

# Theory of Designs in Isabelle/UTP

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## Abstract

This document describes a mechanisation of the UTP theory of designs in Isabelle/UTP. Designs enrich UTP relations with explicit precondition/postcondition pairs, as present in formal notations like VDM, B, and the refinement calculus. If a program's precondition holds, then it is guaranteed to terminate and establish its postcondition, which is an approach known as total correctness. If the precondition does not hold, the behaviour is maximally nondeterministic, which represents unspecified behaviour. In this mechanisation, we create the theory of designs, including its alphabet, signature, and healthiness conditions. We then use these to prove the key algebraic laws of programming. This development can be used to support program verification based on total correctness.

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# 1 Design Signature and Core Laws

```
theory utp-des-core
imports UTP-KAT.utp-kleene
begin
```

UTP designs [2, 4] are a subset of the alphabetised relations that use a boolean observational variable *ok* to record the start and termination of a program. For more information on designs please see Chapter 3 of the UTP book [4], or the more accessible designs tutorial [2].

## 1.1 Definitions

Two named theorem sets exist are created to group theorems that, respectively, provide pre-postcondition definitions, and simplify operators to their normal design form.

```
named-theorems ndes and ndes-simp
```

```
alphabet des-vars =
  ok :: bool
```

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

```
type-synonym 'α des = 'α des-vars-scheme
type-synonym ('α, 'β) rel-des = ('α des, 'β des) urel
type-synonym 'α hrel-des = ('α des) hrel
```

**translations**

$(type) \ ' \alpha \ des \leq (type) \ ' \alpha \ des\text{-vars}\text{-scheme}$   
 $(type) \ ' \alpha \ des \leq (type) \ ' \alpha \ des\text{-vars}\text{-ext}$   
 $(type) \ (' \alpha, ' \beta) \ rel\text{-des} \leq (type) \ (' \alpha \ des, ' \beta \ des) \ urel$   
 $(type) \ ' \alpha \ hrel\text{-des} \leq (type) \ ' \alpha \ des \ hrel$

**notation**  $des\text{-vars}.more_L \ (\Sigma_D)$

**syntax**

$\text{-svid}\text{-des}\text{-alpha} :: \text{svid} \ (\mathbf{v}_D)$

**translations**

$\text{-svid}\text{-des}\text{-alpha} \Rightarrow CONST \ des\text{-vars}.more_L$

**lemma**  $ok\text{-des}\text{-bij}\text{-lens}: \text{bij}\text{-lens} \ (ok +_L \Sigma_D) \ (\text{is} \ \text{bij}\text{-lens} \ ?P)$

**proof** –

**have**  $?P \approx_L 1_L$

**by**  $(meson \ des\text{-vars}.equivs(1) \ des\text{-vars}.equivs(2) \ des\text{-vars}.indeps(1) \ lens\text{-equiv}\text{-sym} \ lens\text{-equiv}\text{-trans} \ lens\text{-plus}\text{-eq}\text{-left})$

**thus**  $?thesis$

**by**  $(simp \ add: \ \text{bij}\text{-lens}\text{-equiv}\text{-id})$

**qed**

Define the lens functor for designs

**definition**  $lmap\text{-des}\text{-vars} :: (' \alpha \Rightarrow ' \beta) \Rightarrow (' \alpha \ des\text{-vars}\text{-scheme} \Rightarrow ' \beta \ des\text{-vars}\text{-scheme}) \ (lmap_D)$

**where**  $[lens\text{-defs}]: lmap\text{-des}\text{-vars} = lmap[des\text{-vars}]$

**syntax**  $\text{-lmap}\text{-des}\text{-vars} :: \text{salph} \Rightarrow \text{salph} \ (lmap_D[-])$

**translations**  $\text{-lmap}\text{-des}\text{-vars} \ a \Rightarrow CONST \ lmap\text{-des}\text{-vars} \ a$

**lemma**  $lmap\text{-des}\text{-vars}: \text{vwb}\text{-lens} \ f \Rightarrow \text{vwb}\text{-lens} \ (lmap\text{-des}\text{-vars} \ f)$

**by**  $(unfold\text{-locales}, \ auto \ simp \ add: \ lens\text{-defs})$

**lemma**  $lmap\text{-id}: lmap_D \ 1_L = 1_L$

**by**  $(simp \ add: \ lens\text{-defs} \ fun\text{-eq}\text{-iff})$

**lemma**  $lmap\text{-comp}: lmap_D \ (f ;_L g) = lmap_D \ f ;_L lmap_D \ g$

**by**  $(simp \ add: \ lens\text{-defs} \ fun\text{-eq}\text{-iff})$

The following notations define liftings from non-design predicates into design predicates using alphabet extensions.

**abbreviation**  $lift\text{-desr} \ (\lceil \_ \rceil_D)$

**where**  $\lceil P \rceil_D \equiv P \oplus_p (\Sigma_D \times_L \Sigma_D)$

**abbreviation**  $lift\text{-pre}\text{-desr} \ (\lceil \_ \rceil_{D<})$

**where**  $\lceil p \rceil_{D<} \equiv \lceil \lceil p \rceil \rceil_{D<}$

**abbreviation**  $lift\text{-post}\text{-desr} \ (\lceil \_ \rceil_{D>})$

**where**  $\lceil p \rceil_{D>} \equiv \lceil \lceil p \rceil \rceil_{D>}$

**abbreviation**  $drop\text{-desr} \ (\lfloor \_ \rfloor_D)$

**where**  $\lfloor P \rfloor_D \equiv P \upharpoonright_e (\Sigma_D \times_L \Sigma_D)$

**abbreviation**  $dcond :: (' \alpha, ' \beta) \ rel\text{-des} \Rightarrow ' \alpha \ upred \Rightarrow (' \alpha, ' \beta) \ rel\text{-des} \Rightarrow (' \alpha, ' \beta) \ rel\text{-des}$

**where**  $dcond \ P \ b \ Q \equiv P \triangleleft \lceil b \rceil_{D<} \triangleright Q$

**syntax**  $-dcond :: logic \Rightarrow uexp \Rightarrow logic \Rightarrow logic \ ((\beta - \triangleleft - \triangleright_D / -) \ [52,0,53] \ 52)$   
**translations**  $-dcond \ P \ b \ Q == CONST \ dcond \ P \ b \ Q$

**definition**  $design :: ('\alpha, '\beta) \ rel-des \Rightarrow ('\alpha, '\beta) \ rel-des \Rightarrow ('\alpha, '\beta) \ rel-des \ (\mathbf{infixl} \vdash \ 59) \ \mathbf{where}$   
 $[upred-defs]: P \vdash Q = (\$ok \wedge P \Rightarrow \$ok' \wedge Q)$

An rdesign is a design that uses the Isabelle type system to prevent reference to ok in the assumption and commitment.

**definition**  $rdesign :: ('\alpha, '\beta) \ urel \Rightarrow ('\alpha, '\beta) \ urel \Rightarrow ('\alpha, '\beta) \ rel-des \ (\mathbf{infixl} \vdash_r \ 59) \ \mathbf{where}$   
 $[upred-defs]: (P \vdash_r Q) = \lceil P \rceil_D \vdash \lceil Q \rceil_D$

An ndesign is a normal design, i.e. where the assumption is a condition

**definition**  $ndesign :: '\alpha \ cond \Rightarrow ('\alpha, '\beta) \ urel \Rightarrow (''\alpha, '\beta) \ rel-des \ (\mathbf{infixl} \vdash_n \ 59) \ \mathbf{where}$   
 $[upred-defs]: (p \vdash_n Q) = (\lceil p \rceil_{<} \vdash_r Q)$

**definition**  $skip-d :: '\alpha \ hrel-des \ (II_D) \ \mathbf{where}$   
 $[upred-defs]: II_D \equiv (true \vdash_r II)$

**definition**  $bot-d :: ('\alpha, '\beta) \ rel-des \ (\perp_D) \ \mathbf{where}$   
 $[upred-defs]: \perp_D = (false \vdash false)$

**definition**  $pre-design :: ('\alpha, '\beta) \ rel-des \Rightarrow ('\alpha, '\beta) \ urel \ (pre_D) \ \mathbf{where}$   
 $[upred-defs]: pre_D(P) = \lfloor \neg P \llbracket true, false / \$ok, \$ok' \rrbracket \rfloor_D$

**definition**  $post-design :: ('\alpha, '\beta) \ rel-des \Rightarrow ('\alpha, '\beta) \ urel \ (post_D) \ \mathbf{where}$   
 $[upred-defs]: post_D(P) = \lfloor P \llbracket true, true / \$ok, \$ok' \rrbracket \rfloor_D$

**syntax**

$-ok-f :: logic \Rightarrow logic \ (-^f \ [1000] \ 1000)$   
 $-ok-t :: logic \Rightarrow logic \ (-^t \ [1000] \ 1000)$   
 $-top-d :: logic \ (\top_D)$

**translations**

$P^f \equiv CONST \ usubst \ (CONST \ subst-upd \ id_s \ (CONST \ out-var \ CONST \ ok) \ false) \ P$   
 $P^t \equiv CONST \ usubst \ (CONST \ subst-upd \ id_s \ (CONST \ out-var \ CONST \ ok) \ true) \ P$   
 $\top_D \Rightarrow CONST \ not-upred \ (CONST \ utp-expr.var \ (CONST \ in-var \ CONST \ ok))$

## 1.2 Lifting, Unrestriction, and Substitution

**lemma**  $drop-desr-inv \ [simp]: \lfloor \lceil P \rceil_D \rfloor_D = P$   
**by**  $(simp \ add: \ prod-mwb-lens)$

**lemma**  $lift-desr-inv:$

**fixes**  $P :: ('\alpha, '\beta) \ rel-des$   
**assumes**  $\$ok \ \# \ P \ \$ok' \ \# \ P$   
**shows**  $\lfloor \lceil P \rceil_D \rfloor_D = P$

**proof**  $-$

**have**  $bij-lens \ (\Sigma_D \times_L \Sigma_D +_L \ (in-var \ ok +_L \ out-var \ ok)) :: (-, '\alpha \ des-vars-scheme \times '\beta \ des-vars-scheme)$   
 $lens)$

**(is**  $bij-lens \ (?P))$

**proof**  $-$

**have**  $?P \approx_L \ (ok +_L \Sigma_D) \times_L \ (ok +_L \Sigma_D) \ (\mathbf{is} \ ?P \approx_L \ ?Q)$

**apply**  $(simp \ add: \ in-var-def \ out-var-def \ prod-as-plus)$

**apply**  $(simp \ add: \ prod-as-plus[THEN \ sym])$

```

  apply (meson lens-equiv-sym lens-equiv-trans lens-indep-prod lens-plus-comm lens-plus-prod-exchange
des-vars.indeps(1))
done
moreover have bij-lens ?Q
  by (simp add: ok-des-bij-lens prod-bij-lens)
ultimately show ?thesis
  by (metis bij-lens-equiv lens-equiv-sym)
qed

with assms show ?thesis
  apply (rule-tac aext-arestr[of - in-var ok +L out-var ok])
  apply (simp add: prod-mwb-lens)
  apply (simp)
  apply (metis alpha-in-var lens-indep-prod lens-indep-sym des-vars.indeps(1) out-var-def prod-as-plus)
  using unrest-var-comp apply blast
done
qed

lemma unrest-out-des-lift [unrest]:  $out\alpha \# p \implies out\alpha \# [p]_D$ 
  by (pred-simp)

lemma lift-dist-seq [simp]:
 $[P ;; Q]_D = ([P]_D ;; [Q]_D)$ 
  by (rel-auto)

lemma lift-des-skip-dr-unit [simp]:
 $([P]_D ;; [II]_D) = [P]_D$ 
 $([II]_D ;; [P]_D) = [P]_D$ 
  by (rel-auto)+

lemma lift-des-skip-dr-unit-unrest:  $\$ok' \# P \implies (P ;; [II]_D) = P$ 
  by (rel-auto)

lemma state-subst-design [usubst]:
 $[\sigma \oplus_s \Sigma_D]_s \dagger (P \vdash_r Q) = ([\sigma]_s \dagger P) \vdash_r ([\sigma]_s \dagger Q)$ 
  by (rel-auto)

lemma design-subst [usubst]:
 $\llbracket \$ok \#_s \sigma; \$ok' \#_s \sigma \rrbracket \implies \sigma \dagger (P \vdash Q) = (\sigma \dagger P) \vdash (\sigma \dagger Q)$ 
  by (simp add: design-def usubst)

lemma design-msubst [usubst]:
 $(P(x) \vdash Q(x)) \llbracket x \rightarrow v \rrbracket = (P(x) \llbracket x \rightarrow v \rrbracket \vdash Q(x) \llbracket x \rightarrow v \rrbracket)$ 
  by (rel-auto)

lemma design-ok-false [usubst]:  $(P \vdash Q) \llbracket false / \$ok \rrbracket = true$ 
  by (simp add: design-def usubst)

lemma ok-pre:  $(\$ok \wedge [pre_D(P)]_D) = (\$ok \wedge (\neg P^f))$ 
  apply (simp add: pre-design-def alpha unrest usubst)
  apply (subst aext-arestr')
  apply (rel-simp)
  apply (rel-auto)
done

```

**lemma** *ok-post*:  $(\$ok \wedge \lceil post_D(P) \rceil_D) = (\$ok \wedge (P^t))$   
**apply** (*simp add: post-design-def alpha unrest usubst*)  
**apply** (*subst aext-arestr'*)  
**apply** (*rel-simp*)  
**apply** (*rel-auto*)  
**done**

### 1.3 Basic Design Laws

**lemma** *design-export-ok*:  $P \vdash Q = (P \vdash (\$ok \wedge Q))$   
**by** (*rel-auto*)

**lemma** *design-export-ok'*:  $P \vdash Q = (P \vdash (\$ok' \wedge Q))$   
**by** (*rel-auto*)

**lemma** *design-export-pre*:  $P \vdash (P \wedge Q) = P \vdash Q$   
**by** (*rel-auto*)

**lemma** *design-export-spec*:  $P \vdash (P \Rightarrow Q) = P \vdash Q$   
**by** (*rel-auto*)

**lemma** *design-ok-pre-conj*:  $(\$ok \wedge P) \vdash Q = P \vdash Q$   
**by** (*rel-auto*)

**lemma** *true-is-design*:  $(false \vdash true) = true$   
**by** (*rel-auto*)

**lemma** *true-is-rdesign*:  $(false \vdash_r true) = true$   
**by** (*rel-auto*)

**lemma** *bot-d-true*:  $\perp_D = true$   
**by** (*rel-auto*)

**lemma** *bot-d-ndes-def* [*ndes-simp*]:  $\perp_D = (false \vdash_n true)$   
**by** (*rel-auto*)

**lemma** *design-false-pre*:  $(false \vdash P) = true$   
**by** (*rel-auto*)

**lemma** *rdesign-false-pre*:  $(false \vdash_r P) = true$   
**by** (*rel-auto*)

**lemma** *ndesign-false-pre*:  $(false \vdash_n P) = true$   
**by** (*rel-auto*)

**lemma** *ndesign-miracle*:  $(true \vdash_n false) = \top_D$   
**by** (*rel-auto*)

**lemma** *top-d-ndes-def* [*ndes-simp*]:  $\top_D = (true \vdash_n false)$   
**by** (*rel-auto*)

**lemma** *skip-d-alt-def*:  $II_D = true \vdash II$   
**by** (*rel-auto*)

**lemma** *skip-d-ndes-def* [*ndes-simp*]:  $II_D = true \vdash_n II$   
**by** (*rel-auto*)

**lemma** *design-subst-ok*:  
 $(P \llbracket \text{true}/\$ok \rrbracket \vdash Q \llbracket \text{true}/\$ok \rrbracket) = (P \vdash Q)$   
 by (*rel-auto*)

**lemma** *design-subst-ok-ok'*:  
 $(P \llbracket \text{true}/\$ok \rrbracket \vdash Q \llbracket \text{true}, \text{true}/\$ok, \$ok' \rrbracket) = (P \vdash Q)$

**proof** –

have  $(P \vdash Q) = ((\$ok \wedge P) \vdash (\$ok \wedge \$ok' \wedge Q))$   
 by (*pred-auto*)

also have  $\dots = ((\$ok \wedge P \llbracket \text{true}/\$ok \rrbracket) \vdash (\$ok \wedge (\$ok' \wedge Q \llbracket \text{true}/\$ok' \rrbracket) \llbracket \text{true}/\$ok \rrbracket))$

by (*metis conj-eq-out-var-subst conj-pos-var-subst upred-eq-true utp-pred-laws.inf-commute ok-vwb-lens*)

also have  $\dots = ((\$ok \wedge P \llbracket \text{true}/\$ok \rrbracket) \vdash (\$ok \wedge \$ok' \wedge Q \llbracket \text{true}, \text{true}/\$ok, \$ok' \rrbracket))$

by (*simp add: usubst*)

also have  $\dots = (P \llbracket \text{true}/\$ok \rrbracket \vdash Q \llbracket \text{true}, \text{true}/\$ok, \$ok' \rrbracket)$

by (*pred-auto*)

finally show *?thesis* ..

qed

**lemma** *design-subst-ok'*:

$(P \vdash Q \llbracket \text{true}/\$ok' \rrbracket) = (P \vdash Q)$

**proof** –

have  $(P \vdash Q) = (P \vdash (\$ok' \wedge Q))$

by (*pred-auto*)

also have  $\dots = (P \vdash (\$ok' \wedge Q \llbracket \text{true}/\$ok' \rrbracket))$

by (*metis conj-eq-out-var-subst upred-eq-true utp-pred-laws.inf-commute ok-vwb-lens*)

also have  $\dots = (P \vdash Q \llbracket \text{true}/\$ok' \rrbracket)$

by (*pred-auto*)

finally show *?thesis* ..

qed

## 1.4 Sequential Composition Laws

**theorem** *design-skip-idem* [*simp*]:

$(II_D ;; II_D) = II_D$

by (*rel-auto*)

**theorem** *design-composition-subst*:

**assumes**

$\$ok' \nmid P1 \ \$ok \nmid P2$

**shows**  $((P1 \vdash Q1) ;; (P2 \vdash Q2)) =$

$((\neg (\neg P1) ;; \text{true})) \wedge \neg (Q1 \llbracket \text{true}/\$ok' \rrbracket ;; (\neg P2))) \vdash (Q1 \llbracket \text{true}/\$ok' \rrbracket ;; Q2 \llbracket \text{true}/\$ok \rrbracket)$

**proof** –

have  $((P1 \vdash Q1) ;; (P2 \vdash Q2)) = (\exists \text{ ok}_0. ((P1 \vdash Q1) \llbracket \llcorner \text{ok}_0 \gg / \$ok' \rrbracket ;; (P2 \vdash Q2) \llbracket \llcorner \text{ok}_0 \gg / \$ok \rrbracket))$

by (*rule seqr-middle, simp*)

also have  $\dots$

$= (((P1 \vdash Q1) \llbracket \text{false}/\$ok' \rrbracket ;; (P2 \vdash Q2) \llbracket \text{false}/\$ok \rrbracket)$

$\vee ((P1 \vdash Q1) \llbracket \text{true}/\$ok' \rrbracket ;; (P2 \vdash Q2) \llbracket \text{true}/\$ok \rrbracket))$

by (*metis (no-types, lifting) calculation disj-comm ok-vwb-lens seqr-bool-split*)

also from *assms*

have  $\dots = (((\$ok \wedge P1 \Rightarrow Q1 \llbracket \text{true}/\$ok' \rrbracket) ;; (P2 \Rightarrow \$ok' \wedge Q2 \llbracket \text{true}/\$ok \rrbracket)) \vee ((\neg (\$ok \wedge P1)) ;; \text{true}))$

by (*simp add: design-def usubst unrest, pred-auto*)

also have  $\dots = ((\neg \$ok ;; \text{true}_h) \vee ((\neg P1) ;; \text{true}) \vee (Q1 \llbracket \text{true}/\$ok' \rrbracket ;; (\neg P2)) \vee (\$ok' \wedge (Q1 \llbracket \text{true}/\$ok' \rrbracket ;; Q2 \llbracket \text{true}/\$ok \rrbracket)))$

by (*rel-auto*)

also have ... = ((( $\neg$  ( $\neg$   $P1$ ) ;;  $true$ ))  $\wedge$   $\neg$  ( $Q1 \llbracket true/\$ok' \rrbracket$  ;; ( $\neg$   $P2$ )))  $\vdash$  ( $Q1 \llbracket true/\$ok' \rrbracket$  ;;  $Q2 \llbracket true/\$ok \rrbracket$ ))  
 by (simp add: precondition-right-unit design-def unrest, rel-auto)  
 finally show ?thesis .  
 qed

**theorem** *design-composition*:

assumes

$\$ok' \# P1 \ \$ok \# P2 \ \$ok' \# Q1 \ \$ok \# Q2$

shows (( $P1 \vdash Q1$ ) ;; ( $P2 \vdash Q2$ )) = ((( $\neg$  ( $\neg$   $P1$ ) ;;  $true$ ))  $\wedge$   $\neg$  ( $Q1$  ;; ( $\neg$   $P2$ )))  $\vdash$  ( $Q1$  ;;  $Q2$ ))

using assms by (simp add: design-composition-subst usubst)

**theorem** *design-composition-runrest*:

assumes

$\$ok' \# P1 \ \$ok \# P2 \ ok \# Q1 \ ok \# Q2$

shows (( $P1 \vdash Q1$ ) ;; ( $P2 \vdash Q2$ )) = ((( $\neg$  ( $\neg$   $P1$ ) ;;  $true$ ))  $\wedge$   $\neg$  ( $Q1^t$  ;; ( $\neg$   $P2$ )))  $\vdash$  ( $Q1$  ;;  $Q2$ ))

**proof** –

have ( $\$ok \wedge \$ok' \wedge (Q1^t$  ;;  $Q2 \llbracket true/\$ok \rrbracket$ )) = ( $\$ok \wedge \$ok' \wedge (Q1$  ;;  $Q2)$ )

**proof** –

have ( $\$ok \wedge \$ok' \wedge (Q1$  ;;  $Q2)$ ) = (( $\$ok \wedge Q1$ ) ;; ( $Q2 \wedge \$ok'$ ))

by (metis (no-types, lifting) conj-comm seqr-post-var-out seqr-pre-var-out)

also have ... = (( $Q1 \wedge \$ok'$ ) ;; ( $\$ok \wedge Q2$ ))

by (simp add: assms(3) assms(4) runrest-ident-var)

also have ... = ( $Q1^t$  ;;  $Q2 \llbracket true/\$ok \rrbracket$ )

by (metis ok-vwb-lens seqr-pre-transfer seqr-right-one-point true-alt-def uovar-convr upred-eq-true utp-pred-laws.inf.left-idem utp-rel.unrest-ouvar vwb-lens-mwb)

finally show ?thesis

by (metis utp-pred-laws.inf.left-commute utp-pred-laws.inf-left-idem)

qed

moreover have ( $\neg$  ( $\neg$   $P1$  ;;  $true$ )  $\wedge$   $\neg$  ( $Q1^t$  ;; ( $\neg$   $P2$ )))  $\vdash$  ( $Q1^t$  ;;  $Q2 \llbracket true/\$ok \rrbracket$ ) =

( $\neg$  ( $\neg$   $P1$  ;;  $true$ )  $\wedge$   $\neg$  ( $Q1^t$  ;; ( $\neg$   $P2$ )))  $\vdash$  ( $\$ok \wedge \$ok' \wedge (Q1^t$  ;;  $Q2 \llbracket true/\$ok \rrbracket$ ))

by (metis design-export-ok design-export-ok')

ultimately show ?thesis using assms

by (simp add: design-composition-subst usubst, metis design-export-ok design-export-ok')

qed

**theorem** *rdesign-composition*:

(( $P1 \vdash_r Q1$ ) ;; ( $P2 \vdash_r Q2$ )) = ((( $\neg$  ( $\neg$   $P1$ ) ;;  $true$ ))  $\wedge$   $\neg$  ( $Q1$  ;; ( $\neg$   $P2$ )))  $\vdash_r$  ( $Q1$  ;;  $Q2$ ))

by (simp add: rdesign-def design-composition unrest alpha)

**theorem** *design-composition-cond*:

assumes

$out\alpha \# p1 \ \$ok \# P2 \ \$ok' \# Q1 \ \$ok \# Q2$

shows (( $p1 \vdash Q1$ ) ;; ( $P2 \vdash Q2$ )) = (( $p1 \wedge \neg$  ( $Q1$  ;; ( $\neg$   $P2$ )))  $\vdash$  ( $Q1$  ;;  $Q2$ ))

using assms

by (simp add: design-composition unrest precondition-right-unit)

**theorem** *rdesign-composition-cond*:

assumes  $out\alpha \# p1$

shows (( $p1 \vdash_r Q1$ ) ;; ( $P2 \vdash_r Q2$ )) = (( $p1 \wedge \neg$  ( $Q1$  ;; ( $\neg$   $P2$ )))  $\vdash_r$  ( $Q1$  ;;  $Q2$ ))

using assms

by (simp add: rdesign-def design-composition-cond unrest alpha)

**theorem** *design-composition-wp*:

assumes

$ok \# p1 \ ok \# p2$



$\$ok \# Q1 \ \$ok' \# Q1 \ \$ok \# Q2 \ \$ok' \# Q2$   
**shows**  $(([p1]_{<} \vdash_r Q1) ;; ([p2]_{<} \vdash_r Q2)) = (([p1 \wedge Q1 \text{ wlp } p2]_{<} \vdash_r (Q1 ;; Q2)))$   
**using** *assms* **by** (*rel-blast*)

**theorem** *rdesign-composition-wp*:

$(([p1]_{<} \vdash_r Q1) ;; ([p2]_{<} \vdash_r Q2)) = (([p1 \wedge Q1 \text{ wlp } p2]_{<} \vdash_r (Q1 ;; Q2)))$   
**by** (*rel-blast*)

**theorem** *ndesign-composition-wp* [*ndes-simp*]:

$((p1 \vdash_n Q1) ;; (p2 \vdash_n Q2)) = ((p1 \wedge Q1 \text{ wlp } p2) \vdash_n (Q1 ;; Q2))$   
**by** (*rel-blast*)

**theorem** *design-true-left-zero*:  $(true ;; (P \vdash Q)) = true$

**proof** –

**have**  $(true ;; (P \vdash Q)) = ((true \llbracket false/\$ok' \rrbracket ;; (P \vdash Q) \llbracket false/\$ok \rrbracket) \vee (true \llbracket true/\$ok' \rrbracket ;; (P \vdash Q) \llbracket true/\$ok \rrbracket))$   
**by** (*rel-auto*)

**also have**  $\dots = ((true \llbracket false/\$ok' \rrbracket ;; true_h) \vee (true ;; ((P \vdash Q) \llbracket true/\$ok \rrbracket)))$   
**by** (*subst-tac, rel-auto*)

**also have**  $\dots = true$

**by** (*subst-tac, simp add: precondition-right-unit unrest*)

**finally show** *?thesis* .

**qed**

**theorem** *design-left-unit-hom*:

**fixes**  $P \ Q :: 'a \ hrel\_des$

**shows**  $(II_D ;; (P \vdash_r Q)) = (P \vdash_r Q)$

**proof** –

**have**  $(II_D ;; (P \vdash_r Q)) = ((true \vdash_r II) ;; (P \vdash_r Q))$   
**by** (*simp add: skip-d-def*)

**also have**  $\dots = (true \wedge \neg (II ;; (\neg P))) \vdash_r (II ;; Q)$

**proof** –

**have**  $out\alpha \# true$

**by** *unrest-tac*

**thus** *?thesis*

**using** *rdesign-composition-cond* **by** *blast*

**qed**

**also have**  $\dots = (\neg (\neg P)) \vdash_r Q$

**by** *simp*

**finally show** *?thesis* **by** *simp*

**qed**

**theorem** *rdesign-left-unit* [*simp*]:

$II_D ;; (P \vdash_r Q) = (P \vdash_r Q)$

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

**theorem** *design-right-semi-unit*:

$(P \vdash_r Q) ;; II_D = ((\neg (\neg P) ;; true) \vdash_r Q)$

**by** (*simp add: skip-d-def rdesign-composition*)

**theorem** *design-right-cond-unit* [*simp*]:

**assumes**  $out\alpha \# p$

**shows**  $(p \vdash_r Q) ;; II_D = (p \vdash_r Q)$

**using** *assms*

**by** (*simp add: skip-d-def rdesign-composition-cond*)

**theorem** *ndesign-left-unit* [simp]:

$$I_D ;; (p \vdash_n Q) = (p \vdash_n Q)$$

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

**theorem** *design-bot-left-zero*:  $(\perp_D ;; (P \vdash Q)) = \perp_D$

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

**theorem** *design-top-left-zero*:  $(\top_D ;; (P \vdash Q)) = \top_D$

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

## 1.5 Preconditions and Postconditions

**theorem** *design-npre*:

$$(P \vdash Q)^f = (\neg \$ok \vee \neg P^f)$$

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

**theorem** *design-pre*:

$$\neg (P \vdash Q)^f = (\$ok \wedge P^f)$$

**by** (*simp add: design-def, subst-tac*)

(*metis (no-types, hide-lams) not-conj-deMorgans true-not-false(2) utp-pred-laws.compl-top-eq utp-pred-laws.sup.idem utp-pred-laws.sup-compl-top*)

**theorem** *design-post*:

$$(P \vdash Q)^t = ((\$ok \wedge P^t) \Rightarrow Q^t)$$

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

**theorem** *rdesign-pre* [simp]:  $pre_D(P \vdash_r Q) = P$

**by** (*pred-auto*)

**theorem** *rdesign-post* [simp]:  $post_D(P \vdash_r Q) = (P \Rightarrow Q)$

**by** (*pred-auto*)

**theorem** *ndesign-pre* [simp]:  $pre_D(p \vdash_n Q) = \lceil p \rceil_<$

**by** (*pred-auto*)

**theorem** *ndesign-post* [simp]:  $post_D(p \vdash_n Q) = (\lceil p \rceil_< \Rightarrow Q)$

**by** (*pred-auto*)

**lemma** *design-pre-choice* [simp]:

$$pre_D(P \sqcap Q) = (pre_D(P) \wedge pre_D(Q))$$

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

**lemma** *design-post-choice* [simp]:

$$post_D(P \sqcap Q) = (post_D(P) \vee post_D(Q))$$

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

**lemma** *design-pre-condr* [simp]:

$$pre_D(P \triangleleft \lceil b \rceil_D \triangleright Q) = (pre_D(P) \triangleleft b \triangleright pre_D(Q))$$

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

**lemma** *design-post-condr* [simp]:

$$post_D(P \triangleleft \lceil b \rceil_D \triangleright Q) = (post_D(P) \triangleleft b \triangleright post_D(Q))$$

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

**lemma** *preD-USUP-mem*:  $pre_D(\bigsqcup_{i \in A} P \cdot i) = (\bigsqcap_{i \in A} pre_D(P \cdot i))$

by (rel-auto)

**lemma** *preD-USUP-ind*:  $\text{pre}_D (\bigsqcup i \cdot P i) = (\bigsqcap i \cdot \text{pre}_D(P i))$   
 by (rel-auto)

## 1.6 Distribution Laws

**theorem** *design-choice*:

$(P_1 \vdash P_2) \sqcap (Q_1 \vdash Q_2) = ((P_1 \wedge Q_1) \vdash (P_2 \vee Q_2))$   
 by (rel-auto)

**theorem** *rdesign-choice*:

$(P_1 \vdash_r P_2) \sqcap (Q_1 \vdash_r Q_2) = ((P_1 \wedge Q_1) \vdash_r (P_2 \vee Q_2))$   
 by (rel-auto)

**theorem** *ndesign-choice* [ndes-simp]:

$(p_1 \vdash_n P_2) \sqcap (q_1 \vdash_n Q_2) = ((p_1 \wedge q_1) \vdash_n (P_2 \vee Q_2))$   
 by (rel-auto)

**theorem** *ndesign-choice'* [ndes-simp]:

$((p_1 \vdash_n P_2) \vee (q_1 \vdash_n Q_2)) = ((p_1 \wedge q_1) \vdash_n (P_2 \vee Q_2))$   
 by (rel-auto)

**theorem** *design-inf*:

$(P_1 \vdash P_2) \sqcup (Q_1 \vdash Q_2) = ((P_1 \vee Q_1) \vdash ((P_1 \Rightarrow P_2) \wedge (Q_1 \Rightarrow Q_2)))$   
 by (rel-auto)

**theorem** *rdesign-inf*:

$(P_1 \vdash_r P_2) \sqcup (Q_1 \vdash_r Q_2) = ((P_1 \vee Q_1) \vdash_r ((P_1 \Rightarrow P_2) \wedge (Q_1 \Rightarrow Q_2)))$   
 by (rel-auto)

**theorem** *ndesign-inf* [ndes-simp]:

$(p_1 \vdash_n P_2) \sqcup (q_1 \vdash_n Q_2) = ((p_1 \vee q_1) \vdash_n (([p_1]_< \Rightarrow P_2) \wedge ([q_1]_< \Rightarrow Q_2)))$   
 by (rel-auto)

**theorem** *design-condr*:

$((P_1 \vdash P_2) \triangleleft b \triangleright (Q_1 \vdash Q_2)) = ((P_1 \triangleleft b \triangleright Q_1) \vdash (P_2 \triangleleft b \triangleright Q_2))$   
 by (rel-auto)

**theorem** *ndesign-dcond* [ndes-simp]:

$((p_1 \vdash_n P_2) \triangleleft b \triangleright_D (q_1 \vdash_n Q_2)) = ((p_1 \triangleleft b \triangleright q_1) \vdash_n (P_2 \triangleleft b \triangleright_r Q_2))$   
 by (rel-auto)

**lemma** *design-UINF-mem*:

**assumes**  $A \neq \{\}$   
**shows**  $(\bigsqcap i \in A \cdot P(i) \vdash Q(i)) = (\bigsqcup i \in A \cdot P(i)) \vdash (\bigsqcap i \in A \cdot Q(i))$   
**using** *assms* **by** (rel-auto)

**lemma** *ndesign-UINF-mem* [ndes-simp]:

**assumes**  $A \neq \{\}$   
**shows**  $(\bigsqcap i \in A \cdot p(i) \vdash_n Q(i)) = (\bigsqcup i \in A \cdot p(i)) \vdash_n (\bigsqcap i \in A \cdot Q(i))$   
**using** *assms* **by** (rel-auto)

**lemma** *ndesign-UINF-ind* [ndes-simp]:

$(\bigsqcap i \cdot p(i) \vdash_n Q(i)) = (\bigsqcup i \cdot p(i)) \vdash_n (\bigsqcap i \cdot Q(i))$   
 by (rel-auto)

**lemma** *design-USUP-mem*:

$(\sqcup i \in A \cdot P(i) \vdash Q(i)) = (\prod i \in A \cdot P(i)) \vdash (\sqcup i \in A \cdot P(i) \Rightarrow Q(i))$   
**by** (*rel-auto*)

**lemma** *ndesign-USUP-mem* [*ndes-simp*]:

$(\sqcup i \in A \cdot p(i) \vdash_n Q(i)) = (\prod i \in A \cdot p(i)) \vdash_n (\sqcup i \in A \cdot [p(i)]_< \Rightarrow Q(i))$   
**by** (*rel-auto*)

**lemma** *ndesign-USUP-ind* [*ndes-simp*]:

$(\sqcup i \cdot p(i) \vdash_n Q(i)) = (\prod i \cdot p(i)) \vdash_n (\sqcup i \cdot [p(i)]_< \Rightarrow Q(i))$   
**by** (*rel-auto*)

## 1.7 Refinement Introduction

**lemma** *ndesign-eq-intro*:

**assumes**  $p_1 = q_1 \ P_2 = Q_2$   
**shows**  $p_1 \vdash_n P_2 = q_1 \vdash_n Q_2$   
**by** (*simp add: assms*)

**theorem** *design-refinement*:

**assumes**  
 $\$ok \# P1 \ \$ok' \# P1 \ \$ok \# P2 \ \$ok' \# P2$   
 $\$ok \# Q1 \ \$ok' \# Q1 \ \$ok \# Q2 \ \$ok' \# Q2$   
**shows**  $(P1 \vdash Q1 \sqsubseteq P2 \vdash Q2) \longleftrightarrow ('P1 \Rightarrow P2' \wedge 'P1 \wedge Q2 \Rightarrow Q1')$

**proof** –

**have**  $(P1 \vdash Q1) \sqsubseteq (P2 \vdash Q2) \longleftrightarrow '(\$ok \wedge P2 \Rightarrow \$ok' \wedge Q2) \Rightarrow (\$ok \wedge P1 \Rightarrow \$ok' \wedge Q1)'$   
**by** (*pred-auto*)

**also with** *assms* **have**  $\dots = '(P2 \Rightarrow \$ok' \wedge Q2) \Rightarrow (P1 \Rightarrow \$ok' \wedge Q1)'$   
**by** (*subst subst-bool-split[of in-var ok], simp-all, subst-tac*)

**also with** *assms* **have**  $\dots = '(\neg P2 \Rightarrow \neg P1) \wedge ((P2 \Rightarrow Q2) \Rightarrow P1 \Rightarrow Q1)'$   
**by** (*subst subst-bool-split[of out-var ok], simp-all, subst-tac*)

**also have**  $\dots \longleftrightarrow '(P1 \Rightarrow P2)' \wedge 'P1 \wedge Q2 \Rightarrow Q1'$   
**by** (*pred-auto*)

**finally show** *?thesis* .

**qed**

**theorem** *rdesign-refinement*:

$(P1 \vdash_r Q1 \sqsubseteq P2 \vdash_r Q2) \longleftrightarrow ('P1 \Rightarrow P2' \wedge 'P1 \wedge Q2 \Rightarrow Q1')$   
**by** (*rel-auto*)

**lemma** *design-refine-intro*:

**assumes**  $'P1 \Rightarrow P2' \ 'P1 \wedge Q2 \Rightarrow Q1'$   
**shows**  $P1 \vdash Q1 \sqsubseteq P2 \vdash Q2$   
**using** *assms* **unfolding** *upred-defs*  
**by** (*pred-auto*)

**lemma** *design-refine-intro'*:

**assumes**  $P_2 \sqsubseteq P_1 \ Q_1 \sqsubseteq (P_1 \wedge Q_2)$   
**shows**  $P_1 \vdash Q_1 \sqsubseteq P_2 \vdash Q_2$   
**using** *assms* *design-refine-intro* [*of P<sub>1</sub> P<sub>2</sub> Q<sub>2</sub> Q<sub>1</sub>*] **by** (*simp add: refBy-order*)

**lemma** *rdesign-refine-intro*:

**assumes**  $'P1 \Rightarrow P2' \ 'P1 \wedge Q2 \Rightarrow Q1'$   
**shows**  $P1 \vdash_r Q1 \sqsubseteq P2 \vdash_r Q2$   
**using** *assms* **unfolding** *upred-defs*

by (pred-auto)

**lemma** *rdesign-refine-intro'*:

assumes  $P2 \sqsubseteq P1$   $Q1 \sqsubseteq (P1 \wedge Q2)$

shows  $P1 \vdash_r Q1 \sqsubseteq P2 \vdash_r Q2$

using *assms unfolding upred-defs*

by (pred-auto)

**lemma** *ndesign-refinement*:

$p1 \vdash_n Q1 \sqsubseteq p2 \vdash_n Q2 \longleftrightarrow (p1 \Rightarrow p2' \wedge '[p1]_< \wedge Q2 \Rightarrow Q1')$

by (simp add: *ndesign-def rdesign-def design-refinement unrest, rel-auto*)

**lemma** *ndesign-refinement'*:

$p1 \vdash_n Q1 \sqsubseteq p2 \vdash_n Q2 \longleftrightarrow (p1 \Rightarrow p2' \wedge Q1 \sqsubseteq ?[p1] ;; Q2)$

by (simp add: *ndesign-refinement, rel-auto*)

**lemma** *ndesign-refine-intro*:

assumes  $p1 \Rightarrow p2' \wedge Q1 \sqsubseteq ?[p1] ;; Q2$

shows  $p1 \vdash_n Q1 \sqsubseteq p2 \vdash_n Q2$

by (simp add: *ndesign-refinement' assms*)

**lemma** *design-top*:

$(P \vdash Q) \sqsubseteq \top_D$

by (rel-auto)

**lemma** *design-bottom*:

$\perp_D \sqsubseteq (P \vdash Q)$

by (rel-auto)

**lemma** *design-refine-thms*:

assumes  $P \sqsubseteq Q$

shows  $'pre_D(P) \Rightarrow pre_D(Q)'$   $'pre_D(P) \wedge post_D(Q) \Rightarrow post_D(P)'$

apply (metis *assms design-pre-choice disj-comm disj-upred-def order-refl rdesign-refinement utp-pred-laws.le-iff-sup*)

apply (metis *assms conj-comm design-post-choice disj-upred-def refBy-order semilattice-sup-class.le-iff-sup*

*utp-pred-laws.inf.coboundedI1*)

done

end

## 2 Design Healthiness Conditions

**theory** *utp-des-healths*

imports *utp-des-core*

begin

### 2.1 H1: No observation is allowed before initiation

**definition** *H1* ::  $('α, 'β) \text{ rel-des} \Rightarrow ('α, 'β) \text{ rel-des}$  **where**

$[upred-defs]: H1(P) = (\$ok \Rightarrow P)$

**lemma** *H1-idem*:

$H1 (H1 P) = H1(P)$

by (pred-auto)

**lemma** *H1-monotone*:

$P \sqsubseteq Q \implies H1(P) \sqsubseteq H1(Q)$   
**by** (*pred-auto*)

**lemma** *H1-Continuous: Continuous H1*  
**by** (*rel-auto*)

**lemma** *H1-below-top*:  
 $H1(P) \sqsubseteq \top_D$   
**by** (*pred-auto*)

**lemma** *H1-design-skip*:  
 $H1(II) = II_D$   
**by** (*rel-auto*)

**lemma** *H1-cond*:  $H1(P \triangleleft b \triangleright Q) = H1(P) \triangleleft b \triangleright H1(Q)$   
**by** (*rel-auto*)

**lemma** *H1-conj*:  $H1(P \wedge Q) = (H1(P) \wedge H1(Q))$   
**by** (*rel-auto*)

**lemma** *H1-disj*:  $H1(P \vee Q) = (H1(P) \vee H1(Q))$   
**by** (*rel-auto*)

**lemma** *design-export-H1*:  $(P \vdash Q) = (P \vdash H1(Q))$   
**by** (*rel-auto*)

The H1 algebraic laws are valid only when  $\alpha(R)$  is homogeneous. This should maybe be generalised.

**theorem** *H1-algebraic-intro*:

**assumes**  
 $(true_h ;; R) = true_h$   
 $(II_D ;; R) = R$   
**shows** *R is H1*

**proof** –  
**have**  $R = (II_D ;; R)$  **by** (*simp add: assms(2)*)  
**also have**  $\dots = (H1(II) ;; R)$   
**by** (*simp add: H1-design-skip*)  
**also have**  $\dots = (\$ok \Rightarrow II) ;; R$   
**by** (*simp add: H1-def*)  
**also have**  $\dots = (((\neg \$ok) ;; R) \vee R)$   
**by** (*simp add: impl-alt-def seqr-or-distl*)  
**also have**  $\dots = (((\neg \$ok) ;; true_h) ;; R) \vee R$   
**by** (*simp add: precond-right-unit unrest*)  
**also have**  $\dots = (((\neg \$ok) ;; true_h) \vee R)$   
**by** (*metis assms(1) seqr-assoc*)  
**also have**  $\dots = (\$ok \Rightarrow R)$   
**by** (*simp add: impl-alt-def precond-right-unit unrest*)  
**finally show** *?thesis* **by** (*metis H1-def Healthy-def'*)  
**qed**

**lemma** *nok-not-false*:  
 $(\neg \$ok) \neq false$   
**by** (*pred-auto*)

**theorem** *H1-left-zero*:

**assumes**  $P$  is  $H1$   
**shows**  $(true ;; P) = true$   
**proof** –  
**from** *assms* **have**  $(true ;; P) = (true ;; (\$ok \Rightarrow P))$   
**by** (*simp add: H1-def Healthy-def'*)  
  
**also from** *assms* **have**  $... = (true ;; (\neg \$ok \vee P))$  (**is**  $- = (?true ;; -)$ )  
**by** (*simp add: impl-alt-def*)  
**also from** *assms* **have**  $... = ((?true ;; (\neg \$ok)) \vee (?true ;; P))$   
**using** *seqr-or-distr* **by** *blast*  
**also from** *assms* **have**  $... = (true \vee (true ;; P))$   
**by** (*simp add: nok-not-false precondition-left-zero unrest*)  
**finally show** *?thesis*  
**by** (*simp add: upred-defs urel-defs*)  
**qed**

**theorem** *H1-left-unit*:  
**fixes**  $P :: 'a \text{ hrel-des}$   
**assumes**  $P$  is  $H1$   
**shows**  $(II_D ;; P) = P$   
**proof** –  
**have**  $(II_D ;; P) = ((\$ok \Rightarrow II) ;; P)$   
**by** (*metis H1-def H1-design-skip*)  
**also have**  $... = (((\neg \$ok) ;; P) \vee P)$   
**by** (*simp add: impl-alt-def seqr-or-distl*)  
**also from** *assms* **have**  $... = (((\neg \$ok) ;; true_h) ;; P) \vee P$   
**by** (*simp add: precondition-right-unit unrest*)  
**also have**  $... = (((\neg \$ok) ;; (true_h ;; P)) \vee P)$   
**by** (*simp add: seqr-assoc*)  
**also from** *assms* **have**  $... = (\$ok \Rightarrow P)$   
**by** (*simp add: H1-left-zero impl-alt-def precondition-right-unit unrest*)  
**finally show** *?thesis* **using** *assms*  
**by** (*simp add: H1-def Healthy-def'*)  
**qed**

**theorem** *H1-algebraic*:  
 $P$  is  $H1 \iff (true_h ;; P) = true_h \wedge (II_D ;; P) = P$   
**using** *H1-algebraic-intro H1-left-unit H1-left-zero* **by** *blast*

**theorem** *H1-nok-left-zero*:  
**fixes**  $P :: 'a \text{ hrel-des}$   
**assumes**  $P$  is  $H1$   
**shows**  $((\neg \$ok) ;; P) = (\neg \$ok)$   
**proof** –  
**have**  $((\neg \$ok) ;; P) = (((\neg \$ok) ;; true_h) ;; P)$   
**by** (*simp add: precondition-right-unit unrest*)  
**also have**  $... = ((\neg \$ok) ;; true_h)$   
**by** (*metis H1-left-zero assms seqr-assoc*)  
**also have**  $... = (\neg \$ok)$   
**by** (*simp add: precondition-right-unit unrest*)  
**finally show** *?thesis* .  
**qed**

**lemma** *H1-design*:  
 $H1(P \vdash Q) = (P \vdash Q)$

by (rel-auto)

**lemma** *H1-rdesign*:

$H1(P \vdash_r Q) = (P \vdash_r Q)$

by (rel-auto)

**lemma** *H1-choice-closed* [closure]:

$\llbracket P \text{ is } H1; Q \text{ is } H1 \rrbracket \implies P \sqcap Q \text{ is } H1$

by (simp add: H1-def Healthy-def' disj-upred-def impl-alt-def semilattice-sup-class.sup-left-commute)

**lemma** *H1-inf-closed* [closure]:

$\llbracket P \text{ is } H1; Q \text{ is } H1 \rrbracket \implies P \sqcup Q \text{ is } H1$

by (rel-blast)

**lemma** *H1-UINF*:

assumes  $A \neq \{\}$

shows  $H1(\bigsqcap i \in A \cdot P(i)) = (\bigsqcap i \in A \cdot H1(P(i)))$

using assms by (rel-auto)

**lemma** *H1-Sup*:

assumes  $A \neq \{\} \ \forall P \in A. P \text{ is } H1$

shows  $(\bigsqcap A) \text{ is } H1$

**proof** –

from assms(2) have  $H1 \text{ ‘ } A = A$

by (auto simp add: Healthy-def rev-image-eqI)

with *H1-UINF*[of  $A \text{ id}$ , OF assms(1)] **show** ?thesis

by (simp add: UINF-as-Sup-image Healthy-def)

**qed**

**lemma** *H1-USUP*:

shows  $H1(\bigsqcup i \in A \cdot P(i)) = (\bigsqcup i \in A \cdot H1(P(i)))$

by (rel-auto)

**lemma** *H1-Inf* [closure]:

assumes  $\forall P \in A. P \text{ is } H1$

shows  $(\bigsqcup A) \text{ is } H1$

**proof** –

from assms have  $H1 \text{ ‘ } A = A$

by (auto simp add: Healthy-def rev-image-eqI)

with *H1-USUP*[of  $A \text{ id}$ ] **show** ?thesis

by (simp add: USUP-as-Inf-image Healthy-def)

**qed**

**lemma** *msubst-H1*:  $(\bigwedge x. P \ x \text{ is } H1) \implies P \ x \llbracket x \rightarrow v \rrbracket \text{ is } H1$

by (rel-auto)

## 2.2 H2: A specification cannot require non-termination

**definition**  $J :: 'a \text{ hrel-des}$  **where**

[upred-defs]:  $J = ((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D)$

**definition** *H2* **where**

[upred-defs]:  $H2 \ (P) \equiv P ;; J$

**lemma** *J-split*:

shows  $(P ;; J) = (P^f \vee (P^t \wedge \$ok'))$



**proof** –  
 have  $(P ;; J) = (P ;; ((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D))$   
 by (*simp add: H2-def J-def design-def*)  
 also have  $\dots = (P ;; ((\$ok \Rightarrow \$ok \wedge \$ok') \wedge \lceil II \rceil_D))$   
 by (*rel-auto*)  
 also have  $\dots = ((P ;; (\neg \$ok \wedge \lceil II \rceil_D)) \vee (P ;; (\$ok \wedge (\lceil II \rceil_D \wedge \$ok'))))$   
 by (*rel-auto*)  
 also have  $\dots = (P^f \vee (P^t \wedge \$ok'))$   
**proof** –  
 have  $(P ;; (\neg \$ok \wedge \lceil II \rceil_D)) = P^f$   
**proof** –  
 have  $(P ;; (\neg \$ok \wedge \lceil II \rceil_D)) = ((P \wedge \neg \$ok') ;; \lceil II \rceil_D)$   
 by (*rel-auto*)  
 also have  $\dots = (\exists \$ok' \cdot P \wedge \$ok' =_u \text{false})$   
 by (*rel-auto*)  
 also have  $\dots = P^f$   
 by (*metis C1 one-point out-var-uvar unrest-as-exists ok-vwb-lens vwb-lens-mwb*)  
 finally show ?thesis .  
 qed  
 moreover have  $(P ;; (\$ok \wedge (\lceil II \rceil_D \wedge \$ok'))) = (P^t \wedge \$ok')$   
**proof** –  
 have  $(P ;; (\$ok \wedge (\lceil II \rceil_D \wedge \$ok'))) = (P ;; (\$ok \wedge II))$   
 by (*rel-auto*)  
 also have  $\dots = (P^t \wedge \$ok')$   
 by (*rel-auto*)  
 finally show ?thesis .  
 qed  
 ultimately show ?thesis  
 by *simp*  
 qed  
 finally show ?thesis .  
 qed

**lemma H2-split:**  
 shows  $H2(P) = (P^f \vee (P^t \wedge \$ok'))$   
 by (*simp add: H2-def J-split*)

**theorem H2-equivalence:**

$P \text{ is } H2 \iff 'P^f \Rightarrow P^t'$

**proof** –  
 have  $'P \Leftrightarrow (P ;; J)' \iff 'P \Leftrightarrow (P^f \vee (P^t \wedge \$ok'))'$   
 by (*simp add: J-split*)  
 also have  $\dots \iff '(P \Leftrightarrow P^f \vee P^t \wedge \$ok')^f \wedge (P \Leftrightarrow P^f \vee P^t \wedge \$ok')^t'$   
 by (*simp add: subst-bool-split*)  
 also have  $\dots = '(P^f \Leftrightarrow P^f) \wedge (P^t \Leftrightarrow P^f \vee P^t)'$   
 by *subst-tac*  
 also have  $\dots = 'P^t \Leftrightarrow (P^f \vee P^t)'$   
 by (*pred-auto robust*)  
 also have  $\dots = '(P^f \Rightarrow P^t)'$   
 by (*pred-auto*)  
 finally show ?thesis  
 by (*metis H2-def Healthy-def' taut-iff-eq*)  
 qed

**lemma H2-equiv:**

$P \text{ is } H2 \longleftrightarrow P^t \sqsubseteq P^f$   
**using** *H2-equivalence refBy-order* **by** *blast*

**lemma** *H2-design*:  
**assumes**  $\$ok' \# P \ \$ok' \# Q$   
**shows**  $H2(P \vdash Q) = P \vdash Q$   
**using** *assms*  
**by** (*simp add: H2-split design-def usubst unrest, pred-auto*)

**lemma** *H2-rdesign*:  
 $H2(P \vdash_r Q) = P \vdash_r Q$   
**by** (*simp add: H2-design unrest rdesign-def*)

**theorem** *J-idem*:  
 $(J ;; J) = J$   
**by** (*rel-auto*)

**theorem** *H2-idem*:  
 $H2(H2(P)) = H2(P)$   
**by** (*metis H2-def J-idem segr-assoc*)

**theorem** *H2-Continuous: Continuous H2*  
**by** (*rel-auto*)

**theorem** *H2-not-okay:  $H2(\neg \$ok) = (\neg \$ok)$*   
**proof** –  
**have**  $H2(\neg \$ok) = ((\neg \$ok)^f \vee ((\neg \$ok)^t \wedge \$ok'))$   
**by** (*simp add: H2-split*)  
**also have**  $\dots = (\neg \$ok \vee (\neg \$ok) \wedge \$ok')$   
**by** (*subst-tac*)  
**also have**  $\dots = (\neg \$ok)$   
**by** (*pred-auto*)  
**finally show** *?thesis* .  
**qed**

**lemma** *H2-true:  $H2(true) = true$*   
**by** (*rel-auto*)

**lemma** *H2-choice-closed [closure]*:  
 $\llbracket P \text{ is } H2; Q \text{ is } H2 \rrbracket \implies P \sqcap Q \text{ is } H2$   
**by** (*metis H2-def Healthy-def' disj-upred-def segr-or-distl*)

**lemma** *H2-inf-closed [closure]*:  
**assumes**  $P \text{ is } H2 \ Q \text{ is } H2$   
**shows**  $P \sqcup Q \text{ is } H2$   
**proof** –  
**have**  $P \sqcup Q = (P^f \vee P^t \wedge \$ok') \sqcup (Q^f \vee Q^t \wedge \$ok')$   
**by** (*metis H2-def Healthy-def J-split assms(1) assms(2)*)  
**moreover have**  $H2(\dots) = \dots$   
**by** (*simp add: H2-split usubst, pred-auto*)  
**ultimately show** *?thesis*  
**by** (*simp add: Healthy-def*)  
**qed**

**lemma** *H2-USUP*:

**shows**  $H2(\prod i \in A \cdot P(i)) = (\prod i \in A \cdot H2(P(i)))$   
**by** (*rel-auto*)

**theorem** *H1-H2-commute*:

$H1 (H2 P) = H2 (H1 P)$

**proof** –

**have**  $H2 (H1 P) = (\$ok \Rightarrow P) ;; J$   
**by** (*simp add: H1-def H2-def*)  
**also have**  $\dots = ((\neg \$ok \vee P) ;; J)$   
**by** (*rel-auto*)  
**also have**  $\dots = (((\neg \$ok) ;; J) \vee (P ;; J))$   
**using** *segr-or-distl* **by** *blast*  
**also have**  $\dots = ((H2 (\neg \$ok)) \vee H2(P))$   
**by** (*simp add: H2-def*)  
**also have**  $\dots = ((\neg \$ok) \vee H2(P))$   
**by** (*simp add: H2-not-okay*)  
**also have**  $\dots = H1(H2(P))$   
**by** (*rel-auto*)

**finally show** *?thesis* **by** *simp*

**qed**

### 2.3 Designs as *H1-H2* predicates

**abbreviation**  $H1-H2 :: ('\alpha, '\beta) \text{rel-des} \Rightarrow (''\alpha, ''\beta) \text{rel-des} \text{ (H)}$  **where**  
 $H1-H2 P \equiv H1 (H2 P)$

**lemma** *H1-H2-comp*:  $\mathbf{H} = H1 \circ H2$

**by** (*auto*)

**theorem** *H1-H2-eq-design*:

$\mathbf{H}(P) = (\neg P^f) \vdash P^t$

**proof** –

**have**  $\mathbf{H}(P) = (\$ok \Rightarrow H2(P))$   
**by** (*simp add: H1-def*)  
**also have**  $\dots = (\$ok \Rightarrow (P^f \vee (P^t \wedge \$ok')))$   
**by** (*metis H2-split*)  
**also have**  $\dots = (\$ok \wedge (\neg P^f) \Rightarrow \$ok' \wedge \$ok \wedge P^t)$   
**by** (*rel-auto*)  
**also have**  $\dots = (\neg P^f) \vdash P^t$   
**by** (*rel-auto*)  
**finally show** *?thesis* .

**qed**

**theorem** *H1-H2-is-design*:

**assumes**  $P \text{ is } H1 P \text{ is } H2$

**shows**  $P = (\neg P^f) \vdash P^t$

**using** *assms* **by** (*metis H1-H2-eq-design Healthy-def*)

**theorem** *H1-H2-eq-rdesign*:

$\mathbf{H}(P) = \text{pre}_D(P) \vdash_r \text{post}_D(P)$

**proof** –

**have**  $\mathbf{H}(P) = (\$ok \Rightarrow H2(P))$   
**by** (*simp add: H1-def Healthy-def*)  
**also have**  $\dots = (\$ok \Rightarrow (P^f \vee (P^t \wedge \$ok')))$   
**by** (*metis H2-split*)  
**also have**  $\dots = (\$ok \wedge (\neg P^f) \Rightarrow \$ok' \wedge P^t)$

by (*pred-auto*)  
 also have ... = ( $\$ok \wedge (\neg P^f) \Rightarrow \$ok' \wedge \$ok \wedge P^t$ )  
 by (*pred-auto*)  
 also have ... = ( $\$ok \wedge [pre_D(P)]_D \Rightarrow \$ok' \wedge \$ok \wedge [post_D(P)]_D$ )  
 by (*simp add: ok-post ok-pre*)  
 also have ... = ( $\$ok \wedge [pre_D(P)]_D \Rightarrow \$ok' \wedge [post_D(P)]_D$ )  
 by (*pred-auto*)  
 also have ... =  $pre_D(P) \vdash_r post_D(P)$   
 by (*simp add: rdesign-def design-def*)  
 finally show ?thesis .  
 qed

**theorem** *H1-H2-is-rdesign*:  
 assumes  $P$  is  $H1$   $P$  is  $H2$   
 shows  $P = pre_D(P) \vdash_r post_D(P)$   
 by (*metis H1-H2-eq-rdesign Healthy-def assms(1) assms(2)*)

**lemma** *H1-H2-refinement*:  
 assumes  $P$  is  $\mathbf{H}$   $Q$  is  $\mathbf{H}$   
 shows  $P \sqsubseteq Q \iff ('pre_D(P) \Rightarrow pre_D(Q)' \wedge 'pre_D(P) \wedge post_D(Q) \Rightarrow post_D(P)')$   
 by (*metis H1-H2-eq-rdesign Healthy-if assms rdesign-refinement*)

**lemma** *H1-H2-refines*:  
 assumes  $P$  is  $\mathbf{H}$   $Q$  is  $\mathbf{H}$   $P \sqsubseteq Q$   
 shows  $pre_D(Q) \sqsubseteq pre_D(P)$   $post_D(P) \sqsubseteq (pre_D(P) \wedge post_D(Q))$   
 using *H1-H2-refinement assms refBy-order* **by** *auto*

**lemma** *H1-H2-idempotent*:  $\mathbf{H} (\mathbf{H} P) = \mathbf{H} P$   
 by (*simp add: H1-H2-commute H1-idem H2-idem*)

**lemma** *H1-H2-Idempotent [closure]*: *Idempotent*  $\mathbf{H}$   
 by (*simp add: Idempotent-def H1-H2-idempotent*)

**lemma** *H1-H2-monotonic [closure]*: *Monotonic*  $\mathbf{H}$   
 by (*simp add: H1-monotone H2-def mono-def segr-mono*)

**lemma** *H1-H2-Continuous [closure]*: *Continuous*  $\mathbf{H}$   
 by (*simp add: Continuous-comp H1-Continuous H1-H2-comp H2-Continuous*)

**lemma** *H1-H2-false*:  $\mathbf{H} \text{ false} = \top_D$   
 by (*rel-auto*)

**lemma** *H1-H2-true*:  $\mathbf{H} \text{ true} = \perp_D$   
 by (*rel-auto*)

**lemma** *design-is-H1-H2 [closure]*:  
 $\llbracket \$ok' \# P; \$ok' \# Q \rrbracket \implies (P \vdash Q) \text{ is } \mathbf{H}$   
 by (*simp add: H1-design H2-design Healthy-def'*)

**lemma** *rdesign-is-H1-H2 [closure]*:  
 $(P \vdash_r Q) \text{ is } \mathbf{H}$   
 by (*simp add: Healthy-def H1-rdesign H2-rdesign*)

**lemma** *top-d-is-H1-H2 [closure]*:  $\top_D \text{ is } \mathbf{H}$   
 by (*simp add: H1-def H2-not-okay Healthy-intro impl-alt-def*)

**lemma** *bot-d-is-H1-H2* [closure]:  $\perp_D$  is **H**  
 by (simp add: bot-d-def closure unrest)

**lemma** *seq-r-H1-H2-closed* [closure]:

assumes  $P$  is **H**  $Q$  is **H**

shows  $(P ;; Q)$  is **H**

**proof** –

obtain  $P_1 P_2$  where  $P = P_1 \vdash_r P_2$

by (metis H1-H2-commute H1-H2-is-rdesign H2-idem Healthy-def assms(1))

moreover obtain  $Q_1 Q_2$  where  $Q = Q_1 \vdash_r Q_2$

by (metis H1-H2-commute H1-H2-is-rdesign H2-idem Healthy-def assms(2))

moreover have  $((P_1 \vdash_r P_2) ;; (Q_1 \vdash_r Q_2))$  is **H**

by (simp add: rdesign-composition rdesign-is-H1-H2)

ultimately show ?thesis by simp

qed

**lemma** *H1-H2-left-unit*:  $P$  is **H**  $\implies H_D ;; P = P$

by (metis H1-H2-eq-rdesign Healthy-def' rdesign-left-unit)

**lemma** *UINF-H1-H2-closed* [closure]:

assumes  $A \neq \{\}$   $\forall P \in A. P$  is **H**

shows  $(\bigcap A)$  is *H1-H2*

**proof** –

from assms have  $A: A = H1-H2 \text{ ' } A$

by (auto simp add: Healthy-def rev-image-eqI)

also have  $(\bigcap ...) = (\bigcap P \in A \cdot H1-H2(P))$

by (simp add: UINF-as-Sup-collect)

also have  $... = (\bigcap P \in A \cdot (\neg P^f) \vdash P^t)$

by (meson H1-H2-eq-design)

also have  $... = (\bigcup P \in A \cdot \neg P^f) \vdash (\bigcap P \in A \cdot P^t)$

by (simp add: design-UINF-mem assms)

also have  $... is H1-H2$

by (simp add: design-is-H1-H2 unrest)

finally show ?thesis .

qed

**definition** *design-inf* ::  $(\alpha, \beta)$  rel-des set  $\Rightarrow (\alpha, \beta)$  rel-des  $(\bigcap_D - [900] 900)$  where  
 $\bigcap_D A = (\text{if } (A = \{\}) \text{ then } \top_D \text{ else } \bigcap A)$

**abbreviation** *design-sup* ::  $(\alpha, \beta)$  rel-des set  $\Rightarrow (\alpha, \beta)$  rel-des  $(\bigcup_D - [900] 900)$  where  
 $\bigcup_D A \equiv \bigcup A$

**lemma** *design-inf-H1-H2-closed*:

assumes  $\forall P \in A. P$  is **H**

shows  $(\bigcap_D A)$  is **H**

apply (auto simp add: design-inf-def closure)

apply (simp add: H1-def H2-not-okay Healthy-def impl-alt-def)

apply (metis H1-def Healthy-def UINF-H1-H2-closed assms empty-iff impl-alt-def)

done

**lemma** *design-sup-empty* [simp]:  $\bigcap_D \{\} = \top_D$

by (simp add: design-inf-def)

**lemma** *design-sup-non-empty* [simp]:  $A \neq \{\} \implies \bigcap_D A = \bigcap A$

by (simp add: design-inf-def)

**lemma** *USUP-mem-H1-H2-closed*:

assumes  $\bigwedge i. i \in A \implies P\ i$  is **H**

shows  $(\bigsqcup_{i \in A} P\ i)$  is **H**

**proof** –

from *assms* have  $(\bigsqcup_{i \in A} P\ i) = (\bigsqcup_{i \in A} \mathbf{H}(P\ i))$

by (auto intro: USUP-cong simp add: Healthy-def)

also have  $\dots = (\bigsqcup_{i \in A} \neg (P\ i)^f) \vdash (P\ i)^t$

by (meson H1-H2-eq-design)

also have  $\dots = (\prod_{i \in A} \neg (P\ i)^f) \vdash (\bigsqcup_{i \in A} \neg (P\ i)^f \Rightarrow (P\ i)^t)$

by (simp add: design-USUP-mem)

also have  $\dots$  is **H**

by (simp add: design-is-H1-H2 unrest)

finally show ?thesis .

qed

**lemma** *USUP-ind-H1-H2-closed*:

assumes  $\bigwedge i. P\ i$  is **H**

shows  $(\bigsqcup i \cdot P\ i)$  is **H**

using *assms* USUP-mem-H1-H2-closed[of UNIV P] by simp

**lemma** *Inf-H1-H2-closed*:

assumes  $\forall P \in A. P$  is **H**

shows  $(\bigsqcup A)$  is **H**

**proof** –

from *assms* have  $A: A = \mathbf{H} \text{ ` } A$

by (auto simp add: Healthy-def rev-image-eqI)

also have  $(\bigsqcup \dots) = (\bigsqcup P \in A \cdot \mathbf{H}(P))$

by (simp add: USUP-as-Inf-collect)

also have  $\dots = (\bigsqcup P \in A \cdot \neg P^f) \vdash P^t$

by (meson H1-H2-eq-design)

also have  $\dots = (\prod P \in A \cdot \neg P^f) \vdash (\bigsqcup P \in A \cdot \neg P^f \Rightarrow P^t)$

by (simp add: design-USUP-mem)

also have  $\dots$  is **H**

by (simp add: design-is-H1-H2 unrest)

finally show ?thesis .

qed

**lemma** *rdesign-ref-monos*:

assumes  $P$  is **H**  $Q$  is **H**  $P \sqsubseteq Q$

shows  $pre_D(Q) \sqsubseteq pre_D(P)$   $post_D(P) \sqsubseteq (pre_D(P) \wedge post_D(Q))$

**proof** –

have  $r: P \sqsubseteq Q \longleftrightarrow ('pre_D(P) \Rightarrow pre_D(Q)' \wedge 'pre_D(P) \wedge post_D(Q) \Rightarrow post_D(P)')$

by (metis H1-H2-eq-rdesign Healthy-if assms(1) assms(2) rdesign-refinement)

from *r assms* show  $pre_D(Q) \sqsubseteq pre_D(P)$

by (auto simp add: refBy-order)

from *r assms* show  $post_D(P) \sqsubseteq (pre_D(P) \wedge post_D(Q))$

by (auto simp add: refBy-order)

qed

## 2.4 H3: The design assumption is a precondition

**definition**  $H3 :: ('\alpha, '\beta) \text{ rel-des} \Rightarrow ('\alpha, '\beta) \text{ rel-des}$  **where**

$[upred-defs]: H3\ (P) \equiv P \;;\ II_D$

**theorem** *H3-idem*:  
 $H3(H3(P)) = H3(P)$   
 by (metis *H3-def design-skip-idem seqr-assoc*)

**theorem** *H3-mono*:  
 $P \sqsubseteq Q \implies H3(P) \sqsubseteq H3(Q)$   
 by (simp add: *H3-def seqr-mono*)

**theorem** *H3-Monotonic*:  
*Monotonic H3*  
 by (simp add: *H3-mono mono-def*)

**theorem** *H3-Continuous*: *Continuous H3*  
 by (rel-auto)

**theorem** *design-condition-is-H3*:  
 assumes  $out\alpha \nmid p$   
 shows  $(p \vdash Q)$  is *H3*  
**proof** –  
 have  $((p \vdash Q) ;; II_D) = (\neg ((\neg p) ;; true)) \vdash (Q^t ;; II\llbracket true/\$ok \rrbracket)$   
 by (simp add: *skip-d-alt-def design-composition-subst unrest assms*)  
 also have  $\dots = p \vdash (Q^t ;; II\llbracket true/\$ok \rrbracket)$   
 using *assms precondition-equiv seqr-true-lemma* by force  
 also have  $\dots = p \vdash Q$   
 by (rel-auto)  
 finally show ?thesis  
 by (simp add: *H3-def Healthy-def'*)  
**qed**

**theorem** *rdesign-H3-iff-pre*:  
 $P \vdash_r Q$  is *H3*  $\iff P = (P ;; true)$   
**proof** –  
 have  $(P \vdash_r Q) ;; II_D = (P \vdash_r Q) ;; (true \vdash_r II)$   
 by (simp add: *skip-d-def*)  
 also have  $\dots = (\neg ((\neg P) ;; true) \wedge \neg (Q ;; (\neg true))) \vdash_r (Q ;; II)$   
 by (simp add: *rdesign-composition*)  
 also have  $\dots = (\neg ((\neg P) ;; true) \wedge \neg (Q ;; (\neg true))) \vdash_r Q$   
 by simp  
 also have  $\dots = (\neg ((\neg P) ;; true)) \vdash_r Q$   
 by (pred-auto)  
 finally have  $P \vdash_r Q$  is *H3*  $\iff P \vdash_r Q = (\neg ((\neg P) ;; true)) \vdash_r Q$   
 by (metis *H3-def Healthy-def'*)  
 also have  $\dots \iff P = (\neg ((\neg P) ;; true))$   
 by (metis *rdesign-pre*)  
 thm *seqr-true-lemma*  
 also have  $\dots \iff P = (P ;; true)$   
 by (simp add: *seqr-true-lemma*)  
 finally show ?thesis .  
**qed**

**theorem** *design-H3-iff-pre*:  
 assumes  $\$ok \nmid P \ \$ok' \nmid P \ \$ok \nmid Q \ \$ok' \nmid Q$   
 shows  $P \vdash Q$  is *H3*  $\iff P = (P ;; true)$   
**proof** –  
 have  $P \vdash Q = \lfloor P \rfloor_D \vdash_r \lfloor Q \rfloor_D$

by (simp add: assms lift-desr-inv rdesign-def)  
 moreover hence  $\lfloor P \rfloor_D \vdash_r \lfloor Q \rfloor_D$  is  $H3 \iff \lfloor P \rfloor_D = (\lfloor P \rfloor_D ;; \text{true})$   
 using rdesign-H3-iff-pre by blast  
 ultimately show ?thesis  
 by (metis assms(1,2) drop-desr-inv lift-desr-inv lift-dist-seq aext-true)  
 qed

**theorem** H1-H3-commute:  
 $H1 (H3 P) = H3 (H1 P)$   
 by (rel-auto)

**lemma** skip-d-absorb-J-1:  
 $(II_D ;; J) = II_D$   
 by (metis H2-def H2-rdesign skip-d-def)

**lemma** skip-d-absorb-J-2:  
 $(J ;; II_D) = II_D$   
**proof** –  
 have  $(J ;; II_D) = ((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D) ;; (true \vdash II)$   
 by (simp add: J-def skip-d-alt-def)  
 also have  $\dots = (((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D) \llbracket false/\$ok' \rrbracket ;; (true \vdash II) \llbracket false/\$ok \rrbracket)$   
 $\quad \vee (((\$ok \Rightarrow \$ok') \wedge \lceil II \rceil_D) \llbracket true/\$ok' \rrbracket ;; (true \vdash II) \llbracket true/\$ok \rrbracket)$   
 by (rel-auto)  
 also have  $\dots = ((\neg \$ok \wedge \lceil II \rceil_D ;; true) \vee (\lceil II \rceil_D ;; \$ok' \wedge \lceil II \rceil_D))$   
 by (rel-auto)  
 also have  $\dots = II_D$   
 by (rel-auto)  
 finally show ?thesis .  
 qed

**lemma** H2-H3-absorb:  
 $H2 (H3 P) = H3 P$   
 by (metis H2-def H3-def seqr-assoc skip-d-absorb-J-1)

**lemma** H3-H2-absorb:  
 $H3 (H2 P) = H3 P$   
 by (metis H2-def H3-def seqr-assoc skip-d-absorb-J-2)

**theorem** H2-H3-commute:  
 $H2 (H3 P) = H3 (H2 P)$   
 by (simp add: H2-H3-absorb H3-H2-absorb)

**theorem** H3-design-pre:  
 assumes  $\$ok \# p \text{ out}\alpha \# p \ \$ok \# Q \ \$ok' \# Q$   
 shows  $H3(p \vdash Q) = p \vdash Q$   
 using assms  
 by (metis Healthy-def' design-H3-iff-pre precondition-right-unit unrest-out $\alpha$ -var ok-vwb-lens vwb-lens-mwb)

**theorem** H3-rdesign-pre:  
 assumes  $\text{out}\alpha \# p$   
 shows  $H3(p \vdash_r Q) = p \vdash_r Q$   
 using assms  
 by (simp add: H3-def)

**theorem** H3-ndesign:  $H3(p \vdash_n Q) = (p \vdash_n Q)$



by (simp add: H3-def ndesign-def unrest-pre-out $\alpha$ )

**theorem** *ndesign-is-H3* [closure]:  $p \vdash_n Q$  is H3

by (simp add: H3-ndesign Healthy-def)

**lemma** *msubst-pre-H3*:  $(\bigwedge x. P\ x \text{ is H3}) \implies P\ x[x \rightarrow [v]_{<}] \text{ is H3}$

by (rel-auto)

## 2.5 Normal Designs as H1-H3 predicates

A normal design [3] refers only to initial state variables in the precondition.

**abbreviation** *H1-H3* ::  $(\alpha, \beta) \text{ rel-des} \implies (\alpha, \beta) \text{ rel-des } (\mathbf{N})$  **where**

*H1-H3*  $p \equiv H1\ (H3\ p)$

**lemma** *H1-H3-comp*:  $H1-H3 = H1 \circ H3$

by (auto)

**theorem** *H1-H3-is-design*:

**assumes**  $P \text{ is H1 } P \text{ is H3}$

**shows**  $P = (\neg P^f) \vdash P^t$

by (metis H1-H2-eq-design H2-H3-absorb Healthy-def' assms(1) assms(2))

**theorem** *H1-H3-is-rdesign*:

**assumes**  $P \text{ is H1 } P \text{ is H3}$

**shows**  $P = \text{pre}_D(P) \vdash_r \text{post}_D(P)$

by (metis H1-H2-is-rdesign H2-H3-absorb Healthy-def' assms)

**theorem** *H1-H3-is-normal-design*:

**assumes**  $P \text{ is H1 } P \text{ is H3}$

**shows**  $P = \lfloor \text{pre}_D(P) \rfloor_{<} \vdash_n \text{post}_D(P)$

by (metis H1-H3-is-rdesign assms drop-pre-inv ndesign-def precond-equiv rdesign-H3-iff-pre)

**lemma** *H1-H3-idempotent*:  $\mathbf{N} (\mathbf{N} P) = \mathbf{N} P$

by (simp add: H1-H3-commute H1-idem H3-idem)

**lemma** *H1-H3-Idempotent* [closure]: *Idempotent*  $\mathbf{N}$

by (simp add: Idempotent-def H1-H3-idempotent)

**lemma** *H1-H3-monotonic* [closure]: *Monotonic*  $\mathbf{N}$

by (simp add: H1-monotone H3-mono mono-def)

**lemma** *H1-H3-Continuous* [closure]: *Continuous*  $\mathbf{N}$

by (simp add: Continuous-comp H1-Continuous H1-H3-comp H3-Continuous)

**lemma** *H1-H3-false*:  $\mathbf{N} \text{ false} = \top_D$

by (rel-auto)

**lemma** *H1-H3-true*:  $\mathbf{N} \text{ true} = \perp_D$

by (rel-auto)

**lemma** *H1-H3-intro*:

**assumes**  $P \text{ is H out}\alpha \nmid \text{pre}_D(P)$

**shows**  $P \text{ is N}$

by (metis H1-H2-eq-rdesign H1-rdesign H3-rdesign-pre Healthy-def' assms)

**lemma** *H1-H3-left-unit*:  $P$  is  $\mathbf{N} \implies II_D ;; P = P$   
 by (metis *H1-H2-left-unit H1-H3-commute H2-H3-absorb H3-idem Healthy-def*)

**lemma** *H1-H3-right-unit*:  $P$  is  $\mathbf{N} \implies P ;; II_D = P$   
 by (metis *H1-H3-commute H3-def H3-idem Healthy-def*)

**lemma** *H1-H3-top-left*:  $P$  is  $\mathbf{N} \implies \top_D ;; P = \top_D$   
 by (metis *H1-H2-eq-design H2-H3-absorb Healthy-if design-top-left-zero*)

**lemma** *H1-H3-bot-left*:  $P$  is  $\mathbf{N} \implies \perp_D ;; P = \perp_D$   
 by (metis *H1-idem H1-left-zero Healthy-def bot-d-true*)

**lemma** *H1-H3-impl-H2 [closure]*:  $P$  is  $\mathbf{N} \implies P$  is  $\mathbf{H}$   
 by (metis *H1-H2-commute H1-idem H2-H3-absorb Healthy-def'*)

**lemma** *H1-H3-eq-design-d-comp*:  $\mathbf{N}(P) = ((\neg P^f) \vdash P^t) ;; II_D$   
 by (metis *H1-H2-eq-design H1-H3-commute H3-H2-absorb H3-def*)

**lemma** *H1-H3-eq-design*:  $\mathbf{N}(P) = (\neg (P^f ;; true)) \vdash P^t$   
 apply (simp add: *H1-H3-eq-design-d-comp skip-d-alt-def*)  
 apply (subst *design-composition-subst*)  
 apply (simp-all add: *usubst unrest*)  
 apply (rel-auto)  
 done

**lemma** *H3-unrest-out-alpha-nok [unrest]*:  
 assumes  $P$  is  $\mathbf{N}$   
 shows  $out\alpha \nVdash P^f$   
**proof** –  
 have  $P = (\neg (P^f ;; true)) \vdash P^t$   
 by (metis *H1-H3-eq-design Healthy-def assms*)  
 also have  $out\alpha \nVdash (...)^f$   
 by (simp add: *design-def usubst unrest, rel-auto*)  
 finally show ?thesis .  
**qed**

**lemma** *H3-unrest-out-alpha [unrest]*:  $P$  is  $\mathbf{N} \implies out\alpha \nVdash pre_D(P)$   
 by (metis *H1-H3-commute H1-H3-is-rdesign H1-idem Healthy-def' precond-equiv rdesign-H3-iff-pre*)

**lemma** *ndesign-H1-H3 [closure]*:  $p \vdash_n Q$  is  $\mathbf{N}$   
 by (simp add: *H1-rdesign H3-def Healthy-def' ndesign-def unrest-pre-out\alpha*)

**lemma** *ndesign-form*:  $P$  is  $\mathbf{N} \implies ([pre_D(P)]_< \vdash_n post_D(P)) = P$   
 by (metis *H1-H2-eq-rdesign H1-H3-impl-H2 H3-unrest-out-alpha Healthy-def drop-pre-inv ndesign-def*)

**lemma** *des-bot-H1-H3 [closure]*:  $\perp_D$  is  $\mathbf{N}$   
 by (metis *H1-design H3-def Healthy-def' design-false-pre design-true-left-zero skip-d-alt-def bot-d-def*)

**lemma** *des-top-is-H1-H3 [closure]*:  $\top_D$  is  $\mathbf{N}$   
 by (metis *ndesign-H1-H3 ndesign-miracle*)

**lemma** *skip-d-is-H1-H3 [closure]*:  $II_D$  is  $\mathbf{N}$   
 by (simp add: *ndesign-H1-H3 skip-d-ndes-def*)

**lemma** *seq-r-H1-H3-closed [closure]*:

**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $(P ;; Q)$  is  $\mathbf{N}$   
**by** (*metis* (*no-types*) *H1-H2-eq-design* *H1-H3-eq-design-d-comp* *H1-H3-impl-H2* *Healthy-def* *assms*(1) *assms*(2) *seq-r-H1-H2-closed* *seqr-assoc*)

**lemma** *dcond-H1-H2-closed* [*closure*]:  
**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $(P \triangleleft b \triangleright_D Q)$  is  $\mathbf{N}$   
**by** (*metis* *assms* *ndesign-H1-H3* *ndesign-dcond* *ndesign-form*)

**lemma** *inf-H1-H2-closed* [*closure*]:  
**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $(P \sqcap Q)$  is  $\mathbf{N}$   
**by** (*metis* *assms* *ndesign-H1-H3* *ndesign-choice* *ndesign-form*)

**lemma** *sup-H1-H2-closed* [*closure*]:  
**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $(P \sqcup Q)$  is  $\mathbf{N}$   
**by** (*metis* *assms* *ndesign-H1-H3* *ndesign-inf* *ndesign-form*)

**lemma** *ndes-seqr-miracle*:  
**assumes**  $P$  is  $\mathbf{N}$   
**shows**  $P ;; \top_D = \lfloor pre_D P \rfloor_{<} \vdash_n false$   
**proof** –  
**have**  $P ;; \top_D = (\lfloor pre_D(P) \rfloor_{<} \vdash_n post_D(P)) ;; (true \vdash_n false)$   
**by** (*simp* *add*: *assms* *ndesign-form* *ndesign-miracle*)  
**also have**  $\dots = \lfloor pre_D P \rfloor_{<} \vdash_n false$   
**by** (*simp* *add*: *ndesign-composition-wp* *wp* *alpha*)  
**finally show** *?thesis* .  
**qed**

**lemma** *ndes-seqr-abort*:  
**assumes**  $P$  is  $\mathbf{N}$   
**shows**  $P ;; \perp_D = (\lfloor pre_D P \rfloor_{<} \wedge post_D P \text{ wlp } false) \vdash_n false$   
**proof** –  
**have**  $P ;; \perp_D = (\lfloor pre_D(P) \rfloor_{<} \vdash_n post_D(P)) ;; (false \vdash_n false)$   
**by** (*simp* *add*: *assms* *bot-d-true* *ndesign-false-pre* *ndesign-form*)  
**also have**  $\dots = (\lfloor pre_D P \rfloor_{<} \wedge post_D P \text{ wlp } false) \vdash_n false$   
**by** (*simp* *add*: *ndesign-composition-wp* *alpha*)  
**finally show** *?thesis* .  
**qed**

**lemma** *USUP-ind-H1-H3-closed* [*closure*]:  
 $\llbracket \bigwedge i. P \ i \text{ is } \mathbf{N} \rrbracket \implies (\bigsqcup i \cdot P \ i) \text{ is } \mathbf{N}$   
**by** (*rule* *H1-H3-intro*, *simp*-*all* *add*: *H1-H3-impl-H2* *USUP-ind-H1-H2-closed* *preD-USUP-ind* *unrest*)

**lemma** *msubst-pre-H1-H3* [*closure*]:  $(\bigwedge x. P \ x \text{ is } \mathbf{N}) \implies P \ x \llbracket x \rightarrow [v]_{<} \rrbracket \text{ is } \mathbf{N}$   
**by** (*metis* *H1-H3-right-unit* *H3-def* *Healthy-if* *Healthy-intro* *msubst-H1* *msubst-pre-H3*)

## 2.6 H4: Feasibility

**definition**  $H_4 :: ('\alpha, '\beta) \text{ rel-des} \Rightarrow (''\alpha, ''\beta) \text{ rel-des}$  **where**  
 $[upred-defs]: H_4(P) = ((P;;true) \Rightarrow P)$

**theorem** *H4-idem*:  
 $H_4(H_4(P)) = H_4(P)$

by (rel-auto)

lemma is-H4-alt-def:

$P$  is  $H_4 \iff (P \mathrel{;;} \text{true}) = \text{true}$

by (rel-blast)

end

## 2.7 UTP theory of Designs

theory utp-des-theory

imports utp-des-healths

begin

## 2.8 UTP theories

interpretation des-theory: utp-theory-continuous **H**

rewrites  $P \in \text{carrier des-theory.thy-order} \iff P \text{ is } \mathbf{H}$

and  $\text{carrier des-theory.thy-order} \rightarrow \text{carrier des-theory.thy-order} \equiv \llbracket \mathbf{H} \rrbracket_H \rightarrow \llbracket \mathbf{H} \rrbracket_H$

and  $\text{le des-theory.thy-order} = (\sqsubseteq)$

and  $\text{eq des-theory.thy-order} = (=)$

and  $\text{des-top: des-theory.utp-top} = \top_D$

and  $\text{des-bottom: des-theory.utp-bottom} = \perp_D$

proof –

show utp-theory-continuous **H**

by (unfold-locales, simp-all add: H1-H2-idempotent H1-H2-Continuous)

then interpret utp-theory-continuous **H**

by simp

show  $\text{utp-top} = \top_D$   $\text{utp-bottom} = \perp_D$

by (simp-all add: H1-H2-false healthy-top H1-H2-true healthy-bottom)

qed (simp-all)

interpretation ndes-theory: utp-theory-continuous **N**

rewrites  $P \in \text{carrier ndes-theory.thy-order} \iff P \text{ is } \mathbf{N}$

and  $\text{carrier ndes-theory.thy-order} \rightarrow \text{carrier ndes-theory.thy-order} \equiv \llbracket \mathbf{N} \rrbracket_H \rightarrow \llbracket \mathbf{N} \rrbracket_H$

and  $\text{le ndes-theory.thy-order} = (\sqsubseteq)$

and  $\text{eq ndes-theory.thy-order} = (=)$

and  $\text{ndes-top: ndes-theory.utp-top} = \top_D$

and  $\text{ndes-bottom: ndes-theory.utp-bottom} = \perp_D$

proof –

show utp-theory-continuous **N**

by (unfold-locales, simp-all add: H1-H3-idempotent H1-H3-Continuous)

then interpret utp-theory-continuous **N**

by simp

show  $\text{utp-top} = \top_D$   $\text{utp-bottom} = \perp_D$

by (simp-all add: H1-H3-false healthy-top H1-H3-true healthy-bottom)

qed (simp-all)

interpretation des-left-unital: utp-theory-left-unital **H**  $\text{II}_D$

by (unfold-locales, simp-all add: H1-H2-left-unit closure)

interpretation ndes-unital: utp-theory-unital **N**  $\text{II}_D$

by (unfold-locales, simp-all add: H1-H3-left-unit H1-H3-right-unit closure)

interpretation ndes-kleene: utp-theory-kleene **N**  $\text{II}_D$

by (unfold-locales, simp add: ndes-top H1-H3-top-left)

**abbreviation**  $ndes\text{-}star :: - \Rightarrow - \text{ } (-^{*D} [999] 999)$  **where**  
 $P^{*D} \equiv ndes\text{-}unital.utp\text{-}star$

## 2.9 Galois Connection

Example Galois connection between designs and relations. Based on Jim's example in COM-PASS deliverable D23.5.

**definition**  $[upred\text{-}defs]: Des(R) = \mathbf{H}([R]_D \wedge \$ok')$

**definition**  $[upred\text{-}defs]: Rel(D) = \lfloor D \llbracket true, true / \$ok, \$ok' \rrbracket \rfloor_D$

**lemma**  $Des\text{-}design: Des(R) = true \vdash_r R$   
**by**  $(rel\text{-}auto)$

**lemma**  $Rel\text{-}design: Rel(P \vdash_r Q) = (P \Rightarrow Q)$   
**by**  $(rel\text{-}auto)$

**interpretation**  $Des\text{-}Rel\text{-}coretract:$

$coretract \mathbf{H} \Leftarrow \langle Des, Rel \rangle \Rightarrow id$

**rewrites**

$\bigwedge x. x \in carrier \mathcal{X}_{\mathbf{H}} \Leftarrow \langle Des, Rel \rangle \Rightarrow id = (x \text{ is } \mathbf{H}) \text{ and}$

$\bigwedge x. x \in carrier \mathcal{Y}_{\mathbf{H}} \Leftarrow \langle Des, Rel \rangle \Rightarrow id = True \text{ and}$

$\pi^* \mathbf{H} \Leftarrow \langle Des, Rel \rangle \Rightarrow id = Des \text{ and}$

$\pi^* \mathbf{H} \Leftarrow \langle Des, Rel \rangle \Rightarrow id = Rel \text{ and}$

$le \mathcal{X}_{\mathbf{H}} \Leftarrow \langle Des, Rel \rangle \Rightarrow id = (\sqsubseteq) \text{ and}$

$le \mathcal{Y}_{\mathbf{H}} \Leftarrow \langle Des, Rel \rangle \Rightarrow id = (\sqsubseteq)$

**proof**  $(unfold\text{-}locales, simp\text{-}all)$

**show**  $\bigwedge x. x \text{ is } id$

**by**  $(simp \text{ add: } Healthy\text{-}def)$

**next**

**show**  $Rel \in \llbracket \mathbf{H} \rrbracket_H \rightarrow \llbracket id \rrbracket_H$

**by**  $(auto \text{ simp add: } Rel\text{-}def \text{ Healthy}\text{-}def)$

**next**

**show**  $Des \in \llbracket id \rrbracket_H \rightarrow \llbracket \mathbf{H} \rrbracket_H$

**by**  $(auto \text{ simp add: } Des\text{-}def \text{ Healthy}\text{-}def \text{ H1-H2-commute } H1\text{-idem } H2\text{-idem})$

**next**

**fix**  $R :: ('a, 'b) \text{ urel}$

**show**  $R \sqsubseteq Rel (Des R)$

**by**  $(simp \text{ add: } Des\text{-}design \text{ Rel}\text{-}design)$

**next**

**fix**  $R :: ('a, 'b) \text{ urel}$  **and**  $D :: ('a, 'b) \text{ rel-des}$

**assume**  $a: D \text{ is } \mathbf{H}$

**then obtain**  $D_1 D_2$  **where**  $D: D = D_1 \vdash_r D_2$

**by**  $(metis \text{ H1-H2-commute } H1\text{-H2-is-rdesign } H1\text{-idem } Healthy\text{-}def')$

**show**  $(Rel D \sqsubseteq R) = (D \sqsubseteq Des R)$

**proof**  $-$

**have**  $(D \sqsubseteq Des R) = (D_1 \vdash_r D_2 \sqsubseteq true \vdash_r R)$

**by**  $(simp \text{ add: } D \text{ Des}\text{-}design)$

**also have**  $\dots = 'D_1 \wedge R \Rightarrow D_2'$

**by**  $(simp \text{ add: } rdesign\text{-}refinement)$

**also have**  $\dots = ((D_1 \Rightarrow D_2) \sqsubseteq R)$

**by**  $(rel\text{-}auto)$

**also have**  $\dots = (Rel D \sqsubseteq R)$

**by**  $(simp \text{ add: } D \text{ Rel}\text{-}design)$

**finally show** *?thesis* ..  
**qed**  
**qed**

From this interpretation we gain many Galois theorems. Some require simplification to remove superfluous assumptions.

**thm** *Des-Rel-coretract.deflation[simplified]*  
**thm** *Des-Rel-coretract.inflation*  
**thm** *Des-Rel-coretract.upper-comp[simplified]*  
**thm** *Des-Rel-coretract.lower-comp*

## 2.10 Fixed Points

**notation** *des-theory.utp-lfp* ( $\mu_D$ )

**notation** *des-theory.utp-gfp* ( $\nu_D$ )

**notation** *ndes-theory.utp-lfp* ( $\mu_N$ )

**notation** *ndes-theory.utp-gfp* ( $\nu_N$ )

**syntax**

$-dmu :: pptrn \Rightarrow logic \Rightarrow logic (\mu_D \cdot \cdot \cdot [0, 10] 10)$   
 $-dnu :: pptrn \Rightarrow logic \Rightarrow logic (\nu_D \cdot \cdot \cdot [0, 10] 10)$   
 $-ndmu :: pptrn \Rightarrow logic \Rightarrow logic (\mu_N \cdot \cdot \cdot [0, 10] 10)$   
 $-ndnu :: pptrn \Rightarrow logic \Rightarrow logic (\nu_N \cdot \cdot \cdot [0, 10] 10)$

**translations**

$\mu_D X \cdot P == \mu_D (\lambda X. P)$   
 $\nu_D X \cdot P == \nu_D (\lambda X. P)$   
 $\mu_N X \cdot P == \mu_N (\lambda X. P)$   
 $\nu_N X \cdot P == \nu_N (\lambda X. P)$

**thm** *des-theory.LFP-unfold*

**thm** *des-theory.GFP-unfold*

Specialise *mu-refine-intro* to designs.

**lemma** *design-mu-refine-intro*:

**assumes**  $\$ok' \# C \ \$ok' \# S \ (C \vdash S) \sqsubseteq F(C \vdash S) \ 'C \Rightarrow (\mu_D F \Leftrightarrow \nu_D F)'$   
**shows**  $(C \vdash S) \sqsubseteq \mu_D F$

**proof** –

**from** *assms* **have**  $(C \vdash S) \sqsubseteq \nu_D F$   
**by** (*simp add: design-is-H1-H2 des-theory.GFP-upperbound*)  
**with** *assms* **show** *?thesis*  
**by** (*rel-auto, metis (no-types, lifting)*)

**qed**

**lemma** *rdesign-mu-refine-intro*:

**assumes**  $(C \vdash_r S) \sqsubseteq F(C \vdash_r S) \ '[C]_D \Rightarrow (\mu_D F \Leftrightarrow \nu_D F)'$   
**shows**  $(C \vdash_r S) \sqsubseteq \mu_D F$   
**using** *assms* **by** (*simp add: rdesign-def design-mu-refine-intro unrest*)

**lemma** *H1-H2-mu-refine-intro*:

**assumes**  $P \text{ is } \mathbf{H} \ P \sqsubseteq F(P) \ '[pre_D(P)]_D \Rightarrow (\mu_D F \Leftrightarrow \nu_D F)'$   
**shows**  $P \sqsubseteq \mu_D F$   
**by** (*metis H1-H2-eq-rdesign Healthy-if assms rdesign-mu-refine-intro*)

Foundational theorem for recursion introduction using a well-founded relation. Contributed by Dr. Yakoub Nemouchi.

**theorem** *rdesign-mu-wf-refine-intro*:

```

assumes   WF: wf R
and       M: Monotonic F
and       H: F ∈ [H]H → [H]H
and induct-step:
  ∧st. (P ∧ [e]< =u <<st>>) ⊢r Q ⊆ F ((P ∧ ([e]<, <<st>>)u ∈u <<R>>) ⊢r Q)
shows (P ⊢r Q) ⊆ μD F
proof –
{
  fix st
  have (P ∧ [e]< =u <<st>>) ⊢r Q ⊆ μD F
  using WF proof (induction rule: wf-induct-rule)
    case (less st)
    hence 0: (P ∧ ([e]<, <<st>>)u ∈u <<R>>) ⊢r Q ⊆ μD F
      by rel-blast
    from M H
    have 1: μD F ⊆ F (μD F)
      by (simp add: des-theory.LFP-lemma3 mono-Monotone-utp-order)
    from 0 1 have 2: (P ∧ ([e]<, <<st>>)u ∈u <<R>>) ⊢r Q ⊆ F (μD F)
      by simp
    have 3: F ((P ∧ ([e]<, <<st>>)u ∈u <<R>>) ⊢r Q) ⊆ F (μD F)
      by (simp add: 0 M monoD)
    have 4: (P ∧ [e]< =u <<st>>) ⊢r Q ⊆ ...
      by (rule induct-step)
    show ?case
      using order-trans[OF 3 4] H M des-theory.LFP-lemma2 dual-order.trans mono-Monotone-utp-order
      by (metis (no-types) partial-object.simps(1) utp-order-def)
  qed
}
thus ?thesis
by (pred-simp)
qed

```

**theorem** *ndesign-mu-wf-refine-intro'*:

```

assumes   WF: wf R
and       M: Monotonic F
and       H: F ∈ [H]H → [H]H
and induct-step:
  ∧st. ((p ∧ e =u <<st>>) ⊢n Q) ⊆ F ((p ∧ (e, <<st>>)u ∈u <<R>>) ⊢n Q)
shows (p ⊢n Q) ⊆ μD F
using assms unfolding ndesign-def
by (rule-tac rdesign-mu-wf-refine-intro[of R F [p]< e], simp-all add: alpha)

```

**theorem** *ndesign-mu-wf-refine-intro*:

```

assumes   WF: wf R
and       M: Monotonic F
and       H: F ∈ [N]H → [N]H
and induct-step:
  ∧st. ((p ∧ e =u <<st>>) ⊢n Q) ⊆ F ((p ∧ (e, <<st>>)u ∈u <<R>>) ⊢n Q)
shows (p ⊢n Q) ⊆ μN F
proof –
{
  fix st

```

```

have (p ∧ e =u <<st>>) ⊢n Q ⊆ μN F
using WF proof (induction rule: wf-induct-rule)
  case (less st)
  hence 0: (p ∧ (e, <<st>>)u ∈u <<R>>) ⊢n Q ⊆ μN F
    by rel-blast
  from M H des-theory.LFP-lemma3 mono-Monotone-utp-order
  have 1: μN F ⊆ F (μN F)
    by (simp add: mono-Monotone-utp-order ndes-theory.LFP-lemma3)
  from 0 1 have 2: (p ∧ (e, <<st>>)u ∈u <<R>>) ⊢n Q ⊆ F (μN F)
    by simp
  have 3: F ((p ∧ (e, <<st>>)u ∈u <<R>>) ⊢n Q) ⊆ F (μN F)
    by (simp add: 0 M monoD)
  have 4: (p ∧ e =u <<st>>) ⊢n Q ⊆ ...
    by (rule induct-step)
  show ?case
  using order-trans[OF 3 4] H M ndes-theory.LFP-lemma2 dual-order.trans mono-Monotone-utp-order

  by (metis (no-types) partial-object.simps(1) utp-order-def)
qed
}
thus ?thesis
  by (pred-simp)
qed
end

```

### 3 Design Proof Tactics

```

theory utp-des-tactics
  imports utp-des-theory
begin

```

The tactics split apart a healthy normal design predicate into its pre-postcondition form, using elimination rules, and then attempt to prove refinement conjectures.

**named-theorems** *ND-elim*

```

lemma ndes-elim: [ P is N; Q(⌊preD(P)⌋< ⊢n postD(P)) ] ⇒ Q(P)
  by (simp add: ndesign-form)

```

```

lemma ndes-ind-elim: [ ⋀ i. P i is N; Q(λ i. ⌊preD(P i)⌋< ⊢n postD(P i)) ] ⇒ Q(P)
  by (simp add: ndesign-form)

```

```

lemma ndes-split [ND-elim]: [ P is N; ⋀ pre post. Q(pre ⊢n post) ] ⇒ Q(P)
  by (metis H1-H2-eq-rdesign H1-H3-impl-H2 H3-unrest-out-alpha Healthy-def drop-pre-inv ndesign-def)

```

Use given closure laws (cls) to expand normal design predicates

```

method ndes-expand uses cls = (insert cls, (erule ND-elim)+)

```

Expand and simplify normal designs

```

method ndes-simp uses cls =
  ((ndes-expand cls: cls)?, (simp add: ndes-simp closure alpha usubst unrest wp prod.case-eq-if))

```

Attempt to discharge a refinement between two normal designs

```

method ndes-refine uses cls =

```



(*ndes-simp* *cls*: *cls*; *rule-tac* *ndesign-refine-intro*; (*insert* *cls*; *rel-simp*; *auto?*))

Attempt to discharge an equality between two normal designs

**method** *ndes-eq* **uses** *cls* =

(*ndes-simp* *cls*: *cls*; *rule-tac* *antisym*; *rule-tac* *ndesign-refine-intro*; (*insert* *cls*; *rel-simp*; *auto?*))

**end**

## 4 Imperative Programming in Designs

**theory** *utp-des-prog*

**imports** *utp-des-tactics*

**begin**

### 4.1 Assignment

**definition** *assigns-d* :: ' $\alpha$  *usubst*  $\Rightarrow$  ' $\alpha$  *hrel-des* ( $\langle \cdot \rangle_D$ ) **where**  
 $[upred-defs]:$  *assigns-d*  $\sigma = (true \vdash_r assigns-r \sigma)$

**syntax**

*-assignmentd* :: *svids*  $\Rightarrow$  *uexprs*  $\Rightarrow$  *logic* (**infixr** :=<sub>D</sub> 62)

**translations**

*-assignmentd* *xs vs* ==> *CONST assigns-d* (*-mk-usubst* (*id<sub>s</sub>*) *xs vs*)

*-assignmentd* *x v* <= *CONST assigns-d* (*CONST subst-upd* (*id<sub>s</sub>*) *x v*)

*-assignmentd* *x v* <= *-assignmentd* (*-spvar* *x*) *v*

*x, y :=<sub>D</sub> u, v* <= *CONST assigns-d* (*CONST subst-upd* (*CONST subst-upd* (*id<sub>s</sub>*) (*CONST pr-var* *x*)  
*u*) (*CONST pr-var* *y*) *v*)

**lemma** *assigns-d-is-H1-H2* [*closure*]:  $\langle \sigma \rangle_D$  is **H**  
**by** (*simp add: assigns-d-def rdesign-is-H1-H2*)

**lemma** *assigns-d-H1-H3* [*closure*]:  $\langle \sigma \rangle_D$  is **N**  
**by** (*metis H1-rdesign H3-ndesign Healthy-def' aext-true assigns-d-def ndesign-def*)

Designs are closed under substitutions on state variables only (via lifting)

**lemma** *state-subst-H1-H2-closed* [*closure*]:

$P$  is **H**  $\implies [\sigma \oplus_s \Sigma_D]_s \uparrow P$  is **H**

**by** (*metis H1-H2-eq-rdesign Healthy-if rdesign-is-H1-H2 state-subst-design*)

**lemma** *assigns-d-ndes-def* [*ndes-simp*]:

$\langle \sigma \rangle_D = (true \vdash_n \langle \sigma \rangle_a)$

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

**lemma** *assigns-d-id* [*simp*]:  $\langle id_s \rangle_D = II_D$

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

**lemma** *assign-d-left-comp*:

$(\langle f \rangle_D ;; (P \vdash_r Q)) = ([f]_s \uparrow P \vdash_r [f]_s \uparrow Q)$

**by** (*simp add: assigns-d-def rdesign-composition assigns-r-comp subst-not*)

**lemma** *assign-d-right-comp*:

$((P \vdash_r Q) ;; \langle f \rangle_D) = ((\neg ((\neg P) ;; true)) \vdash_r (Q ;; \langle f \rangle_a))$

**by** (*simp add: assigns-d-def rdesign-composition*)

**lemma** *assigns-d-comp*:  
 $(\langle f \rangle_D ;; \langle g \rangle_D) = \langle g \circ_s f \rangle_D$   
**by** (*simp add: assigns-d-def redesign-composition assigns-comp*)

**lemma** *assigns-d-comp-ext*:  
**assumes**  $P$  **is** **H**  
**shows**  $(\langle \sigma \rangle_D ;; P) = [\sigma \oplus_s \Sigma_D]_s \uparrow P$

**proof** –  
**have**  $\langle \sigma \rangle_D ;; P = \langle \sigma \rangle_D ;; (pre_D(P) \vdash_r post_D(P))$   
**by** (*metis H1-H2-commute H1-H2-is-rdesign H2-idem Healthy-def' assms*)  
**also have**  $\dots = [\sigma]_s \uparrow pre_D(P) \vdash_r [\sigma]_s \uparrow post_D(P)$   
**by** (*simp add: assign-d-left-comp*)  
**also have**  $\dots = [\sigma \oplus_s \Sigma_D]_s \uparrow (pre_D(P) \vdash_r post_D(P))$   
**by** (*rel-auto*)  
**also have**  $\dots = [\sigma \oplus_s \Sigma_D]_s \uparrow P$   
**by** (*metis H1-H2-commute H1-H2-is-rdesign H2-idem Healthy-def' assms*)  
**finally show** *?thesis* **by** (*simp-all add: closure assms*)  
**qed**

Normal designs are closed under substitutions on state variables only

**lemma** *state-subst-H1-H3-closed* [*closure*]:  
 $P$  **is** **N**  $\implies [\sigma \oplus_s \Sigma_D]_s \uparrow P$  **is** **N**  
**by** (*metis H1-H2-eq-rdesign H1-H3-impl-H2 Healthy-if assign-d-left-comp assigns-d-H1-H3 seq-r-H1-H3-closed state-subst-design*)

**lemma** *H4-assigns-d*:  $\langle \sigma \rangle_D$  **is** *H4*  
**proof** –  
**have**  $(\langle \sigma \rangle_D ;; (false \vdash_r true_h)) = (false \vdash_r true)$   
**by** (*simp add: assigns-d-def redesign-composition assigns-r-feasible*)  
**moreover have**  $\dots = true$   
**by** (*rel-auto*)  
**ultimately show** *?thesis*  
**using** *is-H4-alt-def* **by** *auto*  
**qed**

## 4.2 Guarded Commands

**definition** *GrdCommD* ::  $'\alpha$  *upred*  $\Rightarrow$   $(' \alpha, ' \beta)$  *rel-des*  $\Rightarrow$   $(' \alpha, ' \beta)$  *rel-des* **where**  
 $[upred-defs]$ : *GrdCommD*  $b$   $P = P \triangleleft b \triangleright_D \top_D$

**syntax** *-GrdCommD* :: *uexp*  $\Rightarrow$  *logic*  $\Rightarrow$  *logic*  $(- \rightarrow_D - [60, 61] 61)$   
**translations** *-GrdCommD*  $b$   $P == CONST$  *GrdCommD*  $b$   $P$

**lemma** *GrdCommD-ndes-simp* [*ndes-simp*]:  
 $b \rightarrow_D (p_1 \vdash_n P_2) = ((b \Rightarrow p_1) \vdash_n ([b]_{<} \wedge P_2))$   
**by** (*rel-auto*)

**lemma** *GrdCommD-H1-H3-closed* [*closure*]:  $P$  **is** **N**  $\implies b \rightarrow_D P$  **is** **N**  
**by** (*simp add: GrdCommD-def closure*)

**lemma** *GrdCommD-true* [*simp*]:  $true \rightarrow_D P = P$   
**by** (*rel-auto*)

**lemma** *GrdCommD-false* [*simp*]:  $false \rightarrow_D P = \top_D$   
**by** (*rel-auto*)

**lemma** *GrdCommD-abort* [simp]:  $b \rightarrow_D \text{true} = ((\neg b) \vdash_n \text{false})$   
**by** (*rel-auto*)

### 4.3 Frames and Extensions

**definition** *des-frame* ::  $('α \Rightarrow 'β) \Rightarrow 'β \text{ hrel-des} \Rightarrow 'β \text{ hrel-des}$  **where**  
[upred-defs]: *des-frame*  $x P = \text{frame } (ok \ +_L x \ ;_L \ \Sigma_D) P$

**definition** *des-frame-ext* ::  $('α \Rightarrow 'β) \Rightarrow 'α \text{ hrel-des} \Rightarrow 'β \text{ hrel-des}$  **where**  
[upred-defs]: *des-frame-ext*  $a P = \text{des-frame } a \ (\text{rel-aext } P \ (\text{lmap}_D \ a))$

**syntax**

-*des-frame* ::  $\text{salpha} \Rightarrow \text{logic} \Rightarrow \text{logic } (-: [-]_D \ [99,0] \ 100)$   
-*des-frame-ext* ::  $\text{salpha} \Rightarrow \text{logic} \Rightarrow \text{logic } (-: [-]_D^+ \ [99,0] \ 100)$

**translations**

-*des-frame*  $x P \Rightarrow \text{CONST } \text{des-frame } x P$   
-*des-frame*  $(-\text{salphaset } (-\text{salphamk } x)) P \Leftarrow \text{CONST } \text{des-frame } x P$   
-*des-frame-ext*  $x P \Rightarrow \text{CONST } \text{des-frame-ext } x P$   
-*des-frame-ext*  $(-\text{salphaset } (-\text{salphamk } x)) P \Leftarrow \text{CONST } \text{des-frame-ext } x P$

**lemma** *lmapD-rel-aext-ndes* [ndes-simp]:  
 $(p \vdash_n Q) \oplus_r \text{lmap}_D[a] = (p \oplus_p a \vdash_n Q \oplus_r a)$   
**by** (*rel-auto*)

### 4.4 Alternation

**consts**

*ualtern* ::  $'a \text{ set} \Rightarrow ('a \Rightarrow 'p) \Rightarrow ('a \Rightarrow 'r) \Rightarrow 'r \Rightarrow 'r$   
*ualtern-list* ::  $('a \times 'r) \text{ list} \Rightarrow 'r \Rightarrow 'r$

**definition** *AlternateD* ::  $'a \text{ set} \Rightarrow ('a \Rightarrow 'α \text{ upred}) \Rightarrow ('a \Rightarrow ('α, 'β) \text{ rel-des}) \Rightarrow ('α, 'β) \text{ rel-des} \Rightarrow ('α, 'β) \text{ rel-des}$  **where**  
[upred-defs, ndes-simp]:  
*AlternateD*  $A g P Q = (\bigcap i \in A \cdot g(i) \rightarrow_D P(i)) \sqcap ((\bigwedge i \in A \cdot \neg g(i)) \rightarrow_D Q)$

This lemma shows that our generalised alternation is the same operator as Marcel Oliveira's definition of alternation when the else branch is abort.

**lemma** *AlternateD-abort-alternate*:

**assumes**  $\bigwedge i. P(i) \text{ is } \mathbf{N}$

**shows**

*AlternateD*  $A g P \perp_D =$   
 $((\bigvee i \in A \cdot g(i)) \wedge (\bigwedge i \in A \cdot g(i) \Rightarrow \lfloor \text{pre}_D(P \ i) \rfloor_{<})) \vdash_n (\bigvee i \in A \cdot \lfloor g(i) \rfloor_{<} \wedge \text{post}_D(P \ i))$

**proof** (*cases*  $A = \{\}$ )

**case** *False*

**have** *AlternateD*  $A g P \perp_D =$

$(\bigcap i \in A \cdot g(i) \rightarrow_D (\lfloor \text{pre}_D(P \ i) \rfloor_{<} \vdash_n \text{post}_D(P \ i))) \sqcap ((\bigwedge i \in A \cdot \neg g(i)) \rightarrow_D (\text{false} \vdash_n \text{true}))$

**by** (*simp add: AlternateD-def ndesign-form bot-d-ndes-def assms*)

**also have**  $\dots = ((\bigvee i \in A \cdot g(i)) \wedge (\bigwedge i \in A \cdot g(i) \Rightarrow \lfloor \text{pre}_D(P \ i) \rfloor_{<})) \vdash_n (\bigvee i \in A \cdot \lfloor g(i) \rfloor_{<} \wedge \text{post}_D(P \ i))$

*i*)

**by** (*simp add: ndes-simp False, rel-auto*)

**finally show** *?thesis* **by** *simp*

**next**

**case** *True*

**thus** *?thesis*

**by** (*simp add: AlternateD-def, rel-auto*)

qed

**definition** *AlternateD-list* :: ('α upred × ('α, 'β) rel-des) list ⇒ ('α, 'β) rel-des ⇒ ('α, 'β) rel-des  
**where**

[upred-defs, ndes-simp]:

*AlternateD-list* xs P =

*AlternateD* {0..*length* xs} (λ i. map fst xs ! i) (λ i. map snd xs ! i) P

**ad hoc-overloading**

*ualtern AlternateD* and

*ualtern-list AlternateD-list*

**nonterminal** *gcomm* and *gcomms*

**syntax**

*-altind-els* :: pttrn ⇒ uexp ⇒ uexp ⇒ logic ⇒ logic ⇒ logic (if -∈- · - → - else - fi)

*-altind* :: pttrn ⇒ uexp ⇒ uexp ⇒ logic ⇒ logic (if -∈- · - → - fi)

*-gcomm* :: uexp ⇒ logic ⇒ gcomm (- → - [60, 60] 61)

*-gcomm-nil* :: gcomm ⇒ gcomms (-)

*-gcomm-cons* :: gcomm ⇒ gcomms ⇒ gcomms (- | - [60, 61] 61)

*-gcomm-show* :: logic ⇒ logic

*-altgcomm-els* :: gcomms ⇒ logic ⇒ logic (if / - / else - / fi)

*-altgcomm* :: gcomms ⇒ logic (if / - / fi)

**translations**

*-altind-els* x A g P Q => CONST *ualtern* A (λ x. g) (λ x. P) Q

*-altind-els* x A g P Q <= CONST *ualtern* A (λ x. g) (λ x'. P) Q

*-altind* x A g P => CONST *ualtern* A (λ x. g) (λ x. P) (CONST *Orderings.top*)

*-altind* x A g P <= CONST *ualtern* A (λ x. g) (λ x'. P) (CONST *Orderings.top*)

*-altgcomm* cs => CONST *ualtern-list* cs (CONST *Orderings.top*)

*-altgcomm* (-gcomm-show cs) <= CONST *ualtern-list* cs (CONST *Orderings.top*)

*-altgcomm-els* cs P => CONST *ualtern-list* cs P

*-altgcomm-els* (-gcomm-show cs) P <= CONST *ualtern-list* cs P

*-gcomm* g P => (g, P)

*-gcomm* g P <= -gcomm-show (g, P)

*-gcomm-cons* c cs => c # cs

*-gcomm-cons* (-gcomm-show c) (-gcomm-show (d # cs)) <= -gcomm-show (c # d # cs)

*-gcomm-nil* c => [c]

*-gcomm-nil* (-gcomm-show c) <= -gcomm-show [c]

**lemma** *AlternateD-H1-H3-closed* [closure]:

**assumes**  $\bigwedge i. i \in A \implies P\ i\ \text{is}\ \mathbf{N}\ Q\ \text{is}\ \mathbf{N}$

**shows** if  $i \in A \cdot g(i) \rightarrow P(i)$  else  $Q\ fi\ \text{is}\ \mathbf{N}$

**proof** (cases A = {})

**case** True

**then show** ?thesis

**by** (simp add: *AlternateD-def* closure false-upred-def assms)

**next**

**case** False

**then show** ?thesis

**by** (simp add: *AlternateD-def* closure assms)

qed

**lemma** *AltD-ndes-simp* [ndes-simp]:

$$\text{if } i \in A \cdot g(i) \rightarrow (P_1(i) \vdash_n P_2(i)) \text{ else } Q_1 \vdash_n Q_2 \text{ fi}$$

$$= ((\bigwedge i \in A \cdot g(i) \Rightarrow P_1(i)) \wedge ((\bigwedge i \in A \cdot \neg g(i) \Rightarrow Q_1))) \vdash_n$$

$$((\bigvee i \in A \cdot [g(i)]_{<} \wedge P_2(i)) \vee (\bigwedge i \in A \cdot \neg [g(i)]_{<} \wedge Q_2))$$

**proof** (*cases*  $A = \{\}$ )  
**case** *True*  
**then show** *?thesis* **by** (*simp add: AlternateD-def*)  
**next**  
**case** *False*  
**then show** *?thesis*  
**by** (*simp add: ndes-simp, rel-auto*)  
**qed**

**declare** *UINF-upto-expand-first* [*ndes-simp*]  
**declare** *UINF-Suc-shift* [*ndes-simp*]  
**declare** *USUP-upto-expand-first* [*ndes-simp*]  
**declare** *USUP-Suc-shift* [*ndes-simp*]  
**declare** *true-upred-def* [*THEN sym, ndes-simp*]

**lemma** *AlternateD-mono-refine*:  
**assumes**  $\bigwedge i. P(i) \sqsubseteq Q(i) \wedge R \sqsubseteq S$   
**shows**  $(\text{if } i \in A \cdot g(i) \rightarrow P(i) \text{ else } R \text{ fi}) \sqsubseteq (\text{if } i \in A \cdot g(i) \rightarrow Q(i) \text{ else } S \text{ fi})$   
**using** *assms* **by** (*rel-auto, meson*)

**lemma** *Monotonic-AlternateD [closure]*:  

$$\llbracket \bigwedge i. \text{Monotonic } (F(i)); \text{Monotonic } G \rrbracket \Longrightarrow \text{Monotonic } (\lambda X. \text{if } i \in A \cdot g(i) \rightarrow F(i) \text{ else } G(X) \text{ fi})$$
**by** (*rel-auto, meson*)

**lemma** *AlternateD-eq*:  
**assumes**  $A = B \wedge \bigwedge i. i \in A \Longrightarrow g(i) = h(i) \wedge \bigwedge i. i \in A \Longrightarrow P(i) = Q(i) \wedge R = S$   
**shows**  $\text{if } i \in A \cdot g(i) \rightarrow P(i) \text{ else } R \text{ fi} = \text{if } i \in B \cdot h(i) \rightarrow Q(i) \text{ else } S \text{ fi}$   
**by** (*insert assms, rel-blast*)

**lemma** *AlternateD-empty*:  

$$\text{if } i \in \{\} \cdot g(i) \rightarrow P(i) \text{ else } Q \text{ fi} = Q$$
**by** (*rel-auto*)

**lemma** *AlternateD-true-singleton*:  
**assumes**  $P \text{ is } \mathbf{N}$   
**shows**  $\text{if } \text{true} \rightarrow P \text{ fi} = P$   
**by** (*ndes-eq cls: assms*)

**lemma** *AlternateD-no-ind*:  
**assumes**  $A \neq \{\} \wedge P \text{ is } \mathbf{N} \wedge Q \text{ is } \mathbf{N}$   
**shows**  $\text{if } i \in A \cdot b \rightarrow P \text{ else } Q \text{ fi} = \text{if } b \rightarrow P \text{ else } Q \text{ fi}$   
**by** (*ndes-eq cls: assms*)

**lemma** *AlternateD-singleton*:  
**assumes**  $P(k) \text{ is } \mathbf{N} \wedge Q \text{ is } \mathbf{N}$   
**shows**  $\text{if } i \in \{k\} \cdot b(i) \rightarrow P(i) \text{ else } Q \text{ fi} = \text{if } b(k) \rightarrow P(k) \text{ else } Q \text{ fi} \text{ (is ?lhs = ?rhs)}$

**proof** –  
**have** *?lhs*  $= \text{if } i \in \{k\} \cdot b(i) \rightarrow P(i) \text{ else } Q \text{ fi}$   
**by** (*auto intro: AlternateD-eq simp add: assms ndesign-form*)  
**also have**  $\dots = \text{?rhs}$   
**by** (*simp add: AlternateD-no-ind assms closure*)  
**finally show** *?thesis* .

qed

**lemma** *AlternateD-commute:*

**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } g_1 \rightarrow P \mid g_2 \rightarrow Q \text{ fi} = \text{if } g_2 \rightarrow Q \mid g_1 \rightarrow P \text{ fi}$   
**by** (*ndes-eq cls:assms*)

**lemma** *AlternateD-dcond:*

**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } g \rightarrow P \text{ else } Q \text{ fi} = P \triangleleft g \triangleright_D Q$   
**by** (*ndes-eq cls:assms*)

**lemma** *AlternateD-cover:*

**assumes**  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } g \rightarrow P \text{ else } Q \text{ fi} = \text{if } g \rightarrow P \mid (\neg g) \rightarrow Q \text{ fi}$   
**by** (*ndes-eq cls: assms*)

**lemma** *UINF-ndes-expand:*

**assumes**  $\bigwedge i. i \in A \implies P(i)$  is  $\mathbf{N}$   
**shows**  $(\bigsqcup i \in A \cdot \lfloor \text{pre}_D(P(i)) \rfloor_{<} \vdash_n \text{post}_D(P(i))) = (\bigsqcup i \in A \cdot P(i))$   
**by** (*rule UINF-cong, simp add: assms ndesign-form*)

**lemma** *USUP-ndes-expand:*

**assumes**  $\bigwedge i. i \in A \implies P(i)$  is  $\mathbf{N}$   
**shows**  $(\bigsqcup i \in A \cdot \lfloor \text{pre}_D(P(i)) \rfloor_{<} \vdash_n \text{post}_D(P(i))) = (\bigsqcup i \in A \cdot P(i))$   
**by** (*rule USUP-cong, simp add: assms ndesign-form*)

**lemma** *AlternateD-ndes-expand:*

**assumes**  $\bigwedge i. i \in A \implies P(i)$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
**shows**  $\text{if } i \in A \cdot g(i) \rightarrow P(i) \text{ else } Q \text{ fi} =$   
 $\text{if } i \in A \cdot g(i) \rightarrow (\lfloor \text{pre}_D(P(i)) \rfloor_{<} \vdash_n \text{post}_D(P(i))) \text{ else } \lfloor \text{pre}_D(Q) \rfloor_{<} \vdash_n \text{post}_D(Q) \text{ fi}$   
**apply** (*simp add: AlternateD-def*)  
**apply** (*subst UINF-ndes-expand[THEN sym]*)  
**apply** (*simp add: assms closure*)  
**apply** (*ndes-simp cls: assms*)  
**apply** (*rel-auto*)  
**done**

**lemma** *AlternateD-ndes-expand':*

**assumes**  $\bigwedge i. i \in A \implies P(i)$  is  $\mathbf{N}$   
**shows**  $\text{if } i \in A \cdot g(i) \rightarrow P(i) \text{ fi} = \text{if } i \in A \cdot g(i) \rightarrow (\lfloor \text{pre}_D(P(i)) \rfloor_{<} \vdash_n \text{post}_D(P(i))) \text{ fi}$   
**apply** (*simp add: AlternateD-def*)  
**apply** (*subst UINF-ndes-expand[THEN sym]*)  
**apply** (*simp add: assms closure*)  
**apply** (*ndes-simp cls: assms*)  
**apply** (*rel-auto*)  
**done**

**lemma** *ndesign-ind-form:*

**assumes**  $\bigwedge i. P(i)$  is  $\mathbf{N}$   
**shows**  $(\lambda i. \lfloor \text{pre}_D(P(i)) \rfloor_{<} \vdash_n \text{post}_D(P(i))) = P$   
**by** (*simp add: assms ndesign-form*)

**lemma** *AlternateD-insert:*

**assumes**  $\bigwedge i. i \in (\text{insert } x \ A) \implies P(i)$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$

**shows**  $if\ i \in (insert\ x\ A) \cdot g(i) \rightarrow P(i)\ else\ Q\ fi =$   
 $if\ g(x) \rightarrow P(x) \mid$   
 $(\bigvee\ i \in A \cdot g(i)) \rightarrow if\ i \in A \cdot g(i) \rightarrow P(i)\ fi$   
 $else\ Q$   
 $fi\ (is\ ?lhs = ?rhs)$   
**proof**  $-$   
**have**  $?lhs = if\ i \in (insert\ x\ A) \cdot g(i) \rightarrow ([pre_D(P(i))]_{<} \vdash_n post_D(P(i)))\ else\ ([pre_D(Q)]_{<} \vdash_n post_D(Q))\ fi$   
**using** *AlternateD-ndes-expand* *assms(1)* *assms(2)* **by** *blast*  
**also**  
**have**  $... =$   
 $if\ g(x) \rightarrow ([pre_D(P(x))]_{<} \vdash_n post_D(P(x))) \mid$   
 $(\bigvee\ i \in A \cdot g(i)) \rightarrow if\ i \in A \cdot g(i) \rightarrow [pre_D(P(i))]_{<} \vdash_n post_D(P(i))\ fi$   
 $else\ [pre_D(Q)]_{<} \vdash_n post_D(Q)$   
 $fi$   
**by** (*ndes-simp* *cls:assms*, *rel-auto*)  
**also have**  $... = ?rhs$   
**by** (*simp add: AlternateD-ndes-expand' ndesign-form* *assms*)  
**finally show** *?thesis* .  
**qed**

## 4.5 Iteration

**theorem** *ndesign-iteration-wlp* [*ndes-simp*]:  
 $(p \vdash_n Q) ;; (p \vdash_n Q) \wedge n = ((\bigwedge\ i \in \{0..n\} \cdot (Q \wedge i)\ wlp\ p) \vdash_n Q \wedge Suc\ n)$   
**proof** (*induct n*)  
**case** 0  
**then show** *?case* **by** (*rel-auto*)  
**next**  
**case** (*Suc n*) **note** *hyp = this*  
**have**  $(p \vdash_n Q) ;; (p \vdash_n Q) \wedge Suc\ n = (p \vdash_n Q) ;; (p \vdash_n Q) ;; (p \vdash_n Q) \wedge n$   
**by** (*simp add: upred-semiring.power-Suc*)  
**also have**  $... = (p \vdash_n Q) ;; ((\bigwedge\ i \in \{0..n\} \cdot Q \wedge i\ wlp\ p) \vdash_n Q \wedge Suc\ n)$   
**by** (*simp add: hyp*)  
**also have**  $... = (p \wedge Q\ wlp\ (\bigwedge\ i \in \{0..n\} \cdot Q \wedge i\ wlp\ p)) \vdash_n (Q ;; Q) ;; Q \wedge n$   
**by** (*simp add: upred-semiring.power-Suc ndesign-composition-wp seqr-assoc*)  
**also have**  $... = (p \wedge (\bigwedge\ i \in \{0..n\} \cdot Q \wedge Suc\ i\ wlp\ p)) \vdash_n (Q ;; Q) ;; Q \wedge n$   
**by** (*simp add: upred-semiring.power-Suc wp*)  
**also have**  $... = (p \wedge (\bigwedge\ i \in \{0..n\} \cdot Q \wedge Suc\ i\ wlp\ p)) \vdash_n (Q ;; Q) ;; Q \wedge n$   
**by** (*simp add: USUP-as-Inf-image*)  
**also have**  $... = (p \wedge (\bigwedge\ i \in \{1..Suc\ n\} \cdot Q \wedge i\ wlp\ p)) \vdash_n (Q ;; Q) ;; Q \wedge n$   
**by** (*metis (no-types, lifting) One-nat-def image-Suc-atLeastAtMost image-cong image-image*)  
**also have**  $... = (Q \wedge 0\ wlp\ p \wedge (\bigwedge\ i \in \{1..Suc\ n\} \cdot Q \wedge i\ wlp\ p)) \vdash_n (Q ;; Q) ;; Q \wedge n$   
**by** (*simp add: wp*)  
**also have**  $... = ((\bigwedge\ i \in \{0..Suc\ n\} \cdot Q \wedge i\ wlp\ p)) \vdash_n (Q ;; Q) ;; Q \wedge n$   
**by** (*simp add: atMost-Suc-eq-insert-0 atLeast0AtMost conj-upred-def image-Suc-atMost*)  
**also have**  $... = (\bigwedge\ i \in \{0..Suc\ n\} \cdot Q \wedge i\ wlp\ p) \vdash_n Q \wedge Suc\ (Suc\ n)$   
**by** (*simp add: upred-semiring.power-Suc USUP-as-Inf-image upred-semiring.mult-assoc*)  
**finally show** *?case* .  
**qed**

## Overloadable Syntax

**consts**  
 $uiterate :: 'a\ set \Rightarrow ('a \Rightarrow 'p) \Rightarrow ('a \Rightarrow 'r) \Rightarrow 'r$   
 $uiterate-list :: ('a \times 'r)\ list \Rightarrow 'r$

### syntax

-iterind  $:: \text{pttrn} \Rightarrow \text{uexp} \Rightarrow \text{uexp} \Rightarrow \text{logic} \Rightarrow \text{logic} \text{ (do } \cdot \in \cdot \cdot \rightarrow \cdot \text{ od)}$   
 -itergcomm  $:: \text{gcomms} \Rightarrow \text{logic} \text{ (do } \cdot \text{ od)}$

### translations

-iterind  $x \ A \ g \ P \Rightarrow \text{CONST } \text{uiterate } A \ (\lambda x. g) \ (\lambda x. P)$   
 -iterind  $x \ A \ g \ P \leq \text{CONST } \text{uiterate } A \ (\lambda x. g) \ (\lambda x'. P)$   
 -itergcomm  $cs \Rightarrow \text{CONST } \text{uiterate-list } cs$   
 -itergcomm  $(\text{-gcomm-show } cs) \leq \text{CONST } \text{uiterate-list } cs$

**definition** *IterateD*  $:: 'a \text{ set} \Rightarrow ('a \Rightarrow 'a \text{ upred}) \Rightarrow ('a \Rightarrow 'a \text{ hrel-des}) \Rightarrow 'a \text{ hrel-des}$  **where**  
 $[upred\text{-defs}, ndes\text{-simp}]$ :

*IterateD*  $A \ g \ P = (\mu_N \ X \cdot \text{if } i \in A \cdot g(i) \rightarrow P(i) ;; X \text{ else } II_D \text{ fi})$

**definition** *IterateD-list*  $:: ('a \text{ upred} \times 'a \text{ hrel-des}) \text{ list} \Rightarrow 'a \text{ hrel-des}$  **where**  
 $[upred\text{-defs}, ndes\text{-simp}]$ :

*IterateD-list*  $xs = \text{IterateD } \{0..<\text{length } xs\} \ (\lambda i. \text{fst } (\text{nth } xs \ i)) \ (\lambda i. \text{snd } (\text{nth } xs \ i))$

### adhoc-overloading

*uiterate* *IterateD* **and**  
*uiterate-list* *IterateD-list*

**lemma** *IterateD-H1-H3-closed*  $[closure]$ :

**assumes**  $\bigwedge i. i \in A \implies P \ i \text{ is } \mathbf{N}$   
**shows**  $\text{do } i \in A \cdot g(i) \rightarrow P(i) \text{ od is } \mathbf{N}$

**proof**  $(\text{cases } A = \{\})$

**case** *True*

**then show** *?thesis*

**by**  $(\text{simp add: IterateD-def closure assms})$

**next**

**case** *False*

**then show** *?thesis*

**by**  $(\text{simp add: IterateD-def closure assms})$

**qed**

**lemma** *IterateD-empty*:

$\text{do } i \in \{\} \cdot g(i) \rightarrow P(i) \text{ od} = II_D$

**by**  $(\text{simp add: IterateD-def AlternateD-empty ndes-theory.LFP-const skip-d-is-H1-H3})$

**lemma** *IterateD-list-single-expand*:

$\text{do } b \rightarrow P \text{ od} = (\mu_{NDES} \ X \cdot \text{if } b \rightarrow P ;; X \text{ else } II_D \text{ fi})$

**oops**

**lemma** *IterateD-singleton*:

**assumes**  $P \text{ is } \mathbf{N}$

**shows**  $\text{do } b \rightarrow P \text{ od} = \text{do } i \in \{0\} \cdot b \rightarrow P \text{ od}$

**apply**  $(\text{simp add: IterateD-list-def IterateD-def AlternateD-singleton assms})$

**apply**  $(\text{subst AlternateD-singleton})$

**apply**  $(\text{simp})$

**apply**  $(\text{rel-auto})$

**oops**

**lemma** *IterateD-mono-refine*:

**assumes**

$\bigwedge i. P \ i \text{ is } \mathbf{N} \ \bigwedge i. Q \ i \text{ is } \mathbf{N}$



```

 $\bigwedge i. P\ i \sqsubseteq Q\ i$ 
shows  $(do\ i \in A \cdot g(i) \rightarrow P(i)\ od) \sqsubseteq (do\ i \in A \cdot g(i) \rightarrow Q(i)\ od)$ 
apply (simp add: IterateD-def ndes-theory.utp-lfp-def)
apply (subst ndes-theory.utp-lfp-def)
apply (simp-all add: closure assms)
apply (subst ndes-theory.utp-lfp-def)
apply (simp-all add: closure assms)
apply (rule gfp-mono)
apply (rule AlternateD-mono-refine)
apply (simp-all add: closure segr-mono assms)
done

```

**lemma** *IterateD-single-refine*:

```

assumes
   $P\ is\ N\ Q\ is\ N\ P \sqsubseteq Q$ 
shows  $(do\ g \rightarrow P\ od) \sqsubseteq (do\ g \rightarrow Q\ od)$ 
oops

```

**lemma** *IterateD-refine-intro*:

```

fixes  $V :: (nat, 'a)\ uexpr$ 
assumes vwb-lens w
shows
 $I \vdash_n (w: [I \wedge \neg (\bigvee i \in A \cdot g(i))]_{>}) \sqsubseteq$ 
 $do\ i \in A \cdot g(i) \rightarrow (I \wedge g(i)) \vdash_n (w: [I]_{>} \wedge [V]_{>} <_u [V]_{<})\ od$ 
proof (cases A = {})
case True
with assms show ?thesis
by (simp add: IterateD-empty, rel-auto)

```

**next**

```

case False
then show ?thesis
using assms
apply (simp add: IterateD-def)
apply (rule ndesign-mu-wf-refine-intro[where e=V and R={ (x, y). x < y }])
apply (simp-all add: wf closure)
apply (simp add: ndes-simp unrest)
apply (rule ndesign-refine-intro)
apply (rel-auto)
apply (rel-auto)
apply (metis mwb-lens.put-put vwb-lens-mwb)
done
qed

```

**lemma** *IterateD-single-refine-intro*:

```

fixes  $V :: (nat, 'a)\ uexpr$ 
assumes vwb-lens w
shows
 $I \vdash_n (w: [I \wedge \neg g]_{>}) \sqsubseteq$ 
 $do\ g \rightarrow ((I \wedge g) \vdash_n (w: [I]_{>} \wedge [V]_{>} <_u [V]_{<}))\ od$ 
apply (rule order-trans)
defer
apply (rule IterateD-refine-intro[of w {0}  $\lambda i. g\ I\ V$ , simplified, OF assms(1)])
oops

```

## 4.6 Let and Local Variables

**definition**  $LetD :: ('a, 'α) uexpr \Rightarrow ('a \Rightarrow 'α \text{ hrel-des}) \Rightarrow 'α \text{ hrel-des}$  **where**  
 $[upred-defs]: LetD \ v \ P = (P \ x) \llbracket x \rightarrow \lceil v \rceil_{D<} \rrbracket$

**syntax**

$-LetD \quad :: [letbinds, 'a] \Rightarrow 'a \quad ((let_D \ (-) / in \ (-)) \ [0, 10] \ 10)$

**translations**

$-LetD \ (-binds \ b \ bs) \ e \Rightarrow -LetD \ b \ (-LetD \ bs \ e)$   
 $let_D \ x = a \ in \ e \quad \Rightarrow CONST \ LetD \ a \ (\lambda x. \ e)$

**lemma**  $LetD\text{-ndes-simp} \ [ndes-simp]:$

$LetD \ v \ (\lambda x. \ p(x) \vdash_n \ Q(x)) = (p(x) \llbracket x \rightarrow v \rrbracket) \vdash_n \ (Q(x) \llbracket x \rightarrow \lceil v \rceil_{<} \rrbracket)$   
**by**  $(rel\text{-auto})$

**lemma**  $LetD\text{-H1-H3-closed} \ [closure]:$

$\llbracket \bigwedge x. \ P(x) \text{ is } \mathbf{N} \rrbracket \Longrightarrow LetD \ v \ P \text{ is } \mathbf{N}$   
**by**  $(rel\text{-auto})$

**end**

## 4.7 Design Hoare Logic

**theory**  $utp\text{-des-hoare}$

**imports**  $utp\text{-des-prog}$

**begin**

**definition**  $HoareD :: 's \ upred \Rightarrow 's \ \text{hrel-des} \Rightarrow 's \ upred \Rightarrow \text{bool} \ (\{-\}\{-\}_D)$  **where**  
 $[upred-defs, ndes-simp]: HoareD \ p \ S \ q = ((p \vdash_n \lceil q \rceil_{>}) \sqsubseteq S)$

**lemma**  $assigns\text{-hoare-d} \ [hoare-safe]: 'p \Rightarrow \sigma \dagger q' \Longrightarrow \{p\}\langle\sigma\rangle_D \{q\}_D$   
**by**  $rel\text{-auto}$

**lemma**  $skip\text{-hoare-d}: \{p\}II_D \{p\}_D$   
**by**  $(rel\text{-auto})$

**lemma**  $assigns\text{-backward-hoare-d}:$   
 $\{\sigma \dagger p\}\langle\sigma\rangle_D \{p\}_D$   
**by**  $rel\text{-auto}$

**lemma**  $seq\text{-hoare-d}:$

**assumes**  $C \text{ is } \mathbf{N} \ D \text{ is } \mathbf{N} \ \{p\}C\{q\}_D \ \{q\}D\{r\}_D$   
**shows**  $\{p\}C \ ; \ D\{r\}_D$

**proof** –

**obtain**  $c_1 \ C_2$  **where**  $C: C = c_1 \vdash_n \ C_2$   
**by**  $(metis \ assms(1) \ ndesign\text{-form})$

**obtain**  $d_1 \ D_2$  **where**  $D: D = d_1 \vdash_n \ D_2$   
**by**  $(metis \ assms(2) \ ndesign\text{-form})$

**from**  $assms(3-4)$  **show**  $?thesis$

**apply**  $(simp \ add: \ C \ D)$

**apply**  $(ndes\text{-simp})$

**apply**  $(simp \ add: \ ndesign\text{-refinement})$

**apply**  $(rel\text{-blast})$

**done**

**qed**

end

## 5 Designs parallel-by-merge

```
theory utp-des-parallel
  imports utp-des-prog
begin
```

### 5.1 Definitions

We introduce the parametric design merge, which handles merging of the *ok* variables, and leaves the other variables to the parametrised "inner" merge predicate. As expected, a parallel composition of designs can diverge whenever one of its arguments can.

**definition** *des-merge* ::  $((\alpha, \beta, \gamma) \text{ mrg}, \delta) \text{ urel} \Rightarrow ((\alpha \text{ des}, \beta \text{ des}, \gamma \text{ des}) \text{ mrg}, \delta \text{ des}) \text{ urel}$  (**DM**'(-'))  
**where**

[*upred-defs*]:  $\mathbf{DM}(M) \equiv ((\$0:ok \wedge \$1:ok \Rightarrow \$ok' \wedge \$\mathbf{v}_D:0' =_u \$0:\mathbf{v}_D \wedge \$\mathbf{v}_D:1' =_u \$1:\mathbf{v}_D \wedge \$\mathbf{v}_D:<' =_u \$<:\mathbf{v}_D) ;; (true \vdash_n M))$

Parallel composition is then defined via the above merge predicate and the standard UTP parallel-by-merge operator.

**abbreviation**

*dpar-by-merge* ::  $(\alpha, \beta) \text{ rel-des} \Rightarrow ((\alpha, \beta, \gamma) \text{ mrg}, \delta) \text{ urel} \Rightarrow (\alpha, \gamma) \text{ rel-des} \Rightarrow (\alpha, \delta) \text{ rel-des}$   
 $(- \parallel^D - \text{ - } [85, 0, 86] \text{ } 85)$   
**where**  $P \parallel^D_M Q \equiv P \parallel_{\mathbf{DM}(M)} Q$

### 5.2 Theorems

The design merge predicate is symmetric up to the inner merge predicate.

**lemma** *swap-des-merge*:  $\text{swap}_m ;; \mathbf{DM}(M) = \mathbf{DM}(\text{swap}_m ;; M)$   
**by** (*rel-auto*)

The following laws explain the meaning of a merge of two normal (*H3*) designs. The postcondition is straightforward: we simply distribute the inner merge. However, the precondition is more complex. We'd be forgiven for thinking it would simply be  $p \wedge q$ , but this does not account for the possibility of miraculous behaviour in either argument. When this occurs, divergence is effectively overshadowed by miraculous behaviour, and so the precondition needs to involve the relational preconditions of both the design commitments (*P* and *Q*).

**lemma** *ndes-par-aux*:

$(p \vdash_n P) \parallel^D_M (q \vdash_n Q) = (\neg \text{Pre}(\neg p^< \wedge (q^< \Rightarrow Q)) \wedge \neg \text{Pre}(\neg q^< \wedge (p^< \Rightarrow P))) \vdash_n (P \parallel_M Q)$

**proof** –

**have** *p2*:  $(\lceil p \vdash_n P \rceil_0 \wedge \lceil q \vdash_n Q \rceil_1 \wedge \$<' =_u \$\mathbf{v}) ;;$   
 $(\$0:ok \wedge \$1:ok \Rightarrow \$ok' \wedge \$\mathbf{v}_D:0' =_u \$0:\mathbf{v}_D \wedge \$\mathbf{v}_D:1' =_u \$1:\mathbf{v}_D \wedge \$\mathbf{v}_D:<' =_u \$<:\mathbf{v}_D)$   
 $= (\neg \text{Pre}(\neg p^< \wedge (q^< \Rightarrow Q)) \wedge \neg \text{Pre}(\neg q^< \wedge (p^< \Rightarrow P))) \vdash_n (\lceil P \rceil_0 \wedge \lceil Q \rceil_1 \wedge \$<:\mathbf{v}' =_u \$\mathbf{v})$   
**by** (*rel-auto*, *metis+*)

**show** *?thesis*

**by** (*simp add: des-merge-def par-by-merge-alt-def seqr-assoc[THEN sym] ndesign-composition-wp wp p2*)  
**qed**

**lemma** *ndes-par* [*ndes-simp*]:

$(p \vdash_n P) \parallel^D_M (q \vdash_n Q) = ((p \vee q \wedge \neg \text{Pre}(Q)) \wedge (q \vee p \wedge \neg \text{Pre}(P))) \vdash_n (P \parallel_M Q)$

by (simp add: ndes-par-aux, rel-auto)

**lemma** ndes-par-wlp:

( $p \vdash_n P$ )  $\parallel_M^D$  ( $q \vdash_n Q$ ) = ( $(p \vee q \wedge Q \text{ wlp false}) \wedge (q \vee p \wedge P \text{ wlp false})$ )  $\vdash_n$  ( $P \parallel_M Q$ )  
 by (simp add: ndes-par-aux, rel-auto)

If the commitments are both total relations, then we do indeed get a precondition of simply  $p \wedge q$ .

**lemma** ndes-par-total:

assumes  $\text{Pre}(P) = \text{true}$   $\text{Pre}(Q) = \text{true}$   
 shows ( $p \vdash_n P$ )  $\parallel_M^D$  ( $q \vdash_n Q$ ) = ( $p \wedge q$ )  $\vdash_n$  ( $P \parallel_M Q$ )  
 by (simp add: ndes-par-assms)

**lemma** ndes-par-assigns: ( $p_1 \vdash_n \langle \sigma \rangle_a$ )  $\parallel_M^D$  ( $q_1 \vdash_n \langle \varrho \rangle_a$ ) = ( $p_1 \wedge q_1$ )  $\vdash_n$  ( $\langle \sigma \rangle_a \parallel_M \langle \varrho \rangle_a$ ) (is ?lhs = ?rhs)

by (rule ndes-par-total, simp-all add: Pre-assigns)

**lemma** ndes-par-H1-H3-closed [closure]:

assumes  $P$  is  $\mathbf{N}$   $Q$  is  $\mathbf{N}$   
 shows  $P \parallel_M^D Q$  is  $\mathbf{N}$   
 by (metis assms ndes-par ndesign-H1-H3 ndesign-form)

**lemma** ndes-par-commute:

$P \parallel_M^D \text{swap}_m ; M Q = Q \parallel_M^D P$   
 by (metis par-by-merge-commute-swap swap-des-merge)

**lemma** ndes-merge-miracle:

assumes  $P$  is  $\mathbf{N}$   
 shows  $P \parallel_M^D \top_D = \top_D$   
 by (ndes-simp cls: assms, simp add: prepost)

**lemma** ndes-merge-chaos:

assumes  $P$  is  $\mathbf{N}$   $\text{Pre}(\text{post}_D(P)) = \text{true}$   
 shows  $P \parallel_M^D \perp_D = \perp_D$

**proof** –

obtain  $p_1 P_2$  where  $P = p_1 \vdash_n P_2$   
 by (metis assms(1) ndesign-form)  
 with assms(2) show ?thesis  
 by (simp add: ndes-simp, rel-auto)

qed

end

## 6 Design Weakest Preconditions

**theory** utp-des-wp

imports utp-des-prog utp-des-hoare

**begin**

**definition** wp-design :: ( $'\alpha, '\beta$ ) rel-des  $\Rightarrow$   $'\beta$  cond  $\Rightarrow$   $'\alpha$  cond (infix wp<sub>D</sub> 60) where  
 [upred-defs]:  $Q \text{ wp}_D r = (\lfloor \text{pre}_D(Q) \rfloor ; \text{true} :: ('\alpha, '\beta) \text{ urel} \rfloor_{<} \wedge (\text{post}_D(Q) \text{ wlp } r))$

If two normal designs have the same weakest precondition for any given postcondition, then the two designs are equivalent.

**theorem** wpd-eq-intro:  $\llbracket \bigwedge r. (p_1 \vdash_n Q_1) \text{ wp}_D r = (p_2 \vdash_n Q_2) \text{ wp}_D r \rrbracket \Longrightarrow (p_1 \vdash_n Q_1) = (p_2 \vdash_n Q_2)$

**apply** (*rel-simp robust; metis curry-conv*)  
**done**

**theorem** *wpd-H3-eq-intro*:  $\llbracket P \text{ is } H1-H3; Q \text{ is } H1-H3; \bigwedge r. P \text{ wp}_D r = Q \text{ wp}_D r \rrbracket \implies P = Q$   
**by** (*metis H1-H3-commute H1-H3-is-normal-design H3-idem Healthy-def' wpd-eq-intro*)

**lemma** *wp-d-abort* [*wp*]:  $\text{true wp}_D p = \text{false}$   
**by** (*rel-auto*)

**lemma** *wp-assigns-d* [*wp*]:  $\langle \sigma \rangle_D \text{ wp}_D r = \sigma \dagger r$   
**by** (*rel-auto*)

**theorem** *rdesign-wp* [*wp*]:  
 $(\llbracket p \rrbracket_{<} \vdash_r Q) \text{ wp}_D r = (p \wedge Q \text{ wlp } r)$   
**by** (*rel-auto*)

**theorem** *ndesign-wp* [*wp*]:  
 $(p \vdash_n Q) \text{ wp}_D r = (p \wedge Q \text{ wlp } r)$   
**by** (*simp add: ndesign-def rdesign-wp*)

**theorem** *wpd-seq-r*:  
**fixes** *Q1 Q2 :: 'α hrel*  
**shows**  $((\llbracket p1 \rrbracket_{<} \vdash_r Q1) ;; (\llbracket p2 \rrbracket_{<} \vdash_r Q2)) \text{ wp}_D r = (\llbracket p1 \rrbracket_{<} \vdash_r Q1) \text{ wp}_D ((\llbracket p2 \rrbracket_{<} \vdash_r Q2) \text{ wp}_D r)$   
**apply** (*simp add: wp*)  
**apply** (*subst rdesign-composition-wp*)  
**apply** (*simp only: wp*)  
**apply** (*rel-auto*)  
**done**

**theorem** *wpnd-seq-r* [*wp*]:  
**fixes** *Q1 Q2 :: 'α hrel*  
**shows**  $((p1 \vdash_n Q1) ;; (p2 \vdash_n Q2)) \text{ wp}_D r = (p1 \vdash_n Q1) \text{ wp}_D ((p2 \vdash_n Q2) \text{ wp}_D r)$   
**by** (*simp add: ndesign-def wpd-seq-r*)

**theorem** *wpd-seq-r-H1-H3* [*wp*]:  
**fixes** *P Q :: 'α hrel-des*  
**assumes** *P is N Q is N*  
**shows**  $(P ;; Q) \text{ wp}_D r = P \text{ wp}_D (Q \text{ wp}_D r)$   
**by** (*metis H1-H3-commute H1-H3-is-normal-design H1-idem Healthy-def' assms(1) assms(2) wpnd-seq-r*)

**theorem** *wp-hoare-d-link*:  
**assumes** *Q is N*  
**shows**  $\{p\}Q\{r\}_D \longleftrightarrow (Q \text{ wp}_D r \sqsubseteq p)$   
**by** (*ndes-simp cls: assms, rel-auto*)

**end**

## 7 Refinement Calculus

**theory** *utp-des-refcalc*  
**imports** *utp-des-prog*  
**begin**

**definition** *des-spec* ::  $('a \implies 'α) \Rightarrow 'α \text{ upred} \Rightarrow ('α \Rightarrow 'α \text{ upred}) \Rightarrow 'α \text{ hrel-des}$  **where**  
 $[upred-defs, ndes-simp]: \text{des-spec } x \ p \ q = (\bigsqcup \ v \cdot ((p \wedge \&\mathbf{v} =_u \llbracket v \rrbracket) \vdash_n x: \llbracket q(v) \rrbracket_{>}))$

### syntax

$-init-var \quad :: \text{logic}$   
 $-des-spec \quad :: \text{salpha} \Rightarrow \text{logic} \Rightarrow \text{logic} \Rightarrow \text{logic} \text{ } (-: [-, / -]_D \text{ } [99, 0, 0] \text{ } 100)$   
 $-des-log-const \quad :: \text{pttrn} \Rightarrow \text{logic} \Rightarrow \text{logic} \text{ } (con_D - \cdot - [0, 10] \text{ } 10)$

### translations

$-des-spec \text{ } x \text{ } p \text{ } q \Rightarrow CONST \text{ } des-spec \text{ } x \text{ } p \text{ } (\lambda \text{ } -init-var. \text{ } q)$   
 $-des-spec \text{ } (-salphaset \text{ } (-salphamk \text{ } x)) \text{ } p \text{ } q \leq CONST \text{ } des-spec \text{ } x \text{ } p \text{ } (\lambda \text{ } iv. \text{ } q)$   
 $-des-log-const \text{ } x \text{ } P \Rightarrow \sqcup \text{ } x \cdot P$

### parse-translation <

$let$   
 $\quad fun \text{ } init-var-tr \text{ } [] = Syntax.free \text{ } iv$   
 $\quad \quad | \text{ } init-var-tr \text{ } - = raise \text{ } Match;$   
 $in$   
 $[(\text{@}\{\text{syntax-const } -init-var\}, K \text{ } init-var-tr)]$   
 $end$   
 $>$

**abbreviation**  $choose_D \text{ } x \equiv \{\&x\}:[true, true]_D$

**lemma**  $des-spec-simple-def:$

$x:[pre, post]_D = (pre \vdash_n x:[post]_{>})$   
**by**  $(rel-auto)$

**lemma**  $des-spec-abort:$

$x:[false, post]_D = \perp_D$   
**by**  $(rel-auto)$

**lemma**  $des-spec-skip: \emptyset:[true, true]_D = II_D$

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

**lemma**  $des-spec-strengthen-post:$

**assumes**  $'post' \Rightarrow post'$   
**shows**  $w:[pre, post]_D \sqsubseteq w:[pre, post']_D$   
**using**  $assms$  **by**  $(rel-auto)$

**lemma**  $des-spec-weaken-pre:$

**assumes**  $'pre \Rightarrow pre'$   
**shows**  $w:[pre, post]_D \sqsubseteq w:[pre', post]_D$   
**using**  $assms$  **by**  $(rel-auto)$

**lemma**  $des-spec-refine-skip:$

**assumes**  $vwb-lens \text{ } w \text{ } 'pre \Rightarrow post'$   
**shows**  $w:[pre, post]_D \sqsubseteq II_D$   
**using**  $assms$  **by**  $(rel-auto)$

**lemma**  $rc-iter:$

**fixes**  $V :: (nat, 'a) \text{ } uexpr$   
**assumes**  $vwb-lens \text{ } w$

**shows**  $w:[ivr, ivr \wedge \neg (\bigvee i \in A \cdot g(i))]_D$

$\sqsubseteq (do \text{ } i \in A \cdot g(i) \rightarrow \sqcup \text{ } iv \cdot w:[ivr \wedge g(i) \wedge \ll iv \gg =_u \&\mathbf{v}, ivr \wedge (V <_u V[\ll iv \gg / \mathbf{v}])]_D \text{ } od) \text{ } (is$

$?lhs \sqsubseteq ?rhs)$

**apply**  $(rule \text{ } order-trans)$

```

defer
  apply (simp add: des-spec-simple-def)
  apply (rule IterateD-refine-intro[of - - - V])
  apply (simp add: assms)
  apply (rule IterateD-mono-refine)
  apply (simp-all add: ndes-simp closure)
  apply (rel-auto)
done

end

```

## 8 Theory of Invariants

```

theory utp-des-invariants
  imports utp-des-theory
begin

```

The theory of invariants formalises operation and state invariants based on the theory of designs. For more information, please see the associated paper [1, Section 4].

### 8.1 Operation Invariants

**definition**  $OIH(\psi)(D) = (D \wedge (\$ok \wedge \neg D^f \Rightarrow \psi))$

**declare**  $OIH\text{-}def$  [*upred-defs*]

**lemma**  $OIH\text{-}design$ :

```

  assumes  $D$  is  $H1\text{-}H2$ 
  shows  $OIH(\psi)(D) = ((\neg D^f) \vdash (D^t \wedge \psi))$ 
proof -
  from  $assms$  have  $OIH(\psi)(D) = (((\neg D^f) \vdash D^t) \wedge (\$ok \wedge \neg D^f \Rightarrow \psi))$ 
  by (metis H1-H2-commute H1-H2-is-design H1-idem Healthy-def' OIH-def)
  also have  $\dots = ((\$ok \wedge \neg D^f \Rightarrow \$ok' \wedge D^t) \wedge (\$ok \wedge \neg D^f \Rightarrow \psi))$ 
  by (simp add: design-def)
  also have  $\dots = ((\neg D^f) \vdash (D^t \wedge \psi))$ 
  by (pred-auto)
  finally show ?thesis .
qed

```

**lemma**  $OIH\text{-}idem$ :

```

  assumes  $D$  is  $H1\text{-}H2$   $\$ok' \nmid \psi$ 
  shows  $OIH(\psi)(OIH(\psi)(D)) = OIH(\psi)(D)$ 
  using  $assms$ 
  by (simp add: OIH-design design-is-H1-H2 unrest) (simp add: design-def usubst, rel-auto)

```

**lemma**  $OIH\text{-}of\text{-}design$ :

```

 $\$ok' \nmid P \Longrightarrow OIH(\psi)(P \vdash Q) = (P \vdash (Q \wedge \psi))$ 
  by (simp add: OIH-def design-def usubst, rel-auto)

```

### 8.2 State Invariants

**definition**  $ISH(\psi)(D) = (D \vee (\$ok \wedge \neg D^f \wedge [\psi]_< \Rightarrow \$ok' \wedge D^t))$

**declare**  $ISH\text{-}def$  [*upred-defs*]

**lemma** *ISH-design*:  $ISH(\psi)(D) = (\neg D^f \wedge [\psi]_<) \vdash D^t$   
**by** (*rel-auto*, *metis+*)

**lemma** *ISH-idem*:  $ISH(\psi)(ISH(\psi)(D)) = ISH(\psi)(D)$   
**by** (*simp add: ISH-design usubst design-def, pred-auto*)

**lemma** *ISH-of-design*:  
 $\llbracket \$ok' \# P; \$ok' \# Q \rrbracket \implies ISH(\psi)(P \vdash Q) = ((P \wedge [\psi]_<) \vdash Q)$   
**by** (*simp add: ISH-design design-def usubst, pred-auto*)

**definition**  $OSH(\psi)(D) = (D \wedge (\$ok \wedge \neg D^f \wedge [\psi]_< \Rightarrow [\psi]_>))$

**declare** *OSH-def* [*upred-defs*]

**lemma** *OSH-as-OIH*:  
 $OSH(\psi)(D) = OIH([\psi]_< \Rightarrow [\psi]_>)(D)$   
**by** (*simp add: OSH-def OIH-def, pred-auto*)

**lemma** *OSH-design*:  
**assumes** *D is H1-H2*  
**shows**  $OSH(\psi)(D) = ((\neg D^f) \vdash (D^t \wedge ([\psi]_< \Rightarrow [\psi]_>)))$   
**by** (*simp add: OSH-as-OIH OIH-design assms*)

**lemma** *OSH-of-design*:  
 $\llbracket \$ok' \# P; \$ok' \# Q \rrbracket \implies OSH(\psi)(P \vdash Q) = (P \vdash (Q \wedge ([\psi]_< \Rightarrow [\psi]_>)))$   
**by** (*simp add: OSH-design design-is-H1-H2 unrest, simp add: design-def usubst, pred-auto*)

**definition**  $SIH(\psi) = ISH(\psi) \circ OSH(\psi)$

**declare** *SIH-def* [*upred-defs*]

**lemma** *SIH-of-design*:  
 $\llbracket \$ok' \# P; \$ok' \# Q; ok \# \psi \rrbracket \implies SIH(\psi)(P \vdash Q) = ((P \wedge [\psi]_<) \vdash (Q \wedge [\psi]_>))$   
**by** (*simp add: SIH-def OSH-of-design ISH-of-design unrest, pred-auto*)

**end**

## 9 Meta Theory for UTP Designs

**theory** *utp-designs*  
**imports**  
*utp-des-core*  
*utp-des-healths*  
*utp-des-theory*  
*utp-des-tactics*  
*utp-des-hoare*  
*utp-des-prog*  
*utp-des-parallel*  
*utp-des-wp*  
*utp-des-refcalc*  
*utp-des-invariants*  
**begin end**



## References

- [1] A. Cavalcanti, A. Wellings, and J. Woodcock. The Safety-Critical Java memory model formalised. *Formal Aspects of Computing*, 25(1):37–57, 2012.
- [2] A. Cavalcanti and J. Woodcock. A tutorial introduction to designs in unifying theories of programming. In *Proc. 4th Intl. Conf. on Integrated Formal Methods (IFM)*, volume 2999 of *LNCS*, pages 40–66. Springer, 2004.
- [3] W. Guttman and B. Möller. Normal design algebra. *Journal of Logic and Algebraic Programming*, 79(2):144–173, February 2010.
- [4] T. Hoare and J. He. *Unifying Theories of Programming*. Prentice-Hall, 1998.