-prefix-RR* [*closure*]:
$\llbracket$ $\$tr$ $\sharp$ e; $\$ok$ $\sharp$ e; $\$wait$ $\sharp$ e; $out\alpha$ $\sharp$ e $\rrbracket \Longrightarrow \$tr$ $\hat{}_u$ $e \le_u \$tr'$ *is RR*
apply (*rel-auto*)
apply (*metis* (*no-types*, *lifting*) *Prefix-Order.same-prefix-prefix less-eq-list-def prefix-concat-minus zero-list-def*)
apply (*metis append-minus list-append-prefixD minus-cancel-le order-refl*)
done

lemma *rea-subst-R1-closed* [*closure*]: $P\llbracket v \rrbracket_r$ *is R1*
by (*rel-auto*)

lemma *R5-comp* [*rpred*]:
assumes P *is RR* Q *is RR*
shows $R5(P$;; $Q) = R5(P)$;; $R5(Q)$
proof –
have $R5(RR(P)$;; $RR(Q)) = R5(RR(P))$;; $R5(RR(Q))$
by (*rel-auto*; *force*)
thus *?thesis*
by (*simp add*: *Healthy-if assms*)
qed

lemma *R4-comp* [*rpred*]:
assumes P *is R4* Q *is RR*
shows $R4(P$;; $Q) = P$;; Q
proof –
have $R4(R4(P)$;; $RR(Q)) = R4(P)$;; $RR(Q)$
by (*rel-auto*, *blast*)
thus *?thesis*
by (*simp add*: *Healthy-if assms*)
qed

lemma *rea-rename-RR-closed* [*closure*]:
assumes P *is RR*
shows $P(\!|f|\!)_r$ *is RR*
proof –
have $(RR\ P)(\!|f|\!)_r$ *is RR*
by (*rel-auto*)
thus *?thesis*
by (*simp add*: *Healthy-if assms*)
qed

4.5 Reactive relational calculus

lemma *rea-skip-unit* [*rpred*]:
assumes P *is RR*
shows P ;; $II_r = P$ II_r ;; $P = P$
proof –
have *1*: $RR(P)$;; $II_r = RR(P)$
by (*rel-auto*)
have *2*: II_r ;; $RR(P) = RR(P)$
by (*rel-auto*)
from *1 2* **show** P ;; $II_r = P$ II_r ;; $P = P$
by (*simp-all add*: *Healthy-if assms*)
qed

lemma *rea-true-conj* [*rpred*]:
assumes P *is* $R1$
shows $(true_r \wedge P) = P$ $(P \wedge true_r) = P$
using *assms*
by (*simp-all add*: *Healthy-def R1-def utp-pred-laws.inf-commute*)

lemma *rea-true-disj* [*rpred*]:
assumes P *is* $R1$
shows $(true_r \vee P) = true_r$ $(P \vee true_r) = true_r$
using *assms* **by** (*metis Healthy-def R1-disj disj-comm true-disj-zero*)+

lemma *rea-not-not* [*rpred*]: P *is* $R1 \Longrightarrow (\neg_r \neg_r P) = P$
by (*simp add*: *rea-not-def R1-negate-R1 Healthy-if*)

lemma *rea-not-rea-true* [*simp*]: $(\neg_r\ true_r) = false$
by (*simp add*: *rea-not-def R1-negate-R1 R1-false*)

lemma *rea-not-false* [*simp*]: $(\neg_r\ false) = true_r$
by (*simp add*: *rea-not-def*)

lemma *rea-true-impl* [*rpred*]:
P *is* $R1 \Longrightarrow (true_r \Rightarrow_r P) = P$
by (*simp add*: *rea-not-def rea-impl-def R1-negate-R1 R1-false Healthy-if*)

lemma *rea-true-impl'* [*rpred*]:
P *is* $R1 \Longrightarrow (true \Rightarrow_r P) = P$
by (*simp add*: *rea-not-def rea-impl-def R1-negate-R1 R1-false Healthy-if*)

lemma *rea-false-impl* [*rpred*]:
P *is* $R1 \Longrightarrow (false \Rightarrow_r P) = true_r$
by (*simp add*: *rea-impl-def rpred Healthy-if*)

lemma *rea-impl-true* [*simp*]: $(P \Rightarrow_r true_r) = true_r$
by (*rel-auto*)

lemma *rea-impl-false* [*simp*]: $(P \Rightarrow_r false) = (\neg_r P)$
by (*rel-simp*)

lemma *rea-imp-refl* [*rpred*]: P *is* $R1 \Longrightarrow (P \Rightarrow_r P) = true_r$
by (*rel-blast*)

lemma *rea-impl-conj* [*rpred*]:
$(P \Rightarrow_r Q \Rightarrow_r R) = ((P \wedge Q) \Rightarrow_r R)$
by (*rel-auto*)

lemma *rea-impl-mp* [*rpred*]:
$(P \wedge (P \Rightarrow_r Q)) = (P \wedge Q)$
by (*rel-auto*)

lemma *rea-impl-conj-combine* [*rpred*]:
$((P \Rightarrow_r Q) \wedge (P \Rightarrow_r R)) = (P \Rightarrow_r Q \wedge R)$
by (*rel-auto*)

lemma *rea-impl-alt-def*:
assumes Q *is* $R1$

shows $(P \Rightarrow_r Q) = R1(P \Rightarrow Q)$
proof $-$
have $(P \Rightarrow_r R1(Q)) = R1(P \Rightarrow Q)$
by (*rel-auto*)
thus *?thesis*
by (*simp add*: *assms Healthy-if*)
qed

lemma *rea-impl-disj*:
$(P \Rightarrow_r Q \vee R) = (Q \vee (P \Rightarrow_r R))$
by (*rel-auto*)

lemma *rea-not-true* [*simp*]: $(\neg_r\ true) = false$
by (*rel-auto*)

lemma *rea-not-demorgan1* [*simp*]:
$(\neg_r (P \wedge Q)) = (\neg_r P \vee \neg_r Q)$
by (*rel-auto*)

lemma *rea-not-demorgan2* [*simp*]:
$(\neg_r (P \vee Q)) = (\neg_r P \wedge \neg_r Q)$
by (*rel-auto*)

lemma *rea-not-or* [*rpred*]:
$P\ is\ R1 \Longrightarrow (P \vee \neg_r P) = true_r$
by (*rel-blast*)

lemma *rea-not-and* [*simp*]:
$(P \wedge \neg_r P) = false$
by (*rel-auto*)

lemma *truer-bottom-rpred* [*rpred*]: $P\ is\ RR \Longrightarrow R1(true) \sqsubseteq P$
by (*metis Healthy-def R1-RR R1-mono utp-pred-laws.top-greatest*)

lemma *rea-not-INFIMUM* [*simp*]:
$(\neg_r (\bigsqcup i{\in}A.\ Q(i))) = (\bigsqcap i{\in}A.\ \neg_r Q(i))$
by (*rel-auto*)

lemma *rea-not-USUP* [*simp*]:
$(\neg_r (\bigsqcup i{\in}A \cdot Q(i))) = (\bigsqcap i{\in}A \cdot \neg_r Q(i))$
by (*rel-auto*)

lemma *rea-not-SUPREMUM* [*simp*]:
$A \neq \{\} \Longrightarrow (\neg_r (\bigsqcap i{\in}A.\ Q(i))) = (\bigsqcup i{\in}A.\ \neg_r Q(i))$
by (*rel-auto*)

lemma *rea-not-UINF* [*simp*]:
$A \neq \{\} \Longrightarrow (\neg_r (\bigsqcap i{\in}A \cdot Q(i))) = (\bigsqcup i{\in}A \cdot \neg_r Q(i))$
by (*rel-auto*)

lemma *USUP-mem-rea-true* [*simp*]: $A \neq \{\} \Longrightarrow (\bigsqcup\ i \in A \cdot true_r) = true_r$
by (*rel-auto*)

lemma *USUP-ind-rea-true* [*simp*]: $(\bigsqcup\ i \cdot true_r) = true_r$
by (*rel-auto*)

lemma *UINF-ind-rea-true* [*rpred*]: $A \neq \{\} \Longrightarrow (\prod\ i{\in}A \cdot true_r) = true_r$
  by (*rel-auto*)

lemma *UINF-rea-impl*: $(\prod\ P{\in}A \cdot F(P) \Rightarrow_r G(P)) = ((\bigsqcup\ P{\in}A \cdot F(P)) \Rightarrow_r (\prod\ P{\in}A \cdot G(P)))$
  by (*rel-auto*)

lemma *rea-not-shEx* [*rpred*]: $(\neg_r\ shEx\ P) = (shAll\ (\lambda\ x.\ \neg_r\ P\ x))$
  by (*rel-auto*)

lemma *rea-assert-true*:
  $\{true_r\}_r = II_r$
  by (*rel-auto*)

lemma *rea-false-true*:
  $\{false\}_r = true_r$
  by (*rel-auto*)

lemma *rea-rename-id* [*rpred*]:
  assumes *P is RR*
  shows $P(\|id\|)_r = P$
proof –
  have $(RR\ P)(\|id\|)_r = RR\ P$
    by (*rel-auto*)
  thus *?thesis* **by** (*simp add*: *Healthy-if assms*)
qed

lemma *rea-rename-comp* [*rpred*]:
  assumes *renamer f renamer g P is RR*
  shows $P(\|g \circ f\|)_r = P(\|g\|)_r(\|f\|)_r$
  oops

lemma *rea-rename-false* [*rpred*]: $false(\|f\|)_r = false$
  by (*rel-auto*)

lemma *rea-rename-disj* [*rpred*]:
  $(P \vee Q)(\|f\|)_r = (P(\|f\|)_r \vee Q(\|f\|)_r)$
  by (*rel-blast*)

lemma *rea-rename-UINF-ind* [*rpred*]:
  $(\prod\ i \cdot P\ i)(\|f\|)_r = (\prod\ i \cdot (P\ i)(\|f\|)_r)$
  by (*rel-blast*)

lemma *rea-rename-UINF-mem* [*rpred*]:
  $(\prod\ i{\in}A \cdot P\ i)(\|f\|)_r = (\prod\ i{\in}A \cdot (P\ i)(\|f\|)_r)$
  by (*rel-blast*)

lemma *rea-rename-conj* [*rpred*]:
  assumes *renamer f P is RR Q is RR*
  shows $(P \wedge Q)(\|f\|)_r = (P(\|f\|)_r \wedge Q(\|f\|)_r)$
proof –
  interpret *ren*: *renamer f* **by** (*simp add*: *assms*)
  have $(RR\ P \wedge RR\ Q)(\|f\|)_r = ((RR\ P)(\|f\|)_r \wedge (RR\ Q)(\|f\|)_r)$
    using *injD*[*OF ren.injective*]
    by (*rel-auto*; *blast*)

thus *?thesis* **by** (*simp add*: *Healthy-if assms*)
qed

lemma *rea-rename-USUP-ind* [*rpred*]:
  assumes *renamer f* $\bigwedge$ *i*. *P i is RR*
  shows $(\bigsqcup\ i \cdot P\ i)(\!|f|\!)_r = (\bigsqcup\ i \cdot (P\ i)(\!|f|\!)_r)$
proof −
  interpret *ren*: *renamer f* **by** (*simp add*: *assms*)
  have $(\bigsqcup\ i \cdot RR(P\ i))(\!|f|\!)_r = (\bigsqcup\ i \cdot (RR\ (P\ i))(\!|f|\!)_r)$
    using *injD*[*OF ren.injective*]
    by (*rel-auto*, *blast*, *metis* (*mono-tags*, *hide-lams*))
  thus *?thesis*
    by (*simp add*: *Healthy-if assms cong*: *USUP-all-cong*)
qed

lemma *rea-rename-USUP-mem* [*rpred*]:
  assumes *renamer f* $A \neq \{\}$ $\bigwedge$ *i*. $i \in A \Longrightarrow$ *P i is RR*
  shows $(\bigsqcup\ i{\in}A \cdot P\ i)(\!|f|\!)_r = (\bigsqcup\ i{\in}A \cdot (P\ i)(\!|f|\!)_r)$
proof −
  interpret *ren*: *renamer f* **by** (*simp add*: *assms*)
  have $(\bigsqcup\ i{\in}A \cdot RR(P\ i))(\!|f|\!)_r = (\bigsqcup\ i{\in}A \cdot (RR\ (P\ i))(\!|f|\!)_r)$
    using *injD*[*OF ren.injective*] *assms*(*2*)
    by (*rel-auto*, *blast*, *metis* (*no-types*, *hide-lams*))
  thus *?thesis*
    by (*simp add*: *Healthy-if assms cong*: *USUP-cong*)
qed

lemma *rea-rename-skip-rea* [*rpred*]: *renamer f* $\Longrightarrow II_r(\!|f|\!)_r = II_r$
  using *minus-zero-eq* **by** (*rel-auto*)

lemma *rea-rename-seq* [*rpred*]:
  assumes *renamer f P is RR Q is RR*
  shows $(P\ ;;\ Q)(\!|f|\!)_r = P(\!|f|\!)_r\ ;;\ Q(\!|f|\!)_r$
proof −
  interpret *ren*: *renamer f* **by** (*simp add*: *assms*)
  from *assms*(*1*) **have** $(RR(P)\ ;;\ RR(Q))(\!|f|\!)_r = (RR\ P)(\!|f|\!)_r\ ;;\ (RR\ Q)(\!|f|\!)_r$
    by (*rel-auto*)
      (*metis* (*no-types*, *lifting*) *diff-add-cancel-left′ le-add minus-assoc mono-def ren.minus ren.monotonic trace-class.add-diff-cancel-left trace-class.add-left-mono*)+
  thus *?thesis*
    by (*simp add*: *Healthy-if assms*)
qed

declare *R4-idem* [*rpred*]
declare *R4-false* [*rpred*]
declare *R4-conj* [*rpred*]
declare *R4-disj* [*rpred*]

declare *R4-R5* [*rpred*]
declare *R5-R4* [*rpred*]

declare *R5-conj* [*rpred*]
declare *R5-disj* [*rpred*]

lemma *R4-USUP* [*rpred*]: $I \neq \{\} \Longrightarrow R4(\bigsqcup\ i{\in}I \cdot P(i)) = (\bigsqcup\ i{\in}I \cdot R4(P(i)))$

by (*rel-auto*)

lemma *R5-USUP* [*rpred*]: $I \neq \{\} \Longrightarrow R5(\bigsqcup\ i{\in}I \cdot P(i)) = (\bigsqcup\ i{\in}I \cdot R5(P(i)))$
by (*rel-auto*)

lemma *R4-UINF* [*rpred*]: $R4(\bigsqcap\ i{\in}I \cdot P(i)) = (\bigsqcap\ i{\in}I \cdot R4(P(i)))$
by (*rel-auto*)

lemma *R5-UINF* [*rpred*]: $R5(\bigsqcap\ i{\in}I \cdot P(i)) = (\bigsqcap\ i{\in}I \cdot R5(P(i)))$
by (*rel-auto*)

4.6 UTP theory

We create a UTP theory of reactive relations which in particular provides Kleene star theorems

typedecl *RREL*

abbreviation $RREL \equiv UTHY(RREL, ('t{::}trace,'\alpha)\ rp)$

overloading
rrel-hcond == *utp-hcond* :: (*RREL*, ('*t*::*trace*,'α) *rp*) *uthy* ⇒ (('*t*,'α) *rp* × ('*t*,'α) *rp*) *health*
rrel-unit == *utp-unit* :: (*RREL*, ('*t*::*trace*,'α) *rp*) *uthy* ⇒ ('*t*, 'α) *hrel-rp*
begin
definition *rrel-hcond* :: (*RREL*, ('*t*::*trace*,'α) *rp*) *uthy* ⇒ (('*t*,'α) *rp* × ('*t*,'α) *rp*) *health* **where**
[*upred-defs*]: *rrel-hcond* $T = RR$
definition *rrel-unit* :: (*RREL*, ('*t*::*trace*,'α) *rp*) *uthy* ⇒ ('*t*,'α) *hrel-rp* **where**
[*upred-defs*]: *rrel-unit* $T = II_r$
end

interpretation *rrel-thy*: *utp-theory-kleene* $UTHY(RREL, ('t{::}trace,'\alpha)\ rp)$
rewrites $\bigwedge P.\ P \in carrier\ (uthy\text{-}order\ RREL) \longleftrightarrow P\ is\ RR$
and $P\ is\ \mathcal{H}_{RREL} \longleftrightarrow P\ is\ RR$
and $carrier\ (uthy\text{-}order\ RREL) \to carrier\ (uthy\text{-}order\ RREL) \equiv [\![RR]\!]_H \to [\![RR]\!]_H$
and $[\![\mathcal{H}_{RREL}]\!]_H \to [\![\mathcal{H}_{RREL}]\!]_H \equiv [\![RR]\!]_H \to [\![RR]\!]_H$
and $\top_{RREL} = false$
and $\mathcal{II}_{RREL} = II_r$
and *le* (*uthy-order RREL*) = (⊑)
proof −
interpret *lat*: *utp-theory-continuous* $UTHY(RREL, ('t{::}trace,'\alpha)\ rp)$
by (*unfold-locales*, *simp-all add*: *rrel-hcond-def rrel-unit-def closure Healthy-if rpred*)
show *1*: $\top_{RREL} = (false :: ('t,'\alpha)\ hrel\text{-}rp)$
by (*metis Healthy-if lat.healthy-top rea-no-RR rea-not-rea-true rea-true-RR rrel-hcond-def*)
thus *utp-theory-kleene* $UTHY(RREL, ('t,'\alpha)\ rp)$
by (*unfold-locales*, *simp-all add*: *rrel-hcond-def rrel-unit-def closure Healthy-if rpred*)
qed (*simp-all add*: *rrel-hcond-def rrel-unit-def closure Healthy-if rpred*)

declare *rrel-thy.top-healthy* [*simp del*]
declare *rrel-thy.bottom-healthy* [*simp del*]

abbreviation *rea-star* :: - ⇒ - ($\text{-}^{\star r}$ [*999*] *999*) **where**
$P^{\star r} \equiv P\bigstar_{RREL}$

The supernova tactic explodes conjectures using the Kleene star laws and relational calculus

method *supernova* = ((*safe intro*!: *rrel-thy.Star-inductr rrel-thy.Star-inductl*, *simp-all add*: *closure*) ; *rel-auto*)[*1*]

4.7 Instantaneous Reactive Relations

Instantaneous Reactive Relations, where the trace stays the same.

abbreviation *Instant* :: $('t::trace, '\alpha)$ *hrel-rp* $\Rightarrow$ $('t, '\alpha)$ *hrel-rp* **where**
$Instant(P) \equiv RID(tr)(P)$

lemma *skip-rea-Instant* [*closure*]: II_r *is Instant*
  by (*rel-auto*)

end

5 Reactive Conditions

theory *utp-rea-cond*
  imports *utp-rea-rel*
begin

5.1 Healthiness Conditions

definition *RC1* :: $('t::trace, '\alpha, '\beta)$ *rel-rp* $\Rightarrow$ $('t, '\alpha, '\beta)$ *rel-rp* **where**
[*upred-defs*]: $RC1(P) = (\neg_r (\neg_r P) ;; true_r)$

definition *RC* :: $('t::trace, '\alpha, '\beta)$ *rel-rp* $\Rightarrow$ $('t, '\alpha, '\beta)$ *rel-rp* **where**
[*upred-defs*]: $RC = RC1 \circ RR$

lemma *RC-intro*: $[\![P$ *is* $RR; ((\neg_r (\neg_r P) ;; true_r) = P)]\!] \Longrightarrow P$ *is* RC
  by (*simp add*: *Healthy-def RC1-def RC-def*)

lemma *RC-intro'*: $[\![P$ *is* $RR; P$ *is* $RC1]\!] \Longrightarrow P$ *is* RC
  by (*simp add*: *Healthy-def RC1-def RC-def*)
lemma *RC1-idem*: $RC1(RC1(P)) = RC1(P)$
  by (*rel-auto*, (*blast intro*: *dual-order.trans*)+)

lemma *RC1-mono*: $P \sqsubseteq Q \Longrightarrow RC1(P) \sqsubseteq RC1(Q)$
  by (*rel-blast*)

lemma *RC1-prop*:
  assumes *P is RC1*
  shows $(\neg_r P) ;; R1\ true = (\neg_r P)$
proof −
  have $(\neg_r P) = (\neg_r (RC1\ P))$
    by (*simp add*: *Healthy-if assms*)
  also have ... $= (\neg_r P) ;; R1\ true$
    by (*simp add*: *RC1-def rpred closure*)
  finally show *?thesis* **..**
qed

lemma *R2-RC*: $R2\ (RC\ P) = RC\ P$
proof −
  have $\neg_r$ *RR P is RR*
    by (*metis* (*no-types*) *Healthy-Idempotent RR-Idempotent RR-rea-not*)
  then show *?thesis*
    by (*metis* (*no-types*) *Healthy-def' R1-R2c-seqr-distribute R2-R2c-def RC1-def RC-def RR-implies-R1 RR-implies-R2c comp-apply rea-not-R2-closed rea-true-R1 rea-true-R2c*)
qed

lemma *RC-R2-def*: $RC = RC1 \circ RR$
by (*auto simp add*: *RC-def fun-eq-iff R1-R2c-commute*[*THEN sym*] *R1-R2c-is-R2*)

lemma *RC-implies-R2*: P *is* $RC \Longrightarrow P$ *is* $R2$
by (*metis Healthy-def′ R2-RC*)

lemma *RC-ex-ok-wait*: $(\exists \{\$ok, \$ok', \$wait, \$wait'\} \cdot RC\ P) = RC\ P$
by (*rel-auto*)

An important property of reactive conditions is they are monotonic with respect to the trace. That is, P with a shorter trace is refined by P with a longer trace.

lemma *RC-prefix-refine*:
assumes P *is* RC $s \le t$
shows $P[\![0,\ll s\gg/\$tr,\$tr']\!] \sqsubseteq P[\![0,\ll t\gg/\$tr,\$tr']\!]$
proof −
from *assms*(*2*) **have** $(RC\ P)[\![0,\ll s\gg/\$tr,\$tr']\!] \sqsubseteq (RC\ P)[\![0,\ll t\gg/\$tr,\$tr']\!]$
apply (*rel-auto*)
using *dual-order.trans* **apply** *blast*
done
thus *?thesis*
by (*simp only*: *assms*(*1*) *Healthy-if*)
qed

5.2 Closure laws

lemma *RC-implies-RR* [*closure*]:
assumes P *is* RC
shows P *is* RR
by (*metis Healthy-def RC-ex-ok-wait RC-implies-R2 RR-def assms*)

lemma *RC-implies-RC1*: P *is* $RC \Longrightarrow P$ *is* $RC1$
by (*metis Healthy-def RC-R2-def RC-implies-RR comp-eq-dest-lhs*)

lemma *RC1-trace-ext-prefix*:
$out\alpha \sharp e \Longrightarrow RC1(\neg_r \$tr\ \hat{}_u\ e \le_u \$tr') = (\neg_r \$tr\ \hat{}_u\ e \le_u \$tr')$
by (*rel-auto*, *blast*, *metis* (*no-types*, *lifting*) *dual-order.trans*)

lemma *RC1-conj* [*rpred*]: $RC1(P \wedge Q) = (RC1(P) \wedge RC1(Q))$
by (*rel-blast*)

lemma *conj-RC1-closed* [*closure*]:
$[\![$ P *is* $RC1$; Q *is* $RC1$ $]\!] \Longrightarrow P \wedge Q$ *is* $RC1$
by (*simp add*: *Healthy-def RC1-conj*)

lemma *disj-RC1-closed* [*closure*]:
assumes P *is* $RC1$ Q *is* $RC1$
shows $(P \vee Q)$ *is* $RC1$
proof −
have *1*:$RC1(RC1(P) \vee RC1(Q)) = (RC1(P) \vee RC1(Q))$
apply (*rel-auto*) **using** *dual-order.trans* **by** *blast+*
show *?thesis*
by (*metis* (*no-types*) *Healthy-def 1 assms*)
qed

lemma *conj-RC-closed* [*closure*]:
  assumes P *is RC* Q *is RC*
  shows $(P \wedge Q)$ *is RC*
  by (*metis Healthy-def RC-R2-def RC-implies-RR assms comp-apply conj-RC1-closed conj-RR*)

lemma *rea-true-RC* [*closure*]: $true_r$ *is RC*
  by (*rel-auto*)

lemma *false-RC* [*closure*]: *false is RC*
  by (*rel-auto*)

lemma *disj-RC-closed* [*closure*]: $[\![P$ *is RC*; Q *is RC* $]\!] \Longrightarrow (P \vee Q)$ *is RC*
  by (*metis Healthy-def RC-R2-def RC-implies-RR comp-apply disj-RC1-closed disj-RR*)

lemma *UINF-mem-RC1-closed* [*closure*]:
  assumes $\bigwedge i.\ P\ i$ *is RC1*
  shows $(\bigsqcap\ i{\in}A \cdot P\ i)$ *is RC1*
proof −
  have *1*:$RC1(\bigsqcap\ i{\in}A \cdot RC1(P\ i)) = (\bigsqcap\ i{\in}A \cdot RC1(P\ i))$
    by (*rel-auto*, *meson order.trans*)
  show *?thesis*
    by (*metis* (*mono-tags*, *lifting*) *1 Healthy-def′ UINF-all-cong UINF-alt-def assms*)
qed

lemma *UINF-mem-RC-closed* [*closure*]:
  assumes $\bigwedge i.\ P\ i$ *is RC*
  shows $(\bigsqcap\ i{\in}A \cdot P\ i)$ *is RC*
proof −
  have $RC(\bigsqcap\ i{\in}A \cdot P\ i) = (RC1 \circ RR)(\bigsqcap\ i{\in}A \cdot P\ i)$
    by (*simp add*: *RC-def*)
  also have ... $= RC1(\bigsqcap\ i{\in}A \cdot RR(P\ i))$
    by (*rel-blast*)
  also have ... $= RC1(\bigsqcap\ i{\in}A \cdot RC1(P\ i))$
    by (*simp add*: *Healthy-if RC-implies-RR RC-implies-RC1 assms*)
  also have ... $= (\bigsqcap\ i{\in}A \cdot RC1(P\ i))$
    by (*rel-auto*, *meson order.trans*)
  also have ... $= (\bigsqcap\ i{\in}A \cdot P\ i)$
    by (*simp add*: *Healthy-if RC-implies-RC1 assms*)
  finally show *?thesis*
    by (*simp add*: *Healthy-def*)
qed

lemma *UINF-ind-RC-closed* [*closure*]:
  assumes $\bigwedge i.\ P\ i$ *is RC*
  shows $(\bigsqcap\ i \cdot P\ i)$ *is RC*
  by (*metis* (*no-types*) *UINF-as-Sup-collect′ UINF-as-Sup-image UINF-mem-RC-closed assms*)

lemma *USUP-mem-RC1-closed* [*closure*]:
  assumes $\bigwedge i.\ i \in A \Longrightarrow P\ i$ *is RC1* $A \neq \{\}$
  shows $(\bigsqcup\ i{\in}A \cdot P\ i)$ *is RC1*
proof −
  have $RC1(\bigsqcup\ i{\in}A \cdot P\ i) = RC1(\bigsqcup\ i{\in}A \cdot RC1(P\ i))$
    by (*simp add*: *Healthy-if assms*(*1*) *cong*: *USUP-cong*)
  also from *assms*(*2*) **have** ... $= (\bigsqcup\ i{\in}A \cdot RC1(P\ i))$
    using *dual-order.trans* **by** (*rel-blast*)

also have ... = ($\bigsqcup$ $i{\in}A$ $\cdot$ P i)
  by (*simp add*: *Healthy-if assms*(*1*) *cong*: *USUP-cong*)
finally show *?thesis*
  using *Healthy-def* **by** *blast*
qed

lemma *USUP-mem-RC-closed* [*closure*]:
  assumes $\bigwedge$ *i*. $i \in A \Longrightarrow P\ i$ *is* RC $A \neq \{\}$
  shows ($\bigsqcup$ $i{\in}A$ $\cdot$ P i) *is* RC
  by (*rule RC-intro'*, *simp-all add*: *closure assms RC-implies-RC1*)

lemma *USUP-ind-RC-closed* [*closure*]:
  $[\![$ $\bigwedge$ *i*. P i *is* RC $]\!]$ $\Longrightarrow$ ($\bigsqcup$ i $\cdot$ P i) *is* RC
  by (*metis UNIV-not-empty USUP-mem-RC-closed USUP-mem-UNIV*)

lemma *neg-trace-ext-prefix-RC* [*closure*]:
  $[\![$ $\$tr \sharp e$; $\$ok \sharp e$; $\$wait \sharp e$; $out\alpha \sharp e$ $]\!]$ $\Longrightarrow$ $\neg_r$ $\$tr$ $\hat{}_u$ e $\leq_u$ $\$tr'$ *is* RC
  by (*rule RC-intro*, *simp add*: *closure*, *metis RC1-def RC1-trace-ext-prefix*)

lemma *RC1-unrest*:
  $[\![$ *mwb-lens* x; $x \bowtie tr$ $]\!]$ $\Longrightarrow$ $\$x' \sharp$ *RC1*(P)
  by (*simp add*: *RC1-def unrest*)

lemma *RC-unrest-dashed* [*unrest*]:
  $[\![$ P *is* RC; *mwb-lens* x; $x \bowtie tr$ $]\!]$ $\Longrightarrow$ $\$x' \sharp P$
  by (*metis Healthy-if RC1-unrest RC-implies-RC1*)

lemma *RC1-RR-closed* [*closure*]: P *is* RR $\Longrightarrow$ *RC1*(P) *is* RR
  by (*simp add*: *RC1-def closure*)

end

6 Reactive Programs

theory *utp-rea-prog*
  imports *utp-rea-cond*
begin

6.1 Stateful reactive alphabet

R3 as presented in the UTP book and related publications is not sensitive to state, although reactive programs often need this property. Thus is is necessary to use a modification of *R3* from Butterfield et al. [1] that explicitly states that intermediate waiting states do not propogate final state variables. In order to do this we need an additional observational variable that capture the program state that we call *st*. Upon this foundation, we can define operators for reactive programs [3].

alphabet *'s rsp-vars* = *'t rp-vars* +
  st :: *'s*

declare *rsp-vars.defs* [*lens-defs*]

type-synonym ('s,'t,'α) *rsp* = ('t, ('s, 'α) *rsp-vars-scheme*) *rp*
type-synonym ('s,'t,'α,'β) *rel-rsp* = (('s,'t,'α) *rsp*, ('s,'t,'β) *rsp*) *urel*
type-synonym ('s,'t,'α) *hrel-rsp* = ('s,'t,'α) *rsp hrel*

type-synonym $('s,'t)$ *rdes* = $('s,'t,unit)$ *hrel-rsp*

translations
  $(type)$ $('s,'t,'\alpha)$ *rsp* <= $(type)$ $('t, ('s, '\alpha)$ *rsp-vars-ext*$)$ *rp*
  $(type)$ $('s,'t,'\alpha)$ *rsp* <= $(type)$ $('t, ('s, '\alpha)$ *rsp-vars-scheme*$)$ *rp*
  $(type)$ $('s,'t,unit)$ *rsp* <= $(type)$ $('t, 's$ *rsp-vars*$)$ *rp*
  $(type)$ $('s,'t,'\alpha,'\beta)$ *rel-rsp* <= $(type)$ $(('s,'t,'\alpha)$ *rsp*, $('s1,'t1,'\beta)$ *rsp*$)$ *urel*
  $(type)$ $('s,'t,'\alpha)$ *hrel-rsp* <= $(type)$ $('s, 't, '\alpha)$ *rsp hrel*
  $(type)$ $('s,'t)$ *rdes* <= $(type)$ $('s, 't, unit)$ *hrel-rsp*

notation *rsp-vars-child-lens*$_a$ (Σ_s)
notation *rsp-vars-child-lens* (Σ_S)

syntax
  -svid-st-alpha :: *svid* (Σ_S)

translations
  -svid-st-alpha => *CONST rsp-vars-child-lens*

lemma *st-bij-lemma*: *bij-lens* $(st_a +_L \Sigma_s)$
  by (*unfold-locales*, *auto simp add*: *lens-defs*)

lemma *rea-lens-equiv-st-rest*: $\Sigma_R \approx_L st +_L \Sigma_S$
proof −
  have $st +_L \Sigma_S = (st_a +_L \Sigma_s) ;_L \Sigma_R$
    by (*simp add*: *plus-lens-distr st-def rsp-vars-child-lens-def*)
  also have ... $\approx_L 1_L ;_L \Sigma_R$
    using *lens-equiv-via-bij st-bij-lemma* **by** *auto*
  also have ... $= \Sigma_R$
    by (*simp*)
  finally show *?thesis*
    using *lens-equiv-sym* **by** *blast*
qed

lemma *srea-lens-bij*: *bij-lens* $(ok +_L wait +_L tr +_L st +_L \Sigma_S)$
proof −
  have $ok +_L wait +_L tr +_L st +_L \Sigma_S \approx_L ok +_L wait +_L tr +_L \Sigma_R$
    by (*auto intro*!:*lens-plus-cong*, *rule lens-equiv-sym*, *simp add*: *rea-lens-equiv-st-rest*)
  also have ... $\approx_L 1_L$
    using *bij-lens-equiv-id*[*of* $ok +_L wait +_L tr +_L \Sigma_R$] **by** (*simp add*: *rea-lens-bij*)
  finally show *?thesis*
    by (*simp add*: *bij-lens-equiv-id*)
qed

lemma *st-qual-alpha* [*alpha*]: $x ;_L fst_L ;_L st \times_L st = (\$st{:}x)_v$
  by (*metis* (*no-types*, *hide-lams*) *in-var-def in-var-prod-lens lens-comp-assoc st-vwb-lens vwb-lens-wb*)

interpretation *alphabet-state*:
  lens-interp $\lambda(ok, wait, tr, r). (ok, wait, tr, st_v\ r, more\ r)$
  apply (*unfold-locales*)
  apply (*rule injI*)
  apply (*clarsimp*)
  done

interpretation *alphabet-state-rel*: *lens-interp* $\lambda(ok, ok', wait, wait', tr, tr', r, r')$.

$(ok,\ ok',\ wait,\ wait',\ tr,\ tr',\ st_v\ r,\ st_v\ r',\ more\ r,\ more\ r')$
apply (*unfold-locales*)
apply (*rule injI*)
apply (*clarsimp*)
done

lemma *unrest-st′-neg-RC* [*unrest*]:
assumes *P is RR P is RC*
shows $\$st\acute{}\ \sharp\ P$
proof −
have $P = (\neg_r\ \neg_r\ P)$
by (*simp add*: *closure rpred assms*)
also have ... $= (\neg_r\ (\neg_r\ P)\ ;;\ true_r)$
by (*metis Healthy-if RC1-def RC-implies-RC1 assms*(*2*) *calculation*)
also have $\$st\acute{}\ \sharp$ ...
by (*rel-auto*)
finally show *?thesis* **.**
qed

lemma *ex-st′-RR-closed* [*closure*]:
assumes *P is RR*
shows $(\exists\ \$st\acute{}\ \cdot\ P)$ *is RR*
proof −
have $RR\ (\exists\ \$st\acute{}\ \cdot\ RR(P)) = (\exists\ \$st\acute{}\ \cdot\ RR(P))$
by (*rel-auto*)
thus *?thesis*
by (*metis Healthy-def assms*)
qed

lemma *unrest-st′-R4* [*unrest*]:
$\$st\acute{}\ \sharp\ P \Longrightarrow \$st\acute{}\ \sharp\ R4(P)$
by (*rel-auto*)

lemma *unrest-st′-R5* [*unrest*]:
$\$st\acute{}\ \sharp\ P \Longrightarrow \$st\acute{}\ \sharp\ R5(P)$
by (*rel-auto*)

6.2 State Lifting

abbreviation *lift-state-rel* $(\lceil\text{-}\rceil_S)$
where $\lceil P\rceil_S \equiv P \oplus_p (st \times_L st)$

abbreviation *drop-state-rel* $(\lfloor\text{-}\rfloor_S)$
where $\lfloor P\rfloor_S \equiv P \restriction_e (st \times_L st)$

abbreviation *lift-state-pre* $(\lceil\text{-}\rceil_{S<})$
where $\lceil p\rceil_{S<} \equiv \lceil\lceil p\rceil_<\rceil_S$

abbreviation *drop-state-pre* $(\lfloor\text{-}\rfloor_{S<})$
where $\lfloor p\rfloor_{S<} \equiv \lfloor\lfloor p\rfloor_S\rfloor_<$

abbreviation *lift-state-post* $(\lceil\text{-}\rceil_{S>})$
where $\lceil p\rceil_{S>} \equiv \lceil\lceil p\rceil_>\rceil_S$

abbreviation *drop-state-post* $(\lfloor\text{-}\rfloor_{S>})$
where $\lfloor p\rfloor_{S>} \equiv \lfloor\lfloor p\rfloor_S\rfloor_>$

lemma *st-unrest-state-pre* [*unrest*]: $\&\mathbf{v} \sharp s \Longrightarrow \$st \sharp \lceil s \rceil_{S<}$
  by (*rel-auto*)

lemma *st′-unrest-st-lift-pred* [*unrest*]:
  $\$st\acute{} \sharp \lceil a \rceil_{S<}$
  by (*pred-auto*)

lemma *out-alpha-unrest-st-lift-pre* [*unrest*]:
  $out\alpha \sharp \lceil a \rceil_{S<}$
  by (*rel-auto*)

lemma *R1-st′-unrest* [*unrest*]: $\$st\acute{} \sharp P \Longrightarrow \$st\acute{} \sharp R1(P)$
  by (*simp add*: *R1-def unrest*)

lemma *R2c-st′-unrest* [*unrest*]: $\$st\acute{} \sharp P \Longrightarrow \$st\acute{} \sharp R2c(P)$
  by (*simp add*: *R2c-def unrest*)

lemma *unrest-st-rea-rename* [*unrest*]:
  $\$st \sharp P \Longrightarrow \$st \sharp P(\!|f|\!)_r$
  $\$st\acute{} \sharp P \Longrightarrow \$st\acute{} \sharp P(\!|f|\!)_r$
  by (*rel-blast*)+

lemma *st-lift-R1-true-right*: $\lceil b \rceil_{S<}$;; $R1(true) = \lceil b \rceil_{S<}$
  by (*rel-auto*)

lemma *R2c-lift-state-pre*: $R2c(\lceil b \rceil_{S<}) = \lceil b \rceil_{S<}$
  by (*rel-auto*)

6.3 Reactive Program Operators

6.3.1 State Substitution

Lifting substitutions on the reactive state

definition *usubst-st-lift* ::
  $'s$ *usubst* ⇒ (($'s$,$'t$::*trace*,$'\alpha$) *rsp* × ($'s$,$'t$,$'\beta$) *rsp*) *usubst* ($\lceil$-$\rceil_{S\sigma}$) **where**
[*upred-defs*]: $\lceil \sigma \rceil_{S\sigma} = \lceil \sigma \oplus_s st \rceil_s$

abbreviation *st-subst* :: $'s$ *usubst* ⇒ ($'s$,$'t$::*trace*,$'\alpha$,$'\beta$) *rel-rsp* ⇒ ($'s$, $'t$, $'\alpha$, $'\beta$) *rel-rsp* (**infixr** $\dagger_S$ *80*)
where
$\sigma \dagger_S P \equiv \lceil \sigma \rceil_{S\sigma} \dagger P$

translations
  $\sigma \dagger_S P$ <= $\lceil \sigma \oplus_s st \rceil_s \dagger P$
  $\sigma \dagger_S P$ <= $\lceil \sigma \rceil_{S\sigma} \dagger P$

lemma *st-lift-lemma*:
  $\lceil \sigma \rceil_{S\sigma} = \sigma \oplus_s (fst_L ;_L (st \times_L st))$
  by (*auto simp add*: *upred-defs lens-defs prod.case-eq-if*)

lemma *unrest-st-lift* [*unrest*]:
  fixes x :: $'a \Longrightarrow$ ($'s$, $'t$::*trace*, $'\alpha$) *rsp* × ($'s$, $'t$, $'\alpha$) *rsp*
  assumes $x \bowtie (\$st)_v$
  shows $x \sharp \lceil \sigma \rceil_{S\sigma}$ (**is** *?P*)
  by (*simp add*: *st-lift-lemma*)

(*metis assms in-var-def in-var-prod-lens lens-comp-left-id st-vwb-lens unrest-subst-alpha-ext vwb-lens-wb*)

lemma *id-st-subst* [*usubst*]:
  $\lceil id \rceil_{S\sigma} = id$
  by (*pred-auto*)

lemma *st-subst-comp* [*usubst*]:
  $\lceil \sigma \rceil_{S\sigma} \circ \lceil \varrho \rceil_{S\sigma} = \lceil \sigma \circ \varrho \rceil_{S\sigma}$
  by (*rel-auto*)

definition *lift-cond-srea* ($\lceil$-$\rceil_{S\leftarrow}$) **where**
[*upred-defs*]: $\lceil b \rceil_{S\leftarrow} = \lceil b \rceil_{S<}$

lemma *unrest-lift-cond-srea* [*unrest*]:
  $x \sharp \lceil b \rceil_{S<} \Longrightarrow x \sharp \lceil b \rceil_{S\leftarrow}$
  by (*simp add*: *lift-cond-srea-def*)

lemma *st-subst-RR-closed* [*closure*]:
  assumes *P is RR*
  shows $\lceil \sigma \rceil_{S\sigma} \dagger P$ *is RR*
proof −
  have $RR(\lceil \sigma \rceil_{S\sigma} \dagger RR(P)) = \lceil \sigma \rceil_{S\sigma} \dagger RR(P)$
    by (*rel-auto*)
  thus *?thesis*
    by (*metis Healthy-def assms*)
qed

lemma *subst-lift-cond-srea* [*usubst*]: $\sigma \dagger_S \lceil P \rceil_{S\leftarrow} = \lceil \sigma \dagger P \rceil_{S\leftarrow}$
  by (*rel-auto*)

lemma *st-subst-rea-not* [*usubst*]: $\sigma \dagger_S (\neg_r P) = (\neg_r \sigma \dagger_S P)$
  by (*rel-auto*)

lemma *st-subst-seq* [*usubst*]: $\sigma \dagger_S (P ;; Q) = \sigma \dagger_S P ;; Q$
  by (*rel-auto*)

lemma *st-subst-RC-closed* [*closure*]:
  assumes *P is RC*
  shows $\sigma \dagger_S P$ *is RC*
  apply (*rule RC-intro*, *simp add*: *closure assms*)
  apply (*simp add*: *st-subst-rea-not*[*THEN sym*] *st-subst-seq*[*THEN sym*])
  apply (*metis Healthy-if RC1-def RC-implies-RC1 assms*)
done

6.3.2 Assignment

definition *rea-assigns* :: $('s \Rightarrow 's) \Rightarrow ('s, 't::trace, '\alpha)$ *hrel-rsp* ($\langle$-$\rangle_r$) **where**
[*upred-defs*]: $\langle \sigma \rangle_r = (\$tr\acute{} =_u \$tr \wedge \lceil \langle \sigma \rangle_a \rceil_S \wedge \$\Sigma_S\acute{} =_u \$\Sigma_S)$

syntax
  -assign-rea :: *svids* ⇒ *uexprs* ⇒ *logic* ('(-') $:=_r$ '(-'))
  -assign-rea :: *svids* ⇒ *uexprs* ⇒ *logic* (**infixr** $:=_r$ *62*)

translations
  -assign-rea xs vs => *CONST rea-assigns* (*-mk-usubst* (*CONST id*) *xs vs*)
  -assign-rea x v <= *CONST rea-assigns* (*CONST subst-upd* (*CONST id*) *x v*)

-assign-rea x v <= -assign-rea (-spvar x) v
x,y $:=_r$ *u,v <= CONST rea-assigns (CONST subst-upd (CONST subst-upd (CONST id) (CONST svar x) u) (CONST svar y) v)*

lemma *rea-assigns-RR-closed* [*closure*]:
$\langle\sigma\rangle_r$ *is RR*
apply (*rel-auto*) **using** *minus-zero-eq* **by** *auto*

lemma *st-subst-assigns-rea* [*usubst*]:
$\sigma \dagger_S \langle\varrho\rangle_r = \langle\varrho \circ \sigma\rangle_r$
by (*rel-auto*)

lemma *st-subst-rea-skip* [*usubst*]:
$\sigma \dagger_S II_r = \langle\sigma\rangle_r$
by (*rel-auto*)

lemma *rea-assigns-comp* [*rpred*]:
assumes *P is RR*
shows $\langle\sigma\rangle_r$;; $P = \sigma \dagger_S P$
proof −
have $\langle\sigma\rangle_r$;; $(RR\ P) = \sigma \dagger_S (RR\ P)$
by (*rel-auto*)
thus *?thesis*
by (*metis Healthy-def assms*)
qed

lemma *rea-assigns-rename* [*rpred*]:
renamer f $\Longrightarrow \langle\sigma\rangle_r(\!|f|\!)_r = \langle\sigma\rangle_r$
using *minus-zero-eq* **by** *rel-auto*

lemma *st-subst-RR* [*closure*]:
assumes *P is RR*
shows $(\sigma \dagger_S P)$ *is RR*
proof −
have $(\sigma \dagger_S RR(P))$ *is RR*
by (*rel-auto*)
thus *?thesis*
by (*simp add*: *Healthy-if assms*)
qed

lemma *rea-assigns-st-subst* [*usubst*]:
$\lceil\sigma \oplus_s st\rceil_s \dagger \langle\varrho\rangle_r = \langle\varrho \circ \sigma\rangle_r$
by (*rel-auto*)

6.3.3 Conditional

We guard the reactive conditional condition so that it can't be simplified by alphabet laws unless explicitly simplified.

abbreviation *cond-srea* ::
$('s,'t{::}trace,'\alpha,'\beta)$ *rel-rsp* $\Rightarrow$
$'s$ *upred* $\Rightarrow$
$('s,'t,'\alpha,'\beta)$ *rel-rsp* $\Rightarrow$
$('s,'t,'\alpha,'\beta)$ *rel-rsp* **where**
cond-srea $P\ b\ Q \equiv P \triangleleft \lceil b\rceil_{S\leftarrow} \triangleright Q$

syntax
-cond-srea :: *logic* $\Rightarrow$ *uexp* $\Rightarrow$ *logic* $\Rightarrow$ *logic* ((*3*- $\triangleleft$ - $\triangleright_R$/ -) [*52*,*0*,*53*] *52*)

translations
-cond-srea P b Q == *CONST cond-srea P b Q*

lemma *st-cond-assigns* [*rpred*]:
$\langle\sigma\rangle_r \triangleleft b \triangleright_R \langle\varrho\rangle_r = \langle\sigma \triangleleft b \triangleright_s \varrho\rangle_r$
by (*rel-auto*)

lemma *cond-srea-RR-closed* [*closure*]:
assumes *P is RR Q is RR*
shows $P \triangleleft b \triangleright_R Q$ *is RR*
proof −
have $RR(RR(P) \triangleleft b \triangleright_R RR(Q)) = RR(P) \triangleleft b \triangleright_R RR(Q)$
by (*rel-auto*)
thus *?thesis*
by (*metis Healthy-def′ assms*(*1*) *assms*(*2*))
qed

lemma *cond-srea-RC1-closed*:
assumes *P is RC1 Q is RC1*
shows $P \triangleleft b \triangleright_R Q$ *is RC1*
proof −
have $RC1(RC1(P) \triangleleft b \triangleright_R RC1(Q)) = RC1(P) \triangleleft b \triangleright_R RC1(Q)$
using *dual-order.trans* **by** (*rel-blast*)
thus *?thesis*
by (*metis Healthy-def′ assms*)
qed

lemma *cond-srea-RC-closed* [*closure*]:
assumes *P is RC Q is RC*
shows $P \triangleleft b \triangleright_R Q$ *is RC*
by (*rule RC-intro′*, *simp-all add*: *closure cond-srea-RC1-closed RC-implies-RC1 assms*)

lemma *R4-cond* [*rpred*]: $R4(P \triangleleft b \triangleright_R Q) = (R4(P) \triangleleft b \triangleright_R R4(Q))$
by (*rel-auto*)

lemma *R5-cond* [*rpred*]: $R5(P \triangleleft b \triangleright_R Q) = (R5(P) \triangleleft b \triangleright_R R5(Q))$
by (*rel-auto*)

lemma *rea-rename-cond* [*rpred*]: $(P \triangleleft b \triangleright_R Q)(\!|f|\!)_r = P(\!|f|\!)_r \triangleleft b \triangleright_R Q(\!|f|\!)_r$
by (*rel-auto*)

6.3.4 Assumptions

definition *rea-assume* :: *′s upred* $\Rightarrow$ (*′s*, *′t*::*trace*, *′α*) *hrel-rsp* ($[\text{-}]^\top{}_r$) **where**
[*upred-defs*]: $[b]^\top{}_r = (II_r \triangleleft b \triangleright_R \mathit{false})$

lemma *rea-assume-RR* [*closure*]: $[b]^\top{}_r$ *is RR*
by (*simp add*: *rea-assume-def closure*)

lemma *rea-assume-false* [*rpred*]: $[\mathit{false}]^\top{}_r = \mathit{false}$
by (*rel-auto*)

lemma *rea-assume-true* [*rpred*]: $[\mathit{true}]^\top{}_r = II_r$

by (*rel-auto*)

lemma *rea-assume-comp* [*rpred*]: $[b]^\top{}_r$;; $[c]^\top{}_r = [b \wedge c]^\top{}_r$
by (*rel-auto*)

6.3.5 State Abstraction

We introduce state abstraction by creating some lens functors that allow us to lift a lens on the state-space to one on the whole stateful reactive alphabet.

definition $lmap_R$ :: $('a \Longrightarrow 'b) \Rightarrow ('t{::}trace, 'a)\ rp \Longrightarrow ('t, 'b)\ rp$ **where**
[*lens-defs*]: $lmap_R = lmap_D \circ lmap[rp\text{-}vars]$

definition *map-rsp-st* ::
$('\sigma \Rightarrow '\tau) \Rightarrow$
$('\sigma, '\alpha)\ rsp\text{-}vars\text{-}scheme \Rightarrow ('\tau, '\alpha)\ rsp\text{-}vars\text{-}scheme$ **where**
[*lens-defs*]: $map\text{-}rsp\text{-}st\ f = (\lambda r.\ (\!|st_v = f\ (st_v\ r),\ \ldots = rsp\text{-}vars.more\ r|\!))$

definition *map-st-lens* ::
$('\sigma \Longrightarrow '\psi) \Rightarrow$
$(('\sigma, '\tau{::}trace, '\alpha)\ rsp \Longrightarrow ('\psi, '\tau{::}trace, '\alpha)\ rsp)$ ($map'\text{-}st_L$) **where**
[*lens-defs*]:
$map\text{-}st\text{-}lens\ l = lmap_R$ (|
$lens\text{-}get = map\text{-}rsp\text{-}st\ (get_l)$,
$lens\text{-}put = map\text{-}rsp\text{-}st\ o\ (put_l)\ o\ rsp\text{-}vars.st_v$|)

lemma *map-set-vwb* [*simp*]: $vwb\text{-}lens\ X \Longrightarrow vwb\text{-}lens\ (map\text{-}st_L\ X)$
apply (*unfold-locales*, *simp-all add*: *lens-defs*)
apply (*metis des-vars.surjective rp-vars.surjective rsp-vars.surjective*)+
done

syntax
-map-st-lens :: *logic* ⇒ *salpha* ($map'\text{-}st_L$[-])

translations
-map-st-lens a => *CONST map-st-lens a*

abbreviation $abs\text{-}st_L \equiv (map\text{-}st_L\ 0_L) \times_L (map\text{-}st_L\ 0_L)$

abbreviation *abs-st* ($\langle\text{-}\rangle_S$) **where**
$abs\text{-}st\ P \equiv P \upharpoonright_e abs\text{-}st_L$

lemma *rea-impl-aext-st* [*alpha*]:
$(P \Rightarrow_r Q) \oplus_r map\text{-}st_L[a] = (P \oplus_r map\text{-}st_L[a] \Rightarrow_r Q \oplus_r map\text{-}st_L[a])$
by (*rel-auto*)

lemma *rea-true-ext-st* [*alpha*]:
$true_r \oplus_p abs\text{-}st_L = true_r$
by (*rel-auto*)

6.3.6 Reactive Frames and Extensions

definition *rea-frame* :: $('\alpha \Longrightarrow '\beta) \Rightarrow ('\beta, 't{::}trace, 'r)\ hrel\text{-}rsp \Rightarrow ('\beta, 't, 'r)\ hrel\text{-}rsp$ **where**
[*upred-defs*]: $rea\text{-}frame\ x\ P = frame\ (ok +_L wait +_L tr +_L (x ;_L st) +_L \Sigma_S)\ P$

definition *rea-frame-ext* :: $('\alpha \Longrightarrow '\beta) \Rightarrow ('\alpha, 't{::}trace, 'r)\ hrel\text{-}rsp \Rightarrow ('\beta, 't, 'r)\ hrel\text{-}rsp$ **where**

[*upred-defs*]: *rea-frame-ext a P* = *rea-frame a* ($P \oplus_r$ *map-st*$_L$[*a*])

syntax
-rea-frame :: *salpha* ⇒ *logic* ⇒ *logic* (*-*:[*-*]$_r$ [*99*,*0*] *100*)
-rea-frame-ext :: *salpha* ⇒ *logic* ⇒ *logic* (*-*:[*-*]$_r{}^+$ [*99*,*0*] *100*)

translations
-rea-frame x P => *CONST rea-frame x P*
-rea-frame (*-salphaset* (*-salphamk x*)) *P* <= *CONST rea-frame x P*
-rea-frame-ext x P => *CONST rea-frame-ext x P*
-rea-frame-ext (*-salphaset* (*-salphamk x*)) *P* <= *CONST rea-frame-ext x P*

lemma *rea-frame-R1-closed* [*closure*]:
assumes *P is R1*
shows *x*:[*P*]$_r$ *is R1*
proof –
have *R1*(*x*:[*R1 P*]$_r$) = *x*:[*R1 P*]$_r$
by (*rel-auto*)
thus *?thesis*
by (*metis Healthy-if Healthy-intro assms*)
qed

lemma *rea-frame-R2-closed* [*closure*]:
assumes *P is R2*
shows *x*:[*P*]$_r$ *is R2*
proof –
have *R2*(*x*:[*R2 P*]$_r$) = *x*:[*R2 P*]$_r$
by (*rel-auto*)
thus *?thesis*
by (*metis Healthy-if Healthy-intro assms*)
qed

lemma *rea-frame-RR-closed* [*closure*]:
assumes *P is RR*
shows *x*:[*P*]$_r$ *is RR*
proof –
have *RR*(*x*:[*RR P*]$_r$) = *x*:[*RR P*]$_r$
by (*rel-auto*)
thus *?thesis*
by (*metis Healthy-if Healthy-intro assms*)
qed

lemma *rea-aext-R1* [*closure*]:
assumes *P is R1*
shows *rel-aext P* (*map-st*$_L$ *x*) *is R1*
proof –
have *rel-aext* (*R1 P*) (*map-st*$_L$ *x*) *is R1*
by (*rel-auto*)
thus *?thesis*
by (*simp add*: *Healthy-if assms*)
qed

lemma *rea-aext-R2* [*closure*]:
assumes *P is R2*
shows *rel-aext P* (*map-st*$_L$ *x*) *is R2*

proof –
  have *rel-aext* (*R2 P*) (*map-st*$_L$ *x*) *is R2*
    by (*rel-auto*)
  thus *?thesis*
    by (*simp add*: *Healthy-if assms*)
qed

lemma *rea-aext-RR* [*closure*]:
  assumes *P is RR*
  shows *rel-aext P* (*map-st*$_L$ *x*) *is RR*
proof –
  have *rel-aext* (*RR P*) (*map-st*$_L$ *x*) *is RR*
    by (*rel-auto*)
  thus *?thesis*
    by (*simp add*: *Healthy-if assms*)
qed

lemma *true-rea-map-st* [*alpha*]: (*R1 true* $\oplus_r$ *map-st*$_L$[*a*]) = *R1 true*
  by (*rel-auto*)

lemma *rea-frame-ext-R1-closed* [*closure*]:
  P is R1 $\Longrightarrow$ x:[P]$_r$$^+$ *is R1*
  by (*simp add*: *rea-frame-ext-def closure*)

lemma *rea-frame-ext-R2-closed* [*closure*]:
  P is R2 $\Longrightarrow$ x:[P]$_r$$^+$ *is R2*
  by (*simp add*: *rea-frame-ext-def closure*)

lemma *rea-frame-ext-RR-closed* [*closure*]:
  P is RR $\Longrightarrow$ x:[P]$_r$$^+$ *is RR*
  by (*simp add*: *rea-frame-ext-def closure*)

lemma *rel-aext-st-Instant-closed* [*closure*]:
  P is Instant $\Longrightarrow$ *rel-aext P* (*map-st*$_L$ *x*) *is Instant*
  by (*rel-auto*)

lemma *rea-frame-ext-false* [*frame*]:
  x:[*false*]$_r$$^+$ = *false*
  by (*rel-auto*)

lemma *rea-frame-ext-skip* [*frame*]:
  vwb-lens x $\Longrightarrow$ x:[II_r]$_r$$^+$ = II_r
  by (*rel-auto*)

lemma *rea-frame-ext-assigns* [*frame*]:
  vwb-lens x $\Longrightarrow$ x:[$\langle\sigma\rangle_r$]$_r$$^+$ = $\langle\sigma \oplus_s x\rangle_r$
  by (*rel-auto*)

lemma *rea-frame-ext-cond* [*frame*]:
  x:[$P \triangleleft b \triangleright_R Q$]$_r$$^+$ = x:[P]$_r$$^+$ $\triangleleft$ ($b \oplus_p x$) $\triangleright_R$ x:[Q]$_r$$^+$
  by (*rel-auto*)

lemma *rea-frame-ext-seq* [*frame*]:
  vwb-lens x $\Longrightarrow$ x:[P ;; Q]$_r$$^+$ = x:[P]$_r$$^+$;; x:[Q]$_r$$^+$
  apply (*simp add*: *rea-frame-ext-def rea-frame-def alpha frame*)

apply (*subst frame-seq*)
 apply (*simp-all add*: *plus-vwb-lens closure*)
 apply (*rel-auto*)+
done

lemma *rea-frame-ext-subst-indep* [*usubst*]:
assumes $x \bowtie y$ $\Sigma \sharp v$ P *is* RR
shows $\sigma(y \mapsto_s v) \dagger_S x{:}[P]_r{}^+ = (\sigma \dagger_S x{:}[P]_r{}^+) \;;;\; y :=_r v$
proof −
from *assms*(*1*−*2*) **have** $\sigma(y \mapsto_s v) \dagger_S x{:}[RR\ P]_r{}^+ = (\sigma \dagger_S x{:}[RR\ P]_r{}^+) \;;;\; y :=_r v$
 by (*rel-auto*, (*metis* (*no-types*, *lifting*) *lens-indep.lens-put-comm lens-indep-get*)+)
thus *?thesis*
 by (*simp add*: *Healthy-if assms*)
qed

lemma *rea-frame-ext-subst-within* [*usubst*]:
assumes *vwb-lens x vwb-lens y* $\Sigma \sharp v$ P *is* RR
shows $\sigma(x{:}y \mapsto_s v) \dagger_S x{:}[P]_r{}^+ = (\sigma \dagger_S x{:}[y :=_r (v \upharpoonright_e x) \;;;\; P]_r{}^+)$
proof −
from *assms*(*1*,*3*) **have** $\sigma(x{:}y \mapsto_s v) \dagger_S x{:}[RR\ P]_r{}^+ = (\sigma \dagger_S x{:}[y :=_r (v \upharpoonright_e x) \;;;\; RR(P)]_r{}^+)$
 by (*rel-auto*, *metis*+)
thus *?thesis*
 by (*simp add*: *assms Healthy-if*)
qed

lemma *rea-frame-ext-UINF-ind* [*frame*]:
$a{:}[\bigsqcap\ x \cdot P\ x]_r{}^+ = (\bigsqcap\ x \cdot a{:}[P\ x]_r{}^+)$
by (*rel-auto*)

lemma *rea-frame-ext-UINF-mem* [*frame*]:
$a{:}[\bigsqcap\ x{\in}A \cdot P\ x]_r{}^+ = (\bigsqcap\ x{\in}A \cdot a{:}[P\ x]_r{}^+)$
by (*rel-auto*)

6.4 Stateful Reactive specifications

definition *rea-st-rel* :: $'s$ *hrel* $\Rightarrow$ ($'s$, $'t$::*trace*, $'\alpha$, $'\beta$) *rel-rsp* ($[\text{-}]_S$) **where**
[*upred-defs*]: *rea-st-rel* $b = (\lceil b \rceil_S \wedge \$tr\acute{} =_u \$tr)$

definition *rea-st-rel'* :: $'s$ *hrel* $\Rightarrow$ ($'s$, $'t$::*trace*, $'\alpha$, $'\beta$) *rel-rsp* ($[\text{-}]_S{}'$) **where**
[*upred-defs*]: *rea-st-rel'* $b = R1(\lceil b \rceil_S)$

definition *rea-st-cond* :: $'s$ *upred* $\Rightarrow$ ($'s$, $'t$::*trace*, $'\alpha$, $'\beta$) *rel-rsp* ($[\text{-}]_{S<}$) **where**
[*upred-defs*]: *rea-st-cond* $b = R1(\lceil b \rceil_{S<})$

definition *rea-st-post* :: $'s$ *upred* $\Rightarrow$ ($'s$, $'t$::*trace*, $'\alpha$, $'\beta$) *rel-rsp* ($[\text{-}]_{S>}$) **where**
[*upred-defs*]: *rea-st-post* $b = R1(\lceil b \rceil_{S>})$

lemma *lift-state-pre-unrest* [*unrest*]: $x \bowtie (\$st)_v \Longrightarrow x \sharp \lceil P \rceil_{S<}$
by (*rel-simp*, *simp add*: *lens-indep-def*)

lemma *rea-st-rel-unrest* [*unrest*]:
$[\![\ x \bowtie (\$tr)_v;\ x \bowtie (\$tr\acute{})_v;\ x \bowtie (\$st)_v;\ x \bowtie (\$st\acute{})_v\ ]\!] \Longrightarrow x \sharp [P]_{S<}$
by (*simp add*: *add*: *rea-st-cond-def R1-def unrest lens-indep-sym*)

lemma *rea-st-cond-unrest* [*unrest*]:
$[\![\ x \bowtie (\$tr)_v;\ x \bowtie (\$tr\acute{})_v;\ x \bowtie (\$st)_v\ ]\!] \Longrightarrow x \sharp [P]_{S<}$

by (*simp add*: *add*: *rea-st-cond-def R1-def unrest lens-indep-sym*)

lemma *subst-st-cond* [*usubst*]: $\lceil\sigma\rceil_{S\sigma} \dagger [P]_{S<} = [\sigma \dagger P]_{S<}$
by (*rel-auto*)

lemma *rea-st-cond-R1* [*closure*]: $[b]_{S<}$ *is R1*
by (*rel-auto*)

lemma *rea-st-cond-R2c* [*closure*]: $[b]_{S<}$ *is R2c*
by (*rel-auto*)

lemma *rea-st-rel-RR* [*closure*]: $[P]_S$ *is RR*
using *minus-zero-eq* **by** (*rel-auto*)

lemma *rea-st-rel'-RR* [*closure*]: $[P]_S{}'$ *is RR*
by (*rel-auto*)

lemma *rea-st-post-RR* [*closure*]: $[b]_{S>}$ *is RR*
by (*rel-auto*)

lemma *st-subst-rel* [*usubst*]:
$\sigma \dagger_S [P]_S = [\lceil\sigma\rceil_s \dagger P]_S$
by (*rel-auto*)

lemma *st-rel-cond* [*rpred*]:
$[P \triangleleft b \triangleright_r Q]_S = [P]_S \triangleleft b \triangleright_R [Q]_S$
by (*rel-auto*)

lemma *st-rel-false* [*rpred*]: $[\mathit{false}]_S = \mathit{false}$
by (*rel-auto*)

lemma *st-rel-skip* [*rpred*]:
$[II]_S = (II_r :: ('s, 't{::}trace)\ rdes)$
by (*rel-auto*)

lemma *st-rel-seq* [*rpred*]:
$[P ;; Q]_S = [P]_S ;; [Q]_S$
by (*rel-auto*)

lemma *st-rel-conj* [*rpred*]:
$[P \wedge Q]_S = ([P]_S \wedge [Q]_S)$
by (*rel-auto*)

lemma *rea-st-cond-RR* [*closure*]: $[b]_{S<}$ *is RR*
by (*rule RR-intro*, *simp-all add*: *unrest closure*)

lemma *rea-st-cond-RC* [*closure*]: $[b]_{S<}$ *is RC*
by (*rule RC-intro*, *simp add*: *closure*, *rel-auto*)

lemma *rea-st-cond-true* [*rpred*]: $[\mathit{true}]_{S<} = \mathit{true}_r$
by (*rel-auto*)

lemma *rea-st-cond-false* [*rpred*]: $[\mathit{false}]_{S<} = \mathit{false}$
by (*rel-auto*)

lemma *st-cond-not* [*rpred*]: $(\neg_r [P]_{S<}) = [\neg\ P]_{S<}$
  by (*rel-auto*)

lemma *st-cond-conj* [*rpred*]: $([P]_{S<} \wedge [Q]_{S<}) = [P \wedge Q]_{S<}$
  by (*rel-auto*)

lemma *st-rel-assigns* [*rpred*]:
  $[\langle\sigma\rangle_a]_S = (\langle\sigma\rangle_r :: ('\alpha, 't::trace)\ rdes)$
  by (*rel-auto*)

lemma *cond-st-distr*: $(P \triangleleft b \triangleright_R Q) ;; R = (P ;; R \triangleleft b \triangleright_R Q ;; R)$
  by (*rel-auto*)

lemma *cond-st-miracle* [*rpred*]: P *is* $R1 \Longrightarrow P \triangleleft b \triangleright_R$ *false* $= ([b]_{S<} \wedge P)$
  by (*rel-blast*)

lemma *cond-st-true* [*rpred*]: $P \triangleleft$ *true* $\triangleright_R Q = P$
  by (*rel-blast*)

lemma *cond-st-false* [*rpred*]: $P \triangleleft$ *false* $\triangleright_R Q = Q$
  by (*rel-blast*)

lemma *st-cond-true-or* [*rpred*]: P *is* $R1 \Longrightarrow (R1$ *true* $\triangleleft b \triangleright_R P) = ([b]_{S<} \vee P)$
  by (*rel-blast*)

lemma *st-cond-left-impl-RC-closed* [*closure*]:
  P *is* $RC \Longrightarrow ([b]_{S<} \Rightarrow_r P)$ *is* RC
  by (*simp add*: *rea-impl-def rpred closure*)

end

7 Reactive Weakest Preconditions

theory *utp-rea-wp*
  imports *utp-rea-prog*
begin

Here, we create a weakest precondition calculus for reactive relations, using the recast boolean algebra and relational operators. Please see our journal paper [3] for more information.

definition *wp-rea* ::
  $('t::trace, '\alpha)$ *hrel-rp* $\Rightarrow$
   $('t, '\alpha)$ *hrel-rp* $\Rightarrow$
   $('t, '\alpha)$ *hrel-rp* (**infix** wp_r *60*)
where [*upred-defs*]: $P\ wp_r\ Q = (\neg_r\ P ;; (\neg_r\ Q))$

lemma *in-var-unrest-wp-rea* [*unrest*]: $[\![\ \$x \sharp P;\ tr \bowtie x\ ]\!] \Longrightarrow \$x \sharp (P\ wp_r\ Q)$
  by (*simp add*: *wp-rea-def unrest R1-def rea-not-def*)

lemma *out-var-unrest-wp-rea* [*unrest*]: $[\![\ \$x' \sharp Q;\ tr \bowtie x\ ]\!] \Longrightarrow \$x' \sharp (P\ wp_r\ Q)$
  by (*simp add*: *wp-rea-def unrest R1-def rea-not-def*)

lemma *wp-rea-R1* [*closure*]: $P\ wp_r\ Q$ *is* $R1$
  by (*rel-auto*)

lemma *wp-rea-RR-closed* [*closure*]: $[\![\ P$ *is* $RR;\ Q$ *is* $RR\ ]\!] \Longrightarrow P\ wp_r\ Q$ *is* RR

by (*simp add*: *wp-rea-def closure*)

lemma *wp-rea-impl-lemma*:
$((P\ wp_r\ Q) \Rightarrow_r (R1(P) \ ;;\ R1(Q \Rightarrow_r R))) = ((P\ wp_r\ Q) \Rightarrow_r (R1(P) \ ;;\ R1(R)))$
by (*rel-auto*, *blast*)

lemma *wpR-impl-post-spec*:
assumes P *is* RR
shows $(P\ wp_r\ Q_1 \Rightarrow_r (P \ ;;\ (Q_1 \Rightarrow_r Q_2))) = (P \ ;;\ (Q_1 \Rightarrow_r Q_2))$
by (*simp add*: *R1-seqr-closure RR-implies-R1 assms rea-impl-def rea-not-R1 rea-not-not seqr-or-distr wp-rea-def*)

lemma *wpR-R1-right* [*wp*]:
$P\ wp_r\ R1(Q) = P\ wp_r\ Q$
by (*rel-auto*)

lemma *wp-rea-true* [*wp*]: $P\ wp_r\ true = true_r$
by (*rel-auto*)

lemma *wp-rea-conj* [*wp*]: $P\ wp_r\ (Q \wedge R) = (P\ wp_r\ Q \wedge P\ wp_r\ R)$
by (*simp add*: *wp-rea-def seqr-or-distr*)

lemma *wp-rea-USUP-mem* [*wp*]:
$A \neq \{\} \Longrightarrow P\ wp_r\ (\bigsqcup\ i{\in}A \cdot Q(i)) = (\bigsqcup\ i{\in}A \cdot P\ wp_r\ Q(i))$
by (*simp add*: *wp-rea-def seq-UINF-distl*)

lemma *wp-rea-Inf-pre* [*wp*]:
$P\ wp_r\ (\bigsqcup i{\in}\{0..n{::}nat\}.\ Q(i)) = (\bigsqcup i{\in}\{0..n\}.\ P\ wp_r\ Q(i))$
by (*simp add*: *wp-rea-def seq-SUP-distl*)

lemma *wp-rea-div* [*wp*]:
$(\neg_r\ P \ ;;\ true_r) = true_r \Longrightarrow true_r\ wp_r\ P = false$
by (*simp add*: *wp-rea-def rpred*, *rel-blast*)

lemma *wp-rea-st-cond-div* [*wp*]:
$P \neq true \Longrightarrow true_r\ wp_r\ [P]_{S<} = false$
by (*rel-auto*)

lemma *wp-rea-cond* [*wp*]:
$out\alpha \sharp b \Longrightarrow (P \triangleleft b \triangleright Q)\ wp_r\ R = P\ wp_r\ R \triangleleft b \triangleright Q\ wp_r\ R$
by (*simp add*: *wp-rea-def cond-seq-left-distr*, *rel-auto*)

lemma *wp-rea-RC-false* [*wp*]:
P *is* $RC \Longrightarrow (\neg_r\ P)\ wp_r\ false = P$
by (*metis Healthy-if RC1-def RC-implies-RC1 rea-not-false wp-rea-def*)

lemma *wp-rea-seq* [*wp*]:
assumes Q *is* $R1$
shows $(P \ ;;\ Q)\ wp_r\ R = P\ wp_r\ (Q\ wp_r\ R)$ (**is** *?lhs* = *?rhs*)
proof −
have $?rhs = R1\ (\neg\ P \ ;;\ R1\ (Q \ ;;\ R1\ (\neg\ R)))$
by (*simp add*: *wp-rea-def rea-not-def R1-negate-R1 assms*)
also have ... $= R1\ (\neg\ P \ ;;\ (Q \ ;;\ R1\ (\neg\ R)))$
by (*metis Healthy-if R1-seqr assms*)
also have ... $= R1\ (\neg\ (P \ ;;\ Q) \ ;;\ R1\ (\neg\ R))$

by (*simp add*: *seqr-assoc*)
finally show *?thesis*
by (*simp add*: *wp-rea-def rea-not-def*)
qed

lemma *wp-rea-skip* [*wp*]:
assumes Q *is R1*
shows $II\ wp_r\ Q = Q$
by (*simp add*: *wp-rea-def rpred assms Healthy-if*)

lemma *wp-rea-rea-skip* [*wp*]:
assumes Q *is RR*
shows $II_r\ wp_r\ Q = Q$
by (*simp add*: *wp-rea-def rpred closure assms Healthy-if*)

lemma *power-wp-rea-RR-closed* [*closure*]:
$[\![R\ is\ RR;\ P\ is\ RR]\!] \Longrightarrow R\ \hat{}\ i\ wp_r\ P\ is\ RR$
by (*induct i*, *simp-all add*: *wp closure*)

lemma *wp-rea-rea-assigns* [*wp*]:
assumes P *is RR*
shows $\langle\sigma\rangle_r\ wp_r\ P = \lceil\sigma\rceil_{S\sigma} \dagger P$
proof −
have $\langle\sigma\rangle_r\ wp_r\ (RR\ P) = \lceil\sigma\rceil_{S\sigma} \dagger (RR\ P)$
by (*rel-auto*)
thus *?thesis*
by (*metis Healthy-def assms*)
qed

lemma *wp-rea-miracle* [*wp*]: $false\ wp_r\ Q = true_r$
by (*simp add*: *wp-rea-def*)

lemma *wp-rea-disj* [*wp*]: $(P \vee Q)\ wp_r\ R = (P\ wp_r\ R \wedge Q\ wp_r\ R)$
by (*rel-blast*)

lemma *wp-rea-UINF* [*wp*]:
assumes $A \neq \{\}$
shows $(\bigsqcap\ x{\in}A \cdot P(x))\ wp_r\ Q = (\bigsqcup\ x{\in}A \cdot P(x)\ wp_r\ Q)$
by (*simp add*: *wp-rea-def rea-not-def seq-UINF-distr not-UINF R1-UINF assms*)

lemma *wp-rea-choice* [*wp*]:
$(P \sqcap Q)\ wp_r\ R = (P\ wp_r\ R \wedge Q\ wp_r\ R)$
by (*rel-blast*)

lemma *wp-rea-UINF-ind* [*wp*]:
$(\bigsqcap\ i \cdot P(i))\ wp_r\ Q = (\bigsqcup\ i \cdot P(i)\ wp_r\ Q)$
by (*simp add*: *wp-rea-def rea-not-def seq-UINF-distr′ not-UINF-ind R1-UINF-ind*)

lemma *rea-assume-wp* [*wp*]:
assumes P *is RC*
shows $([b]^{\top}{}_r\ wp_r\ P) = ([b]_{S<} \Rightarrow_r P)$
proof −
have $([b]^{\top}{}_r\ wp_r\ RC\ P) = ([b]_{S<} \Rightarrow_r RC\ P)$
by (*rel-auto*)
thus *?thesis*

by (*simp add*: *Healthy-if assms*)
qed

lemma *rea-star-wp* [*wp*]:
assumes *P is RR Q is RR*
shows $P^{\star r}$ wp_r $Q = (\bigsqcup\ i \cdot P\ \hat{}\ i\ wp_r\ Q)$
proof −
have $P^{\star r}$ wp_r $Q = (Q \wedge P^{+}\ wp_r\ Q)$
by (*simp add*: *assms rrel-thy.Star-alt-def wp-rea-choice wp-rea-rea-skip*)
also have ... = $(II\ wp_r\ Q \wedge (\bigsqcup\ i \cdot P\ \hat{}\ Suc\ i\ wp_r\ Q))$
by (*simp add*: *uplus-power-def wp closure assms*)
also have ... = $(\bigsqcup\ i \cdot P\ \hat{}\ i\ wp_r\ Q)$
proof −
have $P^{\star}$ wp_r $Q = P^{\star r}$ wp_r Q
by (*metis* (*no-types*) *RA1 assms*(*2*) *rea-no-RR rea-skip-unit*(*2*) *rrel-thy.Star-def wp-rea-def*)
then show *?thesis*
by (*simp add*: *calculation ustar-def wp-rea-UINF-ind*)
qed
finally show *?thesis* **.**
qed

lemma *wp-rea-R2-closed* [*closure*]:
$[\![$ *P is R2*; *Q is R2* $]\!] \Longrightarrow P\ wp_r\ Q$ *is R2*
by (*simp add*: *wp-rea-def closure*)

lemma *wp-rea-false-RC1'*: *P is R2* $\Longrightarrow$ *RC1*($P\ wp_r$ *false*) = $P\ wp_r$ *false*
by (*simp add*: *wp-rea-def RC1-def closure rpred seqr-assoc*)

lemma *wp-rea-false-RC1*: *P is R2* $\Longrightarrow P\ wp_r$ *false is RC1*
by (*simp add* :*Healthy-def wp-rea-false-RC1'*)

lemma *wp-rea-false-RR*:
$[\![$ *\$ok* $\sharp$ *P*; *\$wait* $\sharp$ *P*; *P is R2* $]\!] \Longrightarrow P\ wp_r$ *false is RR*
by (*rule RR-R2-intro*, *simp-all add*: *unrest closure*)

lemma *wp-rea-false-RC*:
$[\![$ *\$ok* $\sharp$ *P*; *\$wait* $\sharp$ *P*; *P is R2* $]\!] \Longrightarrow P\ wp_r$ *false is RC*
by (*rule RC-intro'*, *simp-all add*: *wp-rea-false-RC1 wp-rea-false-RR*)

lemma *wp-rea-RC1*: $[\![$ *P is RR*; *Q is RC* $]\!] \Longrightarrow P\ wp_r\ Q$ *is RC1*
by (*rule Healthy-intro*, *simp add*: *wp-rea-def RC1-def rpred closure seqr-assoc RC1-prop RC-implies-RC1*)

lemma *wp-rea-RC* [*closure*]: $[\![$ *P is RR*; *Q is RC* $]\!] \Longrightarrow P\ wp_r\ Q$ *is RC*
by (*rule RC-intro'*, *simp-all add*: *wp-rea-RC1 closure*)

lemma *wpR-power-RC-closed* [*closure*]:
assumes *P is RR Q is RC*
shows $P\ \hat{}\ i\ wp_r\ Q$ *is RC*
by (*metis RC-implies-RR RR-implies-R1 assms power.power-eq-if power-Suc-RR-closed wp-rea-RC wp-rea-skip*)

end

8 Reactive Hoare Logic

theory *utp-rea-hoare*
  imports *utp-rea-prog*
begin

definition *hoare-rp* :: $'\alpha$ *upred* $\Rightarrow$ $('\alpha,$ *real pos*$)$ *rdes* $\Rightarrow$ $'\alpha$ *upred* $\Rightarrow$ *bool* $(\{\!|\text{-}|\!\}/\ \text{-}/\ \{\!|\text{-}|\!\}_r)$ **where**
[*upred-defs*]: *hoare-rp* $p\ Q\ r = ((\lceil p \rceil_{S<} \Rightarrow \lceil r \rceil_{S>}) \sqsubseteq Q)$

lemma *hoare-rp-conseq*:
  $[\![$ `$p \Rightarrow p'$`; `$q' \Rightarrow q$`; $\{\!|p'|\!\}S\{\!|q'|\!\}_r$ $]\!] \Longrightarrow \{\!|p|\!\}S\{\!|q|\!\}_r$
  by (*rel-auto*)

lemma *hoare-rp-weaken*:
  $[\![$ `$p \Rightarrow p'$`; $\{\!|p'|\!\}S\{\!|q|\!\}_r$ $]\!] \Longrightarrow \{\!|p|\!\}S\{\!|q|\!\}_r$
  by (*rel-auto*)

lemma *hoare-rp-strengthen*:
  $[\![$ `$q' \Rightarrow q$`; $\{\!|p|\!\}S\{\!|q'|\!\}_r$ $]\!] \Longrightarrow \{\!|p|\!\}S\{\!|q|\!\}_r$
  by (*rel-auto*)

lemma *false-pre-hoare-rp* [*hoare-safe*]: $\{\!|false|\!\}P\{\!|q|\!\}_r$
  by (*rel-auto*)

lemma *true-post-hoare-rp* [*hoare-safe*]: $\{\!|p|\!\}Q\{\!|true|\!\}_r$
  by (*rel-auto*)

lemma *miracle-hoare-rp* [*hoare-safe*]: $\{\!|p|\!\}false\{\!|q|\!\}_r$
  by (*rel-auto*)

lemma *assigns-hoare-rp* [*hoare-safe*]: `$p \Rightarrow \sigma \dagger q$` $\Longrightarrow \{\!|p|\!\}\langle\sigma\rangle_r\{\!|q|\!\}_r$
  by *rel-auto*

lemma *skip-hoare-rp* [*hoare-safe*]: $\{\!|p|\!\}II_r\{\!|p|\!\}_r$
  by *rel-auto*

lemma *seq-hoare-rp*: $[\![$ $\{\!|p|\!\}Q_1\{\!|s|\!\}_r$; $\{\!|s|\!\}Q_2\{\!|r|\!\}_r$ $]\!] \Longrightarrow \{\!|p|\!\}Q_1$;; $Q_2\{\!|r|\!\}_r$
  by (*rel-auto*)

lemma *seq-est-hoare-rp* [*hoare-safe*]:
  $[\![$ $\{\!|true|\!\}Q_1\{\!|p|\!\}_r$; $\{\!|p|\!\}Q_2\{\!|p|\!\}_r$ $]\!] \Longrightarrow \{\!|true|\!\}Q_1$;; $Q_2\{\!|p|\!\}_r$
  by (*rel-auto*)

lemma *seq-inv-hoare-rp* [*hoare-safe*]:
  $[\![$ $\{\!|p|\!\}Q_1\{\!|p|\!\}_r$; $\{\!|p|\!\}Q_2\{\!|p|\!\}_r$ $]\!] \Longrightarrow \{\!|p|\!\}Q_1$;; $Q_2\{\!|p|\!\}_r$
  by (*rel-auto*)

lemma *cond-hoare-rp* [*hoare-safe*]:
  $[\![$ $\{\!|b \wedge p|\!\}P\{\!|r|\!\}_r$; $\{\!|\neg b \wedge p|\!\}Q\{\!|r|\!\}_r$ $]\!] \Longrightarrow \{\!|p|\!\}P \triangleleft b \triangleright_R Q\{\!|r|\!\}_r$
  by (*rel-auto*)

lemma *repeat-hoare-rp* [*hoare-safe*]:
  $\{\!|p|\!\}Q\{\!|p|\!\}_r \Longrightarrow \{\!|p|\!\}Q$ ˆ $n\{\!|p|\!\}_r$
  by (*induct n*, *rel-auto*+)

lemma *UINF-ind-hoare-rp* [*hoare-safe*]:

$[\![\bigwedge i.\ \{\!|p|\!\} Q(i) \{\!|r|\!\}_r]\!] \Longrightarrow \{\!|p|\!\} \bigsqcap\ i \cdot Q(i) \{\!|r|\!\}_r$
by (*rel-auto*)

lemma *star-hoare-rp* [*hoare-safe*]:
$\{\!|p|\!\} Q \{\!|p|\!\}_r \Longrightarrow \{\!|p|\!\} Q^\star \{\!|p|\!\}_r$
by (*simp add*: *ustar-def hoare-safe*)

lemma *conj-hoare-rp* [*hoare-safe*]:
$[\![\{\!|p_1|\!\} Q_1 \{\!|r_1|\!\}_r;\ \{\!|p_2|\!\} Q_2 \{\!|r_2|\!\}_r]\!] \Longrightarrow \{\!|p_1 \wedge p_2|\!\} Q_1 \wedge Q_2 \{\!|r_1 \wedge r_2|\!\}_r$
by (*rel-auto*)

lemma *iter-hoare-rp* [*hoare-safe*]:
$\{\!|I|\!\}\ P\ \{\!|I|\!\}_r \Longrightarrow \{\!|I|\!\}\ P^{\star r}\ \{\!|I|\!\}_r$
by (*simp add*: *star-hoare-rp utp-star-def rrel-unit-def seq-inv-hoare-rp skip-hoare-rp*)

end

9 Meta-theory for Generalised Reactive Processes

theory *utp-reactive*
imports
utp-rea-core
utp-rea-healths
utp-rea-parallel
utp-rea-rel
utp-rea-cond
utp-rea-prog
utp-rea-wp
utp-rea-hoare
begin end

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