

# Circus in Isabelle/UTP

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## 1 Introduction

This document contains a mechanisation in Isabelle/UTP [1] of Circus [2].

## 2 Circus Trace Merge

```
theory utp-circus-traces
  imports UTP-Stateful-Failures.utp-sf-rdes
begin
```

## 2.1 Function Definition

```

fun tr-par ::
  '∅ set ⇒ '∅ list ⇒ '∅ list ⇒ '∅ list set where
tr-par cs [] = {} |
tr-par cs (e # t) [] = (if e ∈ cs then {} else {[e]} ∩ (tr-par cs t [])) |
tr-par cs [] (e # t) = (if e ∈ cs then {} else {[e]} ∩ (tr-par cs [] t)) |
tr-par cs (e1 # t1) (e2 # t2) =
  (if e1 = e2
   then
    if e1 ∈ cs
    then {[e1]} ∩ (tr-par cs t1 t2)
    else
      ({[e1]} ∩ (tr-par cs t1 (e2 # t2))) ∪
      ({[e2]} ∩ (tr-par cs (e1 # t1) t2))
   else
    if e1 ∈ cs then
      if e2 ∈ cs then {}
      else
        {[e2]} ∩ (tr-par cs (e1 # t1) t2)
    else
      if e2 ∈ cs then
        {[e1]} ∩ (tr-par cs t1 (e2 # t2))
      else
        {[e1]} ∩ (tr-par cs t1 (e2 # t2)) ∪
        {[e2]} ∩ (tr-par cs (e1 # t1) t2)

```

**abbreviation** *tr-inter* :: '∅ list ⇒ '∅ list ⇒ '∅ list set (**infixr** |||<sub>t</sub> 100) **where**  
*x* |||<sub>t</sub> *y* ≡ *tr-par* {} *x y*

## 2.2 Lifted Trace Merge

```

syntax -utr-par ::
  logic ⇒ logic ⇒ logic ⇒ logic ((- ★-/ -) [100, 0, 101] 100)

```

The function *trop* is used to lift ternary operators.

**translations**

*t1* ★<sub>cs</sub> *t2* == (CONST *bop*) (CONST *tr-par* cs) *t1 t2*

## 2.3 Trace Merge Lemmas

**lemma** *tr-par-empty*:

```

tr-par cs t1 [] = {takeWhile (λx. x ∉ cs) t1}
tr-par cs [] t2 = {takeWhile (λx. x ∉ cs) t2}
— Subgoal 1
apply (induct t1; simp)
— Subgoal 2
apply (induct t2; simp)
done

```

**lemma** *tr-par-sym*:

```

tr-par cs t1 t2 = tr-par cs t2 t1
apply (induct t1 arbitrary: t2)
— Subgoal 1
apply (simp add: tr-par-empty)
— Subgoal 2

```

**apply** (*induct-tac* *t2*)

— Subgoal 2.1

**apply** (*clarsimp*)

— Subgoal 2.2

**apply** (*clarsimp*)

**apply** (*blast*)

**done**

**lemma** *tr-inter-sym*:  $x \parallel_t y = y \parallel_t x$

**by** (*simp* *add*: *tr-par-sym*)

**lemma** *trace-merge-nil* [*simp*]:  $x \star_{\{\}} \langle \rangle = \{x\}_u$

**by** (*pred-auto*, *simp-all* *add*: *tr-par-empty*, *metis* *takeWhile-eq-all-conv*)

**lemma** *trace-merge-empty* [*simp*]:

$(\langle \rangle \star_{cs} \langle \rangle) = \{\langle \rangle\}_u$

**by** (*rel-auto*)

**lemma** *trace-merge-single-empty* [*simp*]:

$a \in cs \implies \langle \ll a \gg \star_{cs} \langle \rangle = \{\langle \rangle\}_u$

**by** (*rel-auto*)

**lemma** *trace-merge-empty-single* [*simp*]:

$a \in cs \implies \langle \rangle \star_{cs} \langle \ll a \gg = \{\langle \rangle\}_u$

**by** (*rel-auto*)

**lemma** *trace-merge-commute*:  $t_1 \star_{cs} t_2 = t_2 \star_{cs} t_1$

**by** (*rel-simp*, *simp* *add*: *tr-par-sym*)

**lemma** *csp-trace-simps* [*simp*]:

$v + \langle \rangle = v \langle \rangle + v = v$

$bop (\#) x xs \hat{^}_u ys = bop (\#) x (xs \hat{^}_u ys)$

**by** (*rel-auto*)<sup>+</sup>

Alternative characterisation of traces, adapted from CSP-Prover

**inductive-set**

*parx* :: 'a set => ('a list \* 'a list \* 'a list) set

**for** *X* :: 'a set

**where**

*parx-nil-nil* [*intro*]:

$([], [], []) \in parx X \mid$

*parx-Ev-nil* [*intro*]:

$[] (u, s, []) \in parx X ; a \notin X []$

$\implies (a \# u, a \# s, []) \in parx X \mid$

*parx-nil-Ev* [*intro*]:

$[] (u, [], t) \in parx X ; a \notin X []$

$\implies (a \# u, [], a \# t) \in parx X \mid$

*parx-Ev-sync* [*intro*]:

$[] (u, s, t) \in parx X ; a \in X []$

$\implies (a \# u, a \# s, a \# t) \in parx X \mid$

*parx-Ev-left* [intro]:

$\llbracket (u, s, t) \in \text{parx } X ; a \notin X \rrbracket$   
 $\implies (a \# u, a \# s, t) \in \text{parx } X \mid$

*parx-Ev-right* [intro]:

$\llbracket (u, s, t) \in \text{parx } X ; a \notin X \rrbracket$   
 $\implies (a \# u, s, a \# t) \in \text{parx } X$

**lemma** *parx-implies-tr-par*:  $(t, t_1, t_2) \in \text{parx } cs \implies t \in \text{tr-par } cs \ t_1 \ t_2$

**apply** (*induct rule*: *parx.induct*)

**apply** (*auto*)

**apply** (*case-tac t*)

**apply** (*auto*)

**apply** (*case-tac s*)

**apply** (*auto*)

**done**

**end**

### 3 Syntax and Translations for Event Prefix

**theory** *utp-circus-prefix*

**imports** *UTP-Stateful-Failures.utp-sf-rdes*

**begin**

**syntax**

*-simple-prefix* :: *logic*  $\Rightarrow$  *logic*  $\Rightarrow$  *logic*  $(- \rightarrow - [63, 62] \ 62)$

**translations**

$a \rightarrow P == \text{CONST PrefixCSP} \ll a \gg P$

We next configure a syntax for mixed prefixes.

**nonterminal** *prefix-elem'* **and** *mixed-prefix'*

**syntax** *-end-prefix* :: *prefix-elem'*  $\Rightarrow$  *mixed-prefix'*  $(-)$

Input Prefix:  $\dots?(x)$

**syntax** *-simple-input-prefix* :: *id*  $\Rightarrow$  *prefix-elem'*  $(?'(-'))$

Input Prefix with Constraint:  $\dots?(x : P)$

**syntax** *-input-prefix* :: *id*  $\Rightarrow$   $('\sigma, '\varepsilon)$  *action*  $\Rightarrow$  *prefix-elem'*  $(?'(- : / -'))$

Output Prefix:  $\dots![v]e$

A variable name must currently be provided for outputs, too. Fix?!

**syntax** *-output-prefix* :: *uexp*  $\Rightarrow$  *prefix-elem'*  $(!'(-'))$

**syntax** *-output-prefix* :: *uexp*  $\Rightarrow$  *prefix-elem'*  $(.'(-'))$

**syntax** (**output**) *-output-prefix-pp* :: *uexp*  $\Rightarrow$  *prefix-elem'*  $(!'(-'))$

**syntax**

*-prefix-aux* :: *pttrn*  $\Rightarrow$  *logic*  $\Rightarrow$  *prefix-elem'*

Mixed-Prefix Action:  $c \dots (\text{prefix}) \rightarrow A$

**syntax** *-mixed-prefix* :: *prefix-elim'*  $\Rightarrow$  *mixed-prefix'*  $\Rightarrow$  *mixed-prefix'* (--)

**syntax**

*-prefix-action* ::  
 ('a, 'ε) *chan*  $\Rightarrow$  *mixed-prefix'*  $\Rightarrow$  ('σ, 'ε) *action*  $\Rightarrow$  ('σ, 'ε) *action*  
 ((--  $\rightarrow$  / -) [63, 63, 62] 62)

Syntax translations

**definition** *lconj* :: ('a  $\Rightarrow$  'α *upred*)  $\Rightarrow$  ('b  $\Rightarrow$  'α *upred*)  $\Rightarrow$  ('a  $\times$  'b  $\Rightarrow$  'α *upred*) (**infixr**  $\wedge_l$  35)  
**where** [*upred-defs*]: (*P*  $\wedge_l$  *Q*)  $\equiv$  ( $\lambda (x,y). P\ x \wedge Q\ y$ )

**definition** *outp-constraint* (**infix** =<sub>o</sub> 60) **where**

[*upred-defs*]: *outp-constraint* *v*  $\equiv$  ( $\lambda x. \ll x \gg =_u v$ )

**translations**

*-simple-input-prefix* *x*  $\equiv$  *-input-prefix* *x* *true*  
*-mixed-prefix* (*-input-prefix* *x* *P*) (*-prefix-aux* *y* *Q*)  $\rightarrow$   
*-prefix-aux* (*-pattern* *x* *y*) (( $\lambda x. P$ )  $\wedge_l$  *Q*)  
*-mixed-prefix* (*-output-prefix* *P*) (*-prefix-aux* *y* *Q*)  $\rightarrow$   
*-prefix-aux* (*-pattern -idtdummy* *y*) ((*CONST outp-constraint* *P*)  $\wedge_l$  *Q*)  
*-end-prefix* (*-input-prefix* *x* *P*)  $\rightarrow$  *-prefix-aux* *x* ( $\lambda x. P$ )  
*-end-prefix* (*-output-prefix* *P*)  $\rightarrow$  *-prefix-aux -idtdummy* (*CONST outp-constraint* *P*)  
*-prefix-action* *c* (*-prefix-aux* *x* *P*) *A* == (*CONST InputCSP*) *c* *P* ( $\lambda x. A$ )

Basic print translations; more work needed

**translations**

*-simple-input-prefix* *x*  $\leq$  *-input-prefix* *x* *true*  
*-output-prefix* *v*  $\leq$  *-prefix-aux* *p* (*CONST outp-constraint* *v*)  
*-output-prefix* *u* (*-output-prefix* *v*)  
 $\leq$  *-prefix-aux* *p* ( $\lambda(x1, y1). \text{CONST outp-constraint } u\ x2 \wedge \text{CONST outp-constraint } v\ y2$ )  
*-input-prefix* *x* *P*  $\leq$  *-prefix-aux* *v* ( $\lambda x. P$ )  
*x*!(*v*)  $\rightarrow P \leq \text{CONST OutputCSP } x\ v\ P$

**term** *x*!(1)!(*y*)  $\rightarrow P$

**term** *x*?(*v*)  $\rightarrow P$

**term** *x*?(*v*:*false*)  $\rightarrow P$

**term** *x*!(⟨1⟩)  $\rightarrow P$

**term** *x*?(*v*)!(1)  $\rightarrow P$

**term** *x*!(⟨1⟩)!(2)?(*v*:*true*)  $\rightarrow P$

Basic translations for state variable communications

**syntax**

*-csp-input-var* :: *logic*  $\Rightarrow$  *id*  $\Rightarrow$  *logic*  $\Rightarrow$  *logic* (-?'(-:')) [63, 0, 0] 62)  
*-csp-inputu-var* :: *logic*  $\Rightarrow$  *id*  $\Rightarrow$  *logic* (-?'(-')) [63, 0] 62)  
*-csp-output-var* :: *logic*  $\Rightarrow$  *uexp*  $\Rightarrow$  *logic* (-!'(-')) [63, 0] 62)

**translations**

*c*?(*x*:*A*)  $\rightarrow \text{CONST InputVarCSP } c\ x\ A$   
*c*?(*x*)  $\rightarrow \text{CONST InputVarCSP } c\ x\ (\lambda x. \text{true})$   
*c*?(*x*:*A*)  $\leq \text{CONST InputVarCSP } c\ x\ (\lambda x'. A)$   
*c*?(*x*)  $\leq c?(x:\text{true})$   
*-csp-output-var* *c* *e* == *CONST DoCSP* (*c*·*e*)<sub>u</sub>

**lemma** *outp-constraint-prod*:

(*outp-constraint*  $\ll a \gg x \wedge \text{outp-constraint } \ll b \gg y$ ) =

*outp-constraint*  $\ll(a, b)\gg (x, y)$   
**by** (*simp add: outp-constraint-def, pred-auto*)

**lemma** *subst-outp-constraint* [*usubst*]:  
 $\sigma \uparrow (v =_o x) = (\sigma \uparrow v =_o x)$   
**by** (*rel-auto*)

**lemma** *UINF-one-point-simp* [*rpred*]:  
 $\ll \bigwedge i. P\ i\ is\ R1 \gg \implies (\bigcap x \cdot \ll i \gg =_o x)_{S<} \wedge P(x) = P(i)$   
**by** (*rel-blast*)

**lemma** *USUP-one-point-simp* [*rpred*]:  
 $\ll \bigwedge i. P\ i\ is\ R1 \gg \implies (\bigcup x \cdot \ll i \gg =_o x)_{S<} \Rightarrow_r P(x) = P(i)$   
**by** (*rel-blast*)

**lemma** *USUP-eq-event-eq* [*rpred*]:  
**assumes**  $\bigwedge y. P(y)\ is\ RR$   
**shows**  $(\bigcup y \cdot [v =_o y]_{S<} \Rightarrow_r P(y)) = P(y) \ll y \rightarrow [v]_{S\leftarrow} \gg$   
**proof** –  
**have**  $(\bigcup y \cdot [v =_o y]_{S<} \Rightarrow_r RR(P(y))) = RR(P(y)) \ll y \rightarrow [v]_{S\leftarrow} \gg$   
**apply** (*rel-simp, safe*)  
**apply** *metis*  
**apply** *blast*  
**apply** *simp*  
**done**  
**thus** *?thesis*  
**by** (*simp add: Healthy-if assms*)  
**qed**

**lemma** *UINF-eq-event-eq* [*rpred*]:  
**assumes**  $\bigwedge y. P(y)\ is\ RR$   
**shows**  $(\bigcap y \cdot [v =_o y]_{S<} \wedge P(y)) = P(y) \ll y \rightarrow [v]_{S\leftarrow} \gg$   
**proof** –  
**have**  $(\bigcap y \cdot [v =_o y]_{S<} \wedge RR(P(y))) = RR(P(y)) \ll y \rightarrow [v]_{S\leftarrow} \gg$   
**by** (*rel-simp, safe, metis*)  
**thus** *?thesis*  
**by** (*simp add: Healthy-if assms*)  
**qed**

Proofs that the input constrained parser versions of output is the same as the regular definition.

**lemma** *output-prefix-is-OutputCSP* [*simp*]:  
**assumes** *A is NCSP*  
**shows**  $x!(P) \rightarrow A = OutputCSP\ x\ P\ A\ (\text{is } ?lhs = ?rhs)$   
**by** (*rdes-eq cls: assms*)

**lemma** *OutputCSP-pair-simp* [*simp*]:  
 $P\ is\ NCSP \implies a.(\ll i \gg).(\ll j \gg) \rightarrow P = OutputCSP\ a\ \ll (i, j) \gg P$   
**using** *output-prefix-is-OutputCSP[of P a]*  
**by** (*simp add: outp-constraint-prod lconj-def InputCSP-def closure del: output-prefix-is-OutputCSP*)

**lemma** *OutputCSP-triple-simp* [*simp*]:  
 $P\ is\ NCSP \implies a.(\ll i \gg).(\ll j \gg).(\ll k \gg) \rightarrow P = OutputCSP\ a\ \ll (i, j, k) \gg P$   
**using** *output-prefix-is-OutputCSP[of P a]*  
**by** (*simp add: outp-constraint-prod lconj-def InputCSP-def closure del: output-prefix-is-OutputCSP*)

end

## 4 Circus Parallel Composition

**theory** *utp-circus-parallel*

**imports**

*utp-circus-prefix*

*utp-circus-traces*

**begin**

### 4.1 Merge predicates

**definition** *CSPInnerMerge* ::  $(\alpha \Rightarrow \sigma) \Rightarrow \psi \text{ set} \Rightarrow (\beta \Rightarrow \sigma) \Rightarrow ((\sigma, \psi) \text{ sfrd}) \text{ merge } (N_C)$  **where**  
 $[upred-defs]:$

$CSPInnerMerge \ ns1 \ cs \ ns2 = ($   
 $\ \$ref' \subseteq_u ((\$0-ref \cup_u \$1-ref) \cap_u \ll cs \gg) \cup_u ((\$0-ref \cap_u \$1-ref) - \ll cs \gg) \wedge$   
 $\ \$tr_{<} \leq_u \$tr' \wedge$   
 $\ (\$tr' - \$tr_{<}) \in_u (\$0-tr - \$tr_{<}) \star_{cs} (\$1-tr - \$tr_{<}) \wedge$   
 $\ (\$0-tr - \$tr_{<}) \upharpoonright_u \ll cs \gg =_u (\$1-tr - \$tr_{<}) \upharpoonright_u \ll cs \gg \wedge$   
 $\ \$st' =_u (\$st_{<} \oplus \$0-st \text{ on } \&ns1) \oplus \$1-st \text{ on } \&ns2)$

**definition** *CSPInnerInterleave* ::  $(\alpha \Rightarrow \sigma) \Rightarrow (\beta \Rightarrow \sigma) \Rightarrow ((\sigma, \psi) \text{ sfrd}) \text{ merge } (N_I)$  **where**  
 $[upred-defs]:$

$N_I \ ns1 \ ns2 = ($   
 $\ \$ref' \subseteq_u (\$0-ref \cap_u \$1-ref) \wedge$   
 $\ \$tr_{<} \leq_u \$tr' \wedge$   
 $\ (\$tr' - \$tr_{<}) \in_u (\$0-tr - \$tr_{<}) \star_{\{\}} (\$1-tr - \$tr_{<}) \wedge$   
 $\ \$st' =_u (\$st_{<} \oplus \$0-st \text{ on } \&ns1) \oplus \$1-st \text{ on } \&ns2)$

An intermediate merge hides the state, whilst a final merge hides the refusals.

**definition** *CSPInterMerge* **where**

$[upred-defs]: CSPInterMerge \ P \ cs \ Q = (P \parallel_{(\exists \ \$st' \cdot N_C \ 0_L \ cs \ 0_L)} Q)$

**definition** *CSPFinalMerge* **where**

$[upred-defs]: CSPFinalMerge \ P \ ns1 \ cs \ ns2 \ Q = (P \parallel_{(\exists \ \$ref' \cdot N_C \ ns1 \ cs \ ns2)} Q)$

**syntax**

$-cinter\text{-}merge :: logic \Rightarrow logic \Rightarrow logic \Rightarrow logic \ (- \ll - \rrbracket^I - [85, 0, 86] \ 86)$   
 $-cfinal\text{-}merge :: logic \Rightarrow salpha \Rightarrow logic \Rightarrow salpha \Rightarrow logic \Rightarrow logic \ (- \ll - \rrbracket^F - [85, 0, 0, 86] \ 86)$   
 $-wrC :: logic \Rightarrow logic \Rightarrow logic \Rightarrow logic \ (- \text{wr}[-]_C - [85, 0, 86] \ 86)$

**translations**

$-cinter\text{-}merge \ P \ cs \ Q == CONST \ CSPInterMerge \ P \ cs \ Q$   
 $-cfinal\text{-}merge \ P \ ns1 \ cs \ ns2 \ Q == CONST \ CSPFinalMerge \ P \ ns1 \ cs \ ns2 \ Q$   
 $-wrC \ P \ cs \ Q == P \ wr_R(N_C \ 0_L \ cs \ 0_L) \ Q$

**lemma** *CSPInnerMerge-R2m*  $[closure]: N_C \ ns1 \ cs \ ns2 \text{ is } R2m$   
**by** (rel-auto)

**lemma** *CSPInnerMerge-RDM*  $[closure]: N_C \ ns1 \ cs \ ns2 \text{ is } RDM$   
**by** (rule RDM-intro, simp add: closure, simp-all add: CSPInnerMerge-def unrest)

**lemma** *ex-ref'-R2m-closed*  $[closure]:$

**assumes**  $P \text{ is } R2m$

**shows**  $(\exists \ \$ref' \cdot P) \text{ is } R2m$

**proof** –  
 have  $R2m(\exists \$ref' \cdot R2m P) = (\exists \$ref' \cdot R2m P)$   
 by (rel-auto)  
 thus ?thesis  
 by (metis Healthy-def' assms)  
**qed**

**lemma** *CSPInnerMerge-unrests* [unrest]:  
 $\$ok_{<} \# N_C ns1 cs ns2$   
 $\$wait_{<} \# N_C ns1 cs ns2$   
 by (rel-auto)+

**lemma** *CSPInterMerge-RR-closed* [closure]:  
 assumes  $P$  is RR  $Q$  is RR  
 shows  $P \llbracket cs \rrbracket^I Q$  is RR  
 by (simp add: CSPInterMerge-def parallel-RR-closed assms closure unrest)

**lemma** *CSPInterMerge-unrest-ref* [unrest]:  
 assumes  $P$  is CRR  $Q$  is CRR  
 shows  $\$ref \# P \llbracket cs \rrbracket^I Q$   
**proof** –  
 have  $\$ref \# CRR(P) \llbracket cs \rrbracket^I CRR(Q)$   
 by (rel-blast)  
 thus ?thesis  
 by (simp add: Healthy-if assms)  
**qed**

**lemma** *CSPInterMerge-unrest-st'* [unrest]:  
 $\$st' \# P \llbracket cs \rrbracket^I Q$   
 by (rel-auto)

**lemma** *CSPInterMerge-CRR-closed* [closure]:  
 assumes  $P$  is CRR  $Q$  is CRR  
 shows  $P \llbracket cs \rrbracket^I Q$  is CRR  
 by (simp add: CRR-implies-RR CRR-intro CSPInterMerge-RR-closed CSPInterMerge-unrest-ref assms)

**lemma** *CSPFinalMerge-RR-closed* [closure]:  
 assumes  $P$  is RR  $Q$  is RR  
 shows  $P \llbracket ns1|cs|ns2 \rrbracket^F Q$  is RR  
 by (simp add: CSPFinalMerge-def parallel-RR-closed assms closure unrest)

**lemma** *CSPFinalMerge-unrest-ref* [unrest]:  
 assumes  $P$  is CRR  $Q$  is CRR  
 shows  $\$ref \# P \llbracket ns1|cs|ns2 \rrbracket^F Q$   
**proof** –  
 have  $\$ref \# CRR(P) \llbracket ns1|cs|ns2 \rrbracket^F CRR(Q)$   
 by (rel-blast)  
 thus ?thesis  
 by (simp add: Healthy-if assms)  
**qed**

**lemma** *CSPFinalMerge-CRR-closed* [closure]:  
 assumes  $P$  is CRR  $Q$  is CRR  
 shows  $P \llbracket ns1|cs|ns2 \rrbracket^F Q$  is CRR  
 by (simp add: CRR-implies-RR CRR-intro CSPFinalMerge-RR-closed CSPFinalMerge-unrest-ref assms)



**lemma** *CSPFinalMerge-unrest-ref'* [unrest]:

assumes  $P$  is CRR  $Q$  is CRR  
 shows  $\$ref' \# P \llbracket ns1 | cs | ns2 \rrbracket^F Q$

**proof** –

have  $\$ref' \# CRR(P) \llbracket ns1 | cs | ns2 \rrbracket^F CRR(Q)$   
 by (rel-blast)

thus ?thesis

by (simp add: Healthy-if assms)

**qed**

**lemma** *CSPFinalMerge-CRF-closed* [closure]:

assumes  $P$  is CRF  $Q$  is CRF

shows  $P \llbracket ns1 | cs | ns2 \rrbracket^F Q$  is CRF

by (rule CRF-intro, simp-all add: assms unrest closure)

**lemma** *CSPInnerMerge-empty-Interleave*:

$N_C ns1 \{\} ns2 = N_I ns1 ns2$

by (rel-auto)

**definition** *CSPMerge* ::  $('α \implies 'σ) \Rightarrow 'ψ \text{ set} \Rightarrow ('β \implies 'σ) \Rightarrow (('σ, 'ψ) \text{ sfrd}) \text{ merge } (M_C)$  **where**  
 [upred-defs]:  $M_C ns1 cs ns2 = M_R(N_C ns1 cs ns2) ;; Skip$

**definition** *CSPInterleave* ::  $('α \implies 'σ) \Rightarrow ('β \implies 'σ) \Rightarrow (('σ, 'ψ) \text{ sfrd}) \text{ merge } (M_I)$  **where**  
 [upred-defs]:  $M_I ns1 ns2 = M_R(N_I ns1 ns2) ;; Skip$

**lemma** *swap-CSPInnerMerge*:

$ns1 \bowtie ns2 \implies \text{swap}_m ;; (N_C ns1 cs ns2) = (N_C ns2 cs ns1)$

**apply** (rel-auto)

**using** tr-par-sym **apply** blast

**apply** (simp add: lens-indep-comm)

**using** tr-par-sym **apply** blast

**apply** (simp add: lens-indep-comm)

**done**

**lemma** *SymMerge-CSPInnerMerge-NS* [closure]:  $N_C 0_L cs 0_L$  is SymMerge

by (simp add: Healthy-def swap-CSPInnerMerge)

**lemma** *SymMerge-CSPInnerInterleave* [closure]:

$N_I 0_L 0_L$  is SymMerge

by (metis CSPInnerMerge-empty-Interleave SymMerge-CSPInnerMerge-NS)

**lemma** *SymMerge-CSPInnerInterleave* [closure]:

*AssocMerge* ( $N_I 0_L 0_L$ )

**apply** (rel-auto)

**apply** (rename-tac tr tr<sub>2</sub>' ref<sub>0</sub> tr<sub>0</sub>' ref<sub>0</sub>' tr<sub>1</sub>' ref<sub>1</sub>' tr' ref<sub>2</sub>' tr<sub>i</sub>' ref<sub>3</sub>')  
**oops**

**lemma** *CSPInterMerge-right-false* [rpred]:  $P \llbracket cs \rrbracket^I \text{false} = \text{false}$

by (simp add: CSPInterMerge-def)

**lemma** *CSPInterMerge-left-false* [rpred]:  $\text{false} \llbracket cs \rrbracket^I P = \text{false}$

by (rel-auto)

**lemma** *CSPFinalMerge-right-false* [rpred]:  $P \llbracket ns1 | cs | ns2 \rrbracket^F \text{false} = \text{false}$

by (simp add: CSPFinalMerge-def)

lemma CSPFinalMerge-left-false [rpred]: false  $\llbracket ns1|cs|ns2 \rrbracket^F P = false$   
by (simp add: CSPFinalMerge-def)

lemma CSPInnerMerge-commute:

assumes  $ns1 \bowtie ns2$

shows  $P \parallel_{N_C} ns1 \ cs \ ns2 \ Q = Q \parallel_{N_C} ns2 \ cs \ ns1 \ P$

proof –

have  $P \parallel_{N_C} ns1 \ cs \ ns2 \ Q = P \parallel_{swap_m} ;; N_C \ ns2 \ cs \ ns1 \ Q$   
by (simp add: assms lens-indep-sym swap-CSPInnerMerge)

also have  $\dots = Q \parallel_{N_C} ns2 \ cs \ ns1 \ P$

by (metis par-by-merge-commute-swap)

finally show ?thesis .

qed

lemma CSPInterMerge-commute:

$P \llbracket cs \rrbracket^I Q = Q \llbracket cs \rrbracket^I P$

proof –

have  $P \llbracket cs \rrbracket^I Q = P \parallel_{\exists \$st' \cdot N_C \ 0_L \ cs \ 0_L} Q$

by (simp add: CSPInterMerge-def)

also have  $\dots = P \parallel_{\exists \$st' \cdot (swap_m ;; N_C \ 0_L \ cs \ 0_L)} Q$

by (simp add: swap-CSPInnerMerge lens-indep-sym)

also have  $\dots = P \parallel_{swap_m} ;; (\exists \$st' \cdot N_C \ 0_L \ cs \ 0_L) \ Q$

by (simp add: seqr-exists-right)

also have  $\dots = Q \parallel_{(\exists \$st' \cdot N_C \ 0_L \ cs \ 0_L)} P$

by (simp add: par-by-merge-commute-swap[THEN sym])

also have  $\dots = Q \llbracket cs \rrbracket^I P$

by (simp add: CSPInterMerge-def)

finally show ?thesis .

qed

lemma CSPFinalMerge-commute:

assumes  $ns1 \bowtie ns2$

shows  $P \llbracket ns1|cs|ns2 \rrbracket^F Q = Q \llbracket ns2|cs|ns1 \rrbracket^F P$

proof –

have  $P \llbracket ns1|cs|ns2 \rrbracket^F Q = P \parallel_{\exists \$ref' \cdot N_C \ ns1 \ cs \ ns2} Q$

by (simp add: CSPFinalMerge-def)

also have  $\dots = P \parallel_{\exists \$ref' \cdot (swap_m ;; N_C \ ns2 \ cs \ ns1)} Q$

by (simp add: swap-CSPInnerMerge lens-indep-sym assms)

also have  $\dots = P \parallel_{swap_m} ;; (\exists \$ref' \cdot N_C \ ns2 \ cs \ ns1) \ Q$

by (simp add: seqr-exists-right)

also have  $\dots = Q \parallel_{(\exists \$ref' \cdot N_C \ ns2 \ cs \ ns1)} P$

by (simp add: par-by-merge-commute-swap[THEN sym])

also have  $\dots = Q \llbracket ns2|cs|ns1 \rrbracket^F P$

by (simp add: CSPFinalMerge-def)

finally show ?thesis .

qed

Important theorem that shows the form of a parallel process

lemma CSPInnerMerge-form:

fixes  $P \ Q :: ('s, 'v) \text{ action}$

assumes  $vwb\text{-lens } ns1 \ vwb\text{-lens } ns2 \ P \text{ is } RR \ Q \text{ is } RR$

shows

$P \parallel_{N_C}^{ns1\ cs\ ns2} Q =$   
 $(\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1) \cdot$   
 $P[\langle\langle ref_0 \rangle\rangle, \langle\langle st_0 \rangle\rangle, \langle\langle tt_0 \rangle\rangle / \$ref', \$st', \$tr, \$tr'] \wedge Q[\langle\langle ref_1 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_1 \rangle\rangle / \$ref', \$st', \$tr, \$tr']$   
 $\wedge \$ref' \subseteq_u ((\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle) \cup_u ((\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle) - \langle\langle cs \rangle\rangle)$   
 $\wedge \$tr \leq_u \$tr'$   
 $\wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle$   
 $\wedge \langle\langle tt_0 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle$   
 $\wedge \$st' =_u (\$st \oplus \langle\langle st_0 \rangle\rangle\ on\ \&ns1) \oplus \langle\langle st_1 \rangle\rangle\ on\ \&ns2)$   
**(is ?lhs = ?rhs)**  
**proof** –  
**have**  $P: (\exists \{ \$ok', \$wait' \} \cdot R2(P)) = P$  **(is ?P' = -)**  
**by** (*simp add: ex-unrest ex-plus Healthy-if assms RR-implies-R2 unrest closure*)  
**have**  $Q: (\exists \{ \$ok', \$wait' \} \cdot R2(Q)) = Q$  **(is ?Q' = -)**  
**by** (*simp add: ex-unrest ex-plus Healthy-if assms RR-implies-R2 unrest closure*)  
**from** *assms(1,2)*  
**have**  $?P' \parallel_{N_C}^{ns1\ cs\ ns2} ?Q' =$   
 $(\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1) \cdot$   
 $?P'[\langle\langle ref_0 \rangle\rangle, \langle\langle st_0 \rangle\rangle, \langle\langle tt_0 \rangle\rangle / \$ref', \$st', \$tr, \$tr'] \wedge ?Q'[\langle\langle ref_1 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_1 \rangle\rangle / \$ref', \$st', \$tr, \$tr']$   
 $\wedge \$ref' \subseteq_u ((\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle) \cup_u ((\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle) - \langle\langle cs \rangle\rangle)$   
 $\wedge \$tr \leq_u \$tr'$   
 $\wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle$   
 $\wedge \langle\langle tt_0 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle$   
 $\wedge \$st' =_u (\$st \oplus \langle\langle st_0 \rangle\rangle\ on\ \&ns1) \oplus \langle\langle st_1 \rangle\rangle\ on\ \&ns2)$   
**apply** (*simp add: par-by-merge-alt-def, rel-auto, blast*)  
**apply** (*rename-tac ok wait tr st ref tr' ref' ref\_0 ref\_1 st\_0 st\_1 tr\_0 ok\_0 tr\_1 wait\_0 ok\_1 wait\_1*)  
**apply** (*rule-tac x=ok in exI*)  
**apply** (*rule-tac x=wait in exI*)  
**apply** (*rule-tac x=tr in exI*)  
**apply** (*rule-tac x=st in exI*)  
**apply** (*rule-tac x=ref in exI*)  
**apply** (*rule-tac x=tr @ tr\_0 in exI*)  
**apply** (*rule-tac x=st\_0 in exI*)  
**apply** (*rule-tac x=ref\_0 in exI*)  
**apply** (*auto*)  
**apply** (*metis Prefix-Order.prefixI append-minus*)  
**done**  
**thus** *?thesis*  
**by** (*simp add: P Q*)  
**qed**

**lemma** *CSPInterMerge-form:*

**fixes**  $P\ Q :: ('σ, 'φ)\ action$

**assumes**  $P\ is\ RR\ Q\ is\ RR$

**shows**

$P \llbracket cs \rrbracket^I Q =$

$(\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1) \cdot$   
 $P[\langle\langle ref_0 \rangle\rangle, \langle\langle st_0 \rangle\rangle, \langle\langle tt_0 \rangle\rangle / \$ref', \$st', \$tr, \$tr'] \wedge Q[\langle\langle ref_1 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_1 \rangle\rangle / \$ref', \$st', \$tr, \$tr']$   
 $\wedge \$ref' \subseteq_u ((\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle) \cup_u ((\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle) - \langle\langle cs \rangle\rangle)$   
 $\wedge \$tr \leq_u \$tr'$   
 $\wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle$   
 $\wedge \langle\langle tt_0 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle)$   
**(is ?lhs = ?rhs)**

**proof** –

**have**  $?lhs = (\exists \$st' \cdot P \parallel_{N_C}^{0_L\ cs\ 0_L} Q)$

**by** (*simp add: CSPInterMerge-def par-by-merge-def seqr-exists-right*)

also have ... =

( $\exists \$st'$  .

( $\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1)$  .

$P[\langle\langle ref_0 \rangle\rangle, \langle\langle st_0 \rangle\rangle, \langle\langle tt_0 \rangle\rangle / \$ref', \$st', \$tr, \$tr'] \wedge Q[\langle\langle ref_1 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_1 \rangle\rangle / \$ref', \$st', \$tr, \$tr']$

$\wedge \$ref' \subseteq_u ((\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle) \cup_u ((\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle) - \langle\langle cs \rangle\rangle)$

$\wedge \$tr \leq_u \$tr'$

$\wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle$

$\wedge \langle\langle tt_0 \rangle\rangle \downarrow_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \downarrow_u \langle\langle cs \rangle\rangle$

$\wedge \$st' =_u (\$st \oplus \langle\langle st_0 \rangle\rangle \text{ on } \emptyset) \oplus \langle\langle st_1 \rangle\rangle \text{ on } \emptyset)$

by (simp add: CSPInnerMerge-form pr-var-def assms)

also have ... = ?rhs

by (rel-blast)

finally show ?thesis .

qed

lemma CSPFinalMerge-form:

fixes  $P \ Q :: ('\sigma, '\varphi)$  action

assumes vwb-lens ns1 vwb-lens ns2  $P$  is RR  $Q$  is RR  $\$ref' \# P \$ref' \# Q$

shows

( $P \llbracket ns1 | cs | ns2 \rrbracket^F Q$ ) =

( $\exists (st_0, st_1, tt_0, tt_1)$  .

$P[\langle\langle st_0 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_0 \rangle\rangle / \$st', \$tr, \$tr'] \wedge Q[\langle\langle st_1 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_1 \rangle\rangle / \$st', \$tr, \$tr']$

$\wedge \$tr \leq_u \$tr'$

$\wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle$

$\wedge \langle\langle tt_0 \rangle\rangle \downarrow_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \downarrow_u \langle\langle cs \rangle\rangle$

$\wedge \$st' =_u (\$st \oplus \langle\langle st_0 \rangle\rangle \text{ on } \&ns1) \oplus \langle\langle st_1 \rangle\rangle \text{ on } \&ns2)$

(is ?lhs = ?rhs)

proof -

have ?lhs = ( $\exists \$ref' \cdot P \parallel_{N_C} ns1 \ cs \ ns2 \ Q$ )

by (simp add: CSPFinalMerge-def par-by-merge-def seqr-exists-right)

also have ... =

( $\exists \$ref'$  .

( $\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1)$  .

$P[\langle\langle ref_0 \rangle\rangle, \langle\langle st_0 \rangle\rangle, \langle\langle tt_0 \rangle\rangle / \$ref', \$st', \$tr, \$tr'] \wedge Q[\langle\langle ref_1 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_1 \rangle\rangle / \$ref', \$st', \$tr, \$tr']$

$\wedge \$ref' \subseteq_u ((\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle) \cup_u ((\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle) - \langle\langle cs \rangle\rangle)$

$\wedge \$tr \leq_u \$tr'$

$\wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle$

$\wedge \langle\langle tt_0 \rangle\rangle \downarrow_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \downarrow_u \langle\langle cs \rangle\rangle$

$\wedge \$st' =_u (\$st \oplus \langle\langle st_0 \rangle\rangle \text{ on } \&ns1) \oplus \langle\langle st_1 \rangle\rangle \text{ on } \&ns2))$

by (simp add: CSPInnerMerge-form assms)

also have ... =

( $\exists \$ref'$  .

( $\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1)$  .

( $\exists \$ref' \cdot P$ ) $[\langle\langle ref_0 \rangle\rangle, \langle\langle st_0 \rangle\rangle, \langle\langle tt_0 \rangle\rangle / \$ref', \$st', \$tr, \$tr'] \wedge (\exists \$ref' \cdot Q)[\langle\langle ref_1 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_1 \rangle\rangle / \$ref', \$st', \$tr, \$tr']$

$\wedge \$ref' \subseteq_u ((\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle) \cup_u ((\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle) - \langle\langle cs \rangle\rangle)$

$\wedge \$tr \leq_u \$tr'$

$\wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle$

$\wedge \langle\langle tt_0 \rangle\rangle \downarrow_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \downarrow_u \langle\langle cs \rangle\rangle$

$\wedge \$st' =_u (\$st \oplus \langle\langle st_0 \rangle\rangle \text{ on } \&ns1) \oplus \langle\langle st_1 \rangle\rangle \text{ on } \&ns2))$

by (simp add: ex-unrest assms)

also have ... =

( $\exists (st_0, st_1, tt_0, tt_1)$  .

( $\exists \$ref' \cdot P$ ) $[\langle\langle st_0 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_0 \rangle\rangle / \$st', \$tr, \$tr'] \wedge (\exists \$ref' \cdot Q)[\langle\langle st_1 \rangle\rangle, \langle\langle st_1 \rangle\rangle, \langle\langle tt_1 \rangle\rangle / \$st', \$tr, \$tr']$

$\wedge \$tr \leq_u \$tr'$

$\wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle$

$\wedge \ll tt_0 \gg \upharpoonright_u \ll cs \gg =_u \ll tt_1 \gg \upharpoonright_u \ll cs \gg$   
 $\wedge \$st' =_u (\$st \oplus \ll st_0 \gg \text{ on } \&ns1) \oplus \ll st_1 \gg \text{ on } \&ns2)$   
 by (rel-blast)  
 also have ... = ?rhs  
 by (simp add: ex-unrest assms)  
 finally show ?thesis .  
 qed

**lemma** CSPInterleave-merge:  $M_I \ ns1 \ ns2 = M_C \ ns1 \ \{\} \ ns2$   
 by (rel-auto)

**lemma** csp-wrR-def:  
 $P \ wr[cs]_C \ Q = (\neg_r ((\neg_r \ Q) ;; U0 \wedge P ;; U1 \wedge \$st_{<}' =_u \$st \wedge \$tr_{<}' =_u \$tr) ;; N_C \ 0_L \ cs \ 0_L ;; R1$   
 $true)$   
 by (rel-auto, metis+)

**lemma** csp-wrR-ns-irr:  
 $(P \ wr_R(N_C \ ns1 \ cs \ ns2) \ Q) = (P \ wr[cs]_C \ Q)$   
 by (rel-auto)

**lemma** csp-wrR-CRC-closed [closure]:  
 assumes  $P$  is CRR  $Q$  is CRR  
 shows  $P \ wr[cs]_C \ Q$  is CRC  
**proof** –  
 have  $\$ref \ \# \ P \ wr[cs]_C \ Q$   
 by (simp add: csp-wrR-def rpred closure assms unrest)  
 thus ?thesis  
 by (rule CRC-intro, simp-all add: closure assms)  
 qed

**lemma** ref'-unrest-final-merge [unrest]:  
 $\$ref' \ \# \ P \ \ll ns1 | cs | ns2 \gg^F \ Q$   
 by (rel-auto)

**lemma** inter-merge-CDC-closed [closure]:  
 $P \ \ll cs \gg^I \ Q$  is CDC  
 using le-less-trans by (rel-blast)

**lemma** CSPInterMerge-alt-def:  
 $P \ \ll cs \gg^I \ Q = (\exists \ \$st' \cdot P \ \parallel_{N_C \ 0_L \ cs \ 0_L} Q)$   
 by (simp add: par-by-merge-def CSPInterMerge-def seqr-exists-right)

**lemma** CSPFinalMerge-alt-def:  
 $P \ \ll ns1 | cs | ns2 \gg^F \ Q = (\exists \ \$ref' \cdot P \ \parallel_{N_C \ ns1 \ cs \ ns2} Q)$   
 by (simp add: par-by-merge-def CSPFinalMerge-def seqr-exists-right)

**lemma** merge-csp-do-left:  
 assumes  $vwb\text{-}lens \ ns1 \ vwb\text{-}lens \ ns2 \ ns1 \ \bowtie \ ns2 \ P$  is RR  
 shows  $\Phi(s_0, \sigma_0, t_0) \parallel_{N_C \ ns1 \ cs \ ns2} P =$   
 $(\exists \ (ref_1, st_1, tt_1) \cdot$   
 $\ [s_0]_{S<} \wedge$   
 $\ [\$ref' \mapsto_s \ll ref_1 \gg, \$st' \mapsto_s \ll st_1 \gg, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \ll tt_1 \gg] \ \dagger \ P \wedge$   
 $\ \$ref' \subseteq_u \ll cs \gg \cup_u (\ll ref_1 \gg - \ll cs \gg) \wedge$   
 $\ [\ll trace \gg \in_u t_0 \star_{cs} \ll tt_1 \gg \wedge t_0 \upharpoonright_u \ll cs \gg =_u \ll tt_1 \gg \upharpoonright_u \ll cs \gg]_t \wedge$   
 $\ \$st' =_u \$st \oplus \ll \sigma_0 \gg (\$st)_a \text{ on } \&ns1 \oplus \ll st_1 \gg \text{ on } \&ns2)$

(is ?lhs = ?rhs)

**proof** –

**have** ?lhs =

$(\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1) \cdot$

$[\$ref' \mapsto_s \langle ref_0 \rangle, \$st' \mapsto_s \langle st_0 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_0 \rangle] \dagger \Phi(s_0, \sigma_0, t_0) \wedge$

$[\$ref' \mapsto_s \langle ref_1 \rangle, \$st' \mapsto_s \langle st_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_1 \rangle] \dagger P \wedge$

$\$ref' \subseteq_u (\langle ref_0 \rangle \cup_u \langle ref_1 \rangle) \cap_u \langle cs \rangle \cup_u (\langle ref_0 \rangle \cap_u \langle ref_1 \rangle - \langle cs \rangle) \wedge$

$\$tr \leq_u \$tr' \wedge$

$\&tt \in_u \langle tt_0 \rangle \star_{cs} \langle tt_1 \rangle \wedge \langle tt_0 \rangle \upharpoonright_u \langle cs \rangle =_u \langle tt_1 \rangle \upharpoonright_u \langle cs \rangle \wedge \$st' =_u \$st \oplus \langle st_0 \rangle \text{ on } \&ns1$

$\oplus \langle st_1 \rangle \text{ on } \&ns2)$

**by** (simp add: CSPInnerMerge-form assms closure)

**also have** ... =

$(\exists (ref_1, st_1, tt_1) \cdot$

$[s_0]_{S<} \wedge$

$[\$ref' \mapsto_s \langle ref_1 \rangle, \$st' \mapsto_s \langle st_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_1 \rangle] \dagger P \wedge$

$\$ref' \subseteq_u \langle cs \rangle \cup_u (\langle ref_1 \rangle - \langle cs \rangle) \wedge$

$[\langle trace \rangle \in_u t_0 \star_{cs} \langle tt_1 \rangle \wedge t_0 \upharpoonright_u \langle cs \rangle =_u \langle tt_1 \rangle \upharpoonright_u \langle cs \rangle]_t \wedge$

$\$st' =_u \$st \oplus \langle \sigma_0 \rangle (\$st)_a \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$

**by** (rel-blast)

**finally show** ?thesis .

**qed**

**lemma** merge-csp-do-right:

**assumes** vwb-lens ns1 vwb-lens ns2 ns1  $\bowtie$  ns2 *P* is RR

**shows**  $P \parallel_{N_C} ns1 \text{ cs } ns2 \Phi(s_1, \sigma_1, t_1) =$

$(\exists (ref_0, st_0, tt_0) \cdot$

$[\$ref' \mapsto_s \langle ref_0 \rangle, \$st' \mapsto_s \langle st_0 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_0 \rangle] \dagger P \wedge$

$[s_1]_{S<} \wedge$

$\$ref' \subseteq_u \langle cs \rangle \cup_u (\langle ref_0 \rangle - \langle cs \rangle) \wedge$

$[\langle trace \rangle \in_u \langle tt_0 \rangle \star_{cs} t_1 \wedge \langle tt_0 \rangle \upharpoonright_u \langle cs \rangle =_u t_1 \upharpoonright_u \langle cs \rangle]_t \wedge$

$\$st' =_u \$st \oplus \langle st_0 \rangle \text{ on } \&ns1 \oplus \langle \sigma_1 \rangle (\$st)_a \text{ on } \&ns2)$

(is ?lhs = ?rhs)

**proof** –

**have** ?lhs =  $\Phi(s_1, \sigma_1, t_1) \parallel_{N_C} ns2 \text{ cs } ns1 P$

**by** (simp add: CSPInnerMerge-commute assms)

**also from** assms **have** ... = ?rhs

**apply** (simp add: assms merge-csp-do-left lens-indep-sym)

**apply** (rel-auto)

**using** assms(3) lens-indep-comm tr-par-sym **apply** fastforce

**using** assms(3) lens-indep.lens-put-comm tr-par-sym **apply** fastforce

**done**

**finally show** ?thesis .

**qed**

**lemma** merge-csp-enable-right:

**assumes** vwb-lens ns1 vwb-lens ns2 ns1  $\bowtie$  ns2 *P* is RR

**shows**  $P \parallel_{N_C} ns1 \text{ cs } ns2 \mathcal{E}(s_0, t_0, E_0) =$

$(\exists (ref_0, ref_1, st_0, st_1, tt_0) \cdot$

$[s_0]_{S<} \wedge$

$[\$ref' \mapsto_s \langle ref_0 \rangle, \$st' \mapsto_s \langle st_0 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_0 \rangle] \dagger P \wedge$

$(\forall e \cdot \langle e \rangle \in_u [E_0]_{S<} \Rightarrow \langle e \rangle \notin_u \langle ref_1 \rangle) \wedge$

$\$ref' \subseteq_u (\langle ref_0 \rangle \cup_u \langle ref_1 \rangle) \cap_u \langle cs \rangle \cup_u (\langle ref_0 \rangle \cap_u \langle ref_1 \rangle - \langle cs \rangle) \wedge$

$[\langle trace \rangle \in_u \langle tt_0 \rangle \star_{cs} t_0 \wedge \langle tt_0 \rangle \upharpoonright_u \langle cs \rangle =_u t_0 \upharpoonright_u \langle cs \rangle]_t \wedge$

$\$st' =_u \$st \oplus \langle st_0 \rangle \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$

(is ?lhs = ?rhs)

**proof** –

**have**  $?lhs = (\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1) \cdot$   
 $[\$ref' \mapsto_s \langle ref_0 \rangle, \$st' \mapsto_s \langle st_0 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_0 \rangle] \dagger P \wedge$   
 $[\$ref' \mapsto_s \langle ref_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_1 \rangle] \dagger \mathcal{E}(s_0, t_0, E_0) \wedge$   
 $\$ref' \subseteq_u (\langle ref_0 \rangle \cup_u \langle ref_1 \rangle) \cap_u \langle cs \rangle \cup_u (\langle ref_0 \rangle \cap_u \langle ref_1 \rangle - \langle cs \rangle) \wedge$   
 $\$tr \leq_u \$tr' \wedge \&tt \in_u \langle tt_0 \rangle \star_{cs} \langle tt_1 \rangle \wedge \langle tt_0 \rangle \upharpoonright_u \langle cs \rangle =_u \langle tt_1 \rangle \upharpoonright_u \langle cs \rangle \wedge \$st' =_u \$st$   
 $\oplus \langle st_0 \rangle \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$   
**by** (*simp add: CSPInnerMerge-form assms closure unrest usubst*)  
**also have**  $\dots = (\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1) \cdot [\$ref' \mapsto_s \langle ref_0 \rangle, \$st' \mapsto_s \langle st_0 \rangle, \$tr \mapsto_s \langle \rangle, \$tr'$   
 $\mapsto_s \langle tt_0 \rangle] \dagger P \wedge$   
 $([s_0]_{S<} \wedge \langle tt_1 \rangle =_u [t_0]_{S<} \wedge (\forall e \cdot \langle e \rangle \in_u [E_0]_{S<} \Rightarrow \langle e \rangle \notin_u \langle ref_1 \rangle)) \wedge$   
 $\$ref' \subseteq_u (\langle ref_0 \rangle \cup_u \langle ref_1 \rangle) \cap_u \langle cs \rangle \cup_u (\langle ref_0 \rangle \cap_u \langle ref_1 \rangle - \langle cs \rangle) \wedge$   
 $\$tr \leq_u \$tr' \wedge \&tt \in_u \langle tt_0 \rangle \star_{cs} \langle tt_1 \rangle \wedge \langle tt_0 \rangle \upharpoonright_u \langle cs \rangle =_u \langle tt_1 \rangle \upharpoonright_u \langle cs \rangle \wedge \$st' =_u \$st$   
 $\oplus \langle st_0 \rangle \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$   
**by** (*simp add: csp-enable-def usubst unrest*)  
**also have**  $\dots = (\exists (ref_0, ref_1, st_0, st_1, tt_0) \cdot$   
 $[s_0]_{S<} \wedge$   
 $[\$ref' \mapsto_s \langle ref_0 \rangle, \$st' \mapsto_s \langle st_0 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_0 \rangle] \dagger P \wedge$   
 $(\forall e \cdot \langle e \rangle \in_u [E_0]_{S<} \Rightarrow \langle e \rangle \notin_u \langle ref_1 \rangle) \wedge$   
 $\$ref' \subseteq_u (\langle ref_0 \rangle \cup_u \langle ref_1 \rangle) \cap_u \langle cs \rangle \cup_u (\langle ref_0 \rangle \cap_u \langle ref_1 \rangle - \langle cs \rangle) \wedge$   
 $[\langle trace \rangle \in_u \langle tt_0 \rangle \star_{cs} t_0 \wedge \langle tt_0 \rangle \upharpoonright_u \langle cs \rangle =_u t_0 \upharpoonright_u \langle cs \rangle]_t \wedge$   
 $\$st' =_u \$st \oplus \langle st_0 \rangle \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$   
**by** (*rel-blast*)  
**finally show**  $?thesis$  .  
**qed**

**lemma** *merge-csp-enable-left:*

**assumes** *vwb-lens ns1 vwb-lens ns2 ns1  $\bowtie$  ns2 P is RR*

**shows**  $\mathcal{E}(s_0, t_0, E_0) \parallel_{N_C} ns1 \text{ cs } ns2 P =$

$(\exists (ref_0, ref_1, st_0, st_1, tt_0) \cdot$   
 $[s_0]_{S<} \wedge$   
 $[\$ref' \mapsto_s \langle ref_0 \rangle, \$st' \mapsto_s \langle st_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_0 \rangle] \dagger P \wedge$   
 $(\forall e \cdot \langle e \rangle \in_u [E_0]_{S<} \Rightarrow \langle e \rangle \notin_u \langle ref_1 \rangle) \wedge$   
 $\$ref' \subseteq_u (\langle ref_0 \rangle \cup_u \langle ref_1 \rangle) \cap_u \langle cs \rangle \cup_u (\langle ref_0 \rangle \cap_u \langle ref_1 \rangle - \langle cs \rangle) \wedge$   
 $[\langle trace \rangle \in_u t_0 \star_{cs} \langle tt_0 \rangle \wedge \langle tt_0 \rangle \upharpoonright_u \langle cs \rangle =_u t_0 \upharpoonright_u \langle cs \rangle]_t \wedge$   
 $\$st' =_u \$st \oplus \langle st_0 \rangle \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$

(**is**  $?lhs = ?rhs$ )

**proof** –

**have**  $?lhs = P \parallel_{N_C} ns2 \text{ cs } ns1 \mathcal{E}(s_0, t_0, E_0)$

**by** (*simp add: CSPInnerMerge-commute assms*)

**also from** *assms* **have**  $\dots = ?rhs$

**apply** (*simp add: merge-csp-enable-right assms(4) lens-indep-sym*)

**apply** (*rel-auto*)

**oops**

The result of merge two terminated stateful traces is to (1) require both state preconditions hold, (2) merge the traces using, and (3) merge the state using a parallel assignment.

**lemma** *FinalMerge-csp-do-left:*

**assumes** *vwb-lens ns1 vwb-lens ns2 ns1  $\bowtie$  ns2 P is RR*  $\$ref' \nmid P$

**shows**  $\Phi(s_0, \sigma_0, t_0) \llbracket ns1 | cs | ns2 \rrbracket^F P =$

$(\exists (st_1, t_1) \cdot$   
 $[s_0]_{S<} \wedge$   
 $[\$st' \mapsto_s \langle st_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle t_1 \rangle] \dagger P \wedge$   
 $[\langle trace \rangle \in_u t_0 \star_{cs} \langle t_1 \rangle \wedge t_0 \upharpoonright_u \langle cs \rangle =_u \langle t_1 \rangle \upharpoonright_u \langle cs \rangle]_t \wedge$   
 $\$st' =_u \$st \oplus \langle \sigma_0 \rangle (\$st)_a \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$

(is ?lhs = ?rhs)

**proof** –

**have** ?lhs =

$(\exists (st_0, st_1, tt_0, tt_1) \cdot$

$[\$st' \mapsto_s \langle st_0 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_0 \rangle] \dagger \Phi(s_0, \sigma_0, t_0) \wedge$

$[\$st' \mapsto_s \langle st_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_1 \rangle] \dagger RR(\exists \$ref' \cdot P) \wedge$

$\$tr \leq_u \$tr' \wedge \&tt \in_u \langle tt_0 \rangle \star_{cs} \langle tt_1 \rangle \wedge \langle tt_0 \rangle \upharpoonright_u \langle cs \rangle =_u \langle tt_1 \rangle \upharpoonright_u \langle cs \rangle \wedge$

$\$st' =_u \$st \oplus \langle st_0 \rangle \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$

**by** (simp add: CSPFinalMerge-form ex-unrest Healthy-if unrest closure assms)

**also have** ... =

$(\exists (st_1, tt_1) \cdot$

$[s_0]_{S<} \wedge$

$[\$st' \mapsto_s \langle st_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_1 \rangle] \dagger RR(\exists \$ref' \cdot P) \wedge$

$\langle \text{trace} \rangle \in_u t_0 \star_{cs} \langle tt_1 \rangle \wedge t_0 \upharpoonright_u \langle cs \rangle =_u \langle tt_1 \rangle \upharpoonright_u \langle cs \rangle]_t \wedge$

$\$st' =_u \$st \oplus \langle \sigma_0 \rangle (\$st)_a \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$

**by** (rel-blast)

**also have** ... =

$(\exists (st_1, t_1) \cdot$

$[s_0]_{S<} \wedge$

$[\$st' \mapsto_s \langle st_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle t_1 \rangle] \dagger P \wedge$

$\langle \text{trace} \rangle \in_u t_0 \star_{cs} \langle t_1 \rangle \wedge t_0 \upharpoonright_u \langle cs \rangle =_u \langle t_1 \rangle \upharpoonright_u \langle cs \rangle]_t \wedge$

$\$st' =_u \$st \oplus \langle \sigma_0 \rangle (\$st)_a \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2)$

**by** (simp add: ex-unrest Healthy-if unrest closure assms)

**finally show** ?thesis .

**qed**

**lemma** FinalMerge-csp-do-right:

**assumes** vwb-lens ns1 vwb-lens ns2 ns1  $\bowtie$  ns2  $P$  is  $RR \$ref' \nmid P$

**shows**  $P \llbracket ns1 | cs | ns2 \rrbracket^F \Phi(s_1, \sigma_1, t_1) =$

$(\exists (st_0, t_0) \cdot$

$[\$st' \mapsto_s \langle st_0 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle t_0 \rangle] \dagger P \wedge$

$[s_1]_{S<} \wedge$

$\langle \text{trace} \rangle \in_u \langle t_0 \rangle \star_{cs} t_1 \wedge \langle t_0 \rangle \upharpoonright_u \langle cs \rangle =_u t_1 \upharpoonright_u \langle cs \rangle]_t \wedge$

$\$st' =_u \$st \oplus \langle st_0 \rangle \text{ on } \&ns1 \oplus \langle \sigma_1 \rangle (\$st)_a \text{ on } \&ns2)$

  (is ?lhs = ?rhs)

**proof** –

**have**  $P \llbracket ns1 | cs | ns2 \rrbracket^F \Phi(s_1, \sigma_1, t_1) = \Phi(s_1, \sigma_1, t_1) \llbracket ns2 | cs | ns1 \rrbracket^F P$

**by** (simp add: assms CSPFinalMerge-commute)

**also have** ... = ?rhs

**apply** (simp add: FinalMerge-csp-do-left assms lens-indep-sym conj-comm)

**apply** (rel-auto)

**using** assms(3) lens-indep.lens-put-comm tr-par-sym **apply** fastforce+

**done**

**finally show** ?thesis .

**qed**

**lemma** FinalMerge-csp-do:

**assumes** vwb-lens ns1 vwb-lens ns2 ns1  $\bowtie$  ns2

**shows**  $\Phi(s_1, \sigma_1, t_1) \llbracket ns1 | cs | ns2 \rrbracket^F \Phi(s_2, \sigma_2, t_2) =$

$([s_1 \wedge s_2]_{S<} \wedge \langle \text{trace} \rangle \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \langle cs \rangle =_u t_2 \upharpoonright_u \langle cs \rangle]_t \wedge [(\sigma_1 [\&ns1 | \&ns2]_s \sigma_2)_a]_{S'})$

  (is ?lhs = ?rhs)

**proof** –

**have** ?lhs =

$(\exists (st_0, st_1, tt_0, tt_1) \cdot$



$$\begin{aligned}
& [\$st' \mapsto_s \langle st_0 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_0 \rangle] \dagger \Phi(s_1, \sigma_1, t_1) \wedge \\
& [\$st' \mapsto_s \langle st_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle tt_1 \rangle] \dagger \Phi(s_2, \sigma_2, t_2) \wedge \\
& \$tr \leq_u \$tr' \wedge \langle tt \rangle \in_u \langle tt_0 \rangle \star_{cs} \langle tt_1 \rangle \wedge \langle tt_0 \rangle \upharpoonright_u \langle cs \rangle =_u \langle tt_1 \rangle \upharpoonright_u \langle cs \rangle \wedge \\
& \$st' =_u \$st \oplus \langle st_0 \rangle \text{ on } \&ns1 \oplus \langle st_1 \rangle \text{ on } \&ns2) \\
& \text{by (simp add: CSPFinalMerge-form unrest closure assms)} \\
& \text{also have ... =} \\
& ([s_1 \wedge s_2]_{S<} \wedge [\langle trace \rangle \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \langle cs \rangle =_u t_2 \upharpoonright_u \langle cs \rangle]_t \wedge [\langle \sigma_1 [\&ns1 | \&ns2]_s \sigma_2 \rangle_a]_{S'}) \\
& \text{by (rel-auto)} \\
& \text{finally show ?thesis .} \\
& \text{qed}
\end{aligned}$$

**lemma** *FinalMerge-csp-do'* [rpred]:  
**assumes** *vwb-lens ns1 vwb-lens ns2 ns1*  $\bowtie$  *ns2*  
**shows**  $\Phi(s_1, \sigma_1, t_1) \llbracket ns1 | cs | ns2 \rrbracket^F \Phi(s_2, \sigma_2, t_2) =$   
 $(\exists \text{ trace} \cdot \Phi(s_1 \wedge s_2 \wedge \langle trace \rangle \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \langle cs \rangle =_u t_2 \upharpoonright_u \langle cs \rangle, \sigma_1 [\&ns1 | \&ns2]_s \sigma_2,$   
 $\langle trace \rangle))$   
**by** (simp add: FinalMerge-csp-do assms, rel-auto)

**lemma** *CSPFinalMerge-UNF-mem-left* [rpred]:  
 $(\bigcap i \in A \cdot P(i)) \llbracket ns1 | cs | ns2 \rrbracket^F Q = (\bigcap i \in A \cdot P(i) \llbracket ns1 | cs | ns2 \rrbracket^F Q)$   
**by** (simp add: CSPFinalMerge-def par-by-merge-USUP-mem-left)

**lemma** *CSPFinalMerge-UNF-ind-left* [rpred]:  
 $(\bigcap i \cdot P(i)) \llbracket ns1 | cs | ns2 \rrbracket^F Q = (\bigcap i \cdot P(i) \llbracket ns1 | cs | ns2 \rrbracket^F Q)$   
**by** (simp add: CSPFinalMerge-def par-by-merge-USUP-ind-left)

**lemma** *CSPFinalMerge-UNF-mem-right* [rpred]:  
 $P \llbracket ns1 | cs | ns2 \rrbracket^F (\bigcap i \in A \cdot Q(i)) = (\bigcap i \in A \cdot P \llbracket ns1 | cs | ns2 \rrbracket^F Q(i))$   
**by** (simp add: CSPFinalMerge-def par-by-merge-USUP-mem-right)

**lemma** *CSPFinalMerge-UNF-ind-right* [rpred]:  
 $P \llbracket ns1 | cs | ns2 \rrbracket^F (\bigcap i \cdot Q(i)) = (\bigcap i \cdot P \llbracket ns1 | cs | ns2 \rrbracket^F Q(i))$   
**by** (simp add: CSPFinalMerge-def par-by-merge-USUP-ind-right)

**lemma** *InterMerge-csp-enable-left*:  
**assumes** *P is RR \$st' \# P*  
**shows**  $\mathcal{E}(s_0, t_0, E_0) \llbracket cs \rrbracket^I P =$   
 $(\exists (\text{ref}_0, \text{ref}_1, t_1) \cdot$   
 $[s_0]_{S<} \wedge (\forall e \cdot \langle e \rangle \in_u [E_0]_{S<} \Rightarrow \langle e \rangle \notin_u \langle \text{ref}_0 \rangle) \wedge$   
 $[\$ref' \mapsto_s \langle \text{ref}_1 \rangle, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \langle t_1 \rangle] \dagger P \wedge$   
 $\$ref' \subseteq_u (\langle \text{ref}_0 \rangle \cup_u \langle \text{ref}_1 \rangle) \cap_u \langle cs \rangle \cup_u (\langle \text{ref}_0 \rangle \cap_u \langle \text{ref}_1 \rangle - \langle cs \rangle) \wedge$   
 $[\langle trace \rangle \in_u t_0 \star_{cs} \langle t_1 \rangle \wedge t_0 \upharpoonright_u \langle cs \rangle =_u \langle t_1 \rangle \upharpoonright_u \langle cs \rangle]_t)$   
**(is ?lhs = ?rhs)**  
**apply** (simp add: CSPInterMerge-form ex-unrest Healthy-if unrest closure assms usubst)  
**apply** (simp add: csp-enable-def usubst unrest assms closure)  
**apply** (rel-auto)  
**done**

**lemma** *InterMerge-csp-enable*:  
 $\mathcal{E}(s_1, t_1, E_1) \llbracket cs \rrbracket^I \mathcal{E}(s_2, t_2, E_2) =$   
 $([s_1 \wedge s_2]_{S<} \wedge$   
 $(\forall e \in [(E_1 \cap_u E_2 \cap_u \langle cs \rangle) \cup_u ((E_1 \cup_u E_2) - \langle cs \rangle)]_{S<} \cdot \langle e \rangle \notin_u \$ref') \wedge$   
 $[\langle trace \rangle \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \langle cs \rangle =_u t_2 \upharpoonright_u \langle cs \rangle]_t)$

(is ?lhs = ?rhs)

**proof** –

**have** ?lhs =

$(\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1) \cdot$

$[\$ref' \mapsto_s \langle\langle ref_0 \rangle\rangle, \$st' \mapsto_s \langle\langle st_0 \rangle\rangle, \$tr \mapsto_s \langle\rangle, \$tr' \mapsto_s \langle\langle tt_0 \rangle\rangle] \dagger \mathcal{E}(s_1, t_1, E_1) \wedge$

$[\$ref' \mapsto_s \langle\langle ref_1 \rangle\rangle, \$st' \mapsto_s \langle\langle st_1 \rangle\rangle, \$tr \mapsto_s \langle\rangle, \$tr' \mapsto_s \langle\langle tt_1 \rangle\rangle] \dagger \mathcal{E}(s_2, t_2, E_2) \wedge$

$\$ref' \subseteq_u (\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle \cup_u (\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle - \langle\langle cs \rangle\rangle) \wedge$

$\$tr \leq_u \$tr' \wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle \wedge \langle\langle tt_0 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle)$

**by** (simp add: CSPInterMerge-form unrest closure)

**also have** ... =

$(\exists (ref_0, ref_1, tt_0, tt_1) \cdot$

$[\$ref' \mapsto_s \langle\langle ref_0 \rangle\rangle, \$tr \mapsto_s \langle\rangle, \$tr' \mapsto_s \langle\langle tt_0 \rangle\rangle] \dagger \mathcal{E}(s_1, t_1, E_1) \wedge$

$[\$ref' \mapsto_s \langle\langle ref_1 \rangle\rangle, \$tr \mapsto_s \langle\rangle, \$tr' \mapsto_s \langle\langle tt_1 \rangle\rangle] \dagger \mathcal{E}(s_2, t_2, E_2) \wedge$

$\$ref' \subseteq_u (\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle \cup_u (\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle - \langle\langle cs \rangle\rangle) \wedge$

$\$tr \leq_u \$tr' \wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle \wedge \langle\langle tt_0 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle)$

**by** (rel-auto)

**also have** ... =

$([s_1 \wedge s_2]_{S<} \wedge$

$(\forall e \in [(E_1 \cap_u E_2 \cap_u \langle\langle cs \rangle\rangle) \cup_u ((E_1 \cup_u E_2) - \langle\langle cs \rangle\rangle)]_{S<} \cdot \langle\langle e \rangle\rangle \notin_u \$ref') \wedge$

$[\langle\langle trace \rangle\rangle \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \langle\langle cs \rangle\rangle =_u t_2 \upharpoonright_u \langle\langle cs \rangle\rangle]_t$

    )

**apply** (rel-auto)

**apply** (rename-tac tr st tr' ref')

**apply** (rule-tac x=–  $\llbracket E_1 \rrbracket_e$  st in exI)

**apply** (simp)

**apply** (rule-tac x=–  $\llbracket E_2 \rrbracket_e$  st in exI)

**apply** (auto)

**done**

**finally show** ?thesis .

**qed**

**lemma** InterMerge-csp-enable' [rpred]:

$\mathcal{E}(s_1, t_1, E_1) \llbracket cs \rrbracket^I \mathcal{E}(s_2, t_2, E_2) =$

$(\exists trace \cdot \mathcal{E}(s_1 \wedge s_2 \wedge \langle\langle trace \rangle\rangle \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \langle\langle cs \rangle\rangle =_u t_2 \upharpoonright_u \langle\langle cs \rangle\rangle$

$, \langle\langle trace \rangle\rangle$

$, (E_1 \cap_u E_2 \cap_u \langle\langle cs \rangle\rangle) \cup_u ((E_1 \cup_u E_2) - \langle\langle cs \rangle\rangle)))$

**by** (simp add: InterMerge-csp-enable, rel-auto)

**lemma** InterMerge-csp-enable-csp-do [rpred]:

$\mathcal{E}(s_1, t_1, E_1) \llbracket cs \rrbracket^I \Phi(s_2, \sigma_2, t_2) =$

$(\exists trace \cdot \mathcal{E}(s_1 \wedge s_2 \wedge \langle\langle trace \rangle\rangle \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \langle\langle cs \rangle\rangle =_u t_2 \upharpoonright_u \langle\langle cs \rangle\rangle, \langle\langle trace \rangle\rangle, E_1 - \langle\langle cs \rangle\rangle))$

(is ?lhs = ?rhs)

**proof** –

**have** ?lhs =

$(\exists (ref_0, ref_1, st_0, st_1, tt_0, tt_1) \cdot$

$[\$ref' \mapsto_s \langle\langle ref_0 \rangle\rangle, \$st' \mapsto_s \langle\langle st_0 \rangle\rangle, \$tr \mapsto_s \langle\rangle, \$tr' \mapsto_s \langle\langle tt_0 \rangle\rangle] \dagger \mathcal{E}(s_1, t_1, E_1) \wedge$

$[\$ref' \mapsto_s \langle\langle ref_1 \rangle\rangle, \$st' \mapsto_s \langle\langle st_1 \rangle\rangle, \$tr \mapsto_s \langle\rangle, \$tr' \mapsto_s \langle\langle tt_1 \rangle\rangle] \dagger \Phi(s_2, \sigma_2, t_2) \wedge$

$\$ref' \subseteq_u (\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle \cup_u (\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle - \langle\langle cs \rangle\rangle) \wedge$

$\$tr \leq_u \$tr' \wedge \&tt \in_u \langle\langle tt_0 \rangle\rangle \star_{cs} \langle\langle tt_1 \rangle\rangle \wedge \langle\langle tt_0 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle =_u \langle\langle tt_1 \rangle\rangle \upharpoonright_u \langle\langle cs \rangle\rangle)$

**by** (simp add: CSPInterMerge-form unrest closure)

**also have** ... =

$(\exists (ref_0, ref_1, tt_0) \cdot$

$[\$ref' \mapsto_s \langle\langle ref_0 \rangle\rangle, \$tr \mapsto_s \langle\rangle, \$tr' \mapsto_s \langle\langle tt_0 \rangle\rangle] \dagger \mathcal{E}(s_1, t_1, E_1) \wedge$

$[s_2]_{S<} \wedge$

$\$ref' \subseteq_u (\langle\langle ref_0 \rangle\rangle \cup_u \langle\langle ref_1 \rangle\rangle) \cap_u \langle\langle cs \rangle\rangle \cup_u (\langle\langle ref_0 \rangle\rangle \cap_u \langle\langle ref_1 \rangle\rangle - \langle\langle cs \rangle\rangle) \wedge$

$$[\llbracket \text{trace} \rrbracket \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \llbracket cs \rrbracket =_u t_2 \upharpoonright_u \llbracket cs \rrbracket]_t)$$
 by (*rel-auto*)  
 also have ... =  $([s_1 \wedge s_2]_{S<} \wedge (\forall e \in [(E_1 - \llbracket cs \rrbracket)]_{S<} \cdot \llbracket e \rrbracket \notin_u \$ref') \wedge$   

$$[\llbracket \text{trace} \rrbracket \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \llbracket cs \rrbracket =_u t_2 \upharpoonright_u \llbracket cs \rrbracket]_t)$$
  
 by (*rel-auto*)  
 also have ... =  $(\exists \text{ trace} \cdot \mathcal{E}(s_1 \wedge s_2 \wedge \llbracket \text{trace} \rrbracket \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \llbracket cs \rrbracket =_u t_2 \upharpoonright_u \llbracket cs \rrbracket, \llbracket \text{trace} \rrbracket, E_1 - \llbracket cs \rrbracket))$   
 by (*rel-auto*)  
 finally show *?thesis* .  
 qed

**lemma** *InterMerge-csp-do-csp-enable* [*rpred*]:

$$\Phi(s_1, \sigma_1, t_1) \llbracket cs \rrbracket^I \mathcal{E}(s_2, t_2, E_2) =$$
  

$$(\exists \text{ trace} \cdot \mathcal{E}(s_1 \wedge s_2 \wedge \llbracket \text{trace} \rrbracket \in_u t_1 \star_{cs} t_2 \wedge t_1 \upharpoonright_u \llbracket cs \rrbracket =_u t_2 \upharpoonright_u \llbracket cs \rrbracket, \llbracket \text{trace} \rrbracket, E_2 - \llbracket cs \rrbracket))$$
  
 (is *?lhs* = *?rhs*)

**proof** –

have  $\Phi(s_1, \sigma_1, t_1) \llbracket cs \rrbracket^I \mathcal{E}(s_2, t_2, E_2) = \mathcal{E}(s_2, t_2, E_2) \llbracket cs \rrbracket^I \Phi(s_1, \sigma_1, t_1)$   
 by (*simp add: CSPInterMerge-commute*)  
 also have ... = *?rhs*  
 by (*simp add: rpred trace-merge-commute eq-upred-sym, rel-auto*)  
 finally show *?thesis* .

qed

**lemma** *CSPInterMerge-or-left* [*rpred*]:

$$(P \vee Q) \llbracket cs \rrbracket^I R = (P \llbracket cs \rrbracket^I R \vee Q \llbracket cs \rrbracket^I R)$$
  
 by (*simp add: CSPInterMerge-def par-by-merge-or-left*)

**lemma** *CSPInterMerge-or-right* [*rpred*]:

$$P \llbracket cs \rrbracket^I (Q \vee R) = (P \llbracket cs \rrbracket^I Q \vee P \llbracket cs \rrbracket^I R)$$
  
 by (*simp add: CSPInterMerge-def par-by-merge-or-right*)

**lemma** *CSPFinalMerge-or-left* [*rpred*]:

$$(P \vee Q) \llbracket ns1 | cs | ns2 \rrbracket^F R = (P \llbracket ns1 | cs | ns2 \rrbracket^F R \vee Q \llbracket ns1 | cs | ns2 \rrbracket^F R)$$
  
 by (*simp add: CSPFinalMerge-def par-by-merge-or-left*)

**lemma** *CSPFinalMerge-or-right* [*rpred*]:

$$P \llbracket ns1 | cs | ns2 \rrbracket^F (Q \vee R) = (P \llbracket ns1 | cs | ns2 \rrbracket^F Q \vee P \llbracket ns1 | cs | ns2 \rrbracket^F R)$$
  
 by (*simp add: CSPFinalMerge-def par-by-merge-or-right*)

**lemma** *CSPInterMerge-UINF-mem-left* [*rpred*]:

$$(\bigcap_{i \in A} i \cdot P(i)) \llbracket cs \rrbracket^I Q = (\bigcap_{i \in A} i \cdot P(i) \llbracket cs \rrbracket^I Q)$$
  
 by (*simp add: CSPInterMerge-def par-by-merge-USUP-mem-left*)

**lemma** *CSPInterMerge-UINF-ind-left* [*rpred*]:

$$(\bigcap i \cdot P(i)) \llbracket cs \rrbracket^I Q = (\bigcap i \cdot P(i) \llbracket cs \rrbracket^I Q)$$
  
 by (*simp add: CSPInterMerge-def par-by-merge-USUP-ind-left*)

**lemma** *CSPInterMerge-UINF-mem-right* [*rpred*]:

$$P \llbracket cs \rrbracket^I (\bigcap_{i \in A} i \cdot Q(i)) = (\bigcap_{i \in A} i \cdot P \llbracket cs \rrbracket^I Q(i))$$
  
 by (*simp add: CSPInterMerge-def par-by-merge-USUP-mem-right*)

**lemma** *CSPInterMerge-UINF-ind-right* [*rpred*]:

$$P \llbracket cs \rrbracket^I (\bigcap i \cdot Q(i)) = (\bigcap i \cdot P \llbracket cs \rrbracket^I Q(i))$$
  
 by (*simp add: CSPInterMerge-def par-by-merge-USUP-ind-right*)

**lemma** *CSPInterMerge-shEx-left* [*rpred*]:  
 $(\exists i \cdot P(i)) \llbracket cs \rrbracket^I Q = (\exists i \cdot P(i) \llbracket cs \rrbracket^I Q)$   
**using** *CSPInterMerge-UINF-ind-left*[*of P cs Q*]  
**by** (*simp add: UINF-is-exists*)

**lemma** *CSPInterMerge-shEx-right* [*rpred*]:  
 $P \llbracket cs \rrbracket^I (\exists i \cdot Q(i)) = (\exists i \cdot P \llbracket cs \rrbracket^I Q(i))$   
**using** *CSPInterMerge-UINF-ind-right*[*of P cs Q*]  
**by** (*simp add: UINF-is-exists*)

**lemma** *par-by-merge-seq-remove*:  $(P \parallel_M \text{;;} R \text{ } Q) = (P \parallel_M Q) \text{;;} R$   
**by** (*simp add: par-by-merge-seq-add[THEN sym]*)

**lemma** *utrace-leg*:  $(x \leq_u y) = (\exists z \cdot y =_u x \hat{\cdot}_u \ll z \gg)$   
**by** (*rel-auto*)

**lemma** *trace-pred-R1-true*:  $[P(\text{trace})]_t \text{;;} R1 \text{ true} = [(\exists tt_0 \cdot \ll tt_0 \gg \leq_u \ll \text{trace} \gg \wedge P(tt_0))]_t$   
**apply** (*rel-auto*)  
**using** *minus-cancel-le* **apply** *blast*  
**apply** (*metis diff-add-cancel-left' le-add trace-class.add-diff-cancel-left trace-class.add-left-mono*)  
**done**

**lemma** *wrC-csp-do-init* [*wp*]:  
 $\Phi(s_1, \sigma_1, t_1) \text{ wr}[cs]_C \mathcal{I}(s_2, t_2) =$   
 $(\forall (tt_0, tt_1) \cdot \mathcal{I}(s_1 \wedge s_2 \wedge \ll tt_1 \gg \in_u (t_2 \hat{\cdot}_u \ll tt_0 \gg) \star_{cs} t_1 \wedge t_2 \hat{\cdot}_u \ll tt_0 \gg \downarrow_u \ll cs \gg =_u t_1 \downarrow_u \ll cs \gg,$   
 $\ll tt_1 \gg))$   
**(is ?lhs = ?rhs)**

**proof** –

**have** *?lhs* =

$(\neg_r (\exists (ref_0, st_0, tt_0) \cdot$   
 $[\$ref' \mapsto_s \ll ref_0 \gg, \$st' \mapsto_s \ll st_0 \gg, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \ll tt_0 \gg] \dagger (\neg_r \mathcal{I}(s_2, t_2)) \wedge$   
 $[s_1]_{S<} \wedge$   
 $\$ref' \subseteq_u \ll cs \gg \cup_u (\ll ref_0 \gg - \ll cs \gg) \wedge$   
 $[\ll \text{trace} \gg \in_u \ll tt_0 \gg \star_{cs} t_1 \wedge \ll tt_0 \gg \downarrow_u \ll cs \gg =_u t_1 \downarrow_u \ll cs \gg]_t \wedge$   
 $\$st' =_u \$st) \text{;;} R1 \text{ true})$

**by** (*simp add: wrR-def par-by-merge-seq-remove merge-csp-do-right pr-var-def closure Healthy-if rpred*)

**also have** ... =

$(\neg_r (\exists tt_0 \cdot ([s_2]_{S<} \wedge [t_2]_{S<} \leq_u \ll tt_0 \gg) \wedge [s_1]_{S<} \wedge$   
 $[\ll \text{trace} \gg \in_u \ll tt_0 \gg \star_{cs} t_1 \wedge \ll tt_0 \gg \downarrow_u \ll cs \gg =_u t_1 \downarrow_u \ll cs \gg]_t) \text{;;} R1 \text{ true})$

**by** (*rel-auto*)

**also have** ... =

$(\neg_r (\exists tt_0 \cdot ([s_2]_{S<} \wedge (\exists tt_1 \cdot \ll tt_0 \gg =_u [t_2]_{S<} \hat{\cdot}_u \ll tt_1 \gg)) \wedge [s_1]_{S<} \wedge$   
 $[\ll \text{trace} \gg \in_u \ll tt_0 \gg \star_{cs} t_1 \wedge \ll tt_0 \gg \downarrow_u \ll cs \gg =_u t_1 \downarrow_u \ll cs \gg]_t) \text{;;} R1 \text{ true})$

**by** (*simp add: utrace-leg*)

**also have** ... =

$(\neg_r (\exists tt_1 \cdot [s_1 \wedge s_2 \wedge \ll \text{trace} \gg \in_u (t_2 \hat{\cdot}_u \ll tt_1 \gg) \star_{cs} t_1 \wedge t_2 \hat{\cdot}_u \ll tt_1 \gg \downarrow_u \ll cs \gg =_u t_1 \downarrow_u \ll cs \gg]_t)$

**;;** *R1 true*)

**by** (*rel-auto*)

**also have** ... =

$(\forall tt_1 \cdot \neg_r ([s_1 \wedge s_2 \wedge \ll \text{trace} \gg \in_u (t_2 \hat{\cdot}_u \ll tt_1 \gg) \star_{cs} t_1 \wedge t_2 \hat{\cdot}_u \ll tt_1 \gg \downarrow_u \ll cs \gg =_u t_1 \downarrow_u \ll cs \gg]_t$

**;;** *R1 true*)

**by** (*rel-auto*)

**also have** ... =

$(\forall (tt_0, tt_1) \cdot \neg_r ([s_1 \wedge s_2 \wedge \ll tt_0 \gg \leq_u \ll \text{trace} \gg \wedge \ll tt_0 \gg \in_u (t_2 \hat{\cdot}_u \ll tt_1 \gg) \star_{cs} t_1 \wedge t_2 \hat{\cdot}_u \ll tt_1 \gg \downarrow_u$

$\llbracket cs \rrbracket =_u t_1 \downarrow_u \llbracket cs \rrbracket_t$ )  
 by (simp add: trace-pred-R1-true, rel-auto)  
 also have ... = ?rhs  
 by (rel-auto)  
 finally show ?thesis .  
 qed

**lemma** wrC-csp-do-false [wp]:  
 $\Phi(s_1, \sigma_1, t_1) \text{ wr}[cs]_C \text{ false} =$   
 $(\forall (tt_0, tt_1) \cdot \mathcal{I}(s_1 \wedge \llbracket tt_1 \rrbracket \in_u \llbracket tt_0 \rrbracket \star_{cs} t_1 \wedge \llbracket tt_0 \rrbracket \downarrow_u \llbracket cs \rrbracket =_u t_1 \downarrow_u \llbracket cs \rrbracket, \llbracket tt_1 \rrbracket))$   
 (is ?lhs = ?rhs)

**proof** –  
 have ?lhs =  $\Phi(s_1, \sigma_1, t_1) \text{ wr}[cs]_C \mathcal{I}(\text{true}, \langle \rangle)$   
 by (simp add: rpred)  
 also have ... = ?rhs  
 by (simp add: wp)  
 finally show ?thesis .  
 qed

**lemma** wrC-csp-enable-init [wp]:  
 fixes  $t_1 \ t_2 :: ('a \text{ list}, 'b) \text{ uexpr}$   
 shows  
 $\mathcal{E}(s_1, t_1, E_1) \text{ wr}[cs]_C \mathcal{I}(s_2, t_2) =$   
 $(\forall (tt_0, tt_1) \cdot \mathcal{I}(s_1 \wedge s_2 \wedge \llbracket tt_1 \rrbracket \in_u (t_2 \hat{\ }_u \llbracket tt_0 \rrbracket) \star_{cs} t_1 \wedge t_2 \hat{\ }_u \llbracket tt_0 \rrbracket \downarrow_u \llbracket cs \rrbracket =_u t_1 \downarrow_u \llbracket cs \rrbracket, \llbracket tt_1 \rrbracket))$   
 (is ?lhs = ?rhs)

**proof** –  
 have ?lhs =  
 $(\neg_r (\exists (ref_0, ref_1, st_0, st_1 :: 'b,$   
 $tt_0) \cdot [s_1]_{S<} \wedge$   
 $[\$ref' \mapsto_s \llbracket ref_0 \rrbracket, \$st' \mapsto_s \llbracket st_0 \rrbracket, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \llbracket tt_0 \rrbracket] \dagger (\neg_r \mathcal{I}(s_2, t_2)) \wedge$   
 $(\forall e \cdot \llbracket e \rrbracket \in_u [E_1]_{S<} \Rightarrow \llbracket e \rrbracket \notin_u \llbracket ref_1 \rrbracket) \wedge$   
 $\$ref' \subseteq_u (\llbracket ref_0 \rrbracket \cup_u \llbracket ref_1 \rrbracket) \cap_u \llbracket cs \rrbracket \cup_u (\llbracket ref_0 \rrbracket \cap_u \llbracket ref_1 \rrbracket - \llbracket cs \rrbracket) \wedge$   
 $\llbracket \llbracket trace \rrbracket \in_u \llbracket tt_0 \rrbracket \star_{cs} t_1 \wedge \llbracket tt_0 \rrbracket \downarrow_u \llbracket cs \rrbracket =_u t_1 \downarrow_u \llbracket cs \rrbracket]_t \wedge \$st' =_u \$st) ;;_h$   
 $R1 \text{ true})$   
 by (simp add: wrR-def par-by-merge-seq-remove merge-csp-enable-right pr-var-def closure Healthy-if  
 rpred)  
 also have ... =  
 $(\neg_r (\exists tt_0 \cdot ([s_2]_{S<} \wedge [t_2]_{S<} \leq_u \llbracket tt_0 \rrbracket) \wedge [s_1]_{S<} \wedge$   
 $\llbracket \llbracket trace \rrbracket \in_u \llbracket tt_0 \rrbracket \star_{cs} t_1 \wedge \llbracket tt_0 \rrbracket \downarrow_u \llbracket cs \rrbracket =_u t_1 \downarrow_u \llbracket cs \rrbracket]_t) ;; R1 \text{ true})$   
 by (rel-blast)  
 also have ... =  
 $(\neg_r (\exists tt_0 \cdot ([s_2]_{S<} \wedge (\exists tt_1 \cdot \llbracket tt_0 \rrbracket =_u [t_2]_{S<} \hat{\ }_u \llbracket tt_1 \rrbracket)) \wedge [s_1]_{S<} \wedge$   
 $\llbracket \llbracket trace \rrbracket \in_u \llbracket tt_0 \rrbracket \star_{cs} t_1 \wedge \llbracket tt_0 \rrbracket \downarrow_u \llbracket cs \rrbracket =_u t_1 \downarrow_u \llbracket cs \rrbracket]_t) ;; R1 \text{ true})$   
 by (simp add: utrace-leq)  
 also have ... =  
 $(\neg_r (\exists tt_1 \cdot [s_1 \wedge s_2 \wedge \llbracket trace \rrbracket \in_u (t_2 \hat{\ }_u \llbracket tt_1 \rrbracket) \star_{cs} t_1 \wedge t_2 \hat{\ }_u \llbracket tt_1 \rrbracket \downarrow_u \llbracket cs \rrbracket =_u t_1 \downarrow_u \llbracket cs \rrbracket]_t)$   
 $;; R1 \text{ true})$   
 by (rel-auto)  
 also have ... =  
 $(\forall tt_1 \cdot \neg_r ([s_1 \wedge s_2 \wedge \llbracket trace \rrbracket \in_u (t_2 \hat{\ }_u \llbracket tt_1 \rrbracket) \star_{cs} t_1 \wedge t_2 \hat{\ }_u \llbracket tt_1 \rrbracket \downarrow_u \llbracket cs \rrbracket =_u t_1 \downarrow_u \llbracket cs \rrbracket]_t$   
 $;; R1 \text{ true}))$   
 by (rel-auto)  
 also have ... =  
 $(\forall (tt_0, tt_1) \cdot \neg_r ([s_1 \wedge s_2 \wedge \llbracket tt_0 \rrbracket \leq_u \llbracket trace \rrbracket \wedge \llbracket tt_0 \rrbracket \in_u (t_2 \hat{\ }_u \llbracket tt_1 \rrbracket) \star_{cs} t_1 \wedge t_2 \hat{\ }_u \llbracket tt_1 \rrbracket \downarrow_u$

$\ll cs \gg =_u t_1 \upharpoonright_u \ll cs \gg_t))$   
 by (*simp add: trace-pred-R1-true, rel-auto*)  
 also have ... = ?rhs  
 by (*rel-auto*)  
 finally show ?thesis .  
 qed

**lemma** *wrC-csp-enable-false* [wp]:  
 $\mathcal{E}(s_1, t_1, E) \text{ wr}[cs]_C \text{ false} =$   
 $(\forall (tt_0, tt_1) \cdot \mathcal{I}(s_1 \wedge \ll tt_1 \gg \in_u \ll tt_0 \gg \star_{cs} t_1 \wedge \ll tt_0 \gg \upharpoonright_u \ll cs \gg =_u t_1 \upharpoonright_u \ll cs \gg, \ll tt_1 \gg))$   
 (is ?lhs = ?rhs)  
**proof** –  
 have ?lhs =  $\mathcal{E}(s_1, t_1, E) \text{ wr}[cs]_C \mathcal{I}(\text{true}, \langle \rangle)$   
 by (*simp add: rpred*)  
 also have ... = ?rhs  
 by (*simp add: wp*)  
 finally show ?thesis .  
 qed

## 4.2 Parallel operator

### syntax

*-par-circus* ::  $\text{logic} \Rightarrow \text{salpha} \Rightarrow \text{logic} \Rightarrow \text{salpha} \Rightarrow \text{logic} \Rightarrow \text{logic} \quad (- \ll - \parallel - \gg - [75, 0, 0, 0, 76] \ 76)$   
*-par-csp* ::  $\text{logic} \Rightarrow \text{logic} \Rightarrow \text{logic} \Rightarrow \text{logic} \quad (- \ll - \parallel_C - [75, 0, 76] \ 76)$   
*-inter-circus* ::  $\text{logic} \Rightarrow \text{salpha} \Rightarrow \text{salpha} \Rightarrow \text{logic} \Rightarrow \text{logic} \quad (- \ll - \parallel - \gg - [75, 0, 0, 76] \ 76)$

### translations

*-par-circus*  $P \text{ ns1 } cs \text{ ns2 } Q == P \parallel_{M_C} \text{ ns1 } cs \text{ ns2 } Q$   
*-par-csp*  $P \text{ cs } Q == \text{-par-circus } P \ 0_L \text{ cs } 0_L \ Q$   
*-inter-circus*  $P \text{ ns1 } ns2 \ Q == \text{-par-circus } P \text{ ns1 } \{\} \text{ ns2 } Q$

**abbreviation** *InterleaveCSP* ::  $('s, 'e) \text{ action} \Rightarrow ('s, 'e) \text{ action} \Rightarrow ('s, 'e) \text{ action} \quad (\text{infixr } \parallel 75)$   
**where**  $P \parallel Q \equiv P \ll \emptyset \parallel \emptyset \gg Q$

**abbreviation** *SynchroniseCSP* ::  $('s, 'e) \text{ action} \Rightarrow ('s, 'e) \text{ action} \Rightarrow ('s, 'e) \text{ action} \quad (\text{infixr } \parallel 75)$   
**where**  $P \parallel Q \equiv P \ll UNIV \parallel_C Q$

**definition** *CSP5* ::  $'\varphi \text{ process} \Rightarrow '\varphi \text{ process}$  **where**  
 $[upred-defs]: \text{CSP5}(P) = (P \parallel \text{Skip})$

**definition** *C2* ::  $('s, '\varphi) \text{ action} \Rightarrow ('s, '\varphi) \text{ action}$  **where**  
 $[upred-defs]: \text{C2}(P) = (P \ll \Sigma \parallel \{\} \parallel \emptyset \gg \text{Skip})$

**definition** *CACT* ::  $('s, 'e) \text{ action} \Rightarrow ('s, 'e) \text{ action}$  **where**  
 $[upred-defs]: \text{CACT}(P) = \text{C2}(\text{NCSP}(P))$

**abbreviation** *CPROC* ::  $'e \text{ process} \Rightarrow 'e \text{ process}$  **where**  
 $\text{CPROC}(P) \equiv \text{CACT}(P)$

### lemma *Skip-right-form*:

**assumes**  $P_1 \text{ is } RC \ P_2 \text{ is } RR \ P_3 \text{ is } RR \ \$st' \ \# \ P_2$   
**shows**  $\mathbf{R}_s(P_1 \vdash P_2 \diamond P_3) ;; \text{Skip} = \mathbf{R}_s(P_1 \vdash P_2 \diamond (\exists \ \$ref' \cdot P_3))$

**proof** –

**have**  $1:RR(P_3) ;; \Phi(\text{true}, id, \langle \rangle) = (\exists \ \$ref' \cdot RR(P_3))$   
 by (*rel-auto*)  
**show** ?thesis

by (*rdes-simp cls: assms, metis 1 Healthy-if assms(3)*)  
qed

**lemma** *ParCSP-rdes-def* [*rdes-def*]:

fixes  $P_1 :: ('s, 'e)$  action

assumes  $P_1$  is CRC  $Q_1$  is CRC  $P_2$  is CRR  $Q_2$  is CRR  $P_3$  is CRR  $Q_3$  is CRR

$\$st' \# P_2 \$st' \# Q_2$

$ns1 \bowtie ns2$

shows  $\mathbf{R}_s(P_1 \vdash P_2 \diamond P_3) \llbracket ns1 \parallel cs \parallel ns2 \rrbracket \mathbf{R}_s(Q_1 \vdash Q_2 \diamond Q_3) =$   
 $\mathbf{R}_s(((Q_1 \Rightarrow_r Q_2) \text{ wr}[cs]_C P_1 \wedge (Q_1 \Rightarrow_r Q_3) \text{ wr}[cs]_C P_1 \wedge$   
 $(P_1 \Rightarrow_r P_2) \text{ wr}[cs]_C Q_1 \wedge (P_1 \Rightarrow_r P_3) \text{ wr}[cs]_C Q_1) \vdash$   
 $(P_2 \llbracket cs \rrbracket^I Q_2 \vee P_3 \llbracket cs \rrbracket^I Q_2 \vee P_2 \llbracket cs \rrbracket^I Q_3) \diamond$   
 $(P_3 \llbracket ns1 \parallel cs \parallel ns2 \rrbracket^F Q_3))$

(is  $?P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket ?Q = ?rhs$ )

**proof** –

have 1:  $\bigwedge P Q. P \text{ wr}_R(N_C \ ns1 \ cs \ ns2) \ Q = P \text{ wr}[cs]_C \ Q \bigwedge P Q. P \text{ wr}_R(N_C \ ns2 \ cs \ ns1) \ Q = P \text{ wr}[cs]_C \ Q$

by (*rel-auto*) +

have 2:  $(\exists \$st' \cdot N_C \ ns1 \ cs \ ns2) = (\exists \$st' \cdot N_C \ 0_L \ cs \ 0_L)$

by (*rel-auto*)

have  $?P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket ?Q = (?P \parallel_{M_R(N_C \ ns1 \ cs \ ns2)} ?Q) ;;_h \text{Skip}$

by (*simp add: CSPMerge-def par-by-merge-seq-add*)

also

have ... =  $\mathbf{R}_s(((Q_1 \Rightarrow_r Q_2) \text{ wr}[cs]_C P_1 \wedge$   
 $(Q_1 \Rightarrow_r Q_3) \text{ wr}[cs]_C P_1 \wedge$   
 $(P_1 \Rightarrow_r P_2) \text{ wr}[cs]_C Q_1 \wedge$   
 $(P_1 \Rightarrow_r P_3) \text{ wr}[cs]_C Q_1) \vdash$   
 $(P_2 \llbracket cs \rrbracket^I Q_2 \vee$   
 $P_3 \llbracket cs \rrbracket^I Q_2 \vee$   
 $P_2 \llbracket cs \rrbracket^I Q_3) \diamond$   
 $P_3 \parallel_{N_C \ ns1 \ cs \ ns2} Q_3) ;;_h \text{Skip}$

by (*simp add: parallel-rdes-def swap-CSPInnerMerge CSPInterMerge-def closure assms 1 2*)

also

have ... =  $\mathbf{R}_s(((Q_1 \Rightarrow_r Q_2) \text{ wr}[cs]_C P_1 \wedge$   
 $(Q_1 \Rightarrow_r Q_3) \text{ wr}[cs]_C P_1 \wedge$   
 $(P_1 \Rightarrow_r P_2) \text{ wr}[cs]_C Q_1 \wedge$   
 $(P_1 \Rightarrow_r P_3) \text{ wr}[cs]_C Q_1) \vdash$   
 $(P_2 \llbracket cs \rrbracket^I Q_2 \vee$   
 $P_3 \llbracket cs \rrbracket^I Q_2 \vee$   
 $P_2 \llbracket cs \rrbracket^I Q_3) \diamond$   
 $(\exists \$ref' \cdot (P_3 \parallel_{N_C \ ns1 \ cs \ ns2} Q_3)))$

by (*simp add: Skip-right-form closure parallel-RR-closed assms unrest*)

also

have ... =  $\mathbf{R}_s(((Q_1 \Rightarrow_r Q_2) \text{ wr}[cs]_C P_1 \wedge$   
 $(Q_1 \Rightarrow_r Q_3) \text{ wr}[cs]_C P_1 \wedge$   
 $(P_1 \Rightarrow_r P_2) \text{ wr}[cs]_C Q_1 \wedge$   
 $(P_1 \Rightarrow_r P_3) \text{ wr}[cs]_C Q_1) \vdash$   
 $(P_2 \llbracket cs \rrbracket^I Q_2 \vee$   
 $P_3 \llbracket cs \rrbracket^I Q_2 \vee$   
 $P_2 \llbracket cs \rrbracket^I Q_3) \diamond$   
 $(P_3 \llbracket ns1 \parallel cs \parallel ns2 \rrbracket^F Q_3))$

**proof** –

have  $(\exists \$ref' \cdot (P_3 \parallel_{N_C \ ns1 \ cs \ ns2} Q_3)) = (P_3 \llbracket ns1 \parallel cs \parallel ns2 \rrbracket^F Q_3)$

by (*rel-blast*)

thus *?thesis* by *simp*

qed  
 finally show ?thesis .  
 qed

### 4.3 Parallel Laws

**lemma** *ParCSP-expand*:

$P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket Q = (P \parallel_{RN_C} ns1 \ cs \ ns2 \ Q) ;; Skip$   
 by (simp add: CSPMerge-def par-by-merge-seq-add)

**lemma** *parallel-is-CSP* [closure]:

assumes  $P$  is CSP  $Q$  is CSP  
 shows  $(P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket Q)$  is CSP

**proof** –

have  $(P \parallel_{M_R(N_C \ ns1 \ cs \ ns2)} Q)$  is CSP  
 by (simp add: closure assms)  
 hence  $(P \parallel_{M_R(N_C \ ns1 \ cs \ ns2)} Q) ;; Skip$  is CSP  
 by (simp add: closure)  
 thus ?thesis  
 by (simp add: CSPMerge-def par-by-merge-seq-add)

qed

**lemma** *parallel-is-NCSP* [closure]:

assumes  $ns1 \bowtie ns2$   $P$  is NCSP  $Q$  is NCSP  
 shows  $(P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket Q)$  is NCSP

**proof** –

have  $(P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket Q) = (\mathbf{R}_s(pre_R \ P \vdash \text{peri}_R \ P \diamond \text{post}_R \ P) \llbracket ns1 \parallel cs \parallel ns2 \rrbracket \mathbf{R}_s(pre_R \ Q \vdash \text{peri}_R \ Q \diamond \text{post}_R \ Q))$   
 by (metis NCSP-implies-NSRD NSRD-is-SRD SRD-reactive-design-alt assms wait'-cond-peri-post-cmt)  
 also have ... is NCSP  
 by (simp add: ParCSP-rdes-def assms closure unrest)  
 finally show ?thesis .

qed

**theorem** *parallel-commutative*:

assumes  $ns1 \bowtie ns2$   
 shows  $(P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket Q) = (Q \llbracket ns2 \parallel cs \parallel ns1 \rrbracket P)$

**proof** –

have  $(P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket Q) = P \parallel_{\text{swap}_m} ;; (M_C \ ns2 \ cs \ ns1) \ Q$   
 by (simp add: CSPMerge-def segr-assoc[THEN sym] swap-merge-rd swap-CSPInnerMerge lens-indep-sym assms)  
 also have ... =  $Q \llbracket ns2 \parallel cs \parallel ns1 \rrbracket P$   
 by (metis par-by-merge-commute-swap)  
 finally show ?thesis .

qed

*CSP5* is precisely *C2* when applied to a process

**lemma** *CSP5-is-C2*:

fixes  $P :: 'e \text{ process}$   
 assumes  $P$  is NCSP  
 shows  $CSP5(P) = C2(P)$   
 unfolding CSP5-def C2-def by (rdes-eq cls: assms)

The form of C2 tells us that a normal CSP process has a downward closed set of refusals

**lemma** *csp-do-triv-merge*:



**assumes**  $P$  is CRF  
**shows**  $P \llbracket \Sigma[\{\}|\emptyset] \rrbracket^F \Phi(\text{true}, \text{id}, \langle \rangle) = P$  (**is** ?lhs = ?rhs)  
**proof** –  
 have ?lhs =  $(\exists (st_0, t_0) \cdot [\$st' \mapsto_s \ll st_0 \gg, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \ll t_0 \gg] \dagger \text{CRF}(P) \wedge [\text{true}]_{S<} \wedge [\ll \text{trace} \gg =_u \ll t_0 \gg]_t \wedge \$st' =_u \$st \oplus \ll st_0 \gg \text{ on } \&\mathbf{v} \oplus \ll \text{id} \gg (\$st)_a \text{ on } \emptyset)$   
 by (simp add: FinalMerge-csp-do-right assms closure unrest Healthy-if, rel-auto)  
 also have ... =  $\text{CRF}(P)$   
 by (rel-auto)  
 finally show ?thesis  
 by (simp add: assms Healthy-if)  
**qed**

**lemma** *csp-do-triv-wr*:

**assumes**  $P$  is CRC  
**shows**  $\Phi(\text{true}, \text{id}, \langle \rangle) \text{ wr}[\{\}]_C P = P$  (**is** ?lhs = ?rhs)  
**proof** –  
 have ?lhs =  $(\neg_r (\exists (\text{ref}_0, st_0, tt_0) \cdot [\$ref' \mapsto_s \ll \text{ref}_0 \gg, \$st' \mapsto_s \ll st_0 \gg, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \ll tt_0 \gg] \dagger (\exists \$ref'; \$st' \cdot \text{RR}(\neg_r P)) \wedge \$ref' \subseteq_u \ll \text{ref}_0 \gg \wedge [\ll \text{trace} \gg =_u \ll tt_0 \gg]_t \wedge \$st' =_u \$st) ;; R1 \text{ true})$   
 by (simp add: wrR-def par-by-merge-seq-remove rpred merge-csp-do-right ex-unrest Healthy-if pr-var-def closure assms unrest usubst)  
 also have ... =  $(\neg_r (\exists \$ref'; \$st' \cdot \text{RR}(\neg_r P)) ;; R1 \text{ true})$   
 by (rel-auto, meson order-refl)  
 also have ... =  $(\neg_r (\neg_r P) ;; R1 \text{ true})$   
 by (simp add: Healthy-if closure ex-unrest unrest assms)  
 also have ... =  $P$   
 by (metis CRC-implies-RC Healthy-def RC1-def RC-implies-RC1 assms)  
 finally show ?thesis .  
**qed**

**lemma** *C2-form*:

**assumes**  $P$  is NCSP  
**shows**  $C2(P) = \mathbf{R}_s (\text{pre}_R P \vdash (\exists \text{ref}_0 \cdot \text{peri}_R P \llbracket \ll \text{ref}_0 \gg / \$ref' \rrbracket \wedge \$ref' \subseteq_u \ll \text{ref}_0 \gg) \diamond \text{post}_R P)$   
**proof** –  
 have 1:  $\Phi(\text{true}, \text{id}, \langle \rangle) \text{ wr}[\{\}]_C \text{pre}_R P = \text{pre}_R P$  (**is** ?lhs = ?rhs)  
 by (simp add: csp-do-triv-wr closure assms)  
 have 2:  $(\text{pre}_R P \Rightarrow_r \text{peri}_R P) \llbracket \{\} \rrbracket^I \Phi(\text{true}, \text{id}, \langle \rangle) = (\exists \text{ref}_0 \cdot (\text{peri}_R P) \llbracket \ll \text{ref}_0 \gg / \$ref' \rrbracket \wedge \$ref' \subseteq_u \ll \text{ref}_0 \gg) (\text{is } ?lhs = ?rhs)$   
**proof** –  
 have ?lhs =  $\text{peri}_R P \llbracket \{\} \rrbracket^I \Phi(\text{true}, \text{id}, \langle \rangle)$   
 by (simp add: SRD-peri-under-pre closure assms unrest)  
 also have ... =  $(\exists \$st' \cdot (\text{peri}_R P \parallel_{N_C} \emptyset_L \{\} \emptyset_L \Phi(\text{true}, \text{id}, \langle \rangle)))$   
 by (simp add: CSPInterMerge-def par-by-merge-def segr-exists-right)  
 also have ... =  $(\exists \$st' \cdot \exists (\text{ref}_0, st_0, tt_0) \cdot [\$ref' \mapsto_s \ll \text{ref}_0 \gg, \$st' \mapsto_s \ll st_0 \gg, \$tr \mapsto_s \langle \rangle, \$tr' \mapsto_s \ll tt_0 \gg] \dagger (\exists \$st' \cdot \text{RR}(\text{peri}_R P)) \wedge \$ref' \subseteq_u \ll \text{ref}_0 \gg \wedge [\ll \text{trace} \gg =_u \ll tt_0 \gg]_t \wedge \$st' =_u \$st)$   
 by (simp add: merge-csp-do-right pr-var-def assms Healthy-if closure rpred unrest ex-unrest)  
 also have ... =  $(\exists \text{ref}_0 \cdot (\exists \$st' \cdot \text{RR}(\text{peri}_R P)) \llbracket \ll \text{ref}_0 \gg / \$ref' \rrbracket \wedge \$ref' \subseteq_u \ll \text{ref}_0 \gg)$   
 by (rel-auto)  
 also have ... = ?rhs  
 by (simp add: closure ex-unrest Healthy-if unrest assms)

finally show ?thesis .  
 qed  
 have 3:  $(pre_R P \Rightarrow_r post_R P) \llbracket \Sigma | \{\} | \emptyset \rrbracket^F \Phi(true, id, \langle \rangle) = post_R(P)$  (is ?lhs = ?rhs)  
 by (simp add: csp-do-triv-merge SRD-post-under-pre unrest assms closure)  
 show ?thesis  
 proof –  
 have  $C2(P) = \mathbf{R}_s (\Phi(true, id, \langle \rangle) wr[\{\}]_C pre_R P \vdash$   
 $(pre_R P \Rightarrow_r peri_R P) \llbracket \{\} \rrbracket^I \Phi(true, id, \langle \rangle) \diamond (pre_R P \Rightarrow_r post_R P) \llbracket \Sigma | \{\} | \emptyset \rrbracket^F \Phi(true, id, \langle \rangle))$   
 by (simp add: C2-def, rdes-simp cls: assms, simp add: id-def pr-var-def)  
 also have  $\dots = \mathbf{R}_s (pre_R P \vdash (\exists ref_0 \cdot peri_R P \llbracket \llbracket ref_0 \rrbracket / \$ref' \rrbracket \wedge \$ref' \subseteq_u \llbracket ref_0 \rrbracket) \diamond post_R P)$   
 by (simp add: 1 2 3)  
 finally show ?thesis .  
 qed  
 qed

lemma C2-CDC-form:

assumes  $P$  is NCSP  
 shows  $C2(P) = \mathbf{R}_s (pre_R P \vdash CDC(peri_R P) \diamond post_R P)$   
 by (simp add: C2-form assms CDC-def)

lemma C2-rdes-def:

assumes  $P_1$  is CRC  $P_2$  is CRR  $P_3$  is CRR  $\$st' \# P_2 \$ref' \# P_3$   
 shows  $C2(\mathbf{R}_s(P_1 \vdash P_2 \diamond P_3)) = \mathbf{R}_s(P_1 \vdash CDC(P_2) \diamond P_3)$   
 by (simp add: C2-form assms closure rdes unrest usubst, rel-auto)

lemma C2-NCSP-intro:

assumes  $P$  is NCSP  $peri_R(P)$  is CDC  
 shows  $P$  is C2

proof –

have  $C2(P) = \mathbf{R}_s (pre_R P \vdash CDC(peri_R P) \diamond post_R P)$   
 by (simp add: C2-CDC-form assms(1))  
 also have  $\dots = \mathbf{R}_s (pre_R P \vdash peri_R P \diamond post_R P)$   
 by (simp add: Healthy-if assms)  
 also have  $\dots = P$   
 by (simp add: NCSP-implies-CSP SRD-reactive-tri-design assms(1))  
 finally show ?thesis  
 by (simp add: Healthy-def)

qed

lemma C2-rdes-intro:

assumes  $P_1$  is CRC  $P_2$  is CRR  $P_2$  is CDC  $P_3$  is CRR  $\$st' \# P_2 \$ref' \# P_3$   
 shows  $\mathbf{R}_s(P_1 \vdash P_2 \diamond P_3)$  is C2  
 unfolding Healthy-def  
 by (simp add: C2-rdes-def assms unrest closure Healthy-if)

lemma C2-implies-CDC-peri [closure]:

assumes  $P$  is NCSP  $P$  is C2  
 shows  $peri_R(P)$  is CDC

proof –

have  $peri_R(P) = peri_R (\mathbf{R}_s (pre_R P \vdash CDC(peri_R P) \diamond post_R P))$   
 by (metis C2-CDC-form Healthy-if assms(1) assms(2))  
 also have  $\dots = CDC (pre_R P \Rightarrow_r peri_R P)$   
 by (simp add: rdes rpred assms closure unrest del: NSRD-peri-under-pre)  
 also have  $\dots = CDC (peri_R P)$   
 by (simp add: SRD-peri-under-pre closure unrest assms)

finally show ?thesis  
 by (simp add: Healthy-def)  
 qed

lemma CACT-intro:  
 assumes  $P$  is NCSP  $P$  is C2  
 shows  $P$  is CACT  
 by (metis CACT-def Healthy-def assms(1) assms(2))

lemma CACT-rdes-intro:  
 assumes  $P_1$  is CRC  $P_2$  is CRR  $P_2$  is CDC  $P_3$  is CRR  $\$st' \# P_2 \$ref' \# P_3$   
 shows  $\mathbf{R}_s (P_1 \vdash P_2 \diamond P_3)$  is CACT  
 by (rule CACT-intro, simp add: closure assms, rule C2-rdes-intro, simp-all add: assms)

lemma C2-NCSP-quasi-commute:  
 assumes  $P$  is NCSP  
 shows  $C2(\text{NCSP}(P)) = \text{NCSP}(C2(P))$   
 proof –  
 have 1:  $C2(\text{NCSP}(P)) = C2(P)$   
 by (simp add: assms Healthy-if)  
 also have ... =  $\mathbf{R}_s (\text{pre}_R P \vdash \text{CDC}(\text{peri}_R P) \diamond \text{post}_R P)$   
 by (simp add: C2-CDC-form assms)  
 also have ... is NCSP  
 by (rule NCSP-rdes-intro, simp-all add: closure assms unrest)  
 finally show ?thesis  
 by (simp add: Healthy-if 1)  
 qed

lemma C2-quasi-idem:  
 assumes  $P$  is NCSP  
 shows  $C2(C2(P)) = C2(P)$   
 proof –  
 have  $C2(C2(P)) = C2(C2(\mathbf{R}_s(\text{pre}_R(P) \vdash \text{peri}_R(P) \diamond \text{post}_R(P))))$   
 by (simp add: NCSP-implies-NSRD NSRD-is-SRD SRD-reactive-tri-design assms)  
 also have ... =  $\mathbf{R}_s (\text{pre}_R P \vdash \text{CDC}(\text{peri}_R P) \diamond \text{post}_R P)$   
 by (simp add: C2-rdes-def closure assms unrest CDC-idem)  
 also have ... =  $C2(P)$   
 by (simp add: C2-CDC-form assms)  
 finally show ?thesis .  
 qed

lemma CACT-implies-NCSP [closure]:  
 assumes  $P$  is CACT  
 shows  $P$  is NCSP  
 proof –  
 have  $P = C2(\text{NCSP}(\text{NCSP}(P)))$   
 by (metis CACT-def Healthy-Idempotent Healthy-if NCSP-Idempotent assms)  
 also have ... =  $\text{NCSP}(C2(\text{NCSP}(P)))$   
 by (simp add: C2-NCSP-quasi-commute Healthy-Idempotent NCSP-Idempotent)  
 also have ... is NCSP  
 by (metis CACT-def Healthy-def assms calculation)  
 finally show ?thesis .  
 qed

lemma CACT-implies-C2 [closure]:

**assumes**  $P$  is CACT  
**shows**  $P$  is C2  
**by** (metis CACT-def CACT-implies-NCSP Healthy-def assms)

**lemma** CACT-idem:  $\text{CACT}(\text{CACT}(P)) = \text{CACT}(P)$   
**by** (simp add: CACT-def C2-NCSP-quasi-commute[THEN sym] C2-quasi-idem Healthy-Idempotent Healthy-if NCSP-Idempotent)

**lemma** CACT-Idempotent: Idempotent CACT  
**by** (simp add: CACT-idem Idempotent-def)

**lemma** PACT-elim [RD-elim]:  
 $\llbracket X \text{ is CACT}; P(\mathbf{R}_s(\text{pre}_R(X) \vdash \text{peri}_R(X) \diamond \text{post}_R(X))) \rrbracket \implies P(X)$   
**using** CACT-implies-NCSP NCSP-elim **by** blast

**lemma** Miracle-C2-closed [closure]: Miracle is C2  
**by** (rdes-simp, rule C2-rdes-intro, simp-all add: closure unrest)

**lemma** Chaos-C2-closed [closure]: Chaos is C2  
**by** (rdes-simp, rule C2-rdes-intro, simp-all add: closure unrest)

**lemma** Skip-C2-closed [closure]: Skip is C2  
**by** (rdes-simp, rule C2-rdes-intro, simp-all add: closure unrest)

**lemma** Stop-C2-closed [closure]: Stop is C2  
**by** (rdes-simp, rule C2-rdes-intro, simp-all add: closure unrest)

**lemma** Miracle-CACT-closed [closure]: Miracle is CACT  
**by** (simp add: CACT-intro Miracle-C2-closed csp-theory.top-closed)

**lemma** Chaos-CACT-closed [closure]: Chaos is CACT  
**by** (simp add: CACT-intro closure)

**lemma** Skip-CACT-closed [closure]: Skip is CACT  
**by** (simp add: CACT-intro closure)

**lemma** Stop-CACT-closed [closure]: Stop is CACT  
**by** (simp add: CACT-intro closure)

**lemma** seq-C2-closed [closure]:  
**assumes**  $P$  is NCSP  $P$  is C2  $Q$  is NCSP  $Q$  is C2  
**shows**  $P ;; Q$  is C2  
**by** (rdes-simp cls: assms(1,3), rule C2-rdes-intro, simp-all add: closure assms unrest)

**lemma** seq-CACT-closed [closure]:  
**assumes**  $P$  is CACT  $Q$  is CACT  
**shows**  $P ;; Q$  is CACT  
**by** (meson CACT-implies-C2 CACT-implies-NCSP CACT-intro assms csp-theory.Healthy-Sequence seq-C2-closed)

**lemma** AssignsCSP-C2 [closure]:  $\langle \sigma \rangle_C$  is C2  
**by** (rdes-simp, rule C2-rdes-intro, simp-all add: closure unrest)

**lemma** AssignsCSP-CACT [closure]:  $\langle \sigma \rangle_C$  is CACT  
**by** (simp add: CACT-intro closure)

**lemma** *map-st-ext-CDC-closed* [closure]:

assumes  $P$  is CDC

shows  $P \oplus_r \text{map-st}_L[a]$  is CDC

**proof** –

have  $\text{CDC } P \oplus_r \text{map-st}_L[a]$  is CDC

by (*rel-auto*)

thus ?thesis

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

**qed**

**lemma** *rdes-frame-ext-C2-closed* [closure]:

assumes  $P$  is NCSP  $P$  is C2

shows  $a:[P]_R^+$  is C2

by (*rdes-simp cls:assms(2), rule C2-rdes-intro, simp-all add: closure assms unrest*)

**lemma** *rdes-frame-ext-CACT-closed* [closure]:

assumes *vwb-lens*  $a$   $P$  is CACT

shows  $a:[P]_R^+$  is CACT

by (*rule CACT-intro, simp-all add: closure assms*)

**lemma** *UINF-C2-closed* [closure]:

assumes  $A \neq \{\}$   $\bigwedge i. i \in A \implies P(i)$  is NCSP  $\bigwedge i. i \in A \implies P(i)$  is C2

shows  $(\bigcap i \in A \cdot P(i))$  is C2

**proof** –

have  $(\bigcap i \in A \cdot P(i)) = (\bigcap i \in A \cdot \mathbf{R}_s(\text{pre}_R(P(i)) \vdash \text{peri}_R(P(i)) \diamond \text{post}_R(P(i))))$

by (*simp add: closure SRD-reactive-tri-design assms cong: UINF-cong*)

also have ... is C2

by (*rdes-simp cls: assms, rule C2-rdes-intro, simp-all add: closure unrest assms*)

finally show ?thesis .

**qed**

**lemma** *UINF-CACT-closed* [closure]:

assumes  $A \neq \{\}$   $\bigwedge i. i \in A \implies P(i)$  is CACT

shows  $(\bigcap i \in A \cdot P(i))$  is CACT

by (*rule CACT-intro, simp-all add: assms closure*)

**lemma** *inf-C2-closed* [closure]:

assumes  $P$  is NCSP  $Q$  is NCSP  $P$  is C2  $Q$  is C2

shows  $P \sqcap Q$  is C2

by (*rdes-simp cls: assms, rule C2-rdes-intro, simp-all add: closure unrest assms*)

**lemma** *cond-CDC-closed* [closure]:

assumes  $P$  is CDC  $Q$  is CDC

shows  $P \triangleleft b \triangleright_R Q$  is CDC

**proof** –

have  $\text{CDC } P \triangleleft b \triangleright_R \text{CDC } Q$  is CDC

by (*rel-auto*)

thus ?thesis

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

**qed**

**lemma** *cond-C2-closed* [closure]:

assumes  $P$  is NCSP  $Q$  is NCSP  $P$  is C2  $Q$  is C2

shows  $P \triangleleft b \triangleright_R Q$  is C2

by (rdes-simp cls: assms, rule C2-rdes-intro, simp-all add: closure unrest assms)

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

**lemma** gcomm-C2-closed [closure]:  
 assumes  $P$  is NCSP  $P$  is C2  
 shows  $b \rightarrow_R P$  is C2  
 by (rdes-simp cls: assms, rule C2-rdes-intro, simp-all add: closure unrest assms)

**lemma** AssumeCircus-CACT [closure]:  $[b]_C$  is CACT  
 by (metis AssumeCircus-NCSP AssumeCircus-def CACT-intro NCSP-Skip Skip-C2-closed gcomm-C2-closed)

**lemma** StateInvR-CACT [closure]:  $\text{inv}_R(b)$  is CACT  
 by (simp add: CACT-rdes-intro rdes-def closure unrest)

**lemma** AlternateR-C2-closed [closure]:  
 assumes  
 $\bigwedge i. i \in A \implies P(i)$  is NCSP  $Q$  is NCSP  
 $\bigwedge i. i \in A \implies P(i)$  is C2  $Q$  is C2  
 shows  $(\text{if}_R i \in A \cdot g(i) \rightarrow P(i) \text{ else } Q \text{ fi})$  is C2  
**proof** (cases  $A = \{\}$ )  
 case True  
 then show ?thesis  
 by (simp add: assms(4))  
 next  
 case False  
 then show ?thesis  
 by (simp add: AlternateR-def closure assms)  
**qed**

**lemma** AlternateR-CACT-closed [closure]:  
 assumes  $\bigwedge i. i \in A \implies P(i)$  is CACT  $Q$  is CACT  
 shows  $(\text{if}_R i \in A \cdot g(i) \rightarrow P(i) \text{ else } Q \text{ fi})$  is CACT  
 by (rule CACT-intro, simp-all add: closure assms)

**lemma** AlternateR-list-C2-closed [closure]:  
 assumes  
 $\bigwedge b P. (b, P) \in \text{set } A \implies P$  is NCSP  $Q$  is NCSP  
 $\bigwedge b P. (b, P) \in \text{set } A \implies P$  is C2  $Q$  is C2  
 shows  $(\text{AlternateR-list } A \ Q)$  is C2  
 apply (simp add: AlternateR-list-def)  
 apply (rule AlternateR-C2-closed)  
 apply (auto simp add: assms closure)  
 apply (metis assms nth-mem prod.collapse)+  
 done

**lemma** AlternateR-list-CACT-closed [closure]:  
 assumes  $\bigwedge b P. (b, P) \in \text{set } A \implies P$  is CACT  $Q$  is CACT  
 shows  $(\text{AlternateR-list } A \ Q)$  is CACT  
 by (rule CACT-intro, simp-all add: closure assms)

**lemma** R4-CRR-closed [closure]:  $P$  is CRR  $\implies R4(P)$  is CRR

by (rule CRR-intro, simp-all add: closure unrest R4-def)

**lemma** WhileC-C2-closed [closure]:

assumes  $P$  is NCSP  $P$  is Productive  $P$  is C2

shows  $\text{while}_C b \text{ do } P \text{ od}$  is C2

**proof** –

have  $\text{while}_C b \text{ do } P \text{ od} = \text{while}_C b \text{ do Productive}(\mathbf{R}_s (pre_R P \vdash peri_R P \diamond post_R P)) \text{ od}$

by (simp add: assms Healthy-if SRD-reactive-tri-design closure)

also have  $\dots = \text{while}_C b \text{ do } \mathbf{R}_s (pre_R P \vdash peri_R P \diamond R4(post_R P)) \text{ od}$

by (simp add: Productive-RHS-design-form unrest assms rdes closure R4-def)

also have  $\dots$  is C2

by (simp add: WhileC-def, simp add: closure assms unrest rdes-def C2-rdes-intro)

finally show ?thesis .

**qed**

**lemma** WhileC-CACT-closed [closure]:

assumes  $P$  is CACT  $P$  is Productive

shows  $\text{while}_C b \text{ do } P \text{ od}$  is CACT

using CACT-implies-C2 CACT-implies-NCSP CACT-intro WhileC-C2-closed WhileC-NCSP-closed  
assms by blast

**lemma** IterateC-C2-closed [closure]:

assumes

$\bigwedge i. i \in A \implies P(i) \text{ is NCSP } \bigwedge i. i \in A \implies P(i) \text{ is Productive } \bigwedge i. i \in A \implies P(i) \text{ is C2}$

shows  $(\text{do}_C i \in A \cdot g(i) \rightarrow P(i) \text{ od})$  is C2

unfolding IterateC-def by (simp add: closure assms)

**lemma** IterateC-CACT-closed [closure]:

assumes

$\bigwedge i. i \in A \implies P(i) \text{ is CACT } \bigwedge i. i \in A \implies P(i) \text{ is Productive}$

shows  $(\text{do}_C i \in A \cdot g(i) \rightarrow P(i) \text{ od})$  is CACT

by (metis CACT-implies-C2 CACT-implies-NCSP CACT-intro IterateC-C2-closed IterateC-NCSP-closed  
assms)

**lemma** IterateC-list-C2-closed [closure]:

assumes

$\bigwedge b P. (b, P) \in \text{set } A \implies P \text{ is NCSP}$

$\bigwedge b P. (b, P) \in \text{set } A \implies P \text{ is Productive}$

$\bigwedge b P. (b, P) \in \text{set } A \implies P \text{ is C2}$

shows  $(\text{IterateC-list } A)$  is C2

unfolding IterateC-list-def

by (rule IterateC-C2-closed, (metis assms atLeastLessThan-iff nth-map nth-mem prod.collapse)+)

**lemma** IterateC-list-CACT-closed [closure]:

assumes

$\bigwedge b P. (b, P) \in \text{set } A \implies P \text{ is CACT}$

$\bigwedge b P. (b, P) \in \text{set } A \implies P \text{ is Productive}$

shows  $(\text{IterateC-list } A)$  is CACT

by (metis CACT-implies-C2 CACT-implies-NCSP CACT-intro IterateC-list-C2-closed IterateC-list-NCSP-closed  
assms)

**lemma** GuardCSP-C2-closed [closure]:

assumes  $P$  is NCSP  $P$  is C2

shows  $g \ \&_C \ P$  is C2

by (rdes-simp cls: assms(1), rule C2-rdes-intro, simp-all add: closure assms unrest)

**lemma** *GuardCSP-CACT-closed* [closure]:  
**assumes**  $P$  is CACT  
**shows**  $g \ \&_C \ P$  is CACT  
**by** (rule CACT-intro, simp-all add: closure assms)

**lemma** *DoCSP-C2* [closure]:  
 $do_C(a)$  is C2  
**by** (rdes-simp, rule C2-rdes-intro, simp-all add: closure unrest)

**lemma** *DoCSP-CACT* [closure]:  
 $do_C(a)$  is CACT  
**by** (rule CACT-intro, simp-all add: closure)

**lemma** *PrefixCSP-C2-closed* [closure]:  
**assumes**  $P$  is NCSP  $P$  is C2  
**shows**  $a \rightarrow_C P$  is C2  
**unfolding** PrefixCSP-def **by** (metis DoCSP-C2 Healthy-def NCSP-DoCSP NCSP-implies-CSP assms seq-C2-closed)

**lemma** *PrefixCSP-CACT-closed* [closure]:  
**assumes**  $P$  is CACT  
**shows**  $a \rightarrow_C P$  is CACT  
**using** CACT-implies-C2 CACT-implies-NCSP CACT-intro NCSP-PrefixCSP PrefixCSP-C2-closed  
**assms** **by** blast

**lemma** *ExtChoice-C2-closed* [closure]:  
**assumes**  $\bigwedge i. i \in I \implies P(i)$  is NCSP  $\bigwedge i. i \in I \implies P(i)$  is C2  
**shows**  $(\square i \in I \cdot P(i))$  is C2  
**proof** (cases  $I = \{\}$ )  
**case** True  
**then show** ?thesis **by** (simp add: closure ExtChoice-empty)  
**next**  
**case** False  
**show** ?thesis  
**by** (rule C2-NCSP-intro, simp-all add: assms closure unrest periR-ExtChoice-ind' False)  
**qed**

**lemma** *ExtChoice-CACT-closed* [closure]:  
**assumes**  $\bigwedge i. i \in I \implies P(i)$  is CACT  
**shows**  $(\square i \in I \cdot P(i))$  is CACT  
**by** (rule CACT-intro, simp-all add: closure assms)

**lemma** *extChoice-C2-closed* [closure]:  
**assumes**  $P$  is NCSP  $P$  is C2  $Q$  is NCSP  $Q$  is C2  
**shows**  $P \square Q$  is C2  
**proof** –  
**have**  $P \square Q = (\square I \in \{P, Q\} \cdot I)$   
**by** (simp add: extChoice-def)  
**also have** ... is C2  
**by** (rule ExtChoice-C2-closed, auto simp add: assms)  
**finally show** ?thesis .  
**qed**

**lemma** *extChoice-CACT-closed* [closure]:



**assumes**  $P$  is CACT  $Q$  is CACT  
**shows**  $P \sqcap Q$  is CACT  
**by** (rule CACT-intro, simp-all add: closure assms)

**lemma** *state-srea-C2-closed* [closure]:  
**assumes**  $P$  is NCSP  $P$  is C2  
**shows**  $\text{state } 'a \cdot P$  is C2  
**by** (rule C2-NCSP-intro, simp-all add: closure rdes assms)

**lemma** *state-srea-CACT-closed* [closure]:  
**assumes**  $P$  is CACT  
**shows**  $\text{state } 'a \cdot P$  is CACT  
**by** (rule CACT-intro, simp-all add: closure assms)

**lemma** *parallel-C2-closed* [closure]:  
**assumes**  $ns1 \bowtie ns2$   $P$  is NCSP  $Q$  is NCSP  $P$  is C2  $Q$  is C2  
**shows**  $(P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket Q)$  is C2  
**proof** –  
**have**  $(P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket Q) = (\mathbf{R}_s(\text{pre}_R P \vdash \text{peri}_R P \diamond \text{post}_R P) \llbracket ns1 \parallel cs \parallel ns2 \rrbracket \mathbf{R}_s(\text{pre}_R Q \vdash \text{peri}_R Q \diamond \text{post}_R Q))$   
**by** (metis NCSP-implies-NSRD NSRD-is-SRD SRD-reactive-design-alt assms wait'-cond-peri-post-cmt)  
**also have** ... is C2  
**by** (simp add: ParCSP-rdes-def C2-rdes-intro assms closure unrest)  
**finally show** ?thesis .  
**qed**

**lemma** *parallel-CACT-closed* [closure]:  
**assumes**  $ns1 \bowtie ns2$   $P$  is CACT  $Q$  is CACT  
**shows**  $(P \llbracket ns1 \parallel cs \parallel ns2 \rrbracket Q)$  is CACT  
**by** (meson CACT-implies-C2 CACT-implies-NCSP CACT-intro assms parallel-C2-closed parallel-is-NCSP)

**lemma** *RenameCSP-C2-closed* [closure]:  
**assumes**  $P$  is NCSP  $P$  is C2  
**shows**  $P \llbracket f \rrbracket_C$  is C2  
**by** (simp add: RenameCSP-def C2-rdes-intro RenameCSP-pre-CRC-closed closure assms unrest)

**lemma** *RenameCSP-CACT-closed* [closure]:  
**assumes**  $P$  is CACT  
**shows**  $P \llbracket f \rrbracket_C$  is CACT  
**by** (rule CACT-intro, simp-all add: closure assms)

This property depends on downward closure of the refusals

**lemma** *rename-extChoice-pre*:  
**assumes**  $\text{inj } f$   $P$  is NCSP  $Q$  is NCSP  $P$  is C2  $Q$  is C2  
**shows**  $(P \sqcap Q) \llbracket f \rrbracket_C = (P \llbracket f \rrbracket_C \sqcap Q \llbracket f \rrbracket_C)$   
**by** (rdes-eq-split cls: assms)

**lemma** *rename-extChoice*:  
**assumes**  $\text{inj } f$   $P$  is CACT  $Q$  is CACT  
**shows**  $(P \sqcap Q) \llbracket f \rrbracket_C = (P \llbracket f \rrbracket_C \sqcap Q \llbracket f \rrbracket_C)$   
**by** (simp add: CACT-implies-C2 CACT-implies-NCSP assms rename-extChoice-pre)

**lemma** *interleave-commute*:  
 $P \parallel Q = Q \parallel P$   
**by** (auto intro: parallel-commutative zero-lens-indep)

**lemma** *interleave-unit*:  
**assumes**  $P$  is CPROC  
**shows**  $P \parallel \text{Skip} = P$   
**by** (*metis CACT-implies-C2 CACT-implies-NCSP CSP5-def CSP5-is-C2 Healthy-if assms*)

**lemma** *parallel-miracle*:  
 $P$  is NCSP  $\implies$  Miracle  $\llbracket ns1 \parallel cs \parallel ns2 \rrbracket P = \text{Miracle}$   
**by** (*simp add: CSPMerge-def par-by-merge-seq-add[THEN sym] Miracle-parallel-left-zero Skip-right-unit closure*)

**lemma** *parallel-assigns*:  
**assumes**  $vwb\text{-}lens\ ns1\ vwb\text{-}lens\ ns2\ ns1 \bowtie ns2\ x \subseteq_L ns1\ y \subseteq_L ns2$   
**shows**  $(x :=_C u) \llbracket ns1 \parallel cs \parallel ns2 \rrbracket (y :=_C v) = x, y :=_C u, v$   
**using** *assms* **by** (*rdes-eq*)

**definition** *Accept* ::  $(\text{'s}, \text{'e})$  action **where**  
 $[upred\text{-}defs, rdes\text{-}def]: \text{Accept} = \mathbf{R}_s(\text{true}_r \vdash \mathcal{E}(\text{true}, \langle \rangle, \llbracket UNIV \rrbracket) \diamond \text{false})$

**definition**  $[upred\text{-}defs, rdes\text{-}def]: \text{CACC}(P) = (P \vee \text{Accept})$

**lemma** *CACC-form*:  
**assumes**  $P_1$  is RC  $P_2$  is RR  $\$st' \# P_2\ P_3$  is RR  
**shows**  $\text{CACC}(\mathbf{R}_s(P_1 \vdash P_2 \diamond P_3)) = \mathbf{R}_s(P_1 \vdash (\mathcal{E}(\text{true}, \langle \rangle, \llbracket UNIV \rrbracket) \vee P_2) \diamond P_3)$   
**by** (*rdes-eq cls: assms*)

**lemma** *CACC-refines-Accept*:  
**assumes**  $P$  is CACC  
**shows**  $P \sqsubseteq \text{Accept}$   
**proof** –  
**have**  $\text{CACC}(P) \sqsubseteq \text{Accept}$  **by** *rel-auto*  
**thus** *?thesis* **by** (*simp add: Healthy-if assms*)  
**qed**

**lemma** *DoCSP-CACC*  $[closure]: do_C(e)$  is CACC  
**unfolding** *Healthy-def* **by** (*rdes-eq*)

**lemma** *CACC-seq-closure-left*  $[closure]$ :  
**assumes**  $P$  is NCSP  $P$  is CACC  $Q$  is NCSP  
**shows**  $(P ;; Q)$  is CACC  
**proof** –  
**have**  $1: (P ;; Q) = \text{CACC}(P) ;; Q$   
**by** (*simp add: Healthy-if assms(2)*)  
**also have**  $2: \dots = \mathbf{R}_s((pre_R P \wedge post_R P\ wp_r\ pre_R Q) \vdash (peri_R P \vee \mathcal{E}(\text{true}, \langle \rangle, \llbracket UNIV \rrbracket) \vee post_R P ;; peri_R Q) \diamond post_R P ;; post_R Q)$   
**by** (*rdes-simp cls: assms*)  
**also have**  $\dots = \text{CACC}(\dots)$   
**by** (*rdes-eq cls: assms*)  
**also have**  $\dots = \text{CACC}(P ;; Q)$   
**by** (*simp add: 1 2*)  
**finally show** *?thesis*  
**by** (*simp add: Healthy-def*)  
**qed**

**lemma** *CACC-seq-closure-right*:

**assumes**  $P$  is NCSP  $P \parallel Chaos = Chaos$   $Q$  is NCSP  $Q$  is CACC  
**shows**  $(P \parallel Q)$  is CACC  
**oops**

**lemma** *Chaos-is-CACC [closure]*:  $Chaos$  is CACC

**unfolding** *Healthy-def* **by** (*rdes-eq*)

**lemma** *intChoice-is-CACC [closure]*:

**assumes**  $P$  is NCSP  $P$  is CACC  $Q$  is NCSP  $Q$  is CACC  
**shows**  $P \sqcap Q$  is CACC

**proof** –

**have**  $CACC(P) \sqcap CACC(Q)$  is CACC  
**unfolding** *Healthy-def* **by** (*rdes-eq cls: assms*)  
**thus** *?thesis*  
**by** (*simp add: Healthy-if assms(2) assms(4)*)

**qed**

**lemma** *extChoice-is-CACC [closure]*:

**assumes**  $P$  is NCSP  $P$  is CACC  $Q$  is NCSP  $Q$  is CACC  
**shows**  $P \sqcup Q$  is CACC

**proof** –

**have**  $CACC(P) \sqcup CACC(Q)$  is CACC  
**unfolding** *Healthy-def* **by** (*rdes-eq cls: assms*)  
**thus** *?thesis*  
**by** (*simp add: Healthy-if assms(2) assms(4)*)

**qed**

**lemma** *Chaos-par-zero*:

**assumes**  $P$  is NCSP  $P$  is CACC  $ns1 \bowtie ns2$   
**shows**  $Chaos \llbracket ns1 \parallel cs \parallel ns2 \rrbracket P = Chaos$

**proof** –

**have** *pprop*:  $(\forall (tt_0, tt_1) \cdot \mathcal{I}(\langle \langle tt_1 \rangle \rangle \in_u \langle \langle tt_0 \rangle \rangle \star_{cs} \langle \rangle \wedge \langle \langle tt_0 \rangle \rangle \upharpoonright_u \langle \langle cs \rangle \rangle =_u \langle \rangle \upharpoonright_u \langle \langle cs \rangle \rangle, \langle \langle tt_1 \rangle \rangle)) = false$   
**by** (*rel-simp, auto simp add: tr-par-empty*)  
*(metis append-Nil2 seq-filter-Nil takeWhile.simps(1))*

**have**  $1:P = \mathbf{R}_s(pre_R(P) \vdash peri_R(P) \diamond post_R(P))$   
**by** (*simp add: NCSP-implies-NSRD NSRD-is-SRD SRD-reactive-tri-design assms(1)*)

**have**  $\dots \sqsubseteq \mathbf{R}_s(true_r \vdash \mathcal{E}(true, \langle \rangle, \langle \langle UNIV \rangle \rangle) \diamond false)$   
**by** (*metis 1 Accept-def CACC-refines-Accept assms(2)*)

**hence**  $peri_R P \sqsubseteq (pre_R P \wedge \mathcal{E}(true, \langle \rangle, \langle \langle UNIV \rangle \rangle))$   
**by** (*auto simp add: RHS-tri-design-refine' closure assms*)

**hence**  $peri_R(P) = ((pre_R P \wedge \mathcal{E}(true, \langle \rangle, \langle \langle UNIV \rangle \rangle)) \vee peri_R(P))$   
**by** (*simp add: assms(2) utp-pred-laws.sup.absorb2*)

**with 1 have**  $P = \mathbf{R}_s(pre_R(P) \vdash (pre_R(P) \wedge \mathcal{E}(true, \langle \rangle, \langle \langle UNIV \rangle \rangle) \vee peri_R(P)) \diamond post_R(P))$   
**by** (*simp add: NCSP-implies-CSP SRD-reactive-tri-design assms(1)*)

**also have**  $\dots = \mathbf{R}_s(pre_R(P) \vdash (\mathcal{E}(true, \langle \rangle, \langle \langle UNIV \rangle \rangle) \vee peri_R(P)) \diamond post_R(P))$   
**by** (*rel-auto*)

also have  $Chaos \llbracket ns1 \parallel cs \parallel ns2 \rrbracket \dots = Chaos$   
 by (*rdes-simp cls: assms, simp add: pprop*)

finally show *?thesis* .

qed

**lemma** *Chaos-inter-zero*:

assumes *P is NCSP P is CACC*

shows  $Chaos \parallel P = Chaos$

by (*simp add: Chaos-par-zero assms(1) assms(2)*)

end

## 5 Hiding

**theory** *utp-circus-hiding*

**imports** *utp-circus-parallel*

**begin**

### 5.1 Hiding in peri- and postconditions

**definition** *hide-rea* (*hide<sub>r</sub>*) **where**

[*upred-defs*]:  $hide_r P E = (\exists s \cdot (P \llbracket str^u \ll s \gg, (\ll E \gg \cup_u \$ref' ) / \$tr', \$ref' \rrbracket \wedge \$tr' =_u str^u (\ll s \gg \downarrow_u \ll -E \gg)))$

**lemma** *hide-rea-CRR-closed* [*closure*]:

assumes *P is CRR*

shows *hide<sub>r</sub> P E is CRR*

**proof** –

have  $CRR(hide_r (CRR P) E) = hide_r (CRR P) E$

by (*rel-auto, fastforce+*)

thus *?thesis*

by (*metis Healthy-def' assms*)

qed

**lemma** *hide-rea-CDC* [*closure*]:

assumes *P is CDC*

shows *hide<sub>r</sub> P E is CDC*

**proof** –

have  $CDC(hide_r (CDC P) E) = hide_r (CDC P) E$

by (*rel-blast*)

thus *?thesis*

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

qed

**lemma** *hide-rea-false* [*rpred*]:  $hide_r false E = false$

by (*rel-auto*)

**lemma** *hide-rea-disj* [*rpred*]:  $hide_r (P \vee Q) E = (hide_r P E \vee hide_r Q E)$

by (*rel-auto*)

**lemma** *hide-rea-csp-enable* [*rpred*]:

$hide_r \mathcal{E}(s, t, E) F = \mathcal{E}(s \wedge E - \ll F \gg =_u E, t \downarrow_u \ll -F \gg, E)$

by (*rel-auto*)

**lemma** *hide-rea-csp-do* [*rpred*]:  $hide_r \Phi(s, \sigma, t) E = \Phi(s, \sigma, t \downarrow_u \ll -E \gg)$

by (rel-auto)

**lemma** *filter-eval* [simp]:

(bop Cons x xs)  $\downarrow_u E = (bop Cons x (xs \downarrow_u E) \triangleleft x \in_u E \triangleright xs \downarrow_u E)$

by (rel-simp)

**lemma** *hide-rea-seq* [rpred]:

assumes *P* is CRR \$ref'  $\#$  *P* *Q* is CRR

shows  $hide_r (P ;; Q) E = hide_r P E ;; hide_r Q E$

**proof** –

have  $hide_r (CRR(\exists \$ref' \cdot P) ;; CRR(Q)) E = hide_r (CRR(\exists \$ref' \cdot P)) E ;; hide_r (CRR Q) E$

apply (simp add: hide-rea-def usubst unrest CRR-seqr-form)

apply (simp add: CRR-form)

apply (rel-auto)

using seq-filter-append apply fastforce

apply (metis seq-filter-append)

done

thus ?thesis

by (simp add: Healthy-if assms ex-unrest)

qed

**lemma** *hide-rea-true-R1-true* [rpred]:

$hide_r (R1 true) A ;; R1 true = R1 true$

by (rel-auto, metis append-Nil2 seq-filter-Nil)

**lemma** *hide-rea-shEx* [rpred]:  $hide_r (\exists i \cdot P(i)) cs = (\exists i \cdot hide_r (P i) cs)$

by (rel-auto)

**lemma** *hide-rea-empty* [rpred]:

assumes *P* is RR

shows  $hide_r P \{\} = P$

**proof** –

have  $hide_r (RR P) \{\} = (RR P)$

by (rel-auto; force)

thus ?thesis

by (simp add: Healthy-if assms)

qed

**lemma** *hide-rea-twice* [rpred]:  $hide_r (hide_r P A) B = hide_r P (A \cup B)$

apply (rel-auto)

apply (metis (no-types, hide-lams) semilattice-sup-class.sup-assoc)

apply (metis (no-types, lifting) semilattice-sup-class.sup-assoc seq-filter-twice)

done

**lemma** *st'-unrest-hide-rea* [unrest]:  $\$st' \# P \implies \$st' \# hide_r P E$

by (simp add: hide-rea-def unrest)

**lemma** *ref'-unrest-hide-rea* [unrest]:  $\$ref' \# P \implies \$ref' \# hide_r P E$

by (simp add: hide-rea-def unrest usubst)

## 5.2 Hiding in preconditions

**definition** *abs-rea* :: ('s, 'e) action  $\Rightarrow$  'e set  $\Rightarrow$  ('s, 'e) action (*abs<sub>r</sub>*) **where**

[upred-defs]:  $abs_r P E = (\neg_r (hide_r (\neg_r P) E ;; true_r))$

**lemma** *abs-rea-false* [rpred]:  $abs_r false E = false$

by (*rel-simp*, *metis append.right-neutral seq-filter-Nil*)

**lemma** *abs-rea-conj* [*rpred*]:  $abs_r (P \wedge Q) E = (abs_r P E \wedge abs_r Q E)$   
 by (*rel-blast*)

**lemma** *abs-rea-true* [*rpred*]:  $abs_r true_r E = true_r$   
 by (*rel-auto*)

**lemma** *abs-rea-RC-closed* [*closure*]:  
 assumes *P is CRR*  
 shows *abs<sub>r</sub> P E is CRC*  
**proof** –  
 have *RC1 (abs<sub>r</sub> (CRR P) E) = abs<sub>r</sub> (CRR P) E*  
 apply (*rel-auto*)  
 apply (*metis order-refl*)  
 apply *blast*  
 done  
 hence *abs<sub>r</sub> P E is RC1*  
 by (*simp add: assms Healthy-if Healthy-intro closure*)  
 thus ?thesis  
 by (*rule-tac CRC-intro'', simp-all add: abs-rea-def closure assms unrest*)  
**qed**

**lemma** *hide-rea-impl-under-abs*:  
 assumes *P is CRC Q is CRR*  
 shows  $(abs_r P A \Rightarrow_r hide_r (P \Rightarrow_r Q) A) = (abs_r P A \Rightarrow_r hide_r Q A)$   
 by (*simp add: RC1-def abs-rea-def rea-impl-def rpred closure assms unrest*)  
 (*rel-auto*, *metis order-refl*)

**lemma** *abs-rea-not-CRR*:  $P \text{ is CRR} \implies abs_r (\neg_r P) E = (\neg_r hide_r P E ;; R1 \text{ true})$   
 by (*simp add: abs-rea-def rpred closure*)

**lemma** *abs-rea-wpR* [*rpred*]:  
 assumes *P is CRR \$ref' \# P Q is CRC*  
 shows  $abs_r (P wp_r Q) A = (hide_r P A) wp_r (abs_r Q A)$   
 by (*simp add: wp-rea-def abs-rea-not-CRR hide-rea-seq assms closure*)  
 (*simp add: abs-rea-def rpred closure assms seqr-assoc*)

**lemma** *abs-rea-empty* [*rpred*]:  
 assumes *P is RC*  
 shows  $abs_r P \{\} = P$   
**proof** –  
 have  $abs_r (RC P) \{\} = (RC P)$   
 apply (*rel-auto*)  
 apply (*metis diff-add-cancel-left' order-refl plus-list-def*)  
 using *dual-order.trans* apply *blast*  
 done  
 thus ?thesis  
 by (*simp add: Healthy-if assms*)  
**qed**

**lemma** *abs-rea-twice* [*rpred*]:  
 assumes *P is CRC*  
 shows  $abs_r (abs_r P A) B = abs_r P (A \cup B)$  (*is ?lhs = ?rhs*)

**proof** –  
**have**  $?lhs = \text{abs}_r (\neg_r \text{hide}_r (\neg_r P) A ;; R1 \text{ true}) B$   
**by** (*simp add: abs-rea-def*)  
**thus**  $?thesis$   
**by** (*simp add: abs-rea-def rpred closure unrest segr-assoc assms*)  
**qed**

### 5.3 Hiding Operator

In common with the UTP book definition of hiding, this definition does not introduce divergence if there is an infinite sequence of events that are hidden. For this, we would need a more complex precondition which is left for future work.

**definition** *HideCSP* ::  $(s, e) \text{ action} \Rightarrow e \text{ set} \Rightarrow (s, e) \text{ action}$  (**infixl**  $\setminus_C$  80) **where**  
 $[upred-defs]:$   
 $\text{HideCSP } P \ E = \mathbf{R}_s(\text{abs}_r(\text{pre}_R(P)) \ E \vdash \text{hide}_r(\text{peri}_R(P)) \ E \diamond \text{hide}_r(\text{post}_R(P)) \ E)$

**lemma** *HideCSP-rdes-def* [*rdes-def*]:  
**assumes**  $P \text{ is CRC } Q \text{ is CRR } R \text{ is CRR}$   
**shows**  $\mathbf{R}_s(P \vdash Q \diamond R) \setminus_C A = \mathbf{R}_s(\text{abs}_r(P) \ A \vdash \text{hide}_r \ Q \ A \diamond \text{hide}_r \ R \ A)$  (**is**  $?lhs = ?rhs$ )  
**proof** –  
**have**  $?lhs = \mathbf{R}_s(\text{abs}_r \ P \ A \vdash \text{hide}_r \ (P \Rightarrow_r \ Q) \ A \diamond \text{hide}_r \ (P \Rightarrow_r \ R) \ A)$   
**by** (*simp add: HideCSP-def rdes assms closure*)  
**also have**  $\dots = \mathbf{R}_s(\text{abs}_r \ P \ A \vdash (\text{abs}_r \ P \ A \Rightarrow_r \text{hide}_r \ (P \Rightarrow_r \ Q) \ A) \diamond (\text{abs}_r \ P \ A \Rightarrow_r \text{hide}_r \ (P \Rightarrow_r \ R) \ A))$   
**by** (*metis RHS-tri-design-conj conj-idem utp-pred-laws.sup.idem*)  
**also have**  $\dots = ?rhs$   
**by** (*metis RHS-tri-design-conj assms conj-idem hide-rea-impl-under-abs utp-pred-laws.sup.idem*)  
**finally show**  $?thesis$  .  
**qed**

**lemma** *HideCSP-NCSP-closed* [*closure*]:  $P \text{ is NCSP} \Longrightarrow P \setminus_C E \text{ is NCSP}$   
**by** (*simp add: HideCSP-def closure unrest*)

**lemma** *HideCSP-C2-closed* [*closure*]:  
**assumes**  $P \text{ is NCSP } P \text{ is C2}$   
**shows**  $P \setminus_C E \text{ is C2}$   
**by** (*rdes-simp cls: assms, simp add: C2-rdes-intro closure unrest assms*)

**lemma** *HideCSP-CACT-closed* [*closure*]:  
**assumes**  $P \text{ is CACT}$   
**shows**  $P \setminus_C E \text{ is CACT}$   
**by** (*rule CACT-intro, simp-all add: closure assms*)

**lemma** *HideCSP-Chaos*:  $\text{Chaos} \setminus_C E = \text{Chaos}$   
**by** (*rdes-simp*)

**lemma** *HideCSP-Miracle*:  $\text{Miracle} \setminus_C A = \text{Miracle}$   
**by** (*rdes-eq*)

**lemma** *HideCSP-AssignsCSP*:  
 $\langle \sigma \rangle_C \setminus_C A = \langle \sigma \rangle_C$   
**by** (*rdes-eq*)

**lemma** *HideCSP-cond*:  
**assumes**  $P \text{ is NCSP } Q \text{ is NCSP}$

**shows**  $(P \triangleleft b \triangleright_R Q) \setminus_C A = (P \setminus_C A \triangleleft b \triangleright_R Q \setminus_C A)$   
**by** (*rdes-eq cls: assms*)

**lemma** *HideCSP-int-choice*:

**assumes**  $P$  is NCSP  $Q$  is NCSP  
**shows**  $(P \sqcap Q) \setminus_C A = (P \setminus_C A \sqcap Q \setminus_C A)$   
**by** (*rdes-eq cls: assms*)

**lemma** *HideCSP-guard*:

**assumes**  $P$  is NCSP  
**shows**  $(b \&_C P) \setminus_C A = b \&_C (P \setminus_C A)$   
**by** (*rdes-eq cls: assms*)

**lemma** *HideCSP-seq*:

**assumes**  $P$  is NCSP  $Q$  is NCSP  
**shows**  $(P ;; Q) \setminus_C A = (P \setminus_C A ;; Q \setminus_C A)$   
**by** (*rdes-eq-split cls: assms*)

**lemma** *HideCSP-DoCSP* [*rdes-def*]:

$do_C(a) \setminus_C A = (Skip \triangleleft (a \in_u \ll A \gg) \triangleright_R do_C(a))$   
**by** (*rdes-eq*)

**lemma** *HideCSP-PrefixCSP*:

**assumes**  $P$  is NCSP  
**shows**  $(a \rightarrow_C P) \setminus_C A = ((P \setminus_C A) \triangleleft (a \in_u \ll A \gg) \triangleright_R (a \rightarrow_C (P \setminus_C A)))$   
**apply** (*simp add: PrefixCSP-def Healthy-if HideCSP-seq HideCSP-DoCSP closure assms rdes rpred*)  
**apply** (*simp add: HideCSP-NCSP-closed Skip-left-unit assms cond-st-distr*)  
**done**

**lemma** *HideCSP-empty*:

**assumes**  $P$  is NCSP  
**shows**  $P \setminus_C \{\} = P$   
**by** (*rdes-eq cls: assms*)

**lemma** *HideCSP-twice*:

**assumes**  $P$  is NCSP  
**shows**  $P \setminus_C A \setminus_C B = P \setminus_C (A \cup B)$   
**by** (*rdes-simp cls: assms*)

**lemma** *HideCSP-Skip*:  $Skip \setminus_C A = Skip$

**by** (*rdes-eq*)

**lemma** *HideCSP-Stop*:  $Stop \setminus_C A = Stop$

**by** (*rdes-eq*)

**end**

## 6 Meta theory for Circus

**theory** *utp-circus*

**imports**

*utp-circus-traces*

*utp-circus-parallel*

*utp-circus-hiding*

**begin end**



## 7 Easy to use Circus-M parser

```
theory utp-circus-easy-parser
imports utp-circus UTP.utp-easy-parser
begin recall-syntax
```

We change  $\text{:=}$  so that it refers to the Circus operator

```
no-adhoc-overloading
  uassigns assigns-r
```

```
adhoc-overloading
  uassigns AssignsCSP
```

```
syntax
  -GuardCSP :: uexp  $\Rightarrow$  logic  $\Rightarrow$  logic (infixr && 60)
```

```
no-translations
  -uwhile-top b P == CONST while-top b P
```

```
translations
  -uwhile-top b P == CONST WhileC b P
```

```
end
```

## References

- [1] S. Foster, F. Zeyda, and J. Woodcock. Unifying heterogeneous state-spaces with lenses. In *ICTAC*, LNCS 9965. Springer, 2016.
- [2] M. V. M. Oliveira. *Formal Derivation of State-Rich Reactive Programs using Circus*. PhD thesis, Department of Computer Science - University of York, UK, 2006. YCST-2006-02.